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RESEARCH MEMORANDUM

PERFORMANCE OF FIVE SHORT MULTIELEMENT TURBOJET COMBUSTORS FOR HYDROGEN FUEL IN QUARTER-ANNULUS DUCT

By Robert E. Jones and Warren D. Rayle

Lewis Flight Propulsion Laboratory
Cleveland, Ohio

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By Robert E. Jones and Warren D. Rayle

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Pages 22 and 28: The photographs of figures 5(a) and 7(a) should be interchanged.

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RESEARCH MEMORANDUM

PERFORMANCE OF FIVE SHORT MULTIELEMENT TURBOJET COMBUSTORS FOR HYDROGEN FUEL IN QUARTER-ANNULUS DUCT*

By Robert E. Jones and Warren D. Rayle

SUMMARY

Five short multielement turbojet combustors were designed for use with hydrogen fuel, and their performance was investigated in a quarter-annulus duct. One combustor consisted of an array of U-gutter flameholders; the other four combustors were manifolded arrays of swirl-can combustor elements. Fuel injection into each swirl-can element through a tangential sonic orifice created a swirling fuel-air mixture within the can. The elements varied in size from 1.5 to 2.0 inches in length and similarly in exit diameter.

Four of the test combustors gave combustion efficiencies exceeding 86 percent at a reference velocity of 180 feet per second, an inlet-air total pressure of 5.7 inches of mercury absolute, and an inlet-air temperature of 350° F at over-all combustion lengths as short as 13.5 inches. Reducing the combustion length to 10.2 inches decreased the combustion efficiency by 2 to 8 percent.

An outlet-gas temperature profile of 1569°±65° F was achieved with a combustor consisting of 20 swirl-can elements through regulation of the fuel flow to each row of elements. Temperature profiles for combustors having 8 and 10 swirl-can elements were too irregular to be acceptable. Total-pressure losses of all five combustors varied from about 1 percent of inlet total pressure at a reference velocity of 75 feet per second to 11 percent at a velocity of 180 feet per second.

INTRODUCTION

Hydrogen fuel offers advantages for aircraft in that the high heat release per pound of fuel can greatly increase flight range (refs. 1 and 2) and the high heat capacity furnishes a large heat sink for cooling the airframe at very high flight speeds (ref. 3).

* Title, ~~Confidential~~ Unclassified

The well-known combustion properties of hydrogen, high flame speed, low quenching distance, and high reaction rate, allow the combustion chamber to be shortened without a loss in combustion efficiency. This has been demonstrated for turbojet combustion chambers (refs. 4 and 5).

The length of a combustor is usually dictated by two considerations: the combustion reaction must be essentially complete, and the outlet-gas temperature must be nearly uniform. With a reactive fuel such as hydrogen the second consideration is probably the more critical. In order to obtain a satisfactory outlet temperature profile in a short combustor, the secondary air must be mixed rapidly with the combustion product; therefore, this mixing must start as near the combustor inlet as possible. 4789

One design that should provide this early and rapid mixing consists of many small combustors, or combustor elements, rather than a single large one. A study of individual "swirl-can" elements (ref. 5) has shown that excellent stability and efficiency can be obtained from rather small and simple geometries. In these "swirl-cans," fuel is injected at sonic velocity parallel to the surface of the conical shell and normal to the axis (fig. 1). A small amount of air is admitted through an orifice plate covering the upstream end of the can. Two factors contribute to the rapid mixing of the fuel and the air: (1) the high velocity differential between the two streams and (2) the instability resulting from the superimposition of a high-density gas (air) on a low-density gas (hydrogen) in a centrifugal field. Within the swirl can, then, the combustion is initiated and stabilized. The can discharges a hot mixture, which still contains considerable unburned fuel. The air flowing outside the can serves not only to complete the combustion, but also commences immediately to dilute the hot combustion products. The use of many small cans provides a high interfacial area between the secondary air and the hot gases; consequently, the mixing is rapid. Some of the swirl cans were provided with trailing V-gutters to increase the rate at which the hot fuel-rich gases could mix with the main airstream.

The objective of the research program described herein was to study the performance of two types of multielement combustors in a one-quarter sector of an annular combustor. Four of the test combustors consisted of manifolded arrays of swirl-can combustor elements, and the other combustor was an array of sloping radial fuel injectors within U-gutter flameholders. Combustion efficiency, outlet-temperature distribution, and total-pressure loss were determined. The range of inlet conditions simulated operation of an engine with a compressor sea-level-static total-pressure ratio of 6.8 at altitudes from 70,000 to 90,000 feet at Mach 0.9 and at an altitude of 110,000 feet at Mach 3. To determine the feasibility of these combustors for a dual-fuel engine, tests were included using propane gas as the fuel to simulate the combustion of vaporized JP-type fuels (ref. 6).

SYMBOLS

The following symbols are used in this report:

P	total pressure, in. Hg abs
P_1	combustor inlet-air total pressure, in. Hg abs
T_1	combustor inlet-air total temperature, $^{\circ}F$
T_o	combustor outlet total temperature, $^{\circ}F$

APPARATUS

Installation

A schematic diagram of the combustor installation is shown in figure 2. Air of the desired quantity and pressure was drawn from the laboratory air-supply system, metered with a sharp-edged orifice, heated to the desired combustor-inlet temperature in the heat exchanger, passed through the combustor, and exhausted into the altitude exhaust system. Hot gases for the heat exchanger were provided by two gasoline-fired slave combustors.

A schematic diagram of the hydrogen-fuel system is shown in figure 3. The fuel was commercial hydrogen with a purity of over 99 percent and was metered with a sharp-edged orifice.

The combustor test section consisted of a one-quarter section of an annular combustor having an outside diameter of 25.5 inches and an inside diameter of 10.8 inches. The combustor cross section was approximately 104.5 square inches. The combustor length could be altered by inserting or removing flanged sections between the inlet diffuser and the outlet nozzle.

Ignition was provided by a sparkplug with an extended center electrode. The spark discharged directly to the downstream edge of a swirl can or to a U-gutter.

Instrumentation

The instrumentation stations are shown in figure 2. Combustor-inlet total temperature and total pressure were measured at station 1 with four bare-wire Chromel-Alumel thermocouples and four total-pressure tubes, respectively. Combustor-outlet temperatures and pressures were measured at station 2 with a combined total-pressure and total-temperature probe (containing a platinum - 13-percent-rhodium-platinum thermocouple) in a polar-coordinate traversing mechanism (ref. 7). A two-pen X-Y recording potentiometer connected to the survey system continuously recorded outlet temperature and total-pressure differential across the combustor. Static-pressure taps were also located at stations 1 and 2.

For some of the test runs (model 5) a gas analysis probe was substituted for the combined temperature - total-pressure probe. The exhaust gases from the combustor were quenched in the water-cooled probe and 4789
passed through a modified helium leak detector (mass spectrograph), which reported the concentration of unburned fuel in the exhaust gas. The instrument was calibrated by passing known samples (mixtures of hydrogen and nitrogen) through the instrument. A description of the sampling probe and probe tests is given in the appendix.

Test Combustors

The five combustor models investigated in the course of the program were constructed as shown in figures 4 to 8.

Model 1 was a single combustor made up of sloping radial U-gutters attached to a central circumferential U-gutter (fig. 4(a)). Construction details of this combustor are shown in figures 4(b) and (c). Fuel was injected in the upstream direction from tubes situated within the gutters. Four small V-gutters were added to the inner radius of the central U-gutter to improve the temperature profile. These drew their fuel from the central gutter. The main radial gutters were slotted, and the resulting tabs were adjusted to improve the temperature profile. This combustor was tested at over-all combustion lengths of 13.5 and 17.5 inches measured from the upstream face of the combustor to the exhaust instrumentation plane.

Model 2 was a multielement array made up of eight swirl cans, 2 inches long with a 2-inch exit diameter. The swirl cans were arranged in two rows, five in the outer row and three in the inner. Figure 5 shows the details of this model. A central manifold supplied fuel to a single fuel-injection orifice in each swirl can. Eight V-gutters attached to the exit of each can acted as flame spreaders. This model was tested at combustion lengths of 10.2 and 13.5 inches measured from the upstream face of the swirl can to the instrumentation plane.

Model 3, another multielement array, resembled model 2 except that five smaller swirl cans (1.75 in. long and 1.5 in. in outlet diam.) replaced the three cans in the inner row. The small swirl cans were provided with six V-gutters as flame spreaders (fig. 6). This model was tested at combustion lengths of 10.2 and 13.5 inches.

Model 4 was made up of cylindrical swirl cans arranged in two rows, five cans in the outer row and four in the inner (fig. 7). The exit of each can was slotted and flared to act as a flame spreader. The fuel supply tubes running through each can allowed two injection orifices, one on either side of the can. Furthermore, the fuel flow to each row of elements, being separately controlled, provided a means of varying the outlet-temperature profile. The combustion length for this model was 12.5 inches.

Model 5 consisted of three rows of small swirl cans, again with the fuel supply tube passing through each can (fig. 8). These small cans were not provided with exit flame spreaders. The fuel flow to each row of elements was again individually controlled. For this model the combustion length was 11.0 inches.

PROCEDURE

Combustor performance was evaluated over a range of fuel-air ratios at the following conditions:

Inlet-air total pressure, in. Hg abs, P_1	Airflow rate, lb/sec	Inlet-air total temperature, °F	Reference velocity, ft/sec (a)	Simulated altitude, ft	Flight Mach number
[b]5.7	0.52	350	75	90,000	0.9
[b]9.0	.79	↓	↓	80,000	↓
[b]14.7	1.28	↓	↓	70,000	↓
[c]15.8	2.34	900	210	100,000	3.0
5.7	0.79	350	120	-------	---
5.7	1.28	350	180	-------	---

[a]Based on the maximum combustor cross-sectional area of 0.73 sq ft and inlet conditions.

[b]For an engine having a sea-level-static compressor total-pressure ratio of 6.8.

[c]For an engine having a sea-level-static compressor total-pressure ratio of 5.0.

The last two test conditions were used to determine performance of the combustors at higher air velocities and lowest total pressure.

CALCULATIONS

Combustion efficiency was calculated as the percentage ratio of actual to theoretical increase in enthalpy from the combustor-inlet instrumentation plane (station 1, fig. 2) to the combustor-outlet plane (station 2, fig. 2) using the method described in reference 8. Enthalpy values for hydrogen and its combustion products were obtained from reference 8. A value of 50,965 Btu per pound was used as the lower heat of combustion of hydrogen. The enthalpy of the gases at station 2 was assumed to correspond to the area-average temperature obtained from the traversing probe. A few data points were also calculated using the more precise mass weighting procedure described in reference 5, and good agreement was found between these combustion efficiencies and the area-average combustion efficiencies. The data presented were calculated by the area-average method. When the gas analyzer was used (model 5) the combustion inefficiency (100 - Combustion efficiency) was assumed to be the ratio of the fuel-air ratio at station 2 to the original (over-all) fuel-air ratio. Again the unburned fuel-air ratio at station 2 was assumed to be represented by an area-average of the readings from the traversing probe.

Outlet-temperature distributions were plotted directly from the indications of the exhaust survey probe, and average radial-temperature profiles were constructed from the distributions. Total-pressure loss was measured directly and recorded as a function of probe position.

RESULTS AND DISCUSSION

A summary of the results obtained in this investigation is presented in table I.

Combustion Efficiency

The combustion efficiencies of the five test combustors at their shortest combustion lengths are summarized in figure 9. With the exception of model 4, the combustion efficiencies are nearly identical at the same test condition. As can be seen from table I, increasing the combustor length for models 1, 2, and 3 increased combustion efficiency from 2 to 5 percent. The combustion-efficiency data for model 5 were taken by gas analysis and did not correspond too closely to data taken with the thermocouple system.

However, the data for models 1 through 4 with the thermocouple probe were reproducible and do not seem too unreasonable. The thermocouple-measured efficiencies for model 5 were occasionally as low as 65 percent at the extreme test condition, but were not found to be reproducible. A minimum combustion efficiency of 93.5 percent was measured at the same test condition by gas analysis. Special tests of the gas analyzer and the gas sampling probe led to the conclusion that the readings from the instrument were correct. The appendix describes these tests as well as one possible source of error in the thermocouple readings. However, the efficiencies indicated by the two systems were in substantial agreement when the combustors were operated at pressures of 1/2 atmosphere or greater.

Model 4, the array of cylindrical swirl cans, was more unstable than the other combustors, with intermittent blowout often noted. This probably accounts for the lower efficiencies of this combustor.

Temperature Profiles

A satisfactory turbojet combustor must exhibit high combustion efficiency and a uniform temperature profile. It would be difficult to choose a final combustor type from models 1, 2, 3, and 5 on the basis of combustion efficiency (fig. 9). However, combustor-outlet temperature profiles were very irregular for models 1 to 4 (fig. 10). With model 5, an average outlet-temperature profile of $1569^\circ \pm 65^\circ$ F was obtained by adjusting the relative fuel flow to each row of elements. Figure 11 shows the outlet-temperature distribution for model 5 at an average outlet temperature of 1569° F.

The temperature profile for model 1 was unsatisfactory, since both radial and circumferential temperature gradients were too large for turbine blades to withstand. Further modification of this combustor could have improved the temperature profile, but probably at the expense of increased pressure loss or lower combustion efficiency. Furthermore, such a combustor design would not lend itself to scaling.

The temperature profile for model 2 was less severe circumferentially but more severe radially than model 1. Spreading the two rows of swirl cans apart did not improve the profile markedly. The V-gutters attached to the can exits to spread the hot burning gases were less effective than expected.

Combustor model 3, with five small swirl cans in the inner ring instead of three large ones, showed some profile improvement. As might be expected, the circumferential profile was less irregular downstream of these cans, but the radial profile was little if any better than before.

Model 4 combustor (cylindrical swirl cans) was equipped with a separate fuel control to each row of cans to provide greater control of the temperature profile. However, these elements were only marginally stable and tended towards rich blowout; consequently, the fuel-flow control was not effective in rectifying the temperature profile. The operation of these elements was so unsatisfactory that further research on cylindrical swirl cans was not attempted.

The use of many small swirl-can elements (without V-gutters for flame spreading) seemed to offer the best approach for temperature-profile control. As can be seen from figures 10 and 11, good control was achieved with model 5 by adjusting the rows of swirl cans radially and by controlling the proportion of the total fuel supplied to each row. For the particular run shown in figure 11, the outer and middle rows had the same fuel flow per can, while the inner row flow per can was reduced by about 20 percent. This ratio was maintained for most of the other runs.

Pressure Loss

The total-pressure loss was very low for all five models, 1 to 1.4 percent at a reference velocity of 75 feet per second and from 9.4 to 12.5 percent at 180 feet per second (fig. 12). The pressure losses at the 75-foot-per-second condition are less than one-third those of present-day longer combustors and less than one-half those of previous short combustors (ref. 4). Within the accuracy of the measurements, the five test combustors had substantially the same losses.

Durability

At no time during the experimental program was any failure of the combustors or their fuel tubes noted due to heat distortion or pressure effects. Instead, the fuel flow was sufficient to cool the fuel tubes and the swirl cans. Heating was observed only at very high inlet-air temperatures or low fuel flows. Slight damage was incurred at the tips of the four small V-gutters of model 1, but these gutters were made of stainless steel rather than Inconel.

Comparison with Previous Short Combustors

Figure 13 compares the performance of models 3 and 5 with that of a previous short (19.4 in.) hydrogen combustor described in reference 4. As can be seen, the short multielement combustors have combustion efficiencies comparable to those of the longer combustor.

