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RESEARCH MEMORANDUM

PERFORMANCE AND OPERATIONAL CHARACTERISTICS OF PENTABORANE FUEL IN 48-INCH-DIAMETER RAM-JET ENGINE

By Warren D. Rayle, Dwight H. Reilly, Jr., and John M. Farley

Lewis Flight Propulsion Laboratory
Cleveland, Ohio

NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

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SUMMARY

Pentaborane was used as the fuel for a 48-inch-diameter ram-jet engine in two brief tests in a free-jet facility. Each test lasted about 50 seconds, and through the use of fast-response instrumentation and prescheduled fuel-flow variation provided data on the engine performance for fuel-air ratios from about 0.020 to 0.030. The flameholder and fuel-injector systems were especially designed for use with this fuel. For both tests the combustor-inlet temperature was 530° F, the combustor pressure level was about 1/3 atmosphere, and the combustor-inlet Mach number was about 0.15. Combustor lengths of 8 and 6 feet were used for the first and second tests, respectively.

The combustion efficiencies determined with the 8-foot combustor length decreased from 89 to 84 percent as the fuel-air ratio increased from 0.018 to 0.029. The second test, with a 6-foot combustor length, was carried out with slightly different flow conditions. The combustion efficiencies ranged from 86 to 79 percent as the fuel-air ratio increased from 0.020 to 0.030. The specially designed fuel-injector system operated satisfactorily for both tests with no indication of any clogging of the orifices.

INTRODUCTION

The range of ram-jet vehicles may be considerably increased by high-energy fuel. Among the fuels showing the greatest promise are the boron hydrides and related compounds. Pentaborane, for example, has a heat of combustion about 50 percent greater than that of hydrocarbons. Another advantage of these fuels is their very great reactivity, implying an increased combustion efficiency at conditions where the combustion of hydrocarbons becomes difficult. Accordingly, the NACA has instituted a general program for the study of the problems of using these fuels in full-scale turbojet and ram-jet engines.

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Previous investigations carried out by the NACA with pentaborane and analogous fuels are summarized in reference 1. Data relevant to ram-jet applications are not extensive. A series of tests in a connected-pipe facility (ref. 2) evolved a fuel-injector and flameholder system later used in flight tests of a $9\frac{3}{4}$-inch-diameter ram jet (refs. 3 and 4).

The present report outlines two brief tests using pentaborane as fuel in a 48-inch-diameter ram-jet engine. The tests were conducted in a free-jet facility at the NACA Lewis laboratory. Pentaborane was chosen not as an ideal high-energy fuel, but as an available representa- 3854
tive of a class. The program was intended to determine the combustion efficiency of such a high-energy fuel in a full-scale engine and also to evaluate the fuel-injector and flameholder system especially designed for the 48-inch-diameter engine.

The tests reported herein were conducted with an engine air flow of about 40 pounds per second entering the combustor at a pressure of about 1/3 atmosphere and at a temperature of 530° F. This corresponds to a flight altitude of 80,000 feet and a flight Mach number of 2.75. Two tests were made to determine combustor performance, one with a combustor 8 feet long and a second with a six-foot length. The fuel-air ratio was varied from approximately 0.020 to 0.030 and fuel availability limited the runs to about 60 seconds each. Total fuel used was about 110 pounds.

Quantities metered during each test included engine air flow, fuel-flow rate, combustor-inlet and -outlet total pressures. From these measurements combustion efficiencies and combustor pressure drops were calculated.

FUEL

Pentaborane B_5H_9 is a volatile liquid of moderately low density which has a heating value about 50 percent greater than that of hydrocarbon fuels. Its properties are summarized as follows:

Boiling point, °F	140
Freezing point, °F	-52
Specific gravity	0.623
Heat of combustion, Btu/lb	29,130
Spontaneous-ignition temperature, °F	116
Stoichiometric fuel-air ratio	0.07635

The spontaneous-ignition temperature of pentaborane depends strongly on the test conditions. Tests have shown that in a flowing stream, with time lags of less than 20 milliseconds, temperatures of about 630° F were required (ref. 5). The presence of a flameholder in the stream sharply reduced this value.

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Pentaborane is also subject to thermal decomposition. The rate of formation of nonvolatile decomposition products can be appreciable even at moderate temperatures (ref. 6). The fuel is extremely toxic, concentrations of as little as one part per million being considered hazardous. (See appendix A.)

APPARATUS

Engine Shell

The 48-inch-diameter engine in which these tests were conducted is shown in figures 1 and 2. The engine shell, the exhaust nozzle, and the supersonic diffuser were substantially identical with those previously used for work with hydrocarbon fuels (refs. 7 and 8). The supersonic diffuser (not shown) delivered an air stream of asymmetrically nonuniform profile. In order to rectify this situation, a half screen blocking 25 percent of the (half) area was installed in the diffuser (figs. 1 and 2).

The diffuser discharged into a conical section in which the fuel injectors and the flameholder were mounted. The cylindrical portion of the combustion chamber was 5 feet long for the first test. For the second test it was replaced by a 3-foot section. Thus, the distance from the fuel injectors to the exhaust-nozzle throat, hereinafter referred to as the combustor length, was 8 feet for the first test, 6 feet for the second. The convergent-divergent exhaust nozzle had a throat area of 54.5 percent of the combustion-chamber cross section. Both the exhaust nozzle and the cylindrical sections were provided with water-cooling. In order to obtain data on the isothermal drag of the combustor, a motor-operated clamshell was attached to the exhaust nozzle.

Flameholder and Fuel-Injector System

The flameholder and fuel-injector system designed for the tests reported herein is shown mounted in the engine in figures 1 and 2. The fuel was injected through 40 simple orifices located in sixteen radial spray bars as shown in figure 3. These bars were located near the upstream end of the conical section where the higher air velocity could contribute to a more rapid atomization and mixing of the fuel and could also reduce the probability of the flame becoming seated on the fuel injectors. The direction of the spray was normal to the axis of the (slanted) radial bars, but rotated about 30° downstream from the position normal to the air flow. To avoid thermal decomposition of the pentaborane fuel, the spray bars were constructed with a double wall (fig. 3(c)) with a layer of insulation reducing the rate of heat transfer.

The manifold supplying the bars was located within the apex of the flameholding gutter and, like the bars, was shielded from the flame and the hot air stream by insulation as shown in figure 1.

An annular baffle flameholder was located near the wall of the conical section. Though probably not necessary for stabilization of the pentaborane flame (ref. 2), it did serve to shield the uncooled conical section of the engine and also tended to reduce flow separation or stagnation in the region where mixing of fuel and air occurred. A capacitor-discharge spark igniter (3 joules) was located in the annular baffle. 3854

Fuel System

The pentaborane fuel system used is sketched in figure 4. The large tank containing pentaborane was pressurized with helium to about 600 pounds per square inch gage. The other, containing dried JP-5 fuel which was used to precede and follow the pentaborane, was pressurized to about 630 pounds per square inch gage. Either tank could be drawn from by the activation of the remote-operated valves. The pentaborane line was equipped with two such valves, for greater safety. Both were pneumatically actuated, with solenoids controlling the actuating air. The smaller tank contained dry JP-5 fuel and was used for final purging of the system. The flow of fuel (either pentaborane or JP-5) was controlled by a hydraulically positioned, variable-area valve. This throttling valve was connected in series with a reducing valve in such a way that the pressure drop across the throttling valve remained nearly constant (characteristics of this type of valve are given in ref. 9). Thus the mass-flow rate of a given fuel was a linear function of the valve area, or position. In addition, the valve followed a scheduling signal with speed and precision. The tubing through which the fuel flowed was of minimum size, so that the amount of fuel stored therein during the run was small.

Instrumentation

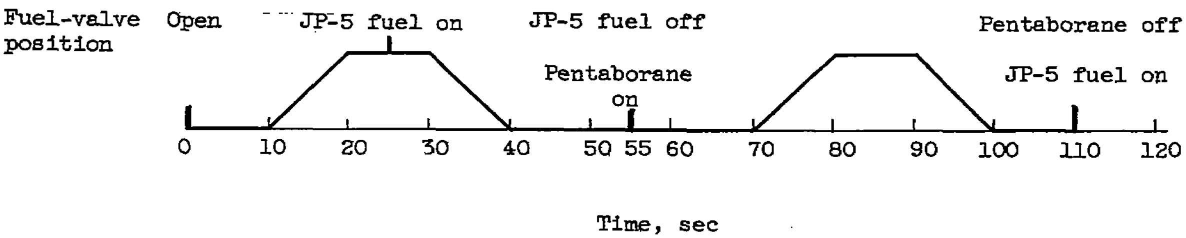
The electrical signals from the fast-response instrumentation were continuously recorded by three instruments, one a pen and moving chart type, the others recording oscillographs.

The fuel-flow rate was measured through the use of two positive-displacement electronic flowmeters, one of which was connected to a self-balancing potentiometer for monitoring purposes. The pressure of the fuel entering the manifold was recorded from pressure transducers (fig. 4).

