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RESEARCH MEMORANDUM

PRELIMINARY INVESTIGATION OF COMBUSTION OF DIBORANE IN A TURBOJET COMBUSTOR

By W. B. Kaufman, J. B. Gibbs
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Cleveland, Ohio

NATIONAL ADVISORY COMMITTEE
FOR AERONAUTICS

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SUMMARY

A preliminary investigation was conducted to determine the combustion characteristics of diborane in a turbojet combustor. A standard J33 combustor and five experimental combustors were investigated. Severe oxide deposits formed in the J33 combustor and on turbine stator blades at the combustor outlet. An experimental combustor was developed which gave satisfactory performance with diborane at the limited test conditions and short durations investigated. Three promising techniques were demonstrated for alleviating oxide deposits on turbine blades and other metal surfaces; namely, extreme cooling, heating, and filming the surfaces with air.

INTRODUCTION

The NACA Lewis laboratory is engaged in a study of special fuels for jet-propelled aircraft. Consideration is being given to those fuels which may increase flight range, thrust, and combustion stability beyond values attainable with conventional hydrocarbon fuels. These special fuels consist primarily of metals and metallic compounds, which produce metallic oxides on combustion. These metallic oxides exist in the liquid and solid states at the lower exhaust temperatures encountered during engine operation. Deposits are therefore likely to form on the metal parts downstream of the combustor. Because of the problem of oxide deposition, these special fuels have heretofore been used only in ram jets and turbojet afterburners where there are no rotating metal parts immersed in the combustor exhaust.

Diborane was evaluated as a ram-jet fuel in reference 1, and the flight range with diborane was estimated to be 30 to 50 percent above the range attainable with aviation gasoline. A comparable extension of flight range might be expected through the use of diborane in turbojet engines, but in the turbojet the oxide deposition would be much more severe. Results obtained with diborane in a turbojet combustor should indicate the extent of the oxide deposits to be expected with other metallic fuels. Reference 1 also reports spatial flame speeds for diborane-air mixtures as high as 169.5 feet per second, which is roughly 50 times the flame speed of paraffinic hydrocarbons. Because of its high flame speed, diborane would be expected to burn efficiently under conditions where ordinary hydrocarbon fuels are inadequate.

An experimental investigation of the combustion characteristics of diborane in a turbojet combustor was initiated at the request of the Bureau of Aeronautics, Department of the Navy. This report presents the preliminary results from this investigation, which were obtained from October to December, 1952, in a direct-connect duct investigation of a single tubular combustor. A combustor from a J33-A-23 turbojet engine was investigated, as well as five additional combustors obtained by using different liner configurations in the standard J33 combustor housing to reduce the oxide deposits. Data are presented on combustion efficiencies, combustor-outlet temperature profiles, and oxide deposits. Three different techniques that were tried for minimizing oxide deposits on metal surfaces immersed in the combustor exhaust are also described.

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FUEL

Source. - The diborane used in this investigation, obtained through the cooperation of the Bureau of Aeronautics, Department of the Navy, was approximately 95-percent diborane by volume, according to the supplier. The major impurities were probably ethane and ethyl ether.

Properties. - Values for several of the physical properties of pure diborane from reference 1 are as follows:

Formula	B_2H_6
Formula weight	27.7
Melting point, °F	-265
Boiling point, °F at 760 mm Hg	-134.5
Heat of combustion, Btu/lb	33,513
Heat of combustion, Btu/cu ft	935,220[a]
Stoichiometric fuel-air ratio	0.0669

[a]Specific gravity of liquid taken as 0.4470, the specific gravity at sea-level boiling temperature.

The melting points of the two forms of boron oxide, B_2O_3, are as follows:

Crystalline, °F	842
Vitreous, °F	1070

FUEL SYSTEM AND OPERATING PROCEDURE

The refrigerated fuel system is shown in figure 1. Chamber A served as a reservoir where methyl cellosolve was cooled by dry ice to -96° F. The coolant was circulated through chamber B and the jacketed fuel line and nozzle housing.

The refrigeration system was started several hours before test time. When the temperature in chamber B reached -96° F, one of the molybdenum steel shipping tanks containing 20 pounds of diborane was transferred from a storage depot (maintained at dry-ice temperatures) to chamber B. The tank was suspended in the coolant by a cantilever arm connected to a strain gage. Each diborane tank was fitted with a siphon extending to the bottom of the cylinder and a gas inlet at the cylinder top. Fuel was forced from the diborane tank by helium pressure, which was controlled by a remotely operated regulator. The helium pressure was preset and the fuel flow was started and stopped by a remotely controlled pressure-operated piston valve. The fuel-flow rate was governed by the applied helium pressure and by the size of the injection nozzle. The coolant flow to chamber B was reduced just before each test to eliminate flow forces on the fuel tank and strain gage. Coolant-bath density changes were insignificant during any run. Fuel lines were purged with helium before and after each run.

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Figure 2 shows the details of the diborane injection nozzle. A simplex hollow-cone pressure atomizer was used, and the nozzle size was varied according to the test condition being investigated so as to maintain a pressure of approximately 380 psi in the fuel system. Figure 2 shows the nozzle cooling system that was used during most of the tests reported herein. For a part of the investigation the nozzle and nozzle housing were streamlined by adding a layer of Plasticine (modeling clay) as indicated by the dashed-line contour in figure 2.

APPARATUS

Combustor installation. - A diagram of the combustor installation is presented in figure 3. Combustion air from the central laboratory supply was regulated by a remote-control valve. The combustor-inlet temperature was regulated without contamination by a heat exchanger. The combustion products were discharged into an exhaust plenum where they were cooled by water sprays and discharged through an atmospheric exhaust system. The major portion of the solid exhaust products and spray water was drained into a sludge trap, and from there the water was pumped into a settling pit.

Combustors. - A total of 6 combustors was investigated. They include a single tubular combustor from a J33-A-23 turbojet engine and five additional combustor models obtained by modifying the dome and liner of the J33 combustor to reduce the oxide deposits. Combustor models 1 through 5 are shown in figure 4. Details of the model 6 combustor are presented in figure 5.

Apparatus for oxide-deposit studies. - During the investigation two devices were used at the combustor outlet to obtain an indication of the oxide deposits to be expected on the turbine blades and other parts of the engine. The first of these devices consisted of two turbine stator blades from a J33 engine. These blades blocked 54 percent of the area of the outlet duct and produced sonic flow for the test conditions reported herein. 2820

The second device consisted of a bank of four 1/2-inch-diameter tubes extending across the combustor exhaust duct. Each of the tubes was designed differently to evaluate techniques for reducing turbine blade deposits. One tube was sealed on both ends so that its surface temperature would approach the temperature of the gas stream. The second tube was water-cooled. The third tube was heated above the gas-stream temperature by passing current from an electric-arc welder through the tube. The fourth tube was formed from porous wire cloth through which 80° F air was passed to provide a cool-air film surrounding the tube.

Instrumentation. - Air flow was metered by an A.S.M.E. orifice. The pressure upstream of the orifice, the combustor-inlet total pressure, and the fuel-tank pressure were indicated by calibrated gages. The orifice pressure differential and the pressure drop through the combustor were indicated by water-filled manometers.

The fuel weight was recorded continuously by means of a strain gage and an oscillograph. The fuel weighing system was calibrated immediately before each run. The fuel-flow rate was computed from the slope of the fuel weight-time curve.

Figure 6 shows the details of construction and the location of the 16 thermocouples at the combustor outlet. Single thermocouples were used to indicate combustor-inlet air temperature, fuel temperature near the injection nozzle, fuel coolant temperature, and the temperature of the tubes used to simulate the turbine blades. The more important temperatures were recorded at regular intervals during each test by self-balancing strip-chart potentiometers. Additional temperatures were manually recorded from the readings of indicating, self-balancing potentiometers.

PROCEDURE

Test conditions. - Three test conditions were investigated, as follows:

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Test condition	Combustor inlet total pressure, in. Hg abs	Combustor inlet temperature, °F	Air flow[a], lb/(sec)(sq ft)	Combustor temperature rise, °F	Simulated flight conditions[b]	
					Altitude, ft	Percent of rated rpm
A	34	230	7.44	810	------	---
B	34	268	6.32	680	40,000	85
C	34	368	5.30	1180	44,000	100

[a]Air flow per unit of maximum cross-sectional area of combustor housing.
[b]Simulating a flight Mach number of 0.6 in a typical turbojet having a 5.2:1 compressor pressure ratio at sea level and rated rpm.

Calculations. - Combustion efficiencies were computed from the following approximate relation:

$$\eta_b = \frac{\text{Equivalence ratio theoretically required for measured temperature rise}}{\text{Actual equivalence ratio}}$$

The data of reference 2 were used for these calculations.

The average combustor-outlet temperature was computed as the arithmetic mean of the 16 outlet thermocouple indications. No correction was made for radiation or velocity effects on the bare-wire thermocouples.

The total-pressure loss through the combustor and obstructions in the outlet duct was computed as the dimensionless ratio of the measured total-pressure drop ΔP to the calculated reference dynamic pressure q_r. The value of q_r was computed from the combustor-inlet density, the air-flow rate, and the maximum cross-sectional area of the combustor housing.

RESULTS AND DISCUSSION

The results of the tests with the 6 combustors are presented in table I. The exact test conditions are also listed in table I; these values did not check closely with the standard test conditions in all cases. Some of the more important results are discussed in the following paragraphs.

