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MEMORANDUM

SOME DESIGN PRINCIPLES FOR TURBOJET COMBUSTORS OPERATING ON BORON-CONTAINING FUELS

By Warner B. Kaufman

Lewis Research Center
Cleveland, Ohio

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

WASHINGTON

June 1959

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NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

MEMORANDUM 6-3-59E

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SOME DESIGN PRINCIPLES FOR TURBOJET COMBUSTORS OPERATING ON BORON-CONTAINING FUELS*

By Warner B. Kaufman

SUMMARY

The problems associated with the use of boron-containing fuels in the primary combustor of a turbojet engine are divided into two groups:

(1) Those presented by fuel decomposition within fuel injectors or on external surfaces thereof and by impingement of fuel on hot surfaces

(2) Those presented by the accumulation of a product of combustion, viscous liquid boric oxide, on combustor surfaces

The first problem can be alleviated by insulating or cooling the fuel passages, by preventing recirculation around the fuel port, and by injecting the fuel in a finely atomized spray. The second problem can be minimized by blanketing the inside surfaces of the combustor liner with uncontaminated combustion air.

Small-diameter air-atomizing fuel injectors, each bathed in a strong jet of air, ran consistently free of fuel decomposition products. The performance of a highly louvered, annular combustor was unaffected by the small quantity of boric oxide deposited on its surfaces. Tests thus far have been of short duration and at only one condition.

The fuels used included pentaborane, a 66-percent blend of pentaborane in JP-4, HEF-2 (propylpentaborane), and HiCal-3 (ethyldecaborane). Combustion efficiencies were 89 to 93 percent. Combustor liner deposits from the first three fuels were similar and unobjectionable. The larger deposit found after the HiCal-3 test was presumed due mostly to high fuel viscosity (poor atomization).

*Title, Unclassified.

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INTRODUCTION

The range potential that boron-containing fuels promise for our military aircraft is recognized as a goal worth pursuing. It was obvious from the first combustion experiments (refs. 1 and 2) that attaining this goal was not merely a matter of substituting a boron-containing fuel for conventional hydrocarbons. Successful combustion of boron fuels in the primary combustor of a turbojet engine is complicated by:

(1) Decomposition of the fuel

(2) Deposition of the combustion products

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Compressor discharge air may enter the combustor at temperatures as high as 600° F. Yellow solid particles (hereafter referred to as "internal decomposition") may form within fuel lines and injectors immersed in this hot air. They pack together and restrict or plug the very small openings usually required in fuel injectors (ref. 2). The degree to which internal decomposition can be prevented determines the minimum size of the fuel injector passages. In the case of pressure-atomizing nozzles, the number of injectors is limited by this minimum size.

A second type of deposit is the hard, porous clinkers that form on the external surfaces of the fuel nozzles (hereafter termed "external decomposition"). They are composed of free boron, boric oxide, and, in the case of alkylated boron hydrides, some carbon. Although representing only a small fraction of the fuel passing through the system, these clinkers can grow very rapidly into large formations. They disrupt the fuel spray patterns or break off and block the turbine stator passages.

The same type of decomposition deposit is formed when fuel impinges on a hot surface (hereafter known as "impingement decomposition"). It is usually caused by a malfunction of the nozzle or by a spray that has a high degree of penetration. A clinker of this type can also become very large in a matter of seconds; in extreme cases, it may bridge back to the fuel nozzle.

Reference 3 shows that the formation of internal decomposition products can be prevented by cooling fuel passages with air that is subsequently used for atomization. External decomposition has been a serious problem, particularly in full-scale engine tests. The mechanism of this type of decomposition is not understood. Impingement decomposition did not occur with the soft, finely atomized spray of the air-atomizing injectors of reference 3.

One of the products of combustion is boric oxide, B_2O_3. Boric oxide, a very viscous liquid at ordinary turbojet combustor temperatures, deposits on exposed surfaces in a thick film. It is driven along the surfaces by the dynamic force of the air stream. Large drops are whipped from the film surface and carried into the turbine. Engine tests of short duration using conventional hydrocarbon combustors have shown that turbine performance is adversely affected by a combination of:

(1) Runoff of boric oxide from the combustor into the turbine

(2) Large drops of oxide impinging on the stator and turbine blades

(3) Accumulation of thick deposits on the suction side of the stator blades

These turbine effects are reflected in high pressure losses and consequently in high thrust losses. Continued buildup of boric oxide by extended operation probably would also affect the performance (outlet temperature distribution, pressure losses) of conventional combustors (ref. 4).

The first two causes of turbine performance deterioration can be minimized if not prevented by special combustor liner design. Fortunately the liquid particles are submicron in size within the combustor (ref. 5); and their deposit mechanism is, therefore, one of diffusion (ref. 6). The number of particles diffusing to a surface is a function of particle concentration near the surface and time; therefore, deposition may be minimized by:

(1) Supplying an oxide-free layer of air along exposed surfaces (ref. 3)

(2) Providing a straight through-put of air through the combustor to avoid recirculation

If this can be done successfully, the oxide reaching the turbine will be in the form of microscopic particles that follow flow streamlines. If the turbine is to tolerate the oxide at all, it should digest the small particles far more easily than the viscous film and large drops.

Recent investigations at Lewis Research Center have resulted in a turbine stator blade design that should alleviate the third cause of turbine performance decay. This straight-back blade design prevents separation of the flow on the suction side. Cascade tests have indicated oxide particles will not accumulate on blades of this design to the extent that turbine performance would be greatly affected (ref. 7).

If the potential of boron-containing fuels is to be realized, the combustion system must meet the following requirements:

(1) No fuel decomposition within injectors, on injectors, or on the combustor walls

(2) Delivery of oxide to the turbine in form of microscopic particles

(3) Efficient combustion with low pressure loss and adequate outlet temperature distribution

This report of a quarter sector of an annular turbojet combustor developed to meet these requirements covers the period August 1955 to December 1957. Pentaborane was the only boron-containing fuel available in quantity for this period and was used almost exclusively. The results of brief tests of a blend of pentaborane in JP-4, HEF-2 (propylpentaborane), and HiCal-3 (ethyldecaborane) in this combustor are also included.

APPARATUS AND PROCEDURE

Combustor Installation

Combustion air was heated and metered to the test installation shown in figure 1. The combustion products were cooled by water sprays and discharged to atmosphere.

The combustor was a quarter sector of an annular turbojet combustor. Two configurations are presented: configuration A (fig. 2), and configuration B (fig. 3); these are discussed in detail in a later section. Some of the evolutionary steps leading to these designs are discussed in appendixes A and B.

Fuel System and Operating Procedure

The fuel and atomizing-air systems are shown schematically in figure 4. The warmup fuel, gasoline or JP-4, was supplied through system A to the five radial injectors in order to bring the combustor to operating conditions before switching over to the test fuel. The test fuel was supplied to the axial injectors through system B. Systems B and C were purged with helium and were pressure checked before each run. The purge fuel in system C, JP-4, was fed into system B so that it could precede the pentaborane to cool the fuel injectors, and follow the pentaborane to purge the lines and injectors. An initial purge immediately followed pentaborane so that the fuel injectors would not become plugged with internal decomposition during shutdown. After the pentaborane tank (system B) was depressurized and closed, the remaining section of system B was purged through valve P. The valves M and N provided a means of purging system B in the event that the fuel injectors or the manifold became plugged. Normal operating pressure was 200 pounds per square inch. All valves were Teflon packed.

Instrumentation

The location of the instrument stations is indicated in figure 1. The arrangement of the bare-wire thermocouples and total-pressure probes is diagrammed in figure 5. Combustion airflow was measured by an ASME orifice, atomizing air by a rotameter, and fuel flow by a rotating-vane flowmeter.

Procedure

The nominal test conditions were as follows:

	Condition I	Condition II
Combustor inlet total pressure, in. Hg abs	32	32
Combustor inlet temperature, $^{\circ}F$	370	370
Combustion airflow, lb/sec	4.5	4.0
Combustor outlet temperature, $^{\circ}F$	1550	2000

Test condition I simulates the combustor environment of an engine having a 5.2:1 compressor pressure ratio at an altitude of 45,000 feet, a flight Mach number of 0.6, and rated engine rpm. Test condition II represents the combustor conditions for a test of the same engine modified for elevated turbine temperatures.

The combustor was brought to operating conditions on JP-4 fuel or gasoline, and reference data were recorded. The outlet temperature was then decreased, and JP-4 was introduced through the test injectors. Simultaneously, the JP-4 fuel in system C was shut off and the test fuel valve was opened. When the test fuel reached the combustor, as evidenced by a temperature rise, the warmup fuel in system A was throttled off while test fuel was throttled up to the desired outlet temperature. On shutdown, the test fuel valve was closed and the system C fuel valve was opened simultaneously. The system was purged until no test fuel remained in the fuel injectors. The test fuel tank was then vented and closed. This operation was followed by a purge of the fuel remaining in system B between the tank and the junction with system C. A final purge with helium was made after the purge fuel tank was vented and closed.

Data Reduction

Combustor outlet temperature. - The combustor outlet temperature was taken as the arithmetic average of the 60 thermocouple readings at station B, figure 5.

Radial outlet temperature profile. - The radial outlet temperature profiles were plotted by averaging the temperatures measured by thermocouples at the same radial depth on rakes 3 to 10. The two outside rakes on each side were not included in order to minimize side-wall effects.

Combustion efficiency. - Combustion efficiency η_B was calculated from the relation

$$\eta_B = \frac{\text{Enthalpy rise across the combustor}}{\text{Heat of combustion of the fuel}}$$

The enthalpy of the stream entering and leaving the combustor was determined from the temperature and pressure measurements and the thermodynamic properties of the reactants and combustion products (ref. 8).

DESIGN CONCEPTS

Fuel Injector

Internal decomposition. - The amount of fuel that will decompose in passages subjected to temperatures of 185° to 400° F for short periods of exposure is small (ref. 9); however, the amount of solids required to plug the tiny restrictions within a fuel injector is also small. Even though passages are sized for high velocity (short residence time), the boundary film along the walls is exposed to a relatively high temperature for a much longer period. Therefore, to prevent internal decomposition, the fuel injector should be designed with:

(1) Passages sized for minimum residence time consistent with reasonable pressure loss

(2) Cavities containing screens, check valves, flow-proportioning devices, and so forth, located outside of the combustor housing

(3) Provisions for leading the boron-containing fuel with a compatible hydrocarbon to cool the passages

(4) Insulation and/or continuous cooling of passages leading to and within the fuel injector

(5) The necessary restrictions within the injector as large as possible

Air used for continuous cooling has advantages. After air has been conducted through a passage concentric with the fuel tube, it can be used to atomize the fuel. The restriction at the end of the fuel passage need not be as small as would be necessary with pressure atomization and is therefore less susceptible to plugging by decomposition solids and dirt. Since air atomization is not as dependent on fuel port size as is pressure atomization, a large number of points of injection may be used. Furthermore, the fuel pressure required to these injectors is very low - on the order of 20 to 50 pounds per square inch gage - a distinct advantage where toxic, easily ignited fuels are concerned.

External decomposition. - The formation of solid material on the fuel injector tip is disastrous to the fuel spray and consequently to the outlet temperature distribution. Usually the fuel will maintain openings through the clinker, but the poor distribution causes impingement on combustor surfaces, hot spots, or an undesirable outlet temperature profile. Large clinkers of this type have been found lodged between the stator blades after a full-scale engine test (ref. 10). External fuel decomposition has also been observed on axial-type as well as radial-type injectors (ref. 11).

The exact mechanism of external fuel decomposition is not completely understood. Because the reactivity of these fuels is very high, burning begins at or near the point of injection. Consequently, local fuel-air ratios are high. It has been observed that combustion efficiency decreases with an increase in over-all fuel-air ratio. It has also been observed that the slightest recirculation in the vicinity of the fuel nozzle port promotes external decomposition. The loss in efficiency and fuel decomposition may be due to (1) rich oxidation of the center core of the fuel spray, and (2) high local temperatures causing thermal degradation of a portion of the fuel. Either process could result in a product that does not burn readily. Recirculation of these products and boric oxide produces rough deposits on the nozzle tip that promote recirculation at an increased rate.

The ideal nozzle, from the standpoint of external decomposition, would be a long tapered tube with the diameter of the downstream end as near that of the fuel discharge port as possible. In addition, a smooth flow of clean air over the tube should be provided to prevent recirculation around the tip.

The air-atomizing nozzle has another advantage over the pressure-atomizing type in this respect: As long as it is sized for good atomization at the maximum flow rate, it will not drip nor will the spray break down at low flow; thus two conditions that could result in external decomposition formations are eliminated.

Impingement decomposition. - When fuel is permitted to impinge on a hot surface, a clinker of the same type as that just described results. Penetration of the fuel spray must be controlled. In the case of the axial-type injector, a compromise between a fuel spray wide enough to promote good temperature distribution and combustion efficiency but narrow enough to prevent impingement and a high concentration of boric oxide near the combustor surfaces is most desirable. A well-distributed spray without penetration to the walls can be achieved with air atomization; however, where the spray angle has been large enough for good distribution, recirculation to the nozzle tip has caused the formation of external decomposition.

Combustor Liner

Boric oxide particles in the combustion products, if allowed to diffuse freely to combustor surfaces, adhere and form a viscous layer. This material is driven along the surface by the dynamic force of the airstream. It flows around the secondary-air entry holes where it is cooled. The increased viscosity of the oxide causes it to pile up and upset the secondary-air mixing patterns. It also flows into the turbine region and toward the bottom of the engine. Large drops sheared from surfaces and carried by the airstream impinge on the stator and rotor blades of the turbine.

The longer an oxide particle remains in the combustor, the greater is its opportunity to diffuse to a wall. Therefore, primary-air inlets must be designed to prevent recirculation in the upstream end of the combustor. Increasing the portion of combustion air admitted through the primary inlet will not in itself satisfy this requirement. The method of admitting it is extremely important. It should be distributed as uniformly as possible across the primary inlet so that even very small disturbances of the airflow disappear within a very short distance.

Diffusion of oxide particles to liner surfaces can be reduced by providing a continuous layer of clean combustion air along inside surfaces. Successful demonstrations of this method of keeping surfaces oxide-free were made in an experimental liner fabricated of porous wire cloth (ref. 3). Obviously, it is desirable to expose as little surface area as possible to oxide deposition; therefore, a short annular-type combustor is preferred since its surface-to-volume ratio is lower than that of tubular combustors.

RESULTS AND DISCUSSION

Because of the variation of hardware during the development program and the short test durations, only the most pertinent of the tests are reported. These are summarized in the following table:

Run	Configuration	Nominal condition	Fuel	Fuel burned, lb	Airflow, lb/sec	Fuel flow, lb/sec	Outlet temperature, °F	Combustion efficiency, percent
1	A	I	JP-4		4.55	0.0731	1250	80
			Pentaborane	30.7	4.44	.0456	1354	91
2	A	I	Blend[a]	14.1	4.47	.0613	1481	90
3	A	I	HEF-2	15.9	4.67	.0615	1440	92
4	A	I	HiCal-3	15.9	4.40	.0593	1406	[b]93
5	B	II	Gasoline		4.21	.1061	1778	85
			Pentaborane	13.8	4.13	.0584	1696	89

[a]66 Percent blend of pentaborane in JP-4.

[b]Estimated efficiency (fuel flowmeter reading erratic).

Configuration A

Configuration A was developed for and used in the full-scale J-65 engine test of pentaborane fuel reported in reference 10.

Fuel injectors. - The quarter-sector combustor was fitted with twelve radial injectors (type 1): six for warmup fuel (JP-4), and the alternately spaced six for test fuel. One of these type-1 injectors is shown schematically in figure 6. Radial injectors rather than axial injectors were used originally to exclude any disturbance of airflow through the primary-air inlet; also, the short inlet tube minimized the cooling air required. Atomizing air and fuel were mixed internally before being discharged through six holes. The resulting spray was a finely atomized mist distributed over a 70° cone. The atomizing-air pressure was about 50 pounds per square inch gage for a flow of 0.006 pound per second. The atomizing-air to fuel weight ratio was 0.6. An annulus between the liner and the shank of the injector was intended to provide a jet of clean air to sweep over the nozzle tip.

Injector 1 was satisfactory with respect to combustion efficiency. However, this type, whether installed radially or axially, was susceptible to external decomposition especially in full-scale engine tests (refs. 10 and 11).

Primary-air inlet. - The best design tested consisted of a 0.05-inch-thick steel plate perforated with 5/64-inch-diameter holes to give 17 percent actual open area (fig. 2). The holes were spaced close enough, 34 per square inch, to insure coalescence of the air jets within a half inch from the downstream face of the plate. Total-pressure measurements at various stations radially and axially throughout the combustor indicated the airflow (cold) to be uniform and unidirectional between the perforated plate and the secondary-air slots. Thus, no strong recirculation existed in the primary zone.

Combustor liner. - The combustor liner diagrammed in figure 2 was fabricated of $2\frac{1}{2}$-inch-wide Inconel strips spot-welded together. Air was metered to each louver by a row of 3/32-inch-diameter holes spaced six per inch. These tiny air jets coalesced to form a continuous film of air over the exposed louver surface. The film was replenished every $1\frac{1}{4}$ inches. The lower limit on the proportion of air that can be admitted to the louvers is determined by: (1) the minimum required for effective filming, (2) the minimum size holes that can be punched in a specified thickness of material, (3) the susceptibility of the holes to plugging with dirt, and (4) the maximum spacing of the holes compatible with coalescence of the tiny air jets into a continuous film. The upper limit is dictated by: (1) the minimum pressure drop required through the combustor to insure adequate penetration of secondary air, and (2) the quantity of secondary air required to produce a satisfactory outlet temperature distribution. A compromise was found necessary between the desired temperature distribution and a tolerable deposit of oxide.

The secondary air entered through twelve slots divided evenly and spaced alternately between the inner and outer liners. These slots were elongated in the direction of the airflow to obtain good penetration of secondary air. The pressure loss through the combustor was quite low, less than 2 percent of the inlet total pressure at the conditions of the tests. Inadequate mixing of secondary air with the hot combustion products resulted in an outlet temperature distribution that was not as flat as desired. The open-area proportions of the total open area of the combustor were: primary-air inlet, 22 percent; louvers, 30 percent; secondary-air slots, 48 percent.

Combustor performance. - Run 1, made at condition I, ran for 11 minutes on pentaborane. The radial combustor outlet temperature profiles, figure 7(a), were flat over the center part of the stator blade span with an averaged spread of 250° F. The two circumferential profiles, figure 7(b), were similar. Since fuel injection location changed with fuel change from JP-4 to pentaborane (alternate nozzles), the hot region at rake 9 was probably a function of the combustor liner rather than fuel distribution. The large fall off in temperature at each end of the circumferential profile curves was due to the lower fuel-air ratio along the sides of the quarter sector. This is reflected by an increase of 200° F above the over-all average outlet temperature of 1354° F when the indicated readings of the center eight rakes are used.

Combustion efficiency was calculated, without corrections to the indicated thermocouple readings, at 80 percent for JP-4 fuel and 91 percent for pentaborane. The rather low efficiency with JP-4 was undoubtedly due to the absence of recirculation in the primary combustion zone. The pentaborane efficiency of 91 percent was about the same as that attained in the past with can-type combustors.

