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RESEARCH MEMORANDUM

ALTITUDE PERFORMANCE OF AN AFTERBURNER WITH PENTABORANE FUEL

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NATIONAL ADVISORY COMMITTEE
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ALTITUDE PERFORMANCE OF AN AFTERBURNER WITH PENTABORANE FUEL

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SUMMARY

An investigation was conducted using pentaborane fuel in an afterburner operating at flight conditions simulating an altitude of 50,000 feet and a flight Mach number of 0.6. The total operating time was limited to $7\frac{1}{2}$ minutes because of the quantity of fuel available. No flame holder was required and spontaneous ignition of the fuel at the turbine-outlet temperature made an ignition source unnecessary.

Data were obtained at afterburner equivalence ratios from 0.15 to 0.40. The maximum combustion efficiency obtained with pentaborane was 88 percent as compared with 82 percent obtained with a typical afterburner using JP-4 fuel at the same afterburner inlet conditions. The maximum augmented thrust ratio obtained in this investigation was 1.46 with a specific fuel consumption of 2.12. At this thrust ratio, afterburner fuel consumption for the JP-4 fuel was approximately 40 percent greater.

INTRODUCTION

The continuing need for increased flight range and reduction in total gross weight of high-speed aircraft clearly emphasizes the desirability of a lower specific fuel consumption for both the turbojet engine and, in particular, its afterburner. Reference 1 points out that operational range as defined by the Breguet equation,

$$R_a = Kh_c\eta \frac{L}{D} \ln \frac{W_i}{W_t}$$

is directly proportional to the chemical heating value for constant efficiency of combustion. Therefore, the use of a fuel with a substantially increased heating value would provide reduced specific fuel consumption and increased flight range for a given tankage capacity.

The boron hydride fuels produce heat releases approximately 50 percent greater per pound than hydrocarbon fuels currently in use. Reference 2 predicts range increases of 51 percent when pentaborane is used in a turbojet engine. The inherently high specific fuel consumption accompanying turbojet afterburner operation prompted the present investigation of the use of pentaborane in an afterburner. The analysis of reference 2 assumes a combustor-outlet temperature below the vaporization temperature of the exhaust product, boron oxide. However, afterburners are usually operated at temperatures above the vaporization temperature of boron oxide. Consequently, a portion of the heat release from pentaborane will be absorbed in the vaporization of boron oxide, and the specific fuel consumption will not be reduced as much as would be indicated by the analysis of reference 2.

The investigation was conducted under conditions simulating flight at an altitude of 50,000 feet and a flight Mach number of 0.6 and was carried out in an NACA Lewis laboratory altitude test chamber as a part of Project Zip.

The data presented herein include the standard afterburner performance parameters of combustion temperature and efficiency, in addition to the augmented thrust ratios obtained and the required specific fuel consumption. Data were obtained at afterburner equivalence ratios from approximately 0.15 to 0.40.

APPARATUS AND INSTRUMENTATION

Afterburner Configuration

The afterburner (shown in fig. 1) used in this investigation was modified to permit the use of pentaborane and was equipped with a variable-area exhaust nozzle. Flow-straightening vanes were installed at the afterburner inlet station of the diffuser to provide more favorable gas-flow patterns. The gas velocity at the afterburner diffuser outlet was approximately 500 feet per second.

Pentaborane fuel was introduced through 30 fuel injectors placed $7\frac{1}{2}$ inches upstream of the aft end of the diffuser inner body. The fuel injectors were of the air-atomizing type and contained a single orifice in each tube (see detail in fig. 1). Alternate fuel injectors were immersed to depths of one-third and two-thirds the distance across the annular passage. Fuel was introduced normal to the air-flow direction.

No flame holder was required, although the shallow-dished blunt end of the diffuser body provided a low-velocity vortex region for flame stabilization. The pentaborane fuel is spontaneously ignitible at the temperature encountered at the fuel-injection station (1760° R), so that an ignition source was unnecessary.

