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RESEARCH MEMORANDUM

PERFORMANCE OF EXPERIMENTAL CHANNELED-WALL ANNULAR TURBOJET COMBUSTOR AT CONDITIONS SIMULATING HIGH-ALTITUDE SUPERSONIC FLIGHT

I - U-SHAPED CHANNEL WALLS FOR SECONDARY-AIR ENTRY

By Eugene V. Zettle and Robert Friedman

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NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

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SUMMARY

The performance of a channeled-wall annular turbojet combustor was investigated at operating conditions representative of high-altitude supersonic flight. The secondary-zone walls of the experimental combustor were formed by U-shaped channels, spaced longitudinally and individually supported; the space between the channels formed long rectangular slots for the introduction of secondary air. The objectives of this design were (1) reduction in pressure losses in the secondary zone and (2) improved combustor durability characteristics.

Combustion efficiencies were between 97 and 100 percent for combustor reference velocities up to 200 feet per second and average combustor-outlet gas temperatures of 2000° F. Reasonably uniform outlet radial temperature profiles were obtained. The total-pressure loss ranged from 3.5 to 8.5 percent for increasing velocities from 125 to 200 feet per second at a temperature ratio across the combustor of about 1.85. This represents a reduction in pressure loss of one-third as compared with losses for an earlier experimental combustor design. Combustor-liner durability and carbon deposition were not evaluated in this investigation.

INTRODUCTION

Advancements in compressor and turbine design techniques indicate that higher air flows per unit frontal area and higher turbine temperatures are possible in future engines. High supersonic flight speeds can more easily be realized with the greater power resulting from these higher air flows and temperatures. The results of the investigations reported in reference 1 indicate that turbojet combustors can be designed to operate at simulated supersonic flight conditions with velocities as high as 225 feet per second and average combustor-outlet gas temperatures of the order of 2000° F. Combustion efficiencies above 95 percent and satisfactory outlet radial temperature profiles were obtained under these conditions. Although the pressure losses of the combustors reported in reference 1 were considered acceptable, gains in thrust and specific fuel consumption can be realized with further reduction in pressure loss. Further, reference 1 indicates that the problem of liner durability for combustor applications involving high temperatures and pressures may be one of the most difficult problems facing the combustor designer.

The preliminary investigation reported herein is part of a research program at the NACA Lewis laboratory to determine design criteria of combustors for turbojet engines operating at high altitudes and supersonic flight speeds. Additional research has been conducted with one of the combustors (combustor B) of reference 1 in an effort to reduce pressure loss and provide improved durability characteristics of the combustor. Limited performance data obtained with one modification are presented in this report. The design, which is similar in principle to a ram-jet configuration of reference 2, incorporates U-shaped channels, spaced longitudinally around the secondary mixing zone. The space between the channels forms long rectangular slots inclined toward the direction of flow of the secondary air. These individually supported channels, free to expand in the axial direction, were expected to decrease warping of the liner wall and to provide a design capable of withstanding higher pressure loadings on the liner walls.

Performance was evaluated at a single inlet-air temperature of 870° F, a range of inlet-air pressures from 10 to 30 pounds per square inch absolute, and a range of combustor velocities from 125 to 200 feet per second. Combustion efficiencies, pressure losses, and combustor-outlet temperature profiles were determined at these conditions. Combustor-liner durability and carbon deposition were not evaluated during this investigation.

APPARATUS

Combustor

The combustor consisted of a one-quarter sector of a single annular combustor designed to fit into a housing with an outside diameter of $25\frac{1}{2}$ inches, an inside diameter of $10\frac{5}{8}$ inches, and a combustor length of approximately 23 inches. The maximum combustor cross-sectional area of the quarter sector was 105 square inches (420 sq in. for complete combustor).

A three-quarter cutaway view of the assembled combustor is shown in figure 1, and a longitudinal cross-sectional view, in figure 2. The combustor is a modification of combustor B of reference 1. The liner of combustor B was cut off to a length of 10 inches, and the secondary walls were replaced with 12 channel-shaped pieces which were attached between the downstream edge of the liner and a heat shield located near the turbine-inlet section (fig. 2). The bottom channels had additional slots cut in them to provide the required secondary-air entry area. The fuel was injected, as in combustor B, through nine hollow-cone swirl-type nozzles (10.5-gal/hr flow capacity, 60° spray angle) at the upstream end of the combustor liner. MIL-F-5624B, grade JP-4, fuel was used throughout the investigation.

Installation

A schematic diagram of the combustor installation is shown in figure 3. Air of desired quantity, pressure, and temperature was drawn from the laboratory air-supply system, passed through the combustor, and exhausted into the altitude exhaust system. Combustor-inlet temperatures were controlled primarily by a gasoline-fired heat exchanger, but an additional direct-fired preheater in the inlet plenum chamber was required for inlet temperatures exceeding 650° F.

Instrumentation

The instrumentation stations are shown in figure 3. Combustor-inlet total temperatures were measured with four bare-wire chromel-alumel thermocouples at station 1. Inlet total pressures were measured at the same station with nine total-pressure tubes, using three tubes in each of three rakes. Combustor-outlet temperatures and pressures were measured at station 2 with the polar-coordinate traversing probe mechanism shown schematically in figure 4. The probe consisted of two elements: a sonic aspirating-type platinum, platinum-rhodium thermocouple and a total-pressure tube. The probe surveying mechanism moved the probe in a path that included five circumferential sweeps at centers of equal areas, as shown in figure 5. A strain-gage pickup measured the difference between the total pressure sensed by the probe and the static pressure measured at selected points on the combustor wall; this difference was considered representative of the dynamic pressure. A two-pen X-Y recording potentiometer recorded a continuous trace of the temperature and dynamic pressure. Pen traces were made only during circumferential movement of the probe.

Calibrated rotameters and sharp-edged orifices were used to measure fuel- and air-flow rates, respectively.

PROCEDURE

The test conditions for which data are presented are listed in the first five columns of table I. Condition C is the standard condition corresponding to an engine with a compressor pressure ratio of 7 operating at a flight Mach number of 2.5 and an altitude of 70,000 feet.

Combustion efficiency, outlet temperature profile, and pressure losses were evaluated for the experimental combustor. Combustion efficiency was computed as the percentage ratio of actual to theoretical increase in enthalpy from the combustor-inlet to the combustor-outlet instrumentation sections by using the method of reference 3. The arithmetic mean of the average temperature of the five circumferential traces at the combustor outlet was used to obtain the value of the combustor-outlet gas enthalpy. The pressure loss was computed as the percentage ratio of total-pressure loss through the combustor to the inlet total pressure.

RESULTS

Combustion-efficiency and pressure-drop data obtained at the five operating conditions with the channeled-wall combustor are summarized in table I.

Combustion Efficiency

Effect of velocity. - The effect of combustor reference velocity on combustion efficiency is shown in figure 6 for a constant inlet-air temperature of 870° F, an inlet-air pressure of 25 pounds per square inch absolute, and an average combustor-outlet temperature of approximately 2000° F. The combustion efficiency remained essentially constant (at 97 to 100 percent) over a range of reference velocities from 125 to 200 feet per second. Combustor reference velocity, as discussed herein, is based on the density of the combustor-inlet air and on the maximum cross-sectional area of the combustor housing.

