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EXPERIMENTAL PERFORMANCE OF A MODULAR TURBOJET COMBUSTOR BURNING NATURAL GAS FUEL

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16. Abstract

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SUMMARY

A swirl-can modular combustor was tested with natural gas fuel. The rectangular combustor array simulated a 90° sector of a turbojet engine combustor. The combustor was tested at an inlet air pressure of 45 psia (31 N/cm^2), inlet air temperatures of 600° and 1200° F (589 and 922 K), and inlet Mach numbers of 0.24 and 0.31. The combustor length from diffuser inlet to combustor exit was 33 inches (84 cm). The combustor was acoustically stable over the entire range of test conditions. Combustion efficiency was close to 100 percent at an average exit temperature of 2200° F (1480 K). Exit temperature distribution was excellent. At an inlet Mach number of 0.24 the pattern factor was 0.15 for a nominal inlet temperature of 600° F (589 K) and 0.11 for a nominal inlet temperature of 1200° F (922 K). Total pressure loss was approximately 6.3 percent for an inlet Mach number of 0.30 and a combustor temperature ratio of 1.7. Simulated altitude relight characteristics of the combustor were poor. At an inlet air temperature of 35° F (275 K) and pressure of 16 psia (11 N/cm^2), the combustor could only be lit at reference velocities below 40 feet per second (12 M/sec).

The test results demonstrate that the modular combustor approach can be used effectively in designing a combustor for gaseous fuel and high average exit temperature, but further work on ignition limits is required.

INTRODUCTION

Recent studies have shown that liquefied natural gas (LNG) fuel offers significant advantages over JP fuels in some turbojet engine applications (e.g., refs. 1 to 3). For example, a 31-percent payload improvement was calculated for a Mach 3 supersonic transport application (ref. 1) assuming that the increased heat sink capacity of LNG was used to allow higher turbine inlet temperatures. Alternatively, the extra heat sink capacity could be used to maintain lower turbine metal temperatures and thereby improve turbine life and reliability. Other advantages of LNG include a higher heating value than JP fuels, reduced tendency to produce smoke, lower flame radiation, and greatly reduced tendency for fuel decomposition (ref. 3).

Modular combustors are being investigated for burning natural gas fuel. Each module acts as a combination carburetor and flame holder. This design concept has several advantages over conventional combustor designs. The module arrangement in the combustor housing and the fuel flow division between groups of modules can be tailored to improve the outlet-temperature profile. Also, from the standpoint of durability, the liner has no diluent-air entry holes, so the usual areas of liner stress concentration and failure are eliminated.

In reference 4, two modular combustor designs were tested with natural gas fuel. The design average exit temperature was 2200° F (1480 K) with inlet-air temperatures up to 1140° F (889 K). In reference 4, both combustors, as initially designed, exhibited an acoustic instability and very center-peaked exit temperature profiles. Results of that work indicated that both the temperature profile and the instability might be controlled by adding blockage between modules. Since the total pressure loss of those combustors already had exceeded the design goal pressure loss, further modifications along those lines were not made.

This report discusses a modified design of the modular combustor approach presented in reference 4. Modifications were aimed at lowering the total pressure loss by using a dump diffuser and at improving the exit temperature profile by using vortex generators downstream of the flame front. Data are included on the various combustor performance parameters.

TEST INSTALLATION

The combustor test section was installed in the same closed-duct test facility (fig. 1) that was used to test the reference 4 combustors. The facility is connected to the laboratory air supply and exhaust systems. Combustion air at pressures up to 150 psia (103 N/cm^2) was passed through a nonvitiating preheater which was capable of heating the air to 600° F (589 K). For those conditions requiring a combustor-inlet temperature of 1200° F (922 K) the air was preheated further by a vitiating preheater consisting of 10 J 71 single combustor cans, which burned white gasoline. Airflow rates and combustor pressures were regulated by remotely controlled valves upstream and downstream of the test section.

Combustor exit temperatures were measured by means of a traversing probe. A description of the test instrumentation is presented in the appendix.

TEST COMBUSTORS

Reference 4 Combustors

The test combustor installation used in reference 4 is shown schematically in figure 2. The test section housing was scaled to simulate a 90° sector of a full annulus of a turbojet engine combustor with a 57-inch (145-cm) diameter outer casing, a length of 33 inches (84 cm), and a duct height of 12 inches (30 cm). For ease of fabrication, the test section was made rectangular in cross section with a width of 30 inches (76.2 cm).

The two combustors tested in reference 4 will hereafter be referred to as model I and model II. Photographs of the combustor arrays of models I and II are shown in figure 3. In a later section of this report, the performances of models I and II are compared with the performance of model III.

Test Combustor

The combustor investigated herein is shown schematically in figure 4. This combustor will hereafter be referred to as the model III combustor. A sketch of an individual combustor module is shown in figure 5.

The array of combustor model III (fig. 6) was mounted on a removeable portion of the top diffuser wall. The fuel tubes in each row of modules were manifolded together outside the combustion chamber. Fuel injection holes were designed so that the fuel would be injected tangentially at sonic velocity at most operating conditions, assuring even fuel distribution through each row. The individual manifold fuel flows were varied to improve the 'radial' outlet temperature profile. To provide a uniform exit temperature distribution and to prevent an acoustic instability, which was present in models I and II (when they had no cross strips), the individual modules in the combustor array were interconnected with cross strips at their downstream edge.

Since the diffuser splitter plates used in the model I and II designs were responsible for a large percent of the pressure loss for those combustors, the splitter plates were replaced by a short dump diffuser (as shown in fig. 4). The diffuser was designed to provide some total-pressure recovery while maintaining good weight flow distribution across the area of the duct. The dump diffuser had a 10° included angle and was 6.5 inches (16.5 cm) long.

The maximum cross sectional area of the combustor was reduced by reducing the radial height between the combustor walls. It was felt that the disadvantages of operating the combustor at a higher velocity at the exit plane of the modules would be outweighed by the advantage of not having to diffuse the air more than might be required for good efficiency and a good exit temperature profile. Our previous efforts to diffuse ducted air in a short distance resulted in separated flow or a nonuniform flow across the area of the duct.

Vortex generators were added along the walls to smooth out the hot and cold temperature streams along the walls (fig. 7). The test results of combustor models I and II indicated that enough cold air would bypass the modules along walls to keep the vortex generators from burning.

RESULTS AND DISCUSSION

The model III combustor was tested at the conditions shown in table I. Test results showed that the combustor had good efficiency, low pressure loss, and an excellent exit temperature profile. Blowout and ignition characteristics of the combustor were poor. The combustor burned stably for all test conditions and did not exhibit any acoustic instability.

Combustion efficiency. - Combustion efficiency was defined as the ratio of actual temperature rise to theoretical temperature rise. The oxygen depletion resulting from preheater vitiation of the combustion air was considered in the combustion efficiency calculations. The combustor exhaust temperatures were mass weighted in calculating efficiency.

