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RESEARCH MEMORANDUM

PERFORMANCE OF PENTABORANE, PENTABORANE - JP-4 FUEL MIXTURES, AND TRIMETHYLBORATE AZEOTROPE FUEL IN A FULL-SCALE TURBOJET ENGINE

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NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

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SUMMARY

This report summarizes the full-scale engine tests of pentaborane, pentaborane - JP-4 fuel mixtures, and trimethylborate - methyl-alcohol azeotrope fuels. The tests were conducted at a simulated altitude of 50,000 feet and a flight Mach number of 0.8. Engine speeds were 90 to 100 percent of rated speed. The four pentaborane fuel tests reported lasted 5 to 22 minutes, since only 110 gallons of fuel were available.

Pentaborane reduces the specific fuel consumption to two-thirds that of JP-4 fuel, but after a few minutes of operation with pentaborane the engine performance deteriorates, because boron oxide collects in the engine. The net thrust drops as much as 12 percent after 20 minutes of operation on pentaborane fuel. The rate of performance deterioration is most rapid during the first 10 minutes of the test.

A physical explanation for the cause of the performance deterioration is given in this report. Also given are one-dimensional flow and thermodynamic relations that permit theoretical calculations of net thrust and specific fuel consumption for pentaborane fuel.

INTRODUCTION

The use of fuels having heats of combustion higher than those of hydrocarbons has been considered for some time, for example, references 1 and 2. Among high-energy fuels of interest are those containing boron and hydrogen, each of which has a higher heating value per pound than current jet-engine fuels. A typical fuel of this type is pentaborane (B_5H_9). Small quantities of pentaborane have been made available by the Bureau of Aeronautics, Department of the Navy, for short-duration exploratory experiments in turbojet engines.

Pentaborane (B_5H_9) has a heating value of 29,100 Btu per pound (ref. 3) contrasted to a heating value of 18,700 Btu per pound for a typical hydrocarbon fuel. Pentaborane is very reactive with air (refs. 4 and 5), and, because of its reactivity, some latitude is permitted in combustor design (refs. 6 to 8).

The major problem in the application of fuels containing boron is the nature of the products of combustion. Boron oxide is a viscous liquid at normal combustor and turbine-outlet temperatures. At lower temperatures, boron oxide is extremely viscous and may be considered a glasslike solid at temperatures below 900° F. Thus the oxide solidifies when contacting relatively cool engine surfaces. The presence of the viscous liquid and solid deposits can cause the engine performance to deteriorate rapidly.

This report summarizes the NACA work on the application of pentaborane (a high-heating-value fuel) to a nonafterburning turbojet engine. The reductions in specific fuel consumption with pentaborane fuel compared with those of JP-4 fuel are shown, and problems encountered in the use of the fuels of this type are discussed. Some tests conducted with trimethylborate azeotrope, a low-heating-value fuel containing boron, are discussed, as they aid in the definition of the problems of using boron-containing fuels.

The specific tests that were conducted at a simulated altitude of 50,000 feet and a Mach number of 0.8 are listed in the following table:

Test	Scope of test	Distinguishing features of turbojet engine	Reference
1	22-Min test of pentaborane	Six-port air-atomizing fuel nozzles, variable-area exhaust nozzle	9
2	10-Min test of pentaborane and an 85% mixture of pentaborane in JP-4	Fuel nozzles located on combustor wall	10
3(a)	6-Min test of 0 to 30% mixture of pentaborane in JP-4	Single-port air-atomizing fuel nozzle	11
3(b)	12-Min test of 0 to 42% mixture of pentaborane in JP-4		11
4	5-Min test of a 50% mixture of pentaborane in JP-4	Wire-cloth combustors	
5	Trimethylborate azeotrope fuel tests over range of turbine-outlet temp. Test times as long as $2\frac{1}{2}$ hr	Air-atomizing fuel nozzles	

Tests 1, 2, and 3 are reported in the references cited. Some of the data presented vary slightly from the reference reports since more refined calculations have been made herein. The results from tests 4 and 5 are published in this report for the first time. In addition to summarizing these tests, analytical methods for evaluating the performance of boron-containing fuels are presented. Included are thermodynamic data for pentaborane, mixtures of pentaborane and JP-4 fuel, and trimethylborate azeotrope fuel.

APPARATUS AND PROCEDURE

The engine used in these investigations consisted of a 12-stage axial-flow compressor, 8 tubular combustors, and a single-stage turbine. A schematic diagram of the engine used in this investigation is shown in figure 1. Combustor configurations are shown in figure 2, and fuel injectors in figure 3. Certain significant features of the engine configuration were modified between tests and are given in table I.

Fuel Systems

A schematic diagram of the fuel system used with pentaborane fuels is shown in figure 4. The JP-4 and trimethylborate fuels were pumped and metered through a conventional fuel system. 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 fuel and/or helium through or around the fuel nozzles.

Fuels

The properties of the three fuels evaluated in this program, pentaborane, trimethylborate - methyl-alcohol azeotrope, and MIL-F-5624A grade JP-4 fuel are presented in table II. The pentaborane and trimethylborate azeotrope were supplied by the Bureau of Aeronautics, Department of the Navy. The purity of the pentaborane was approximately 99 percent.

Instrumentation

The location of instrumentation and number of probes used in tests 1, 2, and 5 were as follows:

Engine location	Number of probes		
	Static pressure	Total pressure	Total temperature
Engine inlet	8	24	12
Compressor outlet	2	12	12
Combustor outlet	-	20	56
Turbine outlet	-	20	5
Exhaust-nozzle inlet	-	24	24

In tests 3 and 4 the instrumentation was the same as given in the table except that no total-pressure probes were at the turbine outlet (station 5). The total-pressure probes used at the combustor outlet and in the tailpipe were purged with a small amount of air to keep boron oxide from plugging the probes.

Engine air flow was measured at the engine inlet by means of a venturi. Fuel flow was measured by a rotating-vane flowmeter. Strip-chart oscillograph records were used to continuously record data while pentaborane was being tested. The number of oscillograph records varied in the tests. These continuous records were used to check the conventional steady-state instrumentation.

Motion pictures were taken of the downstream section of turbine through a window in the tailpipe wall in test 1.

Procedure

The engine operating conditions were established with JP-4 fuel in tests 1, 2, 3, and 5, and with propylene oxide in test 4. A flight Mach number of 0.8 and an altitude of 50,000 feet were simulated. A transition was made from the starting fuel to the test fuels. Engine performance data were collected at frequent intervals. When the variable-area exhaust nozzles were used, the engine speed and exhaust-gas temperature were maintained constant by varying fuel flow and exhaust-nozzle area. When the fixed-area nozzles were used, outlet temperatures increased slightly during the test, and speed was allowed to drop as much as 5 percent.

Following the pentaborane operation in tests 1 and 2, the engine was inspected and boron oxide deposits were photographed. After inspection, the engine was restarted with JP-4 fuel, and oxides were melted and dissipated by operation at near rated conditions. In tests 3(a) and (b), the engine was operated for 33 and 8 minutes, respectively, with JP-4 fuel before shutdown, photographing, and inspection. In tests 4 and 5 the engine was shutdown immediately after operation with the test fuel. The engine was cleaned before restarting.

Small deviations from the desired operation conditions existed during the tests. This was primarily due to the short test periods. The data have been adjusted to a common altitude of 50,000 feet and Mach number of 0.8 in order to eliminate data scatter due to minor variations in test conditions. The engine total-pressure ratios have also been adjusted, where necessary, to correspond to a constant engine temperature ratio. The results that are adjusted for temperature and pressure ratios are indicated on the figures showing test results.

ANALYTICAL CONSIDERATIONS

All symbols are defined in appendix A. Methods of calculating engine performance data are given in appendix B.

The products of combustion of boron-containing fuels include boron oxide, which is liquid at normal turbojet-engine operating temperatures. The presence of the liquid in the form of microscopic particles affects the performance of the engine by changing the properties of the working fluid, such as the specific heat and the gas constant. If the particles are large, the lack of thermal and velocity equilibrium between the particles and gas introduces losses. Also the boron oxide liquid is very viscous and has a tendency to collect on the internal surfaces of the engine thus producing losses by reducing flow areas and by increasing wall friction. Losses due to the collection of oxides in the engine are discussed in the RESULTS AND DISCUSSION.

Nature of the Working Fluid

This section of the report defines the characteristics of the fluid resulting from combustion of pentaborane and presents thermodynamic relations for a range of pentaborane concentrations in JP-4 fuel mixtures. One-dimensional flow relations are given that are used to determine turbojet-engine-component performances with boron-containing fuels. The theoretical performance of a full-scale turbojet engine calculated by these relations is presented for one operating condition. The thermodynamic data and performance calculations are restricted to a case where the boron oxide particles are small and are at velocity and thermal equilibrium with the gas.

Justification for this restriction is based on the observations of the boron oxide particle sizes as reported in reference 12. Boron oxide particles 1.23×10^{-5} cm in diameter were measured at the outlet of a single combustor burning pentaborane. The test conditions of reference 2 were similar to the conditions for the full-scale engine tests presented in this report. Particles of this size tend to follow Brownian motion and are assumed to have infinite drags and heat-transfer rates for most of the processes in the turbojet engine. Reference 12 also presents a semi-theoretical relation for particle size growth. This relation applied to a broad range of turbojet operating conditions and boron oxide concentrations indicates that no particles appreciably larger than 2×10^{-5} cm in diameter should exist in the exhaust stream except those resulting from contact with a wall. Larger particles can be formed by contacting a wall since the wall provides a collecting surface for a boron oxide film. This film then grows and acts as a source for large particles that are eroded away by the dynamic forces of the fast-moving gas stream.

At present it is not possible to analytically predict the rate of formation of large liquid drops due to wall contact and the effect of the large drops on gas flow or the characteristics of the boron oxide film and its influence on engine operation. The losses due to the large drops and films are treated by examining the experimental data in a succeeding section of the report. However, the effect of submicron particles and their effect on engine performance can be studied analytically. The presence of the submicron particles will be felt any time boron-containing fuels are burned at normal turbojet-engine operating conditions, whereas influence of films and large drops may be largely eliminated by proper design.

The reasons for restricting attention to the case of submicron particles are then: (1) The effect of submicron particles will always be present in turbojet engines when boron fuels are used; (2) recognition of this effect is necessary before proper evaluation of other losses can be made; and (3) the submicron particles lend themselves to analytical treatment.

When particle diameters are 0 to 2×10^{-5} cm, the particles will be influenced by molecular motion and, as a first-order approximation, can be assumed to act as large molecules. The effective molecular weight for 1 pound of mixture and X pounds of liquid boron oxide (B_2O_3) is

$$m_{mx} = \frac{1}{X\left(\frac{1}{m_l}\right) + (1 - X)\frac{1}{m_g}}$$

The effective molecular weight of boron oxide particle m_l varies from 6.53×10^6 for a particle whose diameter is 1×10^{-5} cm to 1.76×10^8 for a 3×10^{-5} cm particle (ref. 12). Negligible error is introduced in considering the particle to have infinite molecular weight compared with that of the gas molecules. The molecular weight then reduces to

$$m_{mx} = \frac{m_g}{(1 - X)}$$

The effective gas constant of the mixture is then

$$R_{mx} = \frac{R}{m_{mx}} = \frac{R(1 - X)}{m_g}$$

where R is the universal gas constant.

The concepts regarding the interaction of liquid and gas particles are more involved, but this treatment appears adequate for the subsequent one-dimensional flow relations developed for the performance analysis. The specific heats, ratios of specific heats, gas constants, and enthalpies for the combustion products of pentaborane - JP-4 mixtures based on the previously mentioned assumptions are presented in the figures referred to in appendixes C and D.

Air specific impulse, the total stream momentum per pound of air where Mach number is equal to 1, is defined as

$$S_a = (1 + f)\sqrt{\frac{2(\gamma + 1)}{\gamma g} R_g (1 - X)T}$$

Values for S_a are included with the other thermodynamic data. Air specific impulse S_a is used in subsequent one-dimensional flow relations for the turbojet engine. The use and derivation of air specific impulse is given in reference 13. Its use is convenient because it reflects the thrust contributions from both mass and heat.

Theoretical Performance of Pentaborane Fuel in a Full-Scale Turbojet Engine

The properties of the combustion products of pentaborane fuel defined previously will affect the operation of the components of a turbojet engine. In order to compare the performance of pentaborane with that of a conventional hydrocarbon fuel, the change of the component performance on the engine must be assessed.

The change in performance of these engine components, combustor, turbine nozzles, turbine, tailpipe, and exhaust nozzle, are examined in terms of the net thrust and fuel consumption of the engine. Performance with pentaborane is compared with that of JP-4 fuel.

The engine performance comparison is based on the following equations:

$$\frac{F_n}{w_a} = S_a\left(1 - 0.8\,\frac{p_0}{P_{10}}\right) - \frac{V_0}{g} \tag{1}$$

$$\text{sfc} = \frac{w_f}{F_n} = \frac{f}{\eta_B}\left[\frac{3600}{S_a\left(1 - 0.8\,\frac{p_0}{P_{10}}\right) - \frac{V_0}{g}}\right] \tag{2}$$

where f is the ideal fuel-air ratio for S_a used and where

$$\frac{p_0}{P_{10}} = \underbrace{\left(\frac{p_0}{P_1}\right)\left(\frac{P_1}{P_3}\right)}_{\substack{\text{Inlet and}\\ \text{compressor}}} \underbrace{\left(\frac{P_3}{P_4}\right)}_{\substack{\text{Combus-}\\ \text{tor}}} \underbrace{\left(\frac{P_4}{P_4'}\right)}_{\substack{\text{Turbine}\\ \text{nozzle}}} \underbrace{\left(\frac{P_4'}{P_5}\right)}_{\text{Turbine}} \underbrace{\left(\frac{P_5}{P_9}\right)}_{\substack{\text{Tail-}\\ \text{pipe}}} \underbrace{\left(\frac{P_9}{P_{10}}\right)}_{\substack{\text{Exhaust}\\ \text{nozzle}}} \tag{3}$$

The effect of pentaborane combustion products on engine performance can be established by substituting the appropriate values of S_a, V_0/g, and p_0/P_{10} in equation (1). The effect of pentaborane fuel on component performance is introduced through changes in p_0/P_{10}. As can be seen in examining equation (1), the type of engine and operating conditions strongly influence this comparison. The engine characteristics and operating conditions selected herein are those corresponding to the experimental test, namely, 12-stage axial-flow compressor, single-stage turbine engine at a simulated altitude of 50,000 feet, a Mach number of 0.8, 100 percent of rated speed, and constant turbine-inlet temperature. The more detailed assumptions and relations used in these calculations are given in appendix C.

