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RESEARCH MEMORANDUM

INVESTIGATION OF 70 PERCENT TRIMETHYL BORATE - 30 PERCENT METHYL ALCOHOL FUEL MIXTURE IN A SINGLE J33 COMBUSTOR AND IN A J33 TURBOJET ENGINE

By Louis J. Schafer, Jr., and Robert O. Hickel

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Cleveland, Ohio

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NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS
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RESEARCH MEMORANDUM

INVESTIGATION OF 70 PERCENT TRIMETHYL BORATE - 30 PERCENT METHYL ALCOHOL FUEL MIXTURE IN A SINGLE J33 COMBUSTOR AND IN A J33 TURBOJET ENGINE

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SUMMARY

An experimental investigation was conducted on a single turbojet engine combustor and on a turbojet engine using a fuel mixture consisting of 70 percent trimethyl borate and 30 percent methyl alcohol. Such a fuel mixture when burned in an engine produces boric oxide at about 1/3 the rate that would be obtained if a high-energy fuel such as pentaborane were used. In the single combustor, use of the trimethyl borate fuel resulted in excessive boric oxide deposits in the areas surrounding the air entry holes in the liner of the combustor. The single-combustor combustion efficiency was 82 percent as compared to 97 percent when MIL-F-5624A jet fuel (grade JP-4) is burned. An increase in pressure drop across the combustor was observed with an increase in operating time. In the turbojet engine the boric-oxide deposits were excessive; they were most severe on the domes and liners of the combustors, on the outlet screens of the rear-bearing cooling-air passages, and in the tail cone and tail pipe. The estimated total weight of the boric-oxide deposits on the various engine parts after 1 hour, 50 minutes of operation was about 61 pounds. During the first 45 minutes of engine operation, no change in engine performance was caused by the boric-oxide deposits in the engine. However, after this time the fuel flow could not be maintained and the engine speed and thrust dropped below the rated values.

INTRODUCTION

Improvements in the specific fuel consumption and, hence, airplane range can be realized if fuels having heats of combustion higher than present hydrocarbon fuels are used in jet engines. Two high-energy fuels which are being considered are diborane and pentaborane. One characteristic of these high-energy fuels is the presence of boric oxide in the products of combustion. Because boric oxide has a low melting point and does not vaporize readily, the oxide occurs as a liquid in the products of combustion until it is solidified by coming in contact with a relatively cool engine part (at temperatures less than 1000° F). By this

process, boric-oxide deposits will form in an engine using the previously mentioned high-energy fuels. These deposits may affect the engine performance and necessitate the redesign of some of the engine components. The magnitude of the deposits, their locations in the engine, and their effect on engine performance must be determined before engine design changes can be effected to permit the use of high-energy fuels.

High-energy fuels are not readily available in large quantities at the present time; furthermore, they offer considerable problems in handling. In order to determine where boric oxides will be deposited in turbojet engines, it is convenient to use fuels which produce boric oxide upon combustion, but which are more readily available and more easily handled than the high-energy fuels. Two such fuels are tributyl borate and trimethyl borate.

A preliminary investigation using a 50-50 mixture of tributyl borate and MIL-F-5624A (grade JP-4) fuel was made in a turbojet engine (ref. 1). The mixture of tributyl borate and MIL-F-5624A fuel produced boric oxide in the products of combustion at the rate of about 370 pounds per hour for the test conditions and engine used in reference 1. For a high-energy fuel the rate at which boric oxide would be formed in the engine of reference 1 would be about 5820 pounds per hour for diborane and about 7410 pounds per hour for pentaborane. Although the tributyl-borate fuel blend used in reference 1 produced boric oxide at a relatively low rate as compared with the high-energy fuels being considered, it was used because it was the only boric oxide producing fuel readily available at the time and it could be used to determine the locations within the engine where deposits were most likely to form. The results of reference 1 indicated that the combustors accumulated the greatest amount of deposits. Because the rate of formation of boric oxide was considerably below that which would occur if a high-energy fuel was used, the boric-oxide deposits were not severe and no loss in engine performance was observed.

It was thought that a fuel producing boric oxide at a greater rate than the fuel used in reference 1 should be investigated to determine whether the boric-oxide deposits would be greater than those reported in reference 1, and whether the engine performance would be appreciably affected. A fuel blend consisting of 70 percent trimethyl borate and 30 percent methyl alcohol (by weight) was obtained after the results of reference 1 were reported. The trimethyl borate fuel was investigated in a single J33 turbojet engine combustor and in a J33 turbojet engine. The results of this investigation are reported herein. The single-combustor tests were made to determine whether the deposits in the combustor would be so great as to preclude operation of the engine with trimethyl borate fuel. After the feasibility of using this fuel for the engine tests was demonstrated with the single-combustor investigation, the full-scale engine tests were made. When used in the turbojet engine

of this investigation, the trimethyl borate fuel blend produced boric oxide at the rate of about 2420 pounds per hour at rated engine speed, which is about 6.6 times greater than the fuel used in reference 1. For both the single-combustor and engine tests, the duration of operation with the special fuel blend was about 2 hours.

FUEL

The fuel used in this investigation consisted of a mixture of 70 percent trimethyl borate and 30 percent methyl alcohol by weight. Some measured physical properties of this blend are as follows:

Specific gravity, 60°/60° F	0.8938
Viscosity at 100° F, centistokes	0.424
Net heat of combustion, Btu/lb	9699

This fuel was used in the investigation because it produced more boric oxide than any of the other available boric-oxide-producing fuels and thereby most nearly approached the boric-oxide formation rates of high-energy fuels. The rated engine speed fuel-flow requirements of the turbojet engine used in this investigation resulted in boric-oxide formation in the products of combustion at the rate of about 2420 pounds per hour.

APPARATUS AND PROCEDURE

Single Combustor

Deposition tests were conducted in a single J33 turbojet engine combustor installed in an auxiliary duct facility similar to that described in reference 2. A diagram of the combustor installation showing the location of instrumentation planes is presented in figure 1. The conical inlet section indicated in figure 1 was used in place of the full-scale production engine diffuser in order to provide a symmetrical inlet-air flow to the combustor. The exhaust section was also modified to retain a constant 6-inch I.D. circular cross section downstream of the combustor to the instrumentation plane D-D.

Combustor inlet- and outlet-air pressures were measured by total-pressure tubes at planes A-A and D-D, respectively; inlet-air and exhaust-gas temperatures were determined by exposed single-junction iron-constantan and single shielded chromel-alumel thermocouples at planes B-B and C-C, respectively (fig. 1). Construction details of the temperature and pressure measuring instruments are presented in reference 2. The axial location of the exhaust-gas thermocouples corresponds approximately to the position of the turbine in the full-scale engine. Air

flow and fuel flow rates to the combustor were measured by a square-edged orifice and a calibrated rotameter, respectively.

For injection of the special fuel blend, a production-type, hollow-cone swirl nozzle was modified by enlarging the orifice in the nozzle tip to permit a liquid flow rate of 80 gallons per hour at a nozzle differential pressure of 100 pounds per square inch. An increased capacity was required because of the relatively low heating value of the fuel blend. The nominal angle of the resulting conical spray was 70°.

The single combustor was operated at the following conditions:

	Condition	
	A	B
Inlet-air pressure, in. Hg abs	39.8	53.9
Inlet-air temperature, °F	296	271
Exhaust-gas temperature, °F	1520	1110
Air flow rate, lb/sec	1.84	2.87

A test run of 2 hours' duration was conducted for conditions A and B. During each run, data were recorded for the determination of total-pressure drop through the combustor and the calculation of combustion efficiency. Values of combustion efficiency reported herein were approximated from a theoretical consideration that assumed complete combustion of the fuel to B_2O_3, CO_2, and H_2O. From the temperature rise through the combustor between planes B-B and C-C (fig. 1) and the operating fuel-air ratio, the enthalpy rise of the combustion products and the excess air were determined by using reference 3. Combustion efficiency was then calculated as the ratio of the enthalpy rise of these products through the combustor to the net heat of combustion of the fuel.

Engine Investigation

A standard production J33-9 turbojet engine was used for this investigation. The engine was instrumented to permit the measurement of engine speed, thrust, fuel consumption, and exhaust-gas temperature. Because of the low heating value of the trimethyl borate fuel blend, it was necessary to provide for a greater volume of fuel flow. To accomplish this, the engine was equipped with a dual-type fuel pump and duplex-type fuel nozzles.

The engine was to be operated at an engine speed of 11,500 rpm (maximum rated engine speed). Because of operational difficulties, however, it was necessary to reduce the engine speed after the first 45 minutes of engine operation. The tail pipe nozzle was adjusted to give an exhaust-gas temperature of 1300° F at rated engine speed. Engine data

were recorded at approximately 10-minute intervals so that any change in engine performance due to formation of boric oxide deposits in the engine could be detected.