Operation with Propane Fuel

The operation of these test combustors with propane fuel has been reported (ref. 6). Figure 14 compares the performance of models 1, 3, and 5 with propane fuel, the combustors operating at an inlet total pressure of 14.7 inches of mercury absolute, a reference velocity of 75 feet per second, and an inlet-air temperature of 350° F. The tests were intended to explore the possibility of using a vapor hydrocarbon fuel in such multielement combustors. The operating limits of the combustors were found to be quite close to the 1/2-atmosphere pressure conditions, model 5 being somewhat less stable than models 1 and 3. Intermittent operation often noted with model 5 probably contributed to its lower efficiency. However, at operating pressures above 1/2 atmosphere the performance of the short combustors seems satisfactory.

SUMMARY OF RESULTS

Five experimental combustors using hydrogen fuel were evaluated in a quarter-sector annular duct. Combustor length was varied from 10.2 to 17.5 inches. Four combustors consisted of arrays of many small swirl cans; the other comprised an array of U-gutters into which fuel was injected. The following results were obtained:

1. A minimum combustion efficiency of 93.5 percent was measured with the gas analyzer at a pressure of 5.7 inches of mercury absolute, a reference velocity of 180 feet per second, and an inlet total temperature of 350° F.

2. For the subsonic test conditions, combustion efficiencies as measured by the gas analyzer and thermocouple system varied from 93 to 100 percent.

3. An average outlet radial temperature profile of $1569^\circ \pm 65^\circ$ F was obtained with a combustor comprising 20 swirl-can elements. Combustors with 8 to 10 swirl cans did not give a satisfactory outlet-temperature profile.

4. Combustor total-pressure loss was very low for all models tested, being approximately 1 to 1.4 percent of the inlet total pressure at an inlet total pressure of 5.7 to 14.7 inches of mercury absolute, a reference velocity of 75 feet per second, and an inlet total temperature of 350° F.

CONCLUDING REMARKS

All the short combustors investigated gave high combustion efficiencies and low total-pressure losses. However, only model 5 was judged to have an acceptable temperature profile. It would appear that for future turbojet engines multielement combustors similar to model 5 would offer marked advantages over a conventionally designed turbojet combustor.

Lewis Flight Propulsion Laboratory
National Advisory Committee for Aeronautics 4789
Cleveland, Ohio, April 23, 1958

APPENDIX - COMBUSTION EFFICIENCY MEASUREMENTS

Water-Cooled Gas-Sampling Probe

Figure 15 is a sketch of the water-cooled gas-sampling probe. The probe body was a 3/8- by 1/32-inch-wall stainless-steel tube about 30 inches in length. Cooling water enters at the base of the probe, fills the entire probe body, and leaves through three 1/32-inch-diameter holes at the tip of the probe. The gas sample is drawn into the probe at sonic velocity through an 1/8-inch-diameter orifice and passed down through a tube (1/4-in. diam. by 0.020-in. wall) to the gas analyzer.

Quenching Tests

The effectiveness of the water-cooled probe in quenching the hot gases was established experimentally as follows. A gas sample was made up consisting of 3.4 percent hydrogen and 3.8 percent helium in nitrogen. This mixture was passed through a capillary tube and dumped into the main gas stream about 1/8 inch from the orifice in the gas-sampling probe. Thus the bulk of the gas sample entered the sampling probe and, hence, the mass spectrograph. A length of the capillary tubing immersed in the hot gas stream served as a heat exchanger to raise the temperature of the gas sample to approximately that of the surrounding airstream. Measurements of hydrogen and helium concentrations were made at various operating conditions as shown in the following table:

SUMMARY OF QUENCHING TESTS FOR HYDROGEN IN WATER-COOLED PROBE

Hydrogen reading	Helium reading	Hydrogen-helium ratio	Condition
13	6.2	2.09	Burning
14	7.2	1.94	No burning
18	11.5	1.56	Burning
28	18.5	1.51	No burning
28	17	1.65	Burning
28	17	1.65	No burning

The fact that the hydrogen-to-helium ratio remained substantially constant at all conditions indicated that even at the high stream temperatures little if any of the hydrogen reacted. It was noted that the coil of capillary tubing became red hot, even with the high sample flow rate. This indicates that the heat exchanger was relatively effective in preheating the sample. On the basis of these tests, it was concluded that the water-cooled sampling probe was effective in halting the combustion reaction.

Possible Thermocouple Probe Error

The discrepancies between the efficiencies measured by gas-sampling and those determined by means of the sonic aspirated thermocouple might be attributed to a deterioration of the probe system or to a difficulty of a more fundamental nature. Such a difficulty might be anticipated if the combustor-outlet gases were a nonhomogeneous mixture containing very hot and very cold gas. Such a stream, with temperature and density varying rapidly with time, might be expected, especially in view of the very short mixing length of these combustors and their multiplicity of flame sources. In such a heterogeneous stream, the sonic aspirated thermocouple would not be apt to draw in a truly representative sample. Moreover, even though the flow becomes sonic within the probe, the velocity at the probe entrance is much less than local stream velocity. Consequently, any small volumes of cold dense gas would tend to be drawn in, while the hot low-density gas would more easily flow aside. Any error from heterogeneity would then act to give lower than "actual" time-average temperatures.

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TABLE I. - EXPERIMENTAL DATA

Combustor-inlet total pressure, in. Hg abs	Combustor-inlet total temperature, °F	Air-flow rate, lb/sec	Combustor reference velocity, ft/sec	Fuel-flow rate, lb/hr	Fuel-air ratio	Mean combustor outlet temperature, °F	Mean temperature rise, °F	Combustion efficiency	Total-pressure loss, $\Delta P/P_1$	Combustion length, in.
Hydrogen fuel; model 1										
5.7	350	0.51	75	9.93	0.00544	1327	977	94.3	1.3	13.5
				14.91	.00817	1679	1329	89.8	1.3	
				17.05	.00934	1839	1489	89.8	1.4	
				8.83	.00484	1185	835	89.8	1.2	
		0.79	117	14.73	0.00517	1240	890	90.3	3.4	13.5
				11.17	.00392	1093	743	97.0	3.2	
				21.16	.00742	1561	1211	89.0	3.7	
				24.94	.00875	1728	1378	87.8	4.0	
		1.28	188	22.96	0.00498	1164	814	84.8	10.9	13.5
				15.36	.00333	902	552	83.1	10.2	
				29.46	.00639	1395	1045	87.6	11.7	
				36.76	.00798	1660	1310	90.3	12.3	
9.0	350	0.79	74	26.50	0.00729	1633	1283	96.3	----	13.5
				23.40	.00566	1392	1042	95.9	----	
				14.40	.00348	1067	717	104.5	----	
15.8	900	2.38	211	32.02	0.00380	1535	635	93.9	----	13.5
				42.11	.00488	1683	783	91.3	----	
				63.59	.00742	2042	1142	91.1	----	
		0.78	115	15.79	0.00559	1354	1004	95.4	3.3	17.5
				21.86	.00779	1637	1287	90.9	3.5	
				27.19	.00982	1889	1539	90.7	3.8	
				13.06	.00459	1214	864	98.0	3.2	
		1.29	190	22.91	0.00497	1218	868	89.8	11.3	17.5
				30.62	.00665	1485	1135	92.7	11.7	
				37.80	.00820	1724	1374	93.2	11.9	
				16.61	.00358	1017	667	94.8	11.2	
Hydrogen fuel; model 2										
5.7	350	0.49	72	9.33	0.00529	1286	936	93.0	0.7	10.2
				6.56	.00372	1029	679	92.7	.7	
				12.59	.00714	1546	1196	91.0	.8	
				16.04	.00898	1808	1458	90.9	.9	
		0.81	119	15.59	0.00535	1280	930	90.9	3.7	10.2
				20.50	.00702	1534	1184	91.4	3.8	
				10.42	.00358	1004	654	92.4	3.2	
				13.23	.00453	1156	806	91.9	3.5	
		1.30	191	25.9	0.00437	1051	701	82.2	----	10.2
				30.4	.00616	1357	1007	86.8	12.2	
				16.5	.00244	782	432	86.5	10.4	
				33.8	.00783	1591	1241	86.9	12.5	
9.0	350	0.81	76	13.23	0.00453	1252	902	103.4	1.3	10.2
				9.33	.00320	1007	657	103.0	1.1	
				16.13	.00554	1393	1043	99.7	1.4	
				20.24	.00695	1648	1298	102.0	1.4	
15.8	900	2.37	211	25.4	0.00297	1453	553	103.3	6.3	10.2
				39.4	.00459	1681	781	98.2	6.9	
				49.2	.00577	1841	941	94.3	7.2	
5.7	350	0.45	67	10.06	0.00618	1471	1121	97.2	1.0	13.5
				9.23	.00567	1358	1008	94.3	1.0	13.5
		0.80	118	10.55	0.00364	1050	700	97.3	3.5	13.5
				20.82	.00718	1564	1214	91.9	3.2	
				16.17	.00558	1335	985	93.1	3.7	
		1.28	188	5.67	0.00346	935	585	85.4	----	13.5
				15.95	.00443	1088	738	86.0	----	
				20.42	.00532	1203	853	83.9	----	
				24.50	.00609	1366	1016	88.9	----	
				32.85	.00713	1528	1178	89.4	----	
9.0	350	0.80	75	8.47	0.00292	961	611	104.6	1.2	13.5
				10.97	.00379	1118	768	104.1	1.2	
				15.81	.00546	1403	1053	102.1	1.3	
				20.28	.00700	1648	1298	101.4	1.4	
15.8	900	2.32	206	17.58	0.00210	1300	400	105.7	5.5	13.5
				26.20	.00314	1470	570	100.0	5.7	
				35.20	.00423	1629	729	97.2	5.8	
				58.00	.00547	1793	893	94.0	6.0	

TABLE I. - Concluded. EXPERIMENTAL DATA

Combustor-inlet total pressure, in. Hg abs	Combustor-inlet total temperature, °F	Air-flow rate, lb/sec	Combustor reference velocity, ft/sec	Fuel-flow rate, lb/hr	Fuel-air ratio	Mean combustor outlet temperature, °F	Mean temperature rise, °F	Combustion efficiency	Total-pressure loss, $\Delta P/P_i$	Combustion length, in.
Hydrogen fuel; model 3										
5.7	350	0.51	75	10.90	0.00594	1377	1027	90.9	—	10.2
				8.20	.00447	1141	791	89.6	—	
				5.10	.00278	861	511	87.4	—	
				13.90	.00743	1557	1207	86.2	—	
		0.81	119	14.40	0.00494	1186	836	87.6	—	10.2
				25.00	.00759	1635	1285	89.7	—	
				19.30	.00662	1450	1100	89.4	—	
				10.30	.00353	975	625	87.4	—	
		1.29	190	12.50	0.00269	798	448	82.0	—	10.2
				28.70	.00613	1275	925	80.1	—	10.2
9.0	350	0.81	75	10.20	0.00350	1028	678	96.7	—	10.2
				15.00	.00514	1317	967	97.0	—	
				19.10	.00655	1540	1190	96.8	—	
15.8	900	2.34	208	26.25	0.00300	1459	559	102.8	5.2	10.2
				35.15	.00417	1624	724	97.2	5.2	
				44.00	.00523	1770	870	95.3	5.6	
				54.50	.00648	1941	1041	94.0	5.7	
5.7	350	0.51	75	10.38	0.00563	1391	1041	95.0	1.0	13.5
				13.87	.00756	1647	1297	94.1	1.1	
				8.88	.00487	1246	896	94.1	.9	
		0.79	117	16.55	0.00575	1324	974	89.8	3.2	13.5
				21.36	.00742	1595	1245	91.4	3.4	
				10.85	.00377	1039	689	93.3	2.9	
				6.65	.00308	928	578	95.7	2.8	
		1.29	189	20.94	0.00453	1114	764	87.6	9.7	13.5
				16.32	.00361	954	604	86.7	9.4	
				25.24	.00550	1259	909	87.0	10.2	
				31.35	.00683	1451	1101	86.9	10.6	
9.0	350	0.79	74	8.86	0.00306	956	606	98.7	1.0	13.5
				10.94	.00380	1100	750	101.0	1.0	
				15.35	.00533	1366	1016	100.7	1.1	
				20.24	.00703	1611	1261	96.1	1.3	
15.8	900	2.37	211	21.30	0.00250	1393	493	107.8	—	13.5
				30.95	.00363	1566	666	102.7	—	
				39.40	.00460	1727	827	101.7	—	
				50.60	.00592	1931	1031	101.0	—	
Hydrogen fuel; model 4										
5.7	350	0.51	75	9.60	0.00527	1276	926	92.5	—	12.5
				12.33	.00673	1449	1099	88.2	—	
				7.12	.00389	1055	705	92.0	—	
				5.06	.00276	854	504	91.5	—	
		0.79	117	13.66	0.00478	1095	745	80.6	—	12.5
				10.31	.00358	931	581	82.2	—	
				16.58	.00587	1233	883	79.5	—	
				20.63	.00717	1409	1059	79.7	—	
		1.27	187	17.48	0.00382	889	539	71.1	—	12.5
				22.91	.00501	1073	723	74.8	—	
				27.32	.00598	1206	856	75.6	—	
				32.68	.00715	1356	1006	75.6	—	
9.0	350	0.80	75	20.81	0.00724	1510	1160	86.9	—	12.5
				16.39	.00573	1360	1010	93.6	—	
				12.91	.00451	1191	841	96.5	—	
				9.62	.00336	983	633	95.4	—	
Hydrogen fuel; model 5; gas analysis										
5.7	350	0.50	74	11.41	0.00629	—	—	98.9	1.3	11.0
				16.25	.00896	—	—	98.9	1.4	
				9.00	.00496	—	—	98.9	1.2	
		0.79	117	14.19	0.00498	—	—	98.0	2.9	11.0
				17.85	.00626	—	—	97.9	—	
				23.70	.00832	—	—	97.9	—	
		1.28	188	20.45	0.00445	—	—	93.5	10.7	11.0
				28.00	.00610	—	—	92.1	—	
				36.08	.00787	—	—	92.6	—	
				43.92	.00953	—	—	92.6	—	
9.0	350	0.79	74	11.46	0.00402	—	—	99.9	1.4	11.0
				16.72	.00586	—	—	99.9	1.4	
				27.86	.00977	—	—	99.9	—	
15.8	900	2.34	209	56.16	0.00664	—	—	94.2	—	11.0
				36.60	.00431	—	—	96.2	—	11.0
Propane fuel; model 1										
14.7	350	1.51	74	66.90	0.0142	1141	791	~75.0	1.2	13.5
Propane fuel; model 3										
14.7	350	1.28	73	57.32	0.0124	1164	814	87.9	1.2	13.5
				41.26	.00896	946	596	86.6	1.1	
				68.67	.0149	1341	991	90.6	1.3	
				92.45	.0201	1628	1278	87.2	1.4	
Propane fuel; model 5										
14.7	350	1.26	72	71.41	0.0160	1343	993	85.0	1.1	11.0
				50.35	.0110	1021	661	80.8	1.2	
				56.59	.0128	1134	784	81.3	1.3	
				81.46	.0178	1388	1038	80.3	1.4	

