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RESEARCH MEMORANDUM

ALTITUDE PERFORMANCE OF A FULL-SCALE TURBOJET ENGINE USING PENTABORANE FUELS (u)

By James W. Useller, Warner B. Kaufman, and William L. Jones

Lewis Flight Propulsion Laboratory
Cleveland, Ohio

NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

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RESEARCH MEMORANDUM

ALTITUDE PERFORMANCE OF A FULL-SCALE TURBOJET ENGINE USING PENTABORANE FUELS

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SUMMARY

A brief investigation of the use of 85 percent pentaborane - 15 percent hydrocarbon fuel (JP-4 fuel) and of 100 percent pentaborane fuel mixtures was conducted in a full-scale turbojet engine at a simulated altitude of 50,000 feet and a flight Mach number of 0.8. A total of 120 pounds of pentaborane was used, which limited the test period to about 11 minutes duration.

A tabular and graphical presentation has been made of both the standard engine performance parameters of net thrust, specific fuel consumption, and engine total-pressure ratio, as well as the engine component performance. Subsequent to operation of the engine with the pentaborane fuels, the engine was operated with JP-4 fuel to study the dissipation of the boric oxide deposits and the rate of return of the engine to the normal performance level.

INTRODUCTION

The range of operation of an aircraft can be shown to be a direct function of the heat released per pound of fuel consumed by the propulsion system. Assuming similar efficiency of combustion, the substitution of a fuel with an increased heat of combustion will result in a proportionate increase in the range of operation or a decrease in the specific fuel consumption.

The boron hydride high-energy fuels produce heat releases approximately 50 percent greater per pound of fuel than hydrocarbon fuels currently in use. Of the boron hydrides under consideration, pentaborane has been shown to exhibit promise as a turbojet-engine fuel. Therefore, full-scale turbojet-engine tests were undertaken in an NACA altitude test chamber (ref. 1). The limited availability of pentaborane precluded operation with pentaborane fuel for long periods of time. The investigation of reference 1 was limited to concentrations of pentaborane in JP-4 fuel of less than 42 percent because previous small-scale tests had shown that serious operational difficulties could be presented by the boric oxide deposits of higher concentration fuels. The effect of the oxide deposits was found to be comparatively innocuous at the concentrations investigated and further studies have been made using 85 and 100 percent pentaborane mixtures. The results of the later tests are reported herein.

The engine was operated at conditions simulating flight at an altitude of 50,000 feet and a Mach number of 0.8. This investigation was conducted at the request of the Bureau of Aeronautics, Department of the Navy, as a part of Project Zip. 3578

The data presented herein include the standard engine performance parameters of net thrust, specific fuel consumption, and engine total-pressure ratio that reflect the performance available from the use of pentaborane as a fuel. The influence of the boric oxide deposits from the high-concentration pentaborane fuels on engine component performance is presented. The combustion system used for pentaborane fuel had previously been developed in single-combustor tests by the General Electric Company.

Subsequent to operation of the engine with the pentaborane fuels, the engine was operated with JP-4 fuel to study the dissipation of the boric oxide deposits and the rate at which the engine performance approached normal values. These data are also presented herein.

APPARATUS

Engine. - A schematic sketch of the engine used in this investigation is shown in figure 1. The engine is a standard production model and contains a 12-stage axial-flow-type compressor, eight tubular combustion chambers, and a single-stage turbine. A variable-area exhaust nozzle permitted operation at the maximum allowable turbine-outlet gas temperature, 1250° F, and rated engine speed. The standard engine configuration was modified in that two special fuel nozzles of the atomizing type were installed in each of the combustion chambers as is shown in figure 2, and the turbine shroud was modified as is shown in figure 3 to increase the turbine tip clearance from the leading edge to the trailing edge of the turbine blade.

Fuel system. - A schematic diagram of the fuel system used with the pentaborane fuel is shown in figure 4. The pentaborane fuel was pressurized with helium forcing it from a suspended tank through metering devices into the special fuel nozzles. Provision was made for purging the pentaborane fuel lines with JP-4 and helium to reduce the handling hazards.

Fuels. - Pentaborane fuel of approximately 99 percent purity was supplied by the Bureau of Aeronautics for this investigation. The pentaborane fuel properties are as follows:

Formula weight	63.17
Melting point, °F	-52
Boiling point, °F at 760 mm Hg	136
Heat of combustion, Btu/lb	29,127
Specific gravity, 32° F	0.644
Stoichiometric fuel-air ratio	0.0764
Pounds of B_2O_3 per million Btu	94

Boric oxide, B_2O_3, exhibits the following melting points:

Crystalline, °F	842
Vitreous, °F	1070

Instrumentation. - Location of the instrumentation stations and the instrumentation at each station are shown in figure 1. The total-pressure probes downstream of the combustor were of the purge type to prevent contamination and plugging by the boron oxide. Engine air flow was measured at the engine inlet, station 1. The fuel flow was measured by Potter flow meters and the engine thrust was measured with a null-type thrust cell.

PROCEDURE

The duration of the pentaborane fuel operation was approximately 11 minutes and was limited by the small quantity of fuel available. Special operational and data-recording procedures were necessary. The procedure followed was to establish the engine operating condition with the use of JP-4 fuel and then transfer to the pentaborane fuel. Following approximately 3 minutes operation with 85 percent pentaborane - 15 percent JP-4 fuel mixture, the engine was operated for 6 minutes on 100 percent pentaborane. Engine speed and exhaust-gas temperature were held nearly constant by varying the fuel flow and exhaust-nozzle area. Data were taken at 15-second intervals. In so far as possible, the engine was held at constant operating conditions during the data-recording cycle.

Following the pentaborane fuel operation, the engine was shut down and inspected for boric oxide deposition. After this inspection, the engine was operated with JP-4 fuel to determine the rate of dissipation of the boric oxide deposits.

Data were adjusted to a condition which corresponds to a simulated altitude of 50,000 feet and a flight Mach number of 0.8. In addition to the application of the temperature and pressure adjustments required for NACA standard altitude conditions, the engine total-temperature ratio T_9/T_1 was adjusted to establish a constant T_9/T_1 equal to 3.3. The unadjusted data as taken during the investigation are presented in tabular form in table I. Appendix A contains a list of symbols used herein, and appendix B demonstrates the method of calculation employed.

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DATA PRESENTATION

Engine and component performance. - The standard engine performance parameters of net thrust, specific fuel consumption based on net thrust, and engine total-pressure ratio are shown in figure 5. The data shown at zero time are for operation with the conventional hydrocarbon fuel JP-4. The remaining data shown are for operation with an 85 percent pentaborane - 15 percent JP-4 mixture and with pure pentaborane fuel. Performance during the period of transition from one fuel to the other has been omitted.

The effect of operation with the high-concentration pentaborane fuels on the combustor and turbine performance is presented in figure 6. A cross plot of the data of figure 5 is shown in figure 7, where the change in specific fuel consumption is shown as a function of the pentaborane concentration in a hydrocarbon fuel. The data for concentrations up to 42 percent were taken from reference 1. The data for concentrations of 85 percent and pure pentaborane are from this investigation and are based on the minimum specific fuel consumptions encountered.

Boric oxide deposits. - Following the 11 minutes of operation of the engine with the 85 percent mixture and pure pentaborane, an inspection of the engine component parts revealed the deposits shown in figure 8. The nature of the vitreous deposits can be best seen in figures 8(c) and (d). Approximately 120 pounds of pentaborane were consumed, resulting in about 330 pounds of boric oxide. Of course, an appreciable quantity of this formation was carried off by the exhaust-gas stream.

Deposit dissipation. - Operation of the engine with JP-4 fuel subsequent to the use of the pentaborane fuels dissipated the boric oxide deposits, and the engine performance approached its normal value. The rate of dissipation and return to normal performance are shown in figure 9. Following 80 minutes of operation with JP-4 fuel, visual inspection revealed that only very moderate amounts of boric oxide remained on the engine components, as may be seen in figure 10.

Lewis Flight Propulsion Laboratory
National Advisory Committee for Aeronautics
Cleveland, Ohio, November 9, 1954

APPENDIX A

SYMBOLS

The following symbols are used in this report:

A	area, sq ft
F_d	thrust system scale reading, lb
F_j	jet thrust, lb
F_n	net thrust, lb
f	fuel-air ratio
g	acceleration due to gravity, ft/sec^2
h	enthalpy, Btu/lb
h_f	lower heating value of fuel, Btu/lb
K	thermodynamic constant
M	Mach number
m	mass flow, slugs/sec
N	engine speed, rpm
P	total pressure, lb/sq ft
p	static pressure, lb/sq ft
T	total temperature, $^{\circ}R$
V	inlet velocity, ft/sec
W_a	air flow, lb/sec
W_f	fuel flow, lb/hr
γ	ratio of specific heats
δ_1	ratio of engine-inlet total pressure P_1 to P at $M_1 = 0.8$; altitude, 50,000 ft

θ_a ratio of engine-inlet total temperature T_1 to T at $M_1 = 0.8$; altitude, 50,000 ft

η efficiency

Subscripts:

a air

b combustor

c compressor

cl compressor 12-stage leakage flow

m fuel manifold

mix pentaborane - JP-4 fuel mixture

t turbine

tl turbine cooling

0 free stream

1 engine inlet

3 compressor outlet

4 turbine inlet

5 turbine outlet

9 exhaust-nozzle inlet

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APPENDIX B

METHOD OF CALCULATION

The values used for specific heat at constant pressure, ratio of specific heats, and various enthalpies for air and hydrocarbon products of combustion were obtained from reference 2 and for pentaborane, from reference 3.

Engine air flow. - The compressor-inlet air flow was determined from total and static pressure and temperature measurements at the engine inlet, station 1. The compressor and turbine leakage was measured at two instrumented stations on the compressor and one on the turbine. Therefore,

$$W_{a,3} = W_{a,1} - W_{a,cl_1} - W_{a,cl_2} - W_{a,tl,1}$$

Thrust. - The jet thrust determined from the thrust-system measurements was calculated from the following equation:

$$F_j = F_d + A_s(p_1 - p_0)$$

where A_s is the area of the seal around the engine inlet.