Effect of pressure. - The effect of combustor-inlet pressure on combustion efficiency is shown in figure 7 for a constant combustor inlet-air temperature of 870° F, an average outlet temperature of 2000° F, and a reference velocity of 160 feet per second. The combustion efficiency decreased from 99 percent at 25 pounds per square inch absolute to 86 percent at 10 pounds per square inch absolute.

Combustor-Outlet Temperature and Pressure Profiles

Reproductions of temperature and pressure survey traces for a typical run, corresponding to condition E, are shown in figure 8. These traces illustrate the variations of temperature and pressure along each circumferential probe path shown in figure 5. From these traces combustor-outlet contour patterns of lines of equal temperature and dynamic pressure were constructed, as presented in figure 9. The temperature patterns (fig. 9(a)) indicate large circumferential variations but comparatively small radial temperature changes at any given circumferential position. The large circumferential temperature gradients are probably due to the influence of the combustor walls and would not be expected in a full-annulus combustor that did not contain side walls. The dynamic-pressure patterns (fig. 9(b)) show little variation circumferentially but decrease radially toward the outer wall. The lines of constant dynamic pressure in figure 9(b) also correspond to constant Mach number, as indicated on the figure.

The radial outlet gas-temperature profile using average circumferential readings for the run illustrated in figures 8 and 9 is shown in figure 10. The observation that the radial temperature gradient in figure 9(a) is small is confirmed by this profile of averages, in which the maximum temperature deviation over the extreme radial positions of probe sweep is only 160° F. As noted previously, the dynamic-pressure contours disclose a radial decrease in pressure and Mach number, and consequently mass flow, from root to tip. Preliminary calculations, however, indicate that the change in mass flow is not sufficient to require mass weighting of temperatures for the calculation of combustion efficiency.

Combustor Pressure Losses

The percent of total-pressure loss is shown as a function of reference velocity in figure 11. Outlet total pressure was calculated from the over-all average dynamic pressure and the static-pressure indication; inlet pressure measurements were taken from the inlet total-pressure tubes. The pressure loss increased from about 3.5 to 8.5 percent over a range of velocities from 125 to 200 feet per second at a temperature ratio across the combustor of about 1.85. These pressure losses are less than two-thirds of those shown for combustor B of reference 1.

DISCUSSION

Combustor durability at operating conditions of high outlet temperatures and high combustion-chamber pressures was one of the prime considerations in the combustor design discussed herein. It was hoped to achieve good durability by using many individually supported small pieces for the combustor walls, with each piece free to expand and contract independently. The results reported are preliminary; the durability characteristics of this modification were not adequately evaluated. Nevertheless, the design features do show promise for obtaining good combustor durability. The combustor was operated for about 6 hours with little sign of deterioration and no shift in temperature patterns with time. Furthermore, no carbon deposits were observed; again, however, no attempt was made to evaluate this characteristic specifically.

The combustion-efficiency data shown substantiate the conclusion of reference 1 that high combustion efficiency can be obtained at the high combustor reference velocities that are anticipated in future turbojet engines operating at high altitudes and supersonic flight speeds. Combustion stability and efficiency are satisfactory at pressures as low as 10 pounds per square inch absolute. However, from figure 7 it can be seen that efficiency decreased rapidly at pressures near 10 pounds per square inch absolute.

A true measure of the circumferential temperature variations to be expected in a full-annulus combustor is not possible with the one-quarter-sector test combustor used in this investigation. However, the maximum average radial temperature deviation of only 160° F shown in figure 10 can be considered an excellent indication that a uniform radial temperature profile at high outlet temperatures is possible with the secondary-zone design used, in view of the fact that circumferential variations shown on the traces in figure 8 would not be expected in a full-annulus design not containing side walls.

It is believed that the sharp reduction in pressure losses observed in this experimental combustor is a result of lower entry and mixing losses in the secondary zone. The principal difference between this combustor and combustor B of reference 1 is that the secondary zone is formed by diverging channels and long rectangular slot openings sloping into the path of the incoming secondary air. As the secondary air enters through the spaces between the U-shaped channels and penetrates inward, the hot gases spread outward toward the sheltered region underneath each of the channels and mix with the cold air. In addition, the secondary mixing zone extends from wall to wall of the combustor housing, because the channels diverge to the walls downstream. Thus, the entire available flow area is used for mixing, and the average velocity in this mixing region is reduced.

CONCLUDING REMARKS

The turbojet combustor investigated operated with high efficiency and satisfactory radial temperature profiles at simulated supersonic flight conditions. The pressure losses of this combustor at high reference velocities were less than two-thirds of those of earlier experimental combustors. While the durability characteristics of this design were not determined, features incorporated into the design showed promise of providing adequate durability.

Lewis Flight Propulsion Laboratory
National Advisory Committee for Aeronautics
Cleveland, Ohio, December 9, 1954

REFERENCES

1. Zettle, Eugene V., Norgren, Carl T., and Mark, Herman: Combustion Performance of Two Experimental Turbojet Annular Combustors at Conditions Simulating High-Altitude Supersonic Flight. NACA RM E54A15, 1954.

2. Cervenka, A. J., Bahr, D. W., and Dangle, E. E.: Effect of Fuel-Air Ratio Concentration in Combustion Zone on Combustion Performance of a 16-Inch Ram-Jet Engine. NACA RM E53B19, 1953.

3. Turner, L. Richard, and Bogart, Donald: Constant-Pressure Combustion Charts Including Effects of Diluent Addition. NACA Rep. 937, 1949. (Supersedes NACA TN's 1086 and 1655.)

TABLE I. - EXPERIMENTAL DATA

Condition	Combustor-inlet total pressure, lb/sq in. abs	Combustor reference velocity, ft/sec (a)	Combustor-inlet temperature, °F	Combustor-outlet average temperature, °F	Total air flow, lb/sec	Fuel-air ratio	Combustion efficiency, percent	Total-pressure drop through combustor, lb/sq in.	Total-pressure loss, percent
A	9.8	160	860	2090	2.35	0.0231	85.6	0.47	4.8
B	14.7	160	870	2030	3.53	.0195	94.7	.63	4.5
C	25.0	160	860	1930	5.90	.0170	98.7	1.22	4.9
D	24.7	125	860	2050	4.60	.0196	96.8	.71	3.5
E	25.0	200	840	1980	7.37	.0180	99.6	2.13	8.5

[a]Based on maximum combustor cross-sectional area of 105 sq in. and combustor-inlet air density.