The comparison of engine performance is tabulated as follows:

		$\frac{P_{B_5H_9}}{P_{JP-4}}$	Loss in net thrust, percent	Equations used
Effect of total-pressure drop:				
Combustor	Friction pressure drop	Negligible	Negligible	(C12) and (C13)
	Momentum pressure drop	Negligible	Negligible	
Turbine	Turbine-inlet pressure for equal engine air flow through turbine nozzle	.99	About 2/3	(C14)
	Pressure ratio for constant engine speed	.978	$1\frac{1}{3}$	(C17)
Tailpipe	Friction pressure drop due to increased turbine-discharge Mach number	.997	Negligible	
Exhaust nozzle	No effect, friction neglected	----	None	(C20)
Effect of air-specific-impulse level			$1\frac{1}{4}$	(C9)
Total loss in net thrust			$3\frac{1}{4}$	(C9)

The turbine is the only engine component that significantly changes performance with the use of pentaborane instead of JP-4 fuel. The reduced mass flow and gas properties lower the turbine-inlet pressure and change the turbine expansion ratio at conditions of constant speed, constant turbine-inlet temperature, constant turbine nozzle area, and constant air flow. The lower turbine-inlet pressure reduces compressor work, turbine work, and turbine expansion ratio. The lower turbine-inlet pressure tends to lower the turbine-discharge pressure, but normally this is partially compensated for by the smaller expansion ratio. Because of the change in the mass flow and gas properties, pentaborane fuel required a larger turbine expansion ratio than JP-4 fuel. The net effect of these two changes is a reduction in the net thrust of 2 percent. The lower inlet pressure causes a 2/3 percent loss, and the increased turbine expansion ratio the remaining $1\frac{1}{3}$ percent loss.

In actual practice, the turbine nozzle area is usually reduced by the presence of boron oxide films, so that the refinement of calculating the new turbine-inlet pressure with pentaborane fuel may not be warranted. If the simplification of a constant inlet pressure is assumed with a constant inlet temperature and constant turbine work, the calculated turbine-discharge pressure is dropped enough to lower the net thrust about 2 percent below that of JP-4 fuel, which is essentially the same loss as that including the turbine-inlet pressure change. The change in turbine performance resulting from the expansion of various mixtures of pentaborane with JP-4 fuel is illustrated in figure 5. The change is shown in terms of both turbine work for a fixed pressure ratio and pressure ratio for fixed turbine work.

The net thrust of the engine is also directly affected by the change in gas properties of pentaborane products. Turbojet engines are usually limited to a maximum turbine-inlet temperature T_4. It follows as shown in appendix C, that T_{10} is essentially equal for both fuels. But the air specific impulse is lower for pentaborane than for JP-4 products at the same outlet temperature because of the change in gas properties. For the case considered, the air specific impulse will be reduced 1 percent, which in turn reduces the net thrust $1\frac{1}{4}$ percent. The total loss including turbine and impulse changes is $3\frac{1}{4}$ percent.

The theoretical specific fuel consumption for pentaborane mixtures can now be found by using equation (2) after adjusting the pressure ratio across the engine for the change in turbine performance and adjusting the air specific impulse.

Admittedly, this method for predicting specific fuel consumption is tedious. Approximate methods for estimating specific fuel consumption can be used. Two such methods are compared with the more exact method in the following equations:

Ratio of lower heating values:

$$\frac{sfc_{B_5H_9mx}}{sfc_{JP-4}} \cong \frac{h_{f,JP-4}}{h_{f,B_5H_9mx}} \tag{4}$$

Ratio of fuel specific impulse:

$$\frac{sfc_{B_5H_9mx}}{sfc_{JP-4}} \cong \frac{S_{f,JP-4}}{S_{f,B_5H_9mx}} \tag{5}$$

where

$$S_f = S_a/f$$

(S_f and S_a evaluated at T_9 or T_{10} based on inlet temperature T_1.)

Equation (5) is based on equation (2) and assumes a constant S_a and no change in p_0/P_{10} with change in fuel type.

The more exact method based on equation (2) including the effect of component performance is expressed in ratio form in the following equation:

$$\frac{sfc_{mx}}{sfc_{JP-4}} = \frac{\left\{\frac{f}{\eta_B}\left[\frac{1}{S_{a,9}\left(1 - 0.8\,\frac{p_0}{P_{10}}\right) - \frac{V_0}{g}}\right]\right\}_{mx}}{\left\{\frac{f}{\eta_B}\left[\frac{1}{S_{a,9}\left(1 - 0.8\,\frac{p_0}{P_{10}}\right) - \frac{V_0}{g}}\right]\right\}_{JP-4}} \tag{6}$$

where

$$S_{a,9} = 1 + f\sqrt{2\,\frac{(\gamma + 1)}{\gamma g}\,R_g\,(1 - X)T_9}$$

(f = ideal fuel-air ratio for the $S_{a,9}$ or T_9 used) based on a constant outlet temperature T_9. The change in $S_{a,9}$ is based on an inlet temperature equal to T_1.

A comparison of the three methods is shown in figure 6. The ratios of specific fuel consumption for equations (5) and (6) are very similar. Neglecting the change of the total pressure across the engine (eq. (5)) gives a value for pentaborane that is about $1\frac{1}{2}$ percent low (2-percent relative error). This discrepancy diminishes at higher engine pressure ratios or lower fuel-air ratios as can be seen from examining equation

(6). The specific fuel consumption for pentaborane based on the ratio of heating values is 4 percent low (6-percent relative error). At lower fuel-air ratios the error decreases.

It appears that equation (5) or (6) is an adequate theoretical reference curve for comparing experimental specific fuel consumptions for the turbojet-engine performance.

RESULTS AND DISCUSSION

Effect of Pentaborane Fuel on Over-All Engine Performance

Specific fuel consumption. - The specific fuel consumptions of pentaborane, pentaborane and JP-4 fuel mixtures, and JP-4 fuel plotted against engine total-temperature ratio are shown in figure 7. The data shown for tests 1 and 2 are values obtained during the first 2 minutes of the test. The specific fuel consumption increased with time for these tests as will be shown later. The engine configurations and performance changed slightly from test to test; therefore, the specific fuel consumption should be compared with the appropriate JP-4 reference curve in figure 7.

The specific fuel consumption for various concentrations of pentaborane in JP-4 are shown in figure 8. The data shown have been adjusted to an engine total-temperature ratio of 3.48. The specific fuel consumption is expressed as the ratio of the specific fuel consumption of the mixture compared with the specific fuel consumption of JP-4 fuel. The solid line is the specific-fuel-consumption ratio found by the ratio of heating values of the fuels; the dashed line is the theoretical ratio based on the impulse of the fuels (eq. (6)).

The experimental values nearly coincide with the theoretical values based on the impulse of the fuel. One reason some of the data are lower than the theoretical impulse values is that the combustion of the pentaborane was more complete than that of the JP-4 fuel. Specific fuel consumption was reduced to as low as 0.64 that of JP-4 fuel.

Deterioration in engine performance. - The over-all efficiency and the efficiency of the engine components did not change significantly during the first minute of engine operation. However, in all the tests the engine performance began to deteriorate after 2 to 3 minutes of operation. The magnitude of the loss in engine performance is shown in figure 9. Tests 1 (fig. 9(a)) and 2 (fig. 9(b)) have been selected to show this effect since the largest quantity of pentaborane fuel was used in these tests. The performance deterioration in terms of specific fuel consumption, net thrust, and engine total-pressure ratio is plotted as a function of time and total boron oxide formed. The total boron oxide formed is the total oxide produced by combustion of the fuel. It is assumed that 2.75 pounds of boron oxide are produced for every pound of pentaborane used by the engine. This parameter is used since the performance of pentaborane mixtures as used during part of test 2 is best compared with that of pentaborane on the basis of oxide formed in the engine rather than by test time. The specific-fuel-consumption increases about 8 (test 1) to 11 percent (test 2) more than the initial value. The net thrust drops about 12 to 14 percent in the two tests. Both tests show similar trends, and the losses tend to level out. But, in view of the limited test time of operation, there is no guarantee that further deterioration in performance will not occur.

The loss in performance with extended operation is attributed to the collection of liquid and solid boron oxide in the critical parts of the engine. Further details on the cause of the performance change with time of operation are presented by examining the component performance in the following section of this report.

Effects of Pentaborane Fuel on Component Performance

Standard-combustor performance. - Combustion efficiency and combustor pressure loss are presented as functions of total boron oxide formed in the combustor in figure 10 (tests 1 to 3). The combustor-inlet conditions were as follows: inlet pressure, 2145±85 pounds per square foot; inlet temperature, $930^{\circ}\pm20^{\circ}$ R; and total air flow, 19±0.4 pounds per second. Only small effects of fuel composition, injector design, combustor modifications, or test duration on combustion efficiency and total-pressure loss across the standard combustors are evident. These small differences approach normal data scatter for a series of short-duration tests of this type. The test results are consistent with those of single-combustor tests reported in references 6, 7, 8, and 14.

Representative combustor photographs taken after tests 1 to 3 are shown in figure 11. The heaviest deposits were found in test 1, the longest test. Also, a greater variation in the amount of deposits between the combustors was observed in test 1 (figs. 11(a) and (b)). The combustor deposits apparently did not affect the efficiency or pressure drop, but the deposits did affect the combustor-outlet temperature profile. The shift in temperature profile with time is shown in figure 12 for two representative combustors of test 1. The maximum temperature spread in a single radial survey in combustor A (fig. 12(a)) at the start of the pentaborane test was $\pm100^{\circ}$ F and increased to $\pm150^{\circ}$ F at the end of the run.

The shift in temperature profile was probably caused by deposits on the tip of the nozzle. These deposits were predominately boron oxide. The photograph in figure 13 shows the type of deposit found. The diagram illustrates how the deposit was attached to the fuel nozzle. Part of this deposit might have been formed during the shutdown of the engine. Deposits on the fuel nozzle are extremely undesirable, not only because they can affect the temperature profile, but because they can induce severe deposits on the combustor walls. Clinkers of incompletely burned pentaborane can form very rapidly when the fuel spray deteriorates. These wall deposits in turn can cause deterioration in temperature profiles, pressure drop, and efficiency. There were indications of some of these clinkers being formed in test 1 and to lesser degrees in tests 2 and 3.

Wire-cloth combustor performance. - A wire-cloth combustor designed to minimize the boron oxide accumulation was evaluated with a 50 percent mixture of pentaborane in JP-4 fuel. The principle of filming the surfaces of the combustor liner with cold air is illustrated in figure 14. The development work on this liner is discussed in reference 6. The combustor conditions for the wire-cloth combustor were essentially the same as those for test 3(b) with the standard combustor operating with a fuel mixture of comparable composition (42.1 percent pentaborane in JP-4 fuel). Listed in the following table are the test conditions and a comparison of the results of the two combustors:

	Combustor	
	Wire-cloth	Standard
Pentaborane concentration, percent	50	42.1
Adjusted engine speed, rpm	6524	7485
Engine-inlet total pressure, lb/sq ft abs	497	427.5
Combustor total pressure, lb/sq ft abs	2260	2290
Combustor efficiency	0.94	0.94

The combustion efficiency of the wire-cloth combustor was the same as that of the standard combustor. The amount of deposits in the combustor were much less as can be seen from the photograph in figure 15. The low deposit rate agrees with the single-combustor work of reference 6. However, the combustor-outlet temperature was very poor. The poor profile resulted in intolerable turbine performance. The indicated turbine efficiency was 15 percent lower than normal. New louvered combustor designs are now being tested that retain the low deposit rate of the cloth combustor but are structurally stronger and have a more acceptable outlet-temperature distribution than the wire-cloth design (ref. 15). It is hoped that these new designs will reduce turbine losses.

Turbine performance. - Accurate analysis of the turbine performance data with pentaborane fuel for the wire-cloth combustor is not possible because of the poor temperature profile and type of instrumentation used. It is difficult to distinguish among the effect of temperature profile, effect of boron oxide, and the data scatter caused by the poor profile. The outlet-temperature profiles of the standard combustor (tests 1 to 3) were very similar for both pentaborane and JP-4 fuel and thus are more interpretable. Therefore, these results are emphasized in this section.

Within the accuracy of the experimental data there is about a 2-percent decrease in the calculated turbine stator area during tests 1 to 3 as shown in figure 16. The area was calculated by the method shown in appendix B, and is expressed as the ratio of area calculated at a given time divided by the area calculated during JP-4 fuel operation.

A 1-percent reduction in nozzle area with pentaborane fuel is just sufficient to return the engine to the same total pressure entering the nozzle as that experienced with JP-4 fuel (see appendix C, Turbine-Nozzle section). The 2-percent area reduction increases compressor work slightly above that of JP-4 fuel. The data of test 1 indicate a 2- to 3-percent increase in compressor pressure ratio, which confirms the area change. The small change of the stator area indicates that the oxide film on the nozzle surfaces must be extremely thin. This conclusion would not have been reached on the basis of visual examination of the engine after shutdown. Shown in figures 17(a) and (b) are photographs of the turbine stator after tests 1 and 2, respectively. These photographs show ridges of oxide on the nozzle surfaces. Apparently, during the engine shutdown process the oxide congeals and collects on the engine surfaces.

The variation in turbine efficiency with total boron oxide formed is shown in figure 18 (tests 1 to 3). Standard combustors were used in each of these tests. The turbine efficiency presented for test 3 has been calculated using a measured exhaust-nozzle-inlet total pressure and a constant tailpipe total-pressure loss since no turbine-outlet total-pressure measurements were made. Therefore, any variation in turbine efficiency for test 3 may be a reflection of a variation in either tailpipe pressure loss or a change in turbine performance. In this test, a 1-percent increase in tailpipe pressure loss would result in about a 1-percent decrease in turbine efficiency. The turbine efficiencies for tests 1 and 2 were calculated using measured total pressures at the turbine outlet. Turbine efficiency, as used in this report, is a measure of available shaft work, since it is based on compressor work. Any work absorbed by viscous drag across the turbine is included as a loss. In all cases, turbine efficiency has been calculated by using a ratio of specific heats, which accounts for the temperature and composition of the gas stream.