Fuel Specifications

Pentaborane fuel of approximately 99 percent purity was supplied by the Bureau of Aeronautics, Department of the Navy, for this investigation. The fuel properties are as follows:

Formula weight	63.17
Melting point, $^{\circ}$F	-52
Boiling point, $^{\circ}$F at 760 mm Hg	136
Heat of combustion, Btu/lb	29,127
Specific gravity, 32° F	0.644
Stoichiometric fuel-air ratio	0.076
Pounds B_2O_3 per million Btu	94

Instrumentation

The afterburner inlet conditions of temperature and pressure were surveyed by three rakes with four thermocouples and three rakes with four thermocouples and five total-pressure probes. The rakes were placed approximately 60° apart. The afterburner exit contained a water-cooled total-pressure rake with ten probes placed on centers of equal area at the exhaust-nozzle inlet. The total-pressure probes of the water-cooled rake were of the purging type to preclude plugging with boron oxide. Four static-pressure probes were placed on the exhaust-nozzle lip to measure the ambient static pressure. The afterburner fuel flow was measured by a remote-indicating vane-type flowmeter. The atomizing air supplied to the fuel injectors was measured by a calibrated orifice. Detailed pressure and temperature instrumentation was installed throughout the engine to measure the basic engine performance.

PROCEDURE

All data were obtained with the engine operating at a Reynolds number index of 0.2, simulating flight at an altitude of 50,000 feet and a flight Mach number of 0.6. The engine inlet temperature, however, was not standard altitude temperature, but was 520° R. At this flight condition the afterburner inlet pressure was approximately 830 pounds per square foot absolute. The engine was operated at rated turbine discharge gas temperature (1760° R) and rated rotational speed. After the engine had reached an equilibrium condition, a small quantity of lead fuel (JP-4) was introduced through the fuel injectors to purge the system and cool the injectors to prevent decomposition of the initial pentaborane. The lead fuel was followed by the pentaborane fuel which ignited smoothly upon reaching the afterburner gas stream. Data were obtained at afterburner equivalence ratios (percent of stoichiometric fuel-air ratio) from approximately 0.15 to 0.40. The afterburner was operated at each equivalence ratio for a period of 1 to $1\frac{1}{2}$ minutes with data being taken at 15-second intervals. No data were obtained at equivalence ratios above 0.40 because of the small quantity of pentaborane available. Following afterburner operation with pentaborane fuel, the system was purged with JP-4 fuel and helium.

Throughout the investigation, the primary engine was operated with conventional hydrocarbon fuel, JP-4.

The data are presented in tabular form in table I. Appendix A contains a list of symbols used herein, and appendix B demonstrates the methods of calculation employed.

DATA PRESENTATION

Combustion performance. - The combustion temperature and combustion efficiency for the afterburner operating with pentaborane fuel are shown in figure 2. A maximum combustion efficiency of 88 percent was obtained with pentaborane. A representative afterburner operating at similar inlet conditions achieved a combustion efficiency of 82 percent using a hydrocarbon fuel (JP-4) as reported in reference 3.

Thrust augmentation. - The augmented net thrust ratio and accompanying specific fuel consumption are shown in figure 3. The augmented net thrust ratio is defined as the ratio of the net thrust of the combined engine and afterburner to the net thrust of the engine alone operating at the same flight condition. The maximum augmented thrust ratio obtained in this investigation was 1.46 at an equivalence ratio of 0.40 and a specific fuel consumption of 2.12. At this thrust ratio, where nearly all the boron oxide was vaporized, the afterburner fuel consumption for hydrocarbon fuel would be approximately 40 percent greater, assuming similar efficiency of combustion.

Boron oxide deposition. - The oxide deposition in the afterburner following $7\frac{1}{2}$ minutes of operation is shown in figure 4. Figure 4(a) shows the deposits that were formed on the diffuser body and the fuel injectors. The fuel injectors were maintained relatively free from deposits by the atomizing air supplied to the orifice. When the air supply to an individual injector failed, deposits were formed as shown on the injector to the left of bottom center.