The net thrust was determined by subtracting the inlet momentum from the jet thrust:

$$F_n = F_j - \frac{W_{a,1}V_0}{g}$$

When the test conditions deviated from the desired simulated flight conditions ($M_0 = 0.8$; altitude, 50,000 ft), the data were adjusted by the appropriate values of θ_a and δ_a.

Combustion efficiency. - The combustion efficiency of the engine combustor was defined as

$$\eta_b = \frac{(1 + f)h_{a,9} - h_{a,1}}{fh_c}$$

The JP-4 fuel combustion efficiency was determined from

$$\eta_b = \frac{h_a\Big]_{T_1}^{T_9} + f\left(\frac{A_m + B}{m + 1}\right)\Big]_{T_m}^{T_9}}{fh_f}$$

where $\frac{A_m + B}{m + 1}$ accounts for the difference between the enthalpy of carbon dioxide and water vapor in the burned mixture and the enthalpy removed from the air by their formation (ref. 2). The temperature of the fuel prior to entry into the engine is T_m.

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Pentaborane. - Pentaborane fuel combustion efficiency was calculated as follows:

$$\eta_b = \frac{(h_9 - h_{a,1}) - f(K)}{fh_f}$$

where h_9 and K are from NACA unpublished data based on thermodynamic data of reference 2.

Turbine efficiency. - The turbine efficiency was calculated from

$$\eta_t = \frac{1 - \frac{T_9}{T_4}}{1 - \left(\frac{P_5}{P_4}\right)^{\frac{\gamma-1}{\gamma}}}$$

A 5-percent total-pressure loss in the tailpipe was assumed as determined from previous tests.

REFERENCES

1. King, C. R., Breitwieser, Roland, and Sivo, J. N.: Preliminary Performance Evaluation of Blends of Pentaborane and JP-4 Fuel in a Full-Scale Turbojet Engine. NACA RM E54J05, 1957.

2. Turner, L. Richard, and Bogart, Donald: Constant-Pressure Combustion Charts Including Effects of Diluent Addition. NACA Rep. 937, 1949. (Supersedes NACA TN's 1086 and 1655.)

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.)

TABLE I. - TABULATED ENGINE PERFORMANCE DATA

Run	Fuel		Time of operation, min	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, °R	Compressor outlet total pressure, P_3, lb/sq ft abs	Compressor outlet total temperature, T_3, °R	Combustor outlet total pressure, P_4, lb/sq ft abs	Exhaust-nozzle inlet total pressure, P_9, lb/sq ft abs	Exhaust-nozzle inlet total temperature, T_9, °R	Engine speed, N, rpm	Engine-inlet air flow, $W_{a,1}$, lb/sec	Compressor outlet air flow, $W_{a,3}$, lb/sec	Turbine outlet air flow, $W_{a,5}$, lb/sec	Engine fuel flow W_f, lb/hr	Jet thrust, F_j, lb	Net thrust, F_n, lb
	JP-4, percent by weight	Pentaborane, percent by weight																
1	100	0	----	334	423	520	2224	922	2107	783	1687	7792	19.53	19.07	19.19	1258	1279	879
2	100		----	336	423	520	2227	921	2110	782	1692	7799	19.53	19.07	19.19	1258	1276	880
3	100		----	336	423	520	2227	922	2110	786	1692	7797	19.53	19.07	19.19	1253	1279	883
4	100		----	336	420	520	2235	922	2119	786	1692	7799	19.45	18.99	19.11	1253	1274	886
5	100		----	336	420	520	2231	922	2114	784	1691	7801	19.45	18.99	19.11	1253	1272	884
6	100	0	0	336	420	520	2232	922	2115	783	1660	7801	19.45	19.00	19.12	1253	1260	872
7	16.20	83.80	2.5	333	419	520	2196	909	2079	753	1724	7794	19.43	18.98	19.10	938	1267	874
8	14.93	85.07	2.7	338	419	520	2245	925	2128	754	1720	7961	19.68	19.21	19.33	931	1271	885
9	15.64	84.36	3.1	340	420	520	2207	932	2091	751	1695	7803	19.45	18.99	19.11	889	1238	860
10	15.65	84.35	3.4	343	420	521	2194	920	2078	756	1700	7704	19.18	18.71	18.83	888	1222	856
11	15.56	84.44	3.7	340	423	520	2180	915	2065	752	1697	7685	19.29	18.83	18.95	887	1230	849
12	15.37	84.63	4.0	340	423	521	2174	914	2059	742	1688	7740	19.27	18.82	18.93	885	1217	836
13	15.37	84.63	4.3	340	420	520	2192	916	2077	741	1697	7748	19.45	18.99	19.11	885	1230	852
14	15.09	84.91	4.6	340	423	521	2233	917	2117	756	1764	7854	19.52	19.06	19.18	888	1273	887
15	0	100	4.9	333	419	520	2281	922	2164	769	1722	7985	19.68	19.21	19.33	861	1295	897
16	0	100	5.2	334	420	521	2233	936	2117	748	1776	7819	19.43	18.97	19.09	813	1277	884
17			5.5	340	420	521	2223	926	2107	752	1715	7788	19.44	18.98	19.10	804	1245	866
18			5.8	336	420	521	2206	922	2091	746	1710	7726	19.19	18.75	18.87	804	1232	849
19			6.1	340	423	521	2213	917	2099	749	1726	7733	19.27	18.80	18.92	808	1236	855
20			6.5	334	423	521	2211	914	2097	745	1722	7772	19.27	18.83	18.95	825	1246	851
21			6.8	343	420	521	2200	920	2085	732	1705	7722	19.44	19.00	19.12	813	1219	848
22			7.1	343	422	521	2192	917	2078	734	1720	7696	19.24	18.78	18.90	827	1212	841
23			7.4	347	420	520	2212	916	2098	735	1720	7713	19.21	18.74	18.86	837	1202	846
24			7.7	347	423	521	2224	916	2111	743	1726	7742	19.27	18.82	18.94	859	1219	855
25			8.1	347	423	521	2228	919	2115	740	1732	7744	19.27	18.80	18.92	861	1216	852
26			8.4	347	423	521	2230	920	2117	743	1733	7751	19.27	18.81	18.93	866	1220	856
27			8.9	347	419	522	2241	923	2127	742	1733	7757	19.40	18.93	19.05	872	1227	869
28			9.5	364	423	521	2248	923	2134	736	1736	7755	19.52	19.05	19.17	870	1194	871
29			10.1	361	427	521	2244	922	2131	735	1737	7715	19.37	18.91	19.03	870	1191	853
30			10.5	361	422	521	2242	921	2129	737	1736	7687	19.24	18.78	18.90	870	1184	860
31			10.8	357	427	521	2242	919	2129	739	1748	7672	19.37	18.91	19.03	870	1207	858
Dissipation of deposits with JP-4 fuel																		
32	100	0	0	334	427	517	2260	915	2143	730	1656	7803	19.69	19.21	19.34	1263	1229	820
33			7	339	427	519	2255	923	2139	767	1693	7792	19.65	19.17	19.29	1274	1265	867
34			11	334	428	521	2251	923	2135	772	1688	7799	19.64	19.17	19.29	1263	1278	866
35			17	334	427	519	2235	921	2119	775	1679	7783	19.41	18.92	19.04	1255	1260	855
36			22	334	424	520	2236	923	2120	779	1691	7797	19.31	18.83	18.95	1253	1262	864
37			30	332	427	520	2244	922	2128	790	1681	7799	19.63	19.17	19.29	1260	1293	878
38			36	334	427	520	2247	921	2130	794	1684	7792	19.63	19.16	19.28	1263	1293	883
39			45	334	427	520	2240	923	2124	791	1681	7803	19.63	19.16	19.28	1258	1289	879
40			52	335	427	520	2237	922	2121	796	1686	7792	19.63	19.16	19.28	1258	1293	885
41			59	339	427	521	2237	923	2121	792	1687	7794	19.61	19.14	19.26	1258	1281	883
42			62	342	427	522	2237	923	2121	795	1687	7797	19.59	19.12	19.24	1260	1276	885
43			67	341	427	519	2240	921	2124	795	1687	7794	19.65	19.18	19.30	1263	1283	890
44			77	335	427	520	2237	922	2121	795	1686	7794	19.63	19.16	19.28	1258	1293	885

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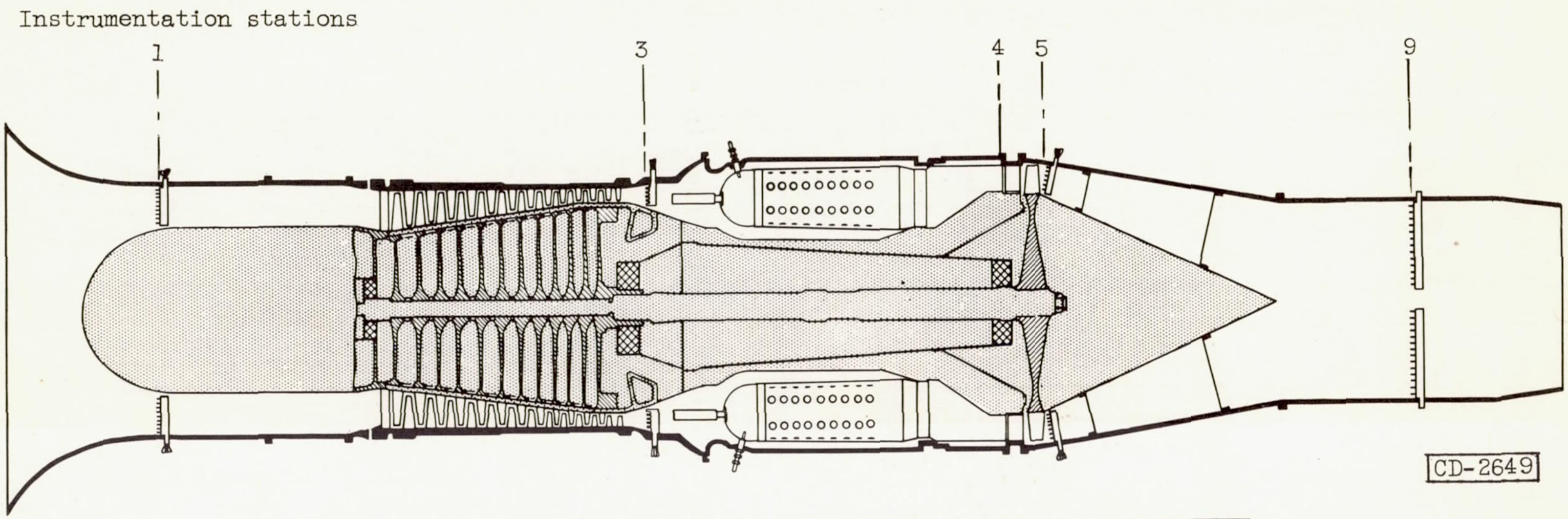

	Sta-tion	Instrumentation		
		Static pressure	Total pressure	Total temperature
Engine inlet	1	8	24	12
Compressor outlet	3	2	12	12
Combustor outlet	4	-	8	16
Exhaust-nozzle inlet	9	-	12	12

Figure 1. - Schematic sketch of turbojet-engine installation.