When the supply of trimethyl borate fuel blend was exhausted, the engine was disassembled and the engine parts were inspected for deposits of boric oxide. Some of the engine parts having the greatest amount of deposits upon them were weighed and the deposits were then removed from the parts. The parts were then weighed in their clean state and in this way the amount of deposit on a weight basis was determined.

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RESULTS AND DISCUSSION

Single Combustor

Deposition. - A photograph of the J33 combustor liner and dome assembly after the 2-hour test at condition A (see APPARATUS AND PROCEDURE) is presented in figure 2. Excessive deposits composed of a white powder and a vitreous, amber material were present throughout the combustor and on the ignition spark plug. Less severe deposition occurred in the dome area of the combustor and on the fuel injection nozzle tip. A chemical analysis of both materials indicated a composition of 98 to 99 percent B_2O_3. No determination was made for the remaining impurities.

Similar results were obtained with a second J33 combustor operated at condition B. There was no noticeable change in deposition resulting from the decrease in exhaust-gas temperature. In both tests, the boric oxide coated the exhaust-gas duct with an even, vitreous coating approximately 1/8 inch thick. Deposits of the oxide were also present on the exhaust thermocouples and pressure rakes.

Extreme buildup of deposits generally occurred in areas surrounding the air entry holes of the liner. Since boric oxide solidifies at 842° and 1070° F for the crystalline and vitreous forms, respectively, it appeared that the cooler combustion air entering through these holes solidified the liquid material in the combustor. Because of the nature of the deposition, it is believed that minor combustor modifications, as might be employed to reduce carbon formation, would not result in any appreciable reduction in boric-oxide deposition. Significant reduction might, however, result from a large increase in inlet-air temperature, which would tend to retain the boric oxide in a fluid state.

Combustion efficiency. - Calculated combustion efficiencies for tests A and B were 82.3 and 82.2 percent, respectively. The over-all average exhaust-gas temperatures and, hence, combustion efficiency remained relatively constant throughout the tests. For comparison purposes, it may be noted that, at conditions similar to those used in the

present investigation, combustion efficiencies obtained with a typical MIL-F-5624A, grade JP-4 fuel would be in excess of 97 percent for this combustor.

Ignition. - Attempts to ignite the special fuel were unsuccessful at the starting conditions normally used with typical MIL-F-5624A jet fuels. Because the stoichiometric fuel-air ratio was much higher for the trimethyl borate blend, it was necessary to provide a substantial increase in the starting fuel rate before ignition was possible. Greatly diminished air flow rates were also required. It is doubtful that ignition could have been accomplished after a 2-hour period owing to excessive oxide deposits on the spark plug.

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Temperature distribution. - A plot of the exhaust-gas temperature distribution after 1 hour's operation at condition A is shown in figure 3. The data indicate that a relatively uniform temperature distribution exists despite excessive liner deposits. An evaluation of the exhaust-gas temperatures at 1-hour intervals for both test conditions yielded similar, symmetrical distributions.

Pressure drop. - Pressure drop through the combustor from planes A-A to D-D (fig. 1) showed a steady increase throughout both test runs. For condition B the pressure drop increased from 3.7 inches mercury absolute at the start of the run to 5.4 inches mercury absolute at its completion. A similar rate of increase was observed for condition A.

Engine Investigation

For this phase of the investigation 18,800 pounds of the trimethyl borate fuel blend were available. Because of the low heating value of this fuel blend, this quantity of fuel permitted operation of the engine for only 1 hour and 50 minutes. The rate at which boric oxide was formed in the products of combustion at rated engine speed was about 2420 pounds per hour. If a typical high-energy fuel had been used, the rate at which boric oxide would have been produced in this engine would be about 5820 and 7410 pounds per hour for diborane and pentaborane, respectively. Consequently, the accumulation of boric oxide on the engine parts of this investigation would be expected to be similar although possibly less than those that would be obtained if a high-energy fuel had been used.

Photographs of various engine parts as they appeared after 1 hour and 50 minutes of engine operation with the trimethyl borate fuel blend are shown in figures 4 to 12. The deposits that formed in the combustion chambers were generally white and crystalline, while the deposits formed downstream of the combustors were vitreous. This vitreous deposit had a reddish, amber color and was opaque. The deposits that formed with the trimethyl borate fuel were in all cases considerably thicker than those

reported in reference 1. The thickest deposits were found in the combustors and in the tail pipe. The turbine rotor was relatively free of boric-oxide deposits.

Combustor domes. - The engine used in this investigation has 14 combustors. The domes from combustors number 9, 10, and 14 are shown in figure 4. The deposits in the domes of combustors 9 and 14 are typical of most of the domes. The dome of combustor 14 contains a spark plug. The dome of combustor 10 is shown because it was one of two domes that were relatively free of deposits. The deposits on these parts were partly vitreous and partly crystalline. The crystalline deposits built up to a thickness of about 1/4 inch in some locations on the domes. The air spinner disks were completely plugged with a coating about 1/4 inch thick. The fuel nozzles were imbedded in the deposit on the spinner disks, but the fuel orifices were not closed in any one of the combustors. When the fuel nozzles were disassembled, none of the screens in the nozzles was plugged. There was a heavy deposit of boric oxide on the spark plug shown in dome number 14 but the gap was not closed.

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Burner liners. - The deposits formed in the burner liners are shown in figure 5. The deposits in these parts were the crystalline type and in some locations in the liner they built up to a thickness of $1\frac{1}{4}$ inches. Deposits such as this would certainly increase the pressure loss through the combustors and perhaps decrease the combustion efficiency. Toward the exit of the burner liners the deposit was the vitreous type and collected at the exit of the burners in large clumps of boric oxide as shown in figure 6. It appears that redesign of the combustors would be necessary for satisfactory operation of the engine with a high-energy fuel.

Turbine nozzle diaphragm. - The deposits that collected on the nozzle diaphragm are shown in figure 7. Most of this part was covered with a vitreous coating although there were some nozzle blades that were covered with a white powdery coating. At the locations between adjacent burner liners the build-up of boric oxide extended into the passages between some of the nozzle blades. This deposit would decrease the flow area through the nozzle diaphragm slightly.

Turbine rotor. - The deposits on the turbine rotor were very similar to those reported in reference 1. The coatings on the rotor blades were thin and vitreous and had radial flow lines on the blade surfaces, showing that the coating flowed along the blade length and was thrown from the blade tips (fig. 8). The turbine disk also had a very thin vitreous coating exhibiting radial flow lines that were similar to those formed on the turbine blades.

Tail cone. - The inside surface of the tail cone was coated with a uniform deposit of the amber-colored vitreous boric oxide, as shown in figure 9. Figure 9(a) is a view looking in the downstream direction. The coating was about 1/4 inch thick. The outside of the inner cone was coated in a similar manner (fig. 9(b)) as well as the heat shield in the inner cone of the tail cone. The deposit on the heat shield must have resulted from the circulation of combustion gas between the turbine rotor and the inner cone.

Tail pipe and tail pipe nozzle. - The inside of the tail pipe was covered with a ripply uneven coating of amber-colored vitreous boric-oxide deposit, as shown in figure 10. A maximum deposit thickness of about 1/2 inch was observed. The section of the tail pipe that shows a strip of very thin coating (the right side of the tail pipe in fig. 10) is immediately downstream of one of the struts in the tail cone. There were four such regions in the tail pipe corresponding to the four struts in the tail cone. These areas of thin coating can also be seen in figure 9(b). 2896

Rear turbine bearing cooling-air screens. - In a J33 engine, the rear turbine bearing is cooled by air which is pumped across the rear bearing housing by a small impeller on the front face of the turbine rotor. The cooling air enters and leaves the air pump through inlet and outlet screens as shown in figure 11. After the air passes through the outlet screen, it is discharged into the space between the combustors and the housing for the compressor and turbine shafts. In flight, the flow of cooling air through the impeller is augmented by the ram pressure existing in the engine nacelle.

In the present investigation, combustion gases leaked radially inward through the gap between the stator and the rotor, and boric-oxide deposits almost completely plugged the cooling-air exit screens as shown in figure 11. This condition may not be as severe in an airplane installation where ram pressure is available, but it is a condition that must be considered in a static installation. After the mixture of bearing cooling air and combustion gases passed through the discharge screens, a white powder was deposited on the outside of the combustors as shown in figure 12. These deposits, though rather thick as shown in figure 12(b), would have no effect on engine performance because they are on the exterior surface of the engine.