Figure 8(a) shows the light deposits typical over most of the liner surfaces. These light deposits existed mostly downstream of the secondary-air slots, where turbulence of the gases was increased. Small deposits were observed on the tips of some of the pentaborane nozzles. The effect of a small amount of recirculation on oxide deposition is emphasized in figure 8(b), where a 1/4-inch-wide weld across the perforated plate (left center of the picture) caused considerable deposition to form in the vicinity. The deposit on the two spark electrodes and the large clinker in the upper right corner of the combustor were the result of fuel impingement. Disruption of the fuel spray pattern by this clinker caused heavy deposits to spread downstream of the clinker, particularly on the outer surface.

The combustion efficiencies of the blend, HEF-2, and HiCal-3 were for all practical purposes identical. The main differences in the results of these runs were in the nature and amount of the deposits on the combustor liner walls. These comparisons are shown in figures 9, 10, and 11. The quantity of boric oxide formed during each test was nearly identical; yet the weight of oxide that remained in the combustor after the HEF-2 run was $2\frac{1}{2}$ times as much as that found after the pentaborane - JP-4 blend run. About 16 times as much remained after the HiCal-3 run as was found after the blend run. The weight of deposits on the side plates of the combustor was not included. The weight of the deposits remaining after pentaborane runs 1 and 5 was not determined.

The heavy deposits that formed during the HiCal-3 test may have been caused by "off-design" operation of the fuel injectors. The fuel injectors were developed for use with pentaborane. Pentaborane has a low viscosity (about 0.5 centistoke) and is very volatile. The viscosity of the HiCal-3 was about 14 centistokes at 77° F. The high viscosity and the low volatility of HiCal-3 could easily alter the fuel spray characteristics so that deposits would form rapidly.

Configuration B

Configuration B was developed for and used in high-temperature turbine tests with pentaborane and HEF-2 fuels in a modified full-scale J-47 engine. The results of these tests are reported in reference 12.

Fuel injectors. - Several fuel injectors were designed, fabricated, and tested in an attempt to prevent the external decomposition formations observed on injector 1. Injector 7, figure 12, was the only one tested that operated consistently free of internal, external, and impingement decomposition. Most of the design techniques discussed earlier are demonstrated by this injector. The screen and fuel orifice are outside the combustor housing, where temperatures are low. The fuel tube diameter is small so that residence time is short. It is insulated and cooled by atomizing air passing through the outside tube, which itself is of small diameter. The fuel port is relatively large, 0.052-inch diameter. The nozzle is tapered so that the downstream end is nearly the diameter of the fuel - atomizing-air port. The nozzle protrudes through a hole in the primary-air inlet, which supplies a strong, smooth flow of air over it. Fuel pressure just downstream of the fuel orifice was approximately 15 pounds per square inch gage for a flow of 0.1 gallon per minute. Atomizing airflow, to produce a finely atomized spray and sufficient cooling to prevent internal decomposition, was about 0.006 pound per second at 36 pounds per square inch gage. The weight ratio of atomizing air to pentaborane for the conditions of the tests was 0.6. Unfortunately, the spray cone angle was only about 25°, which together with the low pressure drop of the highly louvered combustor resulted in a rather marginal outlet temperature distribution.

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The number of injectors used was based on forty for a full-scale combustor. Only nine were used in the quarter-sector combustor to avoid proximity to the side walls. Five type-1 injectors were used in this configuration for gasoline warmup fuel.

Primary-air inlet. - One-inch-diameter holes were punched in the perforated plate at the outer circle of the injectors, and $1\frac{1}{4}$-inch-diameter holes were punched at the inner circle of injectors, as indicated in figure 3. These holes were to keep the over-all fuel-air ratio below 0.7 of stoichiometric at the higher fuel rates of condition II. In addition, more rapid mixing of the fuel and air was accomplished by penetration of the strong jets of air into the fuel spray. The uncontaminated air sweeping over the end of the injector also prevented formations of decomposed fuel thereon. The primary air was increased from 22 to 35 percent of the total combustion air by the addition of the holes.

Combustor liner. - The liner for configuration B, figure 3, was similar to configuration A except for the size and spacing of the louver-air entry holes and the secondary-air slots. Since the spray angle of injector 7 was very narrow, the concentration of oxide near the walls was not as great in the upstream half of the liner as it was in the downstream half. Also, the turbulence created by secondary air required a thicker air film downstream of the slots to accomplish its purpose. Therefore, the size and spacing of the holes controlling the proportioning of air to the louvers were adjusted accordingly. The number of secondary-air slots was doubled because the low pressure drop in the louvered combustor of configuration A did not provide adequate penetration of the air jets. The twenty slots were then spaced opposite each other and reduced in size so that the total open area remained the same as in configuration A.

The proportions of the total combustor liner open area with discharge coefficients assumed were: primary inlet, 35.3 percent; louvers, 22.4 percent; secondary-air slots, 42.2 percent.

Combustor performance. - Combustion was not stable with JP-4 fuel at the elevated temperatures of condition II, run 5. Combustion of clear, unleaded gasoline was stable; however, outlet temperatures were very high near the bottom of the outlet duct (fig. 13(a)).

The radial profile with pentaborane (fig. 13(a)) was of the general shape desired with four of the five averaged temperatures within a 230° spread. The average temperature indicated by thermocouples on the center eight rakes was about 180° higher than the over-all average of 1696° F. The circumferential profile with pentaborane (fig. 13(b)) indicated a cool region down the center of the combustor. The same tendency was found for gasoline. Fuel injector flow calibrations and observations of the combustor hardware revealed no explanation for the phenomenon.

Combustion efficiencies with configuration B were 85 percent for gasoline and 89 percent for pentaborane.

Oxide deposits in streaks on the outer liner surface, corresponding to the region of peak temperatures (rakes 3 and 10), were heavier than in the remainder of the combustor. The streaks may have been caused by vortexes originating from two symmetrical secondary-air slots. The fuel injectors were completely free of internal and external decomposition products, as can be seen in figure 14. No deposits were observed on the primary-air inlet, and the liner surfaces were relatively clean except for the two streaks previously mentioned.

CONCLUSIONS

The design concepts set forth herein are based on very short tests at only one simulated flight condition. Nevertheless, they represent the best compromise made among several problems, including the usual combustor problems of combustion efficiency, outlet temperature distribution, and pressure loss. Additional problems are posed with the use of boron-containing fuels by deposits of decomposed fuel and boric oxide.

Observations based on the results of the limited tests are summarized as follows:

1. Fuel decomposition in and on fuel injectors was prevented by air-cooling fuel passages and by bathing small, streamlined injectors in jets of air. The finely divided fuel spray produced by air atomization prevented deposition of fuel on upstream combustor liner walls. A finely divided spray can also help prevent oxidative cracking by allowing intimate and rapid mixing of fuel and air, provided the spray is well distributed across the combustor. While the injectors described herein did preclude fuel decomposition, they did not distribute the fuel adequately. Two solutions are apparent. The spray cone angle may be increased; however, every attempt to produce a wide spray cone angle has resulted in decomposition products on the injector tips. A second method is to increase the number of points of injection. A given fuel flow rate would then be divided among, say, 80 injectors rather than 40. The spray cone angle of each injector would remain fixed. The fuel concentration per unit of spray cone cross-sectional area would be cut in half. Oxygen starvation of the core of the fuel sprays would thus be reduced or eliminated. Combustion efficiency should approach 100 percent even at conditions more stringent than those of the tests reported herein.

It should be pointed out that, although air atomization has several distinct advantages where boron-containing fuels are used, it does incur a penalty. An auxiliary compressor and possibly an air cooler would be required to bring the atomizing air to 20 to 40 pounds per square inch above compressor discharge pressure.

2. Outlet temperature distribution in the combustors described was not particularly good. Several factors seemed responsible: The fuel sprays were too few in number and did not disperse fuel widely; pressure drop was very low because of extensive air filming, and hence secondary air did not penetrate well. Further effort directed toward adequate filming but with increased pressure drop and better fuel dispersion is required on this problem.

3. Deposits of molten boric oxide were limited by minimizing recirculation in the primary combustion zone and by extensive air filming of combustor liner walls. Boric oxide in the exhaust gases would thus be presented to the turbine in the most desirable manner for its digestion.

4. Matching of fuel, fuel spray, and air distribution has always been basic in combustor design. Substitution of high-viscosity high-boiling fuels like HEF-3 in combustors developed for volatile fuels like pentaborane will necessitate modifications of the combustor.

Lewis Research Center
National Aeronautics and Space Administration
Cleveland, Ohio, March 12, 1959

APPENDIX A

FUEL INJECTOR DEVELOPMENT

The difficulties encountered in preparing a highly reactive fuel, such as pentaborane, for combustion were discussed in a preceding section. The purpose of this appendix is to describe in more or less chronological order several of the designs tested during the development program.

To conserve the supply of pentaborane fuel and reduce fabrication time and cost, pentaborane was injected through only two test injectors. Propylene oxide, a plentiful, relatively reactive fuel, was injected through the remaining injectors in the set in order that local temperatures would be comparable to those of a full set of pentaborane injectors.

Fuel Injector 2

Because of the reactivity of pentaborane, it was postulated that oxidation of the boundary film within the mixing chamber in the tip of injector 1 (fig. 6 and text, p. 9) or recirculation of fine droplets around the injector tip or both were responsible for the formation of external decomposition. Consequently, injector 2 (fig. 15) was designed without mixing chamber surfaces where fuel and atomizing air would remain in contact. The injector also provided positive shrouding of the atomized spray with additional air to prevent recirculation of tiny fuel droplets. The upper part was essentially the same as radial-type injector 1. Previous experience with single-port air-atomizing injectors had shown the resulting spray angle to be about 25°. A helix in the fuel passage and in the air passage along with a conical tip were intended to produce a larger spray angle. Unfortunately, these devices were not effective.

The total-air-to-fuel weight ratio for this injector was 0.6 with a 50-50 split between atomizing air and shroud air. Air pressure to the injector was 30 pounds per square inch gage. Although the injector ran completely free of both internal and external decomposition, concentration of the fuel in a narrow cone spray resulted in impingement on the inner liner (fig. 16). Probably only a very small amount of the fuel was involved in this formation.

To determine whether the freedom from external decomposition was due to elimination of the internal mixing chamber or to the prevention of recirculation of fuel droplets by shroud air, a test was made with shroud air blocked off. A small conical-shaped clinker formed during the test (fig. 17), which indicated that shrouding the spray would prevent external decomposition formations.

Fuel Injector 3

With this conclusion in mind, fuel injector 1 was fitted with several different nozzle caps designed to feed air around the fuel sprays in an attempt to include the good distribution of injector 1 with the cleanliness of injector 2. One of these designs, injector 3, is shown in figure 18. Holes were drilled in the nozzle tip to supply shroud air between the tip and a conical cap. Care was taken to aline the larger holes in the cap with the ports in the tip so that fuel could not impinge on the inside surface of the cap. Bench tests with water sprayed into still air showed a finely atomized spray with no indication of recirculation. Nevertheless, a large clinker did form during a short test, as shown in figure 19.

Fuel Injector 4

Again, the original injector 1 was modified. A concentric tube was spaced from the injector shank to maintain a uniform annulus through which combustion air was directed down over the nozzle tip (fig. 20). In this way a much larger quantity of clean air was provided to sweep over the tip and to shroud the fuel spray than that supplied to injector 3 or by the annulus around the shank of injector 1. A very large clinker of decomposed fuel and boric oxide formed during a test of this type-4 nozzle. Apparently, interaction of the shroud air with the fuel spray caused local recirculation around the nozzle tip.

Fuel Injector 5

Another attempt to shroud each of six individual sprays with sufficient air was made with the design of injector 5 (fig. 21). The nozzle tip was designed for the same purpose as that of injector 3, but the passages conducting the air to the tip were enlarged. Bench tests with water in still air indicated no recirculation. A combustion test with pentaborane resulted in very rapid clinker formation. A small clinker containing six hollow tubes can be seen on the nozzle in figure 22; this was the beginning of a third formation. Two clinkers formed on the same injector earlier in the 3.5-minute run can be seen lodged against the outlet thermocouples in figure 23.

Fuel Injector 6

A somewhat different approach was tried by sandwiching the fuel between two layers of atomizing air and mixing the fuel and air externally (fig. 24). It was hoped that the inside and outside layers of air would atomize sufficiently and still prevent recirculation of tiny fuel droplets in the vicinity of the nozzle. Bench tests showed the atomization to be good and the included spray angle to be 70°. However, this type-6 injector also permitted intolerable external deposit to form.

Of all the designs tested, only the single-hole injector 2 with shroud air remained free of external formations. Every attempt to distribute the spray in a wider cone was unsuccessful. It is doubtful that any of them would have functioned better in an axial direction. The designs described and others not included here emphasize that any disturbance of the smooth flow of air over and around the fuel injection port is disastrous.

APPENDIX B

COMBUSTOR LINER DEVELOPMENT

Primary-Air Inlet

All the primary-air inlet designs tested during this program had a common objective: To admit a portion of the combustion air in a manner that would create as little recirculation as possible in the primary zone.

About 40 percent of the combustion air was intended to flow smoothly over the streamline tubes of inlet 1 (fig. 25) with the space between the tubes acting somewhat like a nozzle. The inlet and the upstream end of the liner were completely free of boric oxide deposits after pentaborane runs. However, because of the large portion of combustion air entering through the primary inlet and the low over-all combustor pressure loss (driving force), dilution of the hot gases by secondary air was inefficient and the resulting outlet temperature distribution was very poor.

Another approach was to direct the primary air over exposed surfaces as the louvers in the liner do. This method worked very well depositwise with inlet 2 (fig. 26), even though it admitted only 20 percent of the combustion air. Unfortunately, the low pressure loss in the remainder of the liner again made the outlet temperature distribution poor.

Several other designs were tested - all of which permitted deposits, produced hot spots, or were difficult to fabricate. These were discarded in favor of the simple perforated plate discussed earlier.

Combustor Liner

The original quarter-sector liner (fig. 25) was constructed of $2\frac{1}{2}$-inch-wide strips spaced 1/16 inch apart. A width of $1\frac{1}{4}$ inches was exposed to oxide particles. The secondary-air station was located at the fuel injection station to insure rapid mixing of fuel with sufficient air. Also, secondary air entering through the holes in the outer liner would sweep around the fuel injectors and thereby prevent external decomposition. This configuration permitted the formation of very little deposit, as can be seen in figure 27. As mentioned earlier, the low pressure loss of less than 1 percent of the inlet total pressure resulted in an unsatisfactory outlet temperature profile. The effective open-area proportions, using primary-air inlet 1, were: primary inlet, 40 percent; secondary-air inlets, 32 percent; louvers, 28 percent.

In liner 2 (fig. 28) the secondary-air inlets were ten rectangular slots spaced alternately on the inner and outer liner at the midsection. This location reduced the length of liner exposed to turbulence, which permitted a decrease in the proportion of air entering the louvers and consequently an increase in secondary mixing air. The louvers were spaced only 1/32 inch apart, and the exposed width was increased to 2 inches. The open-area proportions of this liner were: 27 percent of the air to the louvers, 17 percent to the primary, and 56 percent to the secondary. This width of exposed louvers proved too great to be effectively scrubbed by the boundary-layer air film, and boric oxide deposited in a liquid layer as visible in figure 29. The outlet temperature profile was somewhat improved, however.

Other variations made in the proportions of air entering the various parts led to liner 3 (discussed earlier).

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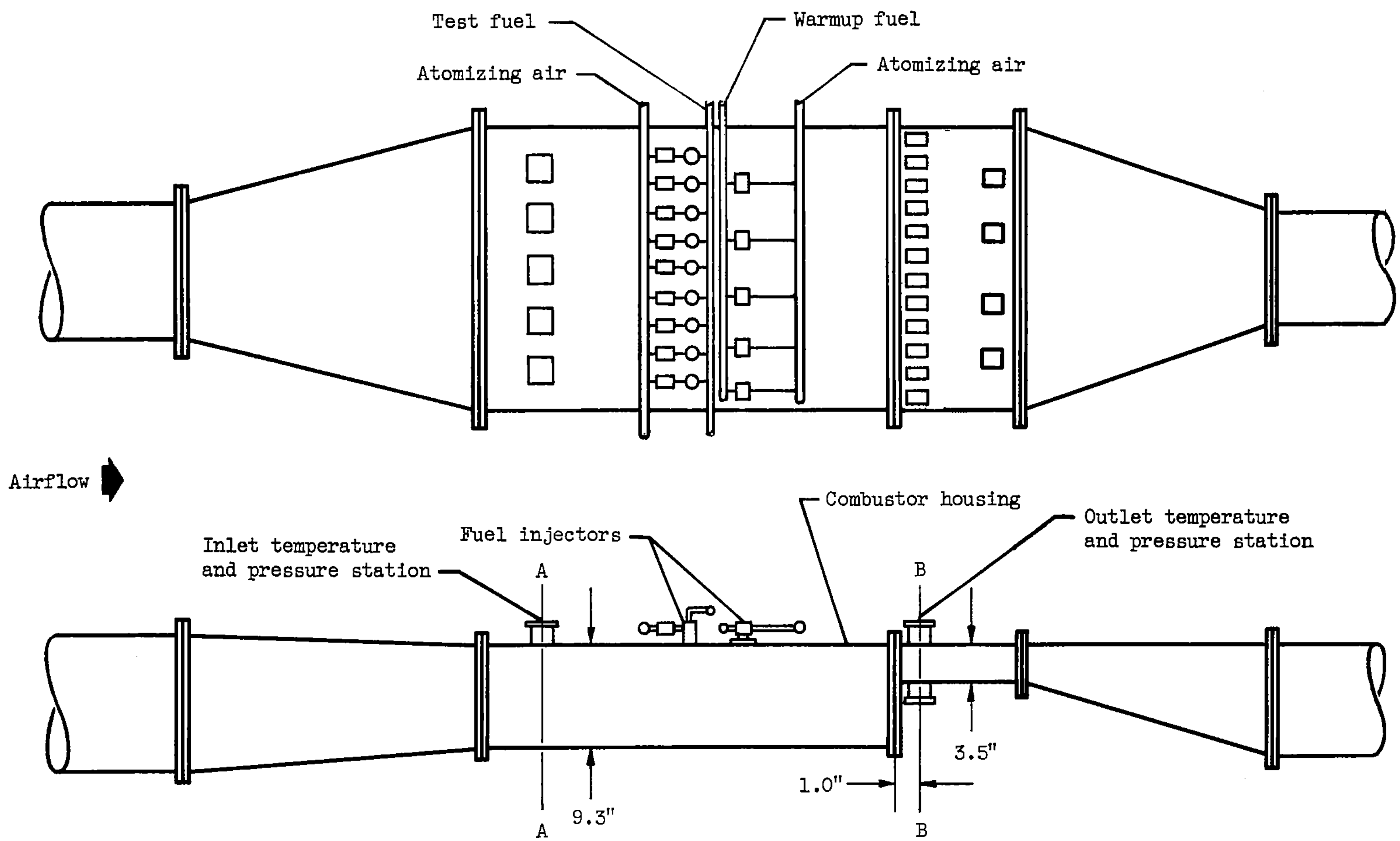

Figure 1. - Combustor installation.