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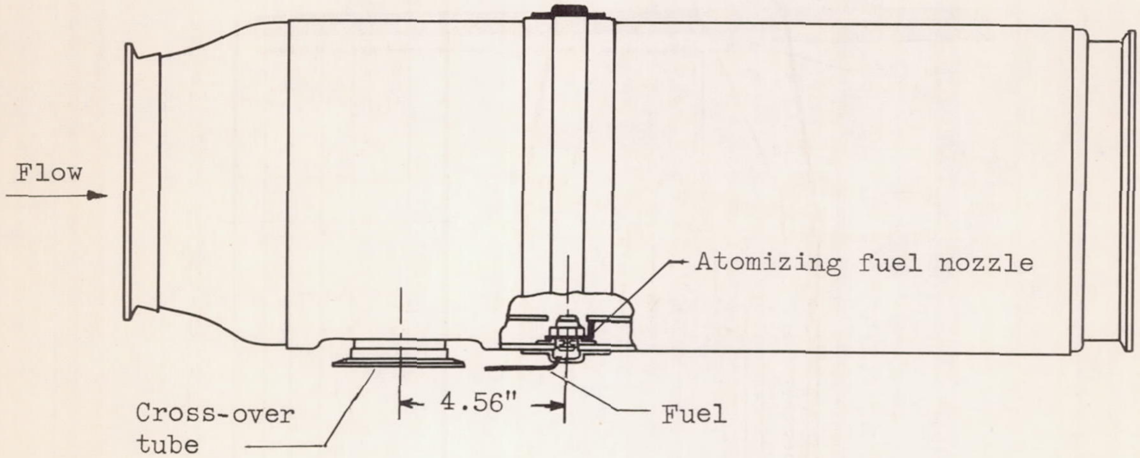

Figure 2. - Conical flow fuel nozzle installed in engine combustion chamber.

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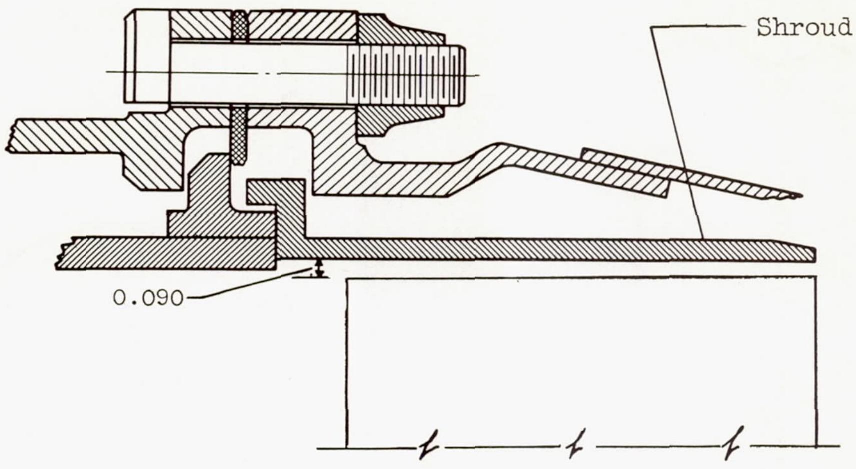
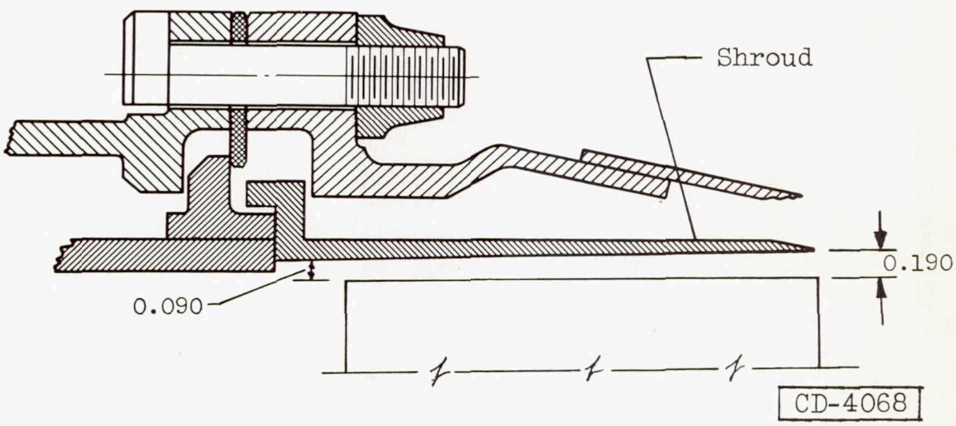


(a) Standard turbine shroud.



(b) Modified turbine shroud.

Figure 3. - Cross section of standard and modified turbine shroud.

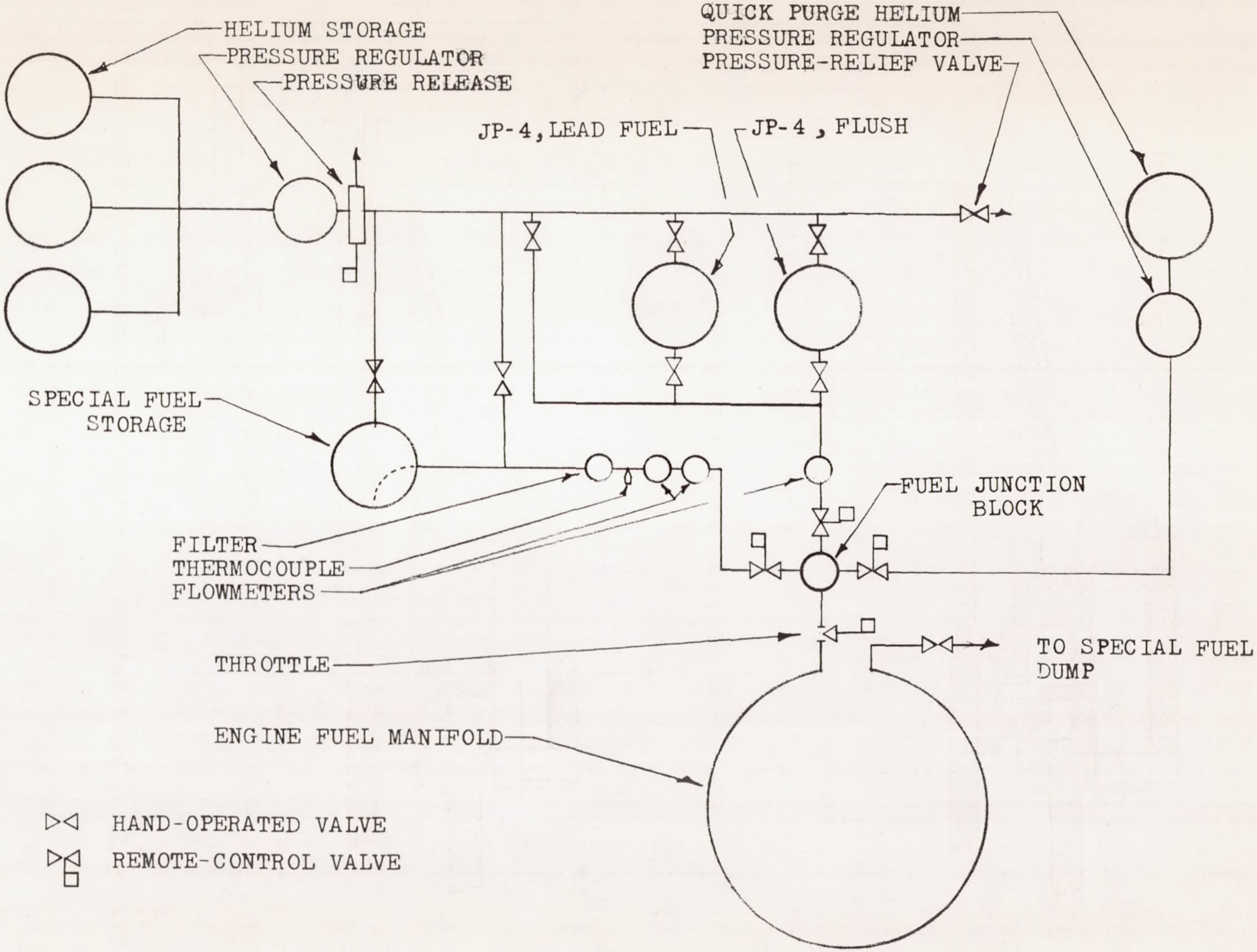


Figure 4. - Diagram of engine fuel system.