In the three tests the turbine efficiency had dropped about 3 to 4 percent when the total boron oxide formed was 240 pounds. Very little additional loss occurred as the total boron oxide formed increased to 800 pounds (22 minutes of operation, test 1). Photographs of the turbine after tests 1 and 3 are shown in figure 19.

At constant engine speed (variable-area exhaust) a 4-percent loss in turbine efficiency lowers the net thrust 3 percent and increases the specific fuel consumption 3 percent (all other engine components are assumed to have the same efficiency).

There is a greater change in engine performance with loss in turbine efficiency when a fixed-area exhaust nozzle is used since the engine speed must be reduced from 100 percent of rated speed as turbine efficiency drops in order not to exceed limiting turbine temperatures. The reduced engine speed produces a further decrease in net thrust. The specific-fuel-consumption increase is about the same as that for constant engine speed.

An example of the drop in engine speed with the use of pentaborane fuel in an engine with a fixed exhaust nozzle is given in figure 20 (test 3). The experimental data shown are for constant outlet temperature and constant pentaborane concentration (35.5 percent). A JP-4 reference point obtained before pentaborane operation is included. Shown on the figure is the calculated engine-speed drop that should occur as the engine is transferred to pentaborane fuel. Extrapolation of the experimental data plotted as functions of total boron oxide formed shows close agreement with the calculated value. This value was based upon experimental data that showed that a 1-percent change in turbine work produces a 60-rpm change in engine speed. Thus, when the effect of boron-containing fuels on net thrust in fixed-area engines is considered, the influence of change in engine speed must be recognized in addition to the effect of the possible change in turbine performance.

A motion picture of the downstream section of the turbine was made during test 1 in order to shed some light on how the oxide affected turbine operation. The oxide obscured the details, but the general flow of the oxide could be seen. Shown in figure 21 is an artist's sketch of the liquid boron oxide flowing through the turbine rotor after about 8 minutes operation with pentaborane fuel. At the start of the pentaborane fuel test the turbine discharge gases became very luminous. After about 1 minute of operation molten oxide began to appear on the outer walls. A great deal of this oxide appeared to be rolling along the walls in the form of spheres. The amount of oxide increased rapidly during the first few minutes, then appeared to reach a more constant rate of flow. The pictures of the turbine and visual observation of similar sections in connected pipe studies (ref. 14) indicate that oxide forms and flows in the following manner: (1) Vapors formed in the flame zone condense to microscopic drops; (2) these microscopic drops diffuse to surfaces in the engine and collect as viscous films; (3) after a few minutes of operation these films are thick enough to flow downstream in the form of large drops; and (4) the films and drops thus formed are large enough to be separated from the gas as the gas winds through the turbine nozzles and turbine rotors. The oxide thus collected can restrict the turbine nozzle area and lower turbine efficiency by "spoiling the gas flow," blocking flow passages, and retarding rotation of the turbine.

Tailpipe. - In addition to the losses in the turbine, the tailpipe total-pressure drop increased with the use of pentaborane fuel. Part of this loss must be attributed to the turbine since the deterioration in turbine performance increased the tailpipe Mach number thus increasing total-pressure losses. The experimental tailpipe pressure loss for test 1 is shown in figure 22. The 5-percent increase in total-pressure drop with increased time of operation increased fuel consumption about 1.03 times the initial value. Photographs of the tailpipe after tests 1 and 2 are shown in figure 23.

Exhaust nozzle. - The area of the fixed exhaust nozzle (test 3) was calculated by the same method as was used in determining the turbine stator area. The area was reduced less than 1 percent by pentaborane fuel. The variable-area nozzles were operable during both tests 1 and 2, although at times the action of the clamshell nozzle (test 1) was a bit sluggish.

Comparison of component losses. - The deterioration in net thrust and change of specific fuel consumption with the use of pentaborane fuel can best be explained by collectively examining the effect of the components on performance. This is shown in figure 24 (data of test 1 are used).

Equation (2) theoretically predicts a $3\frac{1}{4}$-percent reduction in net thrust due to (1) lower exit momentum at a constant engine outlet temperature and (2) higher pressure drop across the turbine due to a change in gas properties. This is shown as a horizontal line on figure 24(b). The comparable line for specific fuel consumption based on equation (6) is also shown (fig. 24(a)).

The apparent improvement in net thrust caused by an increase in compressor pressure ratio is due to the reduction in turbine nozzle area. The improvement shown is based only on total-pressure change up to the nozzle inlet and, therefore, does not include the increased turbine work required and does not recognize the effect of surface roughness on nozzle efficiency.

The change in turbine performance based on the observed change in total pressure across the turbine with the use of pentaborane fuel includes the increased turbine work and the effect of losses in turbine nozzle and turbine rotor sections.

The change in tailpipe performance due to both the increased turbine discharge Mach number and frictional drop is the final loss presented.

At the end of the test, the sum of the component changes and theoretical change in net thrust is only about 1 percent lower than experimental data, which is well within normal data scatter. The specific-fuel-consumption data also agree closely with theoretical values.

The distribution of the $11\frac{1}{2}$-percent net-thrust loss at the end of the test is as follows:

	Percent of $11\frac{1}{2}$-percent loss
Change in properties of working fluid	$27\frac{1}{2}$
Change in turbine performance	47
Change in compressor work due to turbine-nozzle-area change	$-12\frac{1}{2}$
Net change in turbine performance deducting compressor work	$34\frac{1}{2}$
Change in tailpipe performance	38

Effect of Turbine-Outlet Temperature on Engine Performance

All the full-scale turbojet-engine data with pentaborane were taken at a single operating condition. The shortage of pentaborane fuel has prevented investigating engine performance at other operating conditions. The effect of lower turbine-outlet temperatures on performance is of special interest since these are the conditions that will be encountered at part-throttle operation with a single-stage turbine and at full throttle in some of the multistage turbine engines. It would be expected that the engine performance would be adversely affected by low-temperature operation since the viscosity of boron oxide increases very rapidly as the temperature is lowered. For example, the viscosity is 10^4 poises at 1000° F and 10^8 poises at 850° F. The effect of engine-outlet temperatures of 900°, 1050°, and 1250° F was examined with trimethylborate azeotrope fuel. Trimethylborate azeotrope has been used as a substitute fuel in the past (ref. 16) despite its low heating value, since it does contain a reasonable amount of boron. The amount of boron oxide formed by combustion is equal to that from a 25 percent mixture of pentaborane in JP-4 fuel. The results between pentaborane and trimethylborate should not be expected to compare exactly. The thermodynamic properties and mass flows of the exhaust differ. For example, the exhaust gas per pound of air with trimethylborate is 3 percent greater than that of pentaborane. Also, if the accumulation of performance-robbing oxides is determined by a balance between deposition and erosion rates, the low concentration of boron in trimethylborate will favorably affect the performance compared with that of pentaborane. The performance for the three outlet temperature runs with trimethylborate fuel are compared (test 1) on the basis of total boron oxide formed in order to partially compensate for difference in rate of oxide formation.

Combustor pressure drop, turbine efficiency, and tailpipe pressure drop are shown in figures 25(a), (b), and (c), respectively. The following generalizations may be made: Combustor pressure drop does not change appreciably with fuel type, temperature, or amount of boron oxide formed.

The losses encountered in the turbine and tailpipe become more severe as the exhaust-gas temperature is dropped, when compared on the basis of total boron oxide formed. The large losses show that serious performance deterioration can be expected in some multistage-turbine engines or at part-throttle operation, that is, cases where the turbine-outlet temperature is low.

Miscellaneous Observations

Dissipation of engine deposits. - Boron oxides can be removed from the engine by operating the engine with JP-4 fuel. The oxide is eroded by the action of the hot JP-4 fuel combustion gases. An example of the effect of time of operation on the dissipation of the boron oxide deposits formed in test 2 is shown in figure 26. The JP-4 reference point obtained before operation on pentaborane is included to show the standard level of performance. Following 11 minutes of operation with pentaborane fuel in which 330 pounds of boron oxide were formed, the engine returned to nearly the standard level of performance with 30 minutes of operation on JP-4 fuel. After 80 minutes of operation on JP-4 fuel, visual inspection of the engine revealed only a slight amount of oxide on the engine components.

Pentaborane fuel handling problems. - The use of pentaborane fuel introduces several problems because of its toxicity, reactivity, and thermal-decomposition characteristics (refs. 17 to 19, respectively). The pentaborane fuel reactivity and toxicity problems were overcome in these research tests mainly by proper maintenance of the fuel system. This fuel system provided for purging of the pentaborane fuel lines (fig. 4).

No problem due to thermal decomposition of pentaborane was indicated until the fuel reached the engine. At the combustor-inlet temperature of 440° F, extrapolation of data in reference 18 indicates that 5 percent of the fuel will decompose in 30 seconds. In order to guard against any possible chance of fuel reaching this temperature, air-atomizing fuel nozzles and fuel injectors located on the combustor walls were used. The nozzles operated satisfactorily except for external accumulations of deposits previously mentioned and one case where an injector clogged internally (test 3(a)). In the succeeding test (3(b)) the fuel nozzles were shortened 1/2 inch and operated successfully. The total amount of atomizing air used to cool the fuel lines and atomize the fuel was about 1/2 of 1 percent of the engine air flow in tests 1, 3, and 4. The atomizing-air pressure was about 10 percent higher than the combustor pressure in tests 3 and 4.

SUMMARY OF RESULTS

The following results were obtained from performance evaluations of pentaborane, mixtures of pentaborane and JP-4 fuel, JP-4 fuel, and trimethylborate azeotrope fuel in a full-scale engine at a simulated altitude of 50,000 feet and a Mach number of 0.8. Tests conducted with pentaborane and pentaborane mixtures lasted for only 5 to 22 minutes because of limited fuel supplies.

1. The specific fuel consumption of a standard turbojet engine was reduced to two-thirds that of JP-4 fuel with the use of pentaborane.

2. Engine performance deteriorated with continued use of pentaborane fuel. Net thrust dropped about 13 percent after 10 minutes of operation with pentaborane. This rate of deterioration of engine performance is most rapid at the start of the test and tends to level out after about 10 minutes of operation.

3. Boron oxide collects on the surfaces of the combustor, turbine section, and tailpipe. This oxide did not change the efficiency or pressure drop across the combustor but did adversely affect the performance of the turbine stator, rotor, and tailpipe.

4. Engine performance deteriorates more rapidly as the outlet temperatures become lower because of the increased viscosity of the boron oxide.

5. Boron oxide deposits in the engine can be dissipated by operating the engine on JP-4 fuel. The engine returned to the original level of performance after 30 minutes of operation with JP-4 fuel.

CONCLUDING REMARKS

Although the results discussed in this report were attained with only 110 gallons of pentaborane and represent a very limited testing, a pattern of the performance of the fuel in an engine similar to the engine tested can be fairly well established. Pentaborane reduces specific fuel consumption from that of JP-4 fuel, as can be predicted by simple impulse calculations. Unfortunately, after a few minutes the performance deteriorates. The deterioration in performance is rapid during the first few minutes of operation but tends to level out after 10 to 14 minutes.

This performance deterioration is caused by large drops and films of boron oxide that collect in the engine. The turbine nozzle, turbine rotor section, and tailpipe are most seriously affected by the oxide. The oxide is formed in the combustor flame zones as a vapor. The vapor condenses into microscopic drops, which diffuse to engine surfaces and collect as viscous films. These films grow rapidly and in about 1 minute are thick enough to flow downstream or be blown into the gas stream. The large drops and films of boron oxide are large enough to be separated out of the gas into the turbine nozzles and rotor. The bulk of the boron oxide remains in the gas stream as microscopic drops so small they behave essentially like large gas molecules. But the large drops and films formed upstream of the turbine cause the turbine efficiency to drop as much as 4 to 5 percent.

The most obvious way to keep the pentaborane fuel performance from deteriorating is to reduce the amount of surface exposed to the microscopic drops and then keep the oxide off the surface that remains.

If combustors and turbine inlet parts can be kept clean, the excellent theoretical fuel consumption of pentaborane should be attainable for considerably longer periods of operation.

Some problems that will remain with the use of pentaborane and similar fuels are: (1) Operation at low engine-outlet temperatures hardens the boron oxide and reduces the erosion rate thus causing more rapid performance deterioration; (2) the fuel is very reactive and can quickly form hard solid decomposition products; and (3) the fuel is very toxic.

Lewis Flight Propulsion Laboratory
National Advisory Committee for Aeronautics
Cleveland, Ohio, July 25, 1956

APPENDIX A

SYMBOLS

A area, sq ft

C constant

C_{fr} coefficient of friction

c_p specific heat at constant pressure

c_v specific heat at constant volume

F thrust, lb

f fuel-air ratio

g acceleration due to gravity, 32.17 ft/sec^2

H total enthalpy, Btu/lb

h_f lower heating value of fuel, Btu/lb

K thermodynamic constant

L constant

M Mach number

m molecular weight

P total pressure, lb/sq ft

p static pressure, lb/sq ft

R_g gas constant, ft-lb/(lb)(^oR)

R_{mx} gas constant, for gas and liquid mixtures, $R_g(1-x)$, ft-lb/(lb)(^oR)

sfc specific fuel consumption, (lb)(hr)/lb thrust

S_a air specific impulse, sec

S_f fuel specific impulse, sec

T total temperature, ^oR

t static temperature, $^{\circ}R$

V velocity, ft/sec

w_a air flow, lb/sec

w_f fuel flow, lb/hr

w_l liquid flow, lb/sec

w_{mx} mixture flow, lb/sec

X mass fraction of liquids present in total mixture, w_l/w_{mx}

γ ratio of specific heats, c_p/c_v

δ_a ratio of engine-inlet total pressure P to P at M of 0.8 and altitude of 50,000 ft

ρ density, lb/cu ft

θ_a ratio of engine-inlet total temperature T to T at M of 0.8 and altitude of 50,000 ft

η efficiency

φ equivalence ratio

Subscripts:

a air

ac actual

av arithmetical average

B combustor

C compressor

Cl compressor leakage flow

f fuel

g gas

i indicated

j jet

l liquid

mx mixture

n net

r rake

s scale

st stoichiometric fuel-air ratio

T turbine

Tl turbine cooling

Station numbers:

0 ambient or free-stream conditions

1 engine inlet

3 compressor outlet or combustor inlet

4 combustor outlet or turbine inlet

4' turbine nozzle outlet

5 turbine outlet

9 exhaust-nozzle inlet

10 exhaust-nozzle outlet

APPENDIX B

METHOD OF CALCULATION OF EXPERIMENTAL DATA

The reference values used for c_p, γ, R_g, and various enthalpies for air and hydrocarbon products of combustion of pentaborane, pentaborane blends, and trimethylborate azeotrope are from references 20 and 21 and figures 27 and 28.