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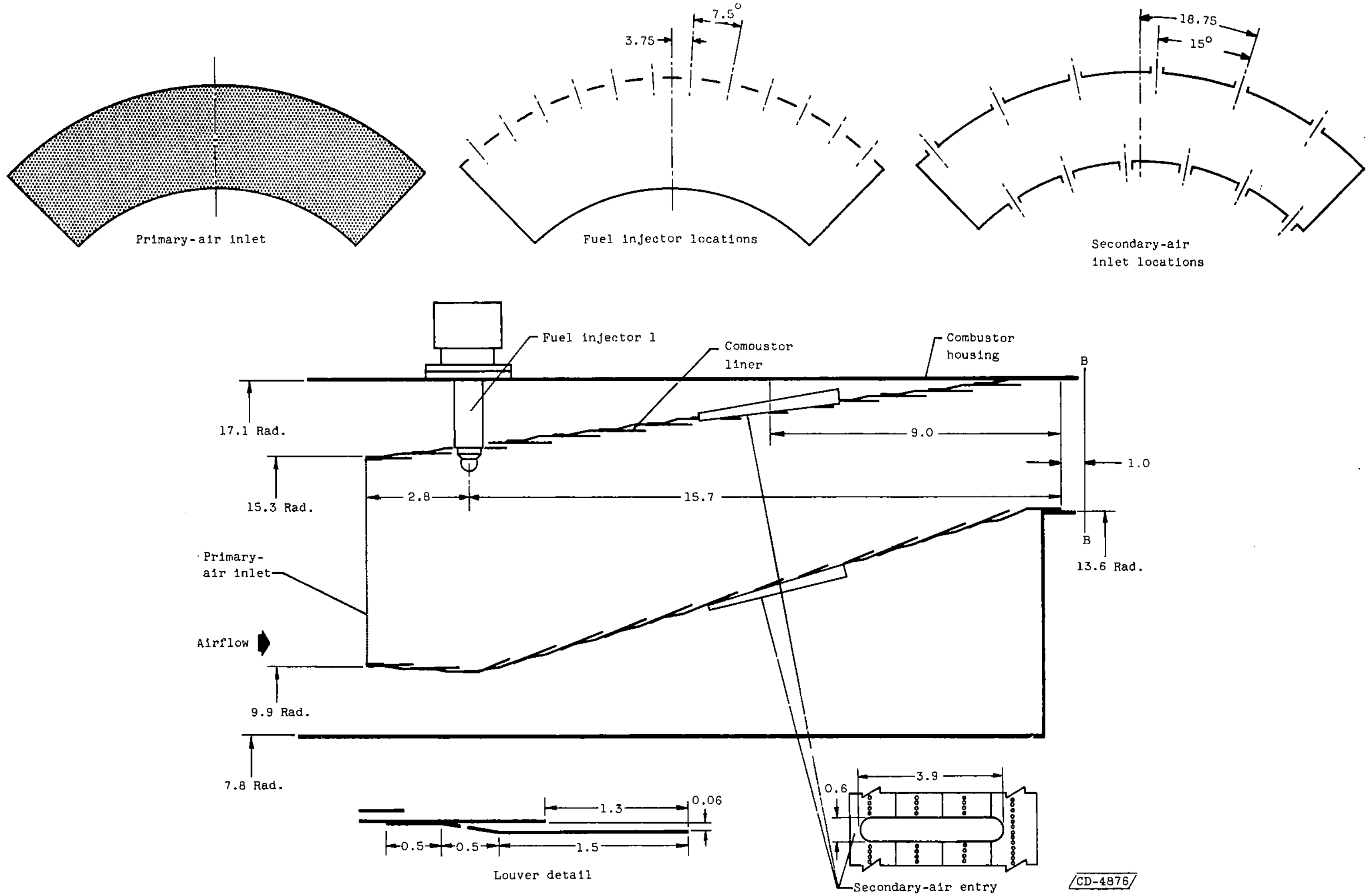

Figure 2. - Configuration A, quarter-sector annular combustor. (All dimensions in inches.)

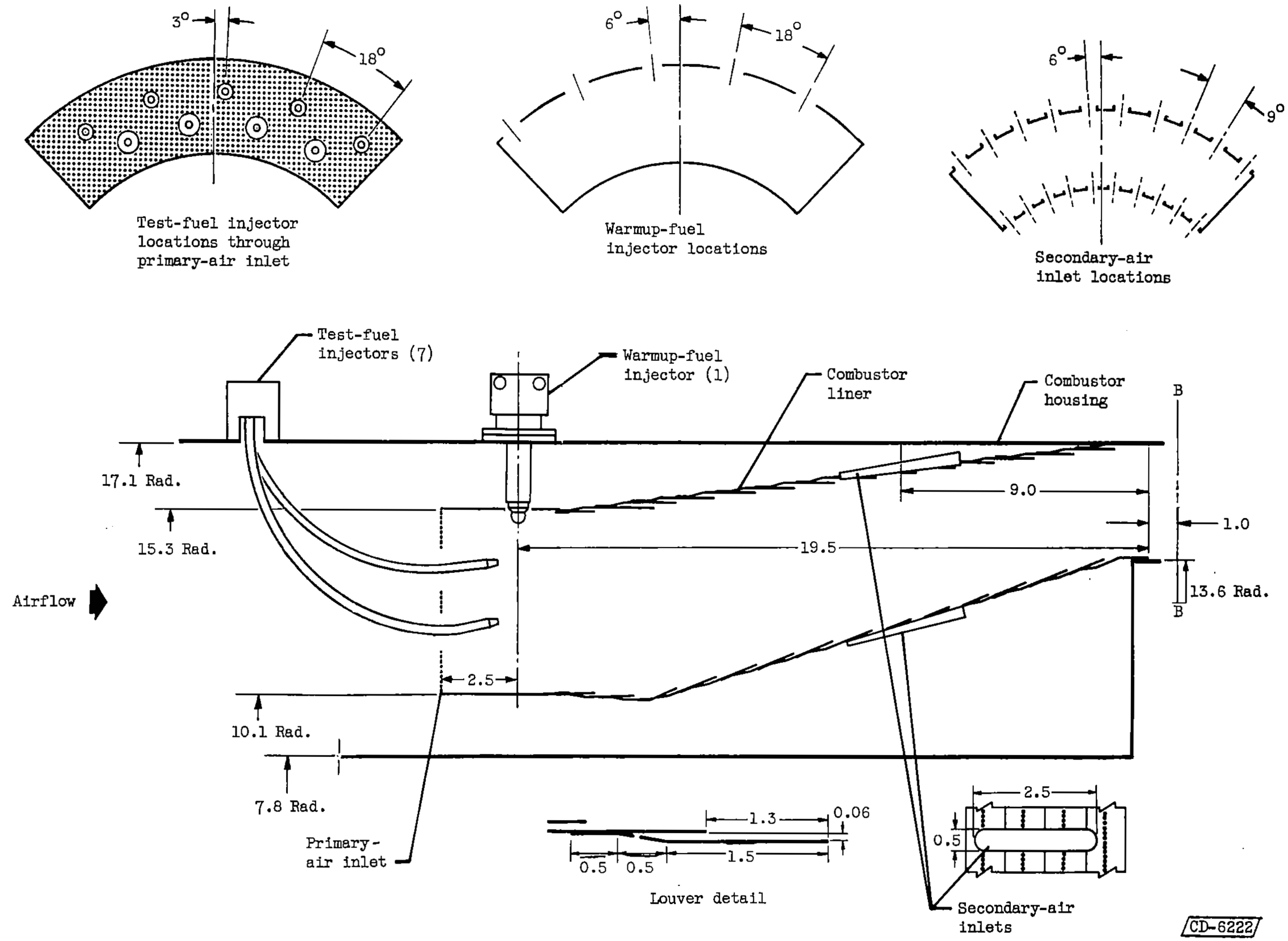

Figure 3. - Configuration B, quarter-sector annular combustor. (All dimensions in inches.)

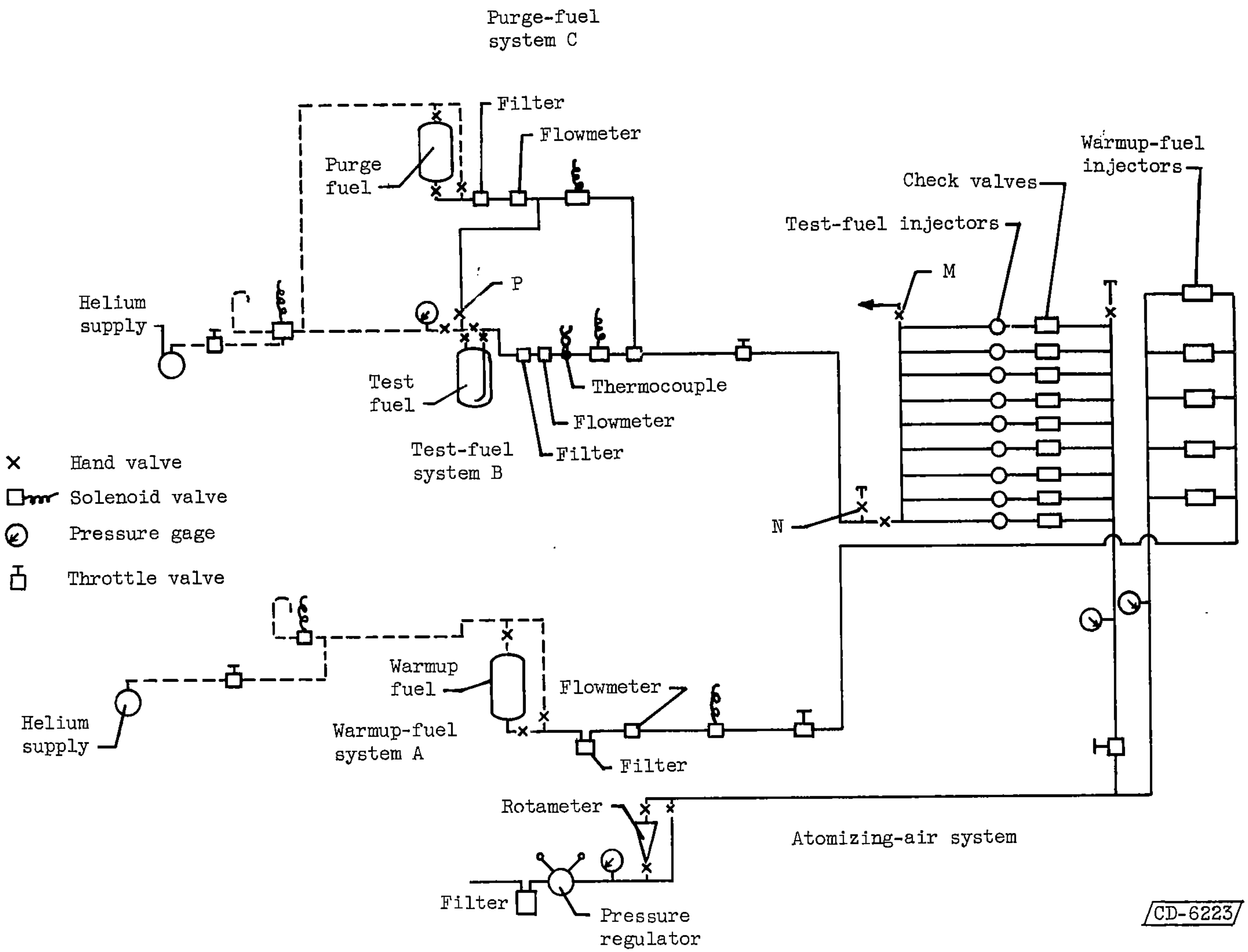

Figure 4. - Fuel and atomizing-air systems.

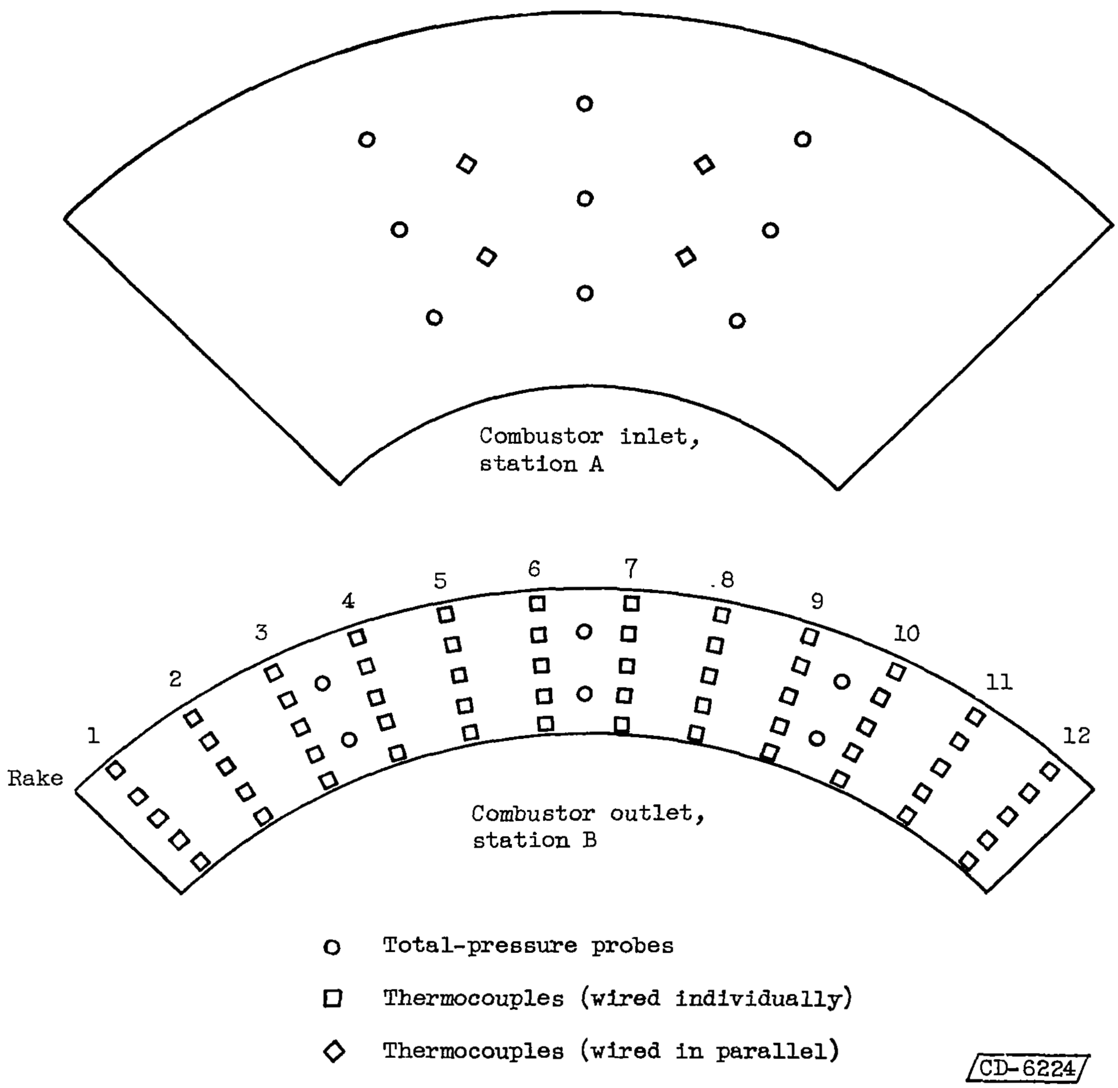

Figure 5. - Location of thermocouples and total-pressure probes.

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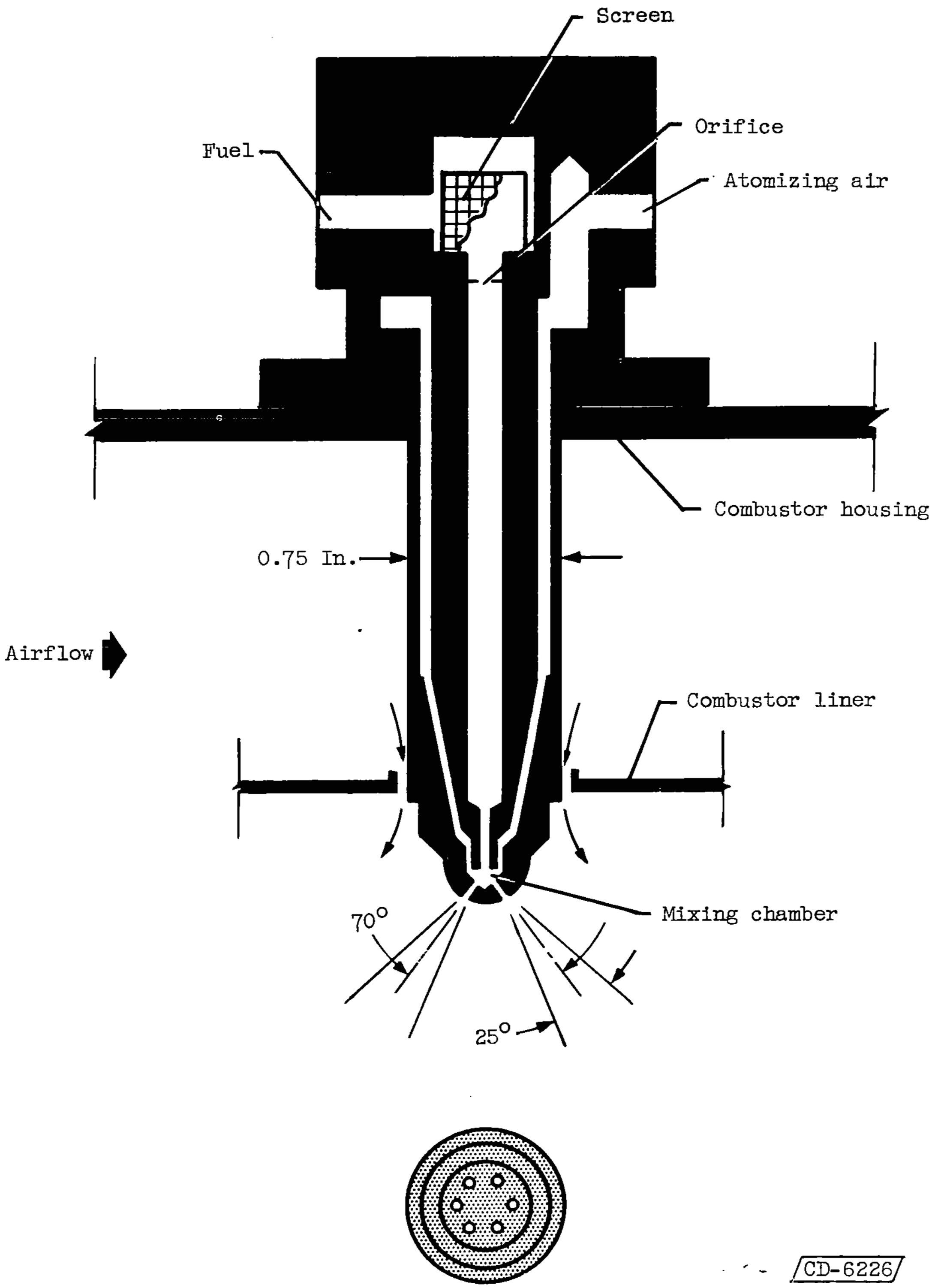

Figure 6. - Radial fuel injector 1.