Combustion efficiency data are shown in figure 8. At fuel-air ratios greater than 0.017, calculated combustion efficiency was close to 100 percent. A drop-off in combustion efficiency was noticed for the 600° F (589 K) inlet-air temperature condition with increasing inlet Mach number and decreasing fuel-air ratios. There was no drop in efficiency at the high inlet-air temperature conditions (1200° F) (922 K). Values of efficiency over 100 percent are believed to be due to two causes: (1) air leaking at the flanges (especially at inlet-air temperatures of 1200° F (922 K)), and (2) the thermocouple probes in the regions of large temperature gradients near the walls being out of position and therefore measuring exit temperatures whose average was higher than the real mean temperature.

Temperature distribution. - To describe the quality of the combustor-outlet temperature profile, the following temperature distribution parameters were established:

$$\text{Stator factor} = \frac{\left(T_{R,\text{local}} - T_{R,\text{design}}\right)_{\max}}{\Delta T_{av}}$$

where $T_{R,\text{local}} - T_{R,\text{design}\ \max}$ is the largest temperature difference between the highest local temperature on any radius and the design temperature for that same radius, and ΔT_{av} is the average temperature rise across the combustor.

$$\text{Rotor factor} = \frac{\left(T_{R,av} - T_{R,design}\right)_{max}}{\Delta T_{av}}$$

where $\left(T_{R,av} - T_{R,design}\right)_{max}$ is the largest temperature difference between the average circumferential temperature at any radius and the design temperature for that same radius. The terms radial and circumferential are used as though the test section were a sector of an annulus. The design radial temperature profile is typical of those encountered in advanced supersonic engines. The shape of the radial profile is generally dictated by the requirements of the turbine stator and rotor. In addition to stator factor and rotor factor, another parameter, used in the aircraft industry and based only on maximum and average temperature rise, was employed. This parameter, the pattern factor, is defined as follows:

$$\text{Pattern factor} = \frac{T_{max} - T_{av}}{\Delta T_{av}}$$

As previously stated, for the combustion efficiency calculations the combustor outlet temperatures were mass-weighted and the average was based on the total number of readings taken in the survey. For the temperature profile calculations, the actual nonweighted temperatures were used; approximately 10 percent of the readings at each side were disregarded to eliminate sidewall effects which would not be present in a complete annular combustor.

Average exhaust temperature profiles in the radial and circumferential directions were determined at various fuel-air ratios and inlet temperature conditions. Average radial and circumferential temperature profiles are presented in figures 9 to 12. These profiles correspond to the four test conditions listed in table I. The design radial profile is included with the radial profile data. Pattern factor and temperature distribution parameters for the performance data shown in figures 9 to 12 are tabulated in table II. The best results were obtained at the high inlet-air temperature conditions (1200° F) (922 K) where deviation from the design radial profile was slight (figs. 11 and 12). For example, the stator factor value for test condition 4 was 0.127. This indicates that the highest hot-spot temperature was 155° F (86 K) higher than the radial design temperature for that condition. A greater deviation from the design radial profile occurred at the lower inlet temperature conditions, but this might be expected from the higher temperature rise required for an average exit temperature of 2200° F (1480 K). The maximum stator factor value for all conditions was 0.18. The average exit temperatures for some of these tests exceeded the average design temperature of 2200° F (1480 K) without serious compromise to the profile parameters.

The radial profiles shown in figures 9 and 10 illustrate the throttling capability available with the modular array design. Exit temperature profile data indicated a skewed air weight-flow distribution coming through the array. With the fuel evenly distributed to all modules, the exhaust temperature was much colder across the bottom of the combustor than the top. The fuel flow in the top row was therefore decreased slightly and the fuel flow in the bottom row increased. The results shown in figure 9 were thus produced with the following percentage split in fuel flow from top to bottom: 21, 23, 23, 33. Figure 9 shows that the result was a slightly overcorrected radial profile with the temperature peaking at the hub rather than at the tip. A slight change in fuel distribution was made for the test condition shown in figure 10. The percentage split in fuel flow from top to bottom was 23, 23, 23, 31. This change shifted the peak in the radial temperature distribution profile closer to the center. Further changes in fuel distribution were not pursued. The data shown in figures 11 and 12 had the same fuel flow distribution as figure 10.

Pressure loss. - Combustor pressure loss was defined by the following expression:

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

Thus, the pressure loss included the diffuser pressure loss. Pressure loss is plotted against diffuser inlet Mach number in figure 13. Pressure loss was approximately 6.3 percent at an inlet Mach number of 0.3 and temperature ratio of 1.7.

Blowout and ignition. - Blowout and ignition data were obtained at a fuel-air ratio of approximately 0.015 at various inlet-air temperatures and are shown in figures 14 and 15 respectively. The nonvitiating preheater was used to attain the inlet-air temperature conditions. Data were taken at constant values of air weight flow and temperature by varying the combustor pressure. In all cases, reignition occurred at somewhat higher values of pressure than those at which the combustor blew out. Blowout was defined as the point at which the combustor exit temperature fell off sharply. Partial-blowout data points are also shown in figure 14 and were points at which the combustor exit temperature started to fall off significantly but at which the combustor was still lit.

As shown in figure 15, the ignition limit of the combustor at a given temperature was almost uniquely defined by a constant value of reference velocity (or Mach number) and was independent of pressure for pressure values greater than 16 psia (11 N/cm^2). At pressures below 16 psia (11 N/cm^2) an effect due to pressure is noticeable and the reference velocity must be decreased to obtain ignition at lower pressures. At an inlet temperature of 35° F (275 K) and 16 psia (11 N/cm^2), the combustor could only be lit at reference velocities below 40 feet per second (12 m/sec).

It should be pointed out that the reference velocity plotted in figures 14 and 15 is based on the 12-inch (30.5-cm) height inside the combustor housing and not the 9-inch (22.9-cm) height between the top and bottom false walls of the combustor. This point is discussed further in the next section.

COMPARISON WITH PREVIOUS WORK

Test results of this program show a significant improvement in combustor performance, especially in exit temperature distribution parameters, over our previous work with natural gas fuel (model I, ref. 4). The following is a comparison of the results of the two combustors.

Inasmuch as the air weight flow, temperature, and pressure conditions were similar, the results may be compared directly. It should be re-emphasized that, in both programs, the reference velocity was computed from the weight flow and a maximum duct height of 12 inches (30.5 cm) rather than with respect to the actual distance between liner walls. The actual reference velocity based on the distance between the liner walls of the combustor model III was approximately 22 percent higher than the comparable reference velocity of the combustor model I for the same inlet flow conditions. Calculated combustion efficiency of the test combustors in both programs was close to 100 percent at the design-operating-point, requiring a 2200° F (1480 K) average exit temperature. A slight decrease in efficiency with fuel-air ratio was noticed in the test with combustor model III at an inlet Mach number of 0.31 and inlet temperature of 600° F (589 K). No such decrease in efficiency was noticed with the combustor model I at the same condition. The decrease in efficiency for the combustor model III may be due to the increase in actual reference velocity for this combustor.

Combustor blowout and ignition characteristics of combustor model III are also poorer than those of combustor model I. As shown in figure 16, if the reference velocities of both combustors are corrected to their actual reference velocities based on the height between combustor walls, the blowout characteristics are similar.

Significant improvements in total pressure loss and exit temperature profile were achieved with combustor model III. The pressure loss for the combustor model I was 8.5 percent at inlet Mach number of 0.3 and a temperature ratio of 1.7. As previously stated, the pressure loss of combustor model III was only 6.3 percent at the same condition. This is a 35-percent reduction in pressure loss while achieving a significantly better exit temperature distribution.