Temperature

Total temperature was determined from calibrated thermocouples. The indicated temperature was adjusted for the impact-recovery factor of 0.85 by the following relation:

$$T = \frac{T_i\left(\frac{P}{p}\right)^{\frac{\gamma-1}{\gamma}}}{1 + 0.85\left[\left(\frac{P}{p}\right)^{\frac{\gamma-1}{\gamma}} - 1\right]} \tag{B1}$$

Engine Air Flow

The compressor-inlet air flow was determined from pitot static-pressure and -temperature measurements at station 1, the bellmouth at the engine inlet. The compressor and turbine leakages were measured at two instrumented stations on the compressor and one on the turbine.

$$w_{a,3} = w_{a,1} - w_{a,Cl} - w_{a,Tl} \tag{B2}$$

Jet Thrust

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

$$F_{j,s} = F_s + A'(p_1 - p_0) \tag{B3}$$

where A' is the area of the seal around the engine. Appropriate minor corrections were made for the specific installation in each of the tests.

The jet thrust was calculated from the measurements of the weight flow and tailpipe pressure by the following equation:

$$F_{j,r} = \frac{w_{g,9}V_9}{g} + A_9(p_9 - p_0) \qquad \text{(B4)}$$

The net thrust was calculated by subtracting the adjusted inlet momentum from the jet thrust. When test conditions deviated from the desired simulated flight conditions (Mach number, 0.8; altitude, 50,000 ft), the data were adjusted by appropriate values of θ_a and δ_a.

Combustion Efficiency

Combustion efficiencies for JP-4 fuel, pentaborane, and pentaborane blends were calculated as follows:

$$\eta_B = \frac{(H_9 - H_{a,1}) - fK}{fh_f} \qquad \text{(B5)}$$

Total enthalpy of the exhaust products H_9 was determined by interpolating figure 27(d) for the appropriate values of T, equivalence ratio φ, and blend composition. Inlet total enthalpy H_1 was read directly from figure 27(e). The constant K is an arbitrary base of figures 27(d) and (e) consistent with the thermodynamic data contained in reference 21 and determined from figure 27(f). Figure 27(g) converts fuel-air ratio to equivalence ratio for various blend concentrations. The thermodynamic data used in figure 27 are based on octene-1, which has the same hydrocarbon ratio as the JP-4 fuel used in the tests reported herein. The combustion efficiency of trimethylborate azeotrope was determined from the same equation. H_9 and K were determined from figures 28(c) and (d). $H_{a,1}$ was determined from figure 27(e).

Turbine Efficiency

The turbine efficiency was calculated by

$$\eta_T = \frac{1 - \frac{T_9}{T_4}}{1 - \left(\frac{P_5}{P_4}\right)^{\frac{\gamma-1}{\gamma}}} \qquad \text{(B6a)}$$

$$= \frac{\dfrac{1}{\dfrac{c_{p,av}\,T_5}{\Delta H_c} + 1}}{1 - \left(\dfrac{P_5}{P_4}\right)^{\frac{\gamma-1}{\gamma}}} \tag{B6b}$$

In tests 3(a), (b), and 4, a 5 percent total-pressure loss in the tailpipe was assumed as determined from previous tests; therefore, P_5 was assumed to equal 1.0526 P_9. P_5 was measured directly in tests 1, 2, and 5.

Compressor Efficiency

The compressor efficiency was found by

$$\eta_C = \frac{\left(\dfrac{P_3}{P_2}\right)^{\frac{\gamma-1}{\gamma}} - 1}{\left(\dfrac{T_3}{T_1} - 1\right)} \tag{B7}$$

Combustor Total-Pressure Loss

The total-pressure loss across the combustor was determined from

$$\Delta P = P_3 - P_4 \tag{B8}$$

Nozzle Area Coefficient

The nozzle-throat-area coefficients at the turbine and exhaust were expressed by the following ratio:

$$\frac{A_{\text{boron fuels}}}{A_{\text{JP-4}}} = \frac{\left(\dfrac{w}{\rho V}\right)_{\text{boron fuels}}}{\left(\dfrac{w}{\rho V}\right)_{\text{JP-4}}} \tag{B9}$$

Sonic velocity exists at the throat and is equal to $\sqrt{\gamma g R_g t}$ for JP-4 fuel and is equal to $\sqrt{\gamma g R_g t(1 - X)}$ for boron fuels where X is the mass fraction of liquids present; therefore,

$$\frac{A_{boron\ fuels}}{A_{JP-4}} = \frac{\left[\frac{w}{p}\sqrt{\frac{R_g t(1 - X)}{\gamma g}}\right]_{boron\ fuels}}{\left(\frac{w}{p}\sqrt{\frac{R_g t}{\gamma g}}\right)_{JP-4}} \tag{B10}$$

or in terms of total temperatures and pressures

$$\frac{A_{boron\ fuels}}{A_{JP-4}} = \frac{\left[\frac{w}{P}\sqrt{\frac{R_g T(1 - X)}{\gamma g}}\left(\frac{\gamma + 1}{2}\right)^{\frac{\gamma+1}{2(\gamma-1)}}\right]_{boron\ fuels}}{\left[\frac{w}{P}\sqrt{\frac{R_g T}{\gamma g}}\left(\frac{\gamma + 1}{2}\right)^{\frac{\gamma+1}{2(\gamma-1)}}\right]_{JP-4}} \tag{B11}$$

APPENDIX C

METHOD OF CALCULATION FOR THEORETICAL PERFORMANCE OF PENTABORANE FUEL

Basic Equation

The theoretical net thrust and net-thrust specific fuel consumption for fuels containing pentaborane in an engine with a choked convergent nozzle can be found from existing thermodynamic data by using the following equations:

$$F_n = F_j - \frac{w_a V_0}{g} \tag{C1}$$

$$F_j = \left(pA + \frac{w_{mx}V}{g}\right)_{10} - p_0 A_{10} \tag{C2}$$

Air specific impulse S_a is defined as the total stream momentum per pound of air at the nozzle throat where Mach number M_{10} equals 1;

$$S_a = \frac{\left(pA + \frac{w_{mx}V}{g}\right)_{10}}{w_a} \tag{C3}$$

Then,

$$\frac{F_n}{w_a} = S_a - \frac{p_0 A_{10}}{w_a} - \frac{V_0}{g} \tag{C4}$$

and

$$\frac{F_n}{w_a} = S_a - \frac{p_0 w_{10}}{p_{10} w_a}\sqrt{\frac{R_g(1 - X)t_{10}}{\gamma_{10} g}} - \frac{V_0}{g} \tag{C5}$$

or, in terms of total temperature and total pressure at the exhaust nozzle,

$$\frac{F_n}{w_a} = S_a - \frac{p_0}{P_{10}}\left(\frac{1 + \gamma_{10}}{2}\right)^{\frac{\gamma_{10}}{\gamma_{10}-1}}(1 + f)\sqrt{\frac{2R_g(1 - X)T_{10}}{\gamma_{10}(1 + \gamma_{10})g}} - \frac{V_0}{g} \tag{C6}$$

Since

$$S_a = (1 + f)\sqrt{\frac{2(\gamma+1)}{\gamma g} R_{10}(1 - X)T_{10}} \qquad (C7)$$

$$\frac{F_n}{w_a} = S_a\left[1 - \frac{p_0(1 + \gamma_{10})^{\frac{1}{\gamma_{10}-1}}}{P_{10}(2)^{\frac{\gamma_{10}}{\gamma_{10}-1}}}\right] - \frac{V_0}{g} \qquad (C8)$$

The function of γ is essentially constant ($\pm 1/2$ percent) over the range of fuel compositions covered in this report; therefore,

$$\frac{F_n}{w_a} = S_a\left(1 - 0.8\,\frac{p_0}{P_{10}}\right) - \frac{V_0}{g} \qquad (C9)$$

Since

$$sfc = w_f/F_n$$

$$sfc = \frac{3600\ f}{\eta_B S_a\left(1 - 0.8\,\frac{p_0}{P_{10}}\right) - \frac{V_0}{g}} \qquad (C10)$$

where $f/\eta_B = f_{ac}$ and $f = \varphi f_{st}$.

With f, S_a, p_0/P_{10}, and V_0 known, equation (C10) can be used directly for evaluating specific fuel consumption. The values of air specific impulse for various equivalence ratios, φ, of pentaborane - JP-4 fuel mixtures are given in figure 29(a). Air specific impulse S_a is evaluated at T_{10} for an inlet temperature equal to T_1. The appropriate temperature T_{10} (fig. 29(b)) is discussed after the effects of components and engine performance are presented.

The effect of the change in the performance of engine components with change in fuel type is introduced through changes in p_0/P_{10} where

$$\frac{p_0}{P_{10}} = \frac{p_0}{P_1}\,\frac{P_1}{P_3}\,\frac{P_3}{P_4}\,\frac{P_4}{P_5}\,\frac{P_5}{P_9}\,\frac{P_9}{P_{10}} \qquad (C11)$$

The total pressure up to the combustor inlet is only indirectly affected by the use of pentaborane fuel. The change in total pressure of the remaining components can be examined by the use of one-dimensional flow relations and the thermodynamic data given in figures 27 and 29. These data are based on the assumptions given in the analytical section.

Combustor Performance

The combustor performance affects specific fuel consumption by changes in combustion efficiency η_B and total-pressure loss P_4/P_3. Combustion efficiency must be evaluated experimentally. Pressure is lost across the combustor because of friction and momentum losses. The friction pressure loss will increase only if oxide collects on the wall and obstructs the flow. As this must be evaluated experimentally, it is neglected in this discussion. Pentaborane combustion products differ from JP-4 products; therefore, momentum pressure drop will change. The two factors producing the change are the changed masses and specific heats. Assuming one-dimensional flow,

$$\frac{P_4}{P_3} = \frac{\left(1 + \gamma_3 M_3^2\right)\left(1 + \frac{\gamma_4 - 1}{2} M_4^2\right)^{\frac{\gamma_4}{\gamma_4 - 1}}}{\left(1 + \gamma_4 M_4^2\right)\left(1 + \frac{\gamma_3 - 1}{2} M_3^2\right)^{\frac{\gamma_3}{\gamma_3 - 1}}} \tag{C12}$$

where M_4 is found from

$$\frac{M_4\left(1 + \frac{\gamma_4 - 1}{2} M_4^2\right)^{\frac{1}{2}}}{1 + \gamma_4 M_4^2} = \frac{M_3\left(1 + \frac{\gamma_3 - 1}{2} M_3^2\right)^{\frac{1}{2}}}{1 + \gamma_3 M_3^2}\left(\frac{S_{a,4}}{S_{a,3}}\right)\sqrt{\frac{1 + \gamma_3}{1 + \gamma_4}} \tag{C13}$$

The momentum pressure drop for pentaborane and JP-4 fuel was calculated for the combustor in the subject engine operating at 100 percent of rated speed and flight Mach number 0.8. The combustor-inlet Mach number M_3 was found by assuming that all the air was passing through an area equal to the maximum inner cross-sectional area of the combustor liner. $S_{a,4}$ and $S_{a,3}$ correspond to $(1 + f)\sqrt{\frac{2(\gamma+1)}{\gamma} R_g(1 - X)T_4}$ and $\sqrt{\frac{2(\gamma+1)}{\gamma} R_g(1 - X)T_3}$, respectively. T_4 is T_3 plus the temperature rise due to combustion. The total-pressure-ratio change for pentaborane is negligible, 0.983 compared with 0.982 for JP-4 fuel.

Turbine Nozzle

Excluding the effect of deposits on the turbine nozzle, a comparison between pentaborane and JP-4 fuel on pressure-ratio characteristics of the nozzle may be found from the continuity expression. The expression for a choked nozzle is as follows:

$$\frac{P_{4,B_5H_9}}{P_{4,JP-4}} = \frac{A_{JP-4}}{A_{B_5H_9}} \frac{w_{mx,B_5H_9}}{w_{mx,JP-4}} \frac{\left[\sqrt{\frac{R_gT_4(1 - X)}{\gamma g}} \left(\frac{\gamma + 1}{2}\right)^{\frac{\gamma+1}{2(\gamma-1)}}\right]_{B_5H_9}}{\left[\sqrt{\frac{R_gT_4}{\gamma g}} \left(\frac{\gamma + 1}{2}\right)^{\frac{\gamma+1}{2(\gamma-1)}}\right]_{JP-4}} \tag{C14}$$

The nozzle throat area is assumed to be the same for both fuels. Restricting the comparison to 100 percent of rated speed, where the mass flow through the compressor is not greatly affected by the pressure ratio across the compressor, the first-order variation in P_4 is indicated by equation (C14). Substituting appropriate values for pentaborane and JP-4 fuel, $P_{4,B_5H_9}/P_{4,JP-4} = 0.99$.

The lower turbine-inlet pressure for pentaborane fuel reduces the compressor and turbine work slightly. The net effect on outlet pressure will be examined in conjunction with the turbine-work equation.