CD-5333

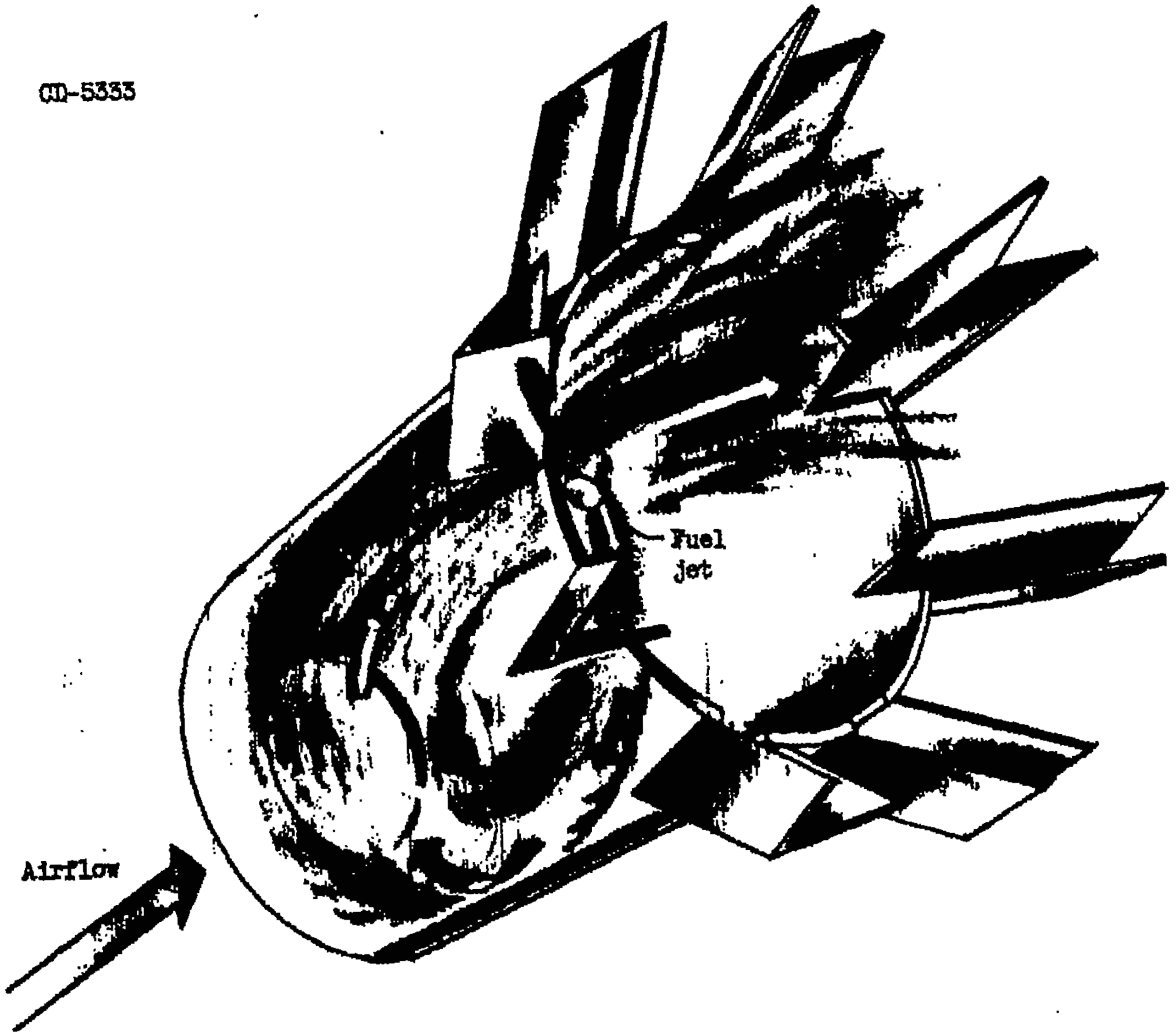


Figure 1. - Operation of swirl-can combustor element.

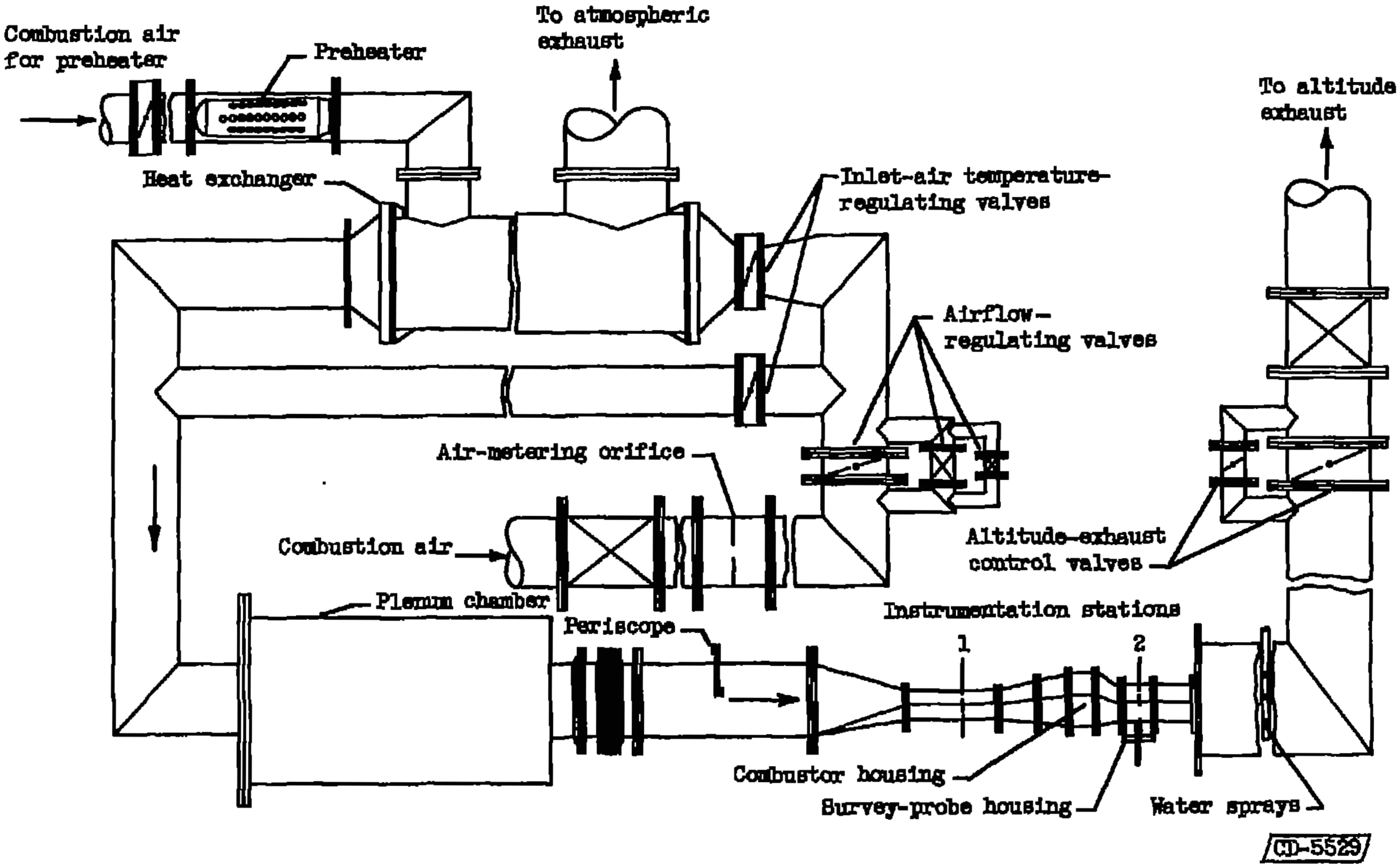


Figure 2. - Test installation.

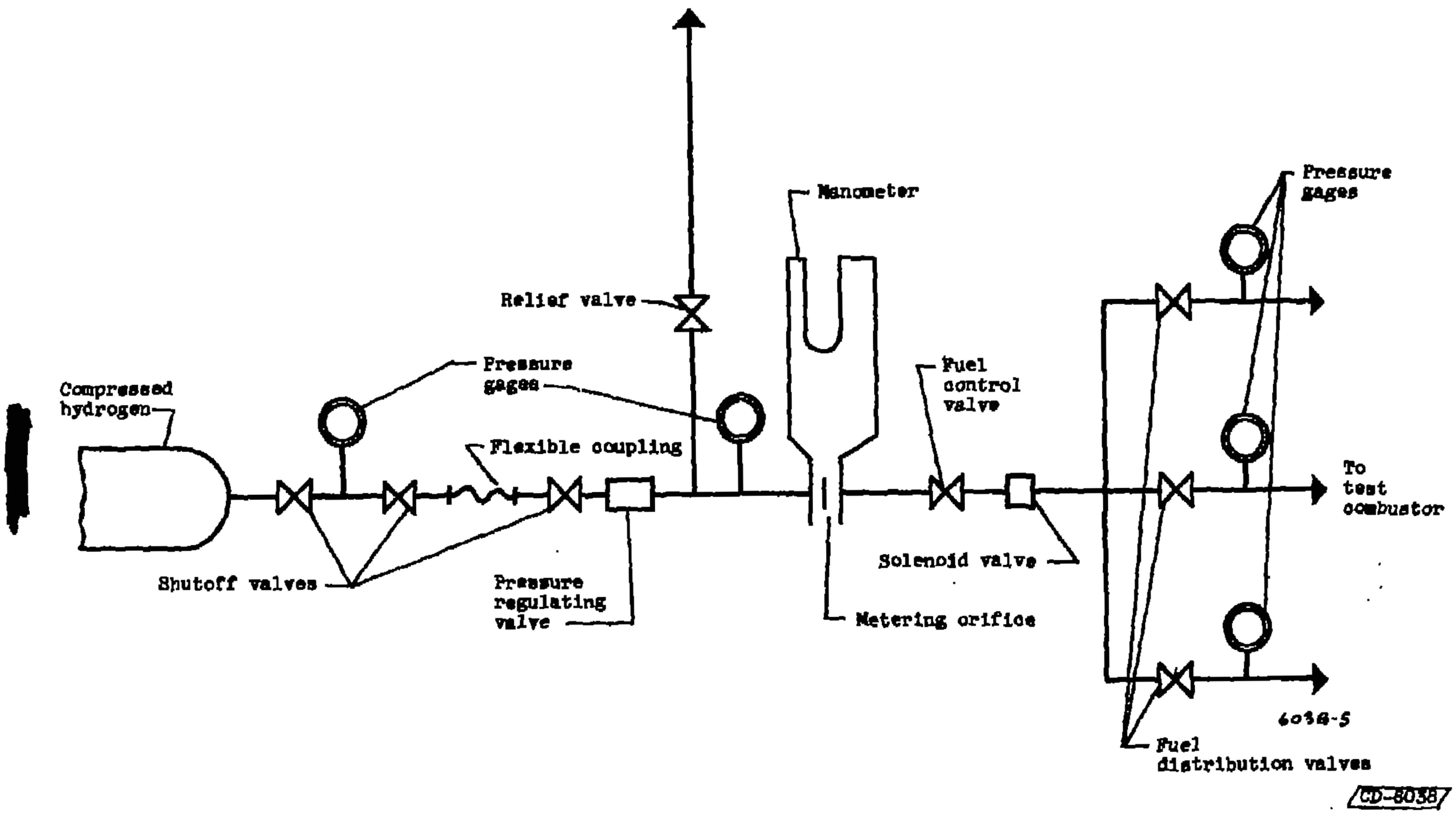
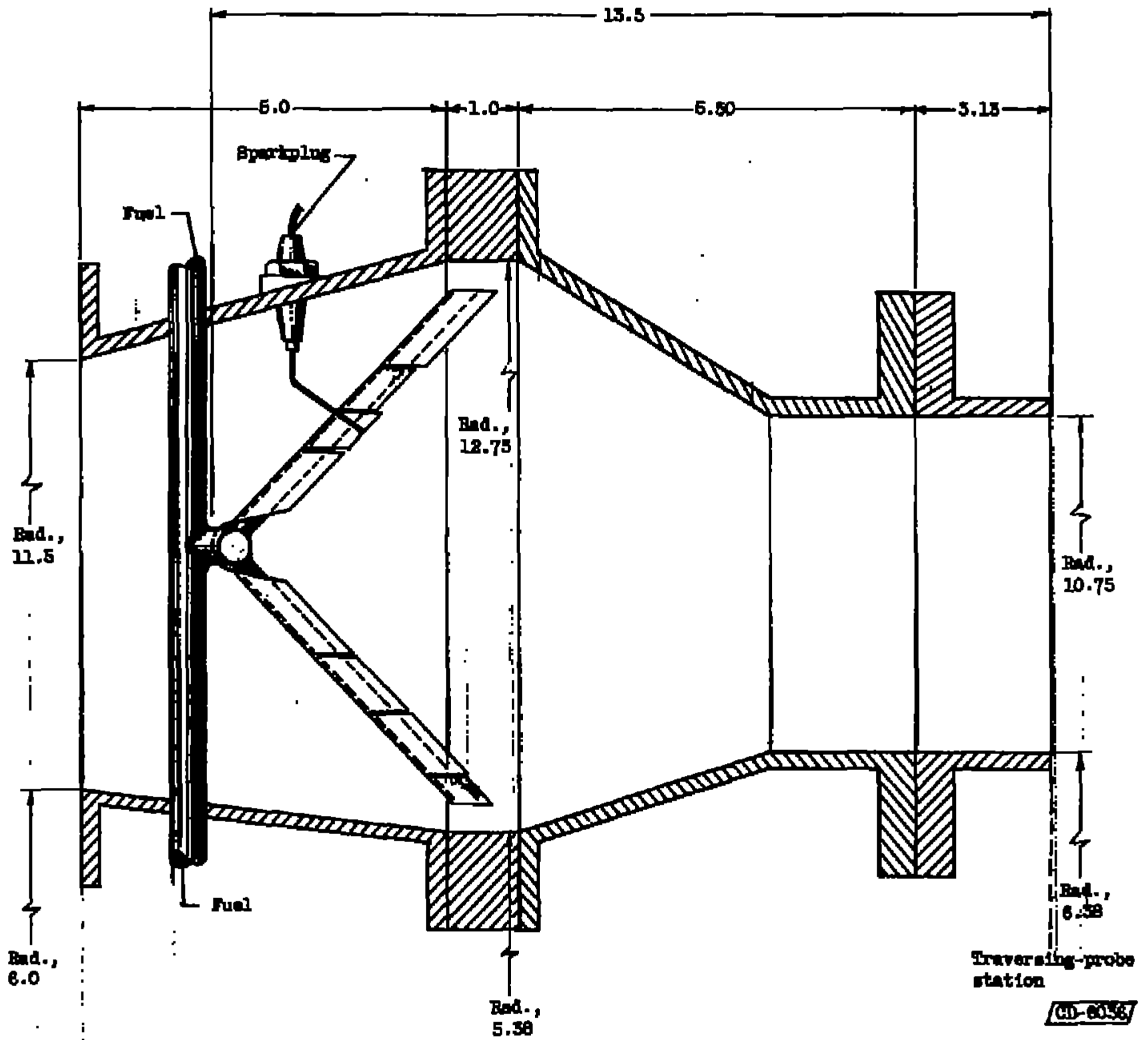


Figure 3. - Schematic diagram of hydrogen-fuel system.