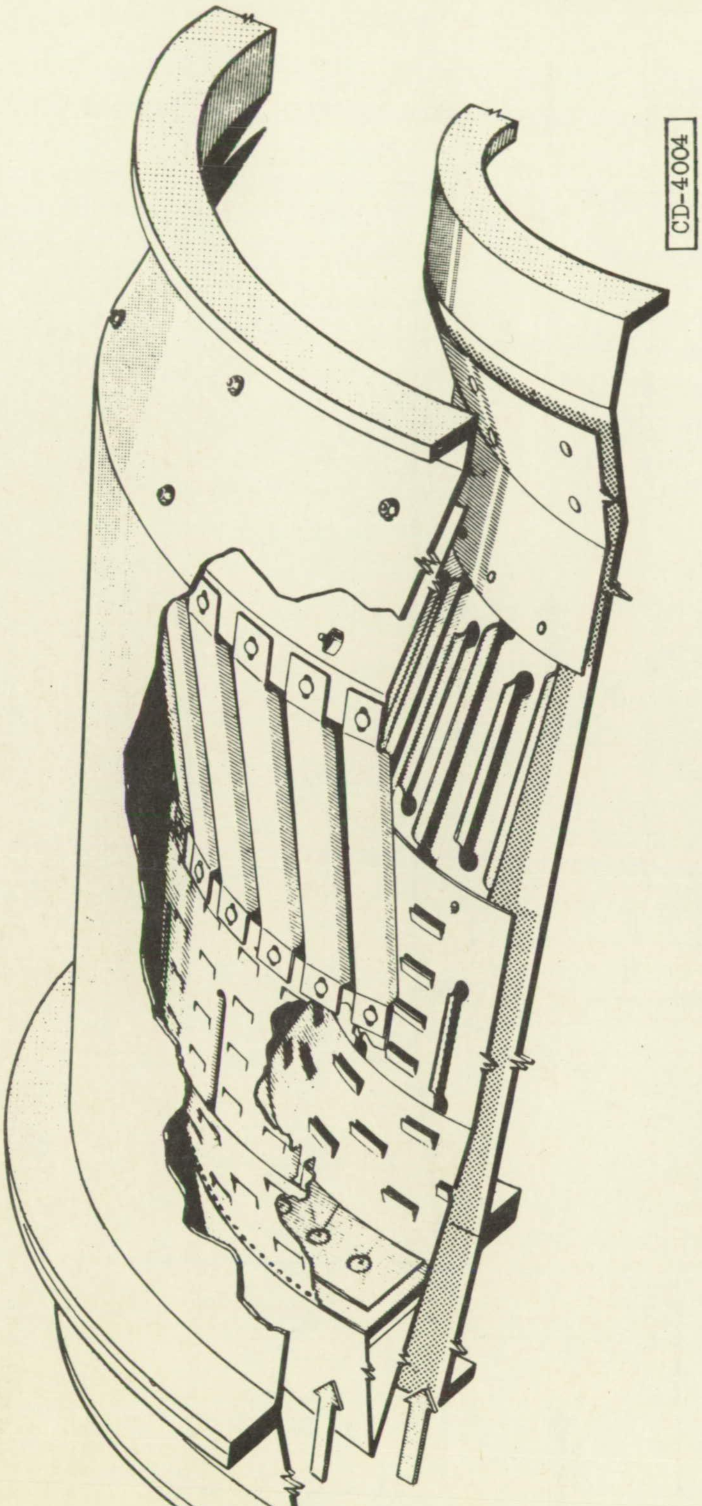


Figure 1. - Three-quarter cutaway view of experimental channeled-wall annular combustor assembled in housing.

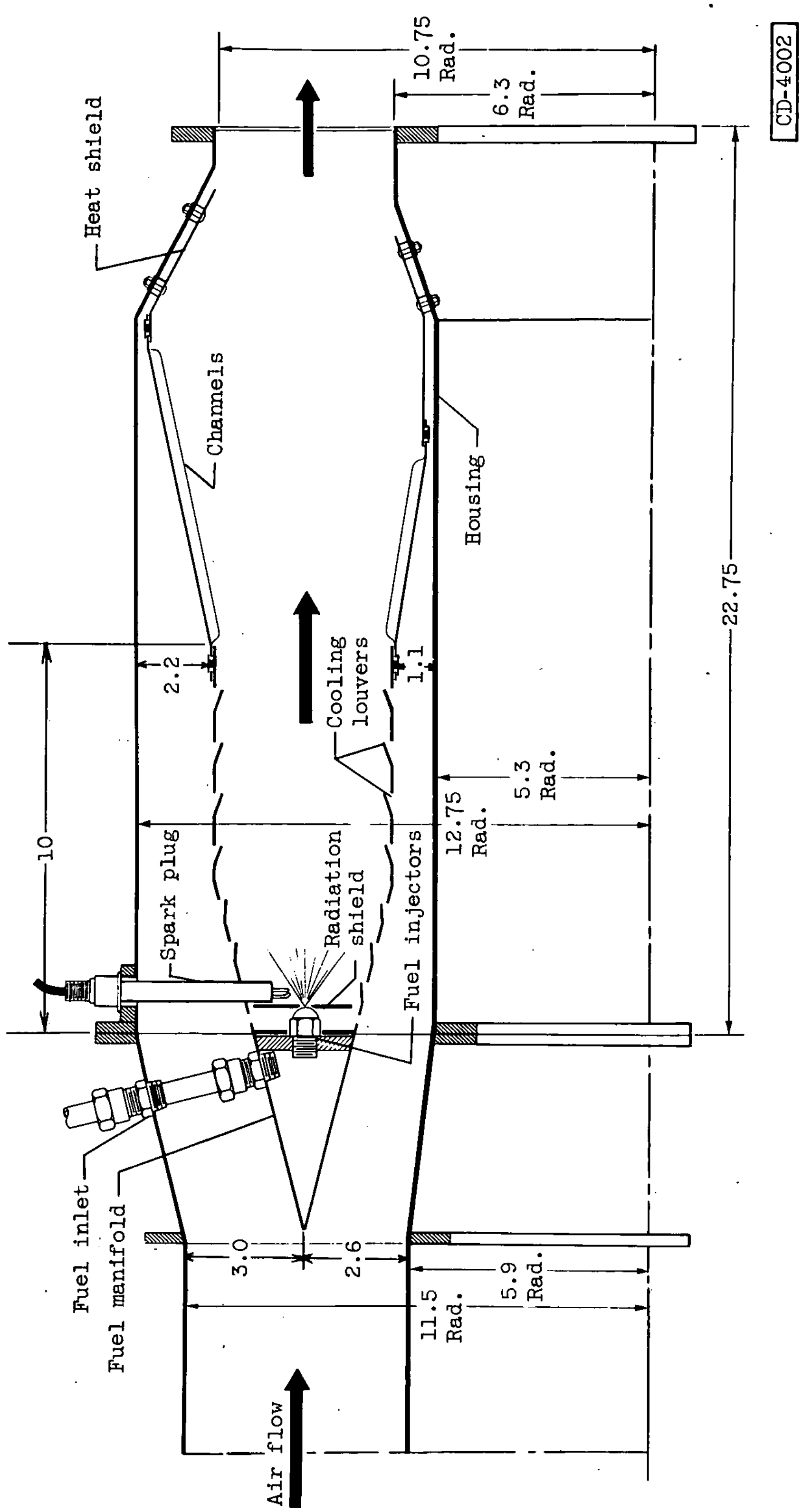


Figure 2. - Longitudinal cross-sectional view of experimental channeled-wall annular combustor. (Dimensions are in inches.)