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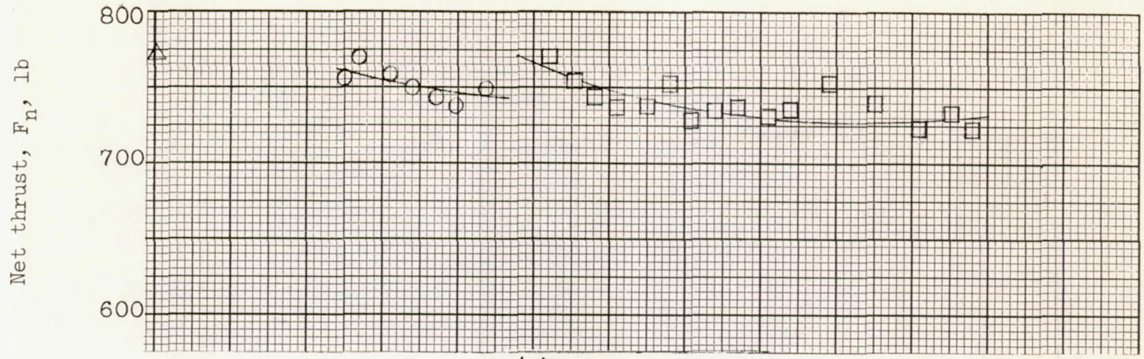
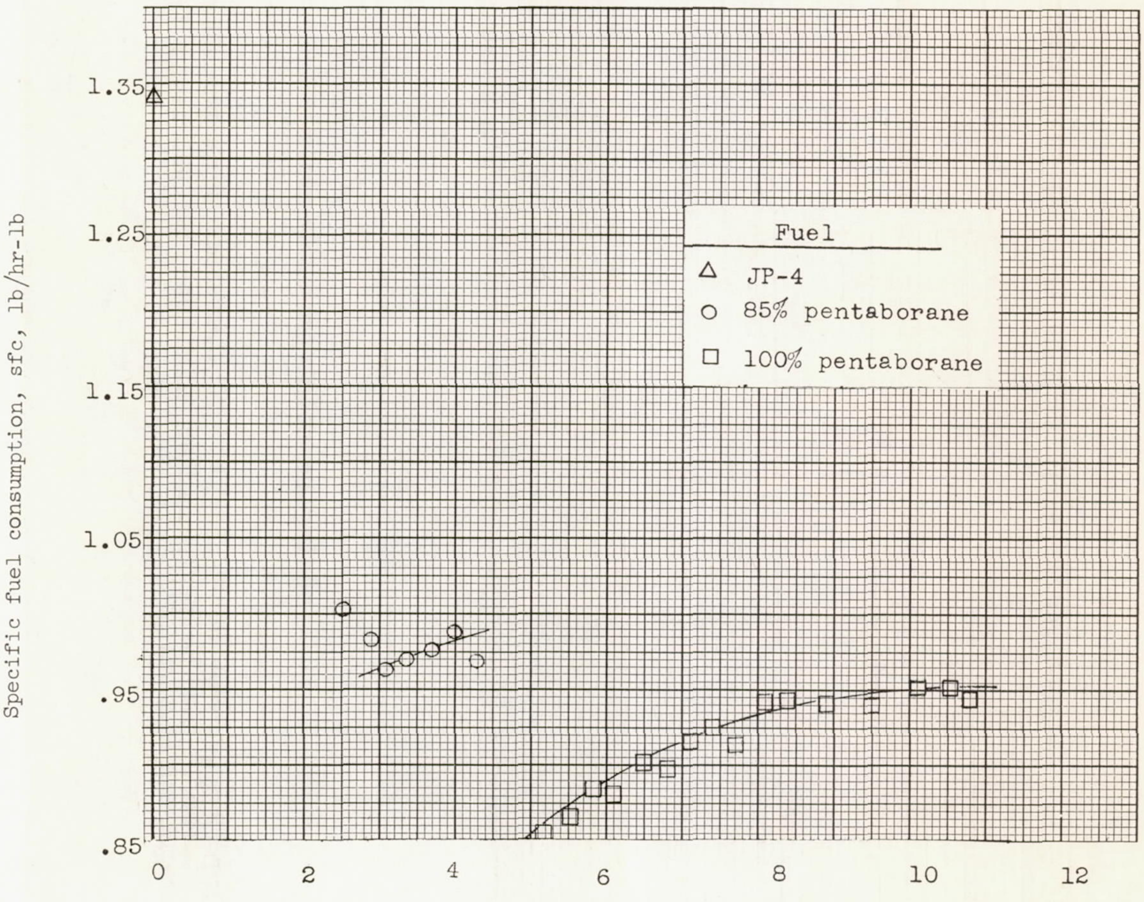
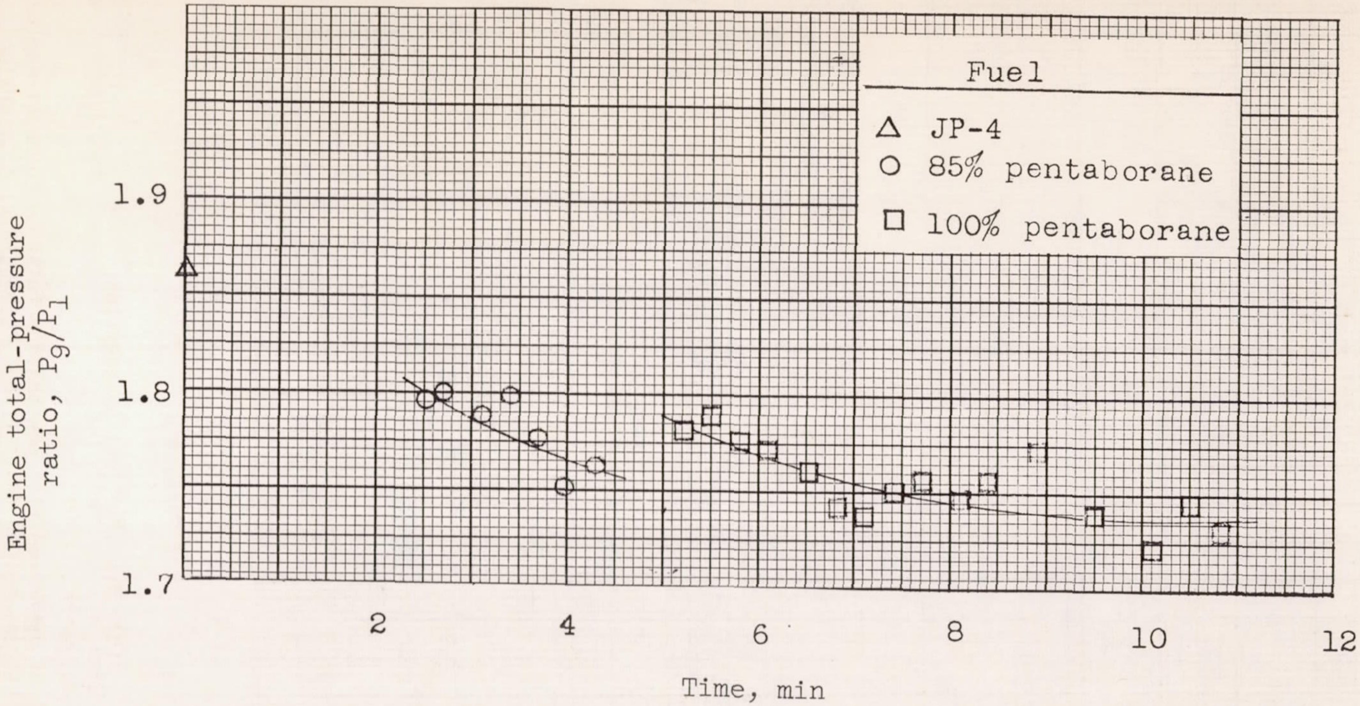


(a) Net thrust.



(b) Specific fuel consumption.

Figure 5. - Effect of operation with pentaborane fuels on turbojet-engine performance. Altitude, 50,000 feet; flight Mach number, 0.8; engine total-temperature ratio, 3.3.



(c) Engine total-pressure ratio.

Figure 5. - Concluded. Effect of operation with pentaborane fuels on turbojet-engine performance. Altitude, 50,000 feet; flight Mach number, 0.8; engine total-temperature ratio, 3.3.

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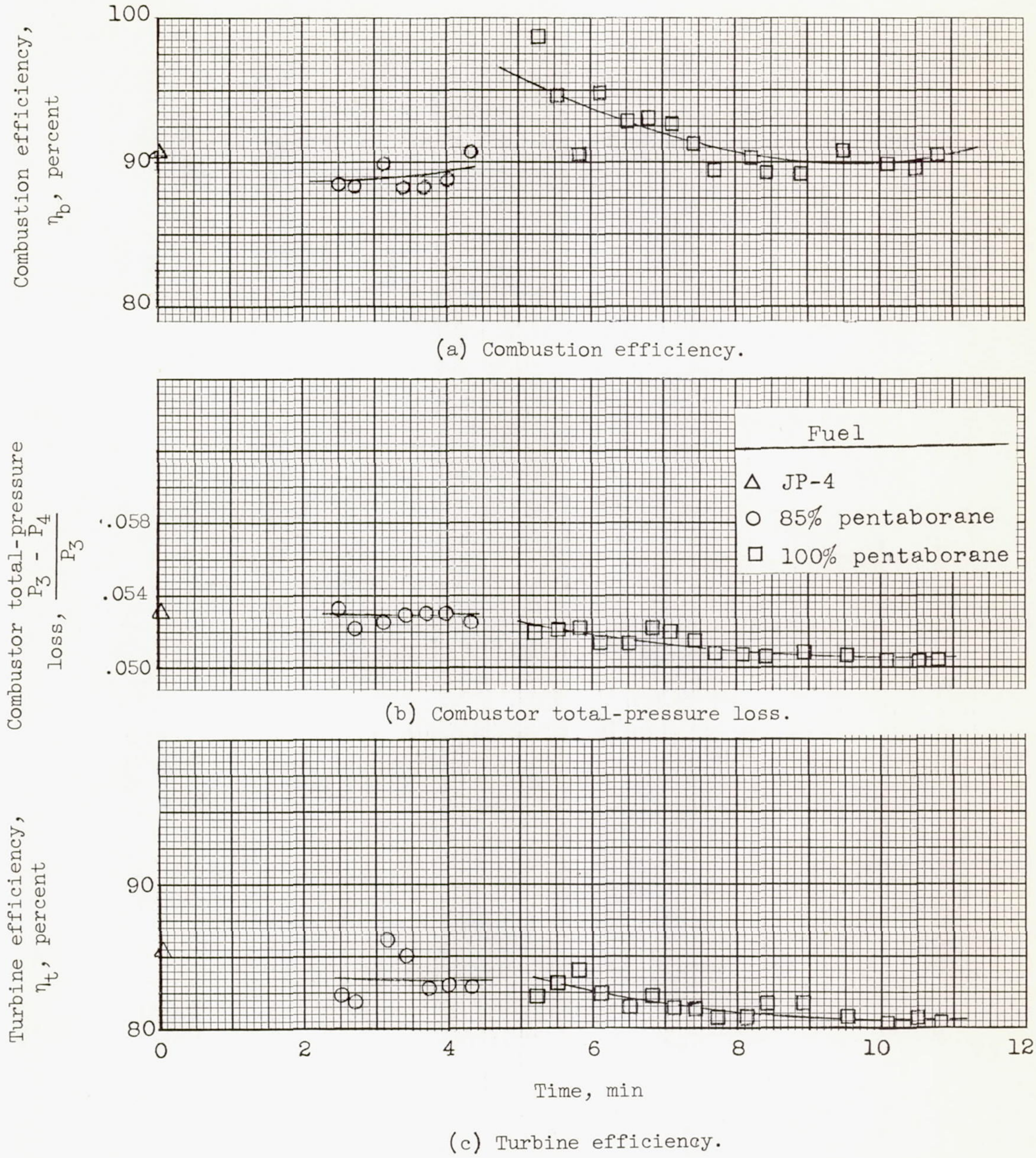