The total pressure and temperature of the air entering the free-jet nozzle were measured by means of manometers and thermocouples. Within the engine, the total pressure was measured at two stations (figs. 1 and 5). The diffuser-outlet total pressure P_3 was determined from a 48-point survey by means of manometers. Three pressure transducers were connected to static taps at this station to provide a more rapid response. At the combustor outlet, station 6, a 36-point survey was used. Twenty-four points were connected to a manometer system and the other twelve were connected to pressure transducers.
3854 The manometer system was especially constructed to minimize the time lag. The readings from all manometers were recorded photographically at intervals of about two seconds during the tests. A periscope located downstream of the engine afforded a view of the combustion chamber through the exhaust nozzle.

PROCEDURE

The fuel-flow control valve was fed a positioning signal of trapezoid wave form as shown:



Thus, for about 30 seconds, the flow would remain steady at the minimum value. It would then increase linearly with time for about ten seconds until it reached the maximum value, hold this flow rate for another ten seconds, decrease linearly with time to its original value and repeat the cycle. In the actual test sequence, the lead fuel (dry JP-5) was turned on at the midpoint of the high plateau. This fuel served to cool the fuel lines and injectors and also removed any air present in the system. The lead fuel was permitted to flow until about the midpoint of the low plateau, when the remote-operated valves were actuated to simultaneously shut off the lead fuel and to turn on the pentaborane. As the pentaborane reached the engine, it was ignited. When the fuel flow again reached the minimum value, a few seconds were allowed for the instruments to attain equilibrium, and the pentaborane was shut off. Simultaneously the lead fuel was turned on to purge out the pentaborane remaining in the lines. Thus the actual burning time extended beyond the nominal run duration while the residual fuel in the lines was expelled.

In reducing the data, the readings from the pressure transducers were used throughout. The manometer readings were used only to calibrate the pressure transducers at the high- and the low-pressure plateaus.

RESULTS AND DISCUSSION

For the first test with the combustor length of 8 feet the engine air flow was about 40 pounds per second at an inlet temperature of 530° F. Figure 6 presents the time variation of relevant parameters. 3854
(Zero time corresponds to the time at which the valves were actuated to admit pentaborane to the fuel lines.) The fuel-air ratio followed the prescheduled trapezoid wave form, from a minimum of about 0.018 to a maximum of 0.029. The combustor-outlet total pressure ranged from 580 to 645 pounds per square foot absolute. The total-pressure ratio across the combustor (including the flow-straightening screen) varied from 0.80 to 0.825 as the inlet Mach number decreased from 0.15 to 0.14. The combustion efficiency reached a maximum of about 89 percent at the low fuel-air ratio and decreased to about 84 percent as the fuel flow increased.

For the second test, the combustor length was 6 feet. Coincident with engine ignition, the supersonic flow through the free-jet nozzle became disestablished - a fact which was not immediately noted. As a result, the air flow through the engine dropped and quite possibly fluctuated with time at least for a few seconds. In addition, the flow profile at the diffuser outlet became more uniform. As previously mentioned, the loss of supersonic flow occurred at or about the moment at which the engine started, as shown by both the pressure transducers and the photographs of the manometers. However, the resultant fluctuations in engine air flow may have persisted for an arbitrary length of time. The efficiencies calculated on the assumption of steady though reduced air flow (see appendix B) exhibit variations at a given value of fuel-air ratio which can best be explained by assuming that the engine air flow did not attain its new steady value until about 16 seconds after ignition. Using the method outlined in appendix B, the air flow was determined to be about 36 pounds per second, at least during the latter half of the test.

The variation of relevant parameters with time is shown for the second test on figure 7. The fuel-air ratio varied from 0.021 to 0.030; the combustor-outlet total pressure ranged from 545 to 590 pounds per square foot absolute. Across the combustor, the total-pressure ratio increased from 0.815 to 0.850 as the combustor-inlet Mach number decreased from 0.154 to 0.148. The combustion efficiency reached a maximum of about 86 percent at the low fuel-air ratio and decreased to approximately 79 percent at the richest fuel-air ratio.

Combustion Performance

Combustion efficiency. - The combustion efficiencies are shown in figure 8 as functions of engine fuel-air ratio for the first and second tests. For the first test, the combustion efficiency seems unaffected by fuel-air ratio for values above about 0.023 but increases from 84 to 89 percent as the fuel-air ratio is decreased to 0.018. For the second test, the decrease of efficiency with increasing fuel-air ratio seems to continue at least as far as the data extend, decreasing from 86 percent at a fuel-air ratio of 0.021 to 79 percent at a fuel-air ratio of 0.030. The scatter of data points for the second run may be attributed to fluctuating air flow during the early portion of the run (see appendix B). At the higher fuel-air ratios the efficiencies obtained from the second test are somewhat lower than those obtained from the first test. This small difference (about 5 percent at high fuel-air ratios) should not be attributed solely to the reduction in combustor length. The reduction in combustor pressure might be a factor. Furthermore (as noted in appendix A), the method used to calculate the engine air flow was conservative. An error of about 2 percent in the calculated air flow would be sufficient to change the combustion-efficiency values by 5 percent. The efficiencies presented are the lowest that could be reasonably calculated from the data.

Comparison of the combustion performance obtained in the first test with the performance of a hydrocarbon-fueled unit in a similar engine shell (ref. 6) shows that an equivalent engine-outlet total pressure (roughly an equivalent thrust) can be obtained with pentaborane flow rates from 61 to 79 percent of the hydrocarbon flow rates. The greater gains appear at the lower fuel-air ratios where the hydrocarbon combustor had efficiencies of about 83 percent. In any event, the data indicate a substantial decrease in the specific fuel consumption for the engine.

The heat rejected to the water-cooled combustor walls (usually included in the combustion efficiencies calculated (see refs. 7 and 8)) is not included in the combustion efficiencies presented herein. Such data could not be obtained with any precision because of the short duration of the tests and the large thermal inertia of the system. A single datum obtained during the first test indicated that the magnitude of the heat rejection was about 2 percent of the total heat input. This value is in general agreement with the results from hydrocarbon tests where from 1 to 3 percent of the heat was rejected.

Combustor pressure loss. - The total-pressure ratio across the combustor is plotted as a function of combustor-inlet Mach number in figure 9. For the first test the ratio varied between 0.80 and 0.825 as the inlet Mach number decreased from 0.155 to 0.142. The points obtained while the fuel flow was increasing showed a higher ratio than those on the decreasing ramp, possibly because of the shifting velocity profiles in the supersonic diffuser. For the second test, the data are more consistent and show a sharper effect of Mach number. The total-pressure ratio ranges from 0.815 to 0.855 with Mach number variation between 0.154 and 0.148. The reduced loss, as well as the increased slope of the curve, may be due to the flatter velocity profile entering the combustor in the second test.

The magnitude of total-pressure loss seems rather large, especially in view of the minimum obstruction offered by the fuel-injector and flameholder to the gas flow. The loss can be broken down into three components: (1) the loss across the flow-straightening screen, (2) the 3854 drag of the fuel injector and flameholder, and (3) the momentum pressure loss resulting from the heat release. Figure 9(a) also shows the total-pressure ratio across the combustor (including the screen) for isothermal flow. The difference between this curve and that for the first test may be attributed to the momentum pressure loss. This difference amounts to 7 or 8 percent, indicating that the pentaborane was burning in a high-velocity air stream, that is, near the fuel injectors. Calculations show that a momentum pressure loss of not more than 5 percent would result if the air stream were fully diffused before combustion started. The pressure loss across the flameholder and fuel injectors is probably no more than half the total isothermal loss, which ranges from 0.10 to 0.13 for burner-inlet Mach numbers of 0.144 to 0.156. This premise is substantiated by earlier unpublished data with a similar screen blocking of only 20 percent of the (half) area, which indicated the total-pressure loss across the screen was approximately 7 percent at conditions corresponding to those discussed herein.

Ignition

The pentaborane fuel was expected to ignite spontaneously at the test conditions investigated. In the first test, however, no ignition occurred in the first 11 seconds after the valves were energized to admit pentaborane to the fuel system. The spark ignitor was then turned on to avoid a waste of fuel and also a possibly hazardous accumulation of unreacted pentaborane in the exhaust system. An examination of the oscillograph record indicated that ignition occurred at approximately the same time as the first spark (within one or two tenths of a second). For the second test, the ignition system was energized before the pentaborane reached the engine. Nevertheless, a time lag equivalent to that of the first run was observed before the fuel ignited. This delay time, about 12 seconds, considerably exceeds the time required for the pentaborane to fill the fuel lines at the initial flow rate. The discrepancy is substantial and probably results from sluggish action of the solenoid-triggered, pneumatically driven valves. In view of the identity between the times required for ignition in the two tests, no positive conclusion can be reached as to whether the pentaborane would ignite spontaneously at the test conditions. Previous data (ref. 5) indicated that the spontaneous ignition of pentaborane depended very strongly on the presence of recirculation and was also a function of the local fuel-air ratio. In the present case, recirculation must certainly have been present in the annular gutter, but the local fuel-air ratio in this region may have been considerably less than stoichiometric even at the richest locations.