C-42375

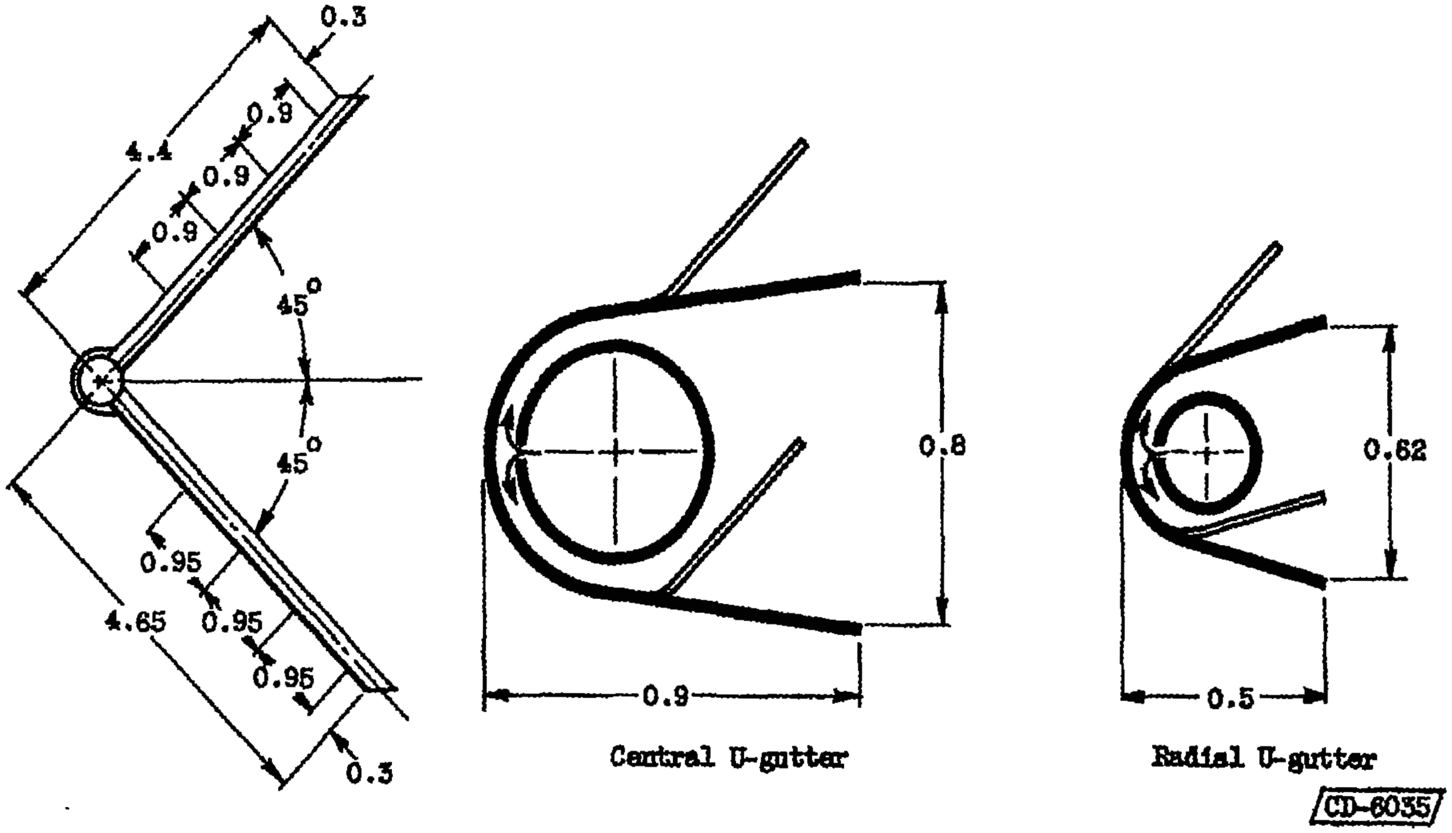
(a) View looking upstream.

Figure 4. - U-Gutter combustor, model 1.



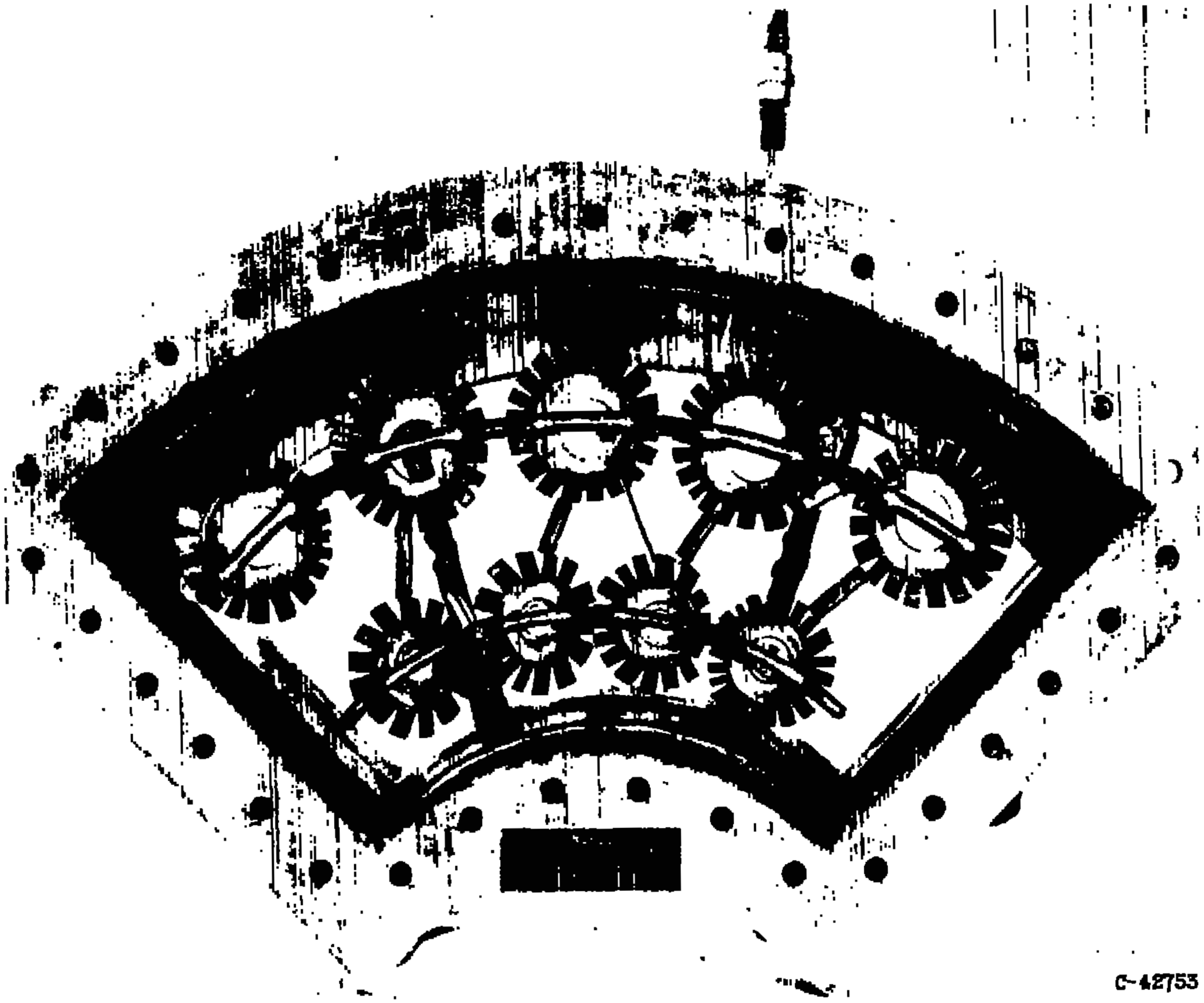
(b) Cross-sectional view of combustor mounted in quarter-sector duct (dimensions in inches).

Figure 4. - Continued. U-gutter combustor, model 1.



(c) Detail of U-gutters. All fuel orifices 0.03 inch in diameter; 20 fuel orifices equally spaced in central gutter (dimensions in inches).

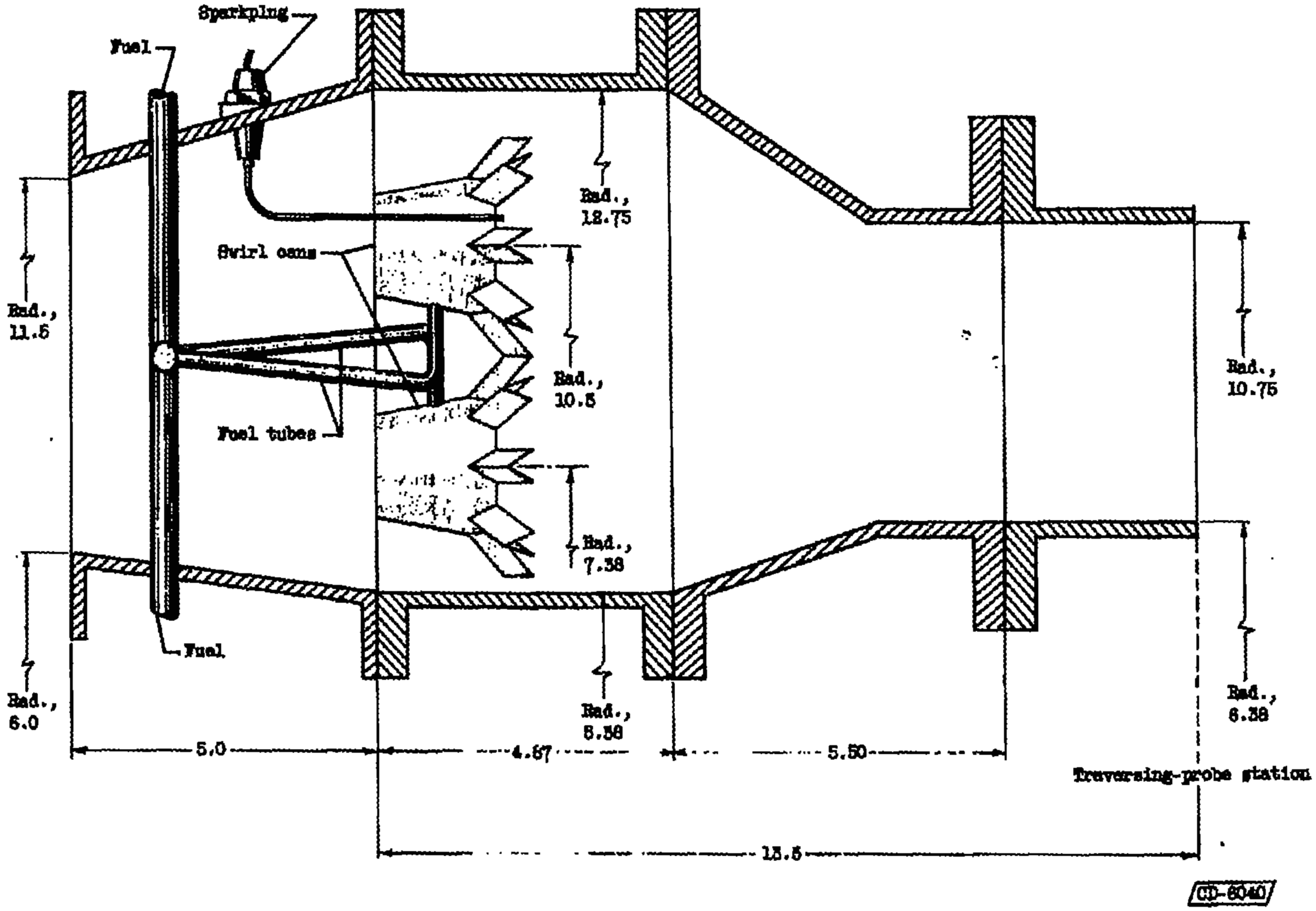
Figure 4. - Concluded. U-gutter combustor, model 1.



C-42753

(a) Combustor mounted in quarter-sector duct; view looking upstream.

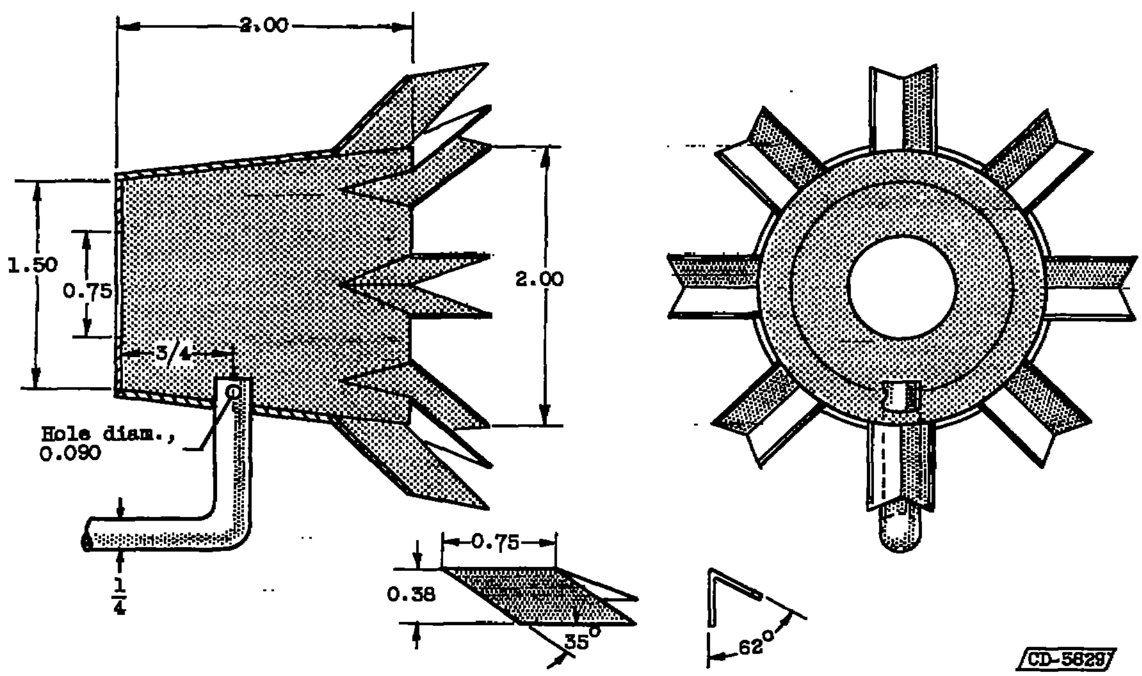
Figure ~~8~~ 7. - Swirl-can combustor, model 2.



(b) Cross-sectional view of combustor mounted in quarter-sector duct (dimensions in inches).