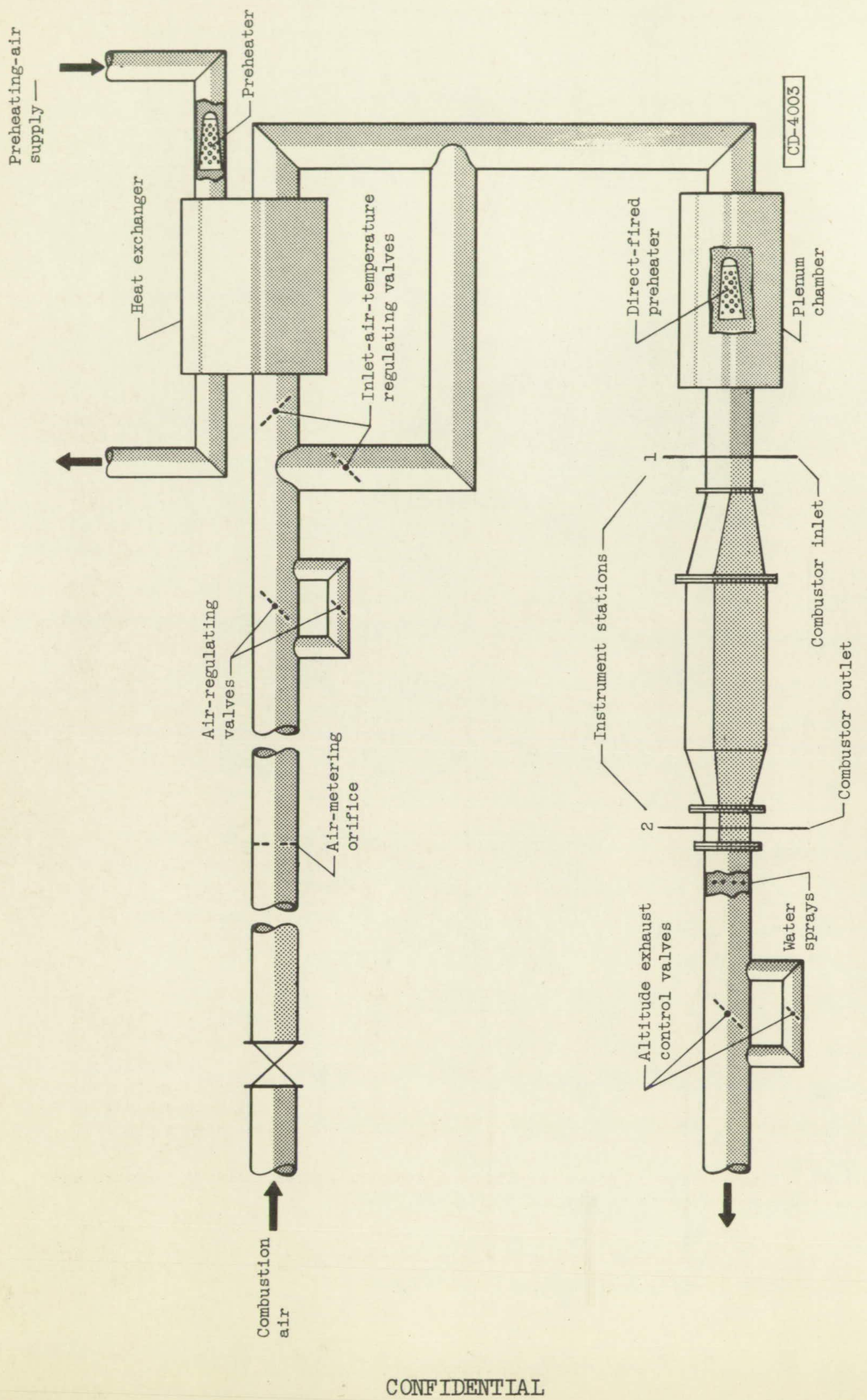


Figure 3. - Installation of experimental annular turbojet combustor.

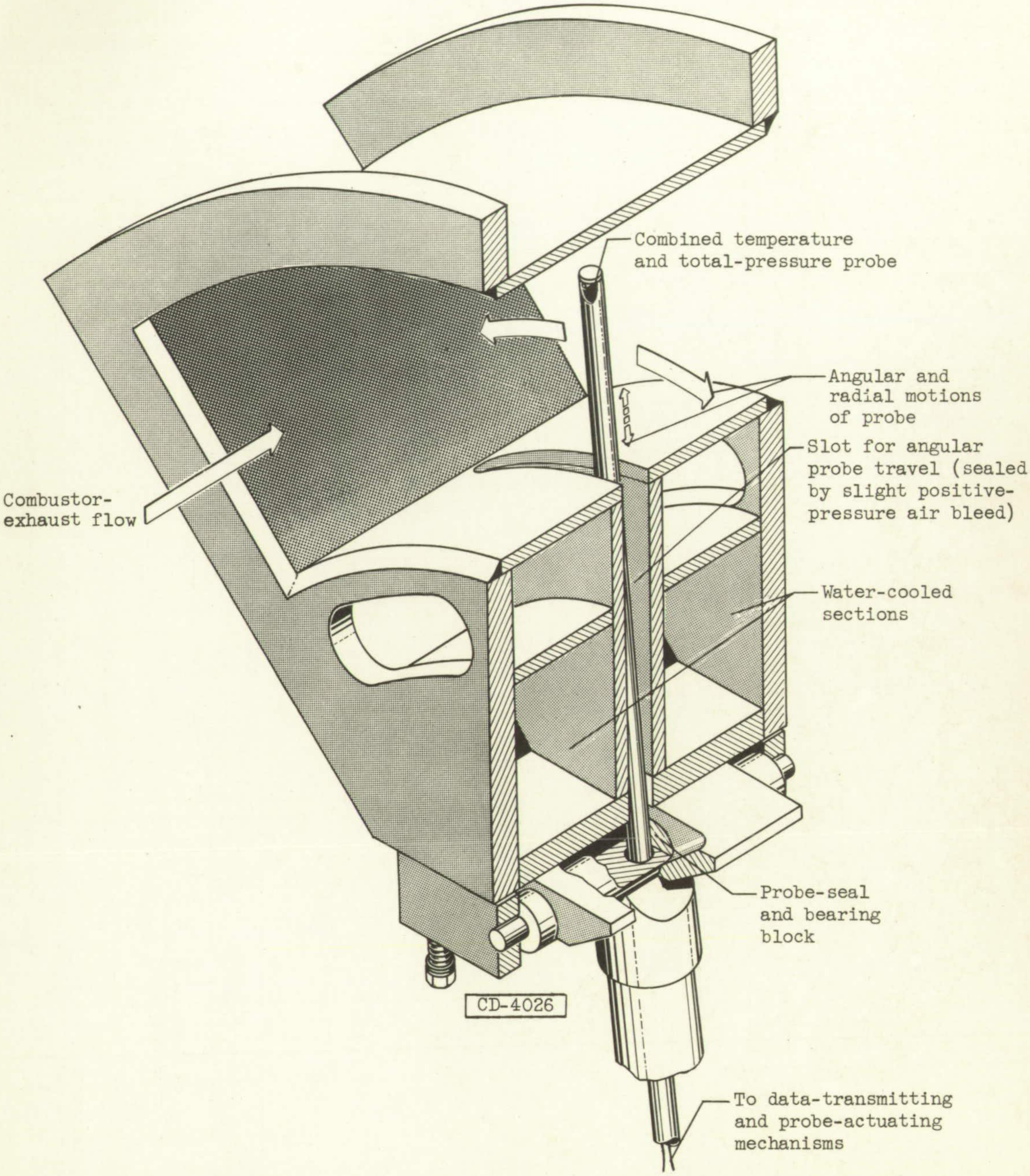


Figure 4. - Cutaway view of polar-coordinate traversing system used for pressure and temperature measurements at station 2 (fig. 3).