Model 1. - After 31.5 minutes operation at test condition A, the standard J33 combustor contained large oxide deposits in the dome and on the injection nozzle and some additional deposits on the liner walls; photographs of these deposits are shown in figure 7(a). The deposits on the nozzle, dome, and liner had a total weight of 716 grams. The large clinker in the dome was a glassy deposit; the other deposits were crystalline. The average combustor-outlet temperature ranged from 370° to 450° F during the test. These temperatures are considerably lower than the desired temperature for test condition A. The low outlet temperature resulted from a fuel-flow rate which was lower than the value anticipated for the particular injection nozzle and fuel-tank pressure used in the test. The low fuel flow was apparently caused by vapor lock and by solid deposits inside the injection nozzle; the nozzle was examined at the conclusion of the test and was found to be filled with a yellow solid. This deposit was probably a boron hydride polymer formed by thermal decomposition of diborane. The injection nozzle and a short length of the fuel line were not cooled on the model 1 combustor, and the minimum temperature of the diborane in the fuel line entering the combustor was -38° F during the test. With such high diborane temperatures vapor lock in the nozzle would be expected; vapor lock results in a marked decrease in fuel-flow rate and severe heating of the small quantity of fuel passing through the nozzle.

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The turbine stator blades, which were located at station C-C (fig. 4), were covered with the oxide deposits shown in figure 7(b). These deposits were crystalline and weighed 2.4 grams.

Model 2. - Combustor 2 had no dome, and a sleeve was inserted in the liner to block most of the air-entry holes and force the air to enter the liner at the open upstream end. During 5 minutes operation at test condition A only slight deposits were formed on the nozzle and on the liner walls as shown in figures 8(a) and (b); combustion was smooth. The performance of the model 2 combustor was therefore satisfactory except for the outlet temperature profile. The difference between the maximum and minimum readings on individual thermocouples at the combustor outlet was approximately 1000° F, and there was a severe hot core in the exhaust gases. The turbine blades located at station C-C were covered with a glassy deposit weighing 37 grams. These deposits are shown in figure 8(c). The fuel line and injection nozzle were cooled on model 2 and all subsequent models as shown in figure 2. The deposits in the nozzle reported for the model 1 combustor were not obtained with the cooled injection nozzle.

Model 3. - Combustor 3 represents a compromise between models 1 and 2 by which it was hoped to retain the good deposit characteristics of model 2 while restoring the uniform outlet temperature profile of model 1. The sleeve used with model 2 was drilled to provide additional liner air-entry holes, and the dome was installed again but with a $3\frac{3}{4}$-inch hole in the center of the dome. The oxide deposits in the combustor were again very slight, but the outlet temperature profile showed little or no improvement over that obtained with model 2.

Model 4. - Combustor 4 represents a compromise between models 1 and 3. The dome had a $3\frac{3}{8}$-inch hole in its center; the injection nozzle
2820 and its housing were streamlined by adding a layer of Plasticine as indicated in figure 2; and the sleeve was removed from the liner. After 5.5 minutes at test condition A the liner and dome contained deposits which were slightly heavier than those for models 2 and 3. The deposits on the nozzle were substantially reduced. The outlet temperature profile was somewhat improved over that of models 2 and 3. The profile was not considered satisfactory, however, as a hot core of gases was obtained with a maximum difference between individual thermocouple readings of 740° F.

Model 5. - The dome was replaced by a short truncated cone having a $2\frac{5}{8}$-inch-diameter opening at its upstream end. The standard liner was shortened by cutting off $1\frac{1}{4}$ inches at its upstream end. After 3.5 minutes operation at test condition A, a glassy deposit covered the walls of the cone. The deposits in the liner were about the same as those for model 4. The combined deposits in the cone and the liner weighed 71.3 grams. The outlet temperature profile was less uniform than with model 4.

The combustion efficiency of the model 5 combustor at test condition A was approximately 98 percent. This value was computed from the fuel-injector pressure differential and a knowledge of the pressure-flow characteristics of the fuel nozzle. The fuel-weighing tank system produced erroneous readings during the tests of models 1 through 5, so accurate values of combustion efficiency are not available for these combustors.

Model 6. - Combustor 6 was similar to the model 4 combustor which had produced the best over-all performance of the earlier designs. The hole in the center of the dome was reduced in size and a row of small holes was added to the dome (fig. 5). After 10.8 minutes at test condition B the combustor contained 61.8 grams of deposits in the liner and dome. After 11 minutes at test condition C the deposits weighed 193.4 grams. These deposits are shown in figure 9. The dome deposits consisted of a thin, continuous, glassy film covering the walls; the liner deposits contained both glassy and crystalline material.

After operation at condition B with an average outlet temperature below the melting point of B_2O_3, the thermocouple rakes at station C-C were covered with heavy crystalline deposits as shown in figure 10(a). After operation at condition C with an average outlet temperature above the melting point of B_2O_3, the outlet thermocouples showed no appreciable deposits (fig. 10(b)).

The tubes installed at station D-D to evaluate various techniques for alleviating turbine deposits are shown in figure 11. The tube on the left in figure 11 is the tube designed to operate at gas-stream temperature. 2820
The deposits on this tube were similar to those on the outlet thermocouples; heavy crystalline deposits were formed at condition B (fig. 11(a)), and no appreciable deposits were formed at condition C (fig. 11(b)).

The tube second from the left is the water-cooled tube which was free of deposits after operation at condition B (fig. 11(a)). Deposits probably formed on this tube and then spalled. Figure 11(b) shows an oxide layer just beginning to break away at the conclusion of operation at condition C. As a layer of low-conductivity oxide formed on this water-cooled tube, the inside surface of the oxide layer approached the water temperature and the outside surface approached the exhaust-gas temperature until the thermal gradient across the oxide layer became sufficient to cause spalling. If the solid particles resulting from this spalling are not so large as to damage the rotor blades, then extreme turbine cooling may be a feasible method for eliminating oxide deposits.

The third tube from the left in figure 11 was electrically heated to 1180° F during operation at condition B, and was covered with a thin glassy deposit (fig. 11(a)) which appears to be far less harmful than the deposits found on the unheated tube. This tube was heated to 1750° F during operation at condition C, and no appreciable deposits formed on the tube (fig. 11(b)).

The tube on the extreme right in figure 11 was formed of porous wire cloth through which 80° F air was passed. After operation at condition B the air-filmed portion of the tube was free of deposits (fig. 11(a)). At one end a heavy deposit was formed, but the tube was not porous near this end due to sealing of the pores during fabrication. During operation at condition C, however, this tube was covered with a heavy deposit (fig. 11(b)); the air flow through the pores was not adequate at this condition.

These data indicate three promising techniques for eliminating severe oxide deposits on turbine blades and other metal parts. The three methods are: (1) extreme cooling; (2) heating; and (3) filming the surfaces with air.

The over-all pressure drop through the combustor and the thermocouples and tubes in the downstream duct is plotted against time in figure 12. The oxide deposits were accumulating throughout the operation at condition B, but had apparently reached an equilibrium level during operation at condition C.

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The combustion efficiencies computed for the model 6 combustor at test conditions B and C were approximately 105 and 96 percent, respectively. The high value presumably resulted from continued malfunctioning of the fuel-weighing tank system, although considerable improvement had been made in the system.

The outlet temperature profiles at the two test conditions are presented in figure 13. The temperature profiles were more uniform than those obtained with models 2 through 5. The maximum difference between individual thermocouple readings was 168° F at condition B and 610° F at condition C. These temperature profiles are very similar to those obtained with production-model combustors.

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SUMMARY OF RESULTS

The results obtained in the investigation of diborane fuel in a standard J33 combustor and five experimental combustors are summarized as follows:

1. Severe oxide deposits formed in the standard J33 combustor and on turbine stator blades at the combustor outlet.

2. An experimental combustor was developed which gave satisfactory performance with diborane for the limited test conditions and short durations investigated. The deposits in the combustor consisted of thin layers of oxide on the walls and did not obstruct the air-entry holes. The combustor-outlet temperature profile was similar to that obtained with production-model combustors. The combustion efficiencies were approximately 100 percent.

3. Three promising techniques were demonstrated for alleviating oxide deposits on turbine blades and other metal surfaces; namely, extreme cooling, heating, and filming the surfaces with air.

Lewis Flight Propulsion Laboratory
National Advisory Committee for Aeronautics
Cleveland, Ohio, December 15, 1952

REFERENCES

1. Gammon, Benson E., Genco, Russell S., and Gerstein, Melvin: A Preliminary Experimental and Analytical Evaluation of Diborane as a Ram-Jet Fuel. NACA RM E50J04, 1950.

2. Gammon, Benson E.: Preliminary Evaluation of the Air and Fuel Specific-Impulse Characteristics of Several Potential Ram-Jet Fuels. III - Diborane, Pentaborane, Boron, and Boron - Octene-1 Slurries. NACA RM E51D25, 1951.