Oxide Deposits

Deposits of boron oxide were found on the water-cooled pressure rakes, combustor walls, and exhaust nozzle after each test. These deposits were white and moderately soft, their thickness ranged from nearly zero on the nozzle and lines to as much as 3/8 inch on the water-cooled rakes, as shown by the photograph of the engine after the test (fig. 10). Considering the brevity of the test cycle, no extrapolation should be made concerning the magnitude of the deposit problem. The oxide deposits were noticeably negligible on the thin strip of uncooled metal at the nozzle outlet.

Fuel-Injector Performance

The fuel injector functioned satisfactorily, with no indication of either overheating or spray-orifice plugging during the brief tests. A somewhat greater injection pressure was required than had been calculated for the pentaborane, implying that a greater number of spray orifices could have been used.

SUMMARY OF RESULTS

The two brief tests of pentaborane fuel in a 48-inch-diameter ram-jet engine in a free-jet facility gave the following results:

1. Combustion efficiencies of from 80 to 89 percent were obtained at combustor-inlet pressures of about 1/3 atmosphere. The maximum efficiency occurred at the minimum fuel-air ratio, 0.018.

2. Although the two tests which were to show the effect of combustor length were not strictly comparable, the decrease in efficiency accompanying a reduction from 8- to 6-foot combustor length was less than 5 percent.

3. For the 8-foot combustor, the total-pressure ratio across the combustor, including a flow-straightening screen, was between 0.80 and 0.825. At similar flow conditions without combustion, the ratio was from 0.87 to 0.90.

4. The fuel-injector and flameholder system designed for these tests performed adequately with no deterioration or plugging noted.

Lewis Flight Propulsion Laboratory 3854
National Advisory Committee for Aeronautics
Cleveland, Ohio, December 2, 1955

APPENDIX A

TOXIC-VAPOR HAZARD

During and immediately after each test, the areas of the fuel stand, the control room, and the exhaust lines were monitored using hand-operated air-sampling devices equipped with a reagent especially sensitive to pentaborane. Immediately after the first test, strong concentrations were detected near the duct carrying the exhaust products to the discharge stack. Since the pressure in this duct was, of necessity, somewhat above atmospheric, probably a small leakage of exhaust products was directly responsible for this contamination. In addition, upon depressurizing of the pentaborane supply tank (the helium being vented into a drum containing a mixture of acetone and alcohol) traces of pentaborane were detected throughout the building. The remainder of the necessary data was taken by operators in gas masks. The traces of pentaborane remained detectable for about 4 hours. The contamination was thought to arise from two sources. The greater than anticipated time lag before ignition may have permitted some raw fuel to flow through the system, this fuel then escaping through slight leaks in the exhaust ducting. The traces detected near the control room and the fuel stand were thought to result from excessively rapid depressurization of the pentaborane tank, giving the traces of fuel vapor in the helium too little time to react with the neutralizing solution. Therefore, for the second test, the spark ignition was energized coincident with the energizing of the pentaborane fuel valve. In addition, a modified operation of the facility was employed which permitted a water spray to be used ahead of the exhausters. The venting arrangement was also changed to better distribute the gas under the liquid surface, and a water sprinkler was employed to spray over the drum in order to aid in the elimination of any traces that might escape.

Even with the added precautions traces of pentaborane in the vicinity of the exhaust ducting were detected after the second test, although at random time intervals and in varying concentrations. In the control room and throughout the immediate environment of the test cell, only a few sublethal traces were found.

APPENDIX B

AIR-FLOW CALCULATIONS

First Test

For the first test, the engine air flow was computed from the equation

$$w_a = kP_0/\sqrt{T_0} \qquad (1)$$

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where

w_a engine air flow, lb/sec

P total pressure, lb/sq ft abs

T total temperature, °R

k constant reflecting diffuser capture area, determined from earlier calibrations

and the subscript 0 refers to conditions upstream of the free-jet nozzle.

Second Test

For the second test, the air flow could not be calculated from the previous relation, since the supersonic flow was disestablished coincident with engine ignition. Therefore, a more roundabout procedure was employed. First it was established that the engine air flow remained constant with varying diffuser pressure recovery. Then the actual value of the engine air flow was determined for the isothermal flow immediately following the test. The fact that the air flow was independent of diffuser pressure recovery was verified by using the total and static pressures at the diffuser outlet (station 3). An engine air flow was calculated for points on the high- and on the low-pressure plateaus of the test by means of the following equation:

$$w_{a,3} = A_3\sqrt{\frac{\gamma g}{RT_3}} \sum p_i M_i \sqrt{\left(1 + \frac{(\gamma-1)M_i^2}{2}\right)} \qquad (2)$$

where

A_3 duct area at station 3, sq ft

g acceleration due to gravity, 32.2 ft/sec^2

M_1 Mach number at a survey point

p static pressure, lb/sq ft

R gas constant for air, 53.3

T_3 total temperature of air, °R

$w_{a,3}$ air flow determined at station 3, lb/sec

3854 γ ratio of specific heats

Although these numerical values were not a good measure of the actual engine air flow, the fact that they remained constant with changing engine pressure was taken to indicate a similarly constant air flow.

The actual engine air flow was then determined from the total pressures at the combustor outlet (station 6) with isothermal flow before and after the test. The total-pressure profiles for the two cases are shown in figure 11. The term r in the abscissa represents the radius at which a pressure was measured, and r_{wall} is the radius of the nozzle at this station. Before the flow breakdown the total-pressure ratio across the exhaust nozzle using the area average at station 6 was about 1.43; after breakdown, 1.30. The shape of the profiles is similar. Assuming, then, that the mass flow through the nozzle would be proportional to the area-averaged total pressure, a value was obtained for the test conditions by use of the following equation:

$$w_a' + w_f' = (w_a + w_f)(P_6'/P_6) \tag{3}$$

where

w_a engine air flow

w_f fuel (JP-5) flow

P_6 average total pressure entering the nozzle

The primes indicate values after flow breakdown, and symbols without primes indicate conditions before flow breakdown, where w_a is given by equation (1). The fuel flows are included because the data were taken with lead fuel (JP-5) flowing (but not burning).

This value of air flow (w_a' from eq. (3)) was then used in computing combustion efficiencies. The assumptions used were such that, if the actual engine air flow differed from that calculated, the actual flow would be the smaller. The reduction in pressure ratio across the exhaust nozzle could only reduce the discharge coefficient; the higher combustor pressures during burning could only reduce the air flow. Any error, then, would mean that the combustion efficiencies calculated would be too low, because the heat-release rate must have been higher if less air were flowing.

COMBUSTION EFFICIENCY

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The combustion efficiency was defined as the ratio of fuel flow ideally required to give the measured exhaust-nozzle total pressure to that actually used. A curve of ideal fuel-air ratio as a function of exhaust-nozzle total-pressure was prepared in the following manner: The convergent-divergent exhaust nozzle was assumed to have a discharge coefficient of 0.99, as in references 6 and 7. At the throat of the nozzle the gas was assumed to be traveling at sonic velocity and to be uniform in pressure and temperature. The liquid boron oxide particles were assumed to be at all times in equilibrium with the surrounding fluid, so that the composition of the gas corresponded to the equilibrium composition at the existing static pressure and temperature. Then, for a given fuel-air ratio, the static temperature and pressure at the throat were calculated by an iterative method using the curves for x (fraction of nongaseous oxide), R (gas constant), and γ (specific heats ratio) and the calculation methods given in reference 3. From γ and the static pressure, the total pressure was calculated.

REFERENCES

1. Olson, Walter T., Breitwieser, Roland, and Gibbons, Louis C.: A Review of NACA Research Through 1954 on Boron Compounds as Fuels for Jet Aircraft (Project Zip). NACA RM E55B01, 1957.

2. Fivel, Herschel J., Tower, Leonard K., and Gibbs, James B.: Pentaborane Combustion Performance in 9.75-Inch-Diameter Ram-Jet Engine in Connected-Pipe Altitude Facility. NACA RM E54I16, 1957.

3. Disher, John H., and Rabb, Leonard: Initial Performance Investigation of Pentaborane Fuel in Free-Flight Ram-Jet Engine. NACA RM E54D28, 1957.

4. Jones, Merle L., and Disher, John H.: Flight Investigation of Pentaborane Fuel in 9.75-Inch-Diameter Ram-Jet Engine at Low Equivalence Ratio. NACA RM E54L02, 1957.

5. Lezberg, Erwin A., and Lord, Albert M.: Spontaneous Ignition of Pentaborane Sprays in a Hot-Air Stream. NACA RM E55F29a, 1957.

6. McDonald, Glen E.: Thermal Stability of Pentaborane in the Range 329° to 419° F. NACA RM E54G16, 1957.

7. Rayle, Warren D., Smith, Ivan D., and Wentworth, Carl B.: Preliminary Results from Free-Jet Tests of a 48-Inch-Diameter Ram-Jet Combustor with an Annular-Piloted Baffle-Type Flameholder. NACA RM E54K15, 1955.