A turbojet is usually limited to a fixed temperature entering the turbine T_4. Holding T_4 constant, the work extracted from a turbine per pound of air is

$$\Delta H_T = (1 + f)\ c_pT_4 \left[1 - \left(\frac{P_5}{P_4}\right)^{\frac{\gamma-1}{\gamma}}\right] \tag{C15}$$

Let

$$C = \frac{\Delta H_{T,JP-4}}{\Delta H_{T,B_5H_9}} = \frac{\left(\frac{P_3}{P_2}\right)^{\frac{\gamma-1}{\gamma}} - 1}{\left(L\ \frac{P_3}{P_2}\right)^{\frac{\gamma-1}{\gamma}} - 1} \tag{C16}$$

and

$$L = \frac{P_{4,B_5H_9}}{P_{4,JP-4}}$$

For the case considered, L = 0.99 and C = 0.992. The pressure ratio for pentaborane is then

$$\left(\frac{P_5}{P_4}\right)_{B_5H_9} = \left\{1 - \frac{\left[\eta_T c_p(1 + f)\right]_{JP-4}}{C\left[\eta_T c_p(1 + f)\right]_{B_5H_9}}\left[1 - \left(\frac{P_5}{P_4}\right)^{\frac{\gamma-1}{\gamma}}\right]_{JP-4}\right\}^{\left(\frac{\gamma}{\gamma-1}\right)_{B_5H_9}} \tag{C17}$$

Let $T_4 = 2100^\circ$ R ($\Delta T = 1230^\circ$ R) and a pressure ratio $(P_5/P_4)_{JP-4} = 0.4$, which closely correspond to the subject engine operating at 100 percent of rated speed at a flight Mach number of 0.8. Then

$$\frac{P_{5,B_5H_9}}{P_{5,JP-4}} = \frac{\frac{P_5}{P_4} P_{4,B_5H_9}}{\frac{P_5}{P_4} P_{4,JP-4}} = \left(\frac{0.392}{0.4}\right) 0.99 = 0.97 \tag{C18}$$

At the condition considered, the loss in total pressure introduces a 2-percent loss in net thrust. A loss of 2/3 percent in net thrust is due to the change in the inlet pressure to the nozzle. The remaining $1\frac{1}{3}$ percent is due to the change of available work of the fluid.

In practice, the experimental data have shown that the turbine nozzle area is usually reduced slightly by the boron oxide films. In view of this, the simplifying assumption that $P_{4,B_5H_9} = P_{4,JP-4}$ appears valid for first-order comparisons. The pressure ratio for pentaborane, and hence P_5, for the same work can be found directly from equation (C17) (C = 1).

For the conditions of the example,

$$\frac{P_{5,B_5H_9}}{P_{5,JP-4(C=1)}} = 0.973 \tag{C19}$$

The calculated total-pressure loss across the turbine neglecting the change in turbine-inlet pressure (eq. (C19)) is essentially the same as the more rigorous value (eq. (C18)) and amounts to 2-percent loss in net thrust.

Tailpipe

The losses in the tailpipe result from friction. The equation for friction loss may be written as follows:

$$\frac{P_9}{P_5} = 1 - \frac{C_{fr}\gamma M_5^2}{2\left(1 + \frac{\gamma-1}{2} M_5^2\right)^{\frac{\gamma}{\gamma-1}}} \tag{C20}$$

Since this section of the report is not concerned with change in C_{fr} due to deposits, the effect of pentaborane fuel will be felt by changes in Mach number M_5, which will be increased when pentaborane is used because P_5 is lower (because of the greater expansion ratio across the turbine). Normally the ratio P_9/P_5 is about 0.96. This value varies for the type of tailpipe used and with the presence of afterburner and flameholder. For the example used, the increased Mach number in the tailpipe with pentaborane fuel dropped P_9/P_5 from 0.96 to 0.955, which is negligible.

Exhaust Nozzle

Exhaust-nozzle performance, excluding deposits, is not changed with change in fuel type.

Selection of $S_{a,9}$

The proper value of T_{10} to introduce into equation (C7) so that equation (C10) can be evaluated is determined from

$$T_{10} = T_9 = T_5 = T_4 - \frac{\Delta H_C}{c_{p,av}}$$

Since the turbine-inlet temperature is limiting, T_4 is assumed constant. Evaluating T_{10} for the conditions cited under the turbine component performance discussion where $\frac{\Delta H_{T,B_5H_9}}{\Delta H_{T,JP-4}} = 0.992$ $\frac{T_{10,B_5H_9}}{T_{10,JP-4}} = 1.002$. For all practical purposes, T_{10} for JP-4 and pentaborane fuel may be considered identical. However, this does not mean that $S_{a,9}$ is identical for both fuels. At a constant T_{10} (T_9), S_a is 1 percent lower with pentaborane than with JP-4 fuel (figs. 29(a) and (b)). Substituting in equation (C8), the net thrust for pentaborane is reduced $1\frac{1}{4}$ percent by the change in air specific impulse S_a.

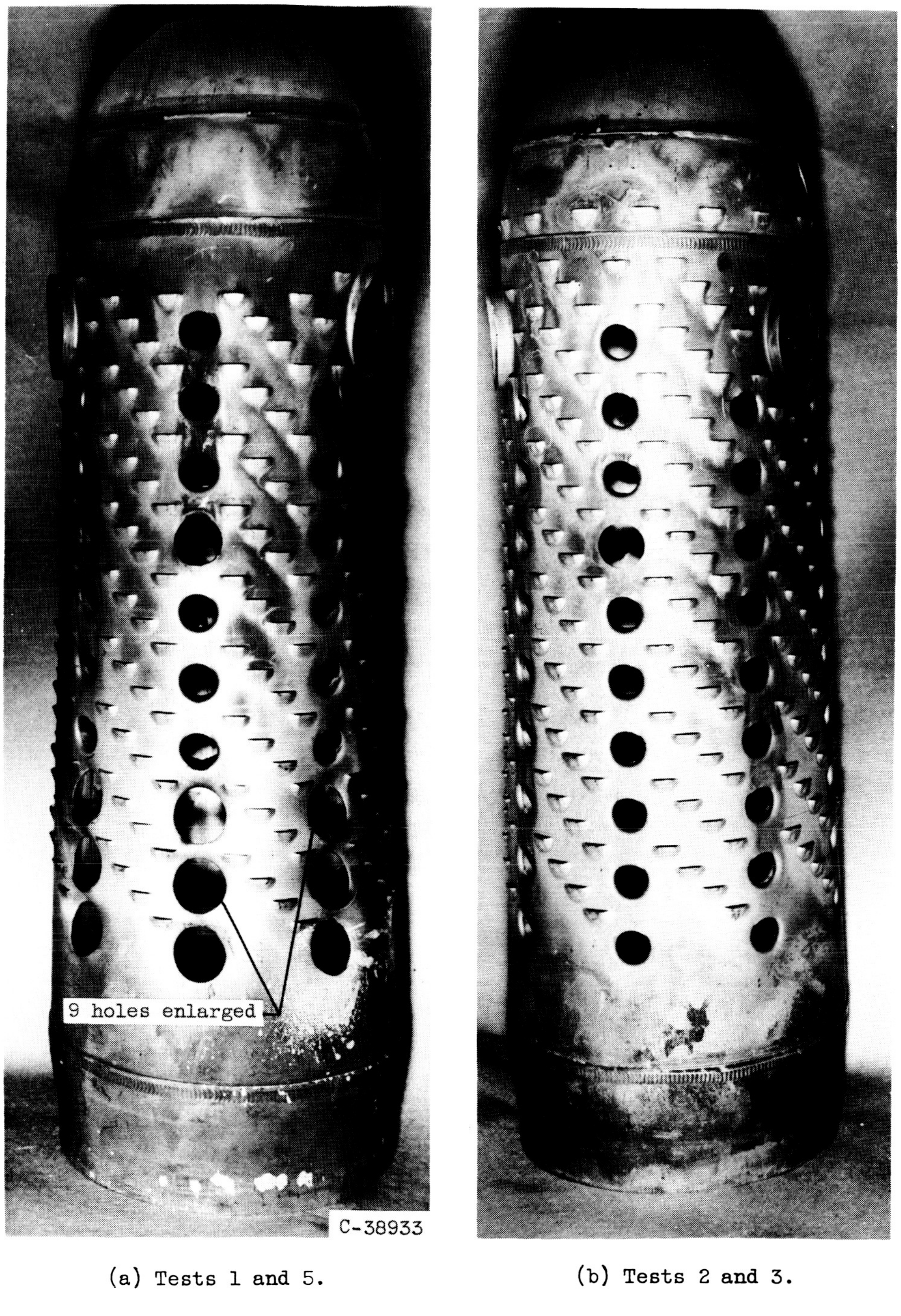
TABLE I. - ENGINE CONFIGURATIONS

Test	Engine	Combustor	Fuel injector	Turbine	Tailpipe	Exhaust nozzle
1	Fig. 1(a)	Fig. 2(a); modified tubular liner; nine enlarged air-entry holes at rear of combustor to improve outlet-temperature profile, standard serrated retaining ring at end of combustor	Fig. 3(a); pentaborane internally mixed with atomizing air and ejected through six ports; starting fuel, JP-4, externally atomized with air	Standard	Standard afterburner shell; flameholder and liner removed	Variable-area clamshell nozzle
2	Fig. 1(b)	Standard (fig. 2(b))	Pentaborane sprayed through two hollow-cone fixed-area fuel injectors located 180° apart on combustor wall at station customarily used for water injection; JP-4 fuel injected through standard duplex fuel nozzles at upstream end of combustor	Turbine shroud modified so that clearance increased from leading edge to trailing edge; cold clearances, 0.90 and 0.190 in., respectively	Standard	Enlarged exhaust nozzle; mechanically operated flaps to provide small modulation to exhaust area
3(a) and (b)	Fig. 1(b)	Standard (fig. 2(b)); solid combustor retaining ring	Fig. 3(c); pentaborane internally mixed with atomizing air and ejected through single port; JP-4 fuel externally atomized with air; configurations for (a) and (b) differed only in length of fuel injector (fig. 3(c))	Tapered turbine shroud; shroud design same as in test 2	Standard	Fixed-area nozzle
4	Fig. 1(b)	Wire-cloth combustor (ref. 8)	Fig. 3(d); pentaborane fuel mixture internally mixed with air ejected through single port; propylene oxide used as starting fuel externally atomized with air	Tapered turbine shroud; shroud design same as in test 2	Standard	Fixed-area nozzle
5	Engine and components were same as in test 1, except fuel injectors were enlarged to handle the higher fuel flow rates (fig. 3(e)).					

TABLE II. - FUEL PROPERTIES

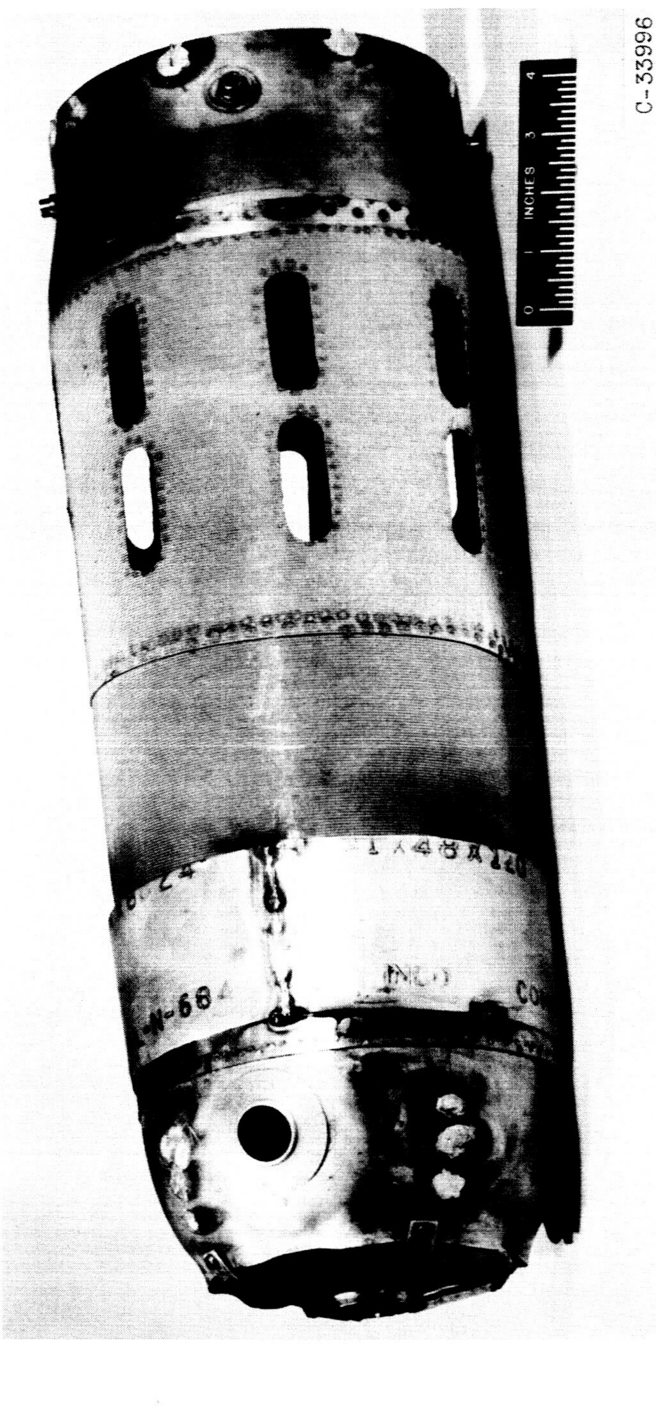
	Pentaborane	Trimethylborate - methyl-alcohol azeotrope
Formula	B_5H_9	$B(OCH_3)_3$-CH_3OH
Formula weight	63.17	135.87
Melting point, °F	-52	------
Boiling point, °F at 760 mm Hg	136	------
Heat of combustion, Btu/lb	[a]29,100	[a]8060
Specific gravity at 32° F	0.644	-----
Stoichiometric fuel-air ratio	0.07635	-----
Pounds of B_2O_3 per million Btu	94	32
MIL-F-5624A, grade JP-4		
Reid vapor pressure, lb/sq in.		2.4
Specific gravity at 32° F		0.778
Hydrogen-carbon ratio		0.168
Net heat of combustion, Btu/lb		18,675

[a]Based on H_2O in gaseous phase.



(a) Tests 1 and 5. (b) Tests 2 and 3.