Table III shows the improvement in exit-temperature distribution parameters for an inlet air temperature of approximately 600° F (589 K), approximate temperature rise of 1600° F (889 K), and inlet Mach number of 0.24. For a combustor temperature rise of 1600° F (889 K), the stator factor value of 0.163 for combustor model III means that the highest hot-spot temperature for this combustor would only be 261° F (145 K) higher than the radial design temperature compared with 502° F (279 K) for combustor model I.

SUMMARY OF RESULTS

A modular combustor design was tested with natural gas fuel over a range of operating conditions. The following results were obtained:

1. Calculated combustion efficiency was close to 100 percent at the design operating point of 2200° F (1480 K) average exit temperature. A drop in efficiency at lower fuel-air ratios occurred for an inlet air temperature condition of 600° F (589 K), but no drop in efficiency occurred at an inlet air temperature of 1200° F (922 K).

2. Pattern factor and temperature distribution parameters were excellent for an average exit temperature of 2200° F (1480 K) with both inlet temperatures of 600° F (589 K), and 1200° F (922 K). For a temperature rise of 1600° F (889 K) and diffuser inlet Mach number of 0.24, typical values of pattern factor, stator factor, and rotor factor were 0.15, 0.163, and 0.0678, respectively.

3. Pressure loss was approximately 6.3 percent for an inlet Mach number of 0.3 and a combustor temperature ratio of 1.7.

4. Blowout and ignition characteristics of the combustor were poor. At a fuel-air ratio of 0.015, an inlet temperature of 35° F (275 K), and pressure of 16 psia (11 N/cm^2), the combustor could only be lit at reference velocities below 40 feet per second (12 m/sec.).

5. The combustor was acoustically stable over a wide range of operating conditions.

Lewis Research Center,
National Aeronautics and Space Administration,
Cleveland, Ohio, September 15, 1970,
720-03.

APPENDIX - INSTRUMENTATION

Airflow and gaseous fuel flow rates were measured by square-edged orifices installed according to ASME specifications. Liquid fuel-flow was measured by a turbine flowmeter.

The location of the pertinent instrumentation planes is shown in figure 17, the arrangement of the pressure and temperature probes is also shown in figure 17. Temperatures (in the inlet section) were measured by 10 Chromel-Alumel thermocouples (section A-A, fig. 17). Pressures were measured by means of five rakes, each consisting of five-point total-pressure tubes, and by four wall static-pressure taps (section B-B, fig. 17). Combustor-outlet total pressures and temperatures were recorded by means of a movable seven-point total-pressure and seven-point total-temperature rake (section C-C, fig. 17). The temperature probes were constructed of platinum - 13-percent rhodium platinum and were of the high-recovery aspirating type (type 6 of ref. 5). The average reading of four static-pressure taps located as shown in section C-C of figure 17 was used as a measure of the static pressure at the combustor exhaust nozzle. The exhaust rake is shown in figure 18.

Temperature and pressure surveys at the combustor exit were made by moving the probe horizontally across the exhaust nozzle at a speed which produced approximately one reading every 1/2 inch (0.0127 m).

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TABLE I. - NOMINAL TEST CONDITIONS

[Desired average combustor exit temperature, 2200° F (1480 K); inlet total pressure, 45 psia (31 N/cm^2).]

Test condition	Combustor inlet temperature		Diffuser inlet Mach number	Combustor reference velocity[a]	
	°F	K		ft/sec	m/sec
1	600	589	0.24	95	29
2	600	589	.31	122	37
3	1200	922	.24	117	36
4	1200	922	.31	147	45

[a]Based on 12-in (30.5-cm) combustor height and total temperature and pressure at diffuser inlet.

TABLE II. - EXIT TEMPERATURE DISTRIBUTION PARAMETERS

Test condition	Combustor inlet temperature		Nominal inlet Mach number	Fuel to air ratio	Pattern factor	Stator factor	Rotor factor	Corrected average exit temperature	
	°F	K						°F	K
1	601	589	0.24	0.0233	0.15	0.163	0.0678	2416	1598
2	595	586	.31	.0201	.21	.180	.0731	2168	1460
3	1220	933	.24	.0175	.11	.150	.0333	2482	1634
4	1184	913	.31	.0177	.13	.127	.0415	2461	1623

TABLE III. - COMPARISON OF EXIT TEMPERATURE DISTRIBUTION PARAMETERS

[Inlet air temperature, 600° F (589 K); inlet Mach number, 0.24; approximate temperature rise, 1600° F (889 K).]

Temperature distribution parameters	Model I (a)	Model III
Pattern Factor	0.31	0.15
Stator Factor	.314	.163
Rotor Factor	.169	.0678

[a]Ref. 4.