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TABLE I - OPERATING CONDITIONS AND RESULTS

Combustor model	Fuel nozzle nominal size, gal/hr	Fuel nozzle spray angle, deg	Test condition	Combustor inlet temperature, °F	Combustor inlet total pressure, in. Hg abs	Air flow, lb/(sec)(sq ft)	Fuel flow, lb/sec	Equivalence ratio	Combustor temperature rise, °F	Combustor efficiency, percent	Fuel injector pressure differential, lb/sq in.	Combustor velocity, ft/sec	Duration of operation, min	Weight of deposits (liner + dome), g	Time at which data was recorded, min	Average combustor outlet temperature, °F	Maximum individual outlet temperature, °F	Minimum individual outlet temperature, °F
1	6.0	80	A	245	40.5	7.59	------	------	185	---	400	104	31.5	716	15	430	----	----
2	7.5	80	A	244	46.3	7.40	------	------	1028	---	380	87	5.0	< 50	3	1273	1715	680
3	7.5	45	A	234	46.5	7.48	------	------	916	---	400	87	4.5	< 50	1.5	1150	1365	710
3	7.5	45	A	239	34.4	7.44	------	------	881	---	380	114	3.5	< 50	2	1120	1670	670
4	7.5	45	A	239	49.2	7.33	------	------	722	---	380	78	6.5	< 50	3	961	1400	660
5	7.5	80	A	240	35.1	7.48	0.0204	0.152	1115	98	380	113	3.5	71	2	1355	1810	820
6	4.0	60	B	275	34.8	6.26	.0040	.0558	324	105	350	104	10.6	61.8	3	587	690	522
6	6.0	60	C	370	35.2	5.54	.0141	.142	1014	98	560	99	11.0	193.4	7	1384	1742	1132

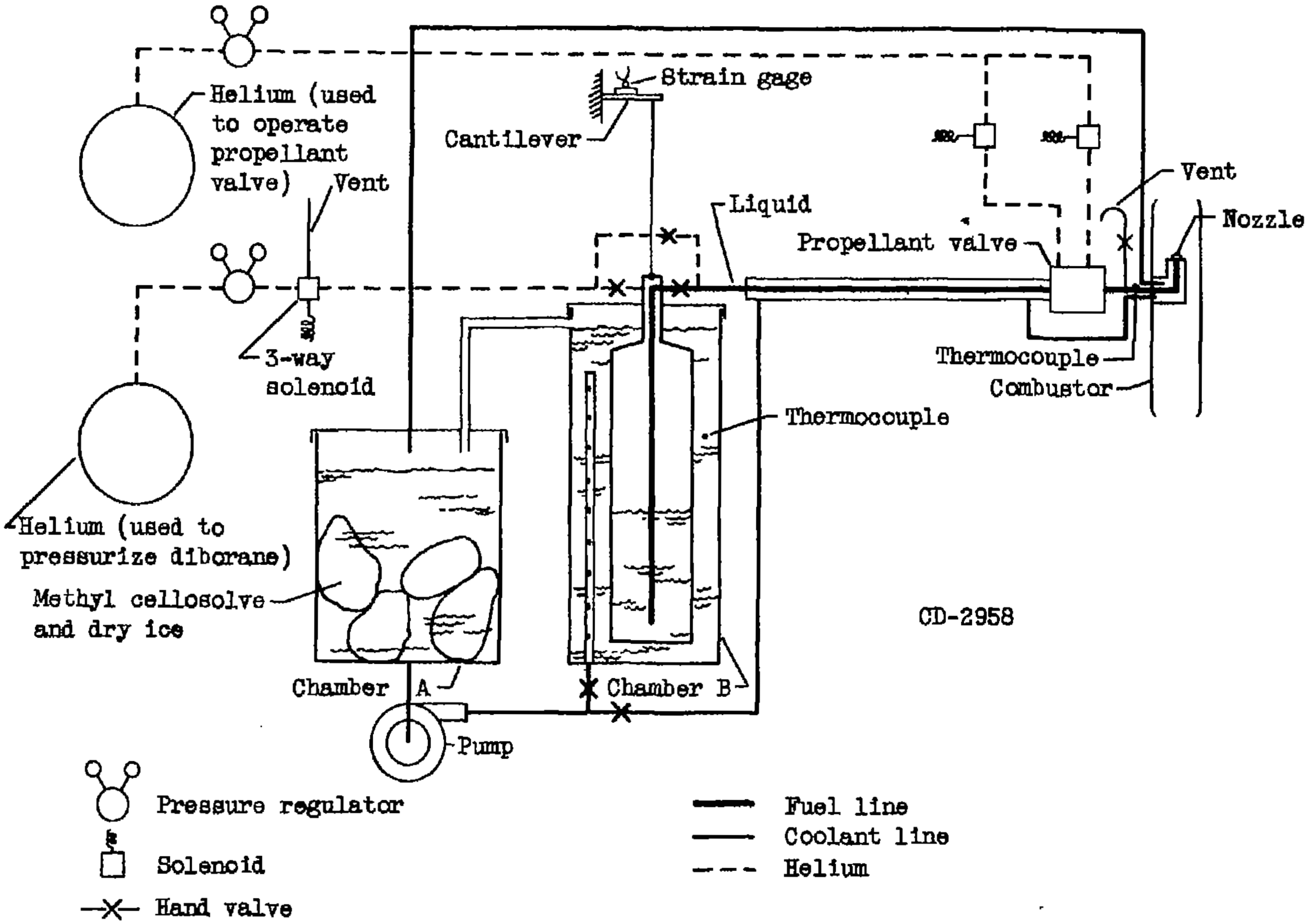

Figure 1. - Fuel system.

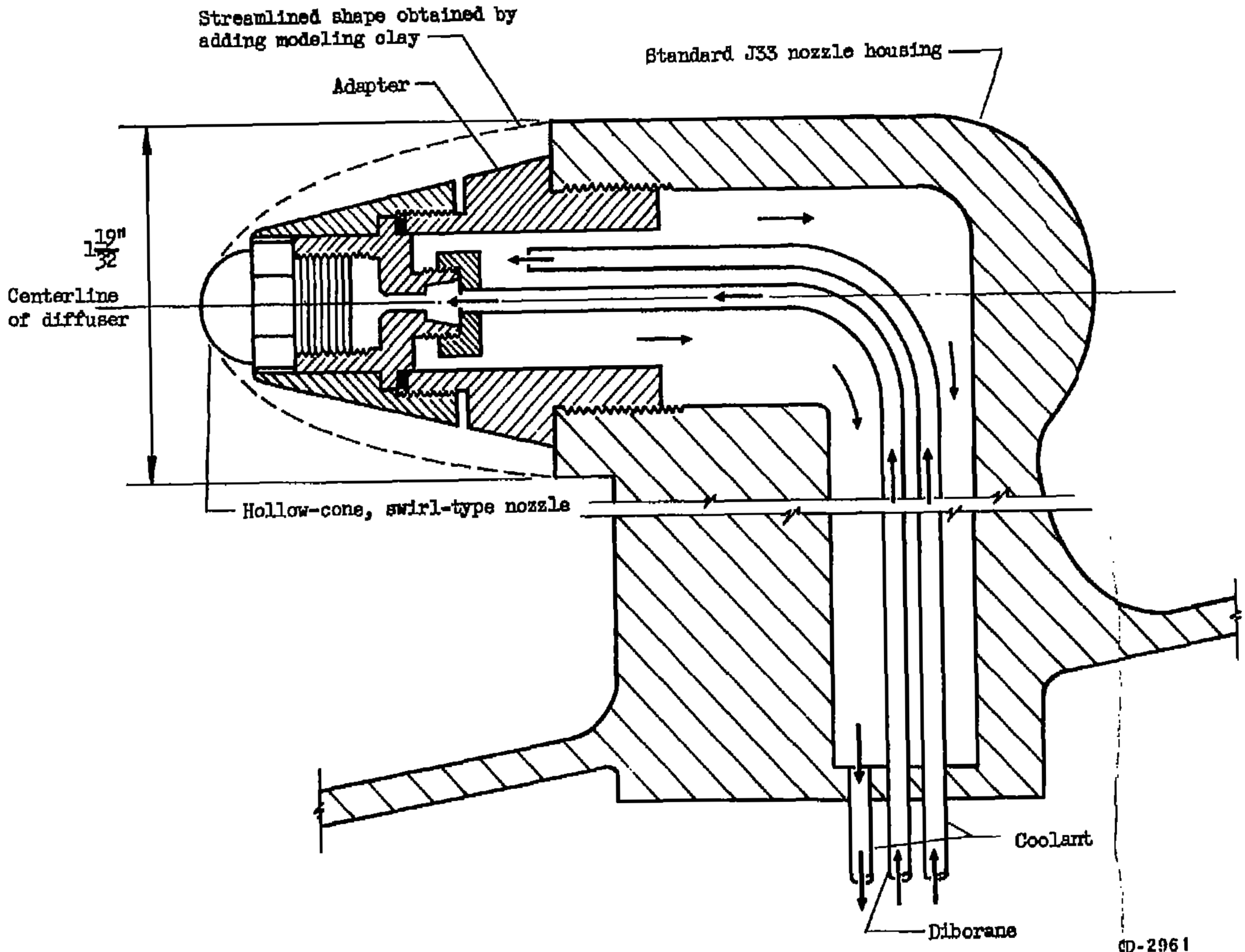

Figure 2. - Diborane injection nozzle.