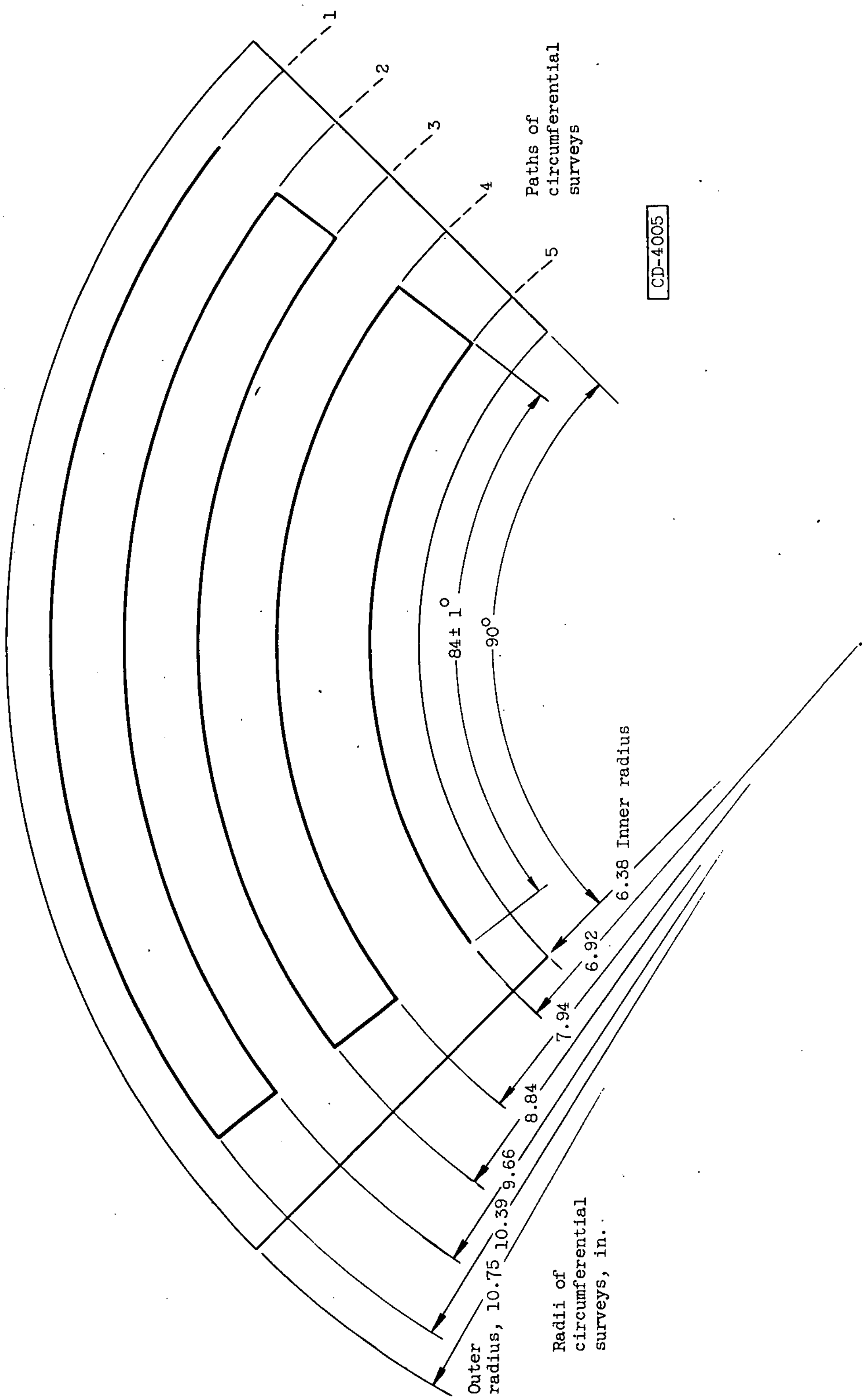


Figure 5. - Paths of probe tip of polar-coordinate survey system across combustor-outlet section, showing circumferential sweeps at five radii at centers of equal areas.

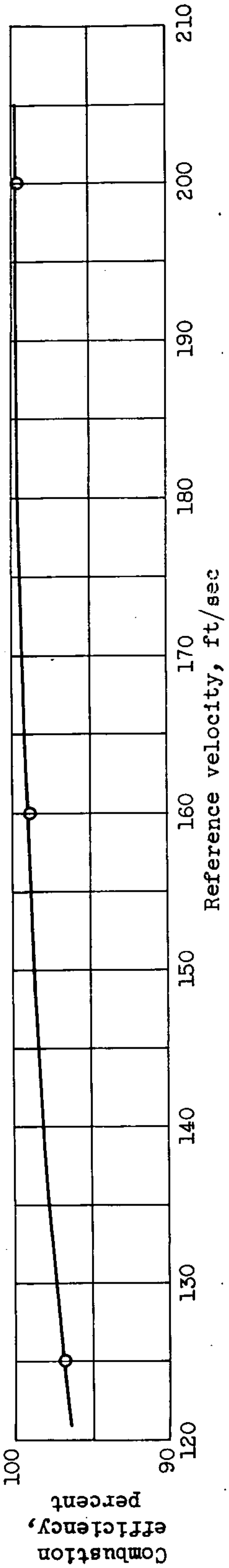


Figure 6. - Effect of velocity on combustion efficiency of experimental annular combustor. Inlet-air pressure, 25 pounds per square inch absolute; inlet-air temperature, 870° F; average outlet temperature, 2000° F.