The deposits on the afterburner and diffuser walls, the total-pressure rake at the exhaust-nozzle inlet, and the exhaust nozzle are shown in figure 4(b). This photograph, taken immediately after the test, shows the deposits before hydrolysis from atmospheric moisture occurred. The deposits on the afterburner and diffuser walls consisted of a thin transparent coat of glass.

The relatively minor boron oxide deposits shown in figure 4 presented no particular obstacle to the use of pentaborane in the afterburner configuration investigated.

Lewis Flight Propulsion Laboratory
National Advisory Committee for Aeronautics
Cleveland, Ohio, December 28, 1954

APPENDIX A

SYMBOLS

The following symbols are used in this report:

C_V	velocity coefficient
F	thrust, lb
f	fuel-air ratio
g	acceleration due to gravity, ft/sec^2
h	enthalpy, Btu/lb
h_c	lower heating value, Btu/lb
h_p	enthalpy of products per pound of engine air, Btu/lb
J	Joules constant, 778 ft-lb/Btu
K	constant
K_{ab},K_e	constants that convert the enthalpies of the combustion products to the same base as the heats of combustion of the fuels
L/D	over-all lift over drag of airplane
P	total pressure, lb/sq ft abs
p	static pressure, lb/sq ft abs
R	gas constant
R_a	range, miles
sfc	specific fuel consumption, lb/(lb)(hr)
T	total temperature, $^{\circ}$R
t	static temperature, $^{\circ}$R
V	velocity, ft/sec
W	gross weight, lb

w_a air flow, lb/sec

w_f fuel flow, lb/hr

w_p weight flow of products, lb/sec

γ ratio of specific heats

η combustion efficiency

Subscripts:

a air

ab afterburner

aug augmented

e engine

i initial

inj fuel injector

j jet

n net

t terminal

0 free stream

1 engine inlet

5 turbine outlet

9 exhaust-nozzle inlet

10 exhaust-nozzle outlet

APPENDIX B

METHOD OF CALCULATION

Combustion temperature. - The total and static temperatures of the afterburner combustion products were calculated from the following equation:

$$T_9 = \frac{1}{C_V^2} \frac{g}{R} \left(\frac{F_j}{w_{p,9}}\right)^2 \left[\frac{1}{\left(\frac{V_{eff}}{\sqrt{gRT}}\right)}\right]^2 \frac{1}{1 - x}$$

and

$$t_{10} = \frac{1}{C_V^2} \frac{g}{R} \left(\frac{F_j}{w_{p,9}}\right)^2 \left[\frac{1}{\gamma + 1 - \frac{p_0\left(1 + \frac{\gamma-1}{2}\right)^{\frac{\gamma}{\gamma-1}}}{P_9}}\right]^2 \frac{\gamma}{1 - x}$$

where F_j is the measured thrust, $\frac{V_{eff}}{\sqrt{gRT}}$ is the effective velocity parameter, and x is the weight fraction of the combustion products that are liquid. Equations upon which these equations are based are discussed in references 4 and 5.

Combustion efficiency. - The afterburner combustion efficiency was defined as follows:

$$\eta_{ab} = \frac{\left(1 + \frac{w_{a,inj}}{w_{a,5}}\right)h_{p,10} + \left(\frac{w_{p,10}}{w_{a,5}}\right)\left(\frac{V_{10}^2}{2gJ}\right) - h_{p,5} - \frac{w_{a,inj}}{w_{a,5}} h_{a,inj} - f_e(1 - \eta_e)K_e - f_{ab}K_{ab}}{f_e(1 - \eta_e)(18,700) + f_{ab}(29,127)}$$

where $h_{p,10}$, K_e, and K_{ab} are from unpublished NACA data based on thermodynamic data of reference 6. (All the combustion products were assumed to be in thermal and phase equilibrium at the nozzle exit.) The lower heating value of the JP-4 fuel was 18,700 Btu per pound, and that of the pentaborane was 29,127 Btu per pound.