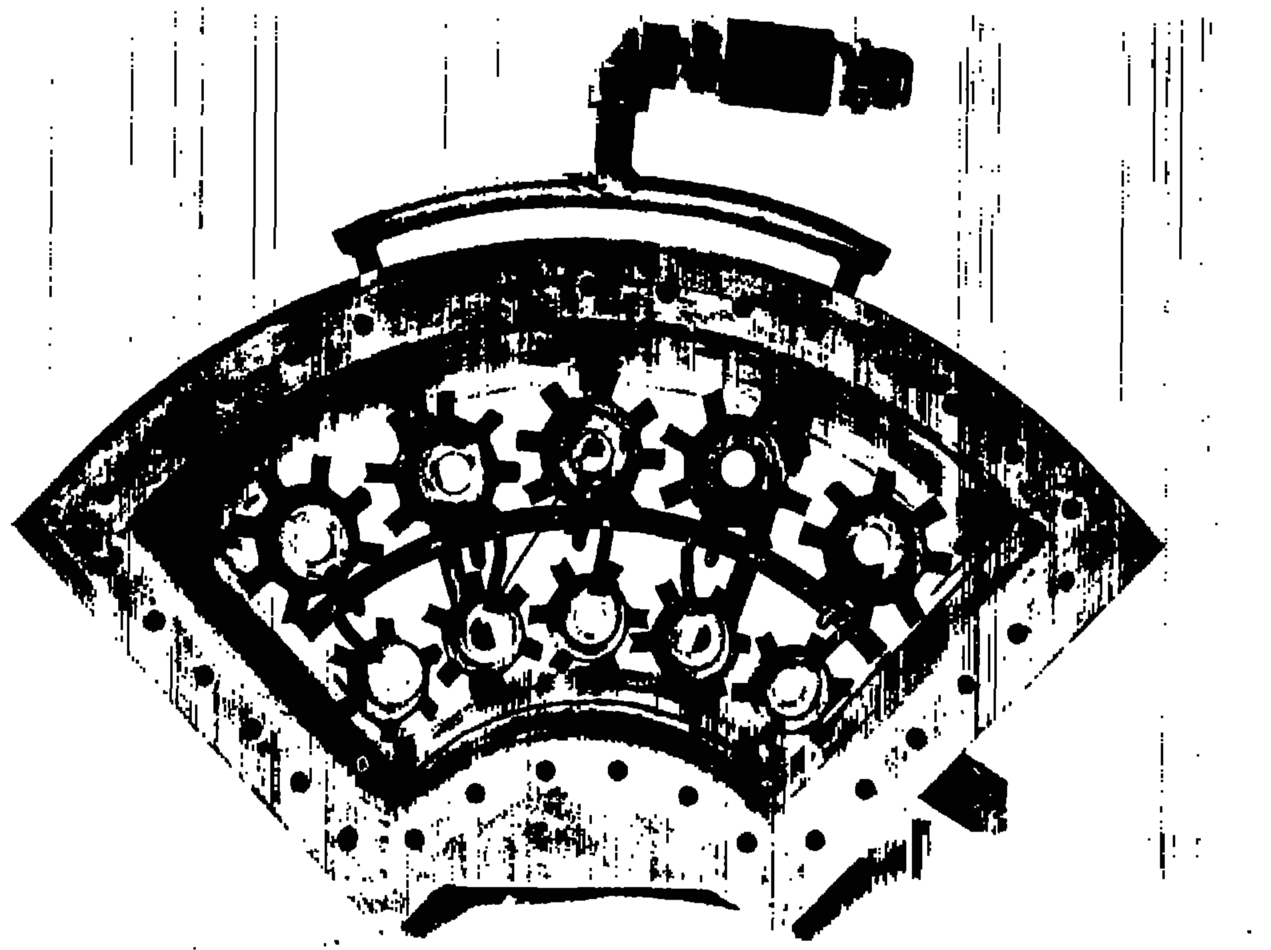
Figure 5. - Continued. Swirl-can combustor, model 2.

4789



(c) Detail of individual swirl can (dimensions in inches).

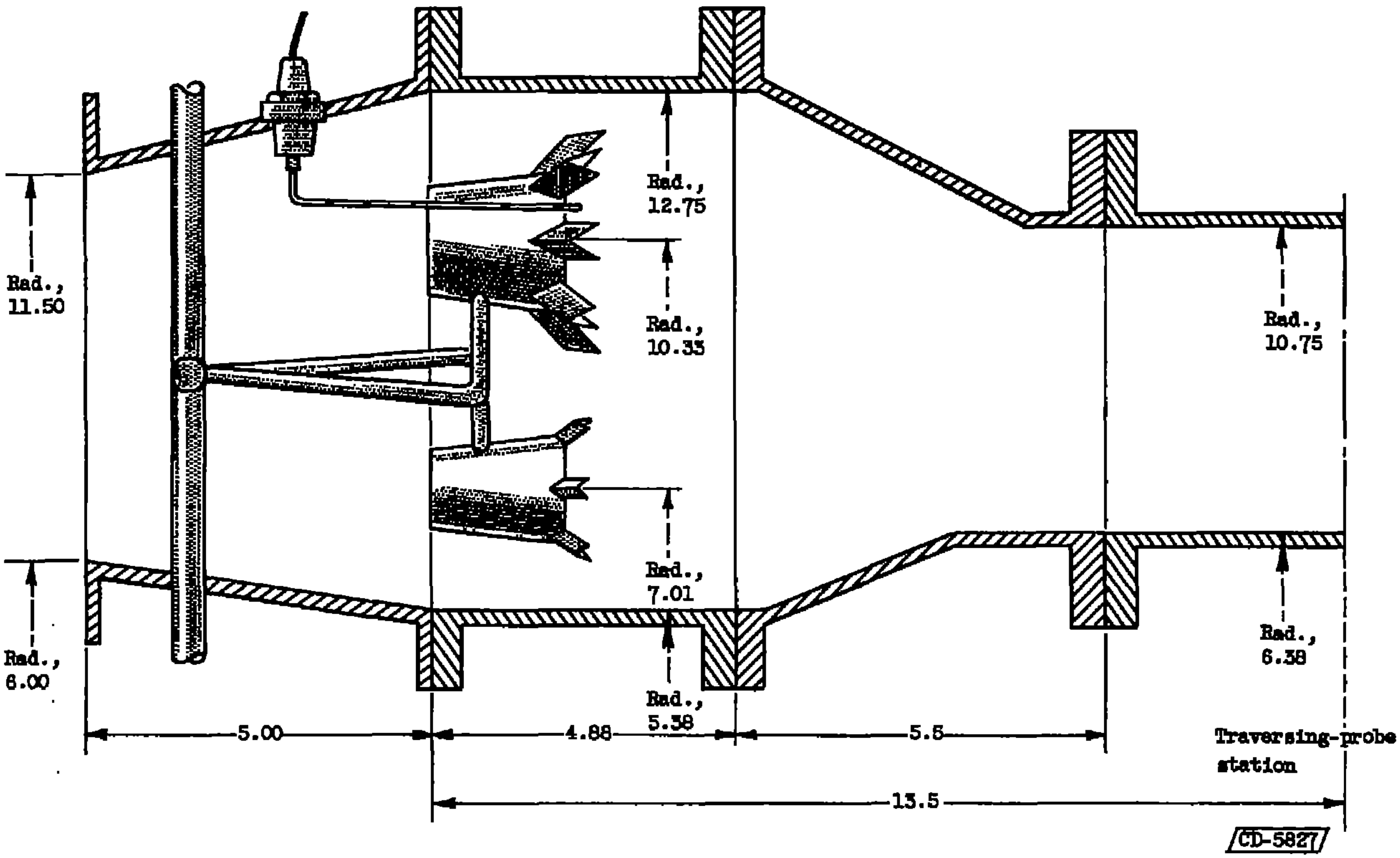
Figure 5. - Concluded. Swirl-can combustor, model 2.



C-42929

(a) Combustor mounted in quarter-sector duct; view looking upstream.

Figure 6. - Swirl-can combustor, model 3.

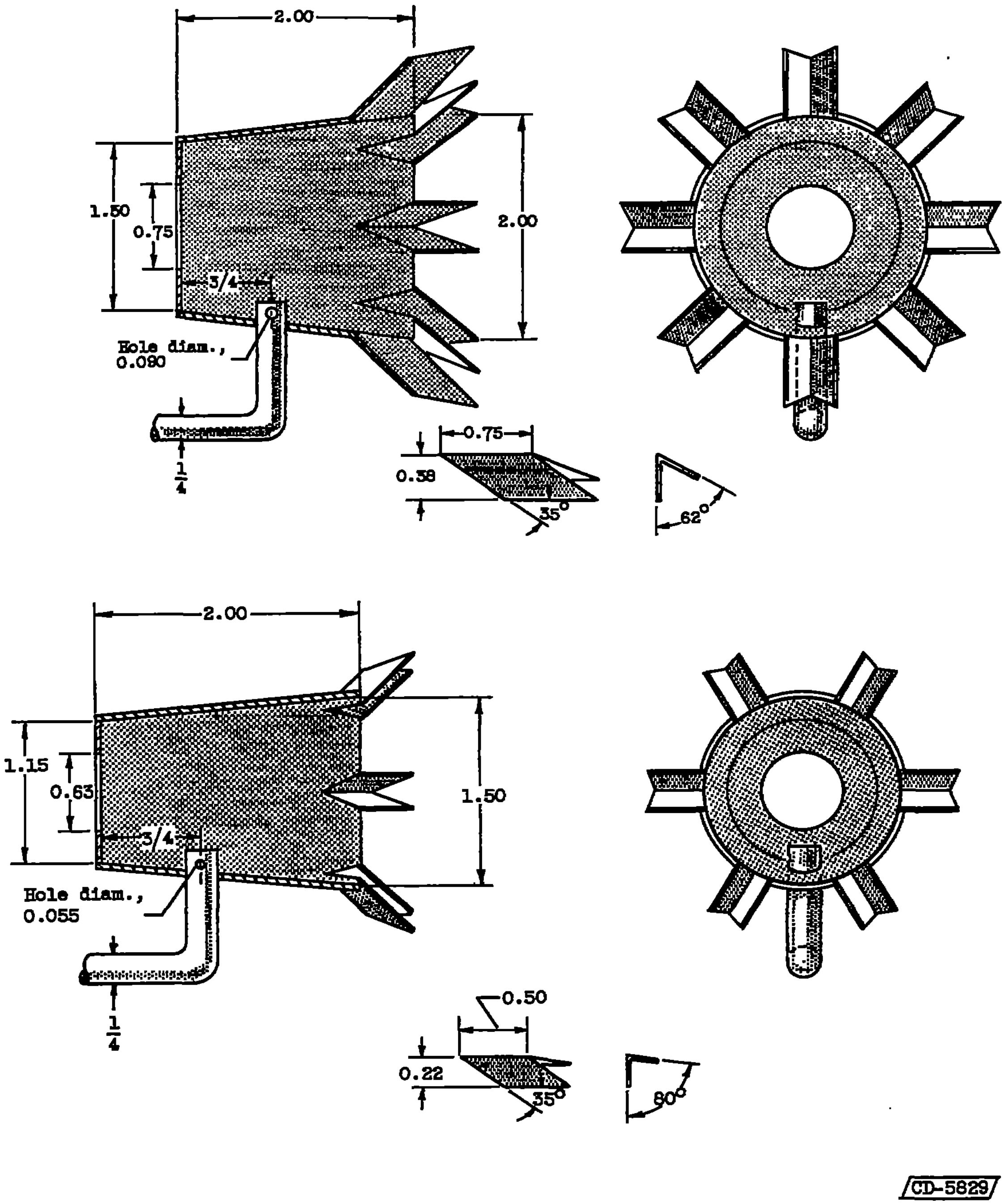


(b) Cross-sectional view of combustor mounted in quarter-sector duct (dimensions in inches).

Figure 6. - Continued. Swirl-can combustor, model 3.

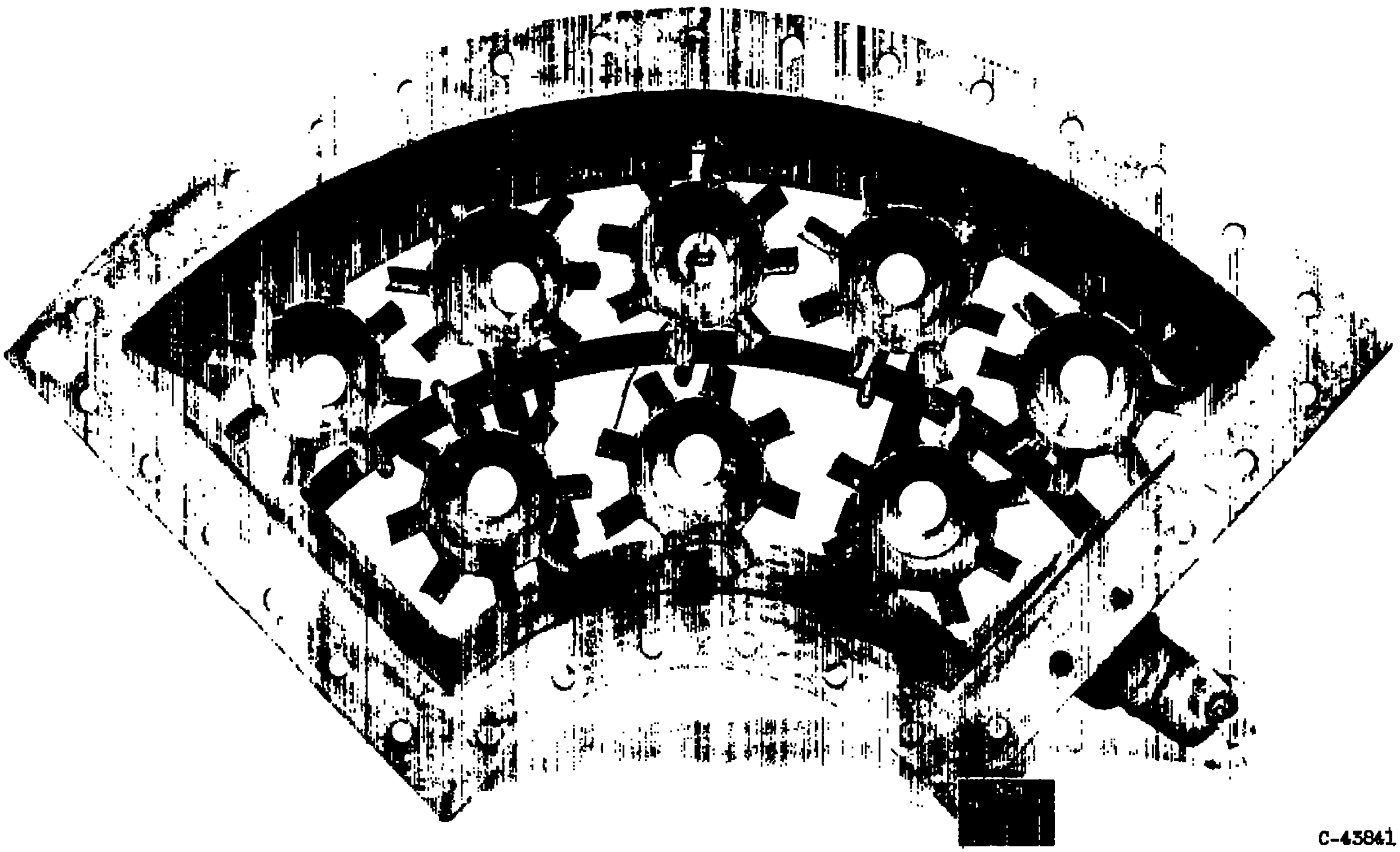
4789

CM-4 back



(c) Detail of individual swirl cans (dimensions in inches).