Figure 6. - Effect of operation with pentaborane fuel on turbojet-engine component performance. Altitude, 50,000 feet; flight Mach number, 0.8; engine total-temperature ratio, 3.3.

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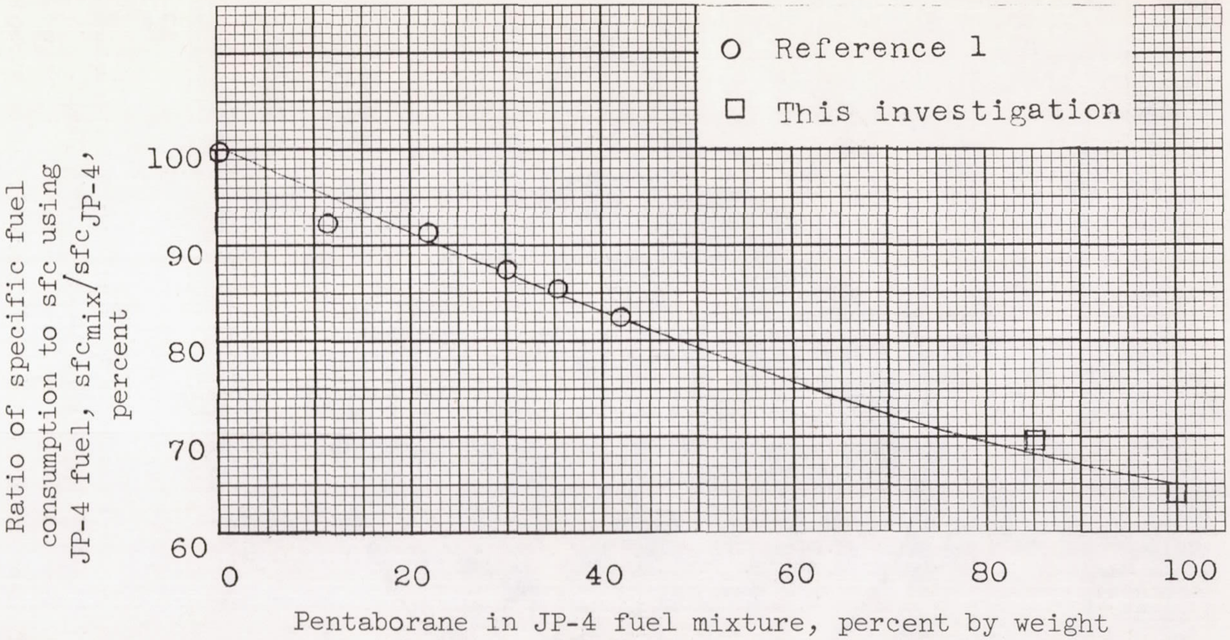

Figure 7. - Change in turbojet-engine specific fuel consumption with pentaborane concentration in hydrocarbon fuel mixture. Altitude, 50,000 feet; flight Mach number, 0.8; engine total-temperature ratio, 3.3.

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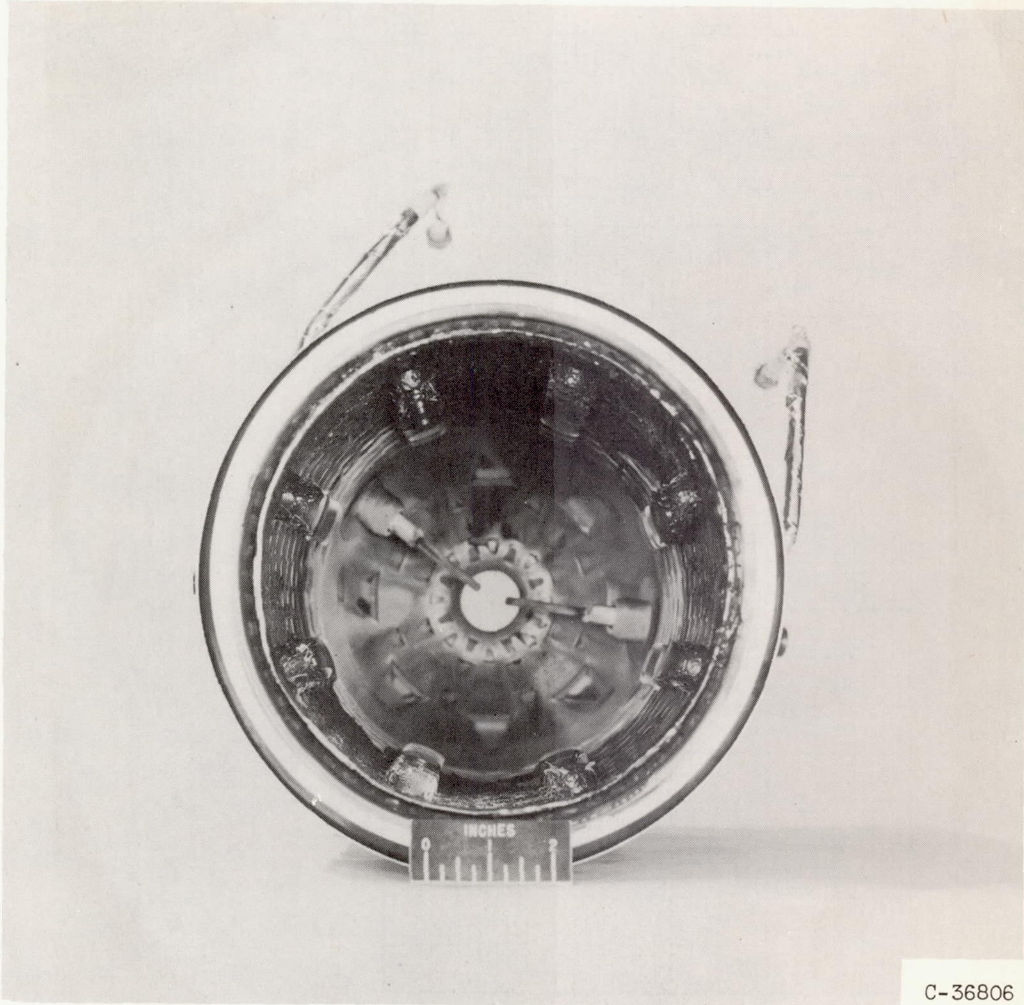

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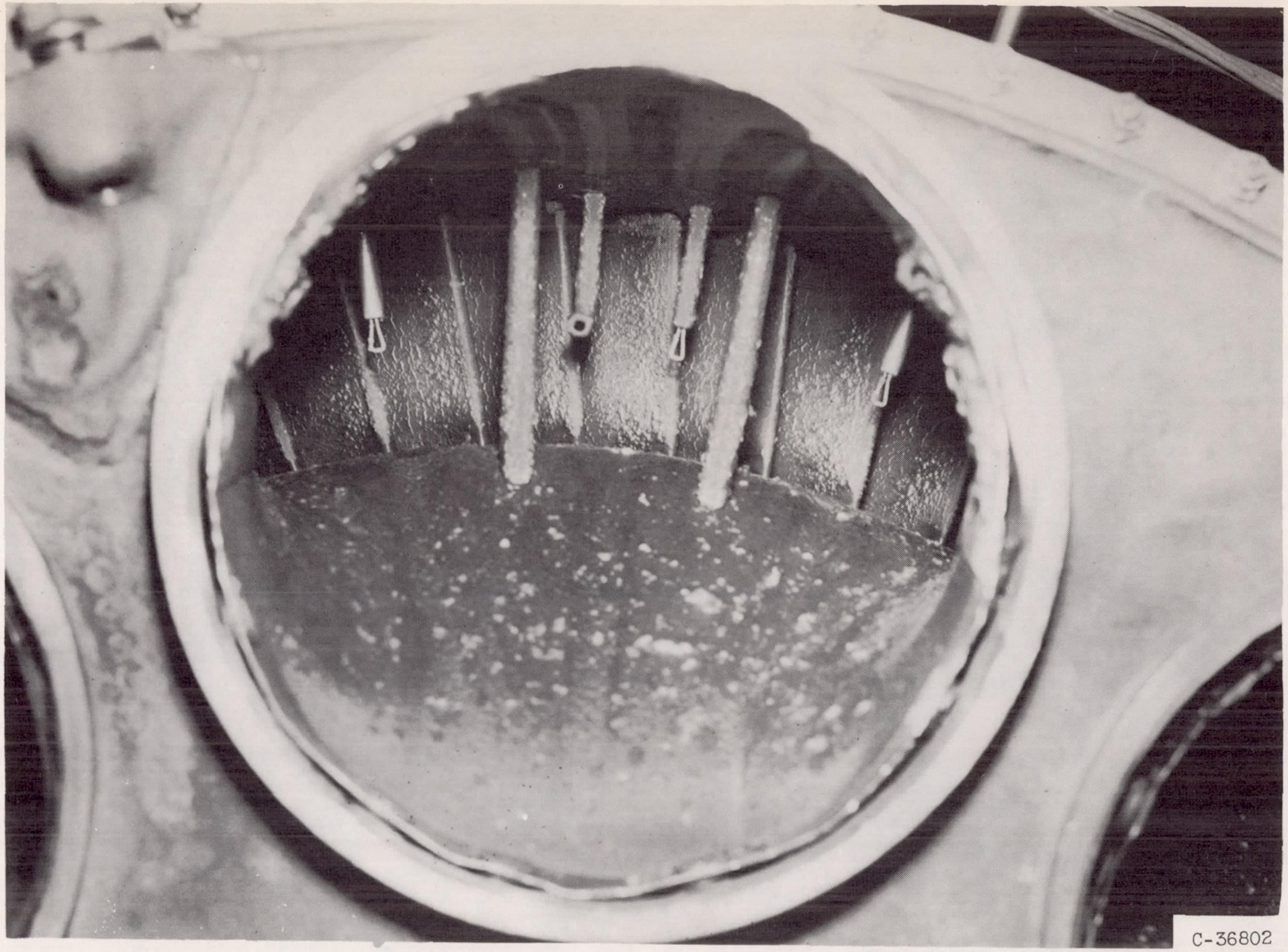
(a) Combustor.