Figure 2. - Combustors used in full-scale engine tests.



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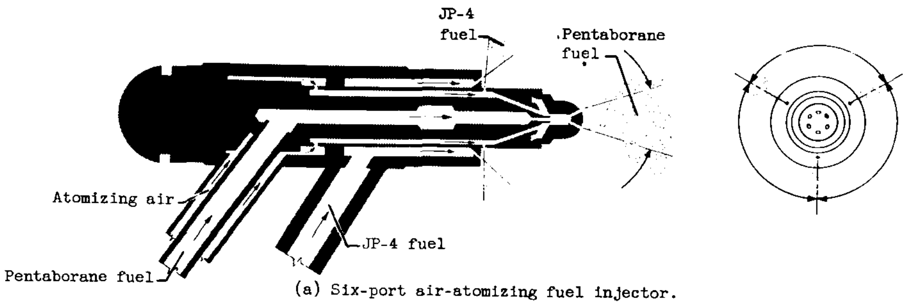
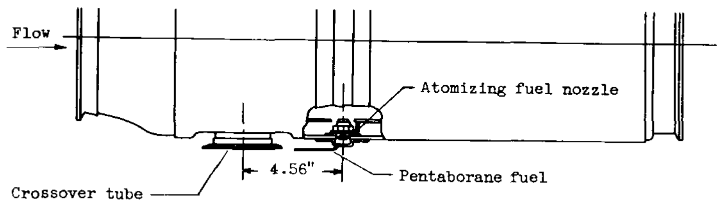
(c) Test 4.

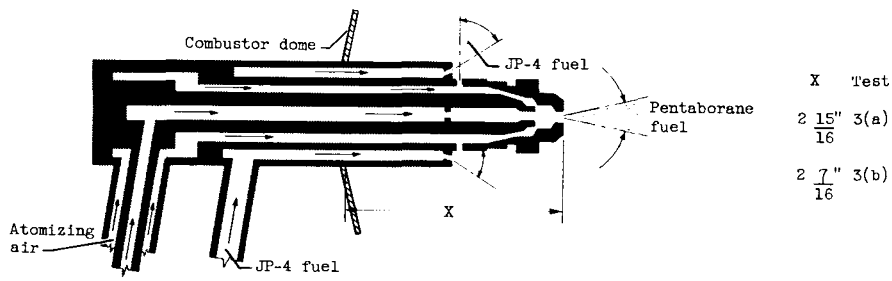
Figure 2. - Concluded. Combustors used in full-scale engine tests.



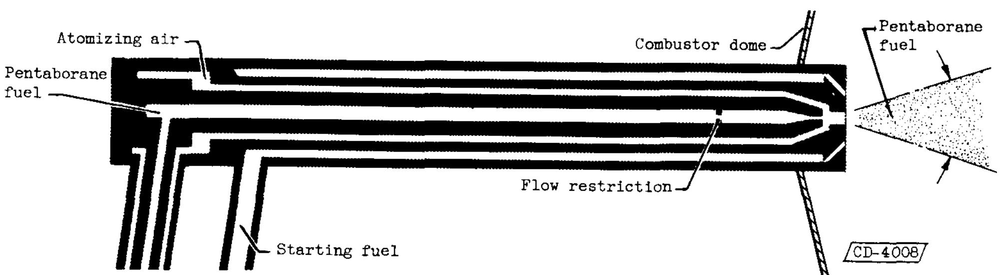
(a) Six-port air-atomizing fuel injector.



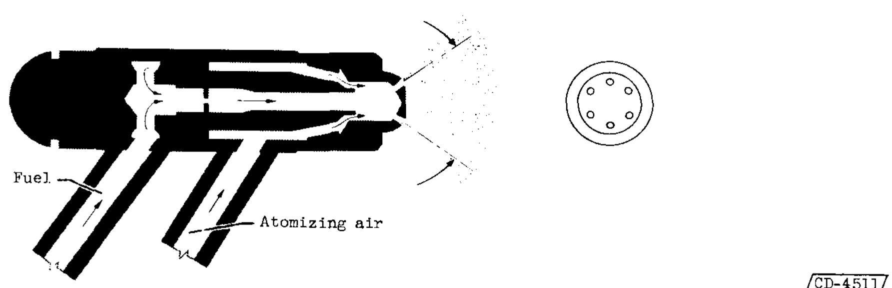
(b) Hollow-cone fuel sprays located on combustor walls.



(c) Single-port air-atomizing fuel injector.



(d) Single-port air-atomizing fuel injector.



(e) Six-port air-atomizing fuel injector.

Figure 3. - Fuel injectors used in full-scale engine tests.

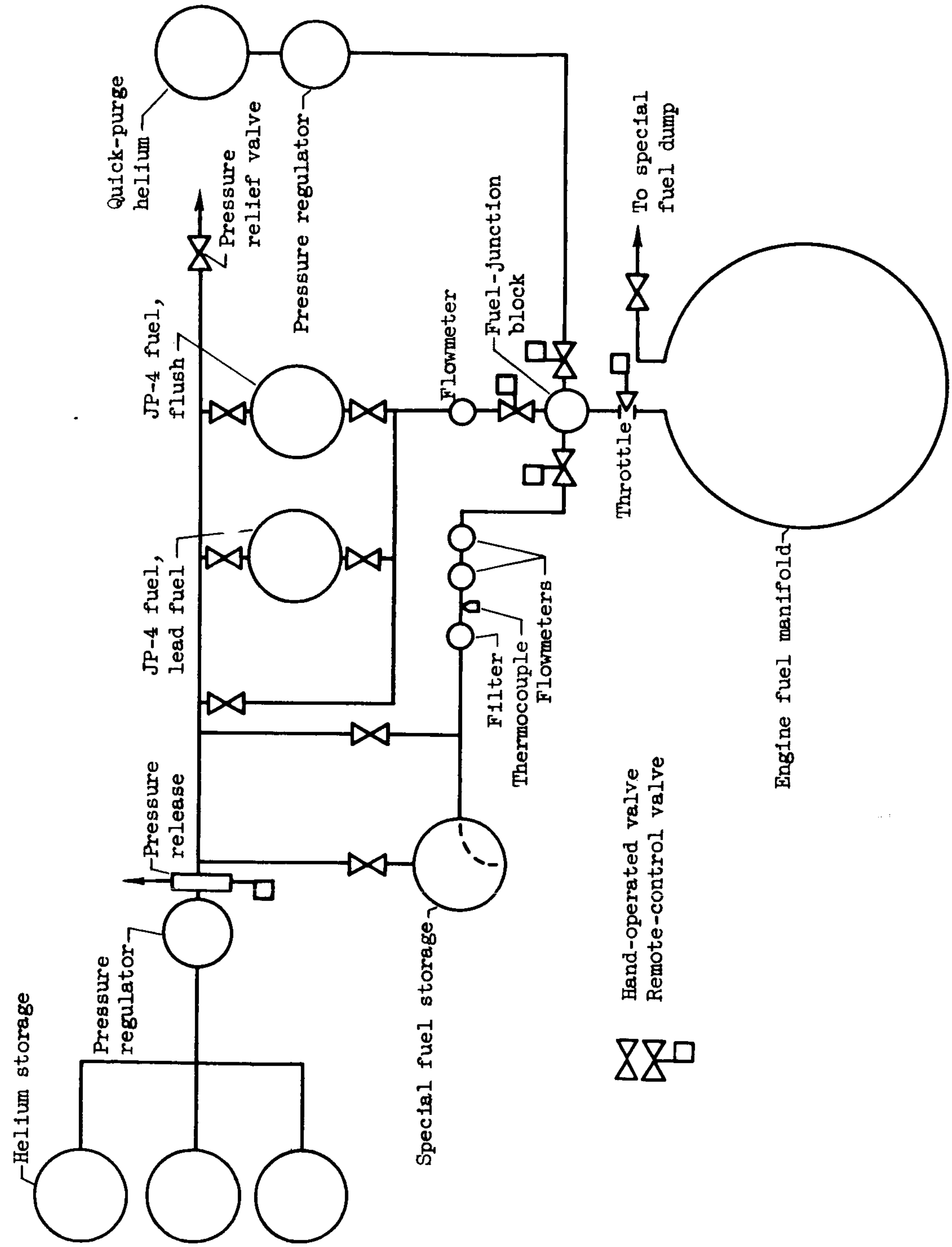
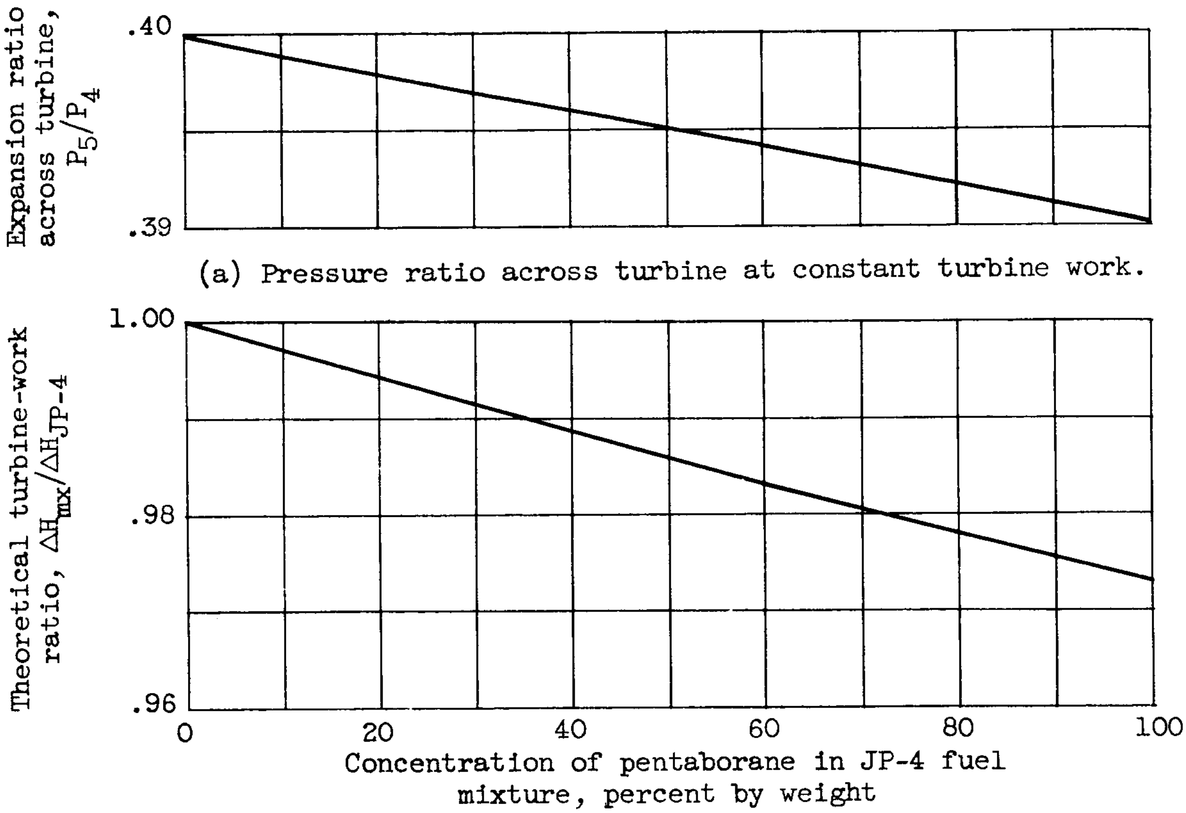


Figure 4. - Diagram of engine fuel system.



(a) Pressure ratio across turbine at constant turbine work.

(b) Turbine work with constant pressure ratio (0.4).

Figure 5. - Effect of exhaust-gas composition of pentaborane - JP-4 fuel mixtures on theoretical turbine performance. Compressor-outlet temperature, 900° R; combustor-outlet temperature, 2100° R.

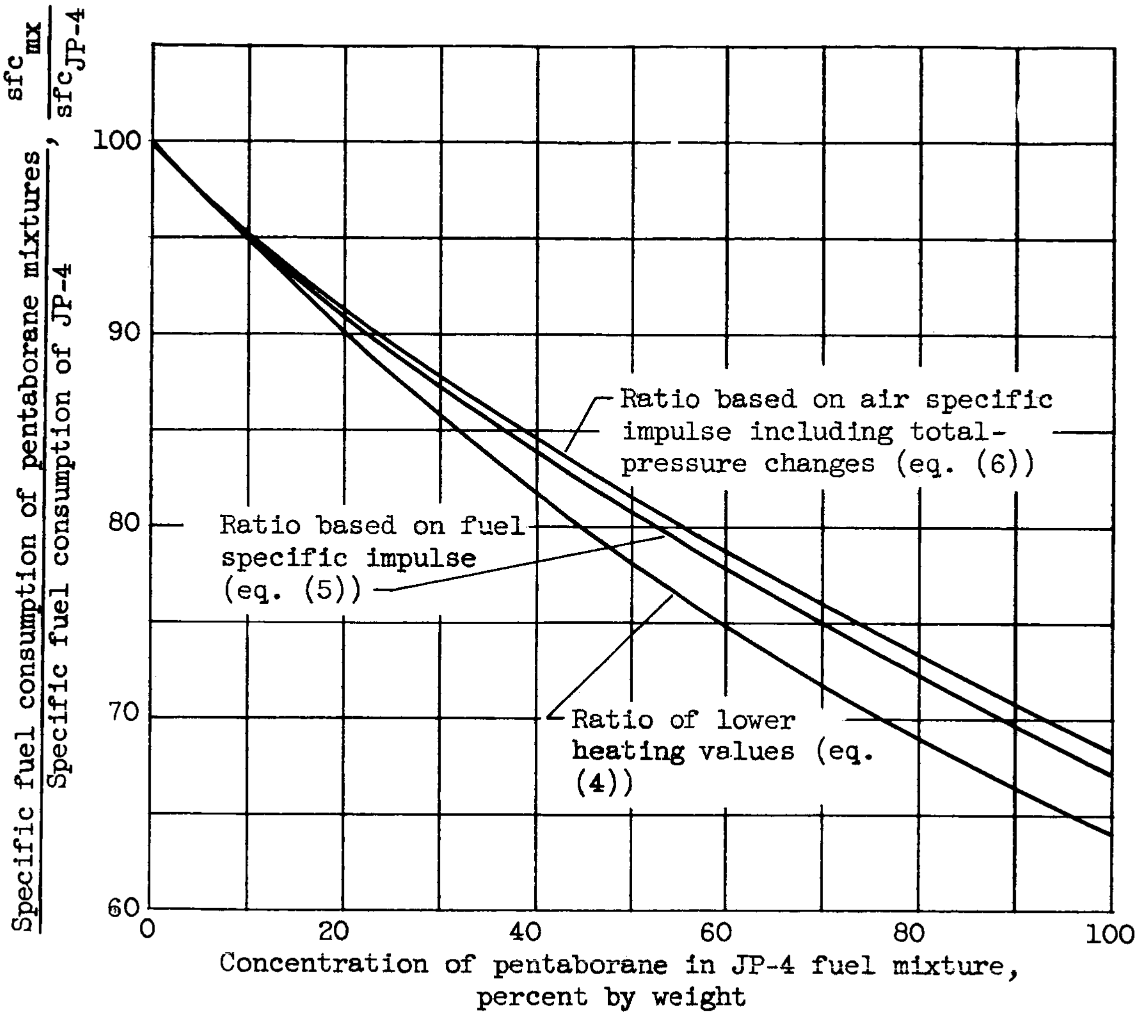


Figure 6. - Comparison of methods for calculating specific fuel consumption for pentaborane - JP-4 fuel mixtures. Flight Mach number, 0.8; altitude, 50,000 feet; 100 percent of rated engine speed.