3854 8. Wentworth, Carl B., Dobson, Wilbur F., and Rayle, Warren D.: Preliminary Results from Free-Jet Tests of a 48-Inch-Diameter Ram-Jet Combustor with an Annular Can-Type Flame Holder. NACA RM E54L07, 1955.

9. Otto, Edward W., Gold, Harold, and Hiller, Kirby W.: Design and Performance of Throttle-Type Fuel Controls for Engine Dynamic Studies. NACA TN 3445, 1955.

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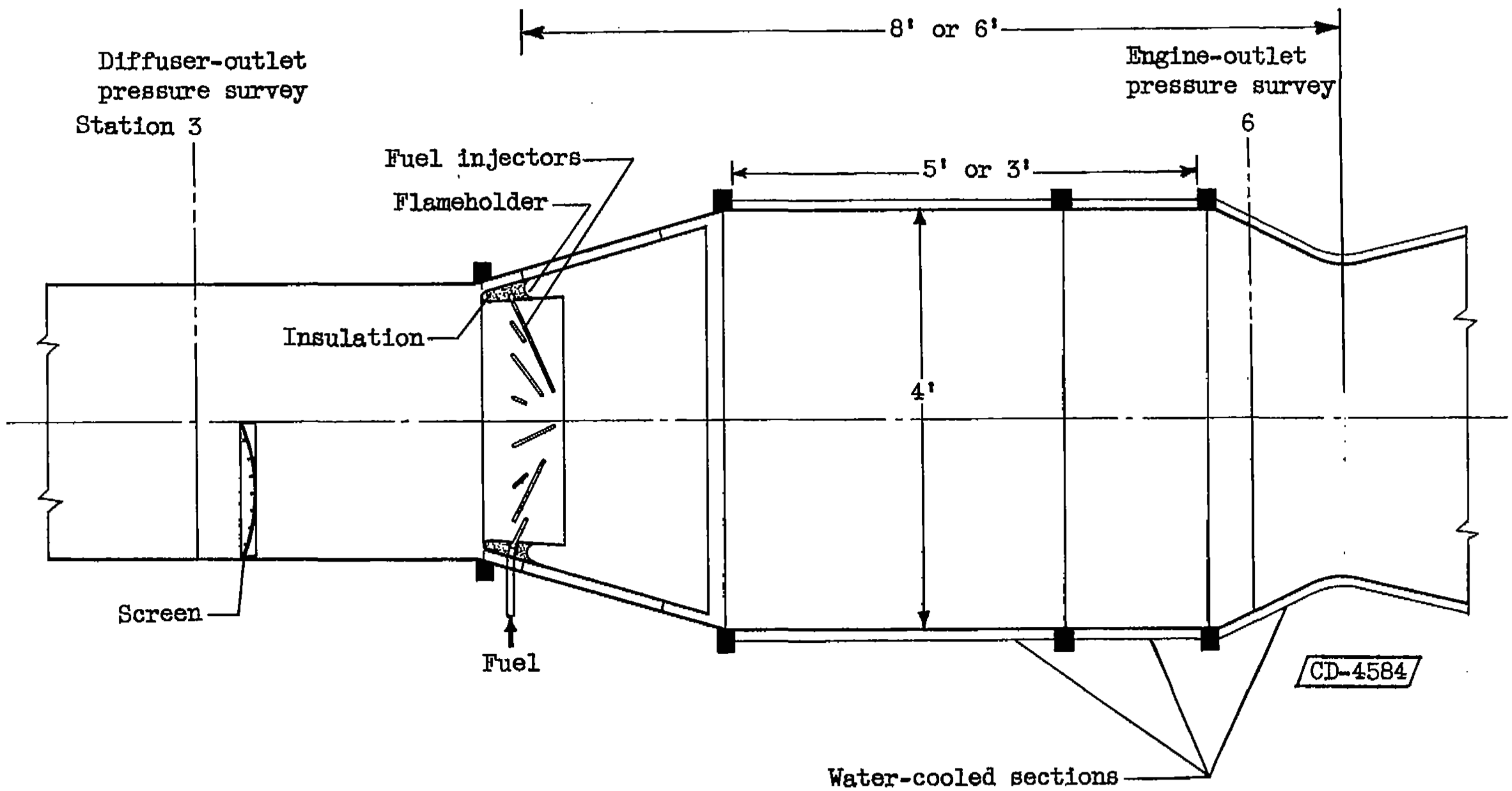

Figure 1. - Ram-jet engine used to study pentaborane combustion.

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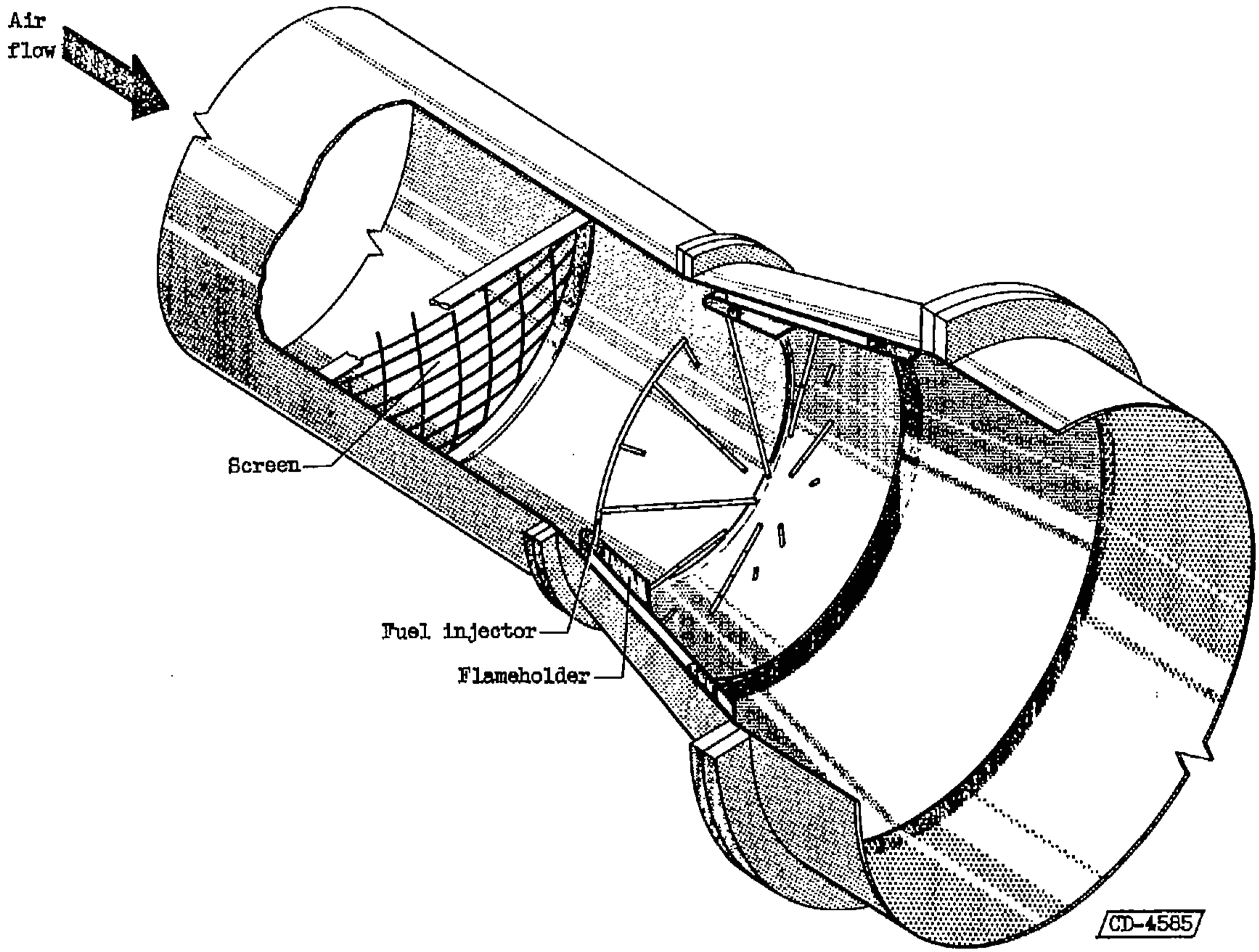

Figure 2. - Cutaway view of 48-inch-diameter ram-jet engine showing flameholder and fuel injector.