Weight of boric oxide deposited on various engine parts. - After all the fuel was used, the engine was disassembled and the engine parts exhibiting large amounts of deposits were weighed before and after they were cleaned so that the weight of the deposit formed on the various parts could be determined. The burner domes and liners of combustors number 9, 10, and 14 were chosen as typical, and the weights of deposits on these parts were used as a basis for calculating the weight of deposit

in all 14 combustors. Photographs of burner domes 9, 10, and 14 are shown in figure 4, and burner liner 14 is shown in figure 5. The weights of boric-oxide deposits on the engine parts are presented in the following table:

Part	Deposit, lb
Burner dome 9	0.16
10	0.03
14	0.18
Burner liner 9	1.63
10	1.36
14	1.55
Tail cone	6.88
Short tail-pipe section[a]	7.53
Nozzle diaphragm	2.31

[a]This is a short ($26\frac{1}{2}$ in.) section of tail pipe immediately downstream of the tail cone. This section is easily removed for quick inspection of turbine blades.

The deposits on the turbine blades and rotor disk were not weighed because they were so small they were considered negligible. The amount of deposits on the outside of the combustors (fig. 12) was not determined because this was a very light, powdery form of deposit; furthermore, much of the deposit on the combustors was unavoidably knocked off during disassembly of the engine and the weight would not be accurate.

From the weights in the preceding table, it was possible to estimate the total weight of boric oxide that was deposited on the various engine components, including the tail pipe, as about 61 pounds.

Effect of boric-oxide deposits on engine performance. - The variation of engine performance during the investigation is shown in figure 13, which presents the variation of engine speed, exhaust-gas temperature, fuel flow, and thrust with engine operating time. During the first 45 minutes of operation, there was little variation in engine performance. After 45 minutes of operation, the engine speed, exhaust-gas temperature, fuel flow, and thrust decreased steadily until the fuel supply was exhausted. It was not possible to maintain rated engine speed (11,500 rpm) by increasing the throttle opening, because opening the throttle did not increase the fuel flow. This indicated that there

was a restriction in the fuel lines upstream of the throttle. Prior to the start of this investigation, all fuel filters except one were removed from the fuel system in order to reduce fuel pressure losses to a minimum. At the conclusion of engine operation, the filter was examined and found to have an accumulation of a white powdery substance which apparently clogged the filter to such an extent that the fuel flow was restricted. When the drop in engine speed was observed, it was thought best to continue operation rather than shut the engine down to correct the difficulty because it was felt it might be difficult, if not impossible, to restart the engine once a large amount of deposits had formed within the engine. 2896

No change in the engine performance resulted from the build-up of deposits in the engine during the first 45 minutes of operation. No conclusions can be drawn concerning the effect of deposits on the engine performance after the first 45 minutes when the speed began to decrease because it is not possible to separate the effect of the fuel filter's plugging from the effects of the deposit formation on the engine components.

SUMMARY OF RESULTS

The results obtained in the investigation of a fuel mixture containing 70 percent trimethyl borate and 30 percent alcohol in a single J33 combustor and in a J33 turbojet engine are summarized as follows:

1. Extreme build-up of boric-oxide deposits generally occurred in areas surrounding the air entry holes in the liner of the single combustor.

2. The combustion efficiency of the single combustor operating on trimethyl borate fuel was about 82 percent, and remained constant throughout the tests. At conditions similar to those in the present investigation, combustion efficiency with MIL-F-5624A jet fuel (grade JP-4) would be in excess of 97 percent.

3. The exhaust-gas-temperature distribution near the outlet of the single combustor was relatively uniform in spite of the excessive boric-oxide deposits in the combustor.

4. The pressure drop through the single combustor increased steadily with operating time.

5. In the turbojet engine used in this investigation heavy deposits of boric oxide formed on nearly all of the engine parts exposed to the combustion gases. The boric-oxide deposits in the engine were heaviest in the combustors and on the outlet screen for the rear turbine bearing

cooling air. It appears that redesign of the combustors would be necessary for successful operation of the engine with high-energy fuel. In general, the heaviest boric-oxide deposits formed on the parts of the engine where the combustion gas was suddenly chilled. The deposits on the turbine blades were very thin.

6. The estimated total weight of boric oxide formed in the engine and tail pipe after 1 hour and 50 minutes of engine operation was 61 pounds.

7. The engine performance was not affected for about the first 45 minutes of operation. No conclusions could be drawn concerning the effects of deposits on the engine performance after the first 45 minutes of operation.

Lewis Flight Propulsion Laboratory
National Advisory Committee for Aeronautics
Cleveland, Ohio, March 25, 1953

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3. Huff, Vearl N., Gordon, Sanford, and Morrell, Virginia E.: General Method and Thermodynamic Tables for Computation of Equilibrium Composition and Temperature of Chemical Reactions. NACA Rep. 1037, 1951. (Supersedes NACA TN's 2113 and 2161.)

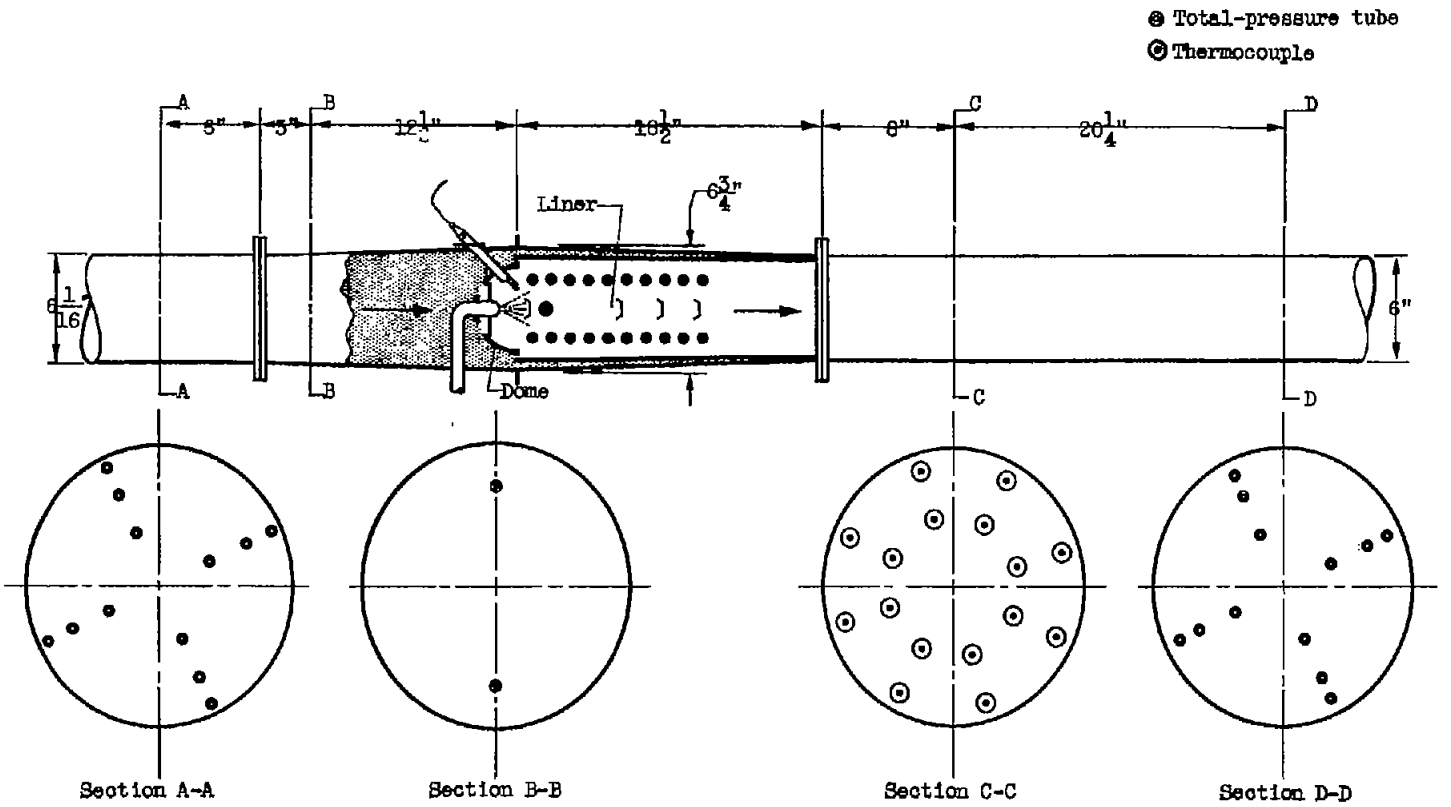

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Figure 1. - Cross section of J33 single-combustor installation, showing auxiliary ducting and location of temperature and pressure measuring instruments in instrumentation planes.

Figure 2. - J33 single combustor after 2-hour test run with trimethylborate - methyl alcohol fuel blend at condition A.