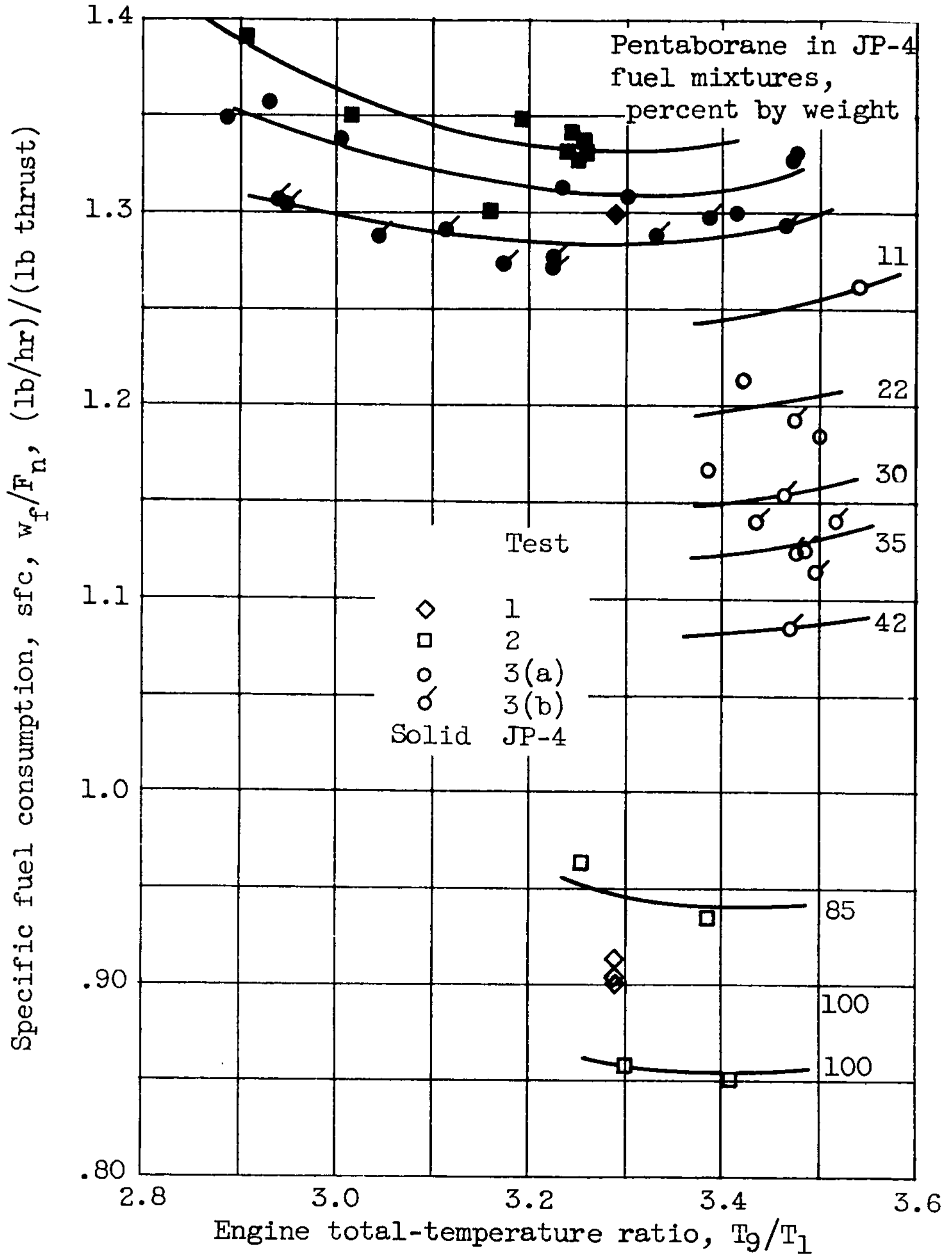


Figure 7. - Variation of specific fuel consumption based on net thrust with engine total-temperature ratio for a range of mixtures of pentaborane and JP-4 fuel. Altitude, 50,000 feet; flight Mach number, 0.8; corrected engine speed, 90 to 98 percent of rated speed.

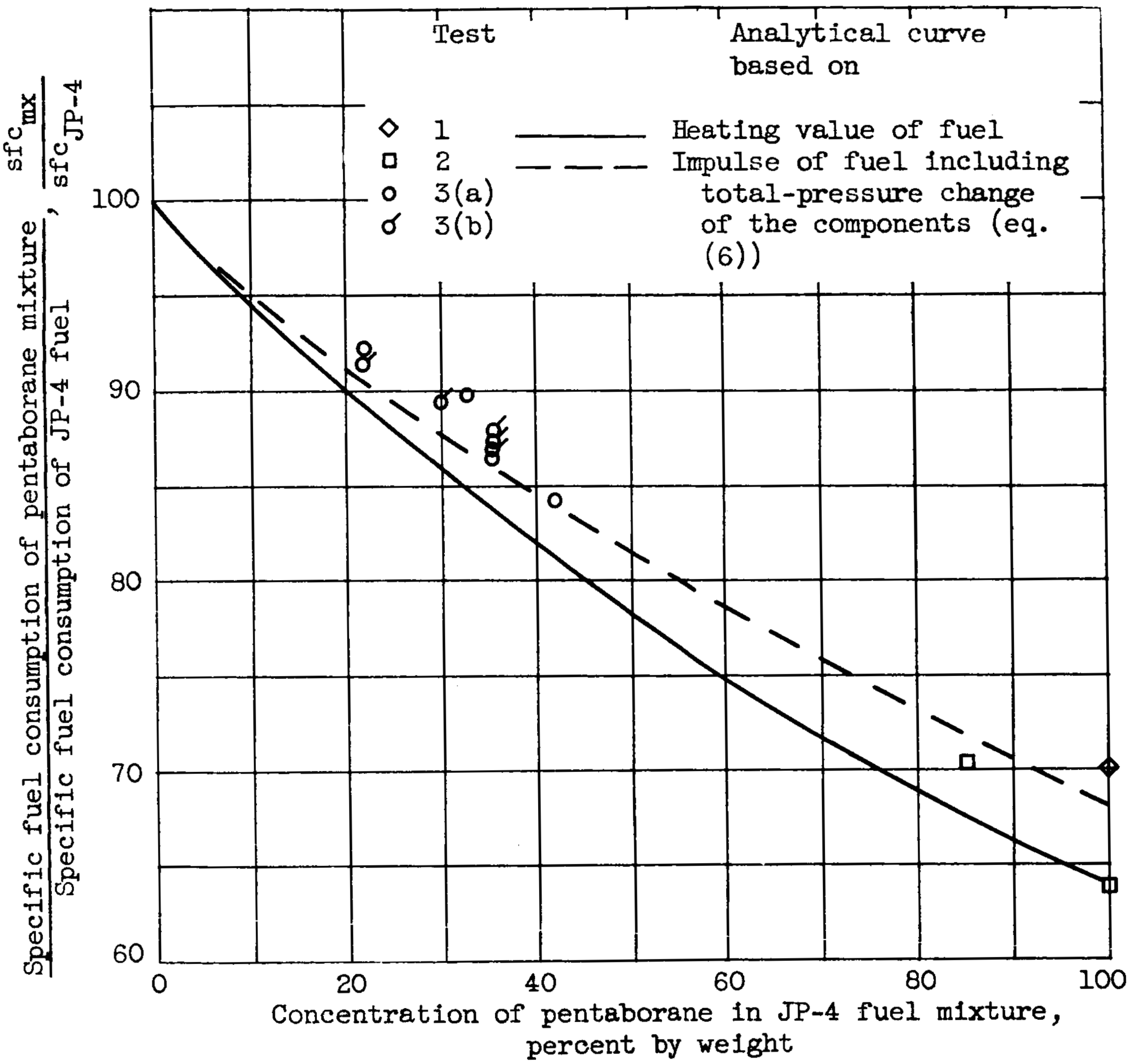


Figure 8. - Effect of pentaborane mixture concentration in JP-4 fuel on specific fuel consumption based on net thrust. Engine total-temperature ratio, 3.48; altitude, 50,000 feet; flight Mach number, 0.8; corrected engine speed, 90 to 98 percent of rated speed.

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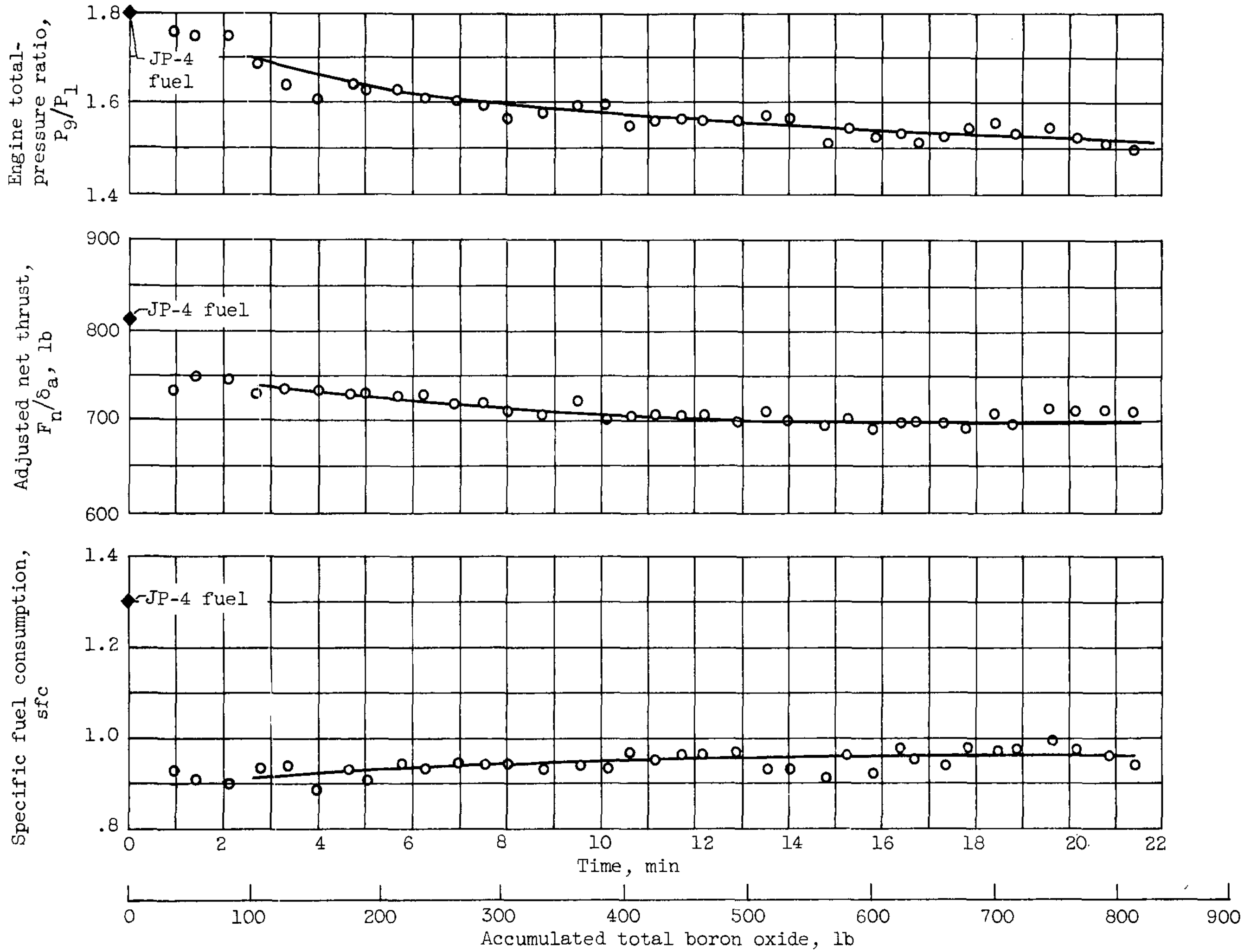

(a) Test 1; engine total-temperature ratio, 3.3.

Figure 9. - Effect of operation with 100 percent pentaborane fuel on turbojet-engine performance. Altitude, 50,000 feet; flight Mach number, 0.80; corrected engine speed, 98 percent of rated.