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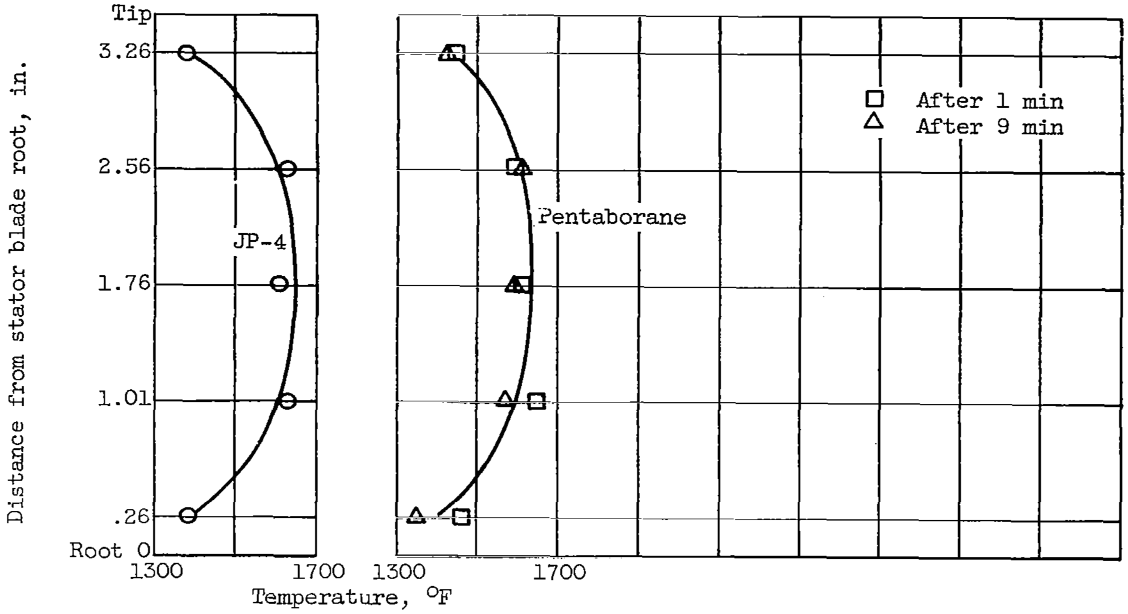
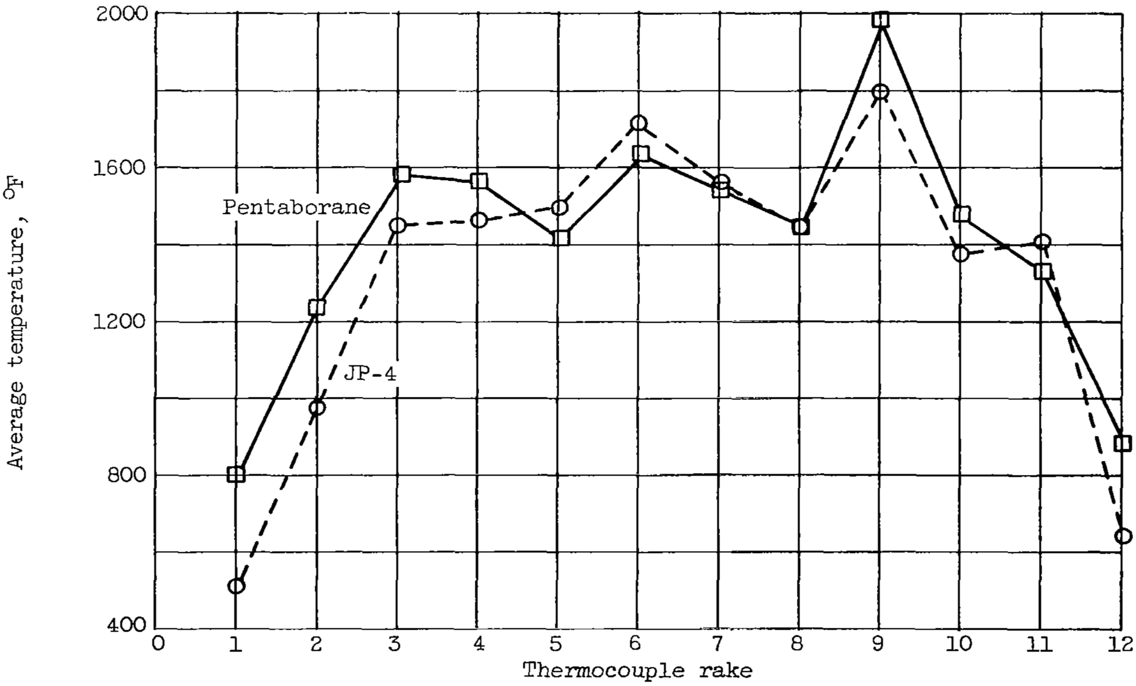
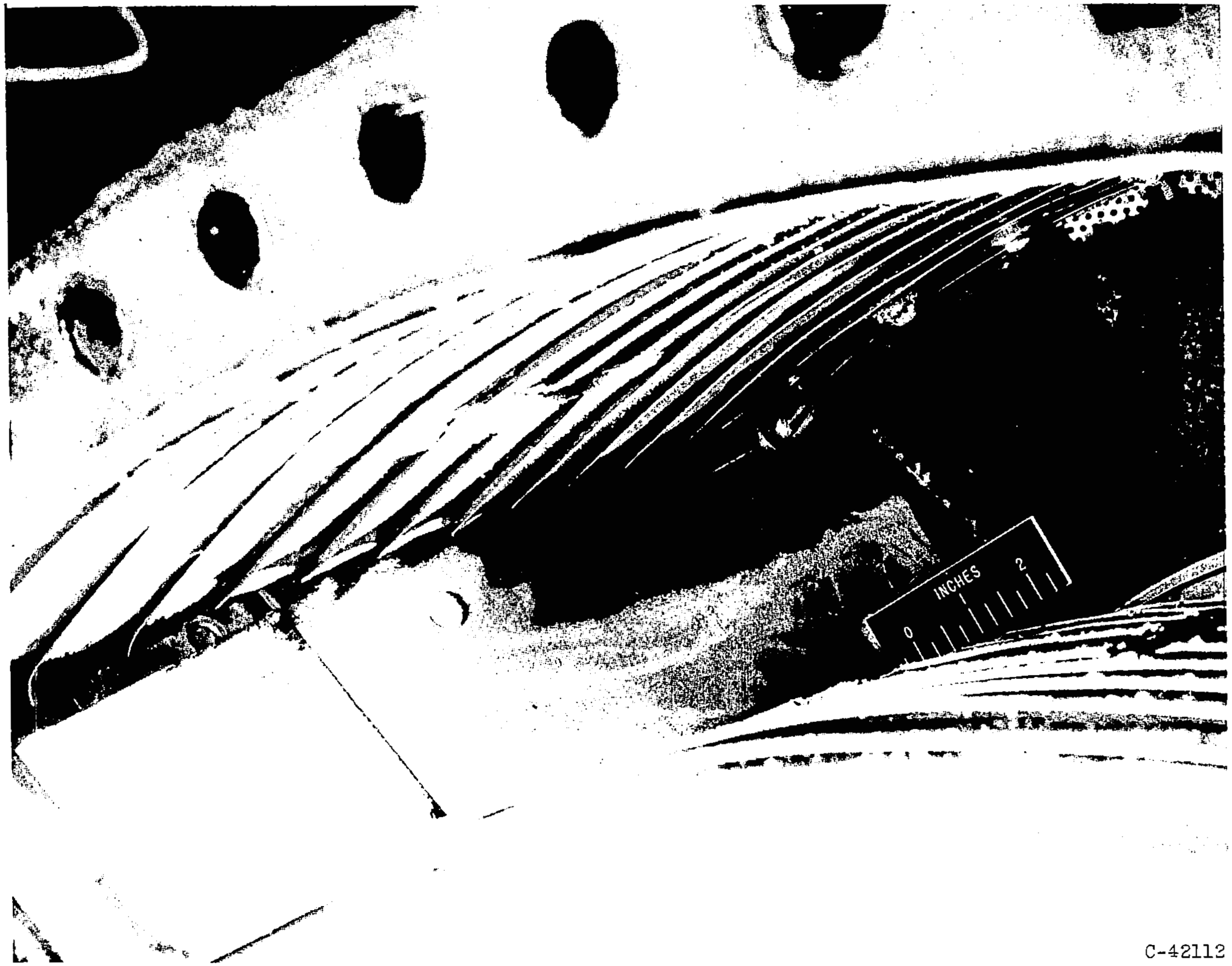


(a) Radial profiles.



(b) Circumferential profiles.

Figure 7. - Combustor outlet temperature profiles for run 1, pentaborane and JP-4 fuels.



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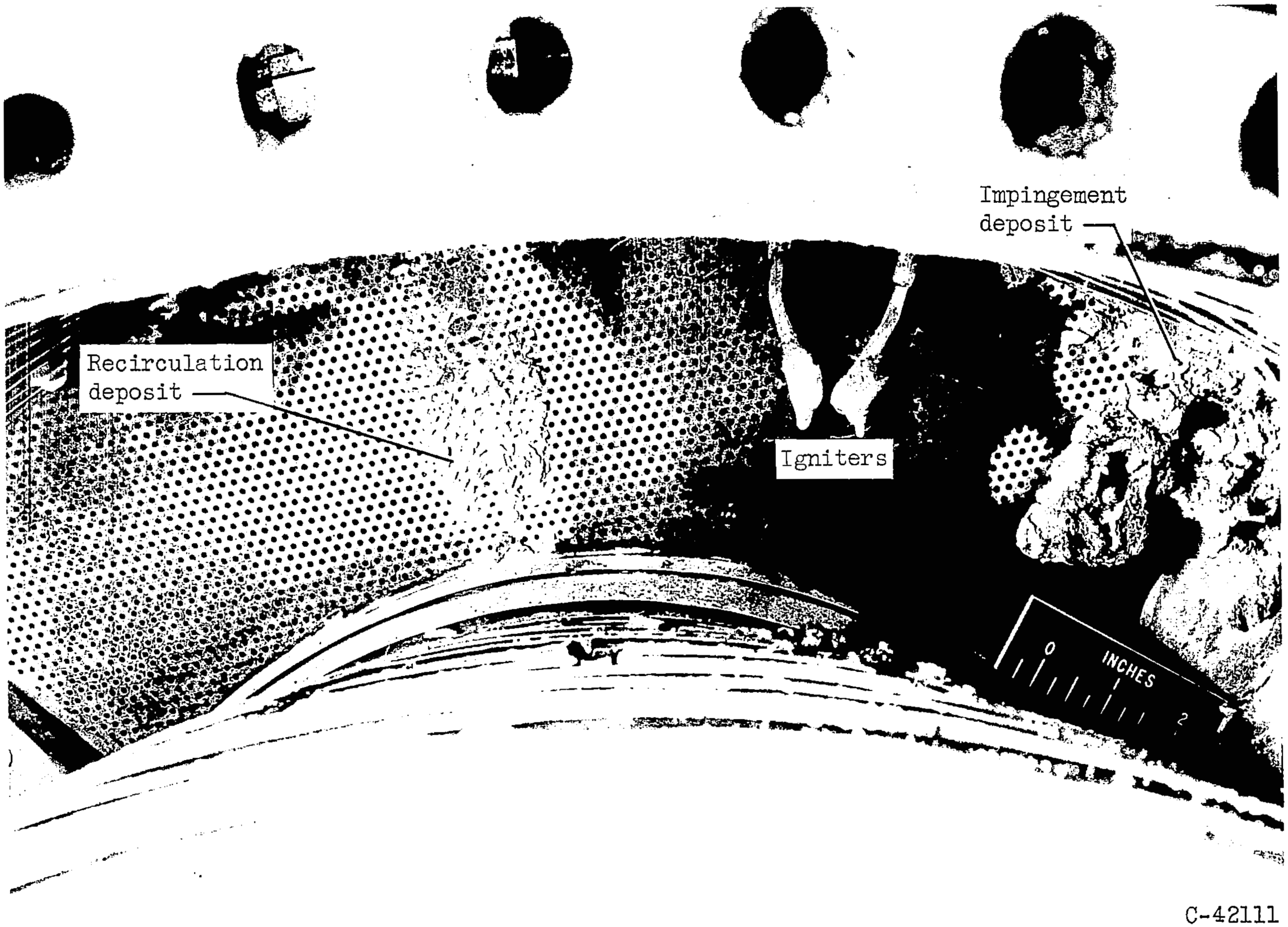
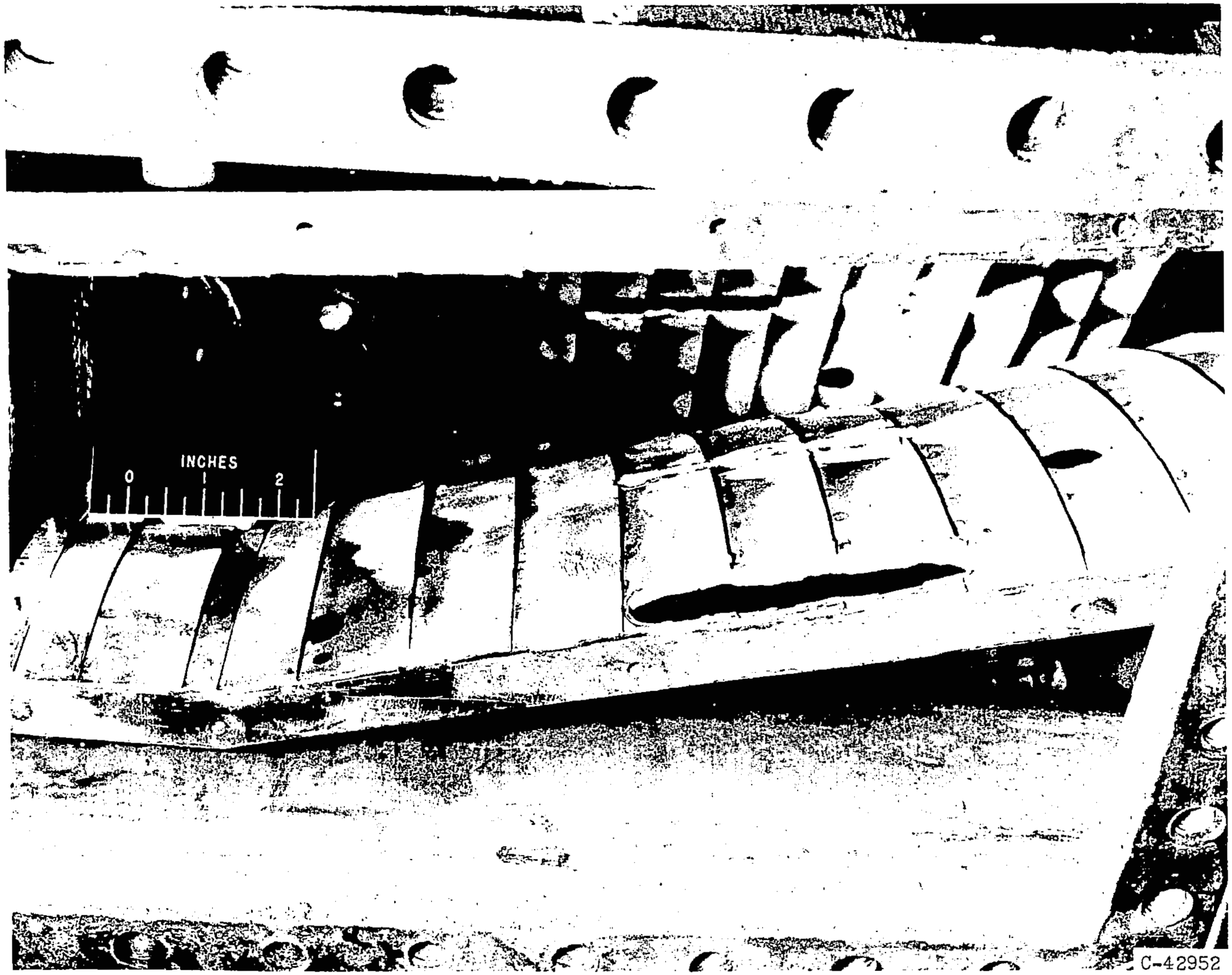
(a) Liner deposits.

Figure 8. - Deposits in combustor liner of configuration A after run 1, pentaborane fuel.



(b) Recirculation and impingement deposits.

Figure 8. - Concluded. Deposits in combustor liner of configuration A after run 1, pentaborane fuel.

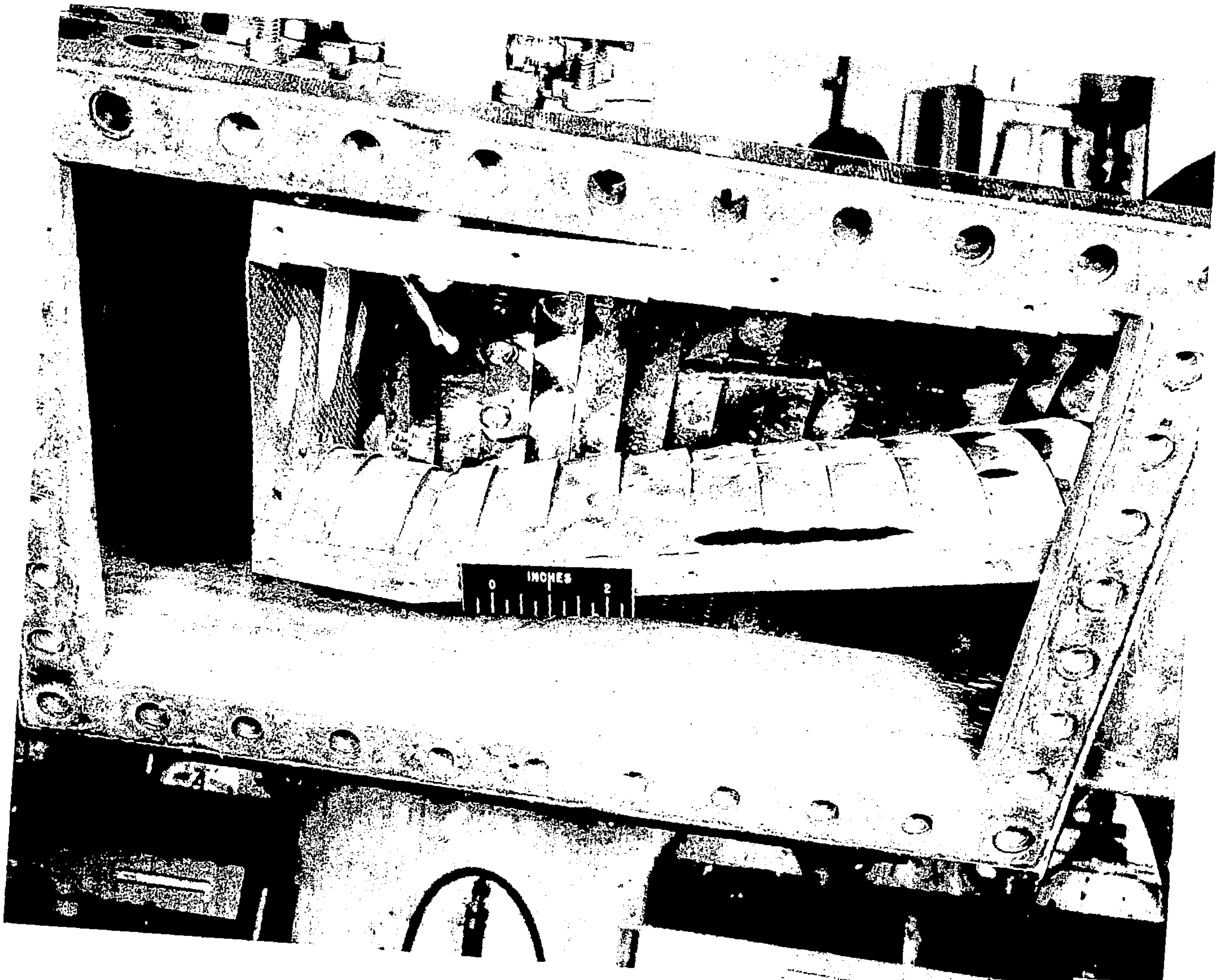


(a) Side view.

Figure 9. - Deposits in combustor liner of configuration A after run 2, pentaborane - JP-4 blend fuel.