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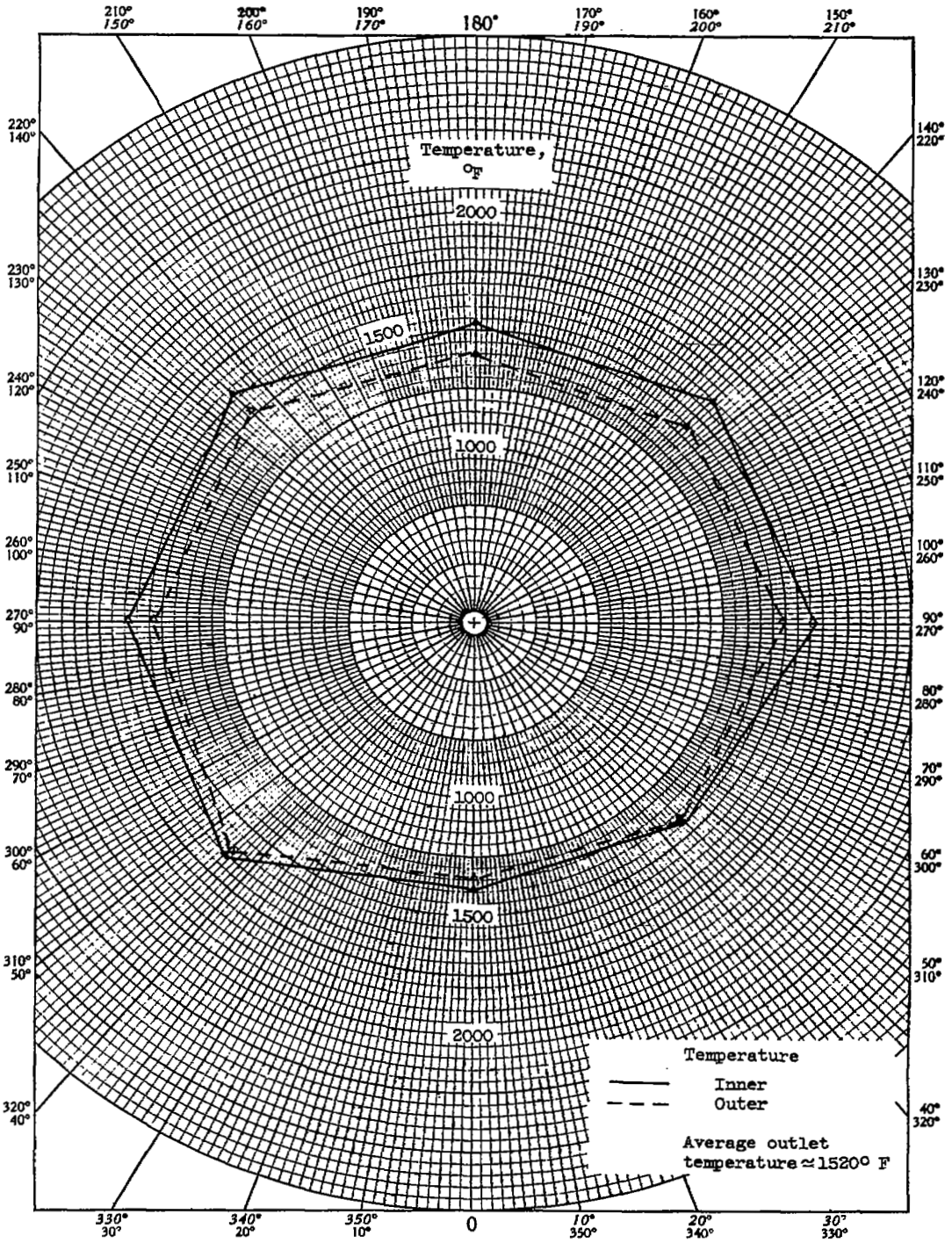

Figure 3. - Average combustor outlet temperature distribution for J33 single combustor after 1-hour operation with trimethyl borate - alcohol blend at condition A.

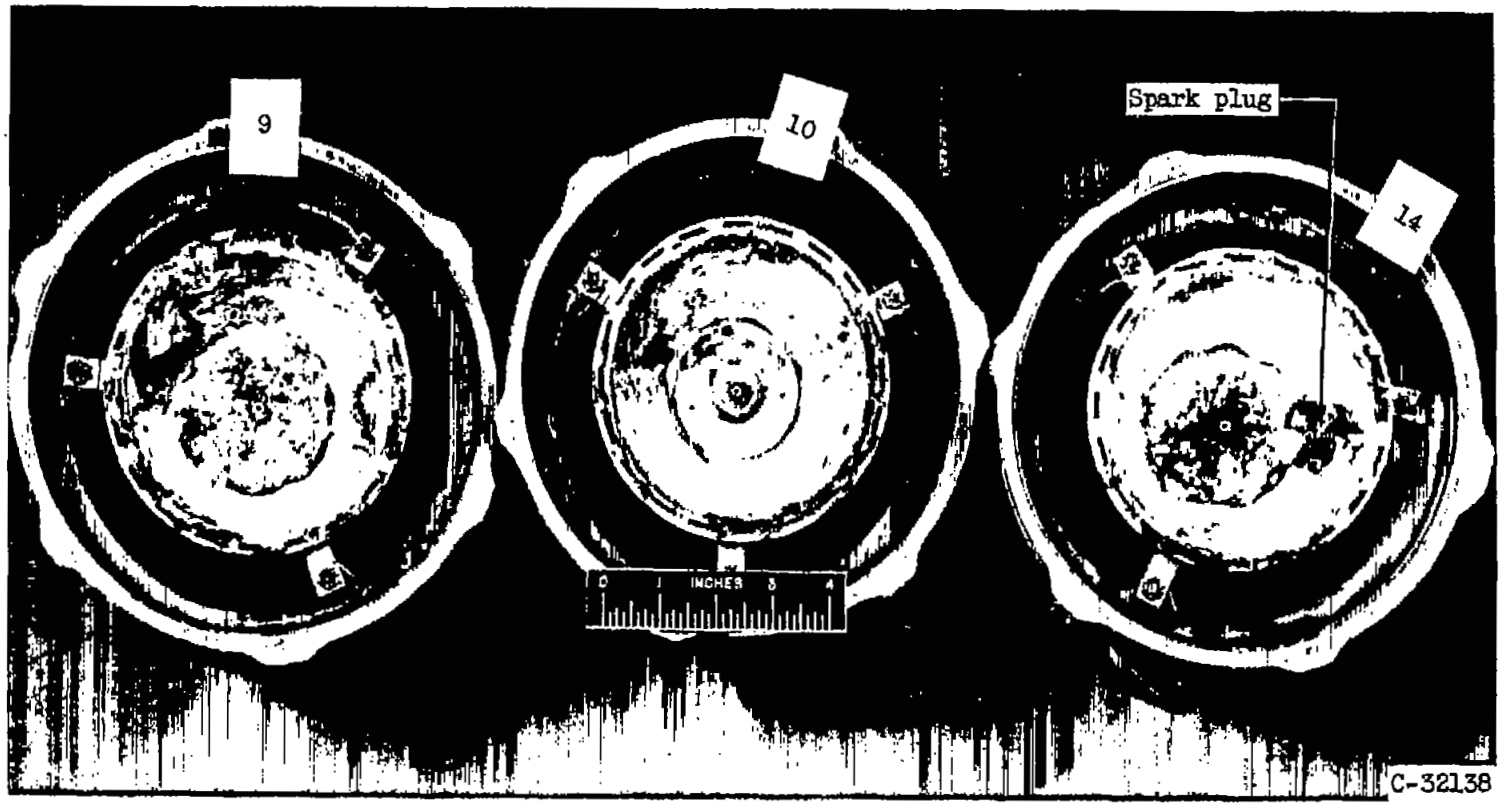

Figure 4. - Boric-oxide deposits on combustor domes and fuel nozzles of combustors 9, 10, and 14.