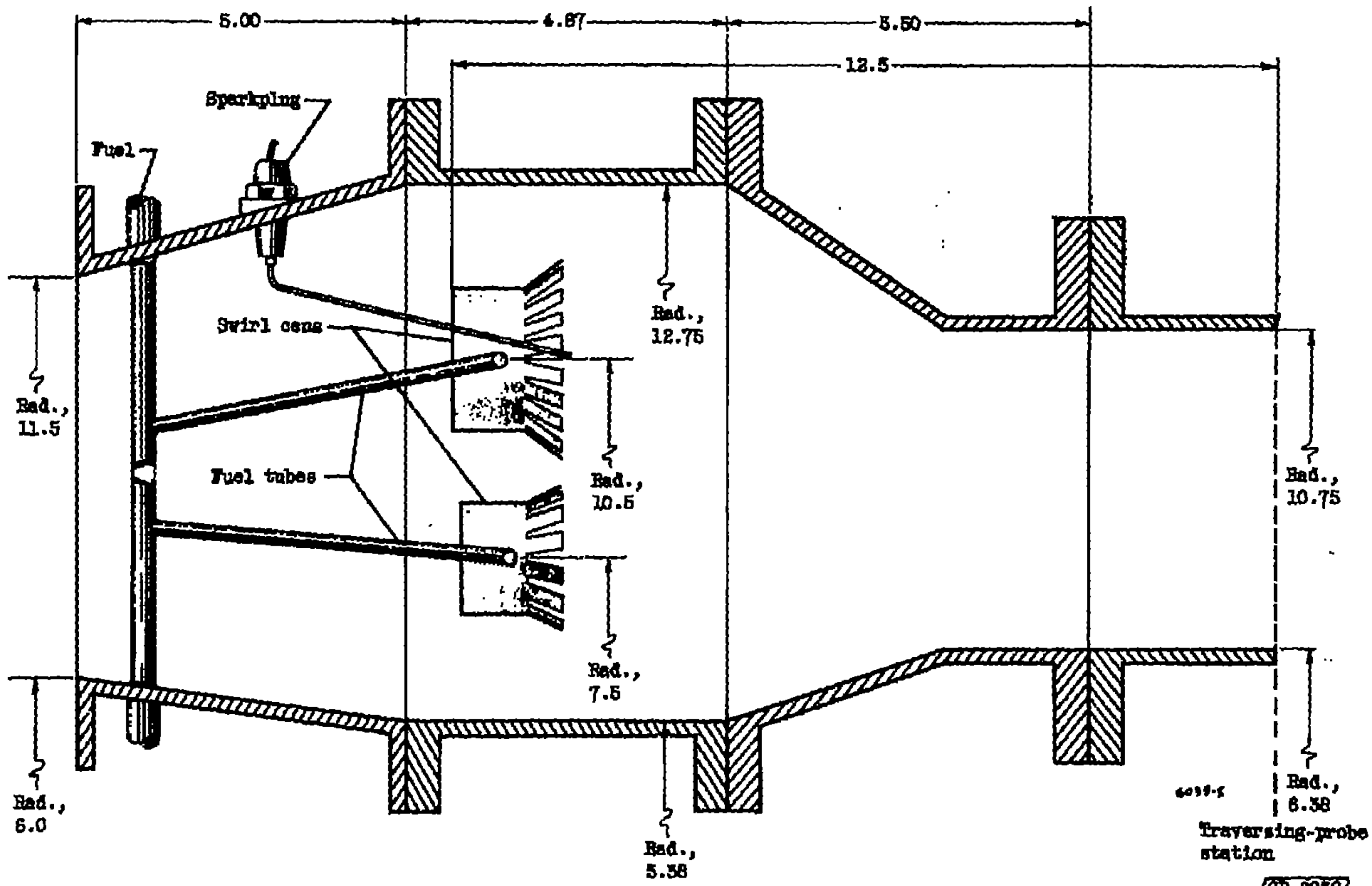
Figure 6. - Concluded. Swirl-can combustor, model 3.



C-43841

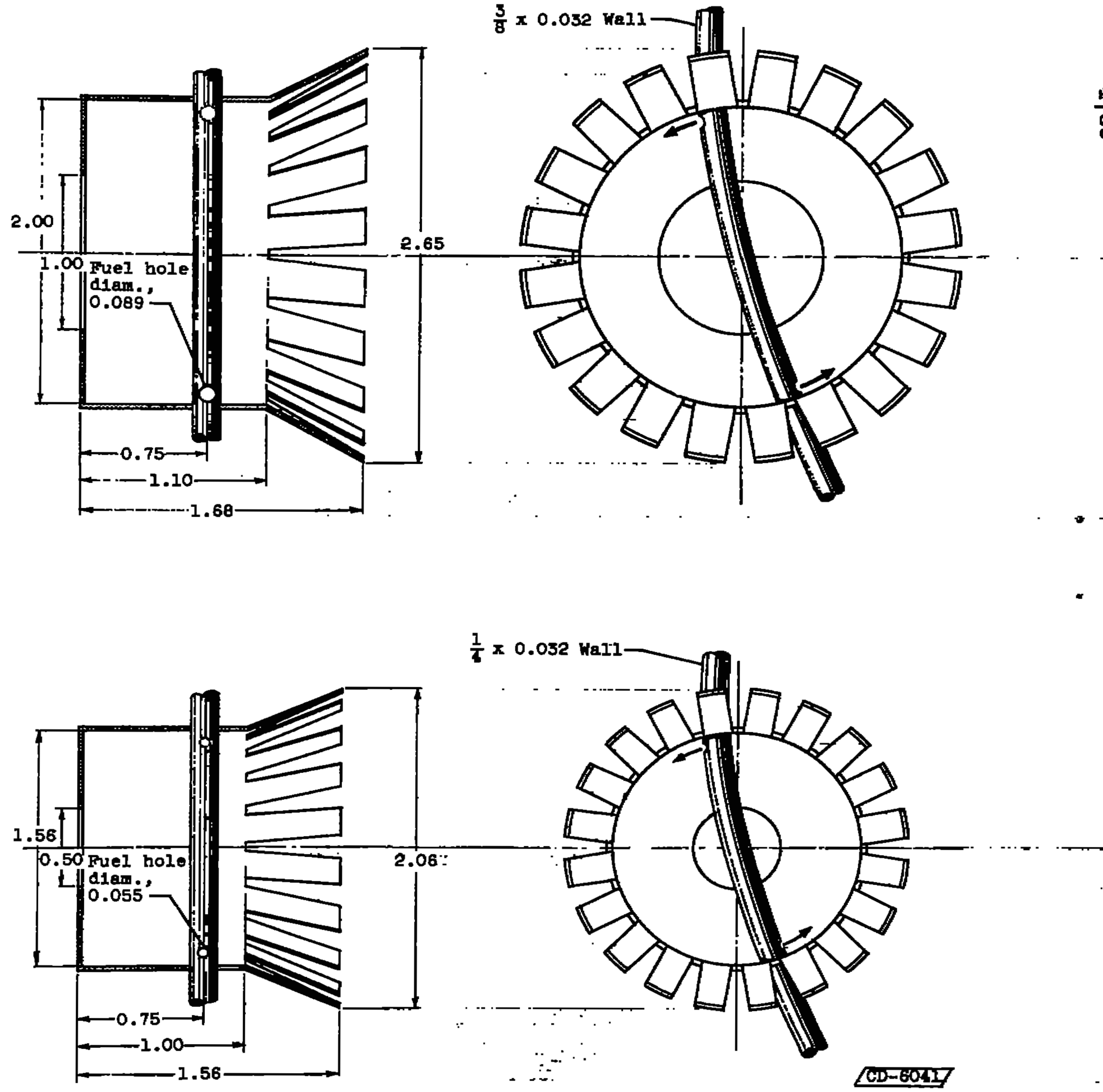
(a) Combustor mounted in quarter-sector duct; view looking upstream.

Figure 5. - Swirl-can combustor, model 4.



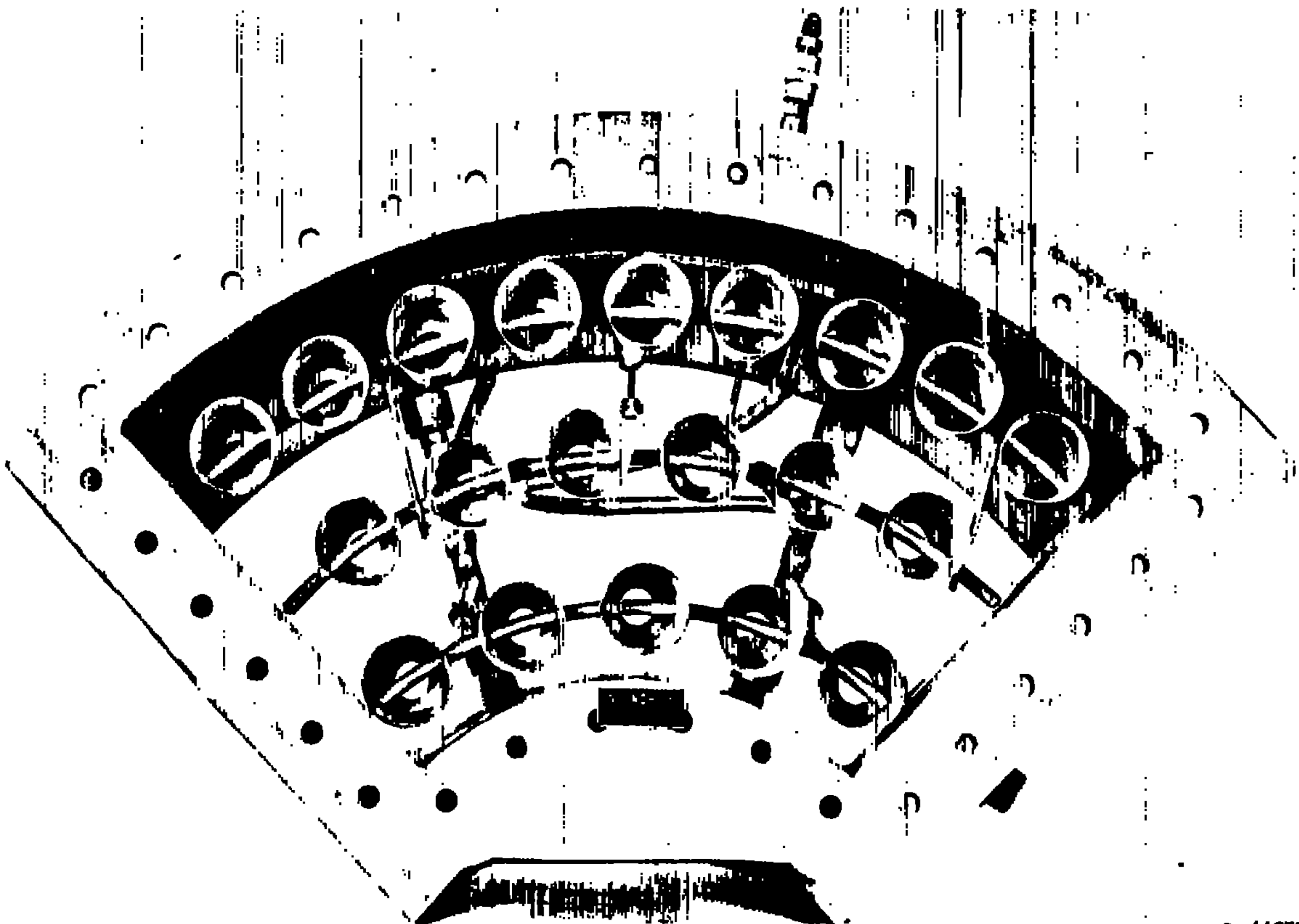
(b) Cross-sectional view of combustor mounted in quarter-sector duct (dimensions in inches).

Figure 7. - Continued. Swirl-can combustor, model 4.



(c) Detail of individual swirl cans.

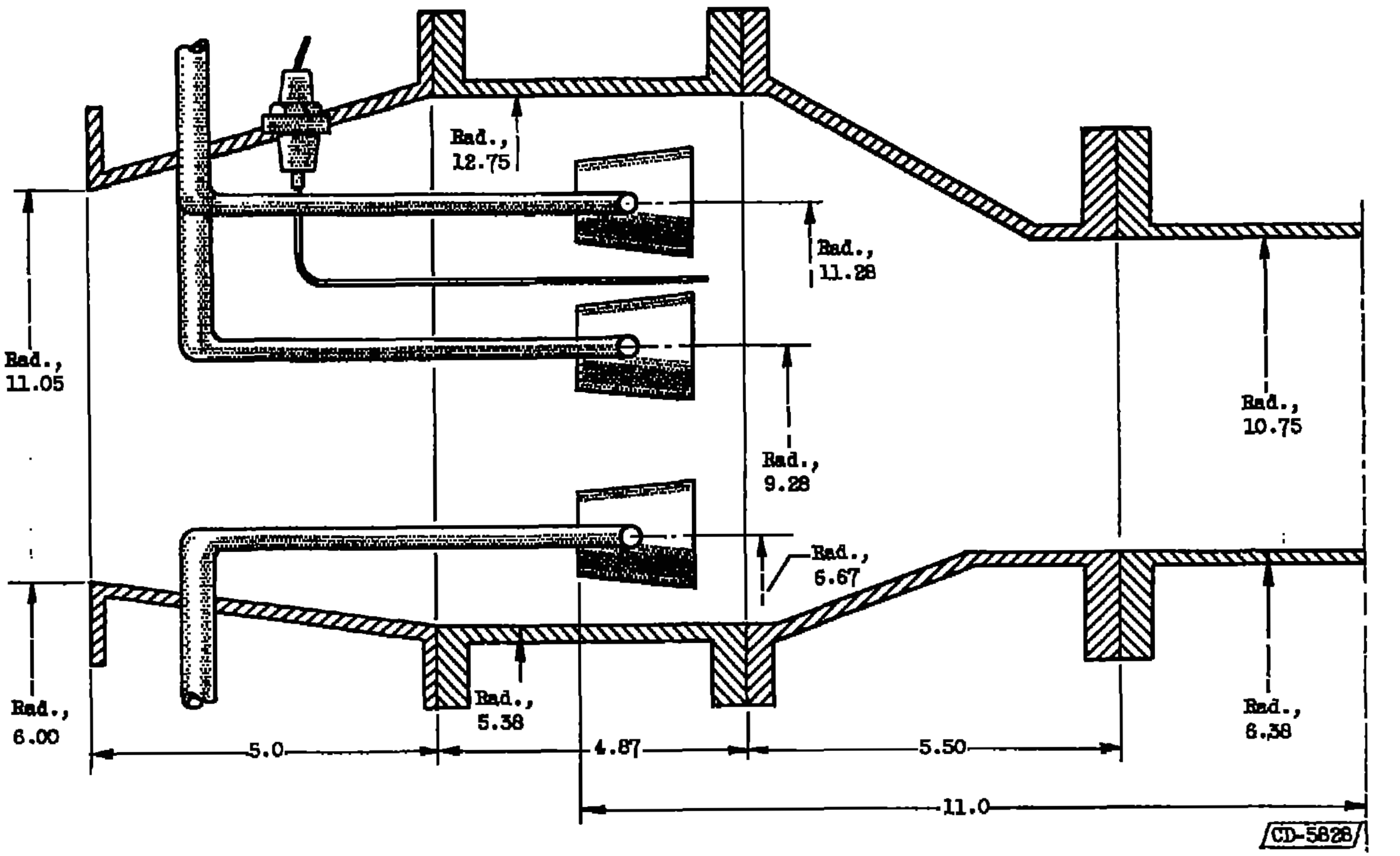
Figure 7. - Concluded. Swirl-can combustor, model 4 (dimensions in inches).



C-44233

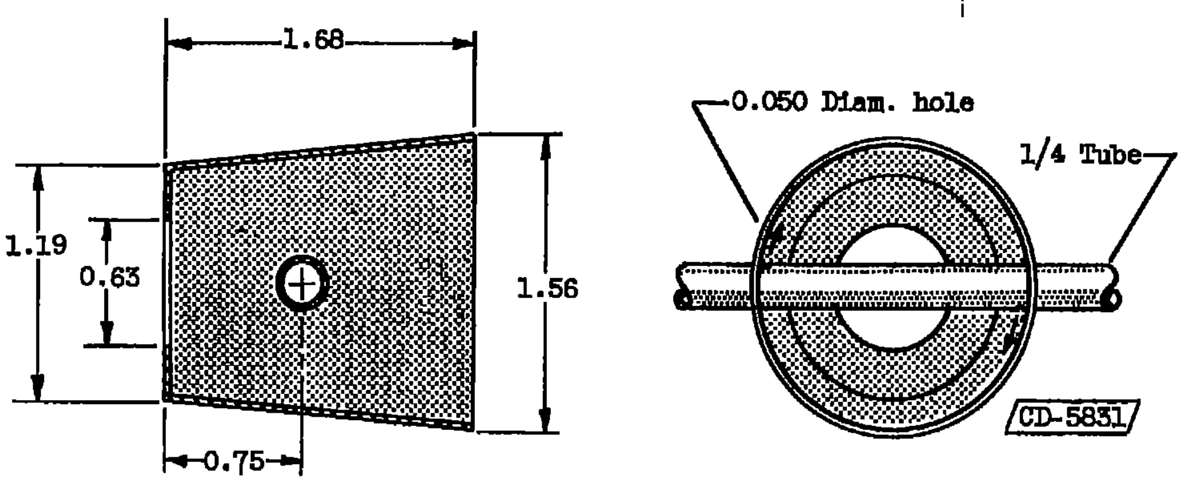
(a) Combustor mounted in quarter-sector duct; view looking upstream.