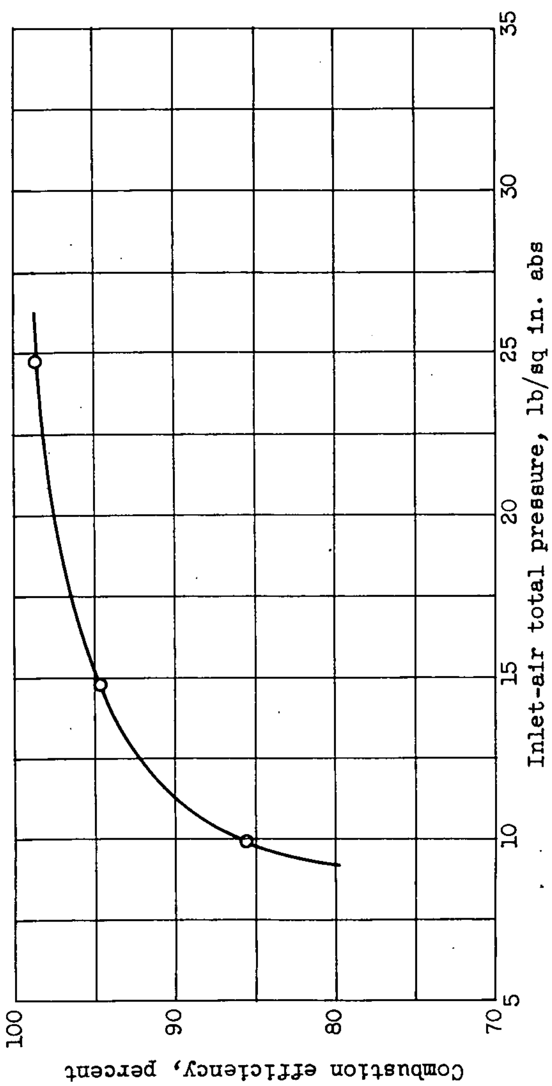
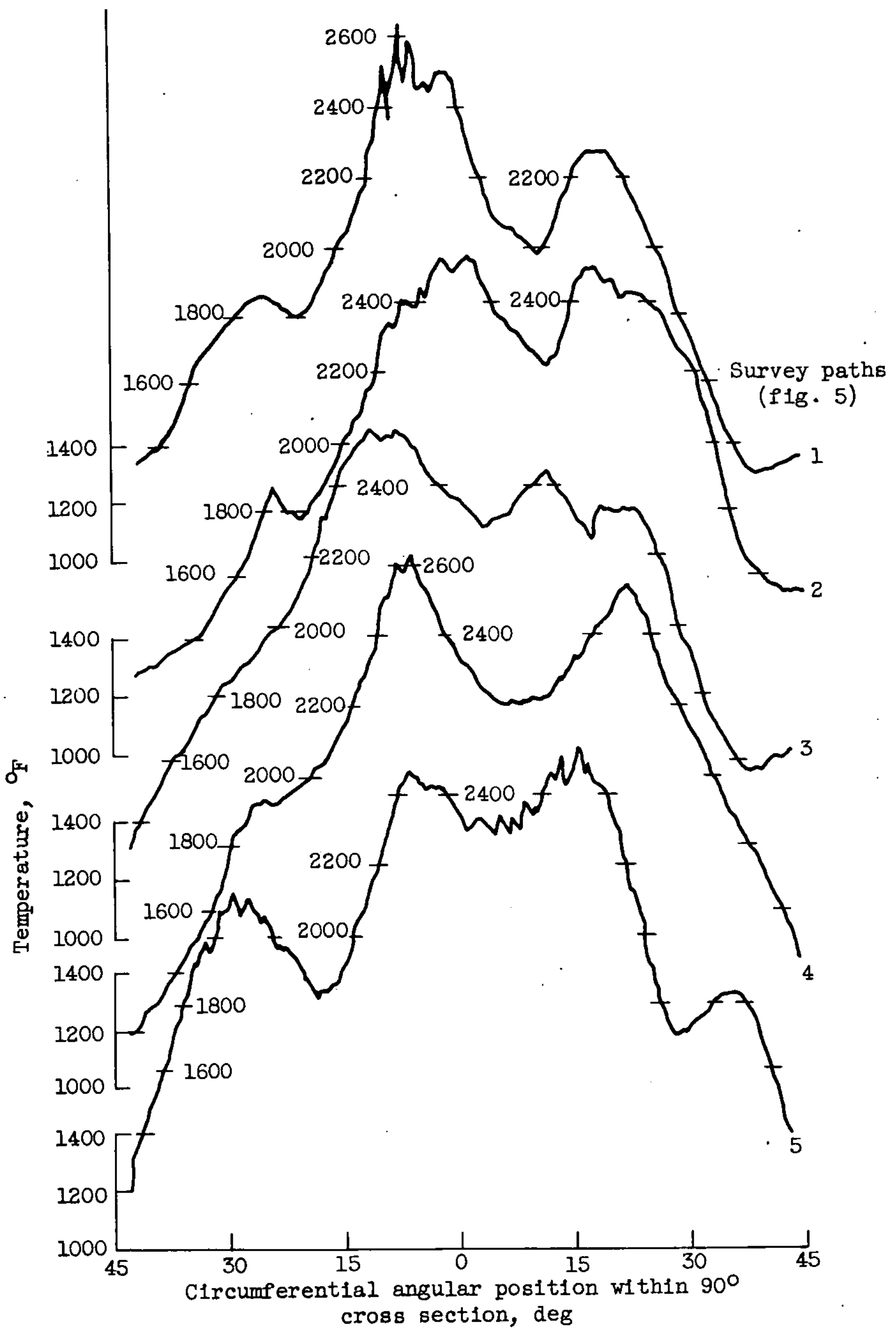
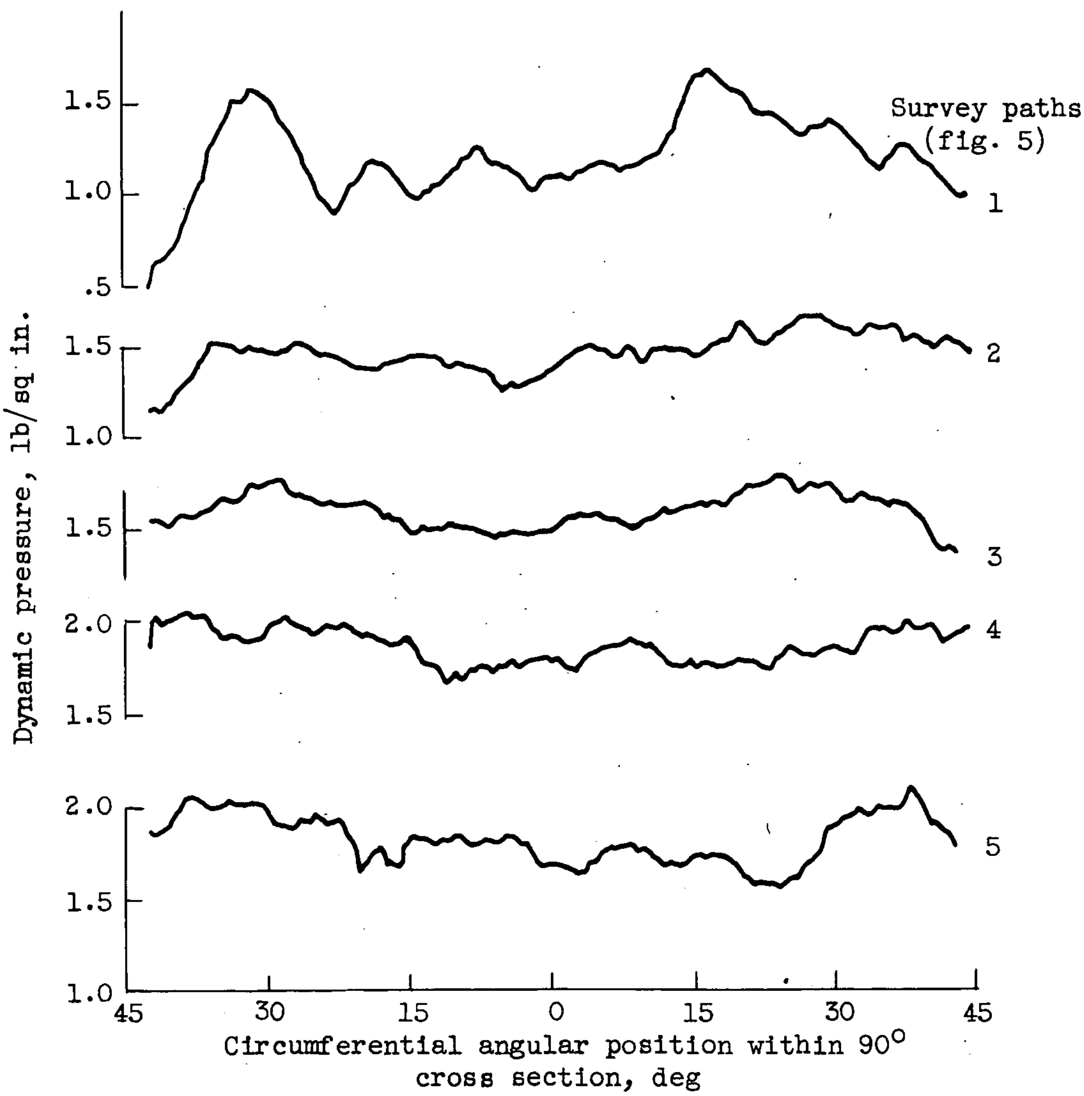


Figure 7. - Effect of pressure on combustion efficiency of experimental annular combustor. Reference velocity, 160 feet per second; inlet-air temperature, 870° F; average outlet temperature, 2000° F.