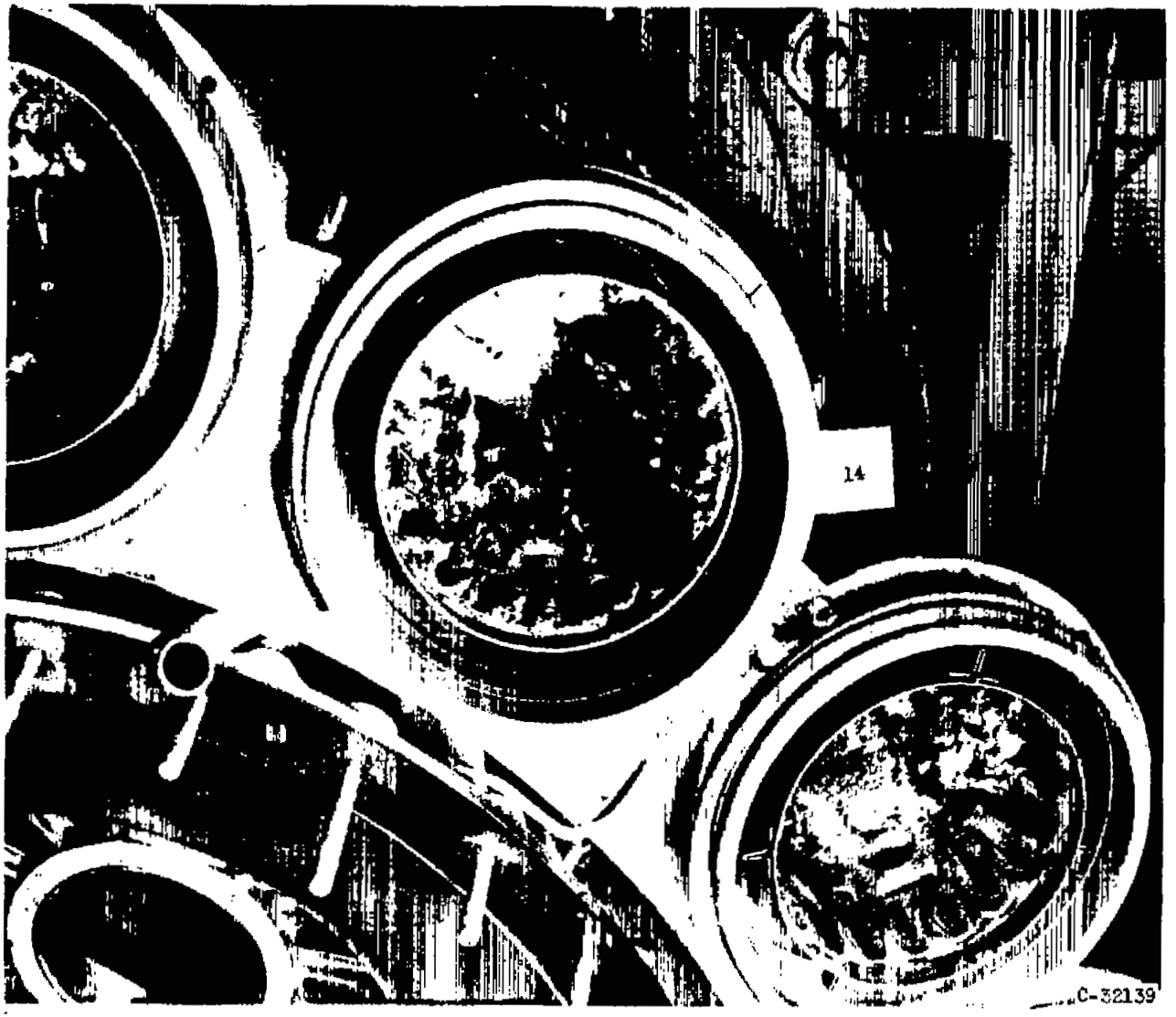

Figure 5. - Boric-oxide deposits on combustor liner 14. View looking downstream.

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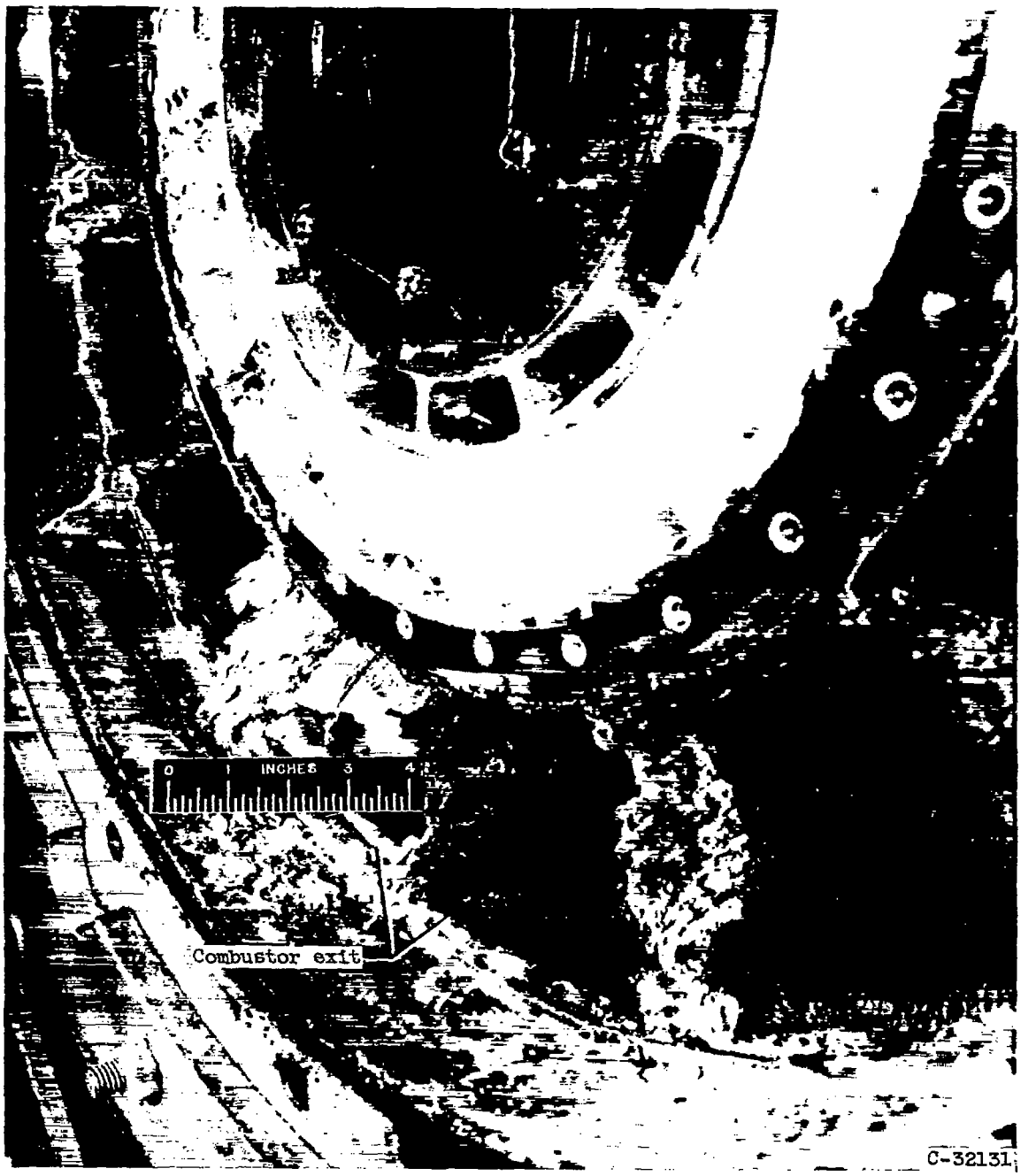

Figure 6. - Boric-oxide deposits at exit of combustors.