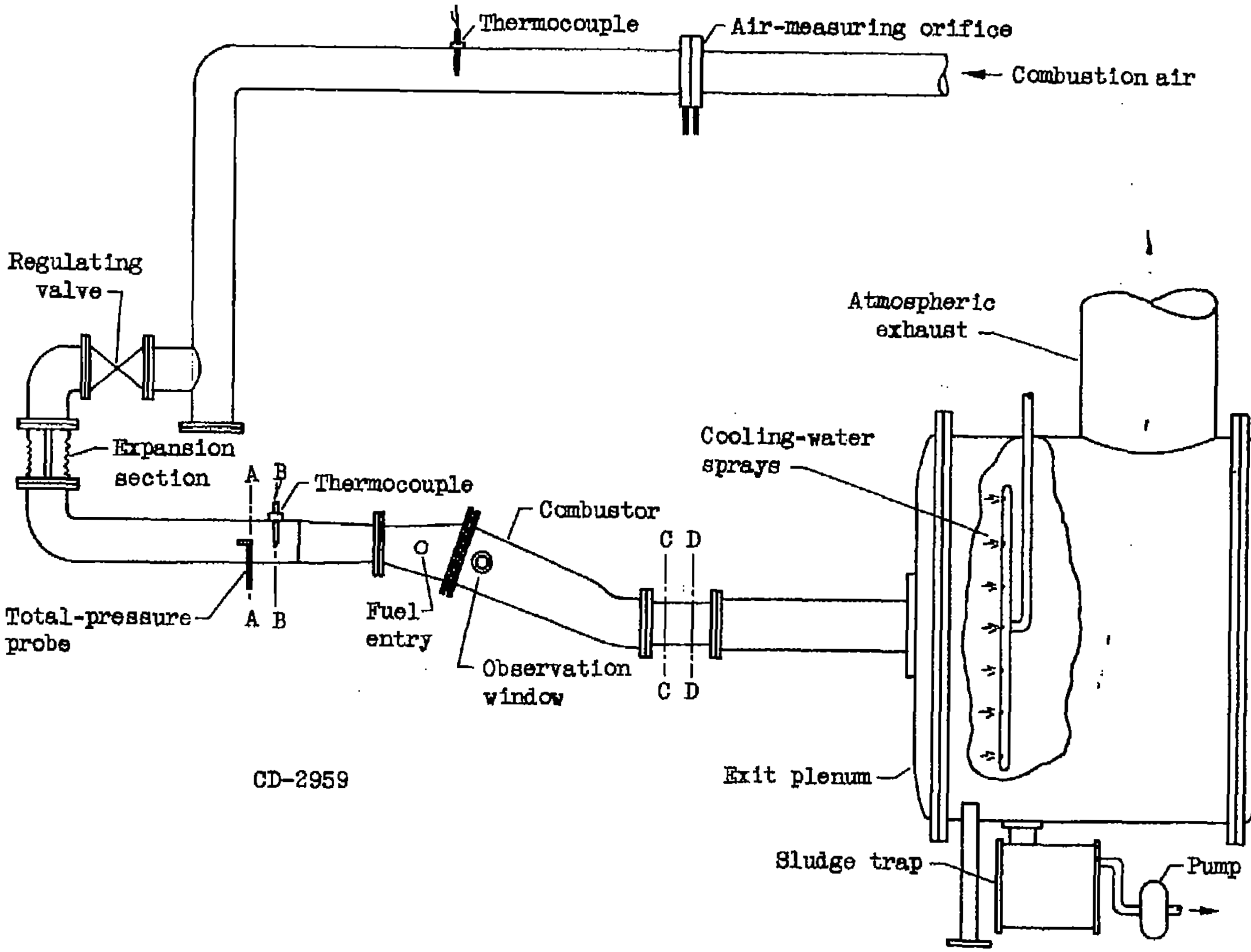

Figure 3. - Combustor installation.

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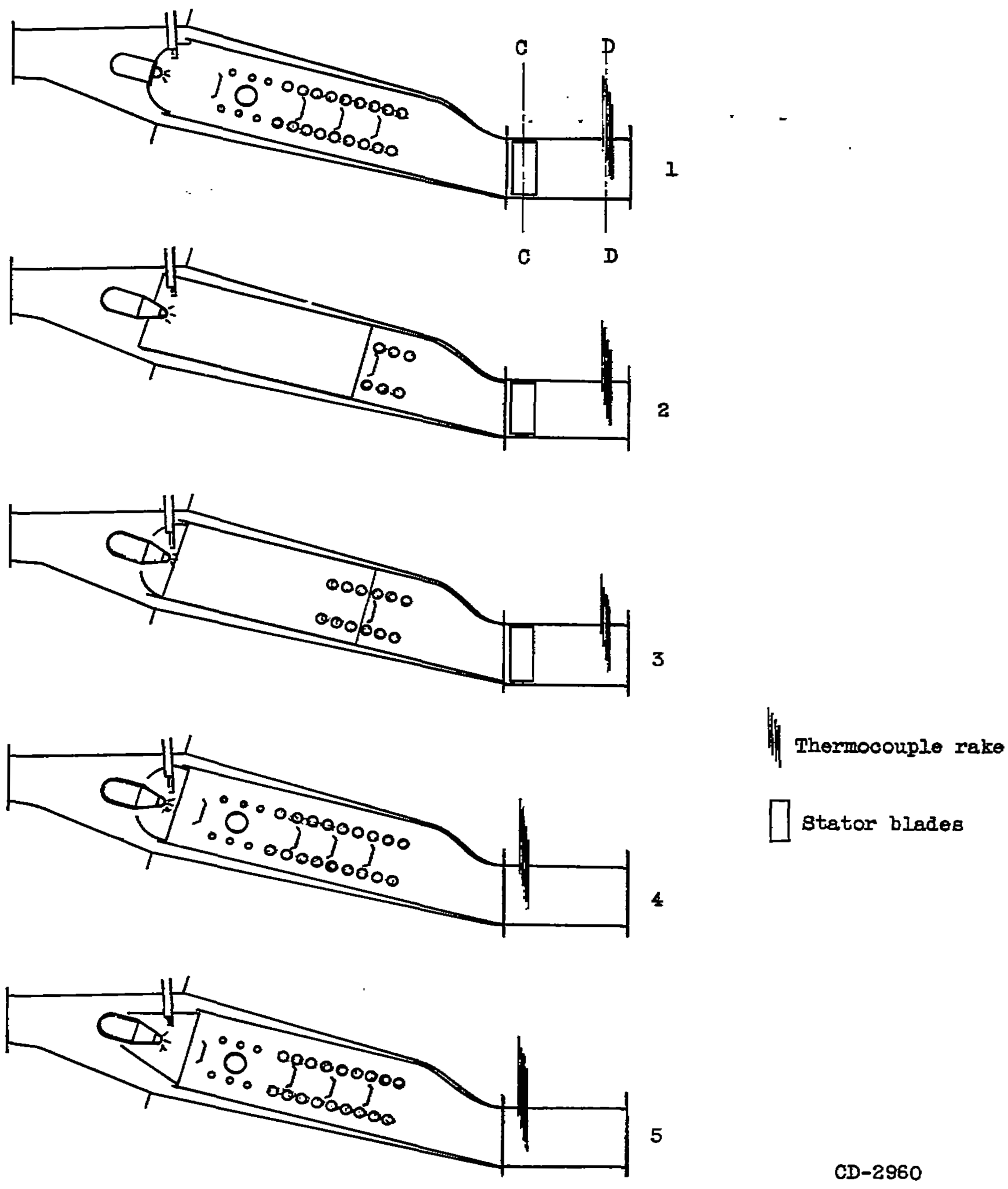

Figure 4. - Combustors.

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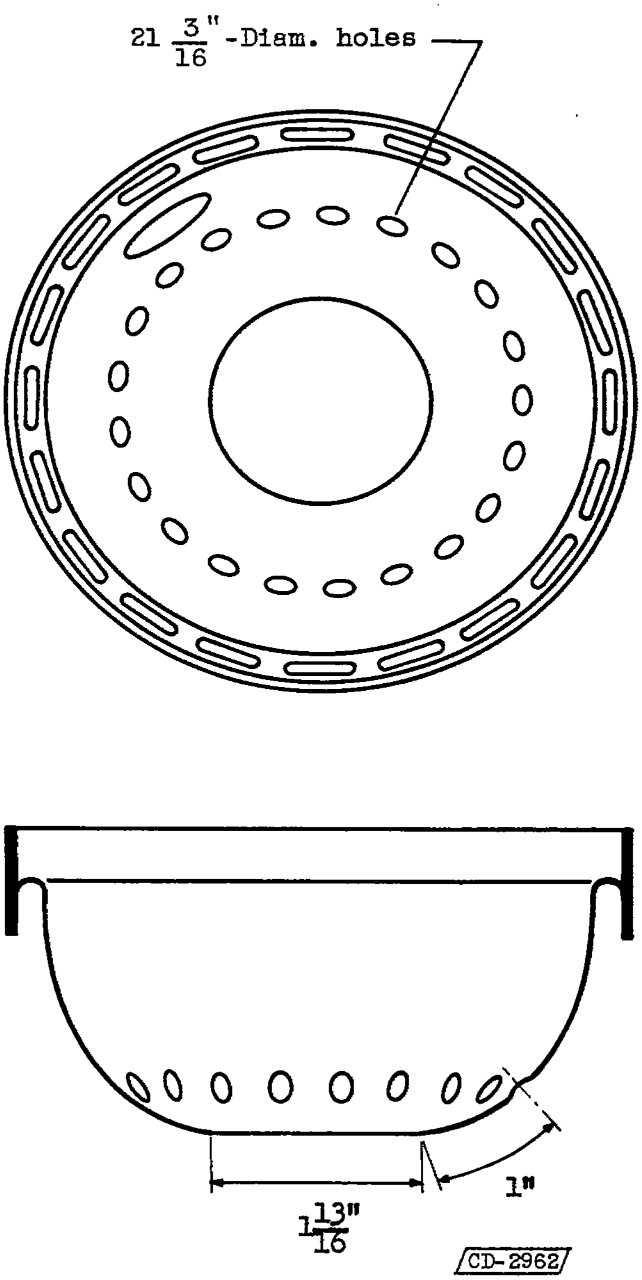