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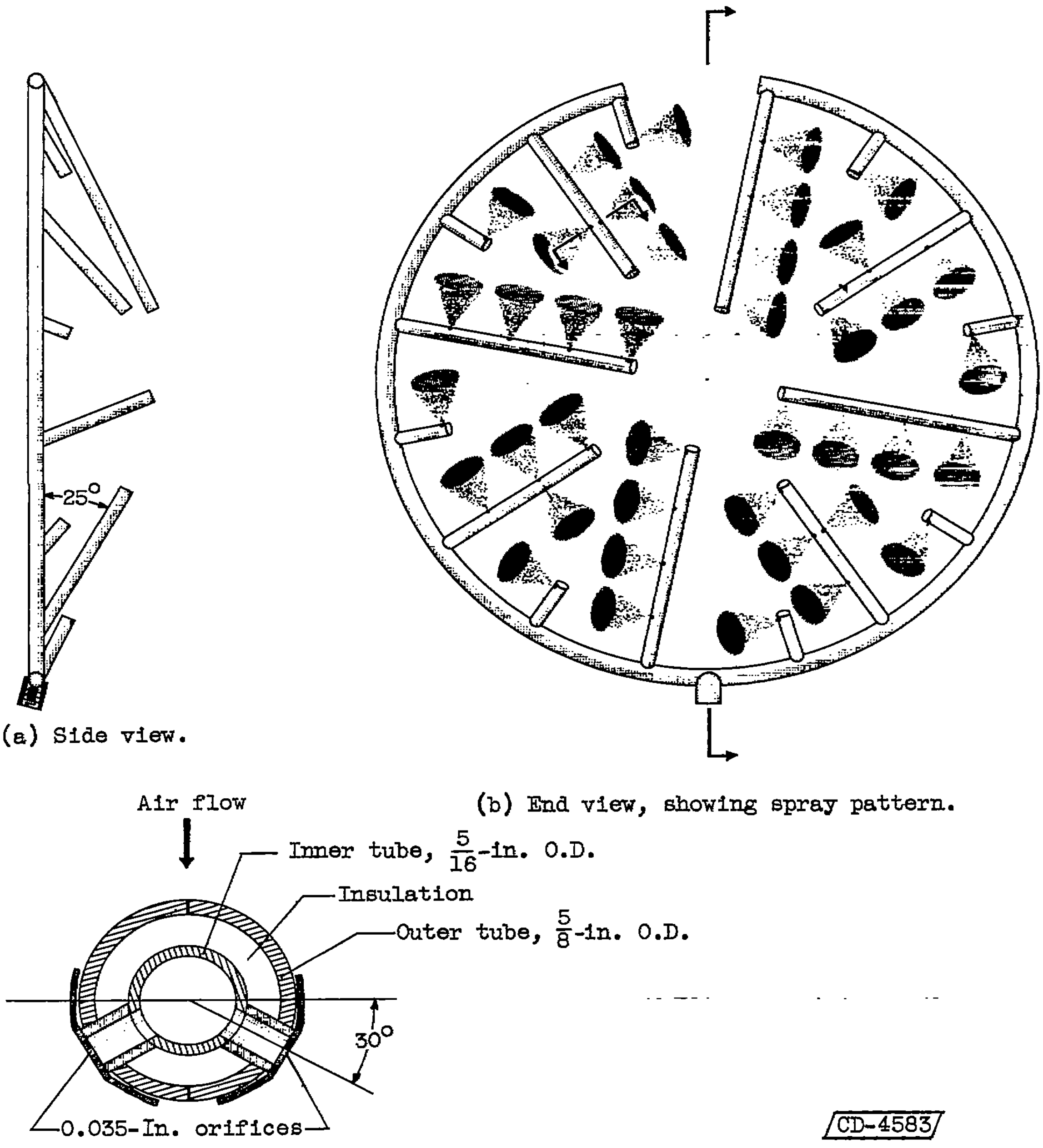

(a) Side view.

(b) End view, showing spray pattern.

(c) Spray-bar cross section.

Figure 3. - Pentaborane fuel injector.

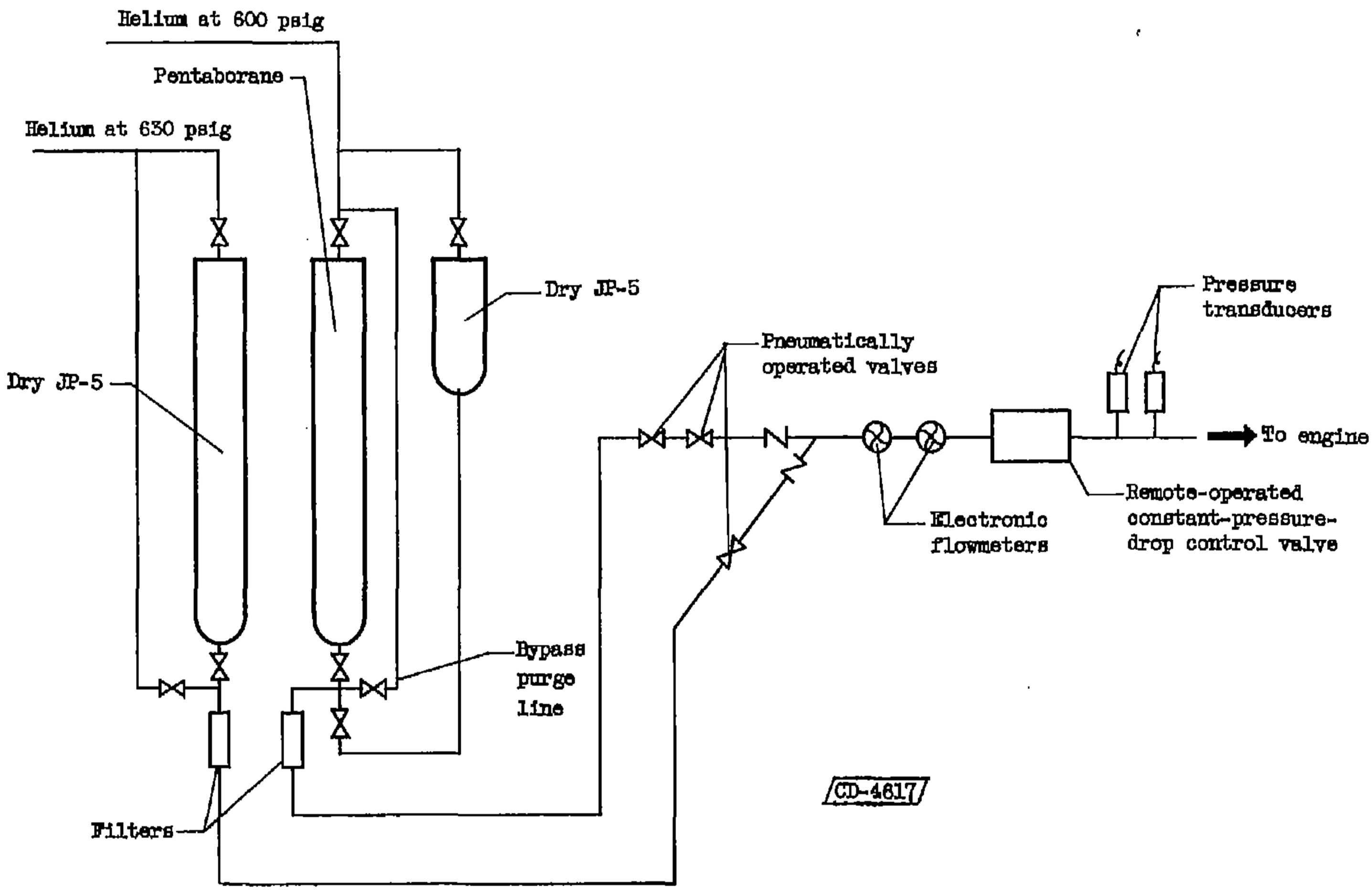

Figure 4. - Fuel system for pentaborane combustion tests.

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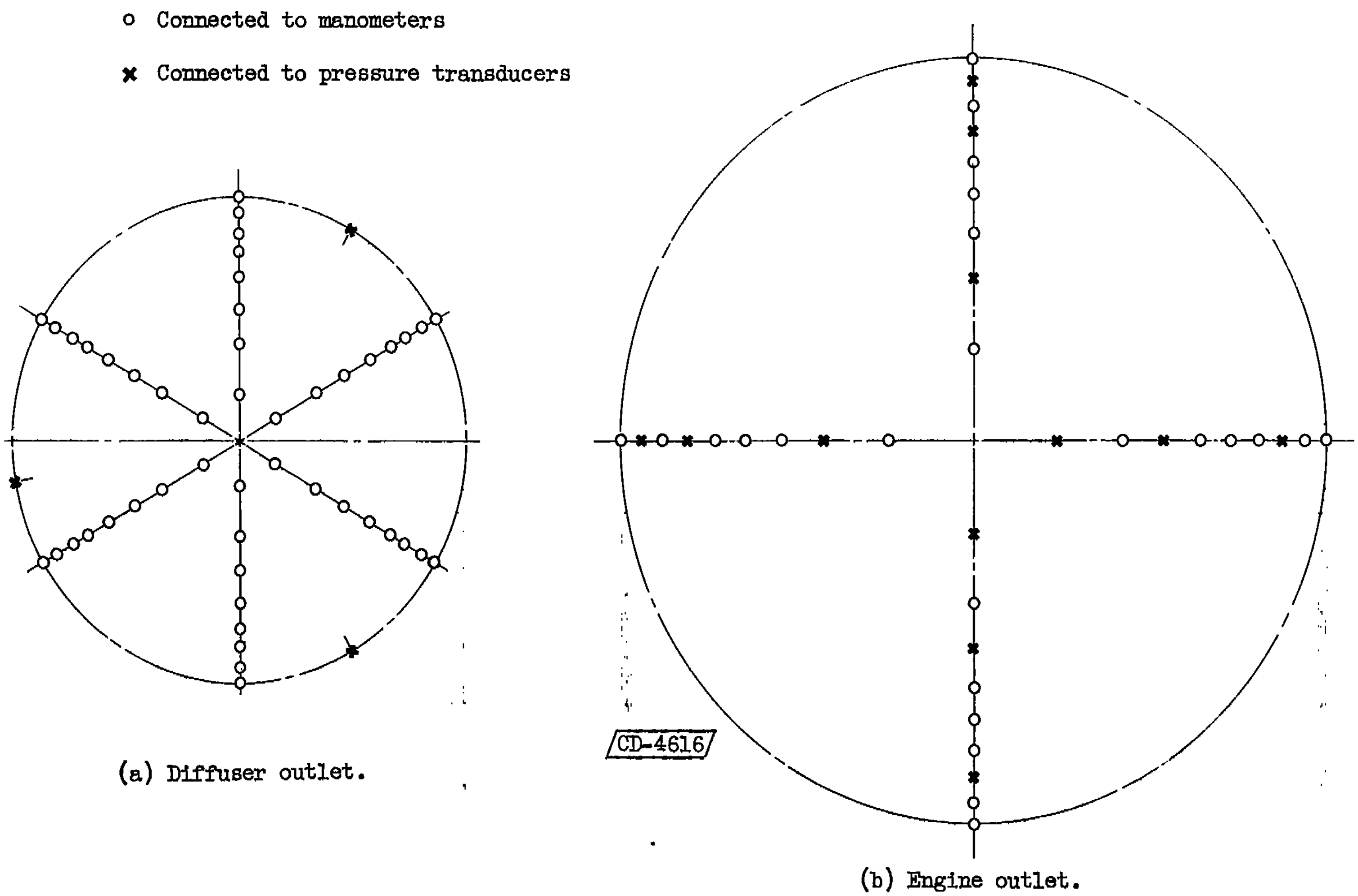