(b) Rear view.

Figure 9. - Concluded. Deposits in combustor liner of configuration A after run 2, pentaborane - JP-4 blend fuel.



(a) Side view.

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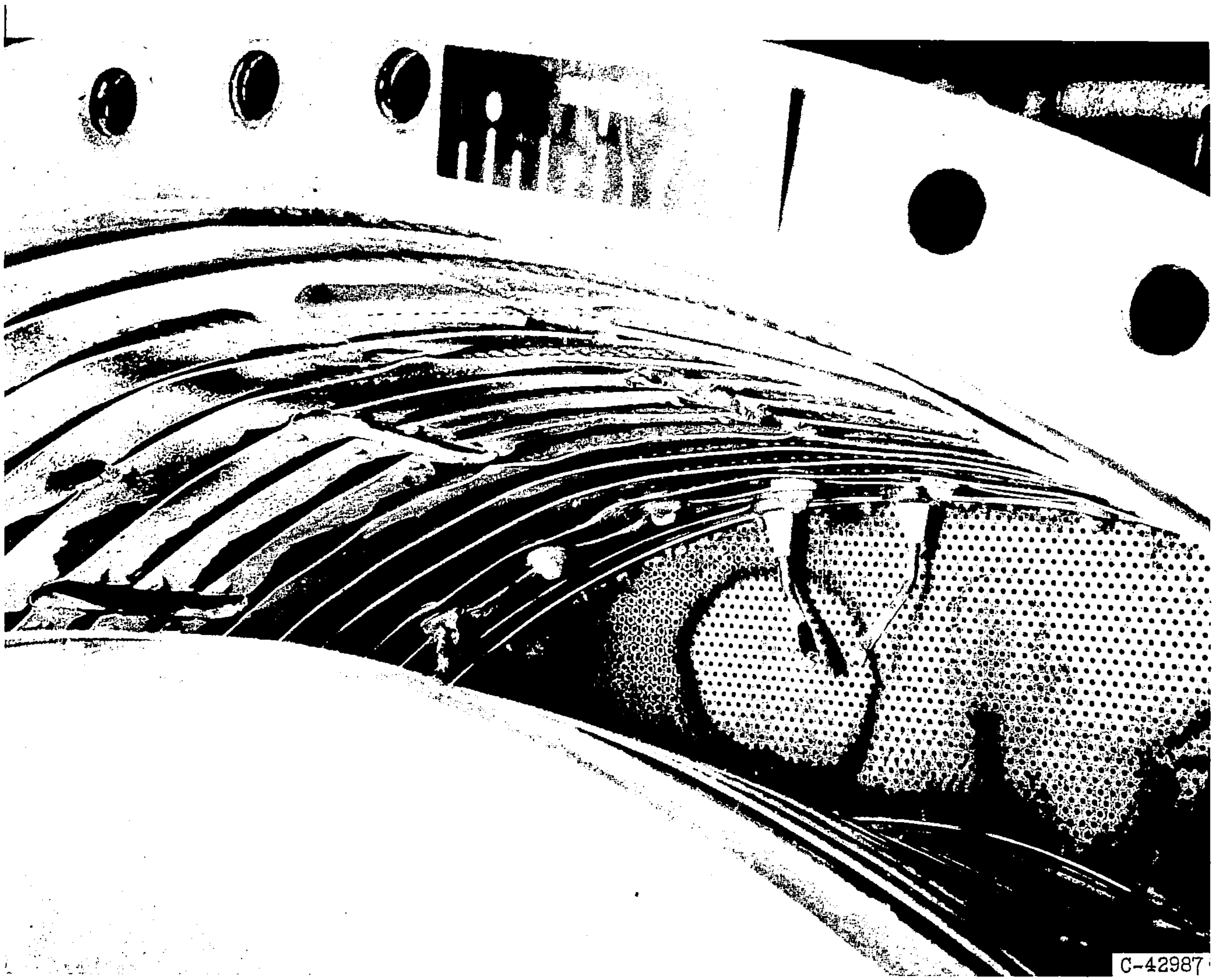
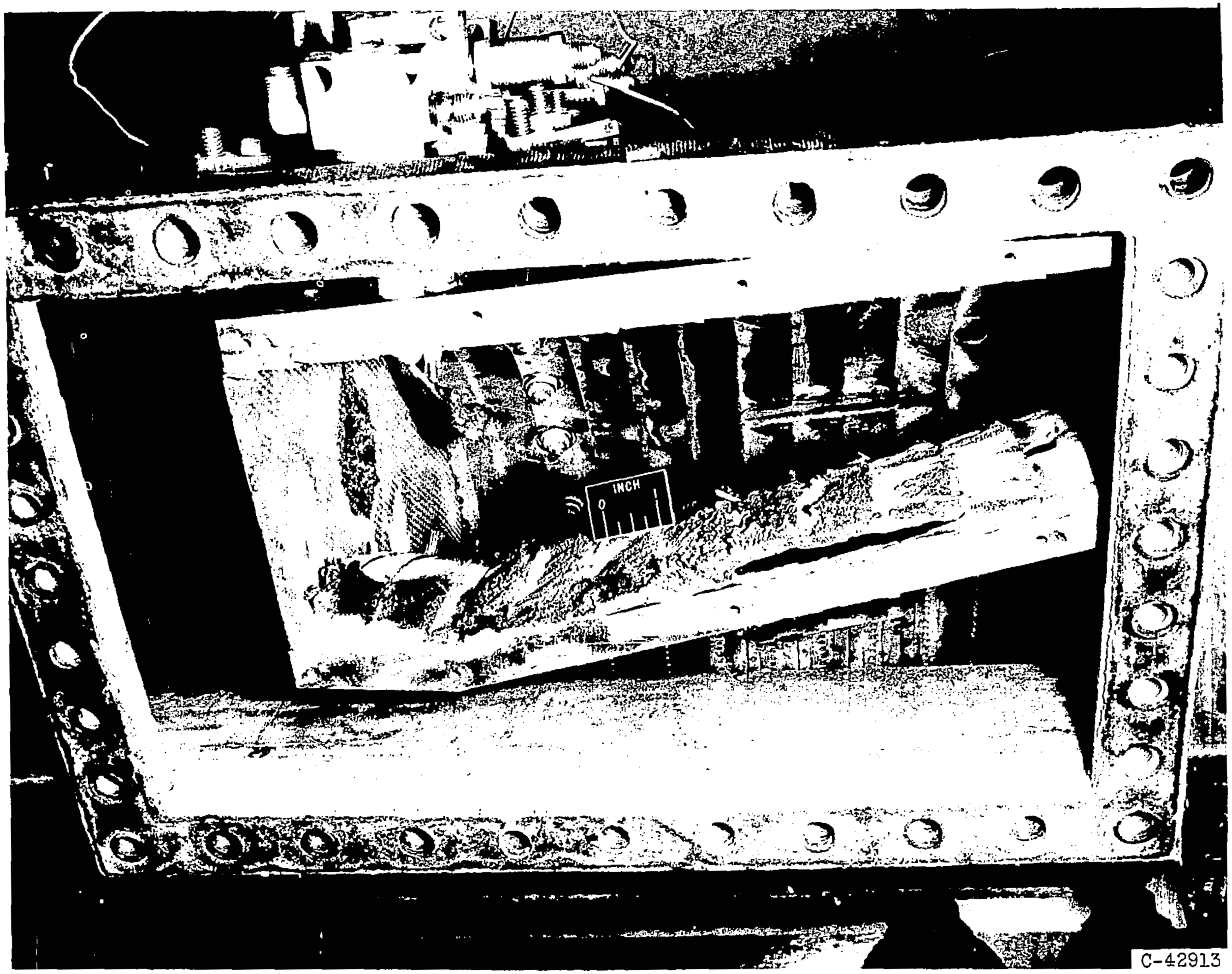
Figure 10. - Deposits in combustor liner of configuration A after run 3, HEF-2 fuel.



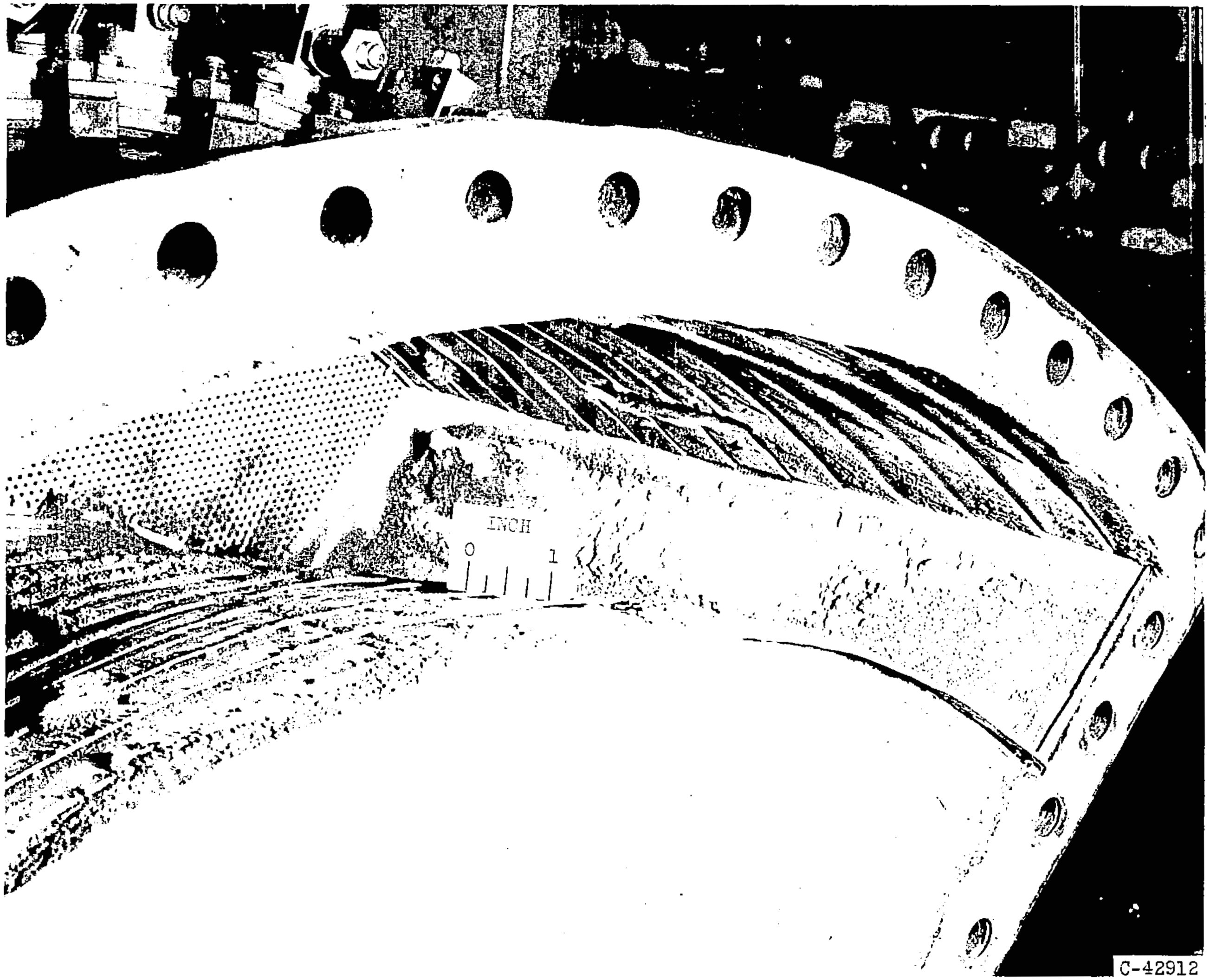
(b) Rear view.

Figure 10. - Concluded. Deposits in combustor liner of configuration A after run 3, HEF-2 fuel.



(a) Side view.

Figure 11. - Deposits in combustor liner of configuration A after run 4, HiCal-3 fuel.



(b) Rear view.

Figure 11. - Concluded. Deposits in combustor liner of configuration A after run 4, HiCal-3 fuel.

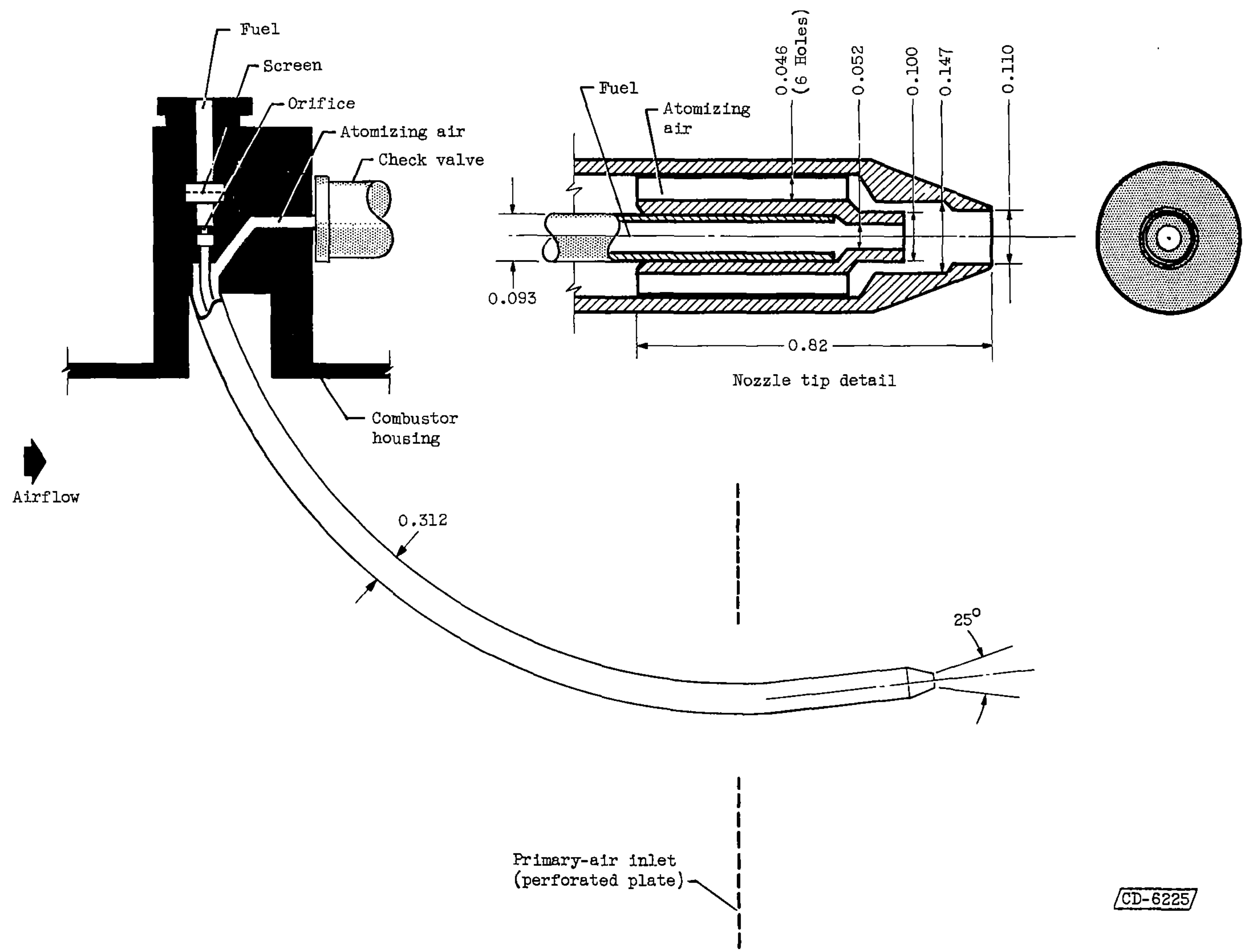
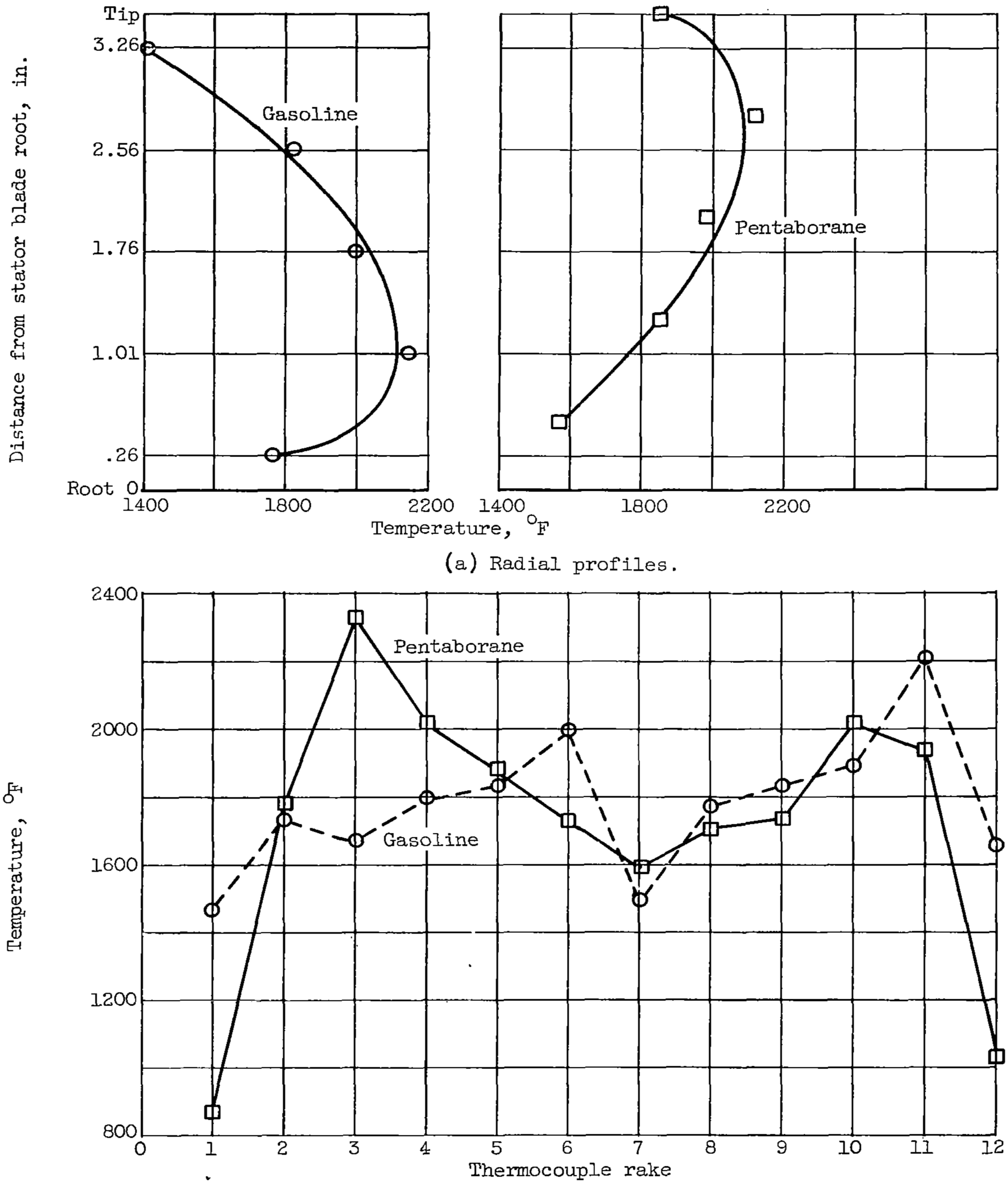