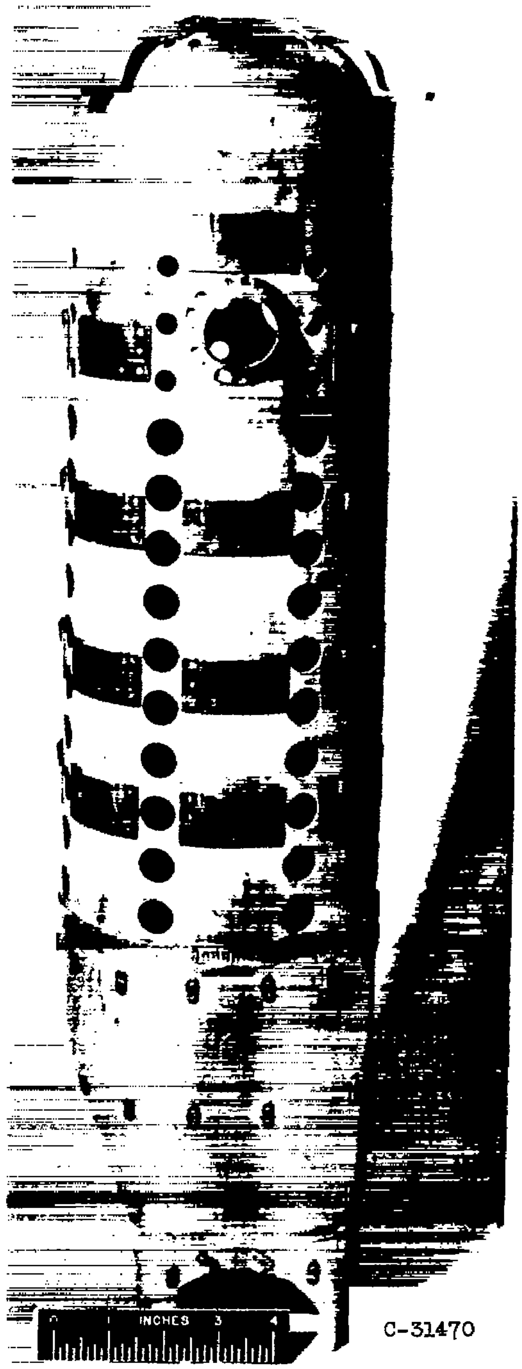

(a) Dome. (b) Photograph of dome and liner assembly.

Figure 5. - Details of model 6 combustor.

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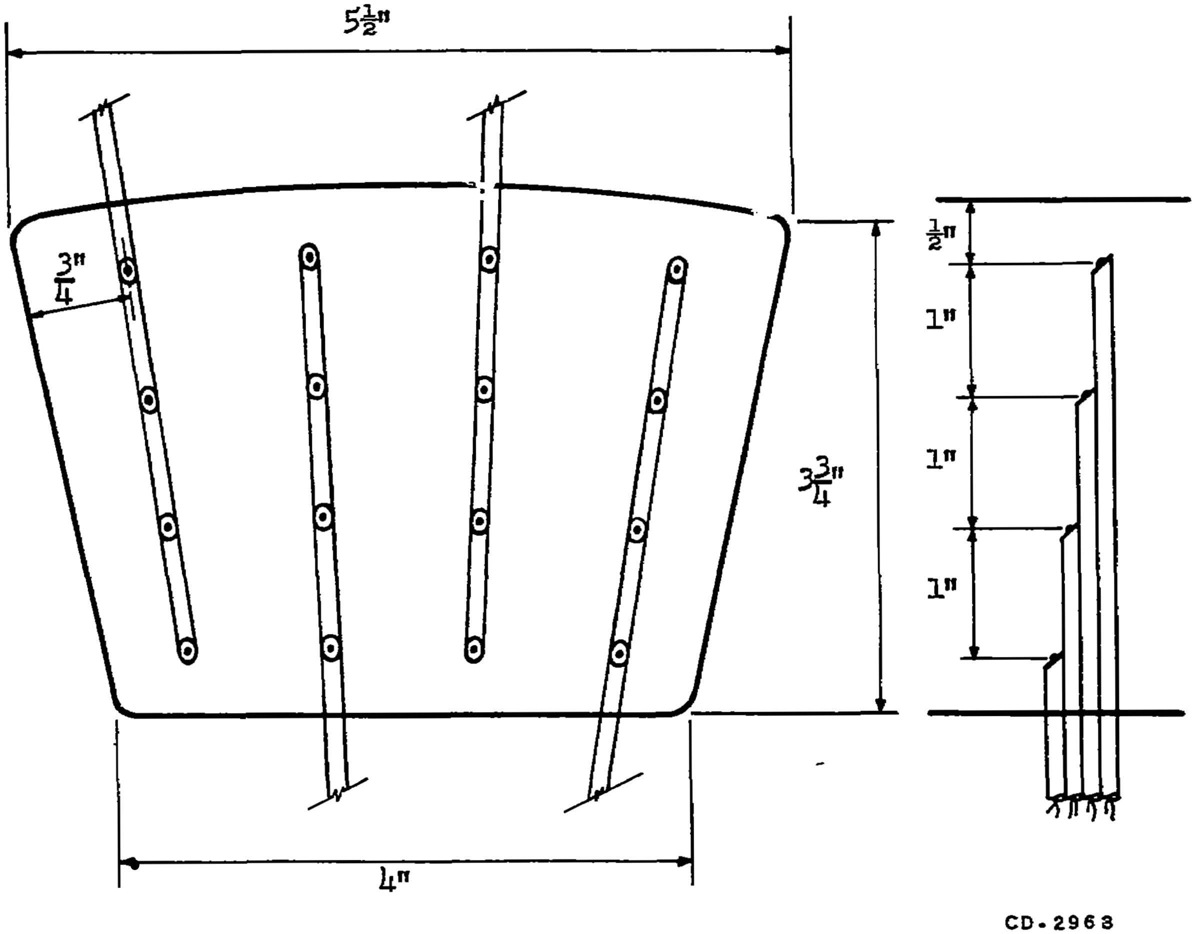

Figure 6. - Combustor-outlet instrumentation.

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(a) Liner and dome.

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(b) Blades.

Figure 7. - Deposits with model 1 combustor.

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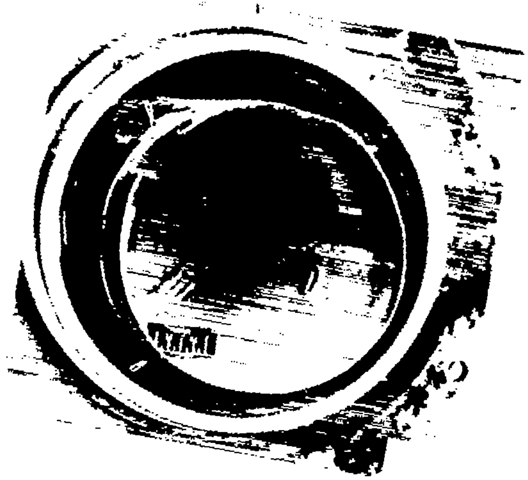

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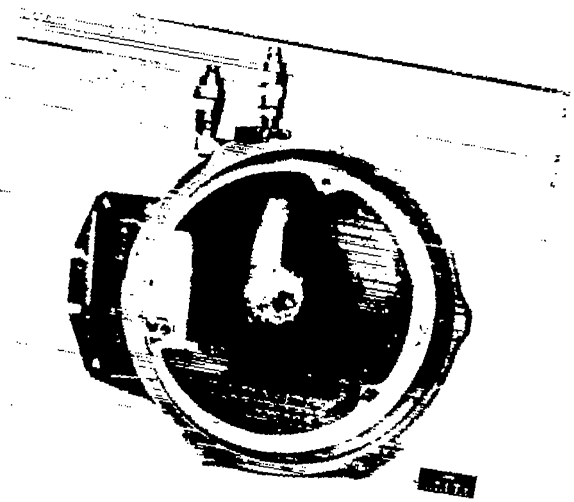
(a) Liner.