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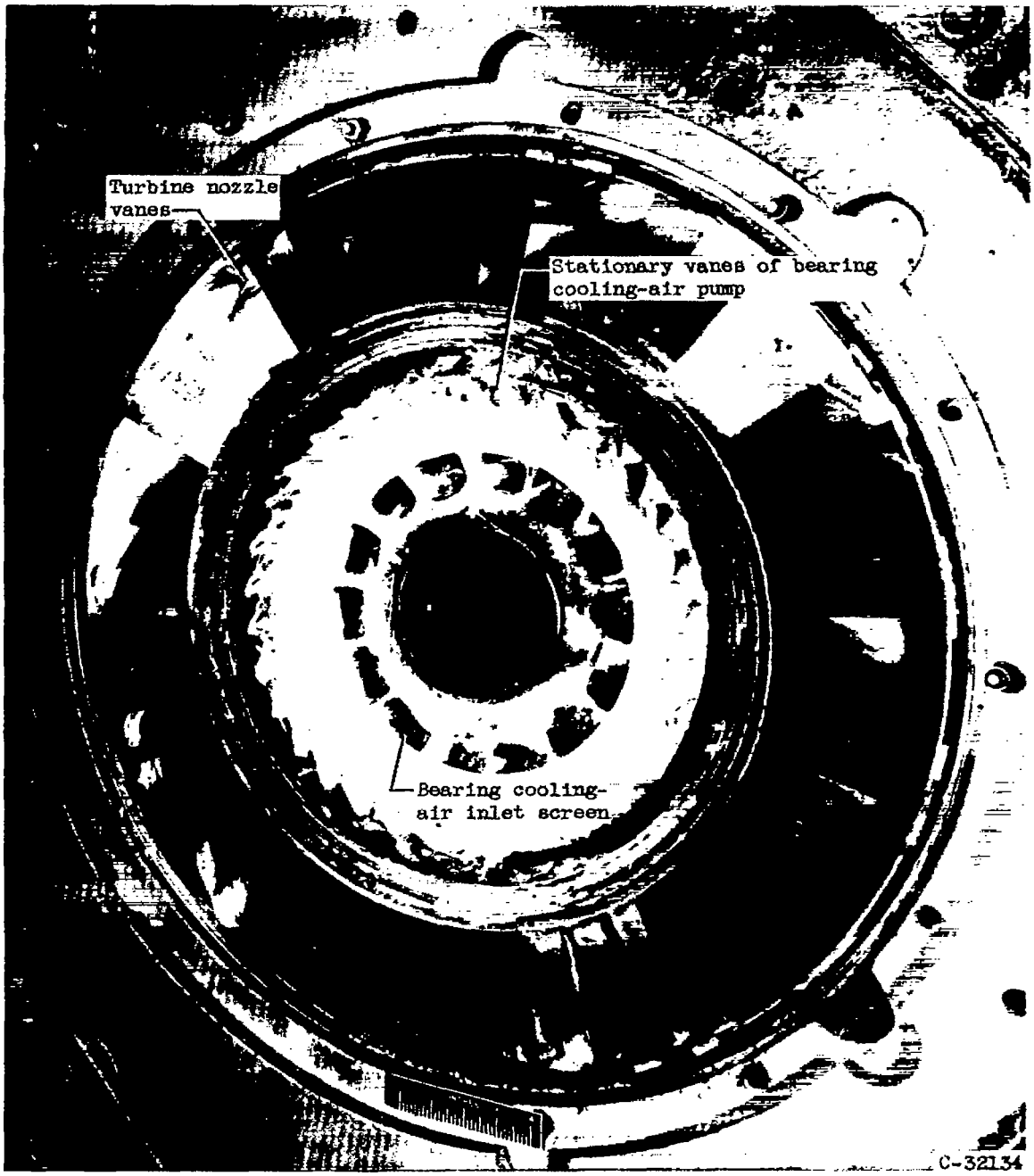

Figure 7. - Boric-oxide deposits on nozzle diaphragm and stationary vane of bearing cooling-air pump.

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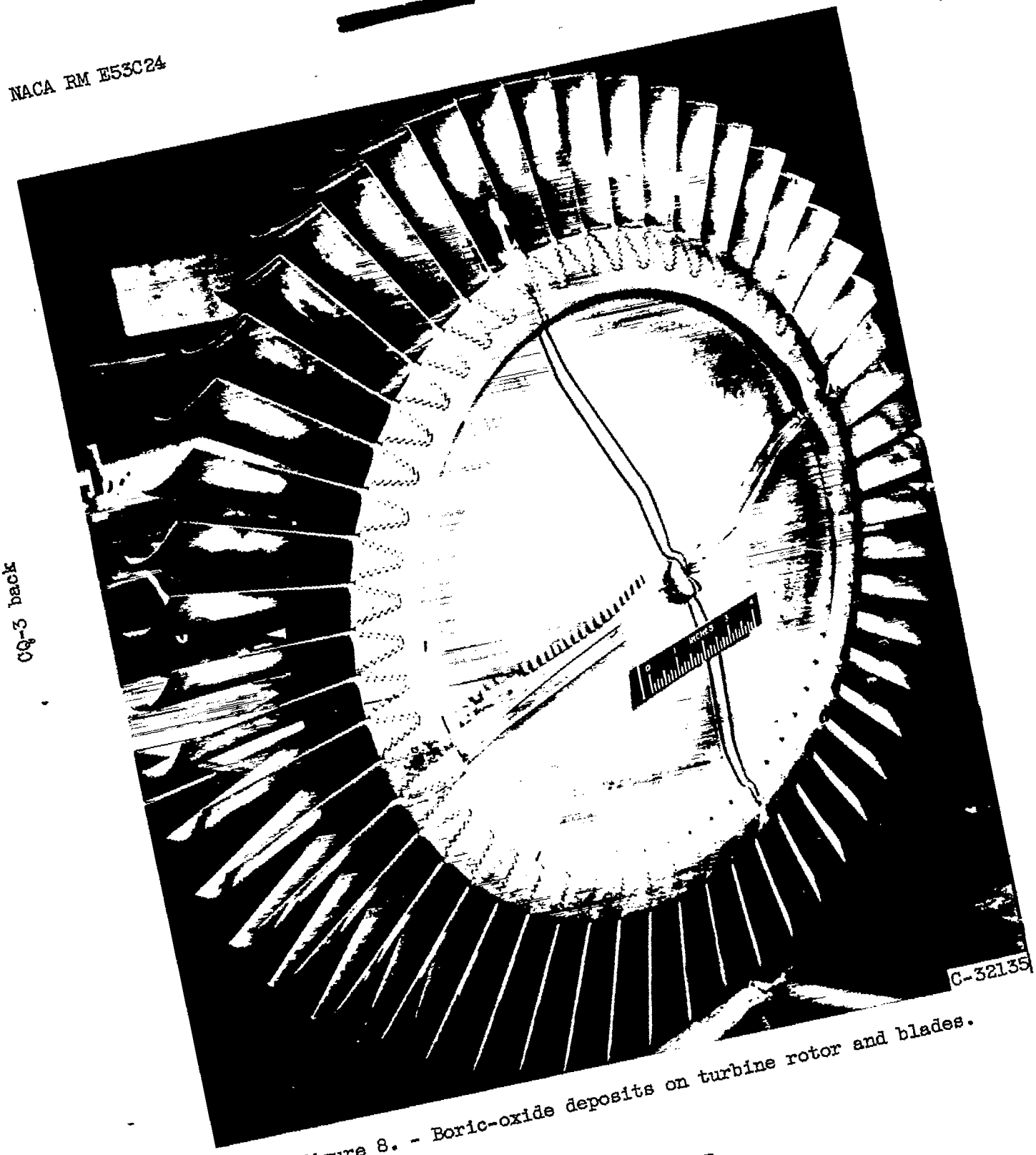

Figure 8. - Boric-oxide deposits on turbine rotor and blades.

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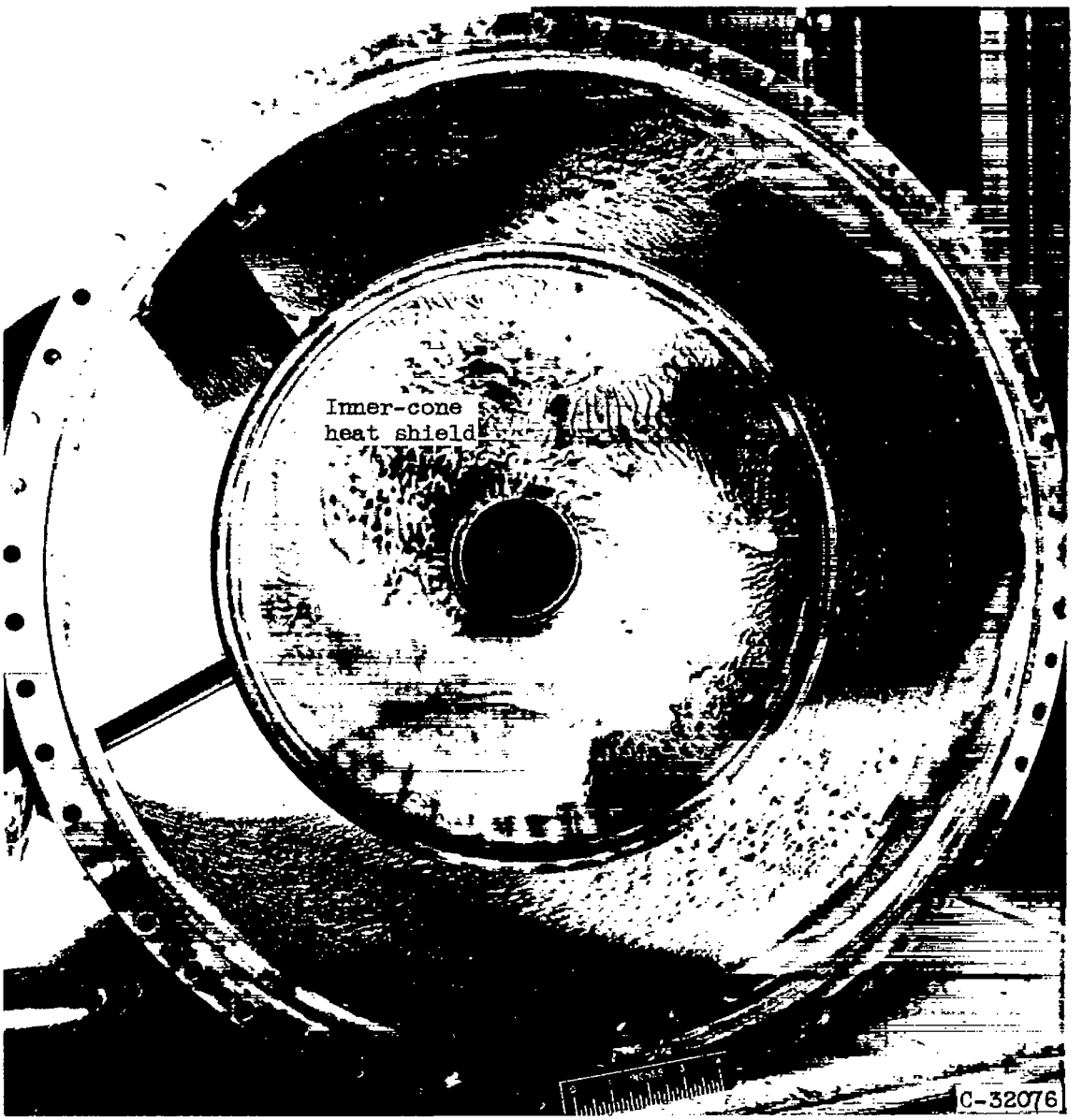