Specific fuel consumption. - The specific fuel consumption was based on the net thrust and the total fuel flow as follows:

$$sfc = \frac{w_{f,e} + w_{f,ab}}{F_{n,aug}}$$

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5. 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.

6. 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.)

TABLE I. - TABULATED AFTERBURNER PERFORMANCE DATA

Run	Altitude ambient pressure, p_0, lb/sq ft abs	Engine inlet total pressure, P_1, lb/sq ft abs	Engine inlet total temperature, T_1, $^{\circ}R$	Engine inlet air flow, $w_{a,1}$, lb/sec	Turbine outlet total pressure, P_5, lb/sq ft abs	Turbine outlet total temperature, T_5, $^{\circ}R$	Exhaust-nozzle inlet total pressure, P_9, lb/sq ft abs	Engine fuel flow, $w_{f,e}$, lb/hr	Jet thrust, F_j, lb	Net thrust, F_n, lb	Air flow to fuel injectors, $w_{a,inj}$, lb/sec	Afterburner fuel flow, $w_{f,ab}$, lb/hr
1	320	425	520	20.33	837	1756	791	1339	1605	1169	0.37	754
2	324	427	520	20.33	856	1765	810	1343	1609	1174	.37	751
3	325	427	520	20.50	826	1760	781	1320	1609	1174	.37	751
4	326	425	520	20.33	841	1768	797	1343	1608	1181	.37	751
5	322	425	520	20.35	841	1787	796	1349	1625	1188	.36	772
6	346	428	520	20.43	840	1762	781	1333	1712	1328	.34	1521
7	346	429	520	20.46	833	1757	771	1326	1741	1353	.34	1560
8	348	429	520	20.48	831	1760	774	1333	1750	1367	.34	1557
9	339	430	520	20.51	830	1744	777	1320	1687	1279	.34	1187
10	339	425	520	20.35	808	1746	761	1306	1661	1265	.34	1184
11	336	425	520	20.35	809	1735	763	1306	1647	1244	.34	1110
12	338	425	520	20.35	809	1731	771	1295	1468	1070	.34	587
13	316	425	520	20.33	829	1746	794	1343	1552	1102	.34	537
14	346	425	520	20.33	814	1732	778	1306	1447	1072	.34	537