Figure 8. - Boric oxide deposits in turbojet-engine components following 11 minutes of operation with pentaborane fuels.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(b) Combustor - turbine-inlet transition.

Figure 8. - Continued. Boric oxide deposits in turbojet-engine components following 11 minutes of operation with pentaborane fuels.

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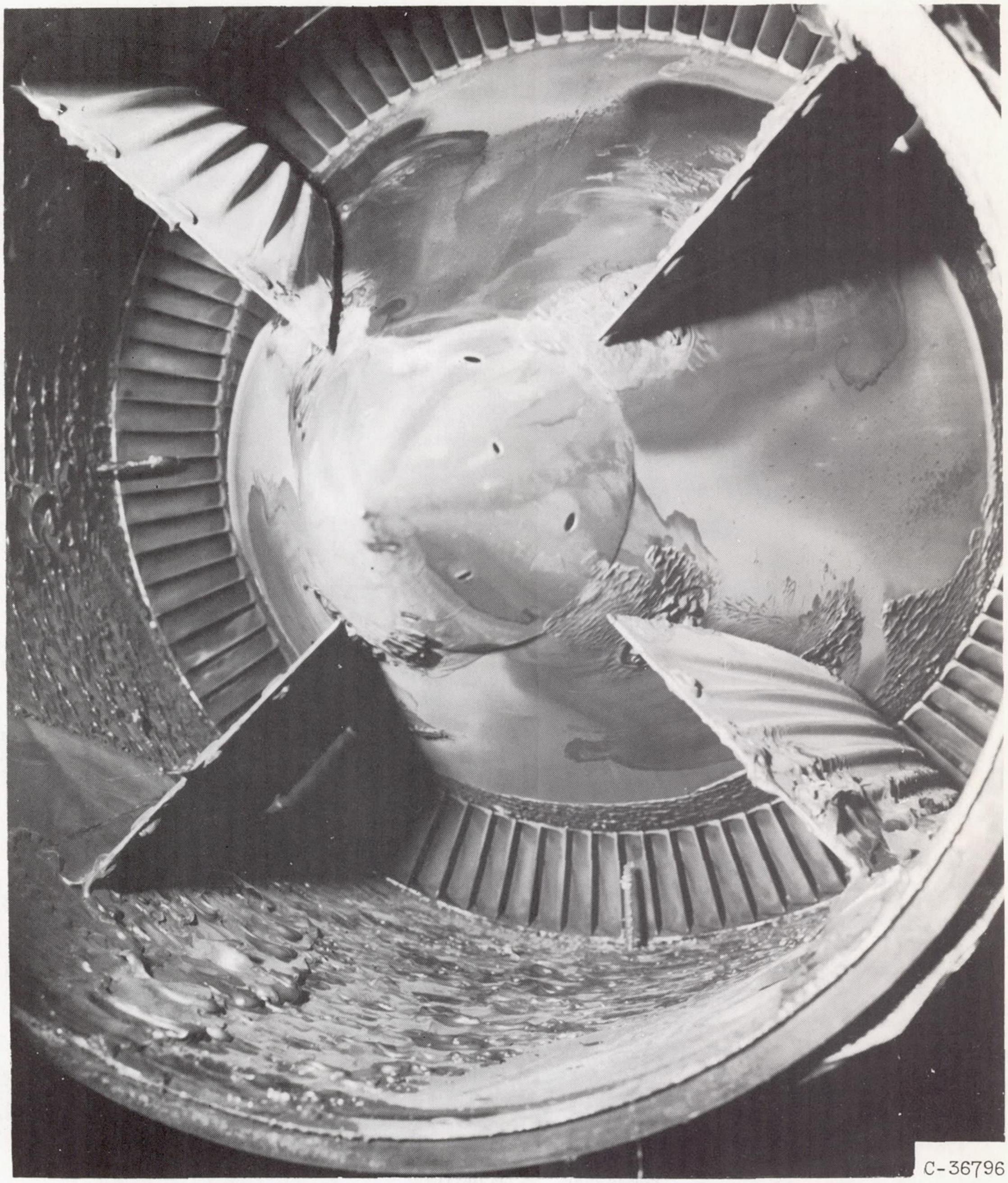

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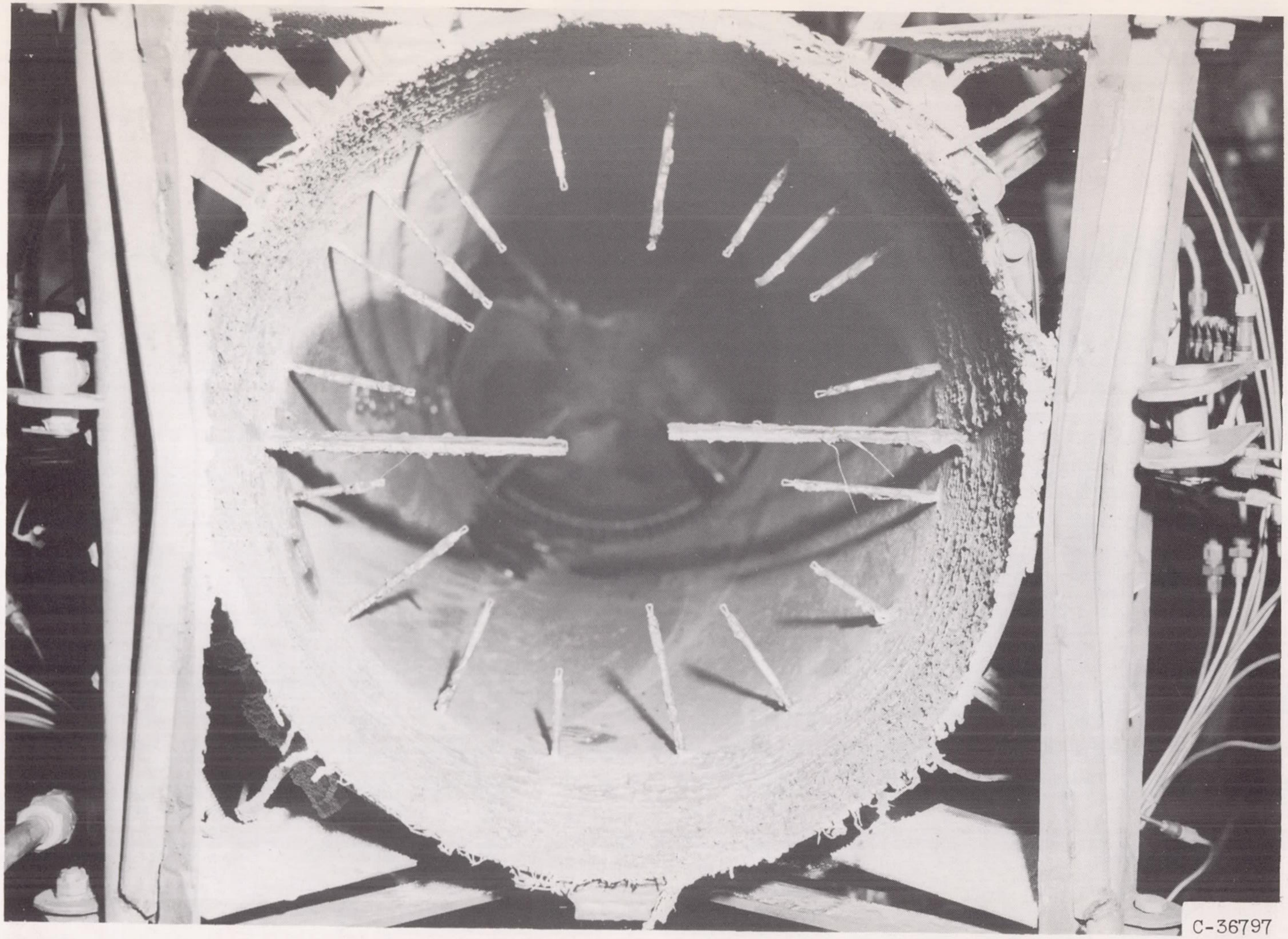
(c) Exhaust tail pipe and diffuser.

Figure 8. - Continued. Boric oxide deposits in turbojet-engine components following 11 minutes of operation with pentaborane fuels.