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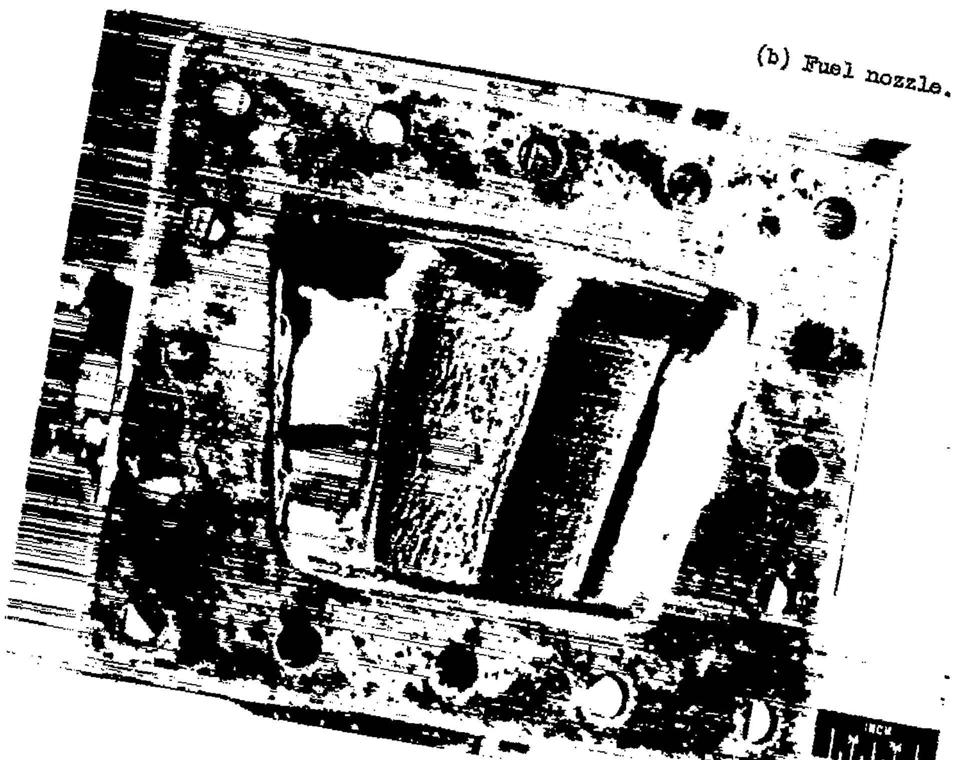
(b) Fuel nozzle.



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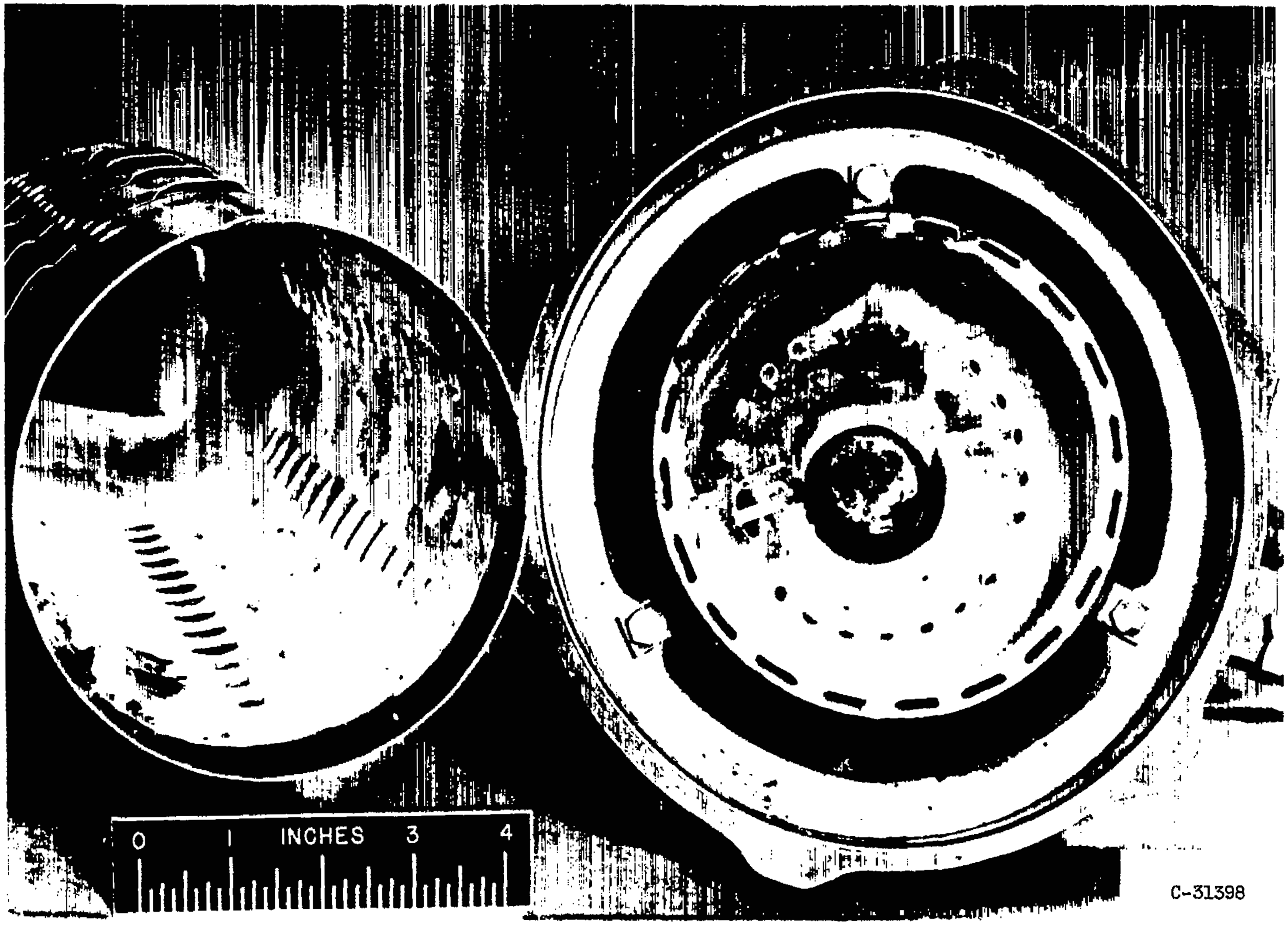
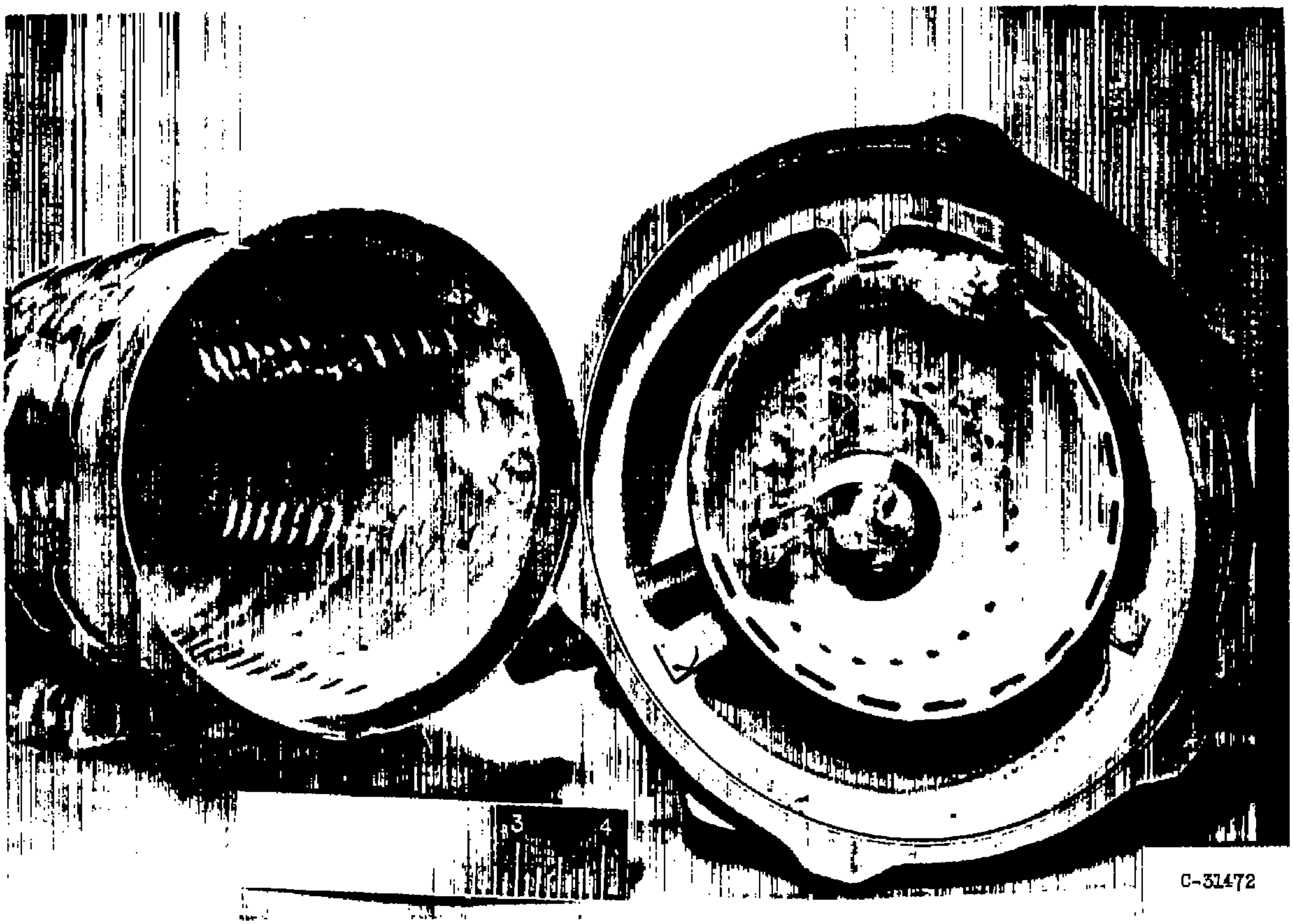
(c) Blades.

Figure 8. - Deposits with model 2 combustor.



(a) After 10.8 minutes at test condition B.

Figure 9. - Deposits on liner and dome of model 6 combustor.



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(b) After 11.0 minutes at test condition C.

Figure 9. - Concluded. Deposits on liner and dome of model 6 combustor.