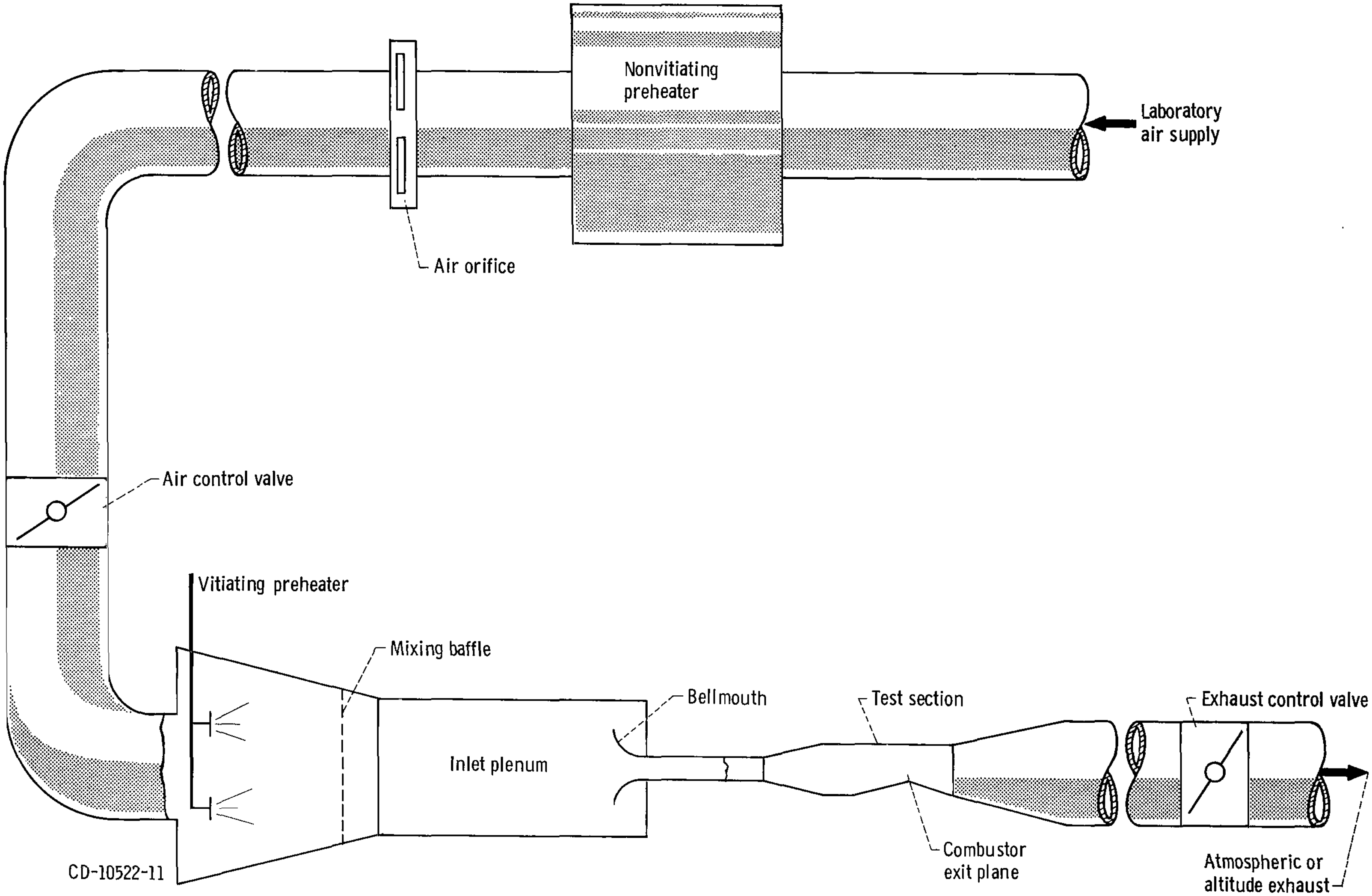


Figure 1. - Test facility. Combustor installation and auxiliary equipment.

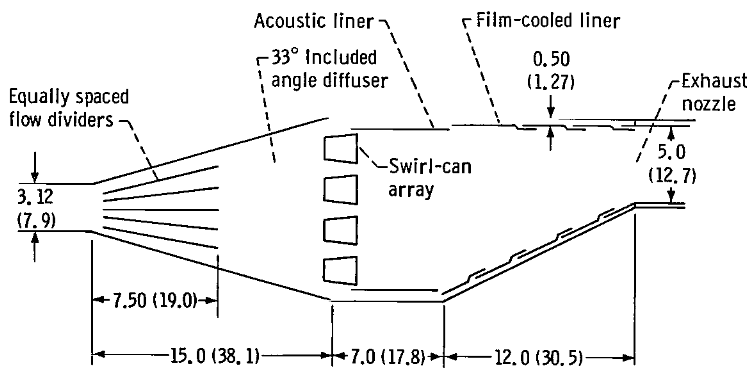
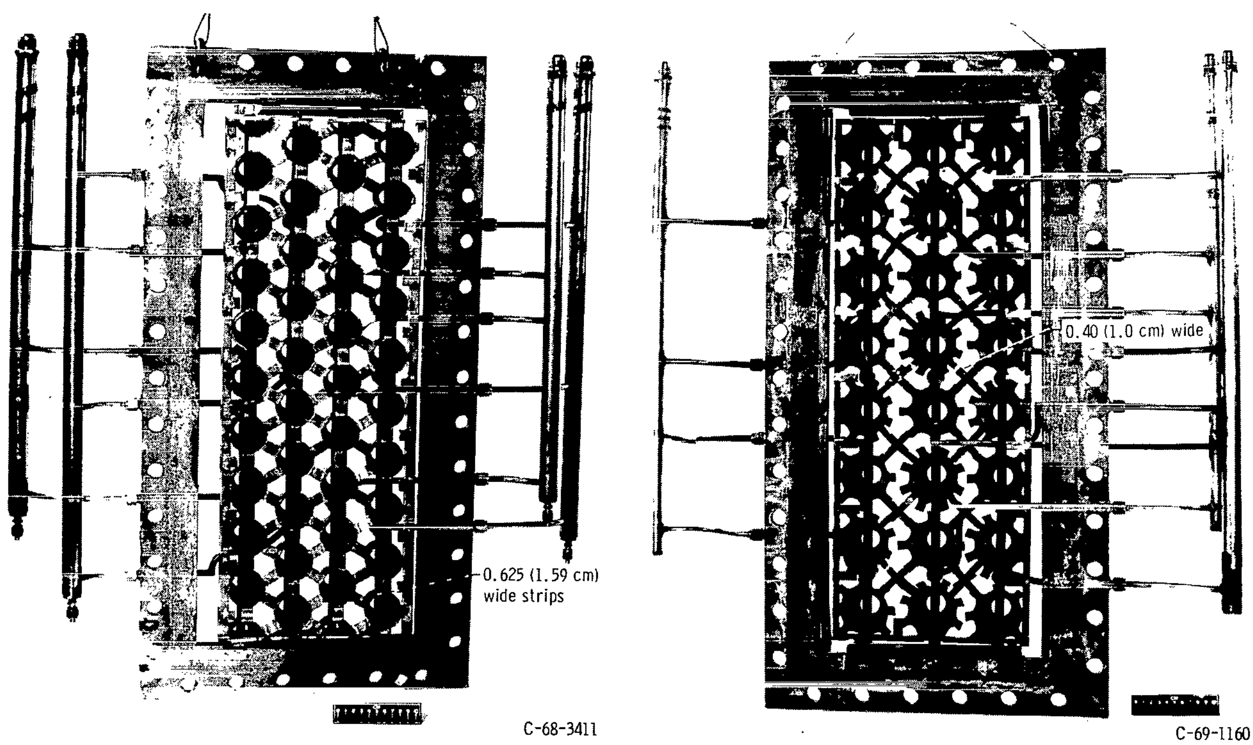


Figure 2. - Reference 4 combustor installation in test section. (Dimensions are in inches (cm).)



(a) Model I.

(b) Model II.

Figure 3. - Reference 4 combustor arrays (looking upstream).

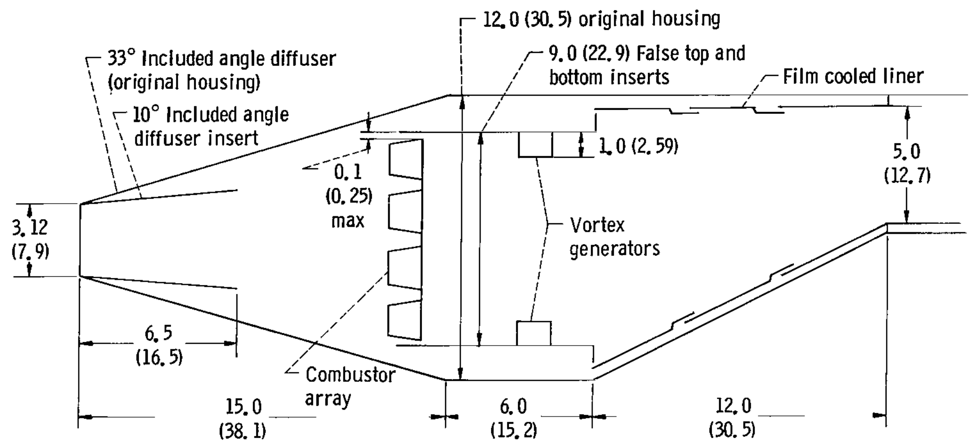


Figure 4. - Combustor model III configuration. (Dimensions are in inches (cm).)