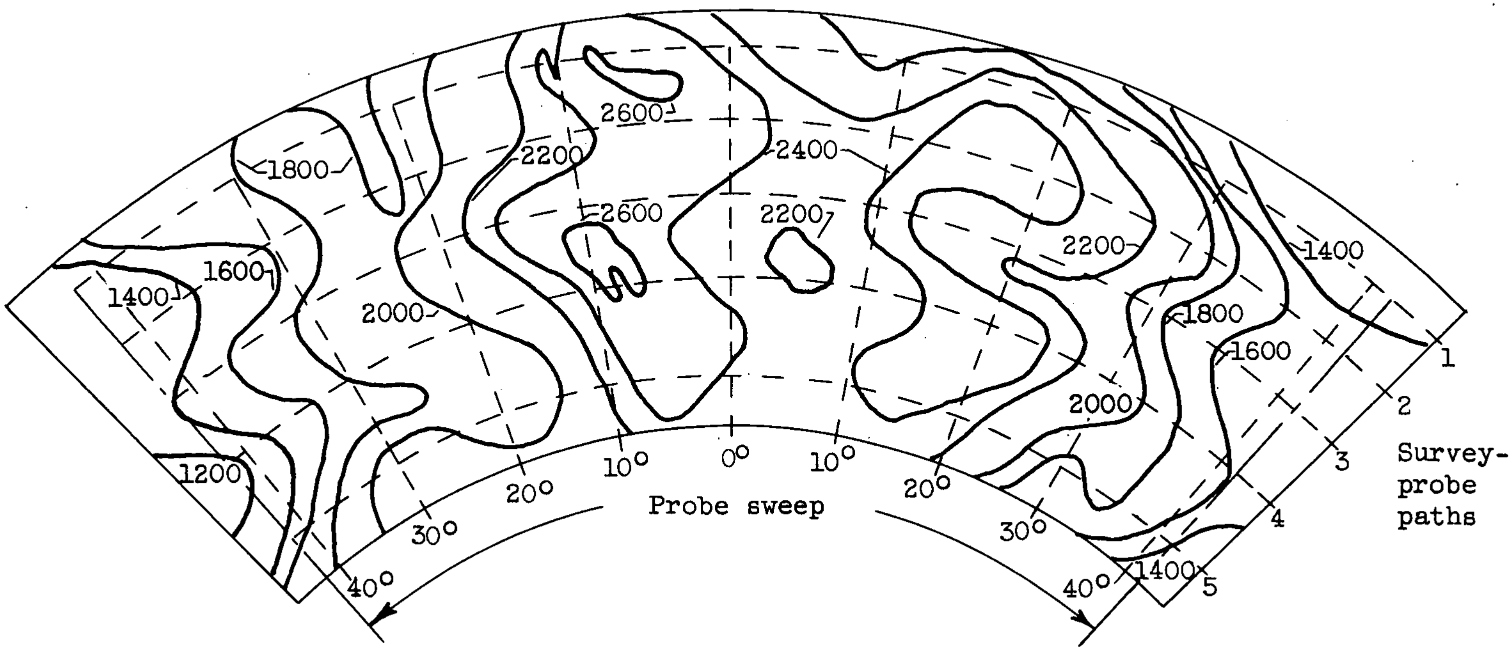
(a) Temperature surveys.

Figure 8. - Experimental-combustor exhaust measurements taken by polar-coordinate survey system. Reference velocity, 200 feet per second; inlet-air pressure, 25 pounds per square inch absolute; inlet-air temperature, 840° F; outlet temperature, 1980° F.



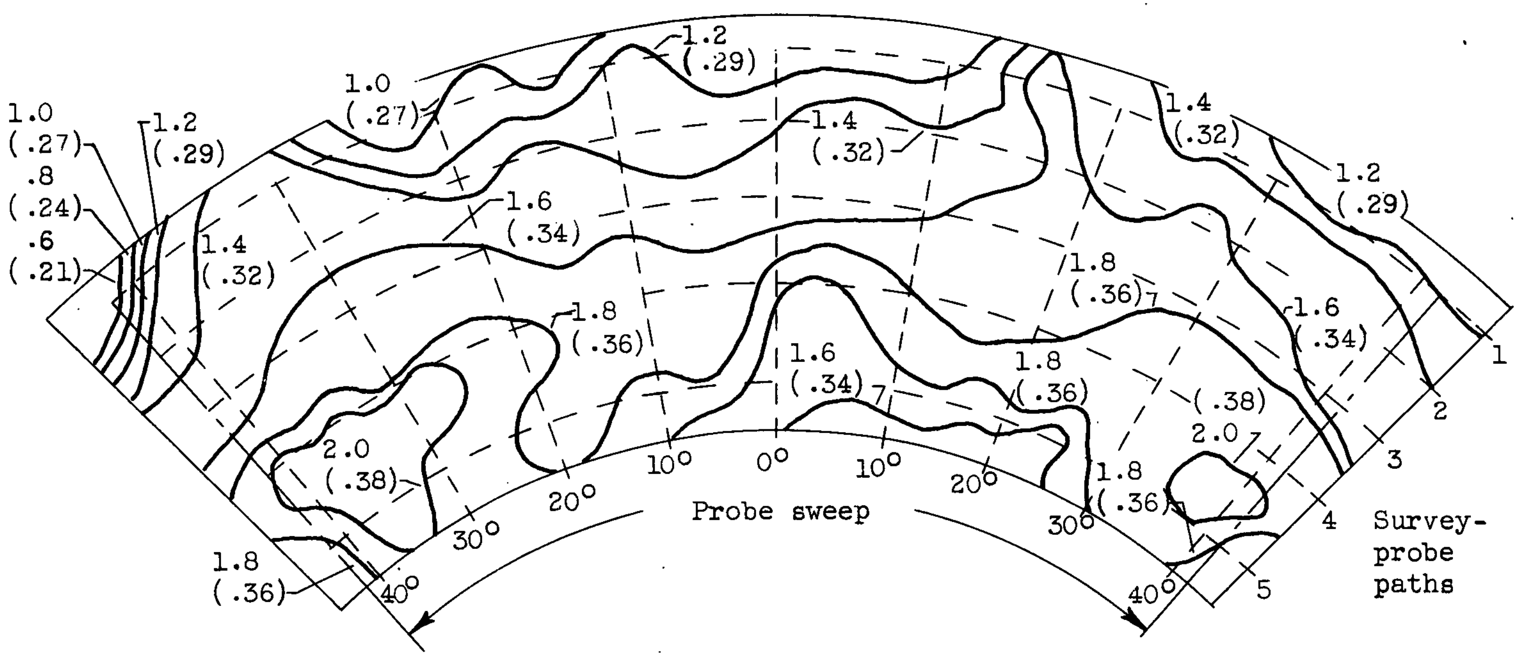
(b) Pressure surveys.