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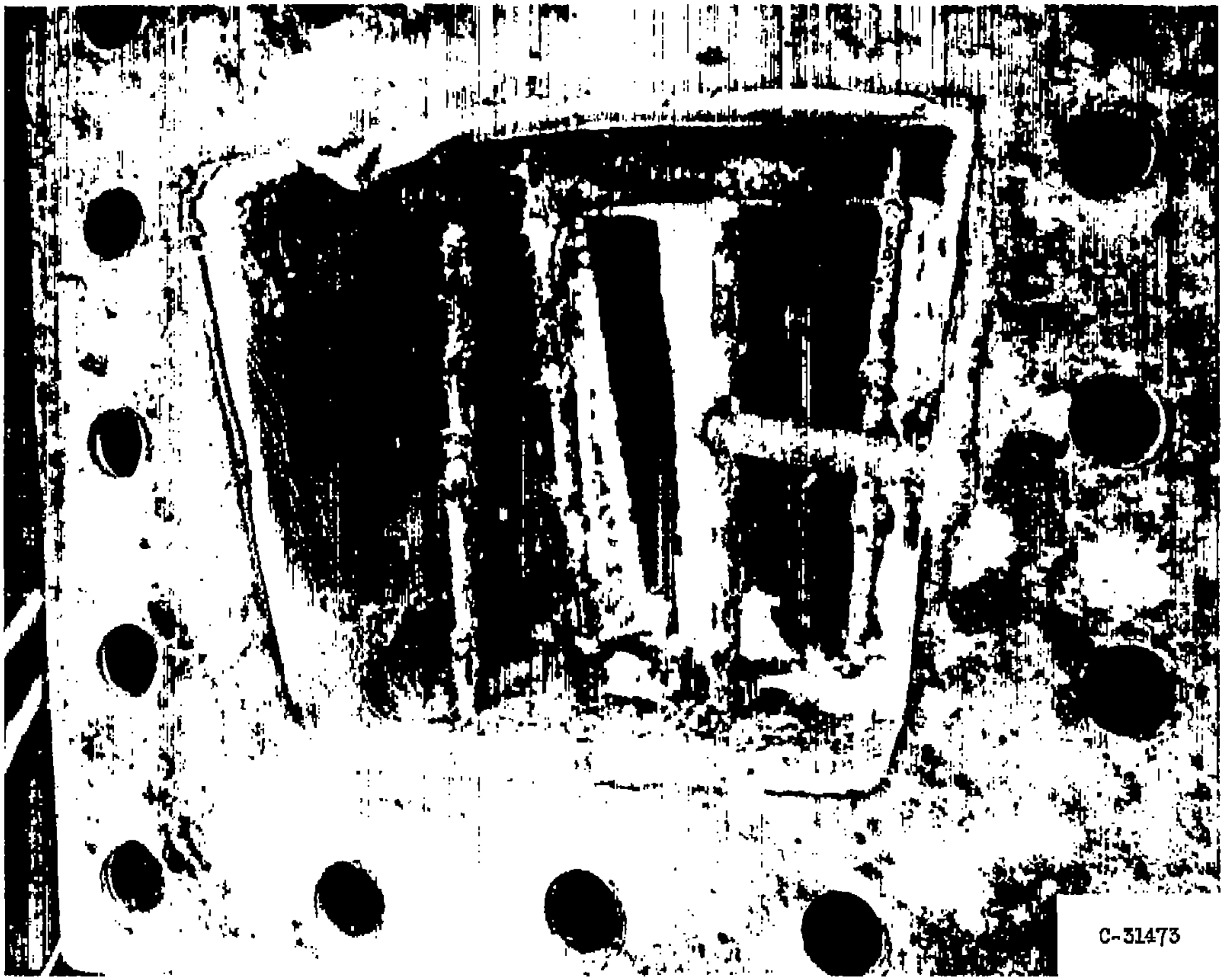
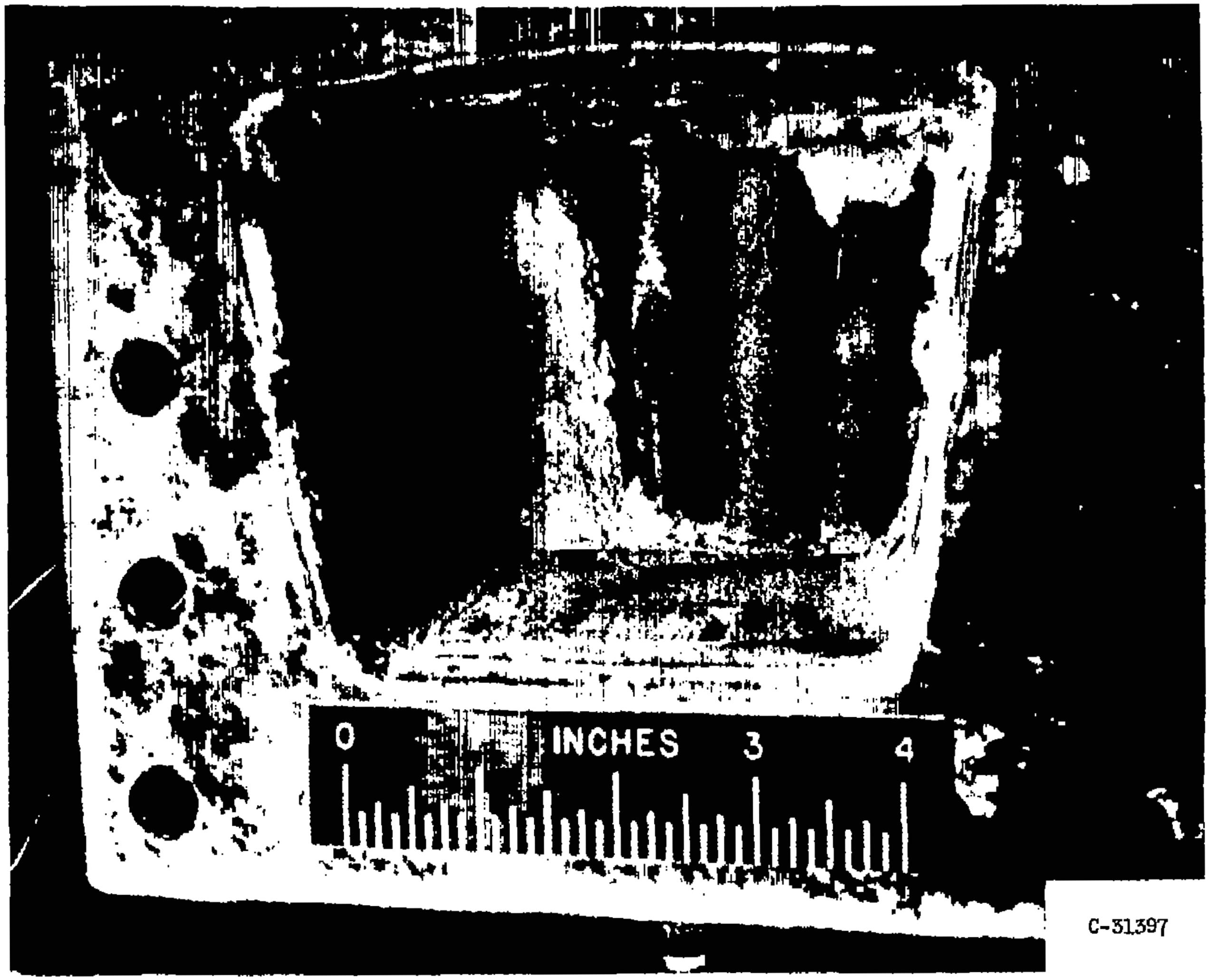
(a) After 10.8 minutes at test condition B.

Figure 10. - Deposits on the outlet thermocouples of model 8 combustor.



(b) After 11.0 minutes at test condition C.

Figure 10. - Concluded. Deposits on the outlet thermocouples of model 6 combustor.