Figure 8. - Swirl-can combustor, model 5.



(b) Cross-sectional view of combustor mounted in quarter-sector duct (dimensions in inches).

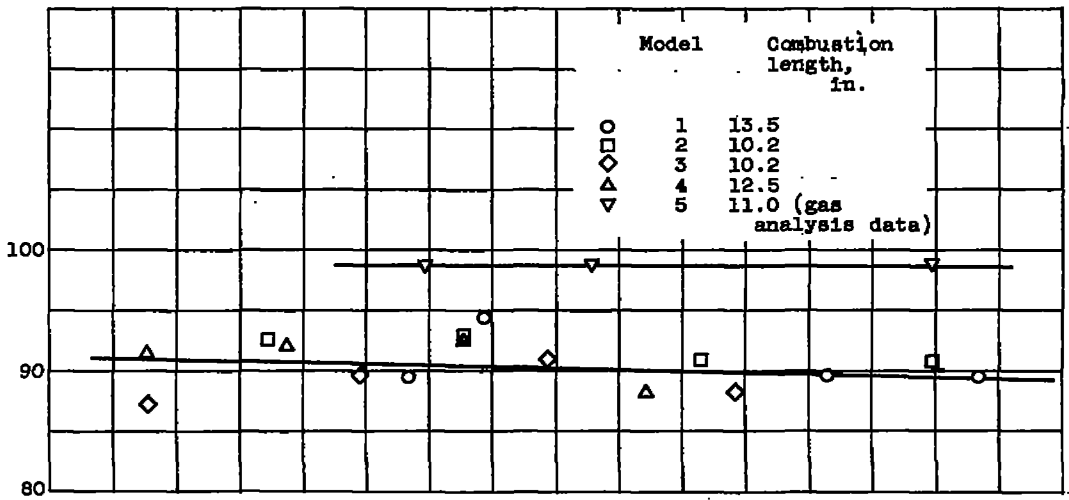
Figure 8. - Continued. Swirl-can combuster, model 5.



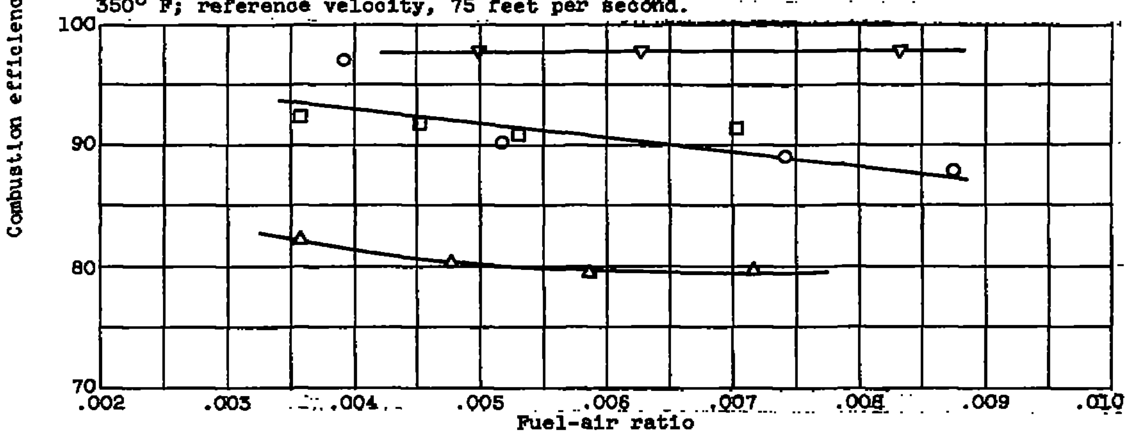
(c) Detail of individual swirl can (dimensions in inches).

Figure 8. - Concluded. Swirl-can combustor, model 5.

4789



(a) Inlet-air total pressure, 5.7 inches of mercury absolute; inlet-air temperature, 350° F; reference velocity, 75 feet per second.

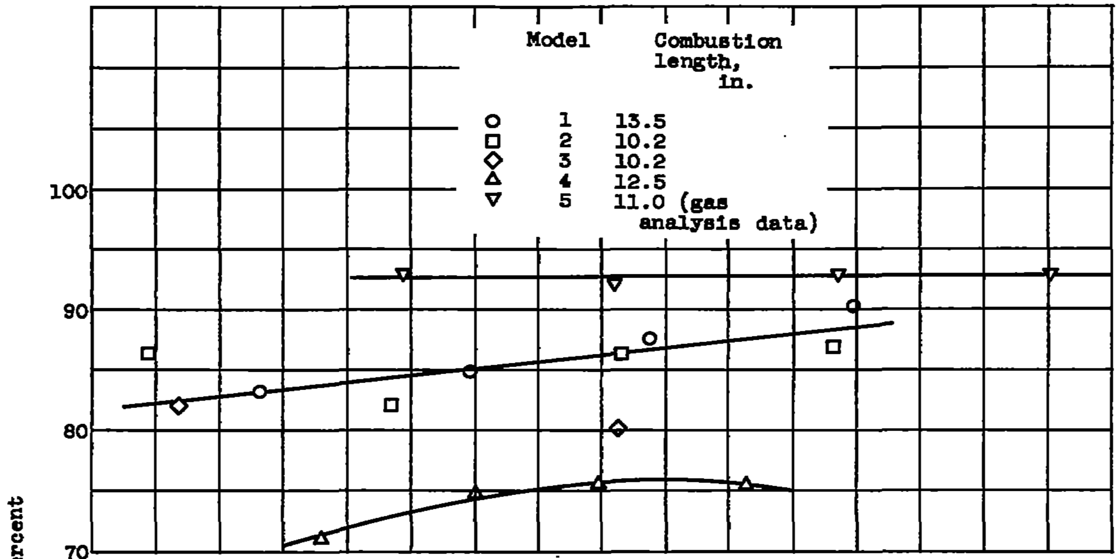


(b) Inlet-air total pressure, 5.7 inches of mercury absolute; inlet-air temperature, 350° F; reference velocity, 115 feet per second.

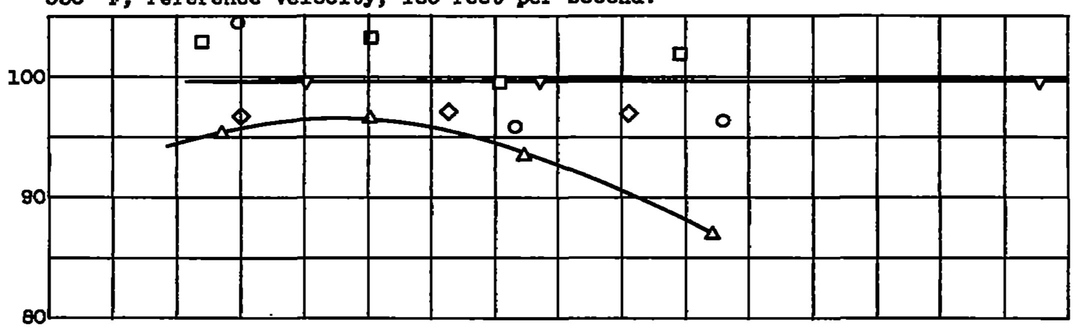
Figure 9. - Combustion efficiency of five short combustors with hydrogen fuel.

4789

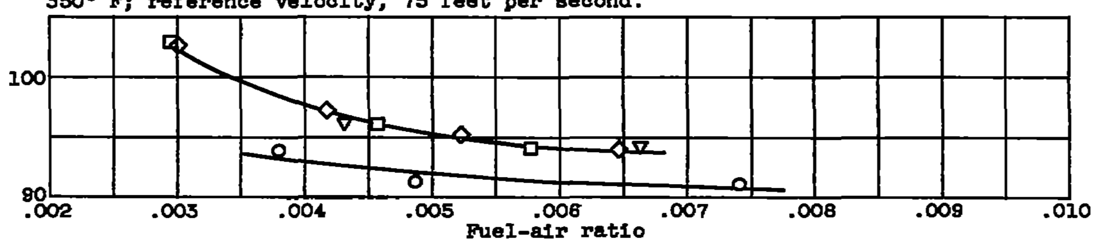
CM-5 back



(c) Inlet-air total pressure, 5.7 inches of mercury absolute; inlet-air temperature, 350° F; reference velocity, 180 feet per second.



(d) Inlet-air total pressure, 9.0 inches of mercury absolute; inlet-air temperature, 350° F; reference velocity, 75 feet per second.



(e) Inlet-air total pressure, 15.8 inches of mercury absolute; inlet-air temperature, 900° F, reference velocity, 210 feet per second.

Figure 9. - Concluded. Combustion efficiency of five short combustors with hydrogen fuel.

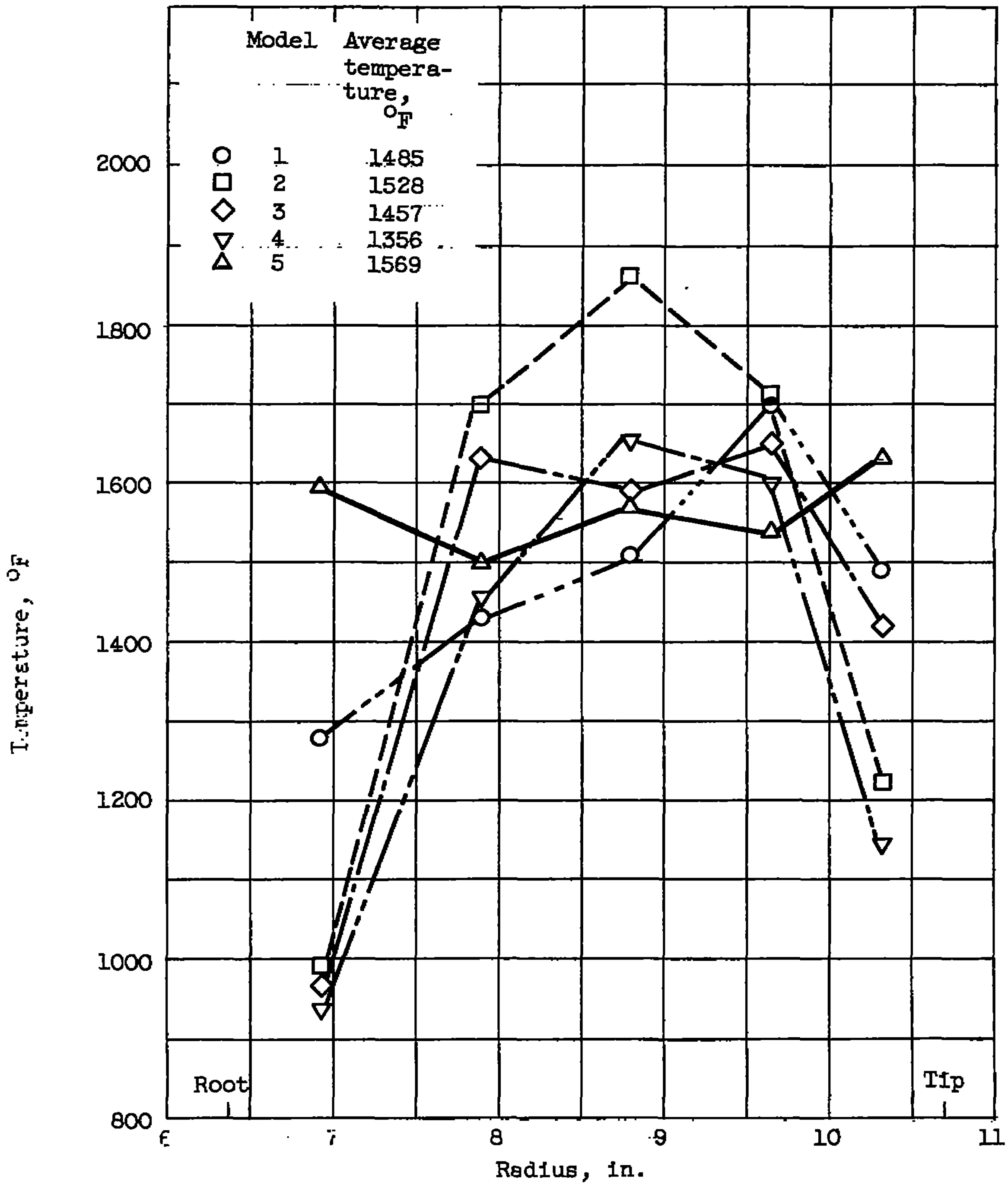


Figure 10. - Comparison of turbine-inlet temperature profiles for five experimental combustors. Combustor inlet-air total pressure, 5.7 inches of mercury absolute; inlet-air temperature, 350° F; reference velocity, 180 feet per second.

4789

[redacted]

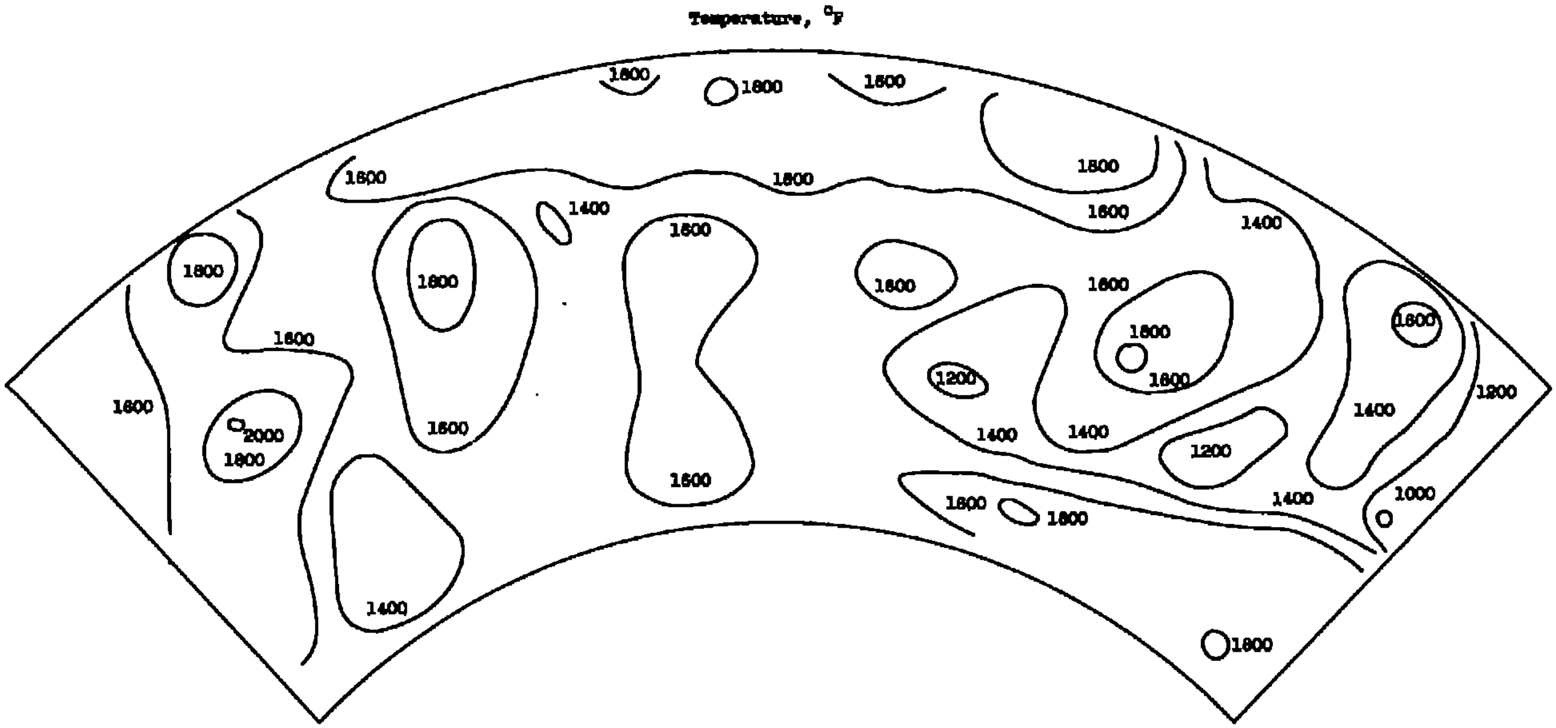


Figure 11. - Temperature contours of model 5. Inlet-air total pressure, 5.7 inches of mercury absolute; inlet-air temperature, 350° F; reference velocity, 180 feet per second; fuel-air ratio, 0.0823; outlet average temperature, 1589° F.