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Figure 5. - Location of instrumentation for pressure surveys.

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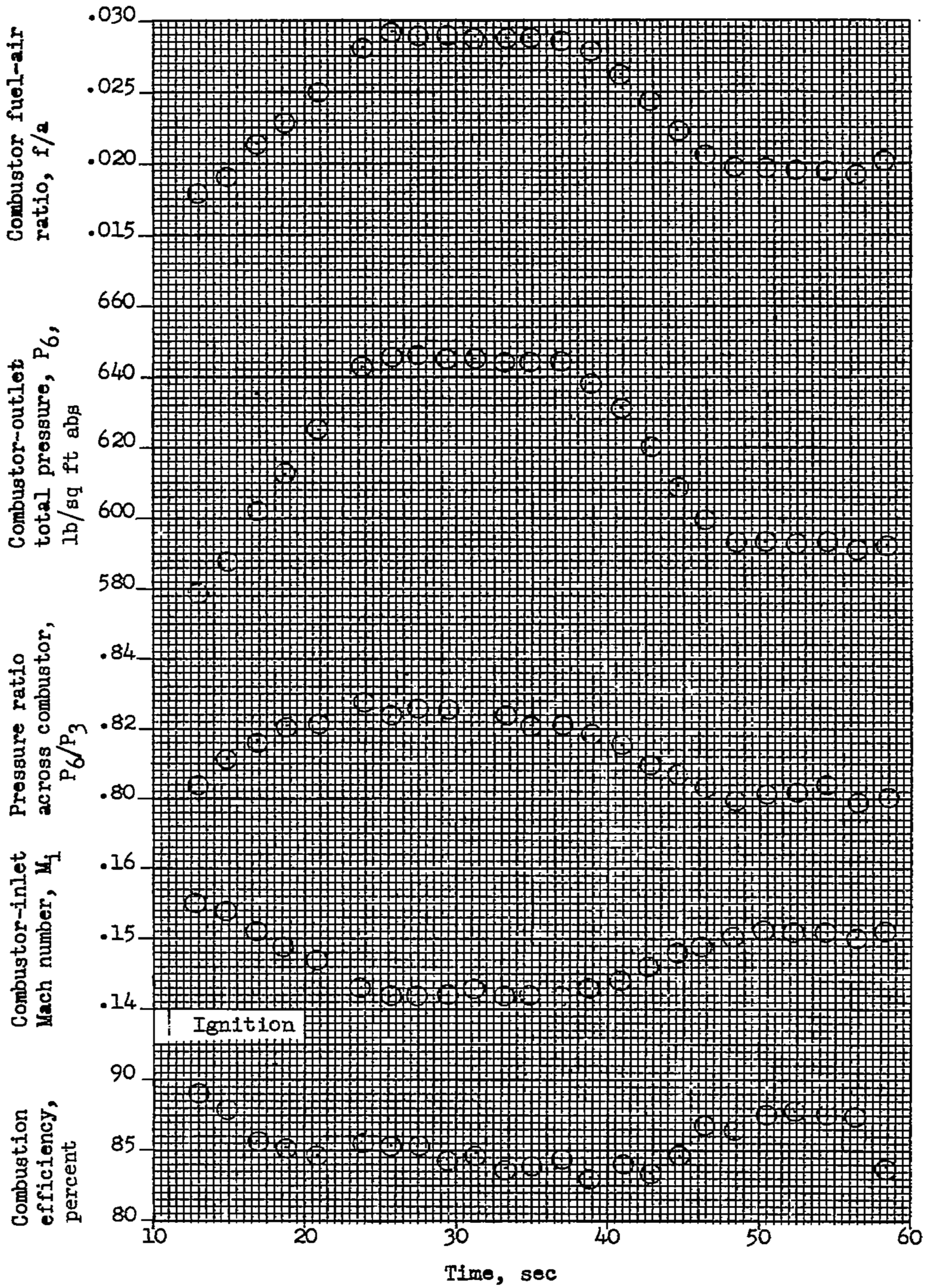

Figure 6. - Performance of pentaborane combustor in first test as indicated by fast-response instrumentation. Combustor length, 8 feet.

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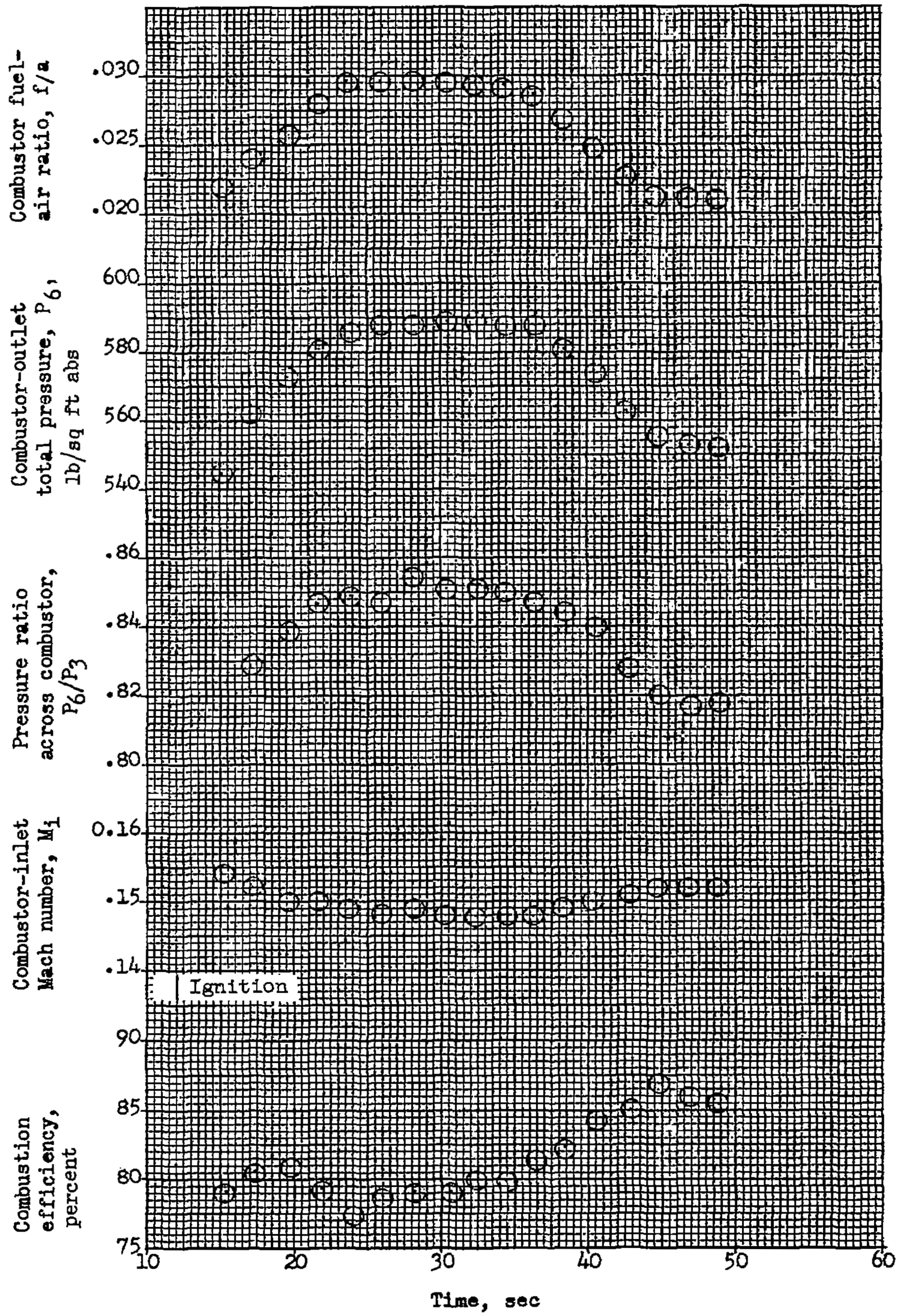

Figure 7. - Performance of pentaborane combustor in second test as indicated by fast-response instrumentation. Combustor length, 6 feet.