(a) View looking downstream.

Figure 9. - Boric-oxide deposits on inner surface of tail cone.

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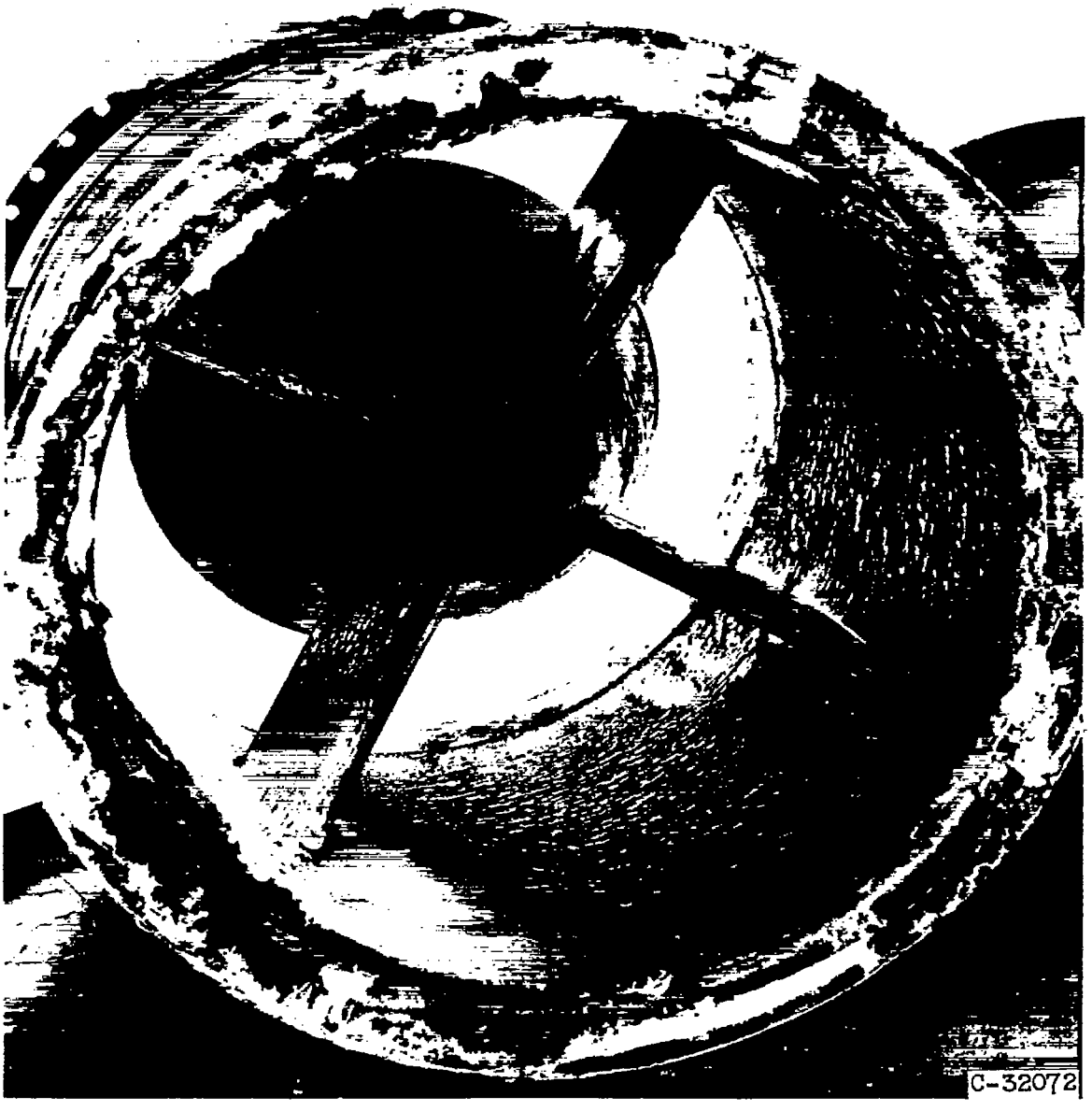

(b) View looking upstream.

Figure 9. - Concluded. Boric-oxide deposits on inner surface of tail cone.

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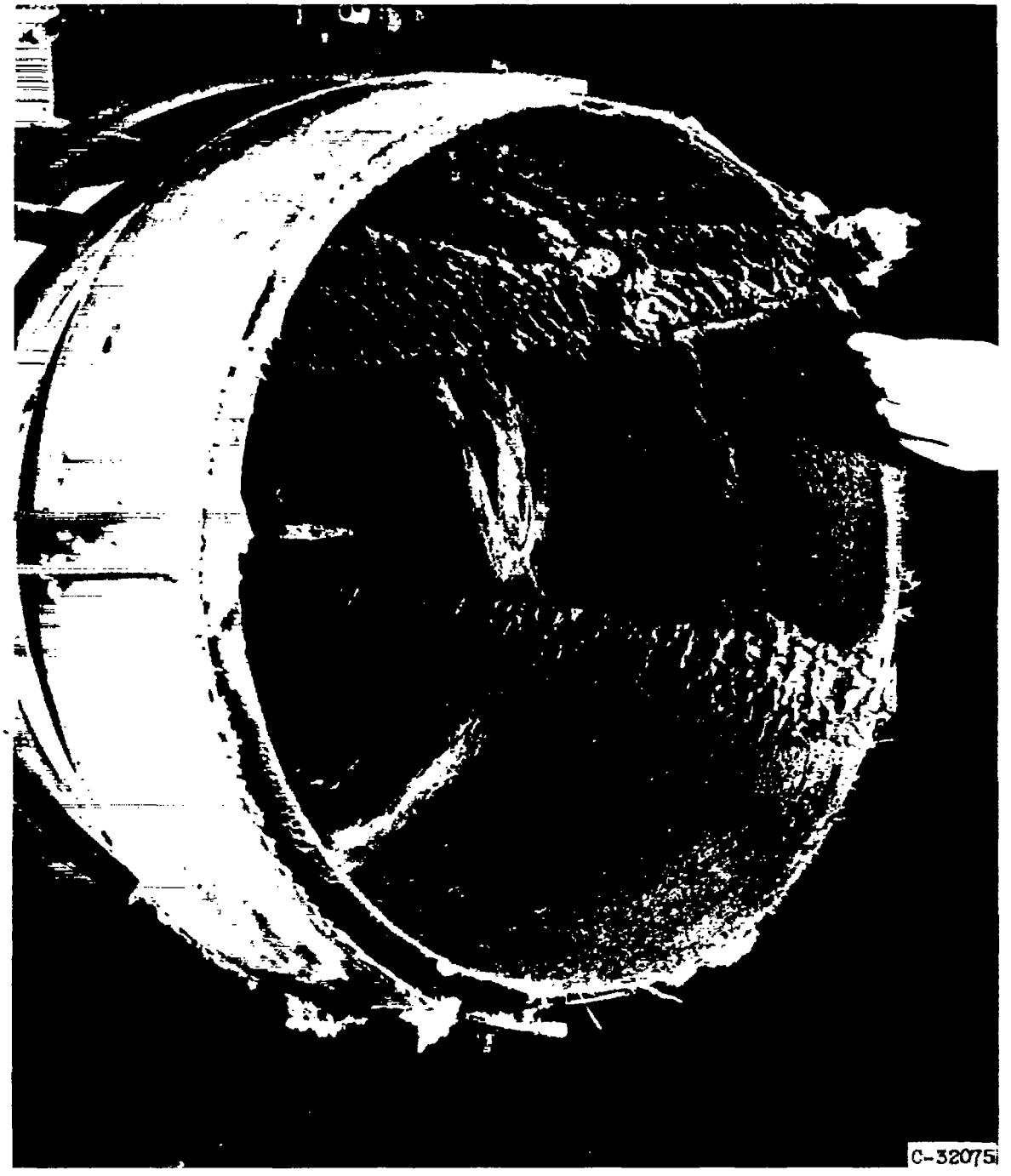

Figure 10. - Boric-oxide deposits at exit of tail pipe.