Figure 8. - Concluded. Experimental-combustor exhaust measurements taken by polar-coordinate survey system. Reference velocity, 200 feet per second; inlet-air pressure, 25 pounds per square inch absolute; inlet-air temperature, 840° F; outlet temperature, 1980° F.



(a) Isothermal patterns, °F.

Figure 9. - Contour patterns at outlet of experimental channeled-wall annular combustor. Reference velocity, 200 feet per second; inlet-air pressure, 25 pounds per square inch absolute; inlet-air temperature, 840° F; average outlet temperature, 1980° F.



(b) Isobaric patterns of dynamic pressure, pounds per square inch. (Mach number values in parentheses.)

Figure 9. - Concluded. Contour patterns at outlet of experimental channeled-wall annular combustor. Reference velocity, 200 feet per second; inlet-air pressure, 25 pounds per square inch absolute; inlet-air temperature, 840° F; average outlet temperature, 1980° F.

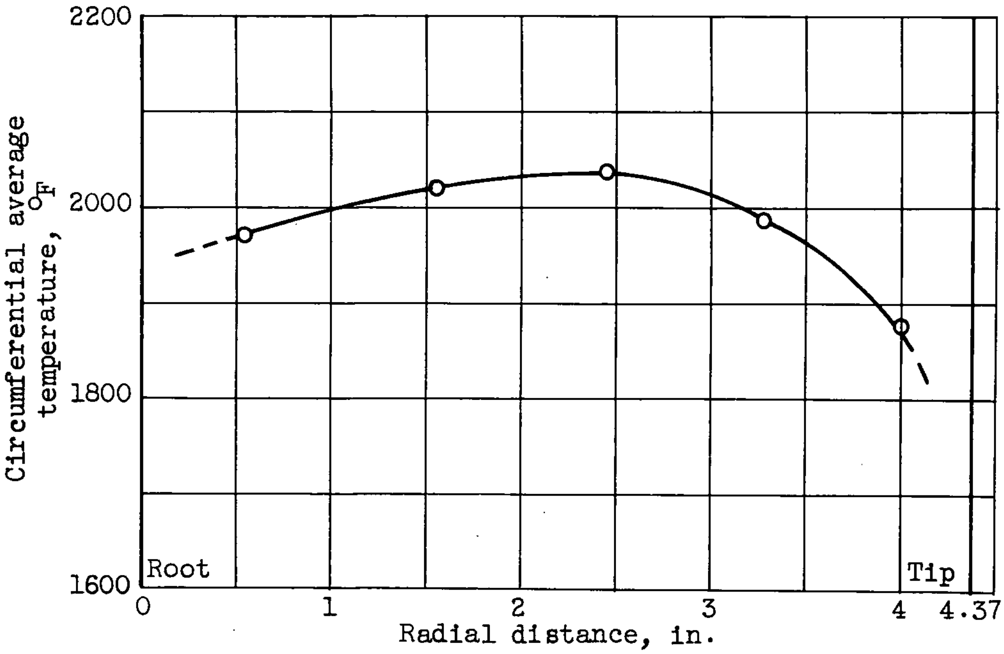


Figure 10. - Radial temperature profile at outlet of experimental annular combustor. Reference velocity, 200 feet per second; inlet-air pressure, 25 pounds per square inch absolute; inlet-air temperature, 840° F; outlet temperature, 1980° F.

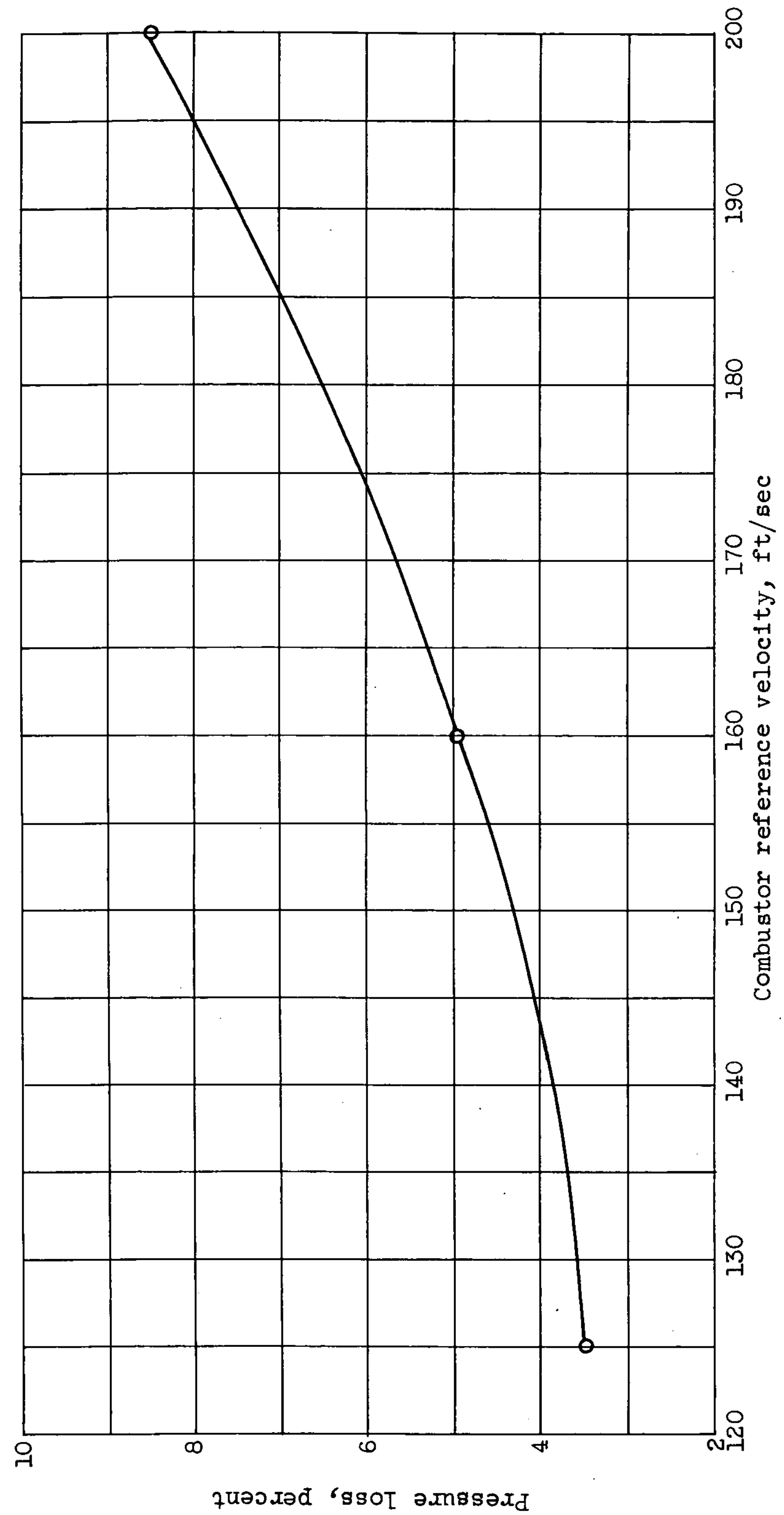


Figure 11. - Effect of velocity on pressure loss of experimental annular turbojet combustor. Inlet-air pressure, 25 pounds per square inch absolute; inlet-air temperature, 870° F; average outlet temperature, 2000° F.

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