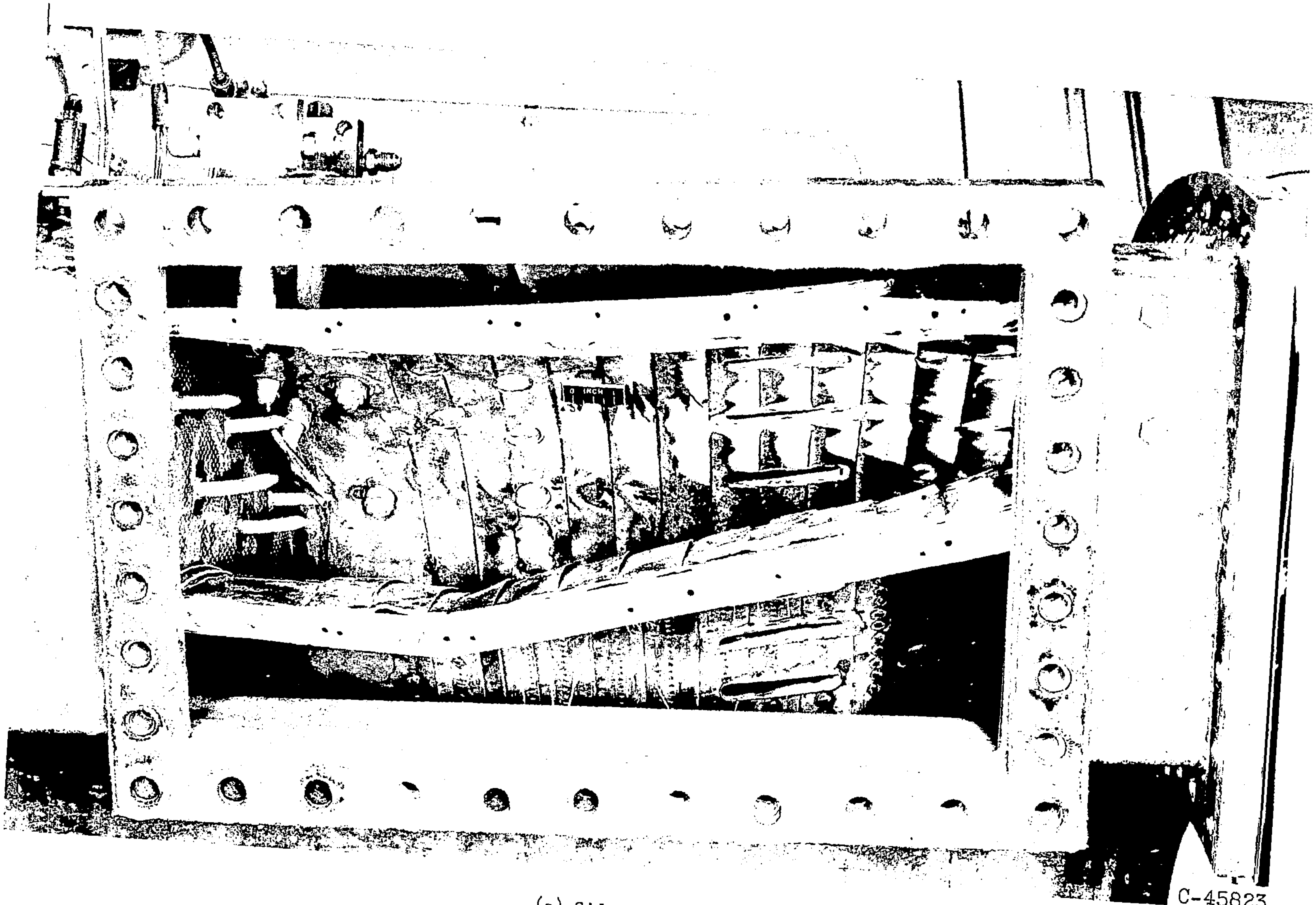
Figure 12. - Test fuel injector 7. (All dimensions in inches.)



(a) Radial profiles.

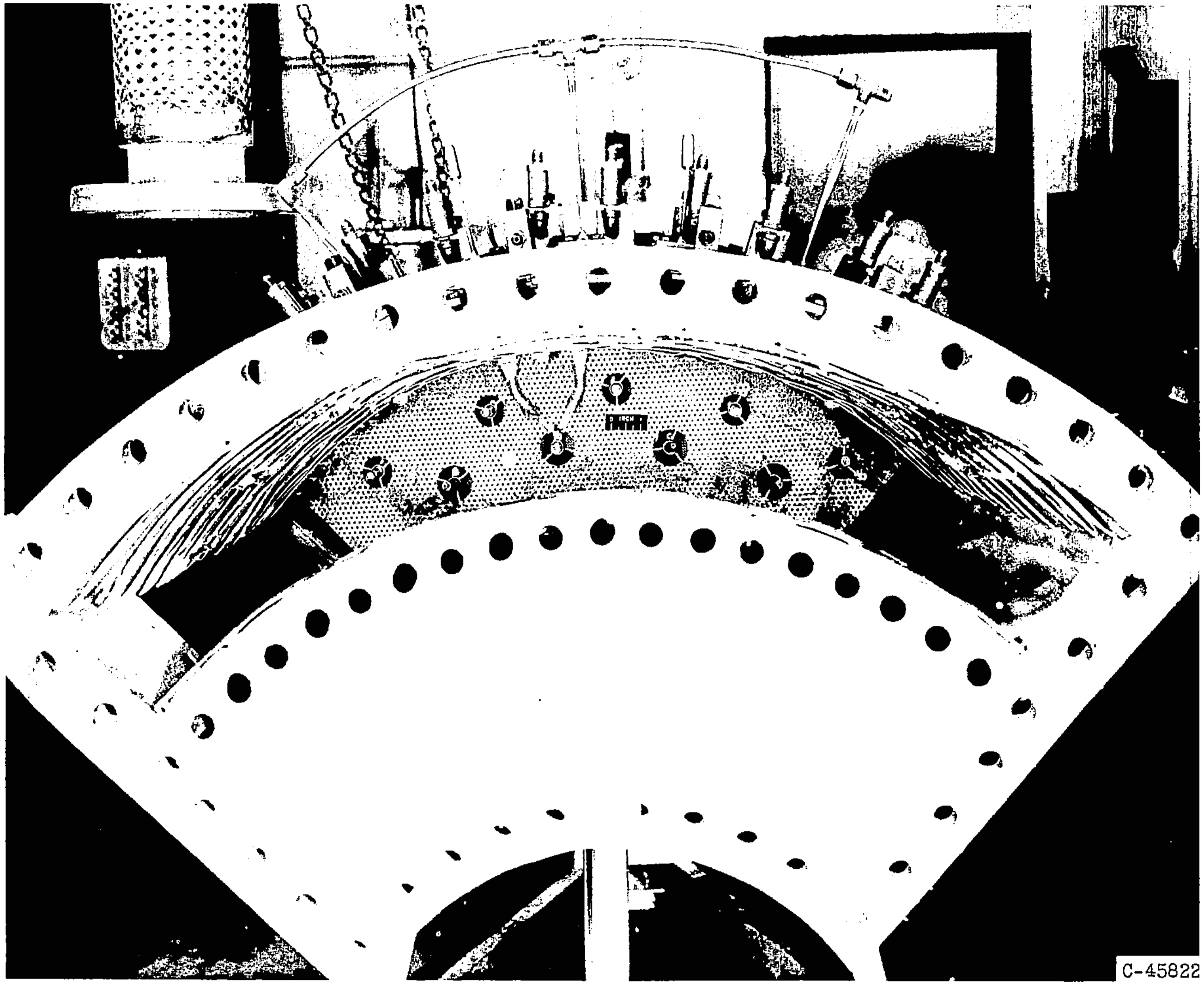
(b) Circumferential profiles.

Figure 13. - Combustor outlet temperature profiles for run 5, pentaborane and gasoline fuels.



(a) Side view.

Figure 14. - Deposits in combustor liner of configuration B after run 5, pentaborane fuel.



(b) Rear view.

Figure 14. - Concluded. Deposits in combustor liner of configuration B after run 5, pentaborane fuel.

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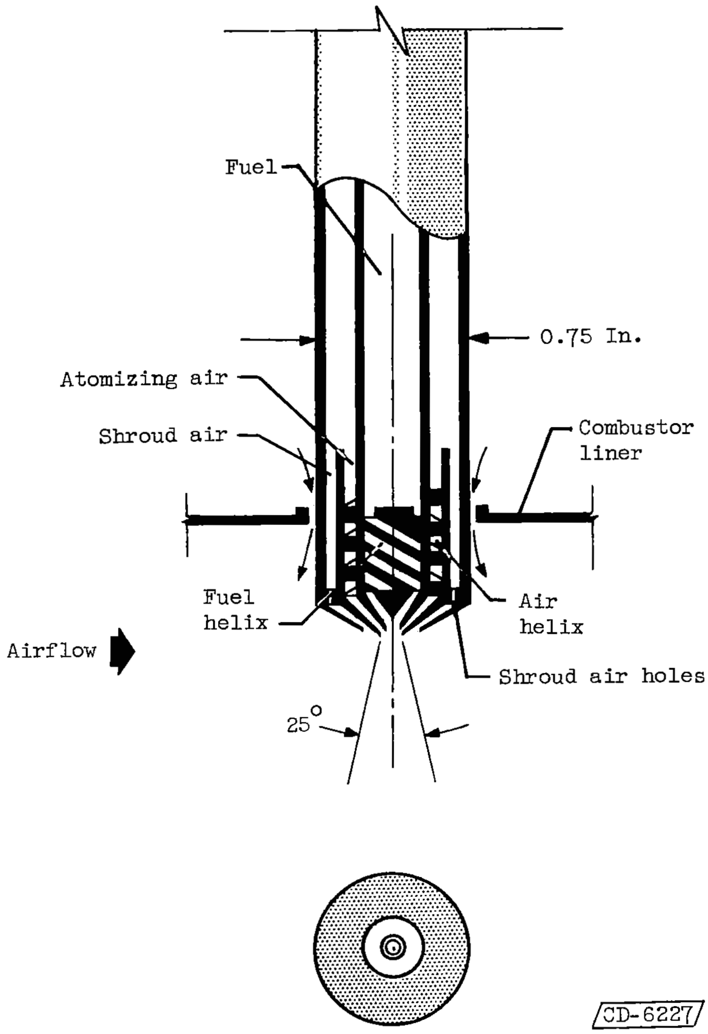

Figure 15. - Fuel injector 2.

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Figure 16. - Impingement deposit from fuel injector 2 after 9.4-minute run on pentaborane fuel.

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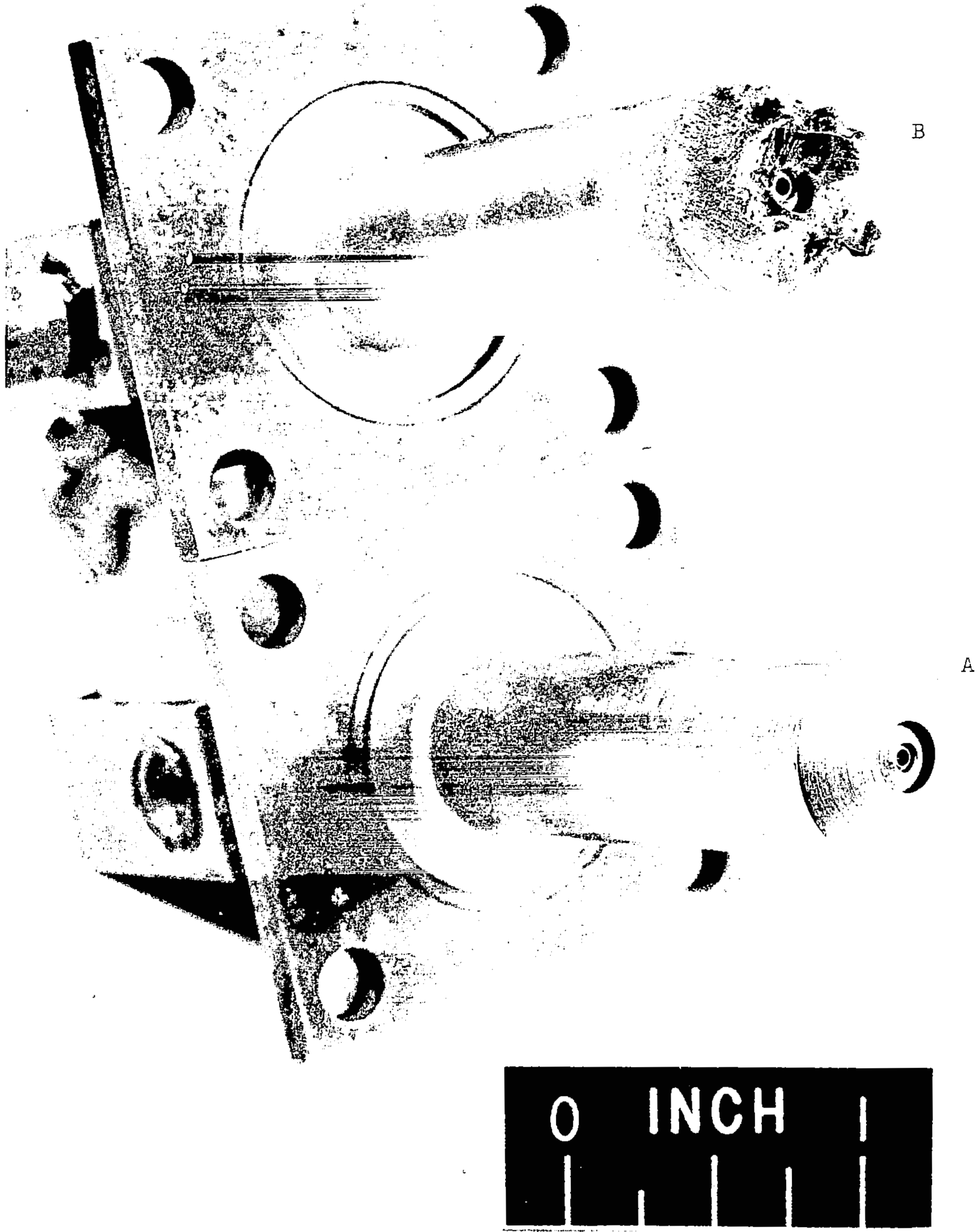

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Figure 17. - Fuel injector 2: (A) clean; (B) with external decomposition deposit formed during 9.3-minute pentaborane run with shroud air blocked off.

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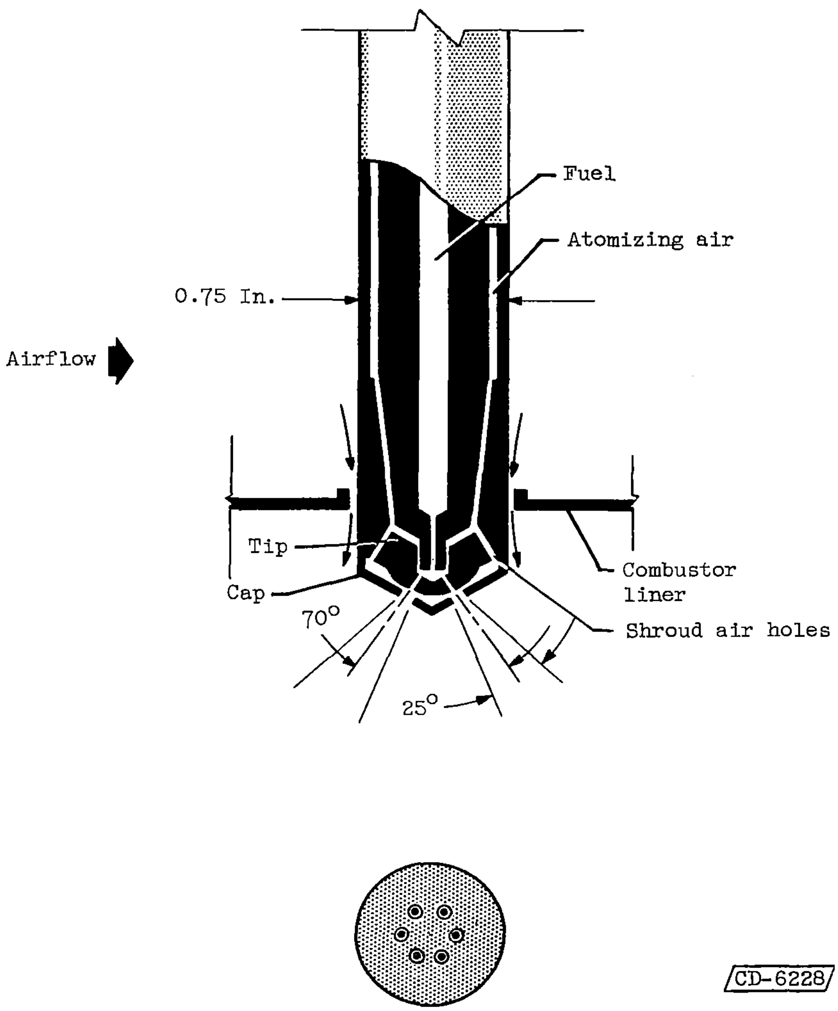

Figure 18. - Fuel injector 3.

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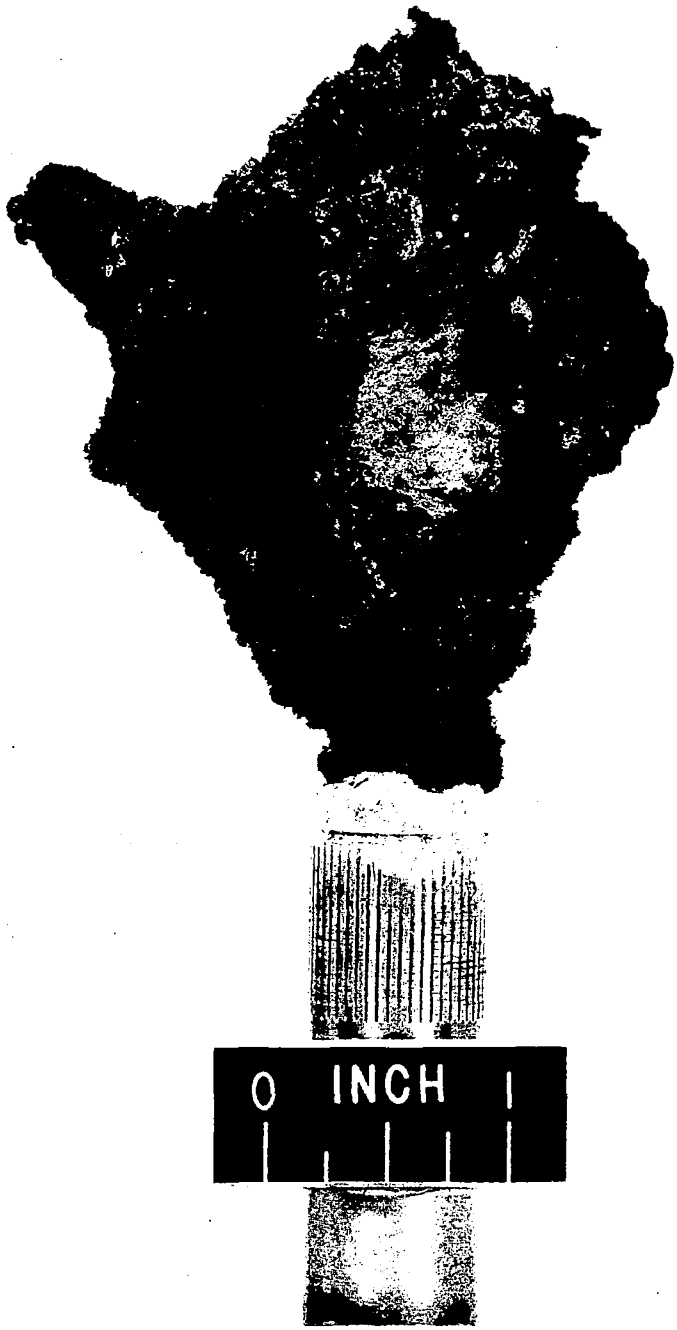

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Figure 19. - External decomposition deposit formed on injector 3 during 8.3-minute run on pentaborane fuel.