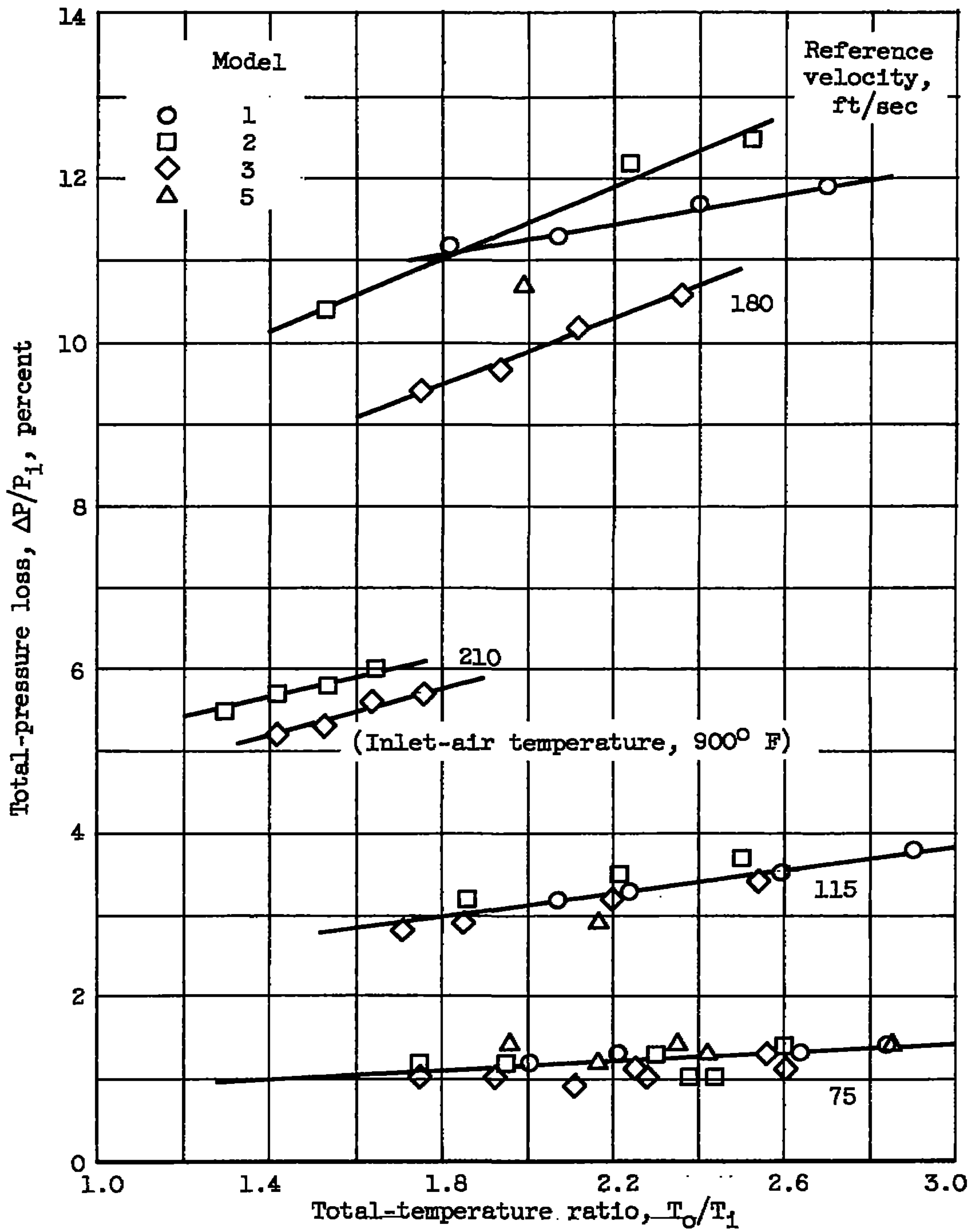


Figure 12. - Total-pressure loss in percent of inlet total pressure for models 1, 2, 3, and 5. Inlet-air temperature, 350° F, except as noted.

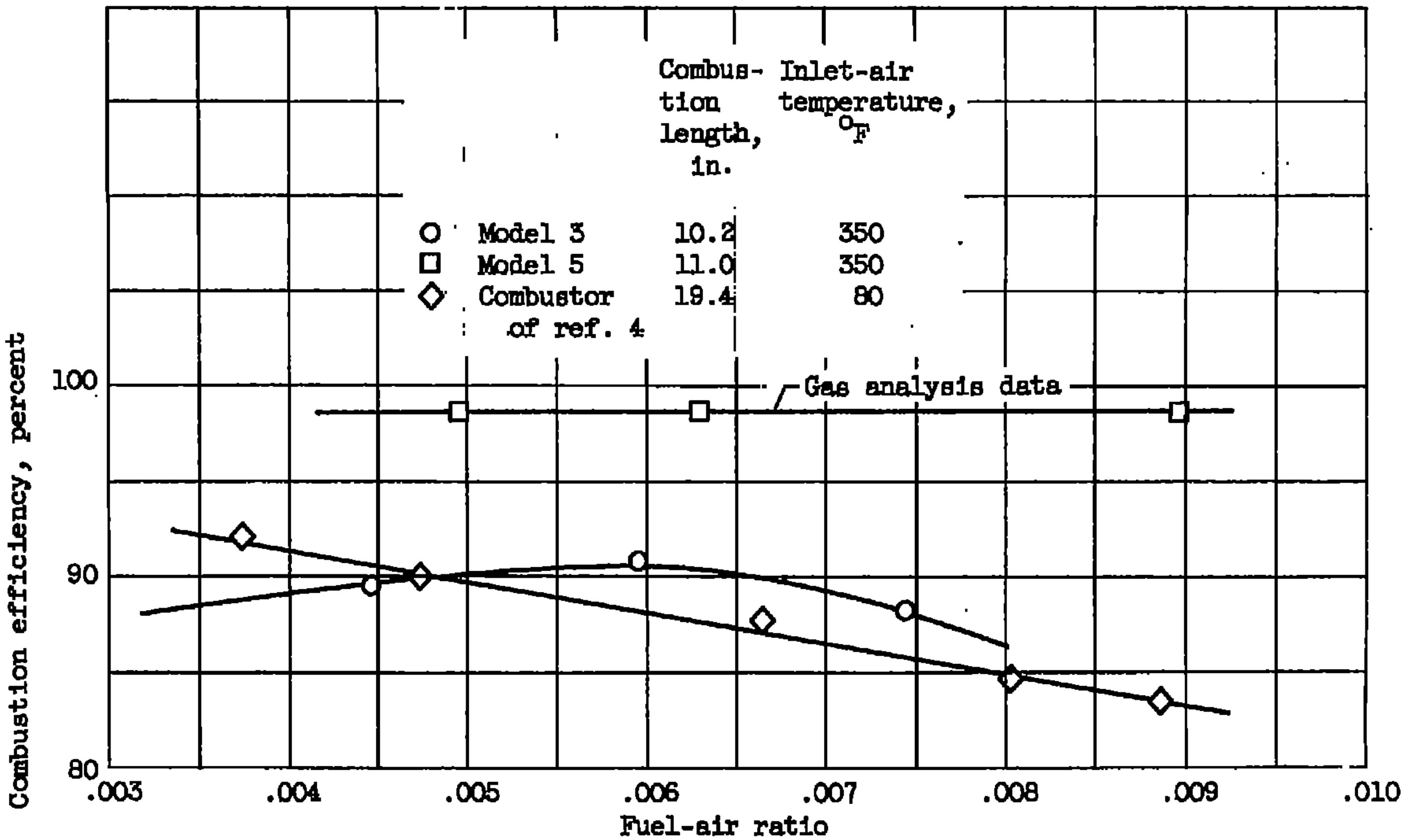


Figure 13. - Comparison of combustion efficiency of models 3 and 5 with previous short combustor (ref. 4). Inlet-air total pressure, 5.7 inches of mercury absolute; reference velocity, 75 feet per second.

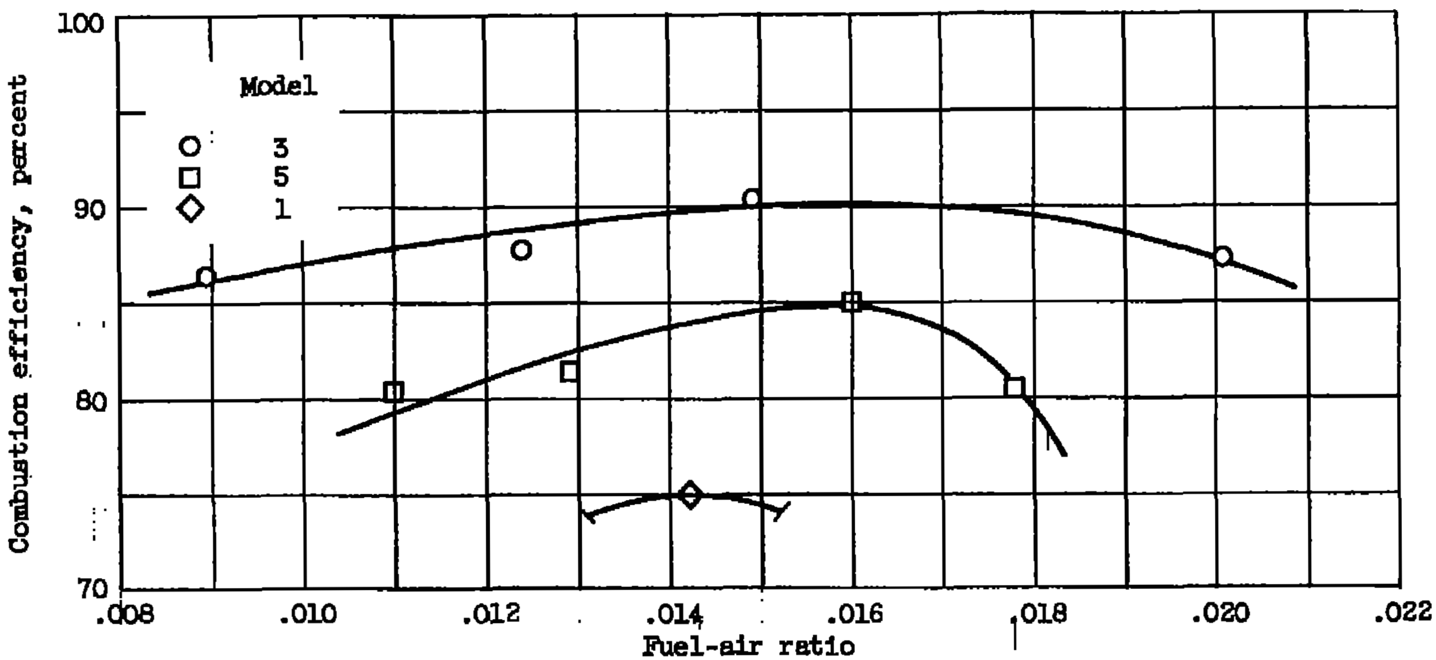


Figure 14. - Combustion efficiency of models 1, 3, and 5 with propane fuel. Inlet-air total pressure, 14.7 inches of mercury absolute; inlet-air temperature, 350° F; reference velocity, 75 feet per second (ref. 8).

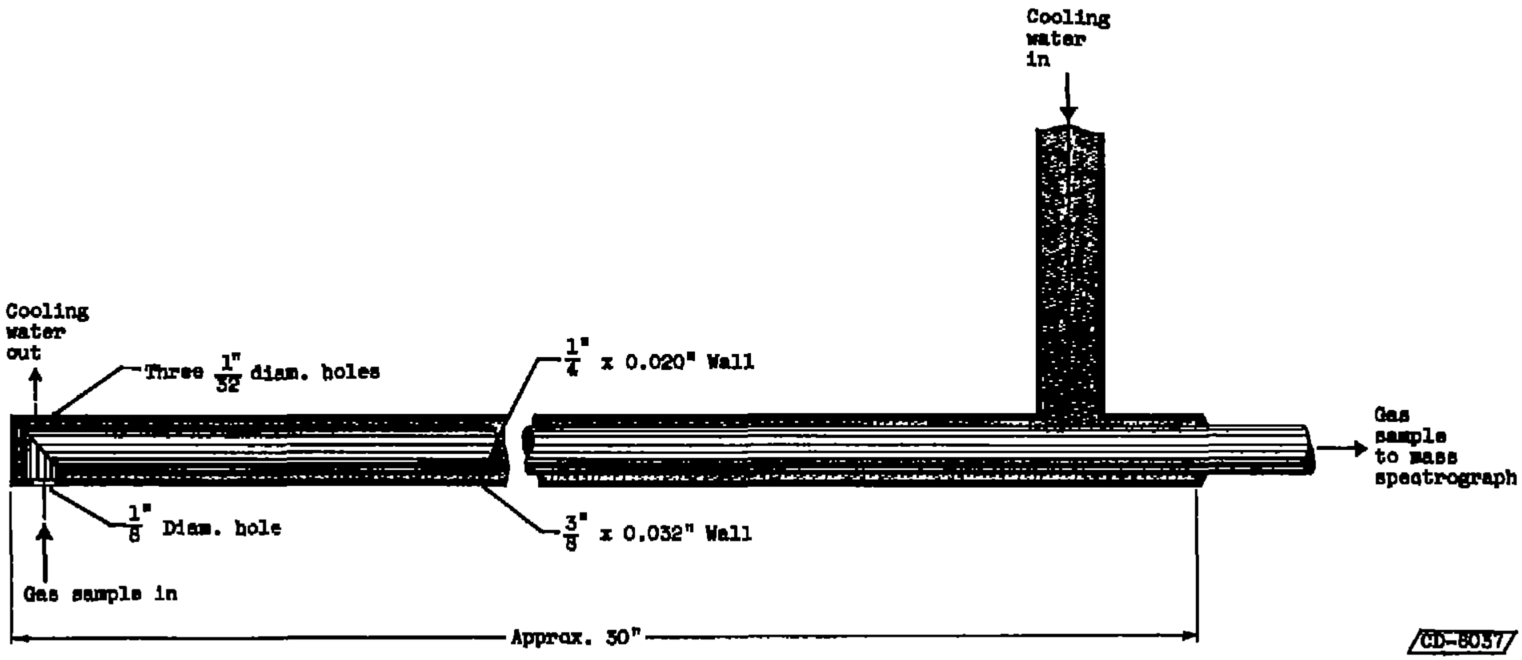


Figure 15. - Detail of water-cooled gas-sampling probe.