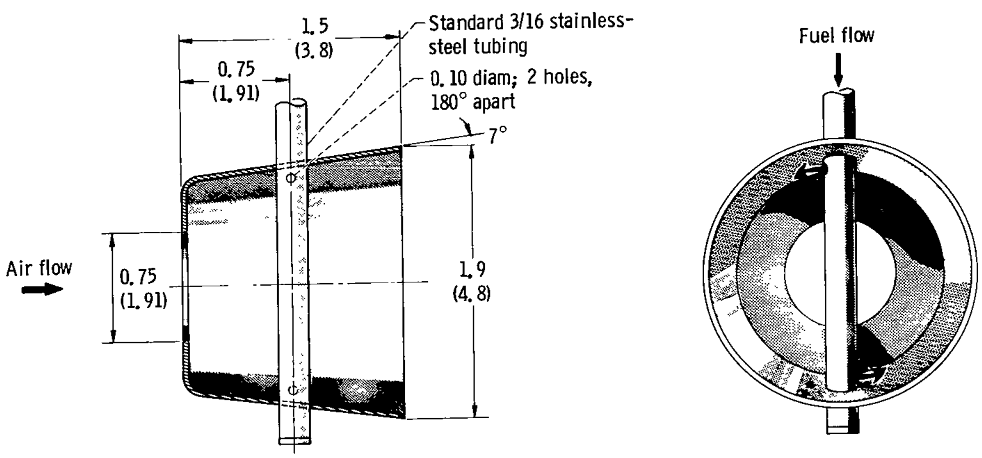


Figure 5. - Model III swirl-can combustor module. (Dimensions are in inches (cm).)

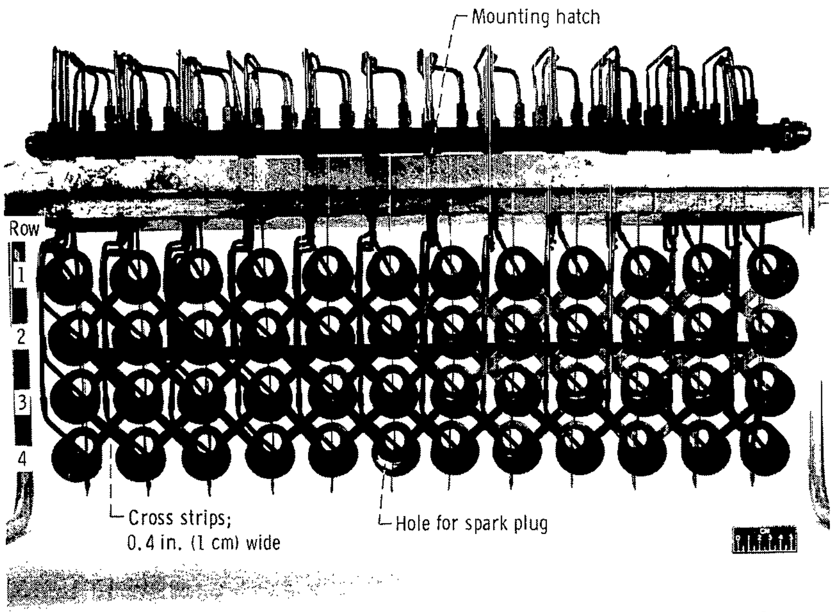
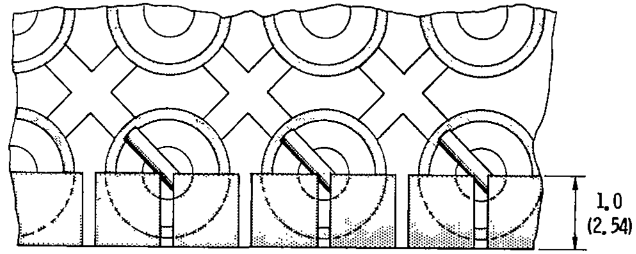
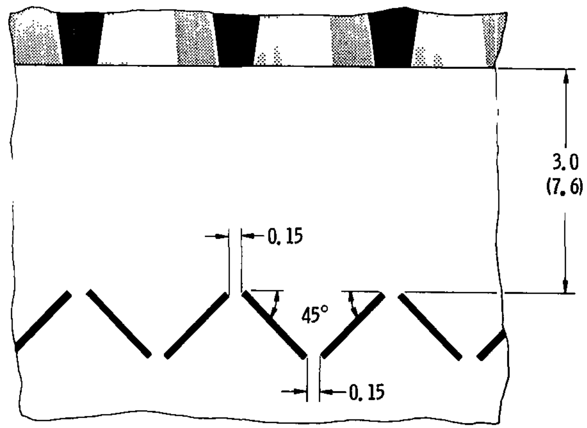


Figure 6. - Model III test combustor array (looking upstream).



(a) Looking upstream.



(b) Top or bottom view.

Figure 7. - Vortex generator tabs used on top and bottom walls for mixing.

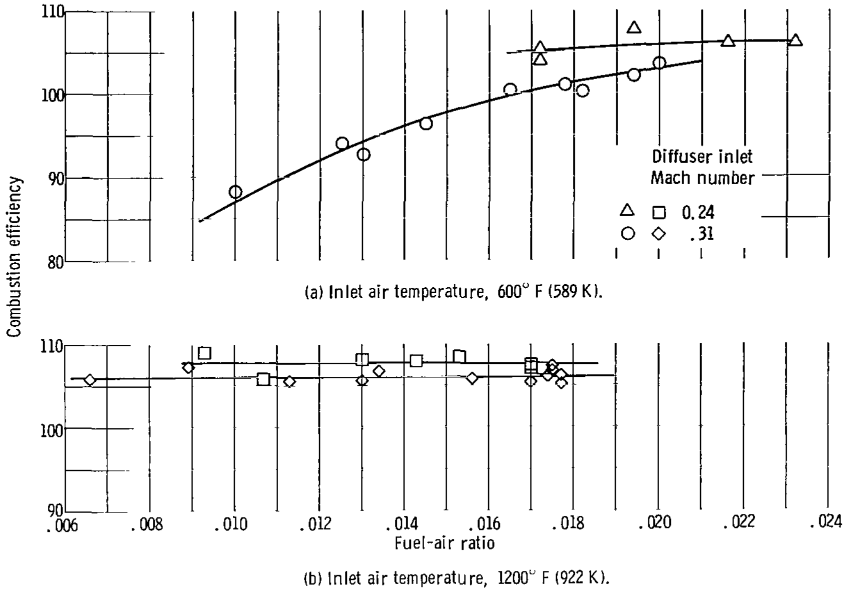


Figure 8. - Combustion efficiency. Inlet total pressure 45 psia (31 N/cm^2).