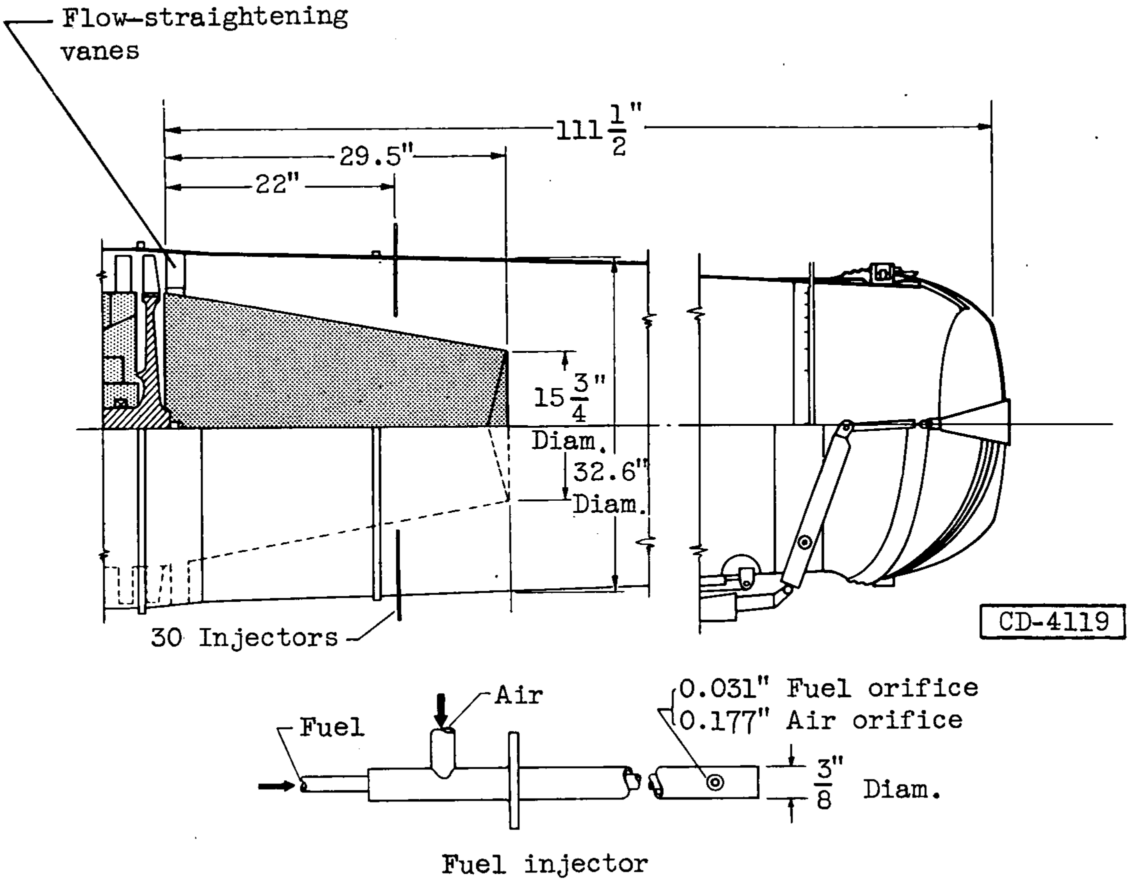
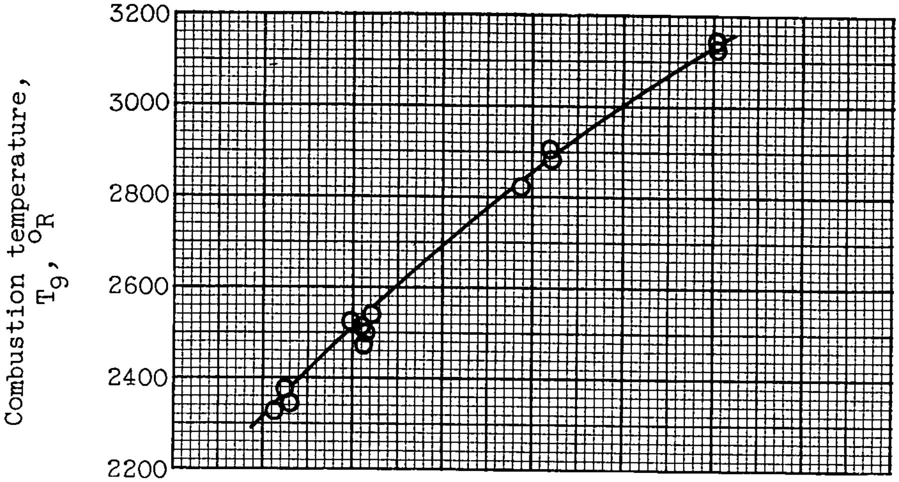
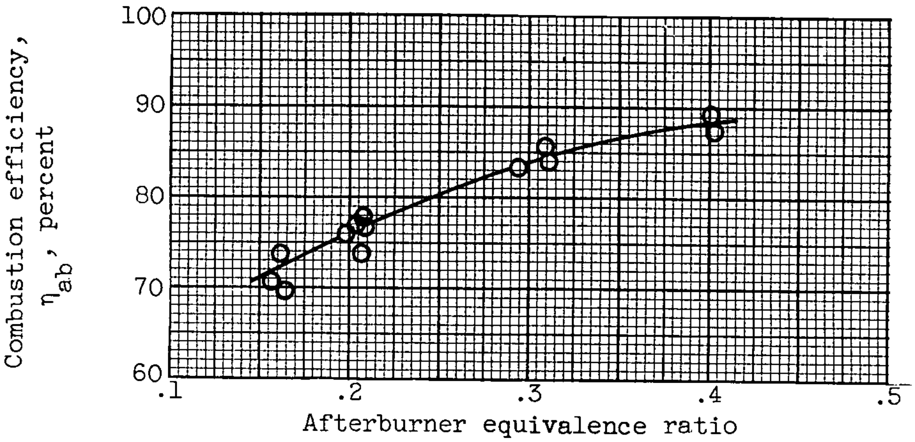


Figure 1. - Schematic diagram of afterburner configuration used in investigation of pentaborane fuel.