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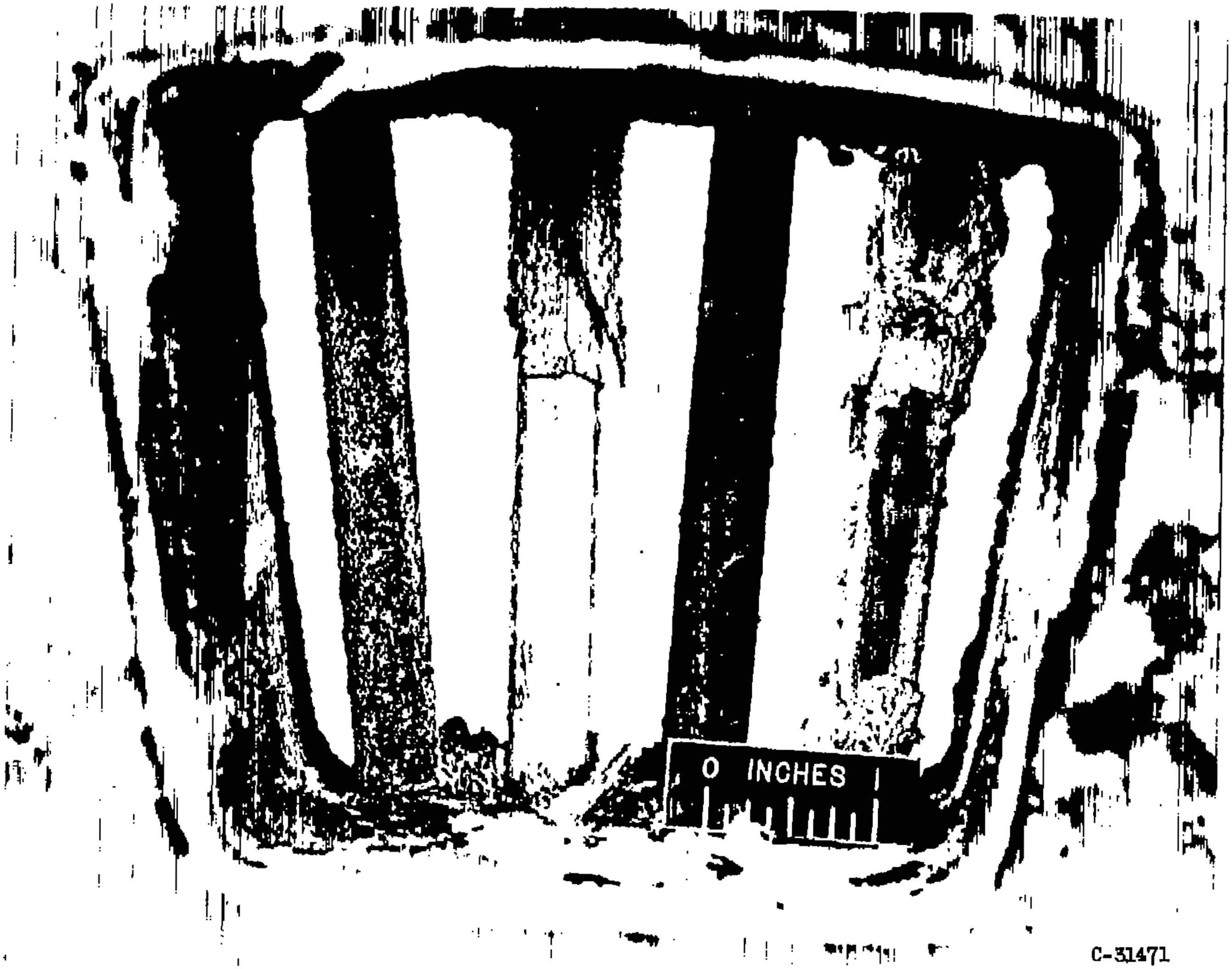
(a) After 10.8 minutes at test condition B.

Figure 11. - Deposits on special tubes at outlet of model 6 combustor.



(b) After 11.0 minutes at test condition C.

Figure 11. - Concluded. Deposits on special tubes at outlet of model 6 combustor.

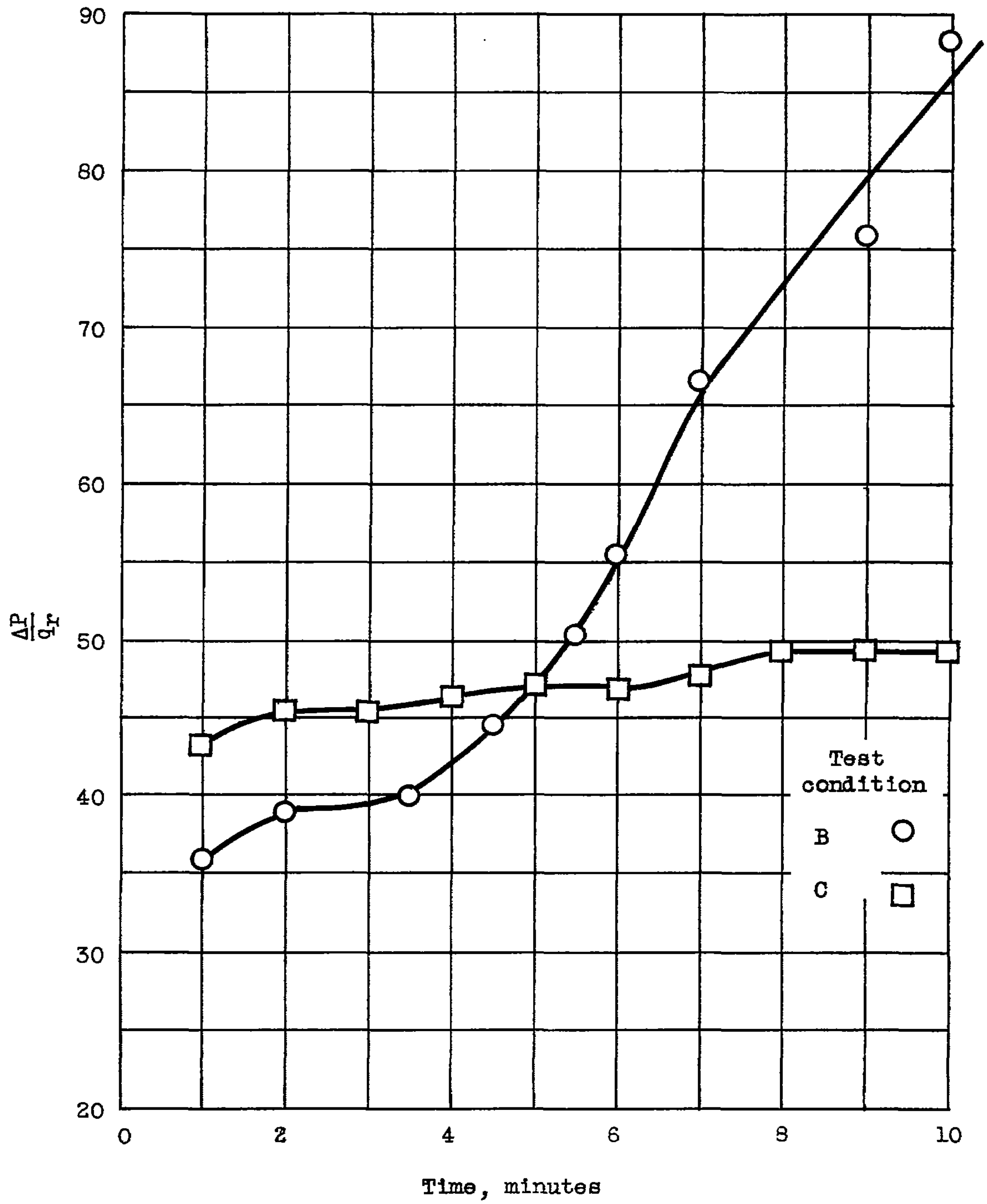


Figure 12. - Variation with time of the total pressure drop through the model 6 combustor plus obstructions in the exhaust duct.

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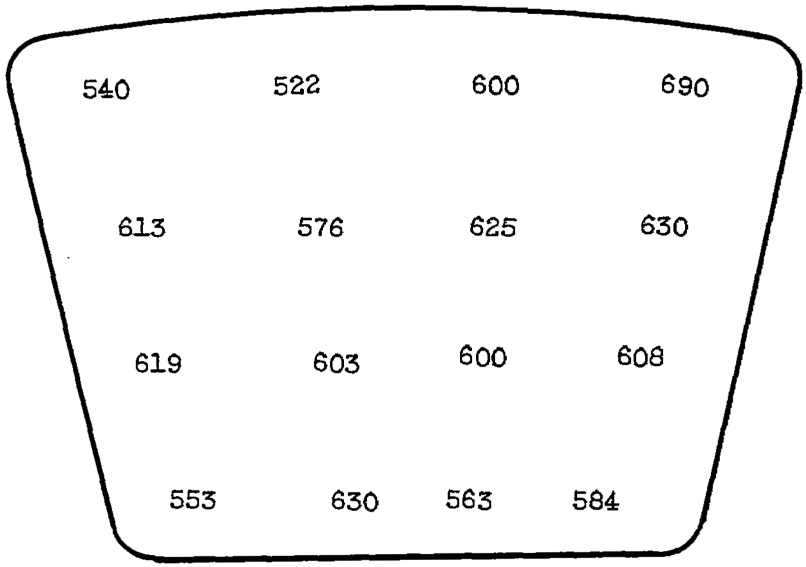
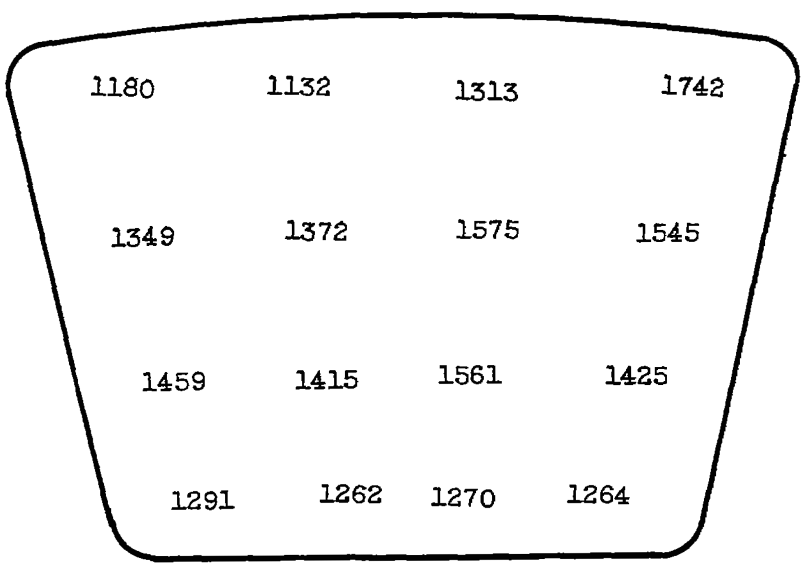


(a) Test condition B.



(b) Test condition C.

Figure 13. - Outlet temperatures for model 6 combustor. Temperatures in degrees F.

[redacted]

[redacted]