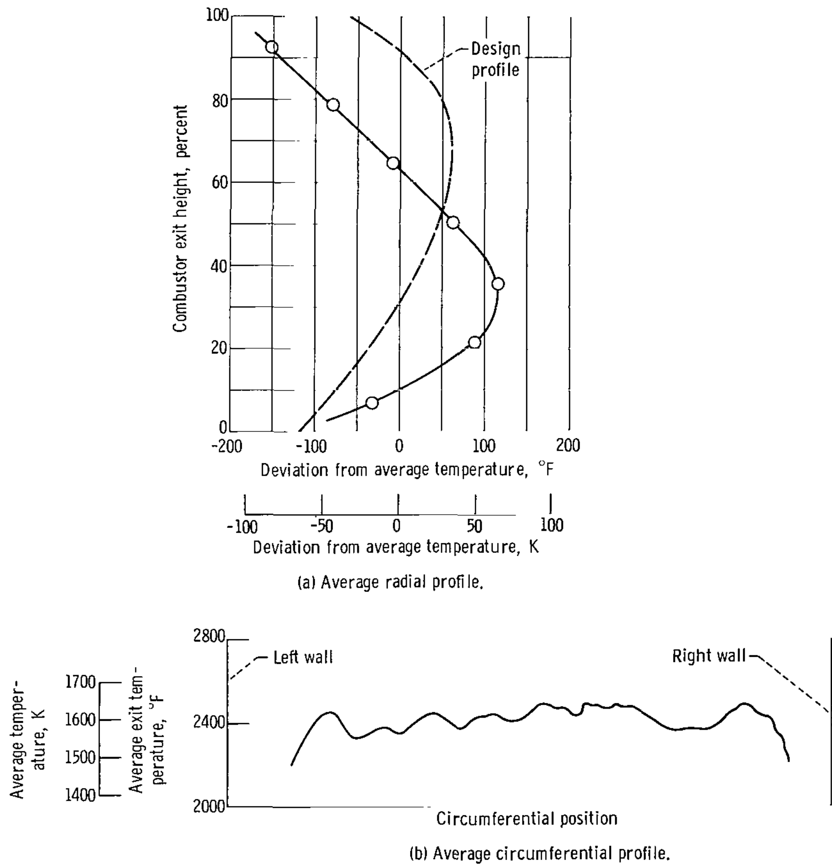
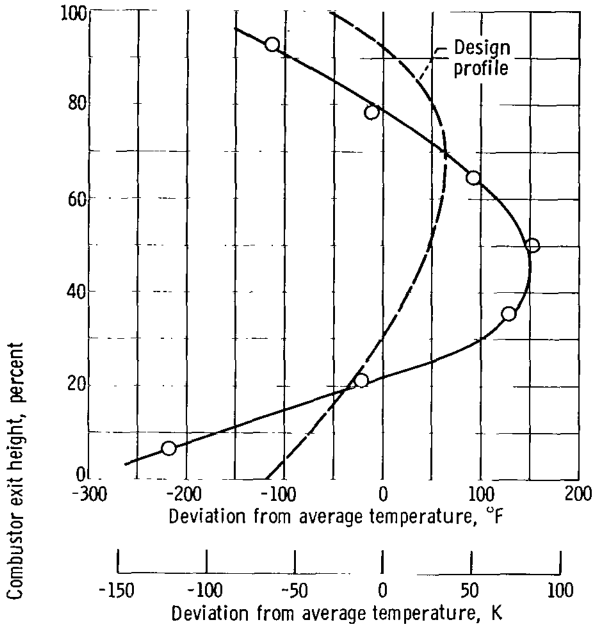
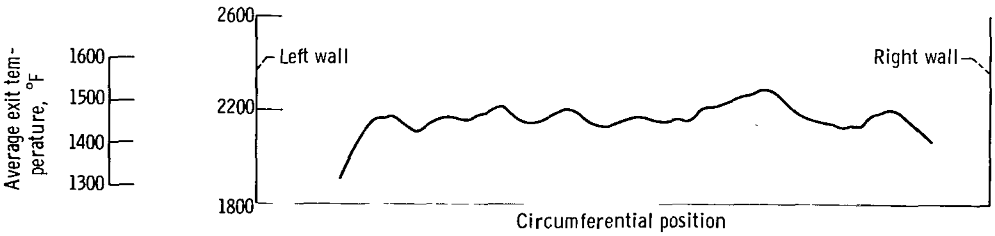


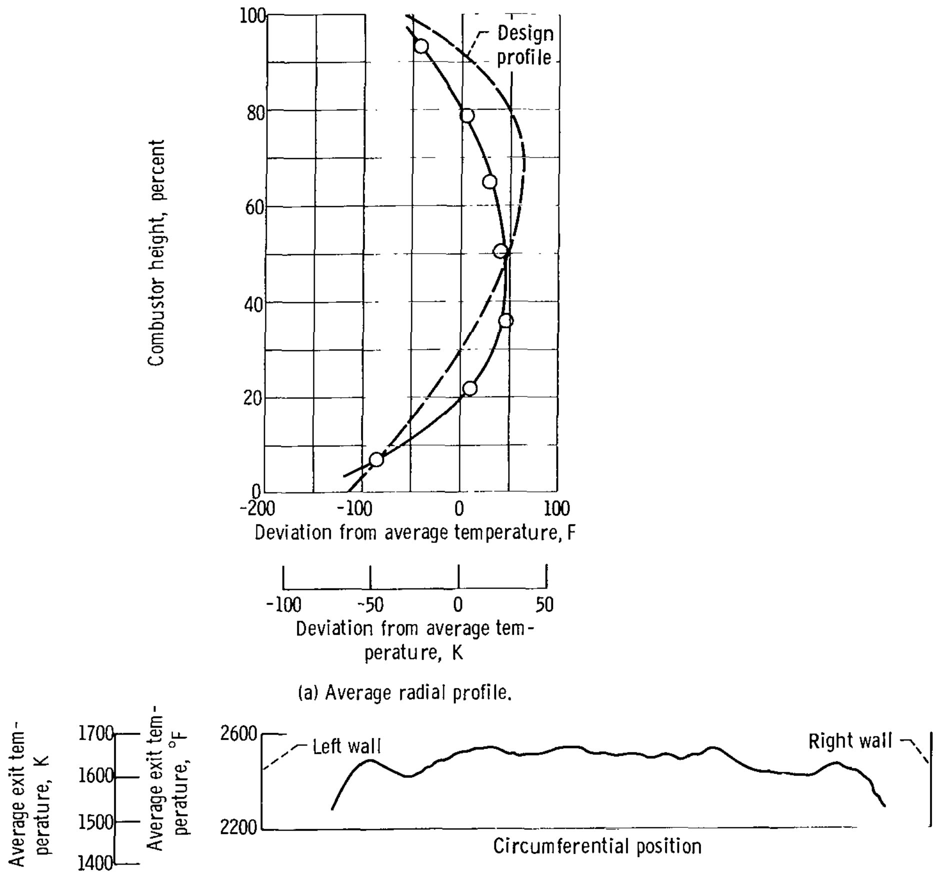
Figure 9. - Temperature profiles; test condition 1. Inlet temperature, 601° F (589 K); average outlet temperature, 2416° F (1598 K); diffuser inlet Mach number, 0.222; inlet total pressure, 45 psia (31 N/cm^2); percentage fuel split from tip to hub, 21, 23, 23, 33.





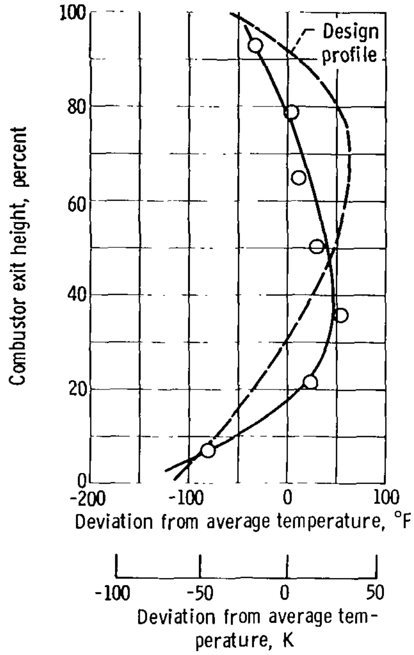
(b) Average circumferential profile.