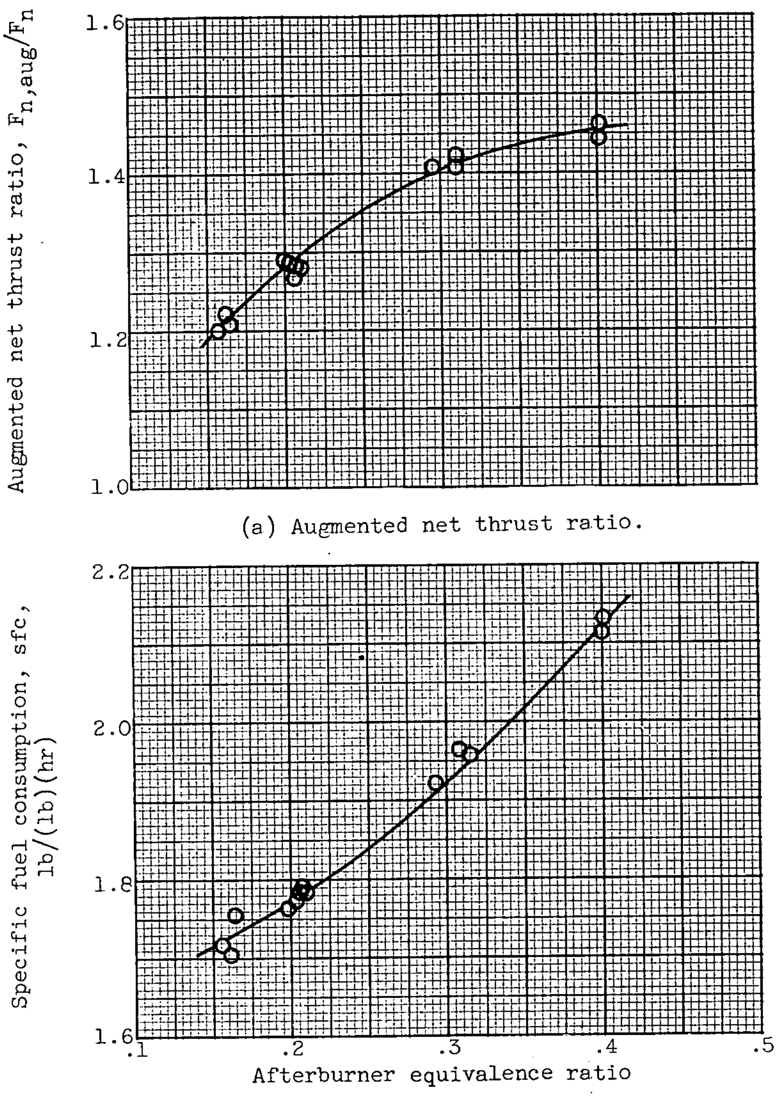


(a) Combustion temperature.