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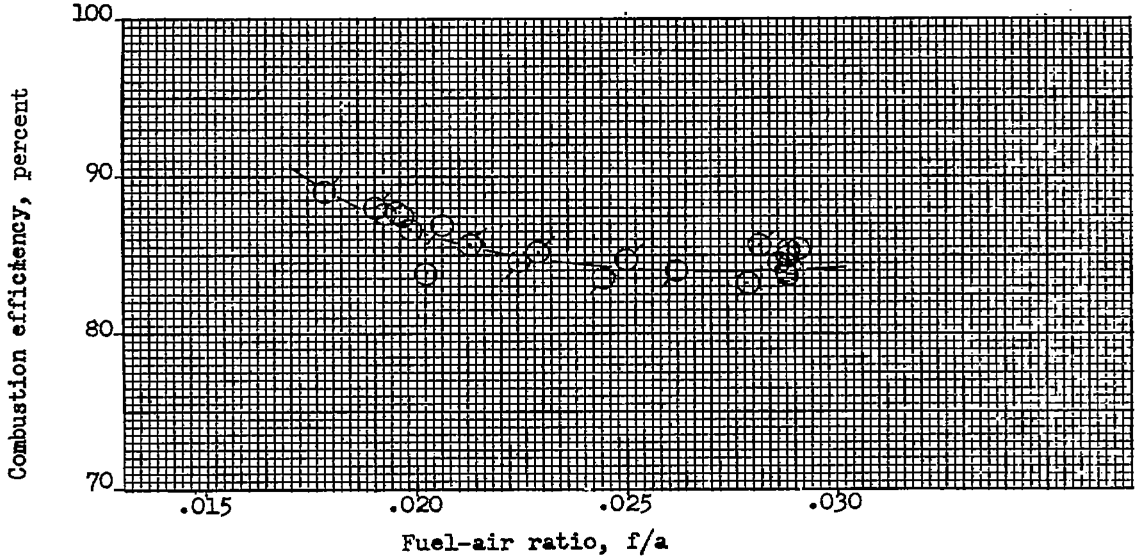
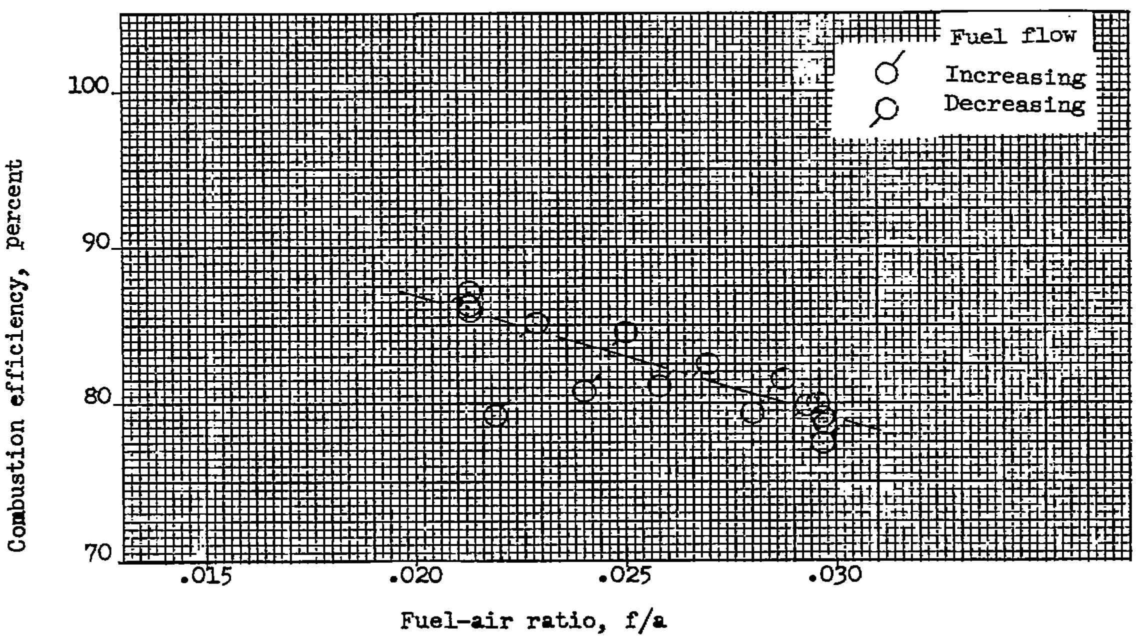


(a) First test; combustor length, 8 feet.



(b) Second test; combustor length, 6 feet (free-jet air flow broken down).

Figure 8. - Effect of fuel-air ratio on combustion efficiency of pentaborane in 48-inch ram-jet engine.

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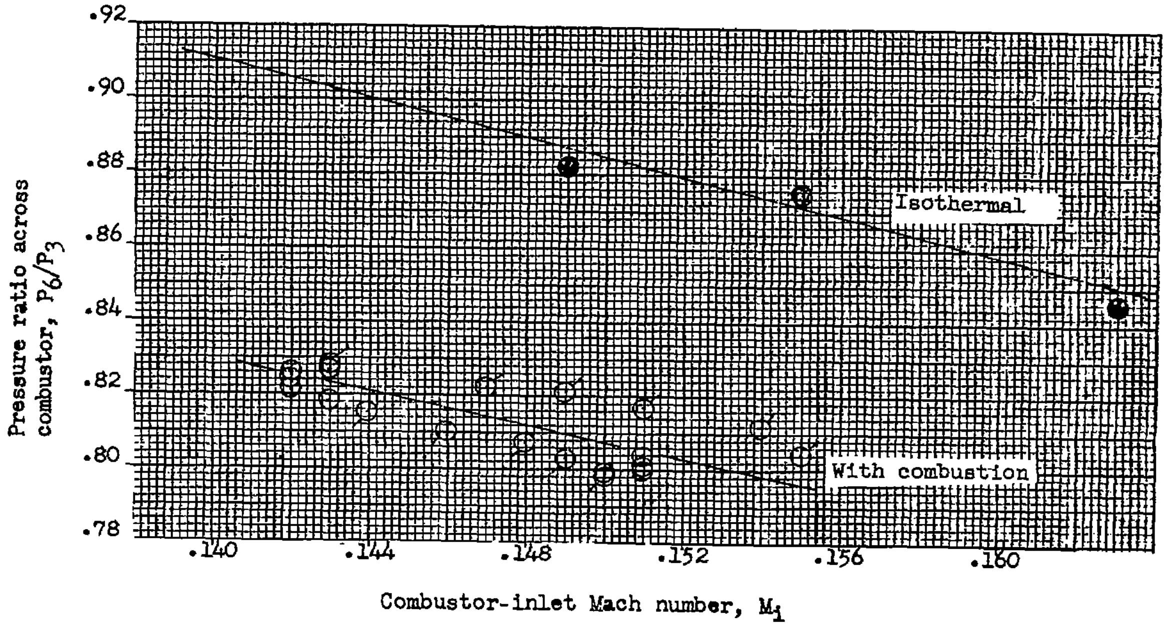
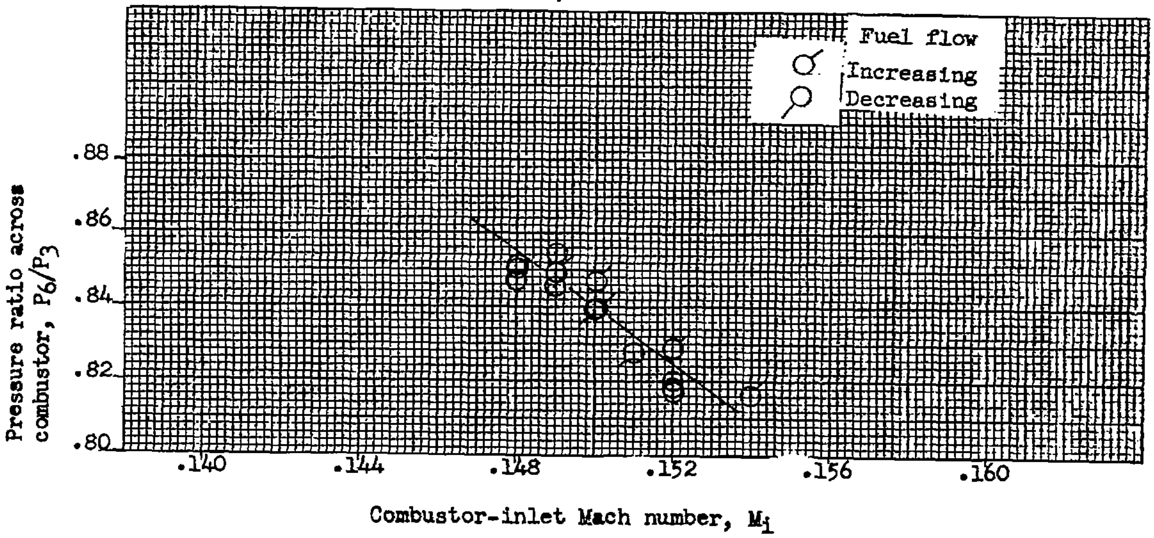


(a) First test; combustor length, 8 feet.