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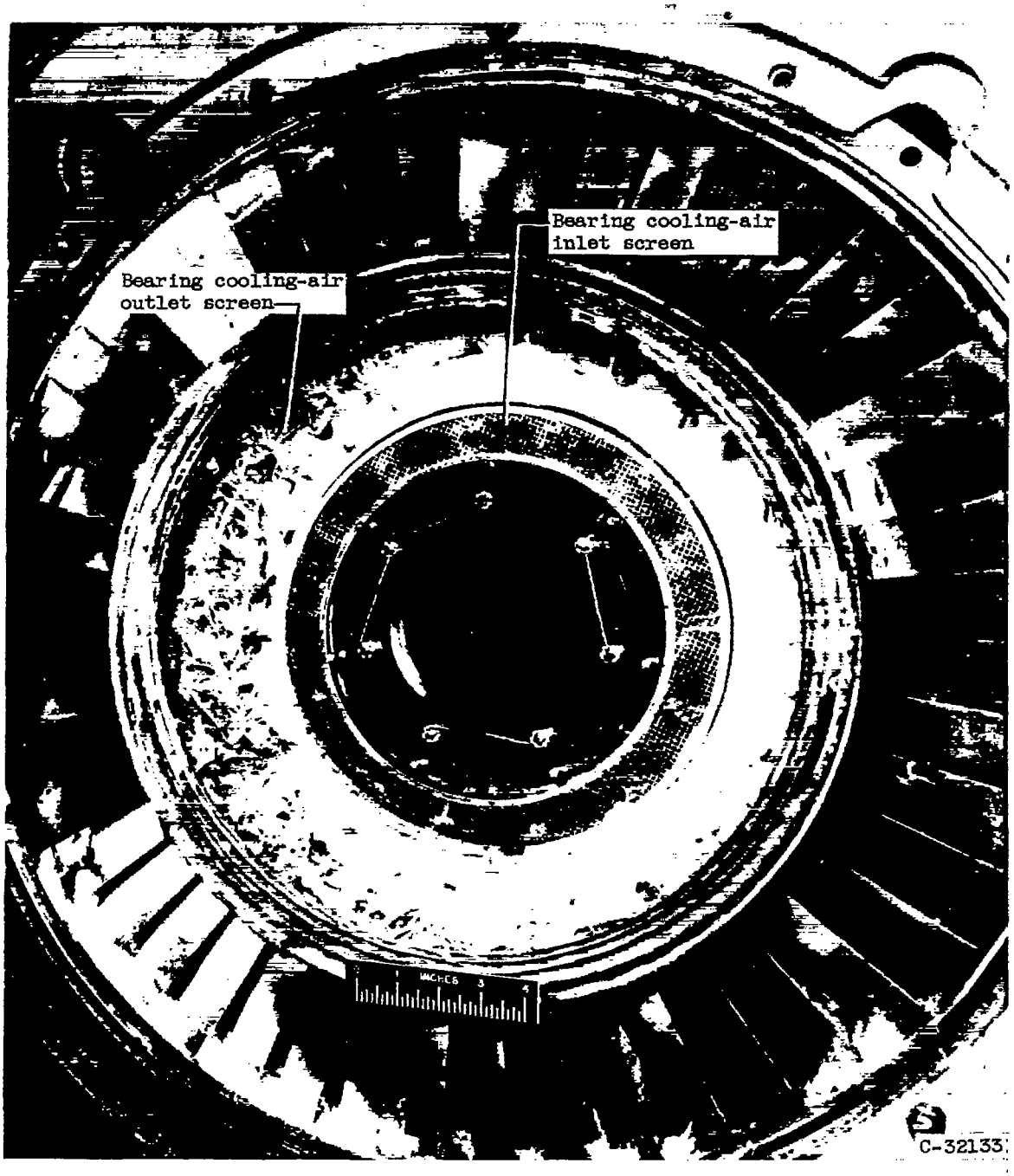

Figure 11. - Boric-oxide deposits on outlet screens in bearing cooling-air discharge passages.

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(a) View of combustor surfaces facing radially outward.

Figure 12. - Boric-oxide deposits on outer surface of combustors.

[redacted]

(b) View of combustor surfaces facing radially inward.

Figure 12. - Concluded. Boric-oxide deposits on outer surface of combustors.

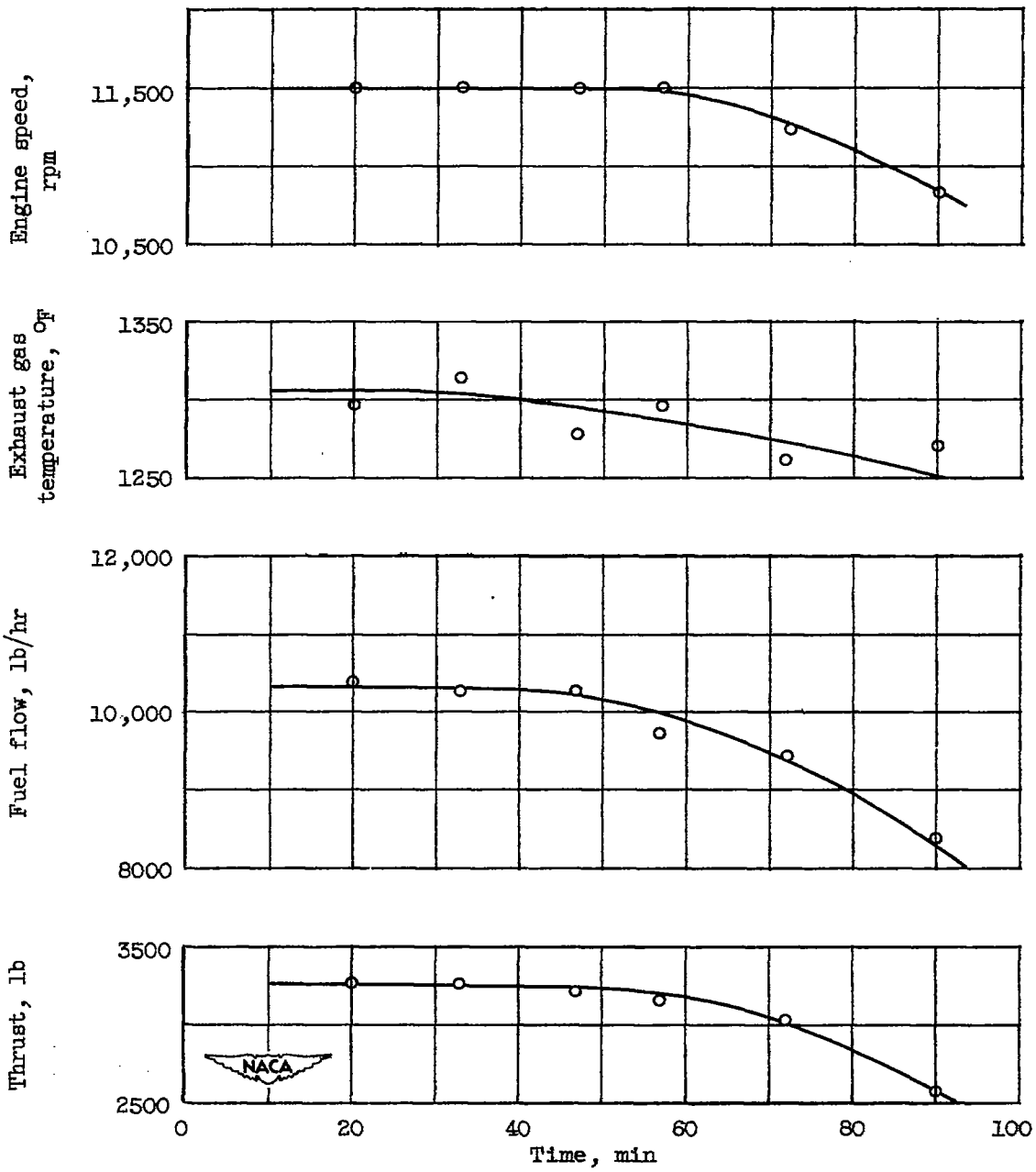

Figure 13. - Variation of engine performance with operating time when trimethyl borate - alcohol blend was used.

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