(d) Engine exhaust nozzle.

Figure 8. - Concluded. Boric oxide deposits in turbojet-engine components following 11 minutes of operation with pentaborane fuels.

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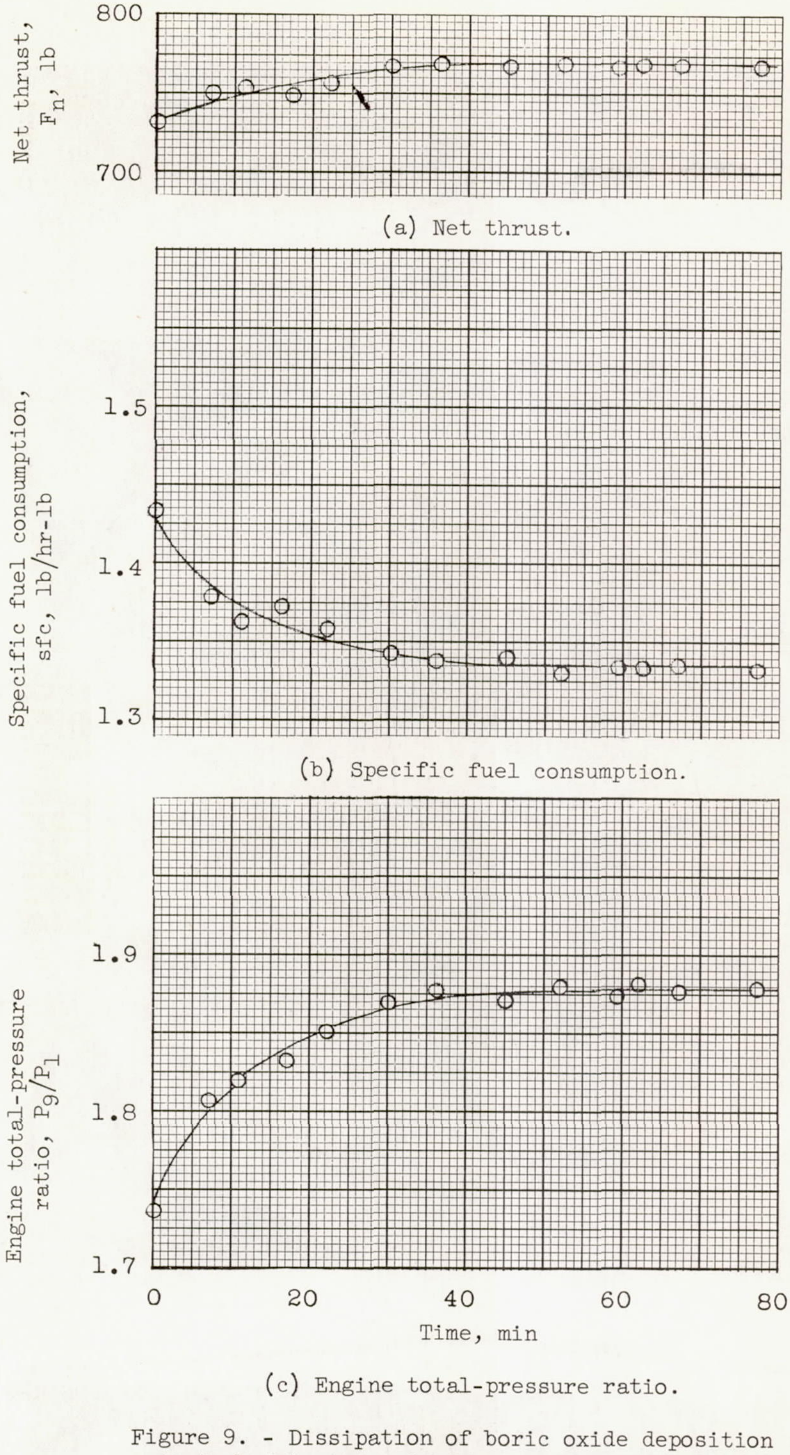
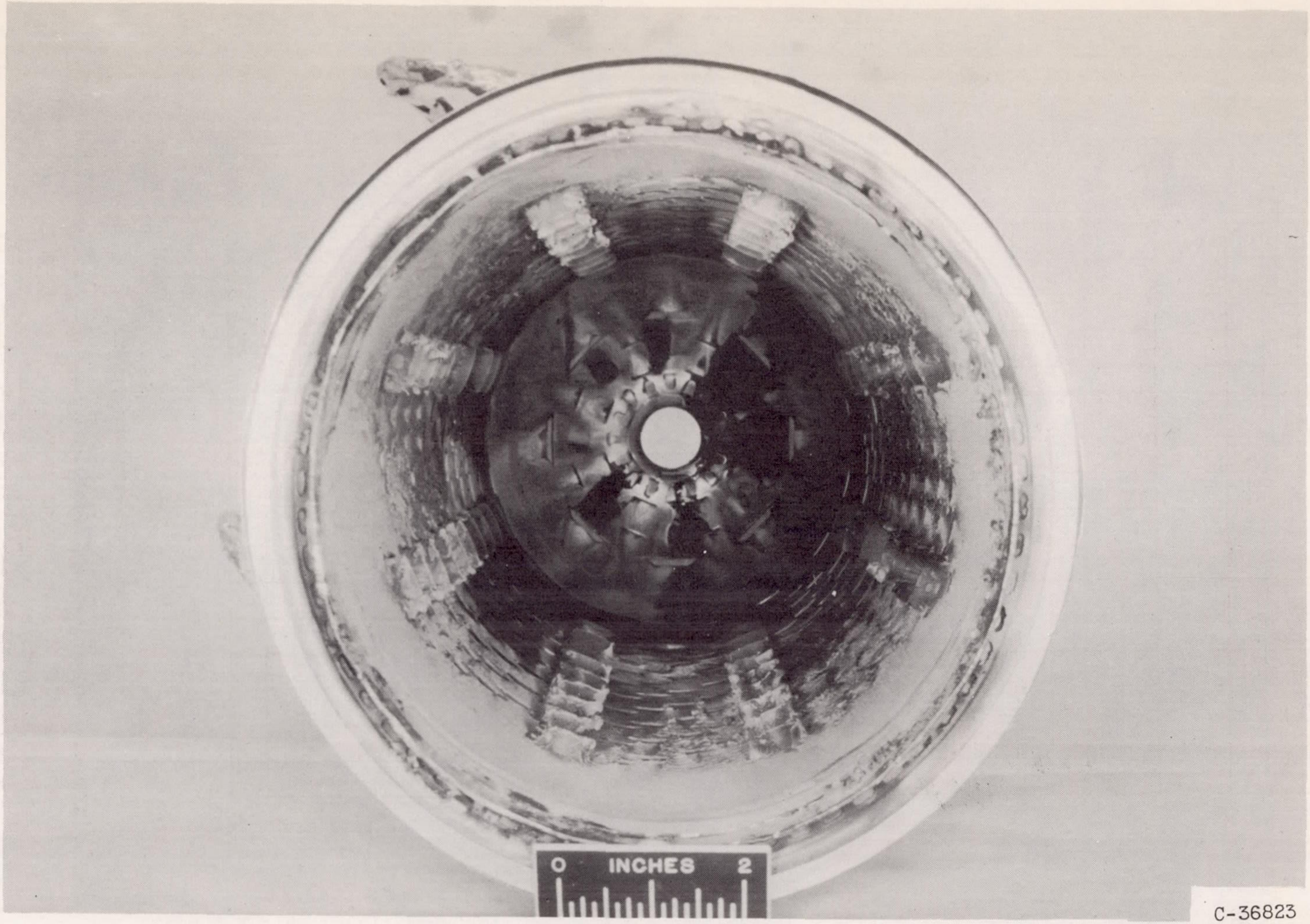


Figure 9. - Dissipation of boric oxide deposition in turbojet engine during operation with JP-4 fuel and return to normal performance operation. Altitude, 50,000 feet; flight Mach number, 0.8; engine total-temperature ratio, 3.3.



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(a) Combustor.

Figure 10. - Reduced boric oxide deposits in turbojet-engine components following 80 minutes operation with JP-4 fuel.

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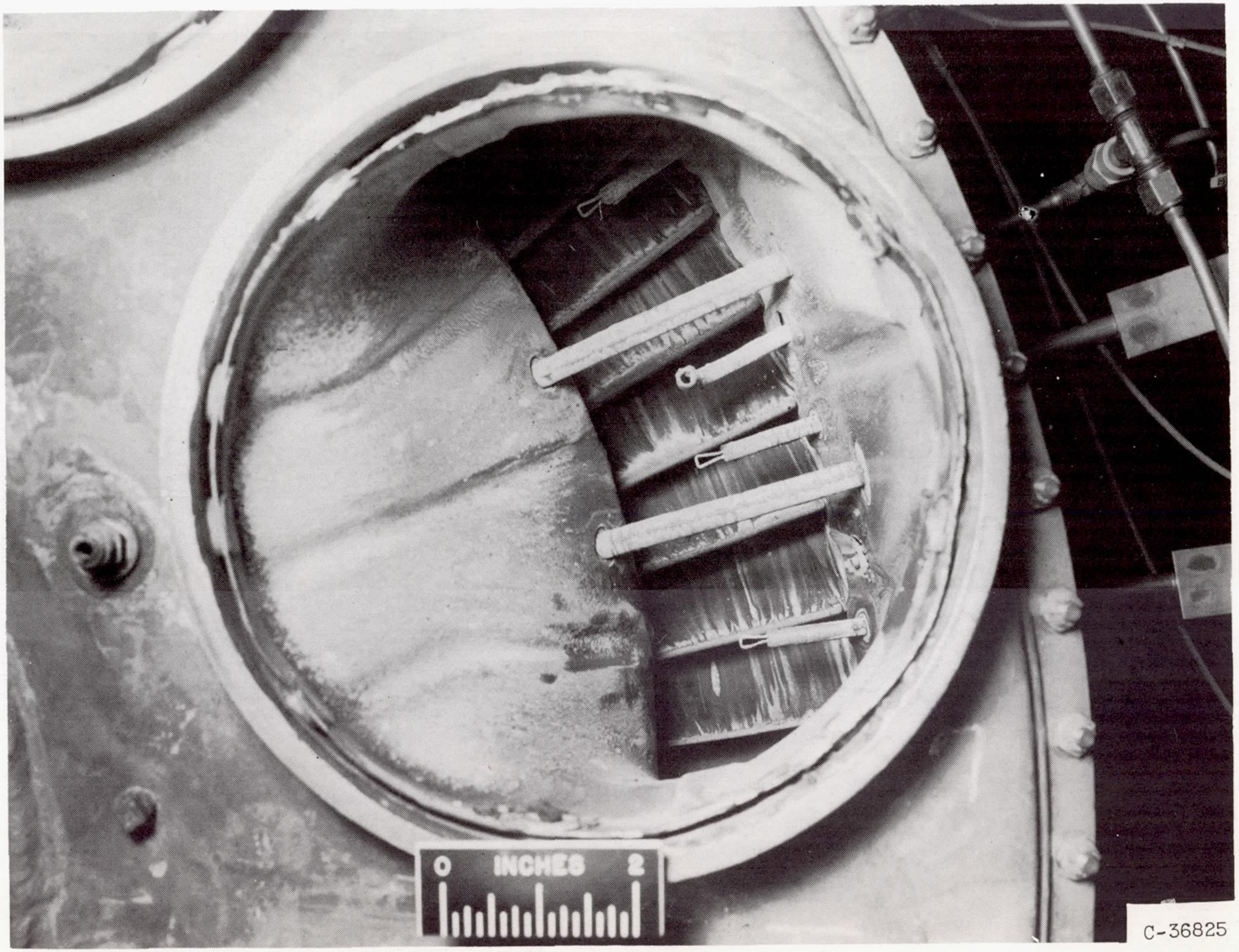