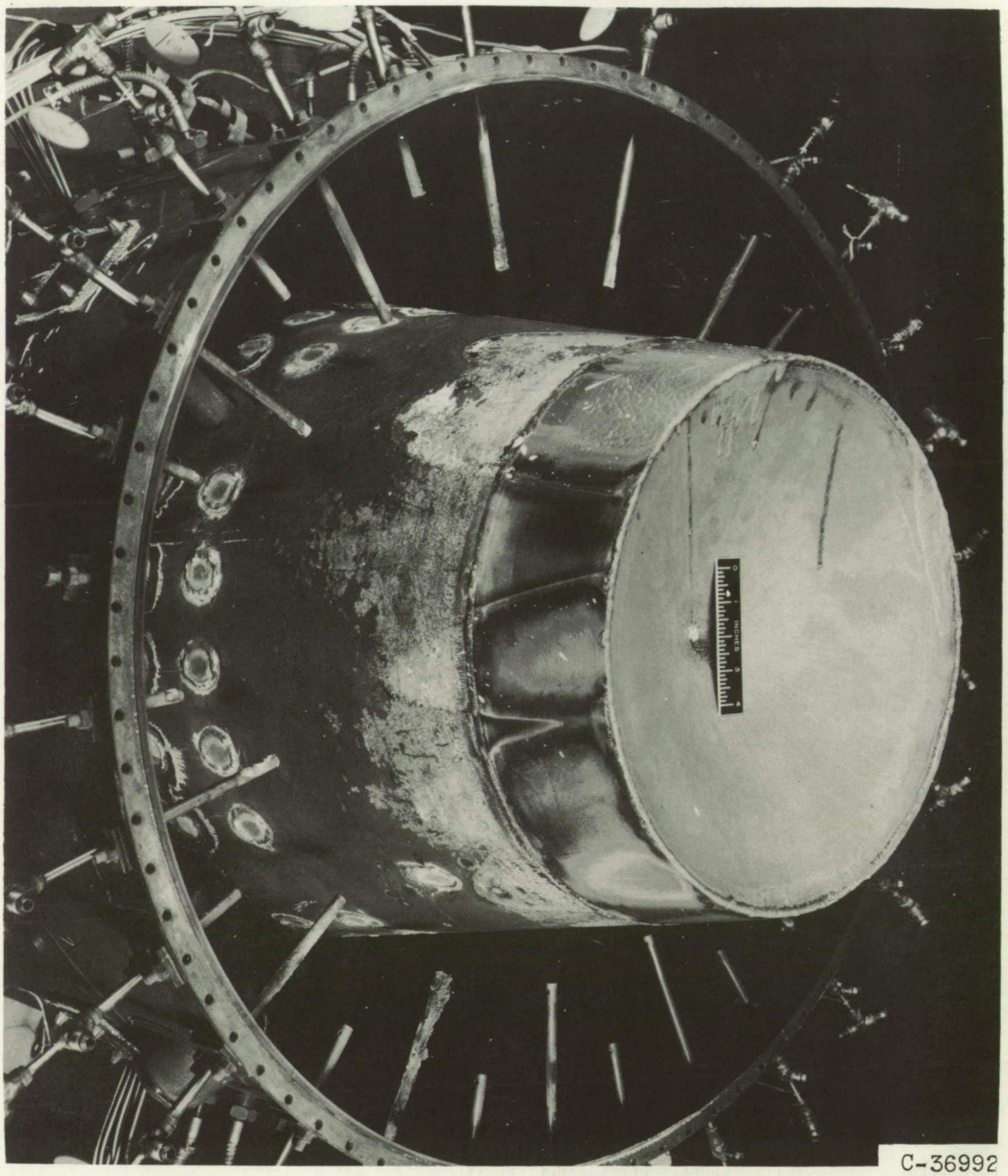
(b) Combustion efficiency.

Figure 2. - Combustion performance of turbojet-engine afterburner operating with pentaborane fuel. Altitude, 50,000 feet; flight Mach number, 0.6.



(b) Specific fuel consumption.

Figure 3. - Performance of turbojet-engine afterburner operating with pentaborane fuel. Altitude, 50,000 feet; flight Mach number, 0.6.