(b) Second test; combustor length, 6 feet (free-jet air flow broken down).

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Figure 9. - Effect of inlet gas velocity on combustor total-pressure ratio for pentaborane combustor in 48-inch ram-jet engine.

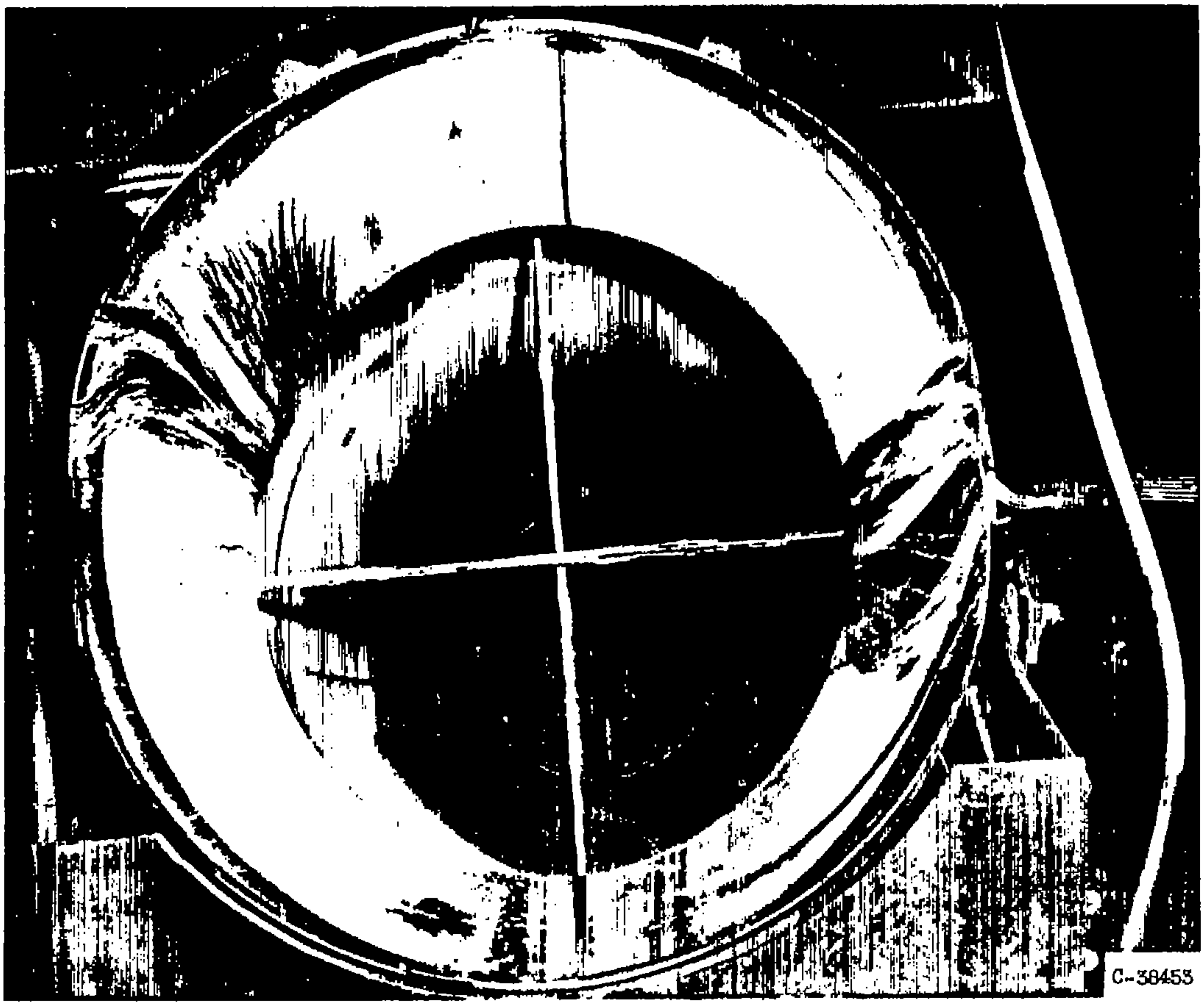

Figure 10. - Oxide deposits on 48-inch-diameter ram-jet engine after 1 minute of pentaborane combustion.

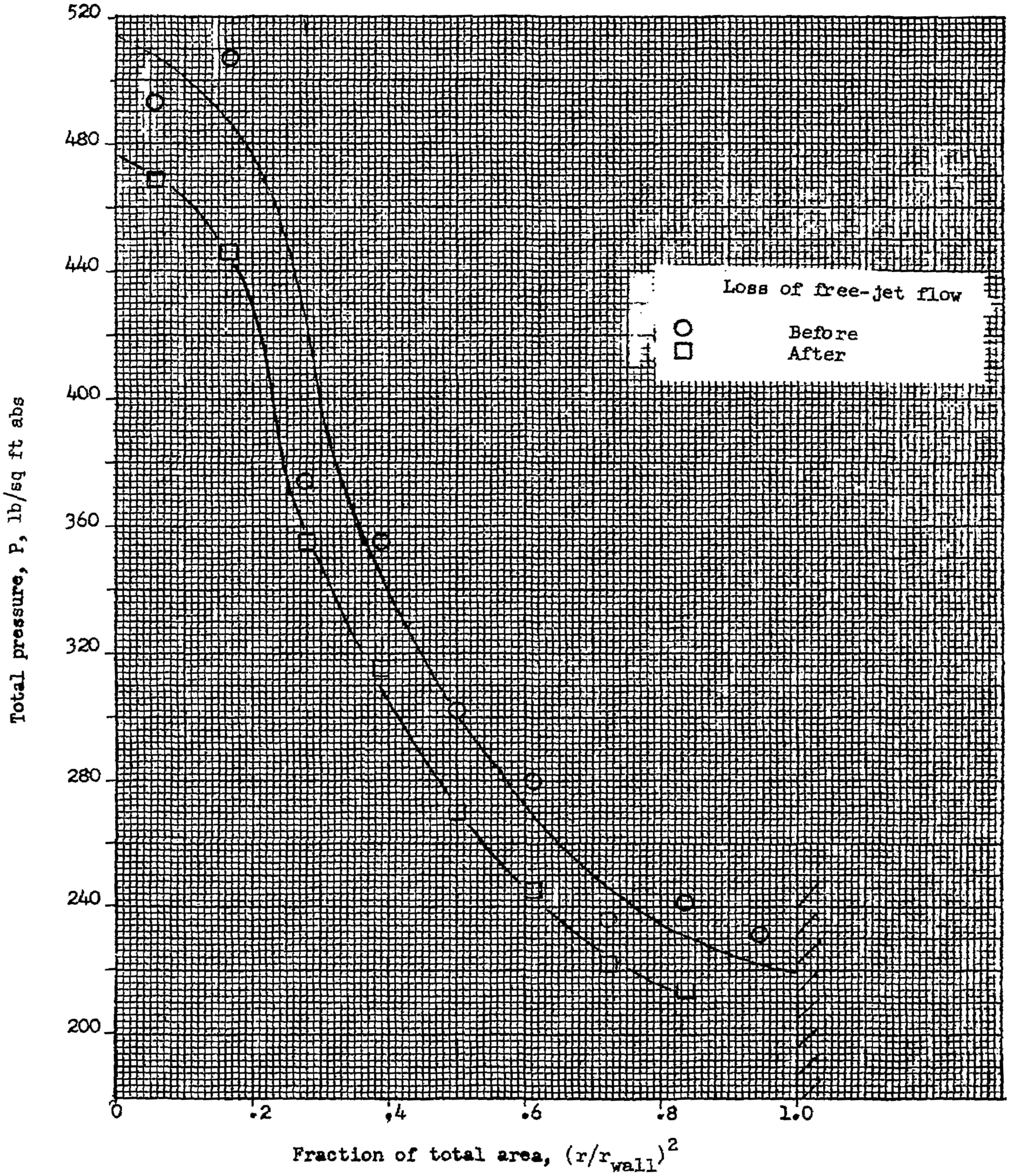

Figure 11.- Pressure profiles at ram-jet-engine outlet before and after loss of free-jet flow.

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