(b) Combustor - turbine-inlet transition.

Figure 10. - Continued. Reduced boric oxide deposits in turbojet-engine components following 80 minutes operation with JP-4 fuel.

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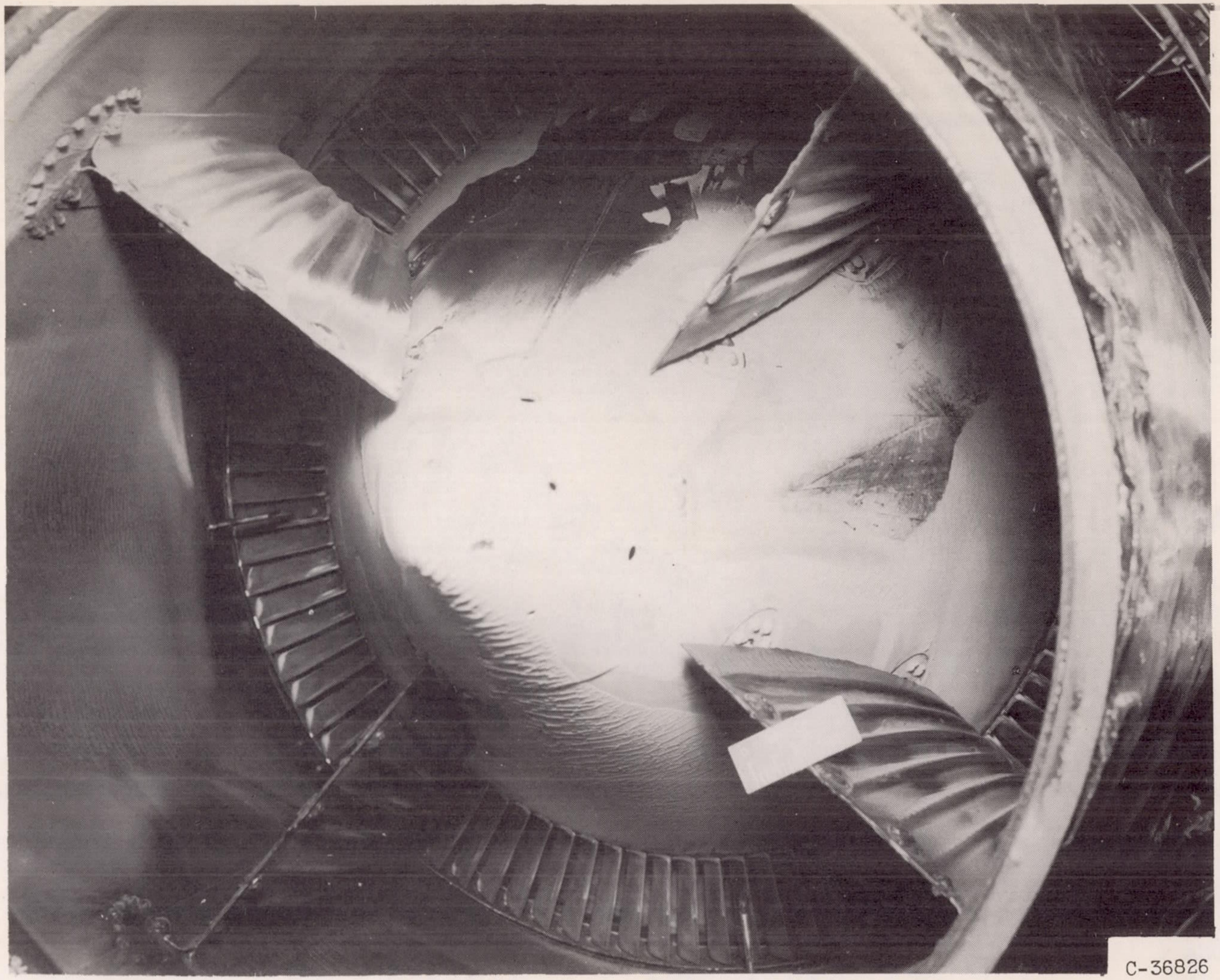

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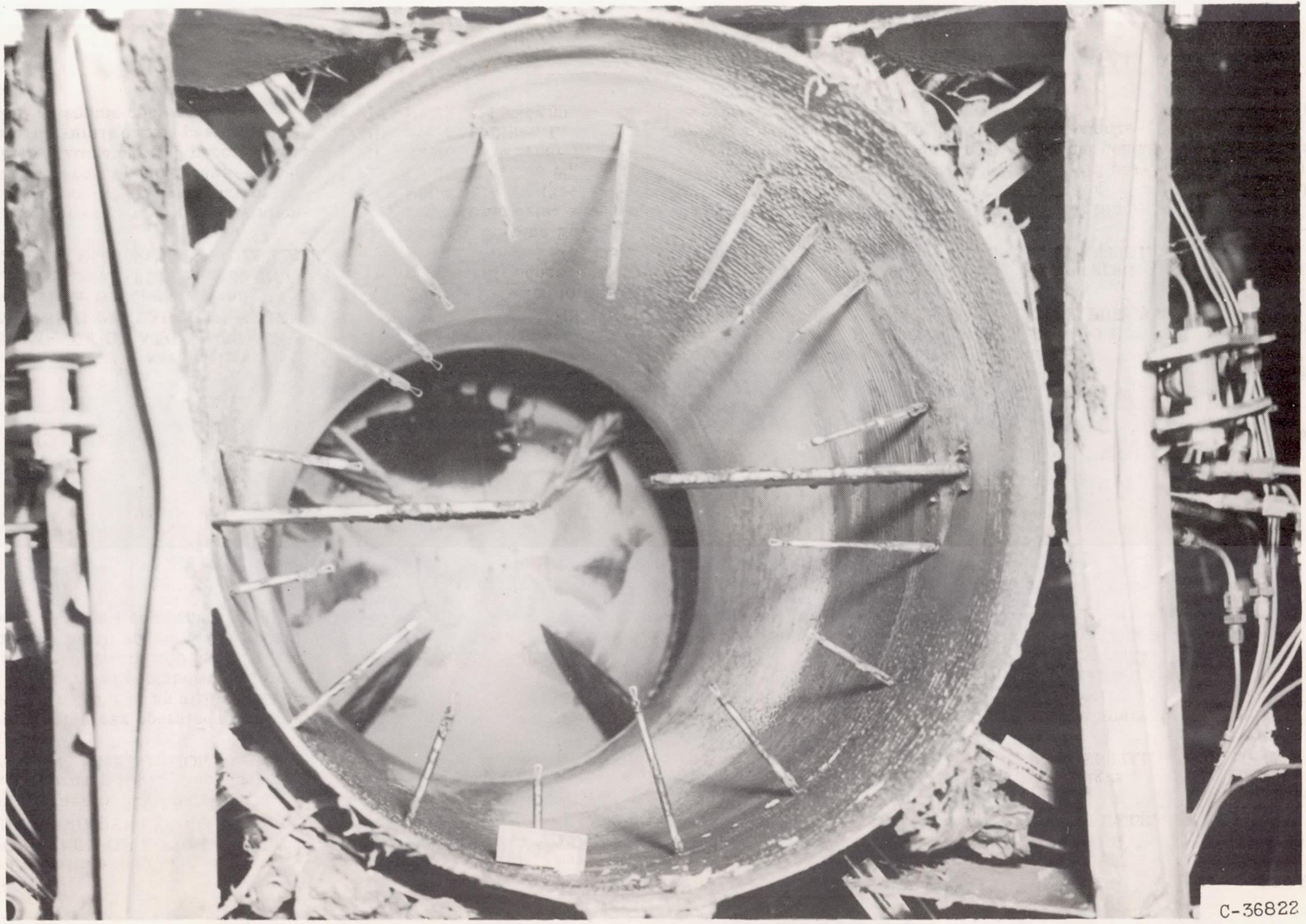
(c) Exhaust tail pipe and diffuser.

Figure 10. - Continued. Reduced boric oxide deposits in turbojet-engine components following 80 minutes operation with JP-4 fuel.



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(d) Engine exhaust nozzle.

Figure 10. - Concluded. Reduced boric oxide deposits in turbojet-engine components following 80 minutes operation with JP-4 fuel.