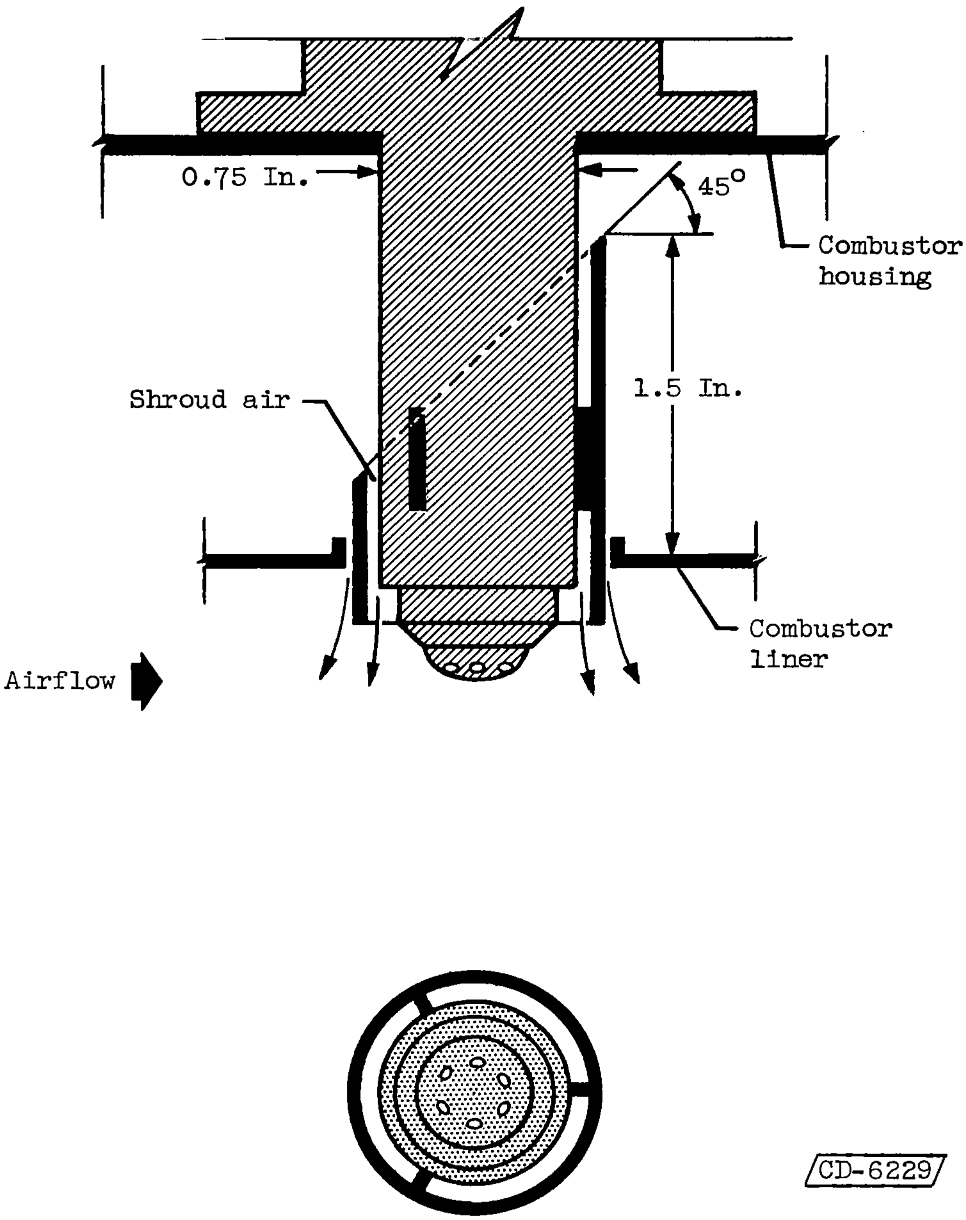

Figure 20. - Fuel injector 4.

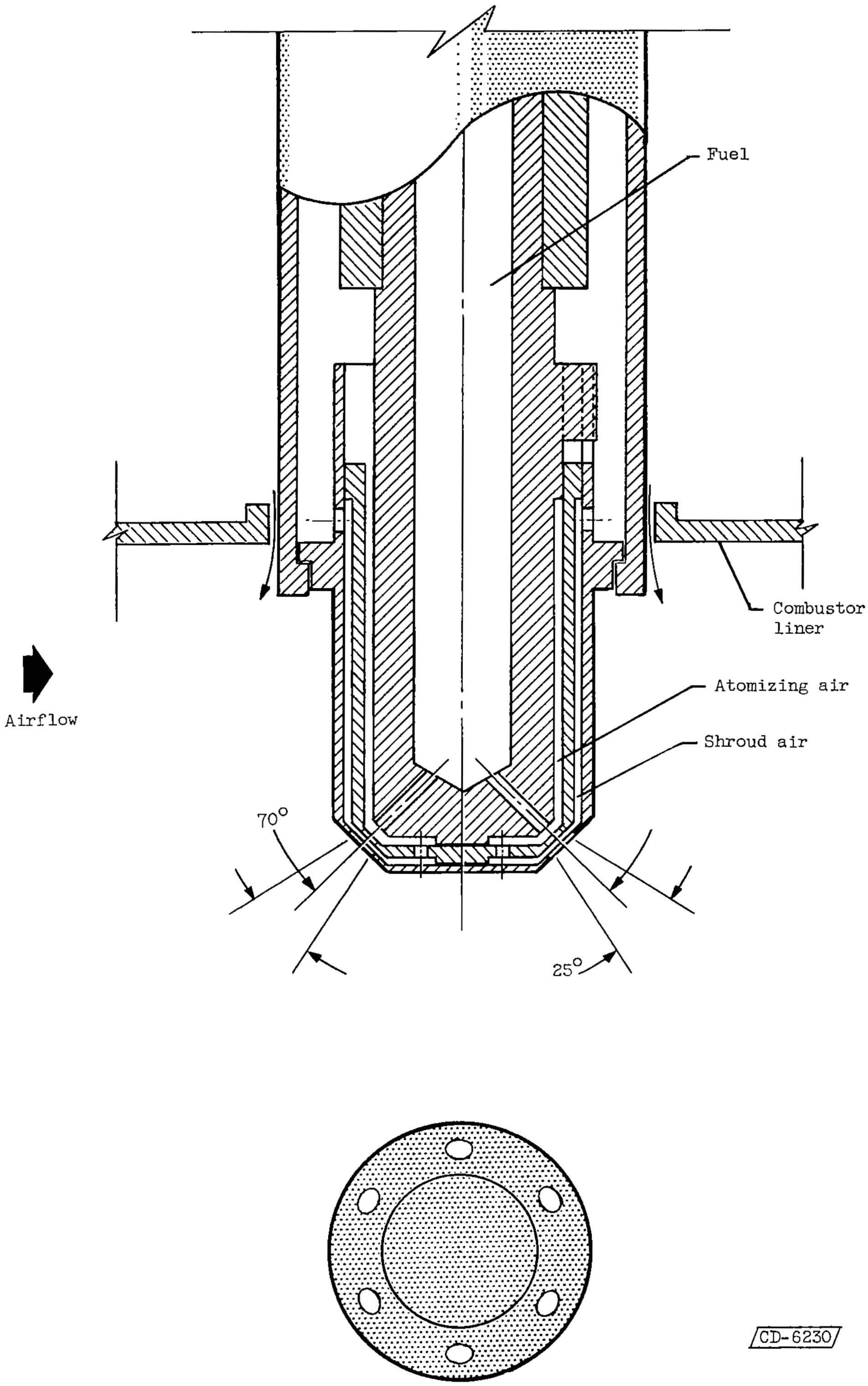

Figure 21. - Fuel injector 5.

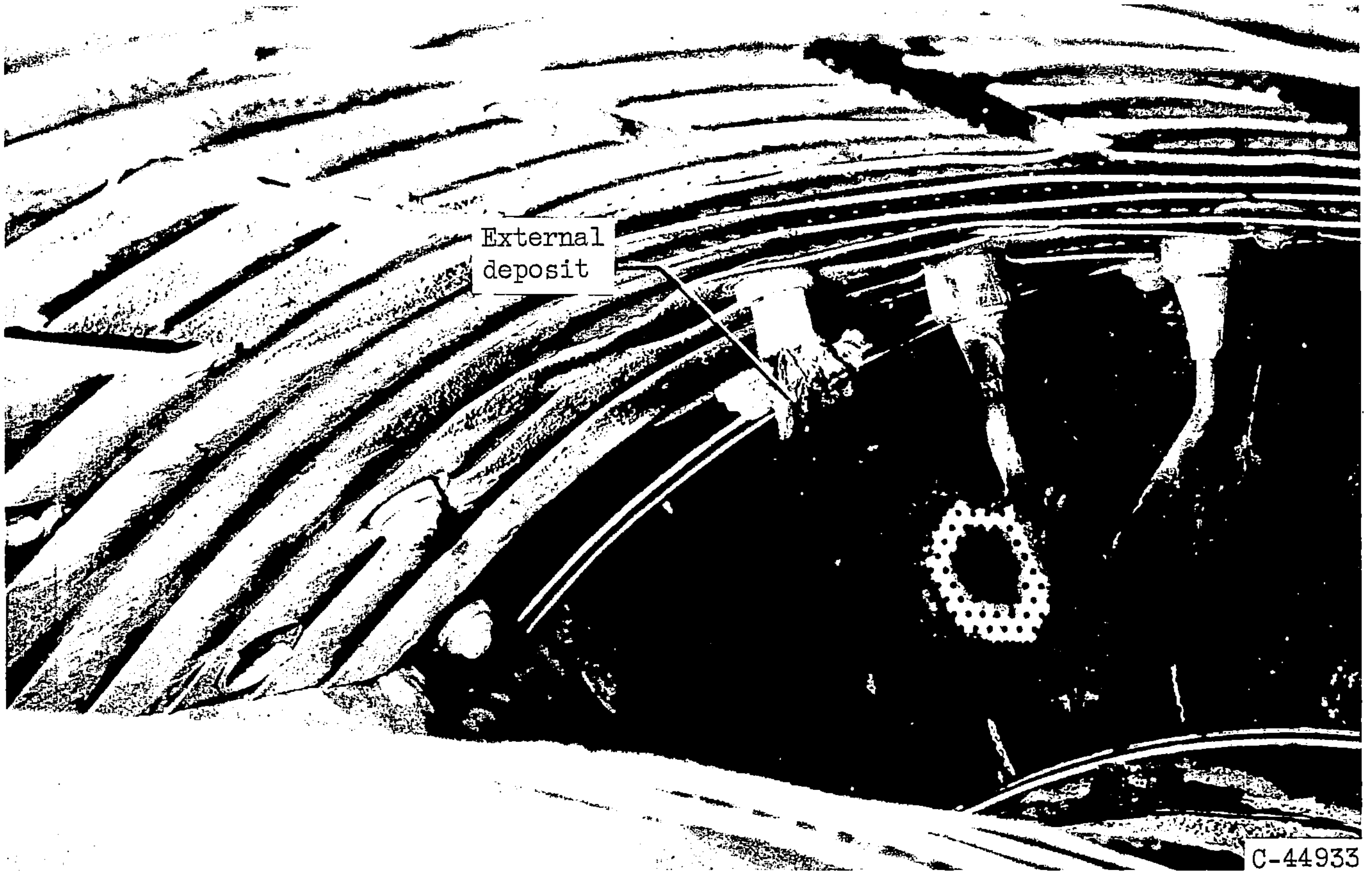

Figure 22. - External decomposition formed on injector 5 during 3.5-minute run on pentaborane fuel.

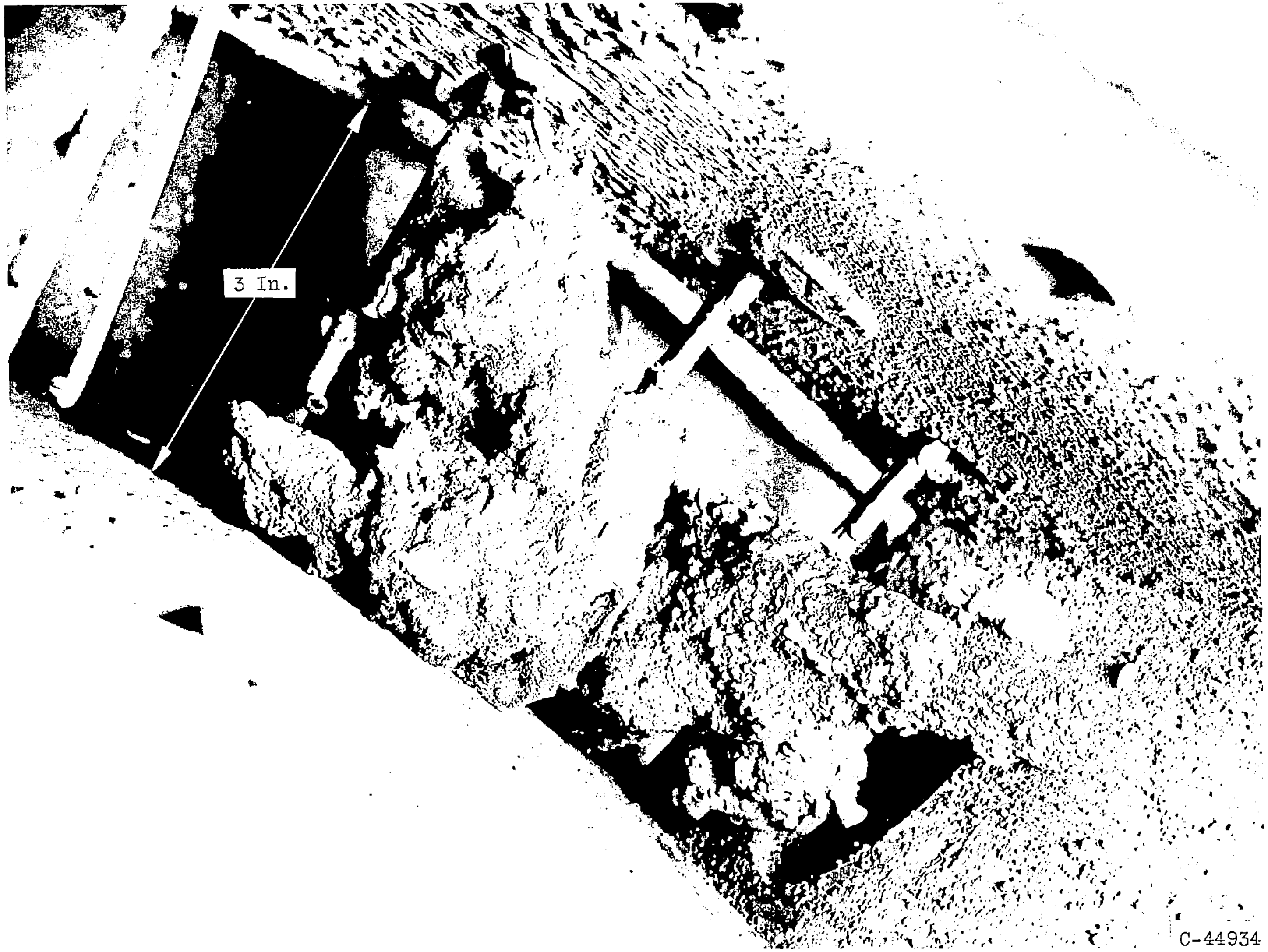

Figure 23. - Clinkers that formed on fuel injector 5 shown lodged against outlet thermocouple rakes.

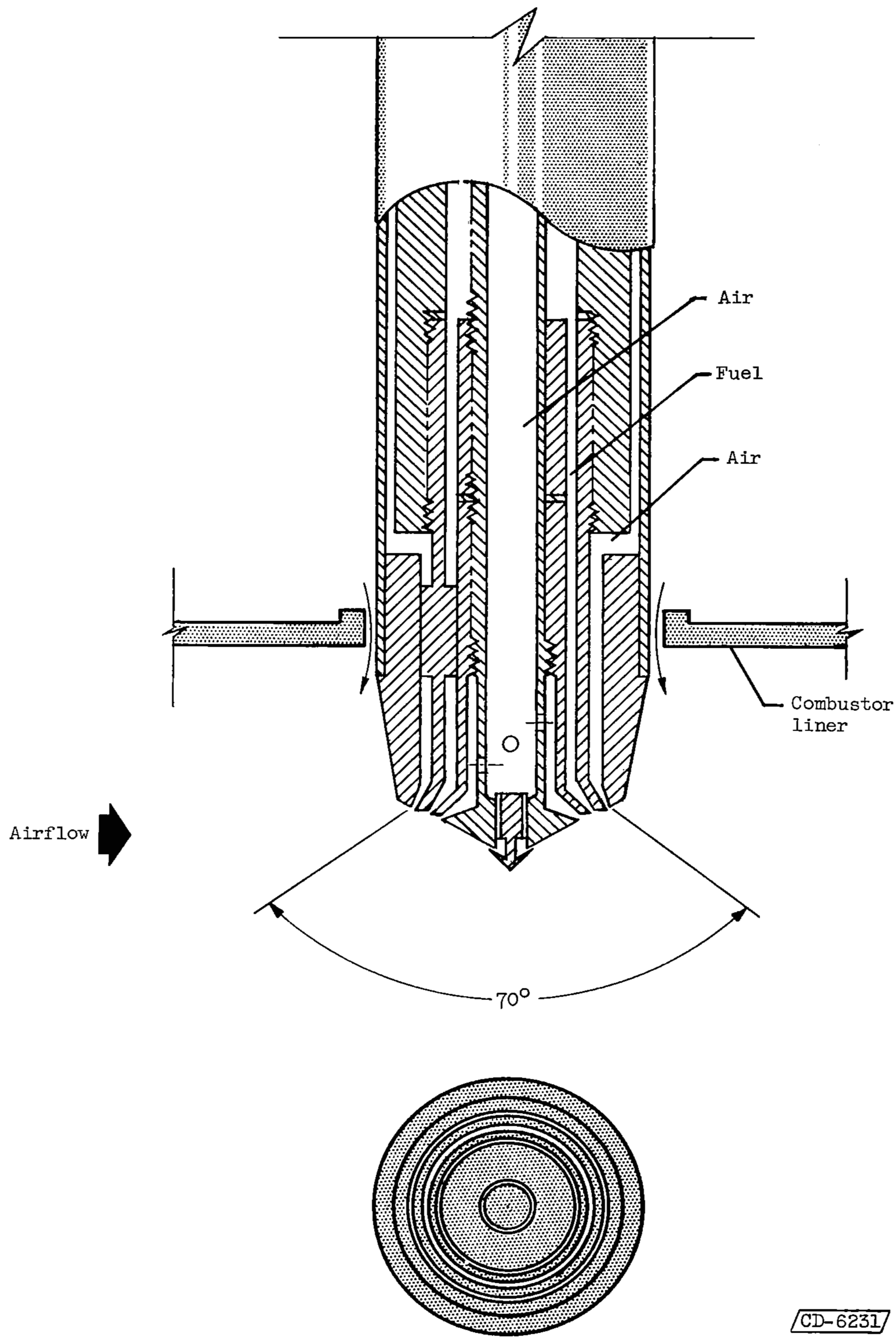

Figure 24. - Fuel injector 6.