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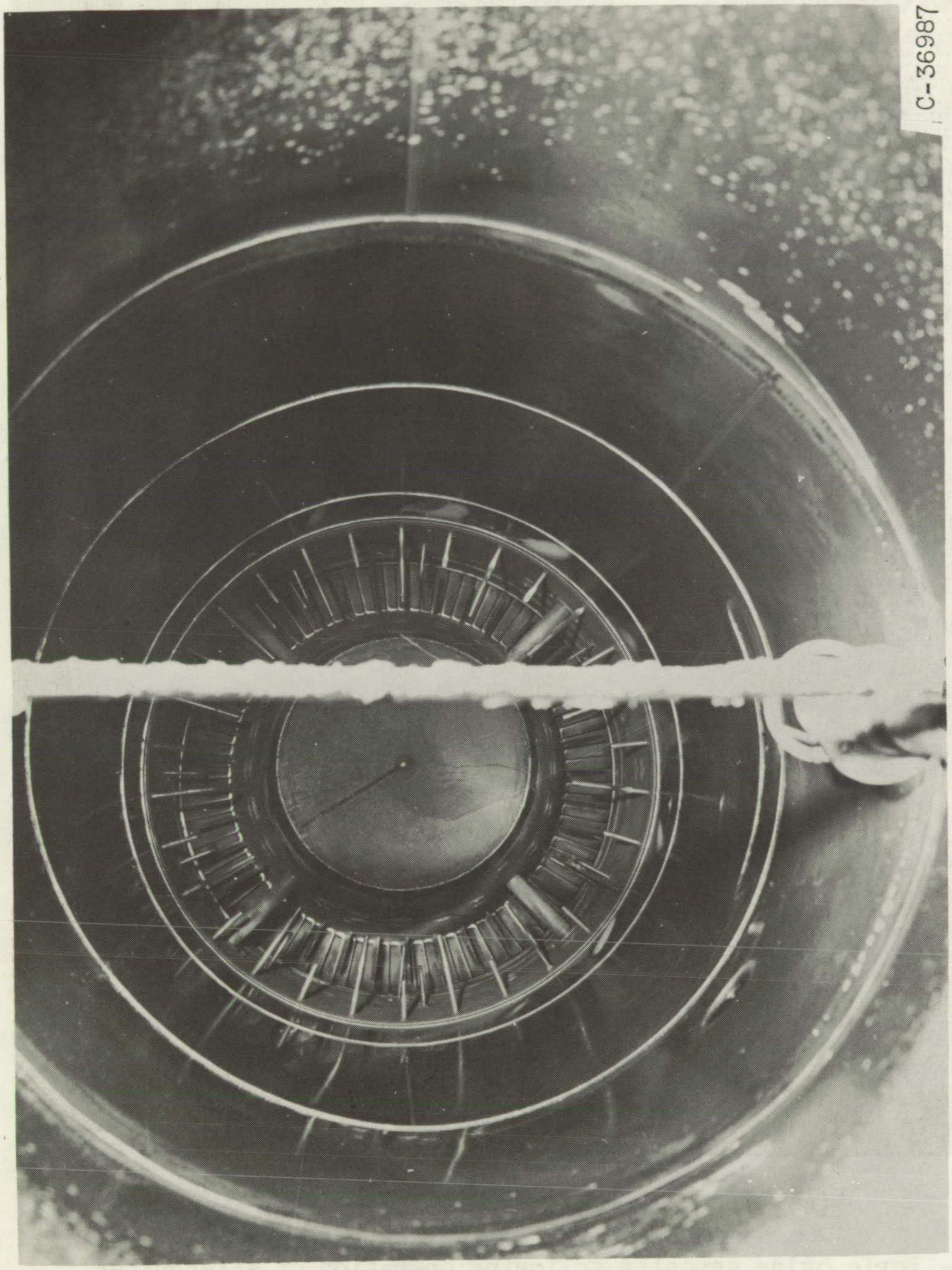
(a) Diffuser body and fuel injectors.

Figure 4. - Boric oxide deposits following operation of afterburner with pentaborane fuel. Altitude, 50,000 feet; flight Mach number, 0.6.



(b) Upstream view of afterburner wall.

Figure 4. - Concluded. Boric oxide deposits following operation of afterburner with pentaborane fuel. Altitude 50,000 feet; flight Mach number, 0.6.

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