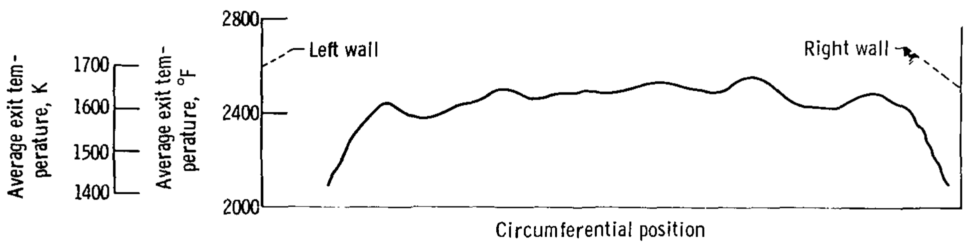
Figure 10. - Temperature profiles; test condition 2. Inlet temperature, 595° F (586 K); average outlet temperature, 2168° F (1460 K); diffuser inlet Mach number, 0.306; inlet total pressure, 45 psia (31 N/cm²); percentage fuel split from tip to hub, 23, 23, 23, 31.



(b) Average circumferential profile.

Figure 11. - Temperature profiles; test condition 3. Inlet temperature, 1220° F (933 K); average outlet temperature, 2484° F (1634 K); diffuser inlet Mach number, 0.242; inlet total pressure, 45 psia (31 N/cm^2); percentage fuel split from tip to hub, 23, 23, 23, 31.





(b) Average circumferential profile.

Figure 12. - Temperature profiles; test condition 4. Inlet temperature, 1184° F (913 K); average outlet temperature, 2461° F (1623 K); diffuser inlet Mach number, 0.318; inlet total pressure, 45 psia (31 N/cm²); percentage fuel split from tip to hub, 23, 23, 23, 31.

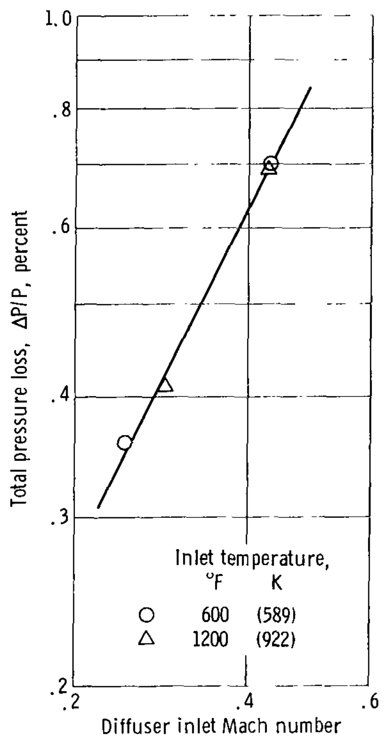


Figure 13. - Total pressure loss as function of inlet Mach number. Temperature ratio, 1.7.

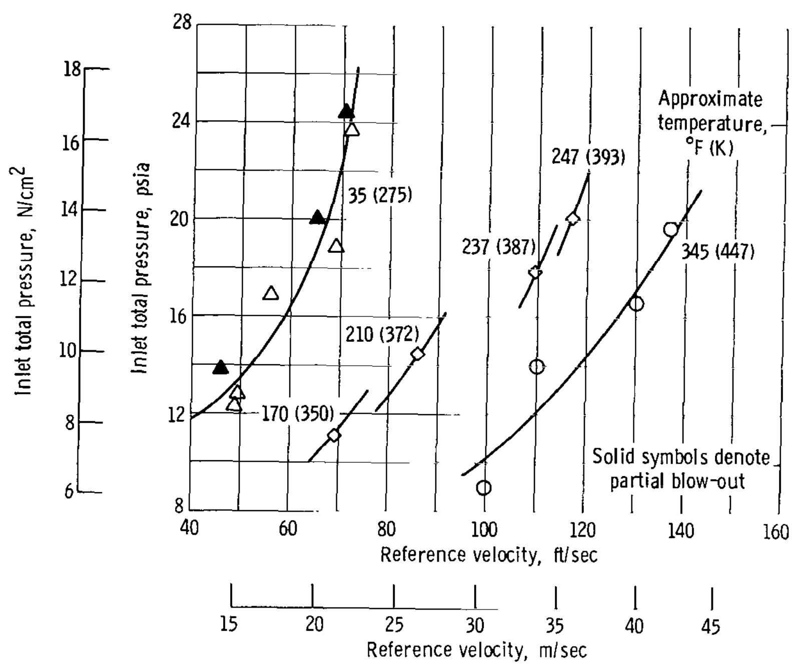


Figure 14. - Blowout limits.

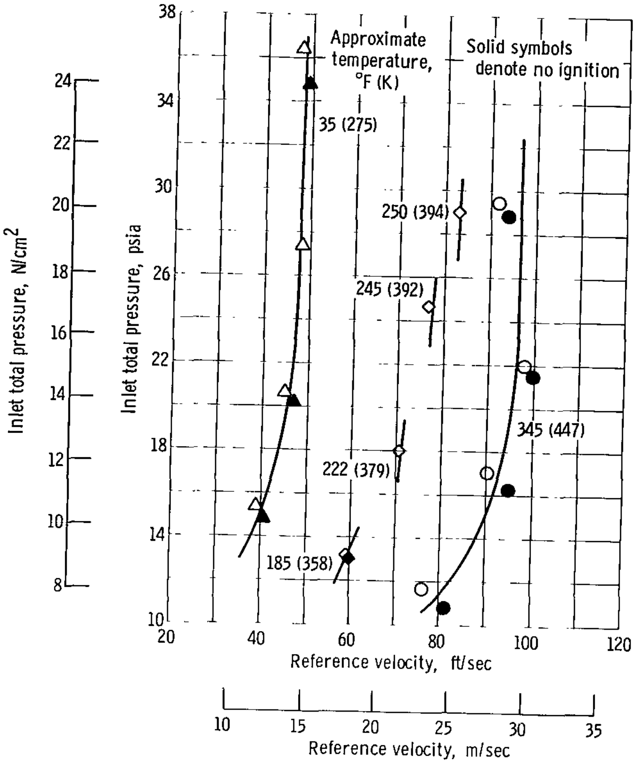


Figure 15. - Ignition limits.