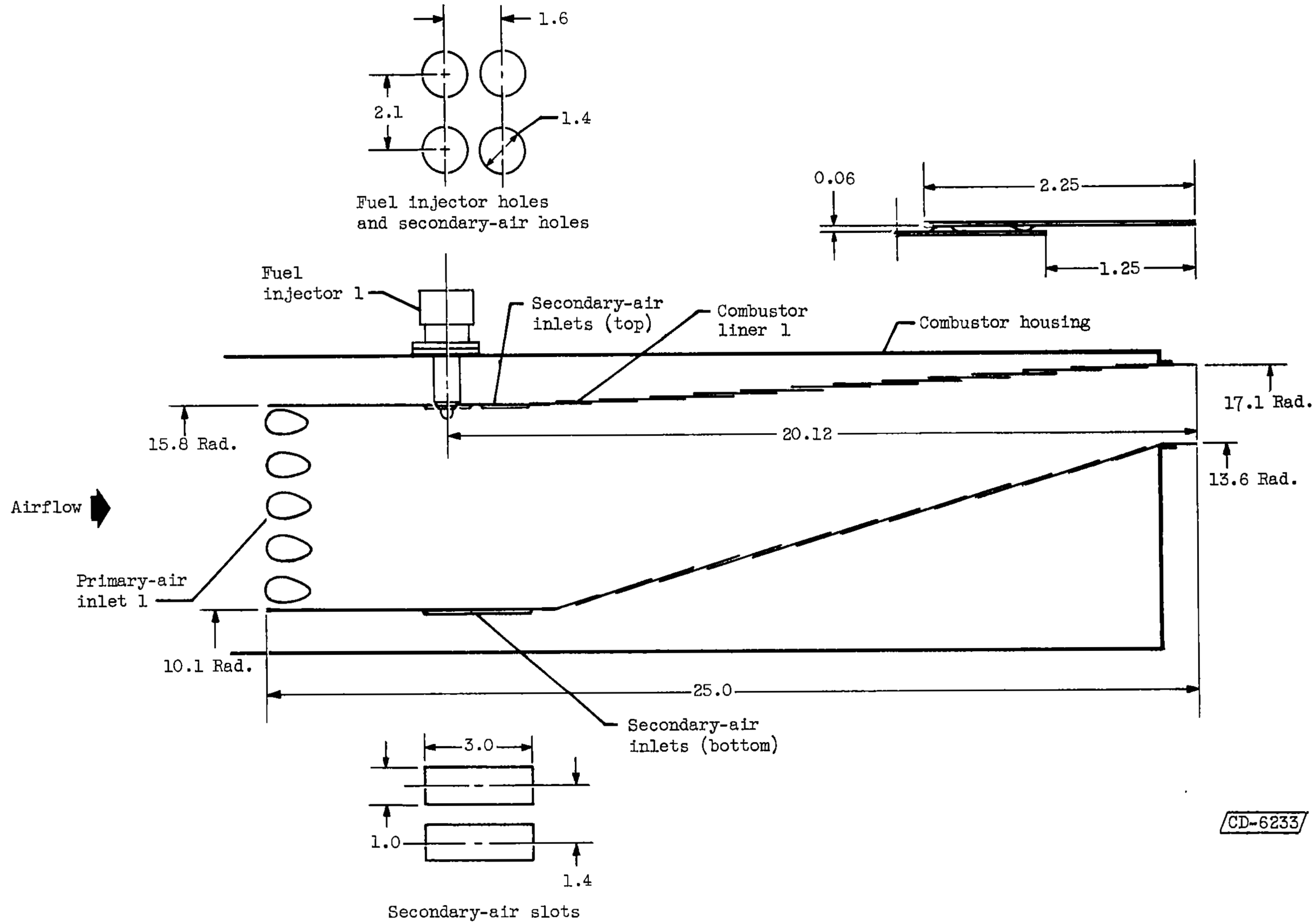

Figure 25. - Original quarter-sector configuration. (All dimensions in inches.)

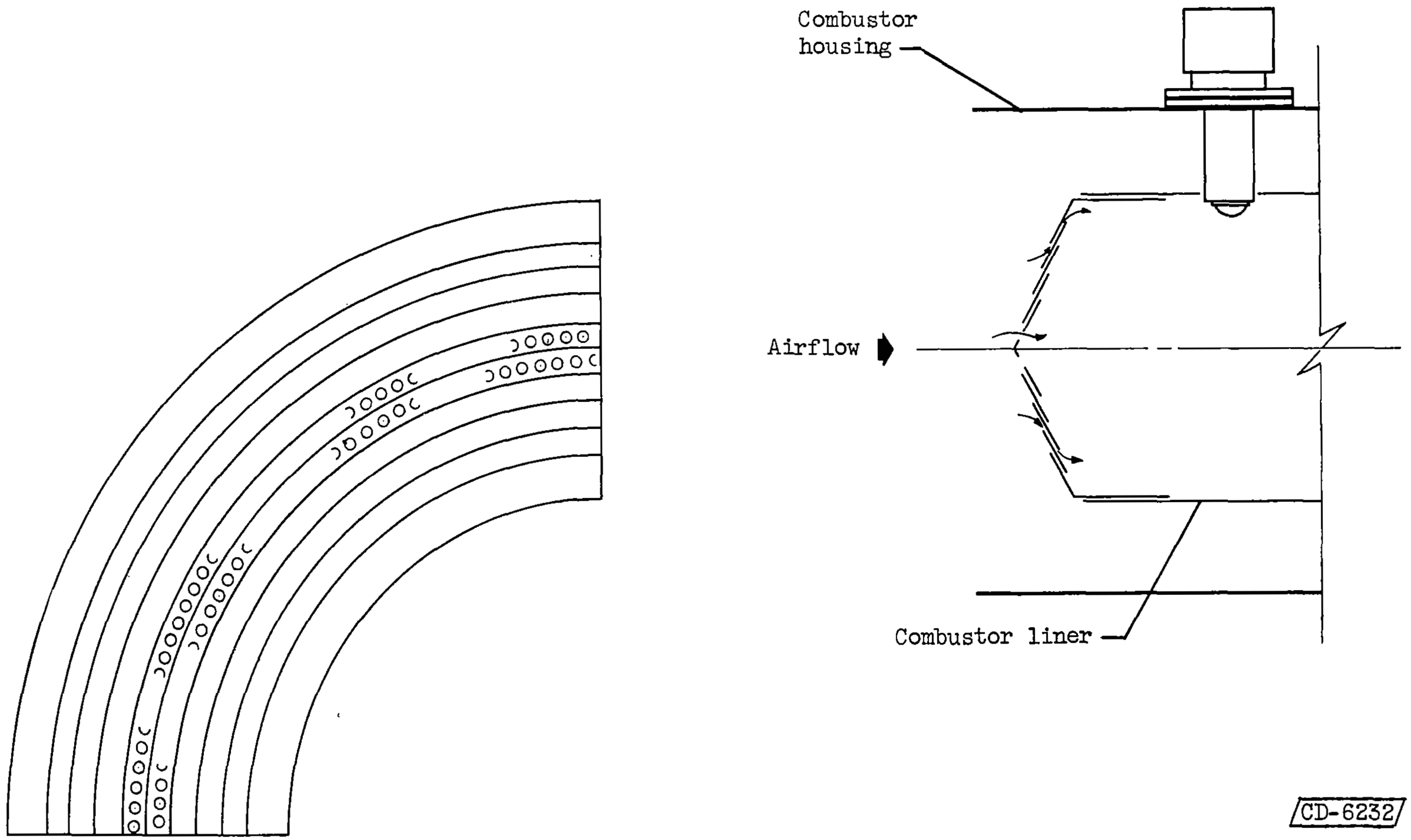

Figure 26. - Primary-air inlet 2.

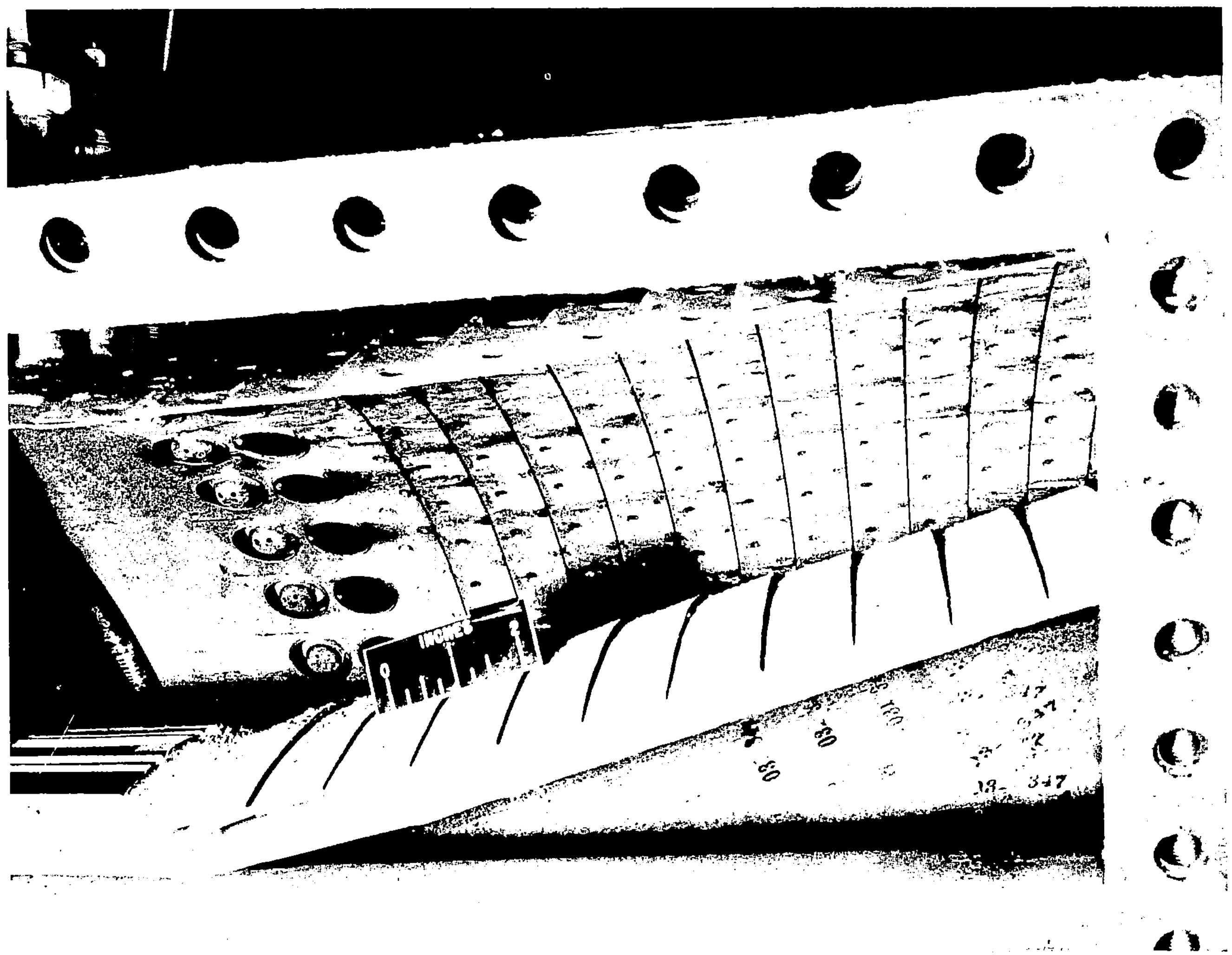

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Figure 27. - Deposits in combustor liner 1 after 3.5-minute run on pentaborane fuel.

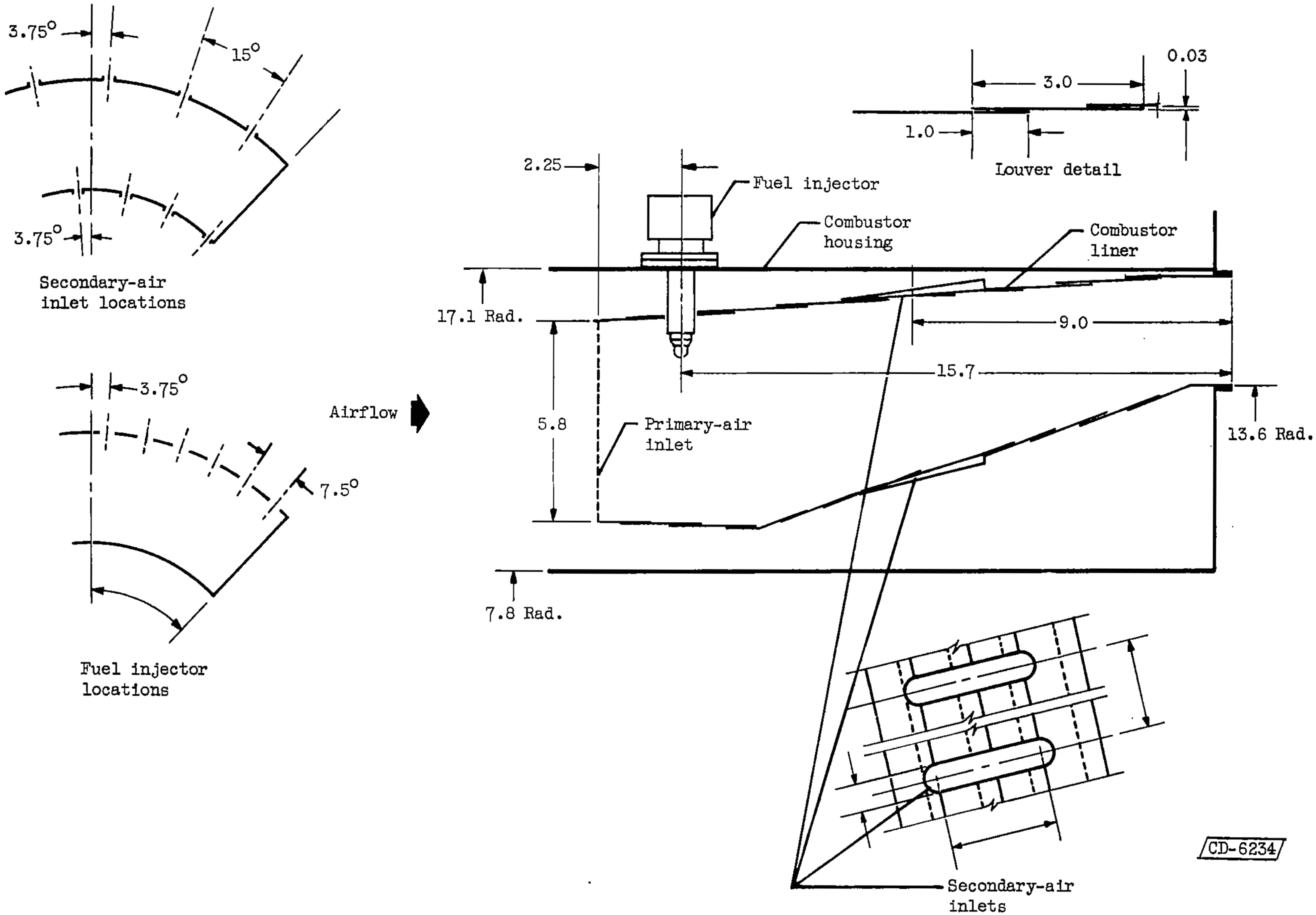

Figure 28. - Combustor liner 2. (All dimensions in inches.)

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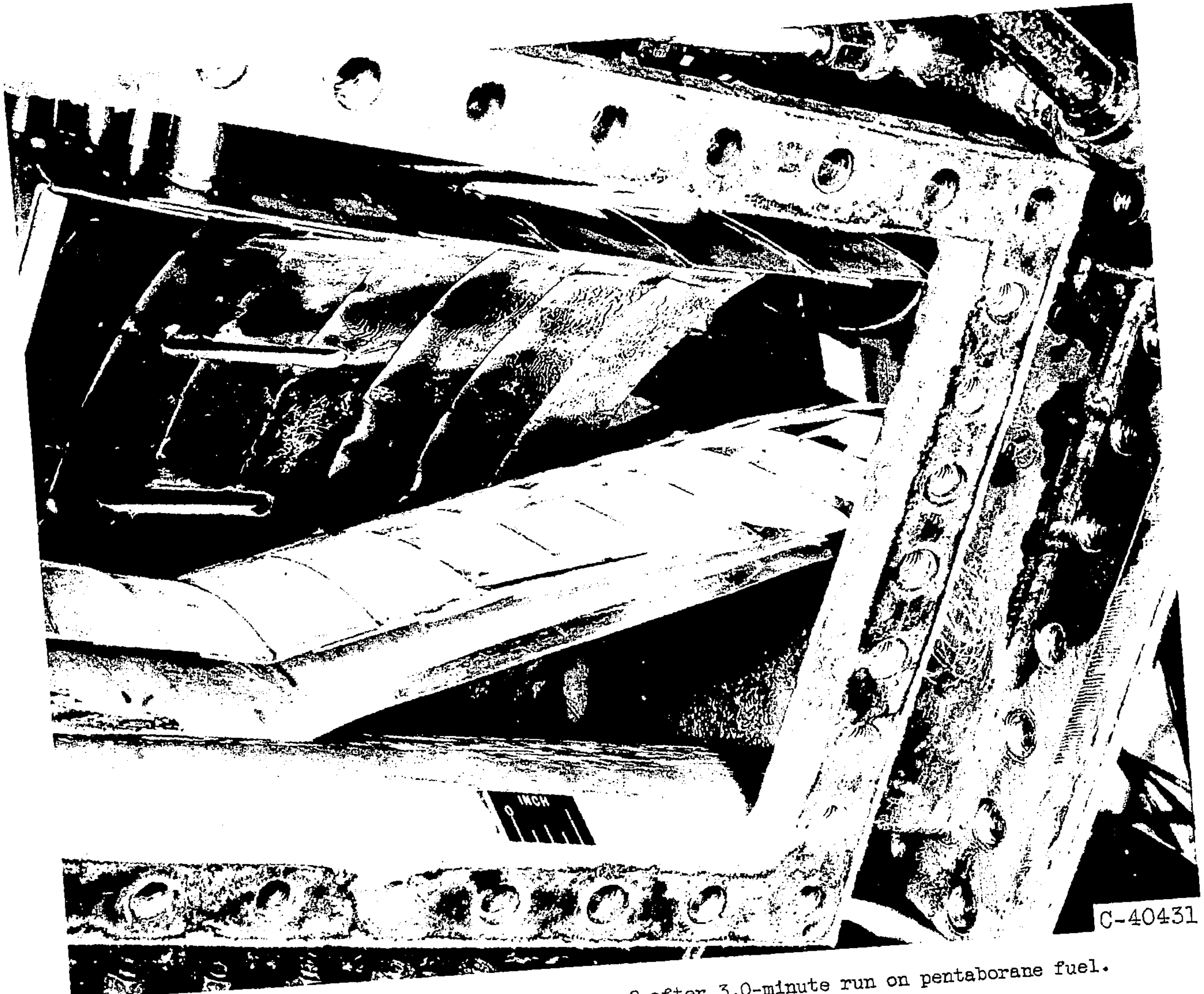

Figure 29. - Deposits in combustor liner 2 after 3.0-minute run on pentaborane fuel.

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