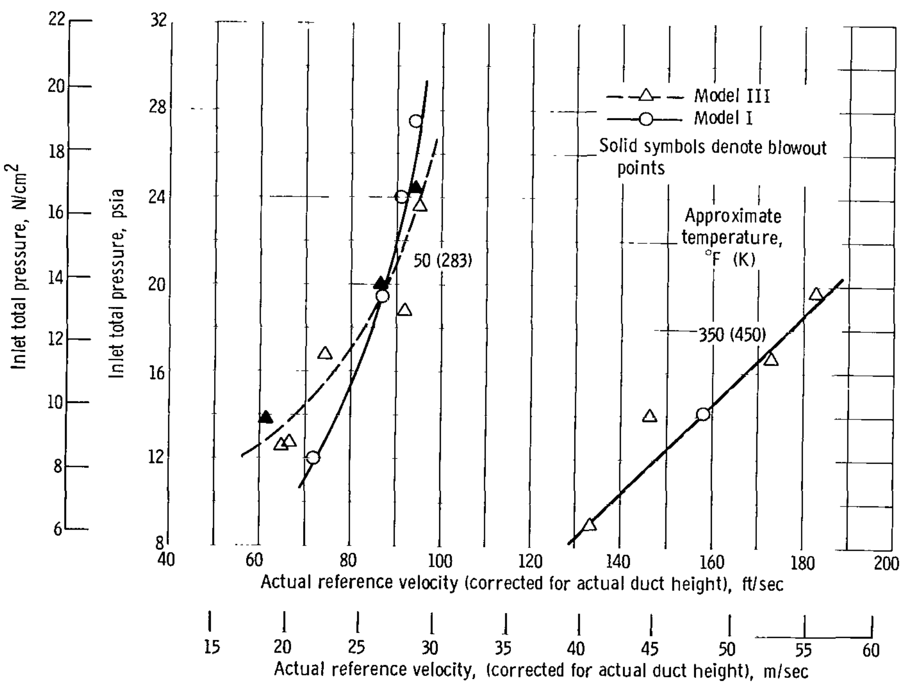


Figure 16. - Comparison of blowout limits for combustor models I (ref. 4) and III.

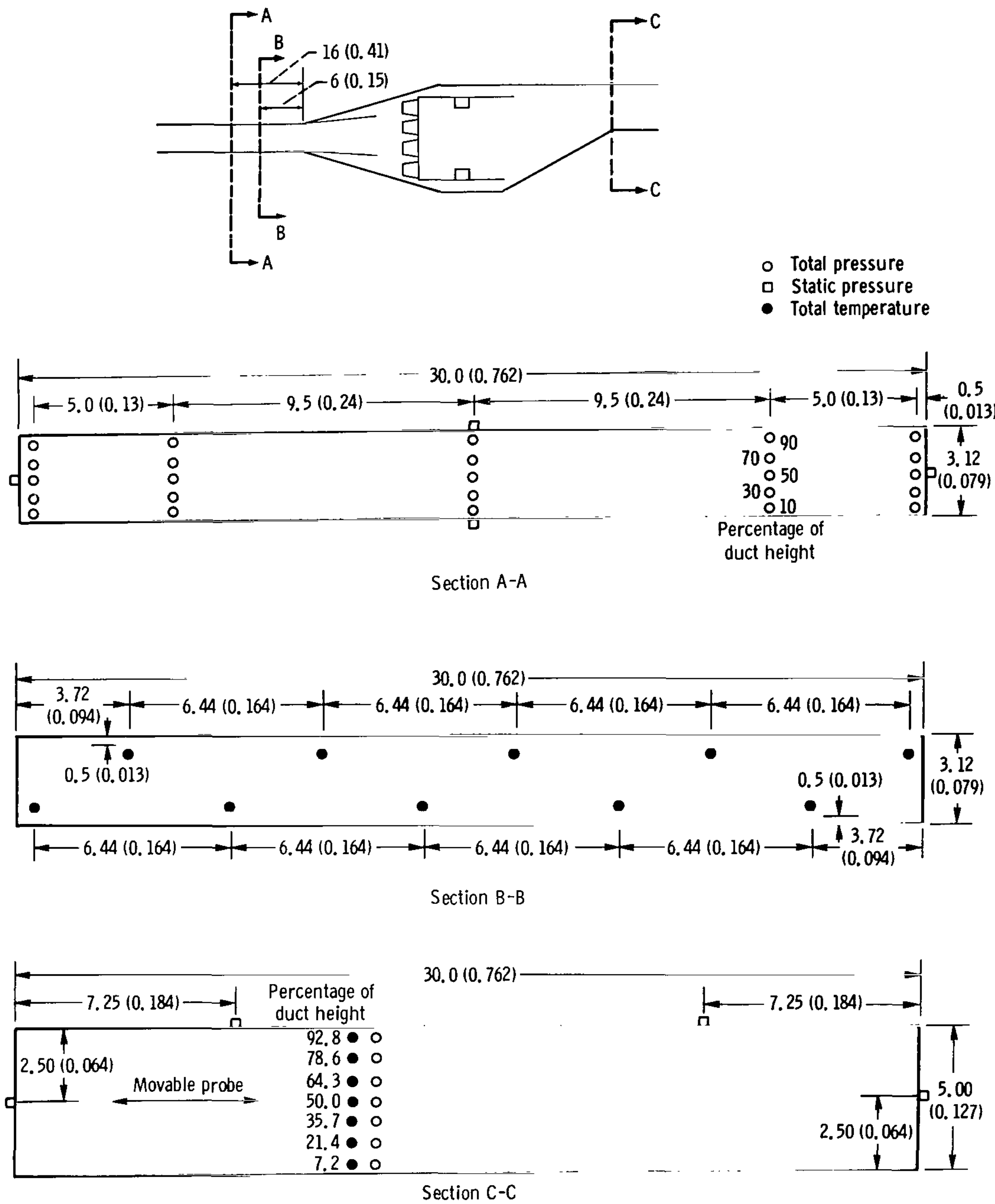


Figure 17. - Location of temperature and pressure probes in instrumentation planes. (All dimensions are in inches (m).)

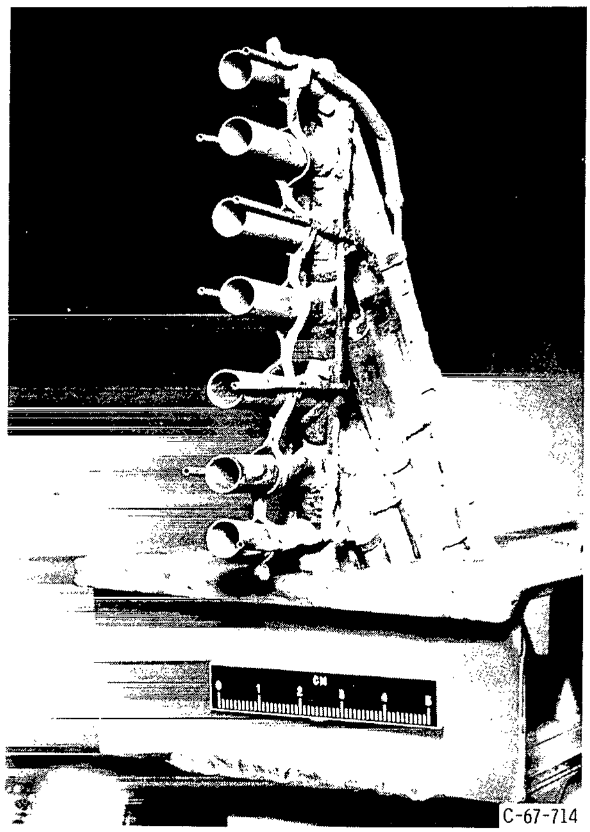


Figure 18. - Exhaust rake.

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