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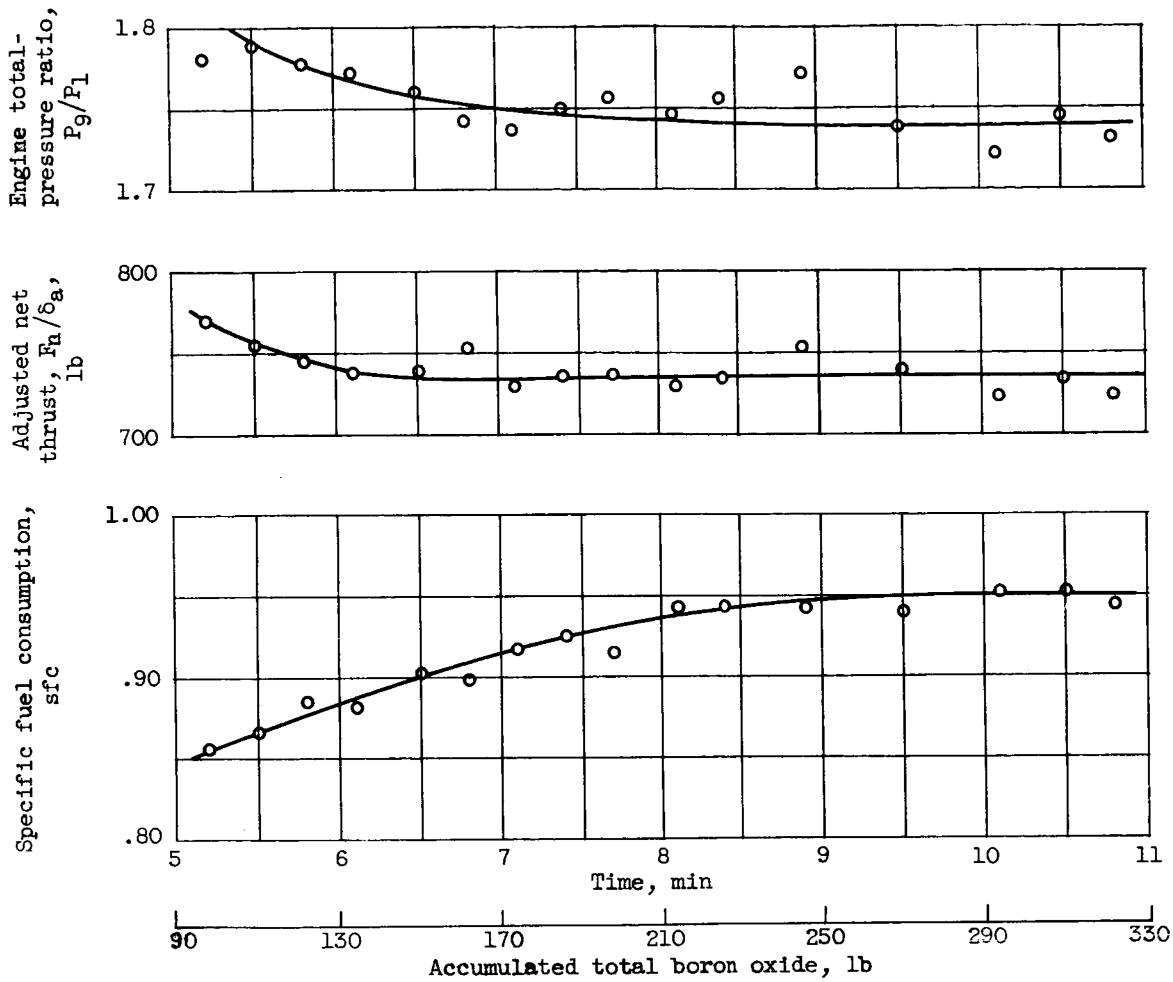


(b) Test 2; engine total-temperature ratio, 3.4.

Figure 9. - Concluded. Effect of operation with 100 percent pentaborane fuel on turbojet-engine performance. Altitude, 50,000 feet; flight Mach number, 0.8; corrected engine speed, 98 percent of rated speed.

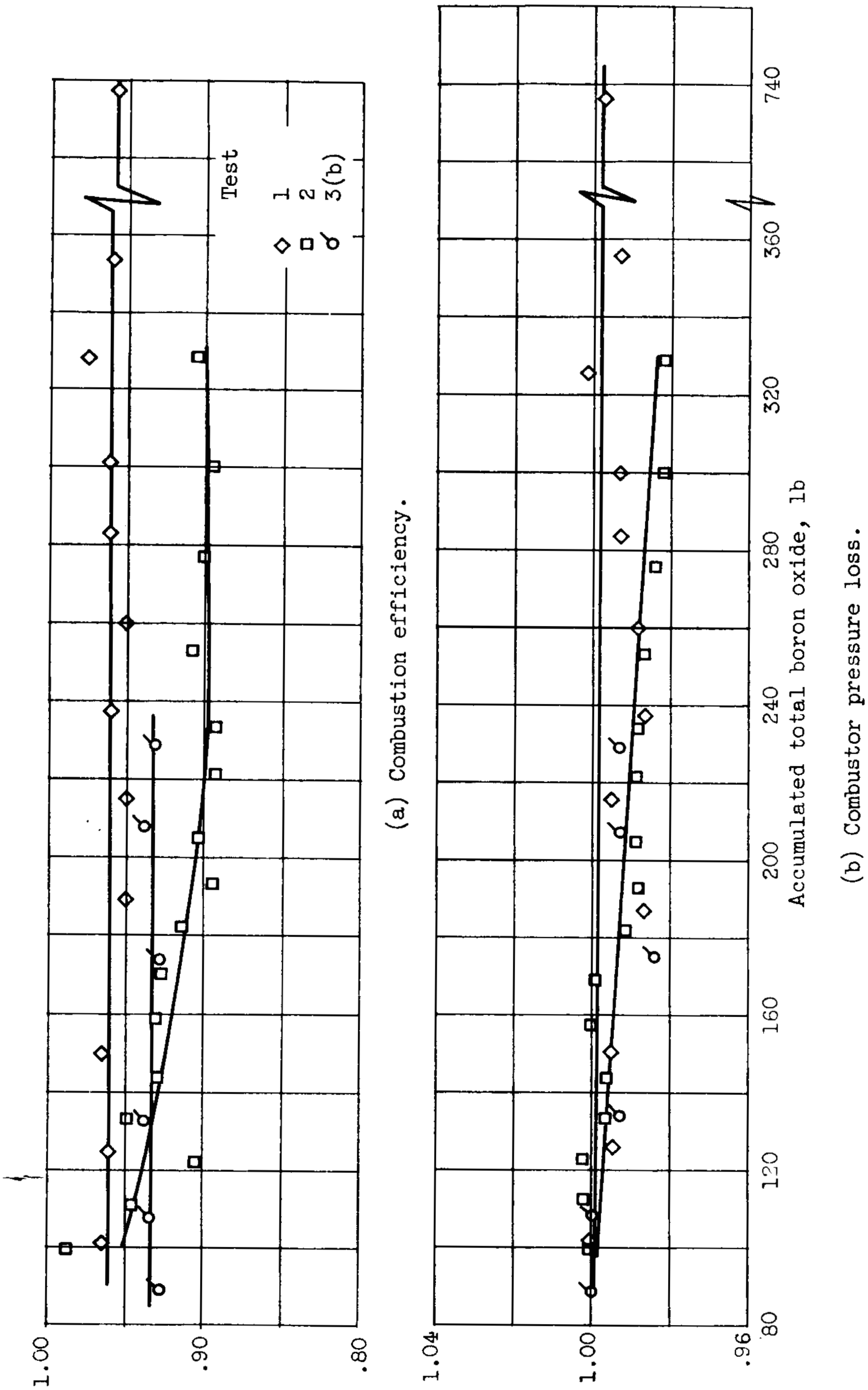
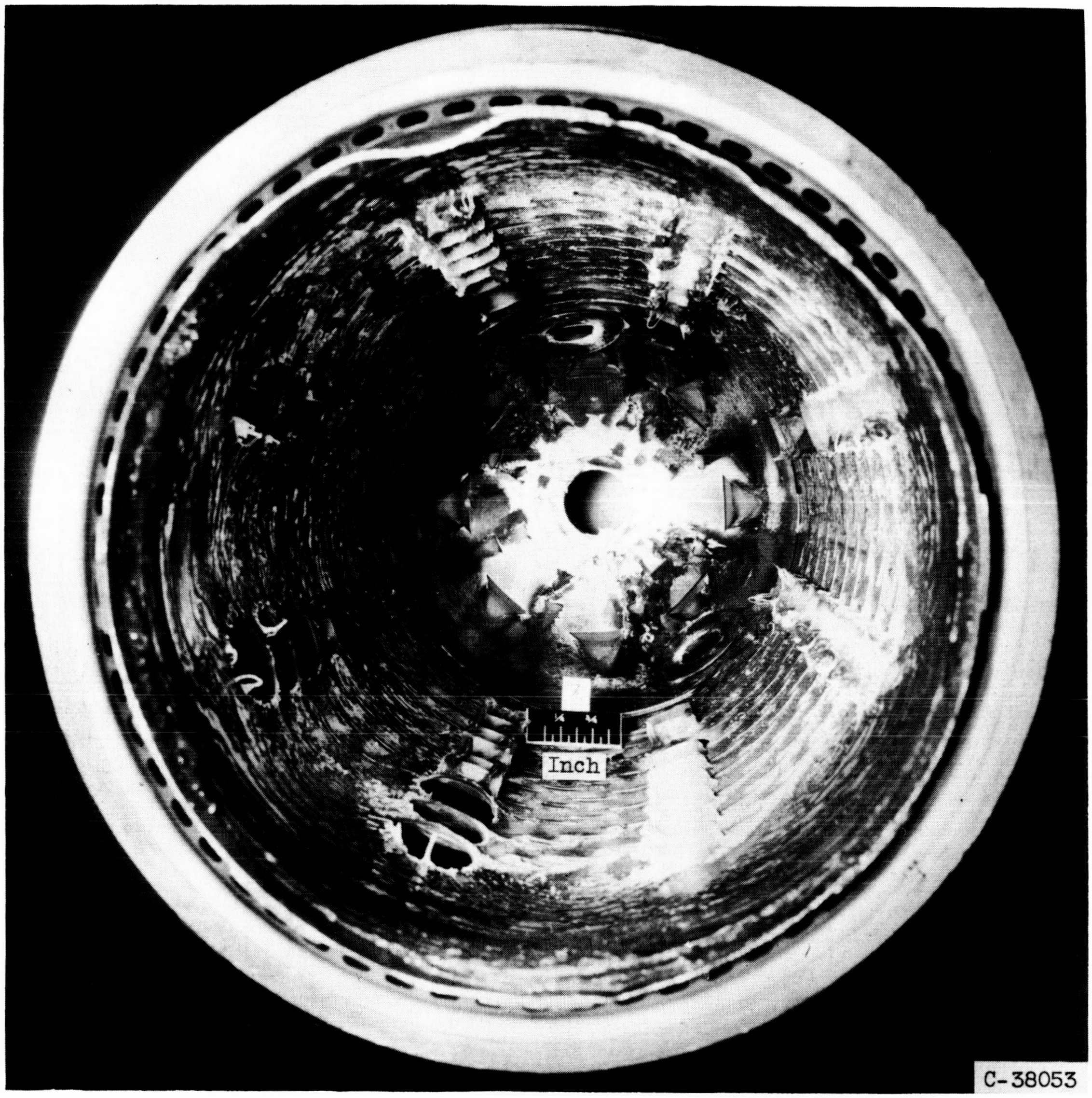


Figure 10. - Effect of boron oxide on combustion performance. Altitude, 50,000 feet; flight Mach number, 0.8; corrected engine speed, 90 to 98 percent of rated speed.

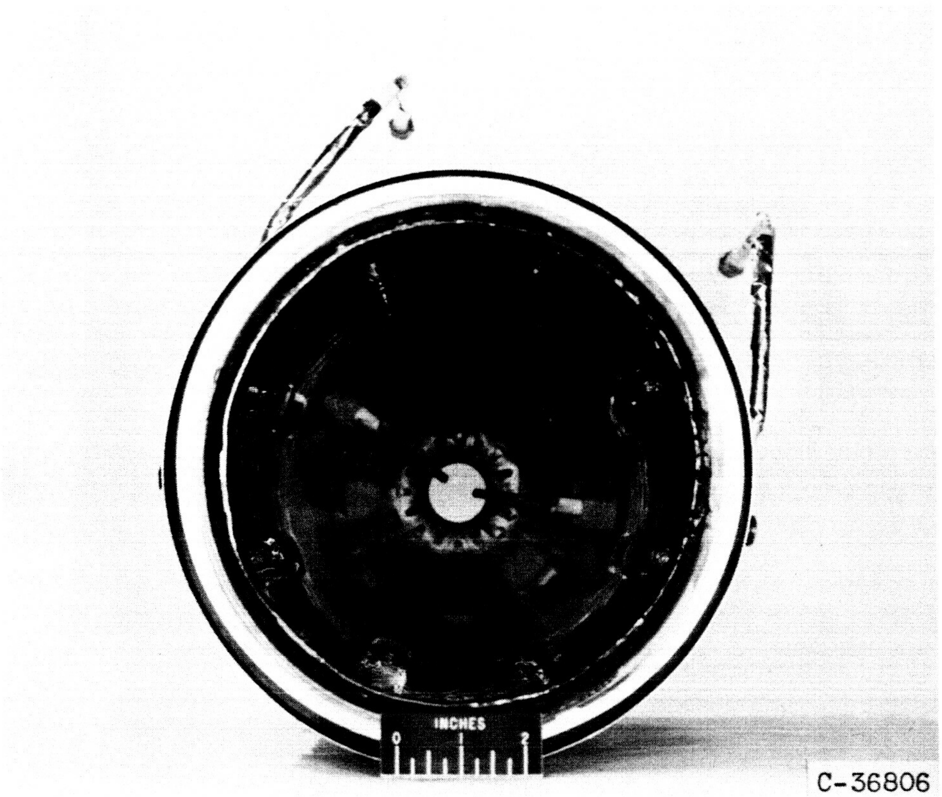
(a) Test 1, combustion chamber with greater deposits. Total test time, 22 minutes.

Figure 11. - Boron oxide deposits on turbojet-engine components after operation with pentaborane.



(b) Test 1, relatively clean combustion chamber. Total test time, 22 minutes.

Figure 11. - Continued. Boron oxide deposits on turbojet-engine components after operation with pentaborane.



(c) Test 2. Total test time, 11 minutes.

Figure 11. - Continued. Boron oxide deposits on turbojet-engine components after operation with pentaborane.

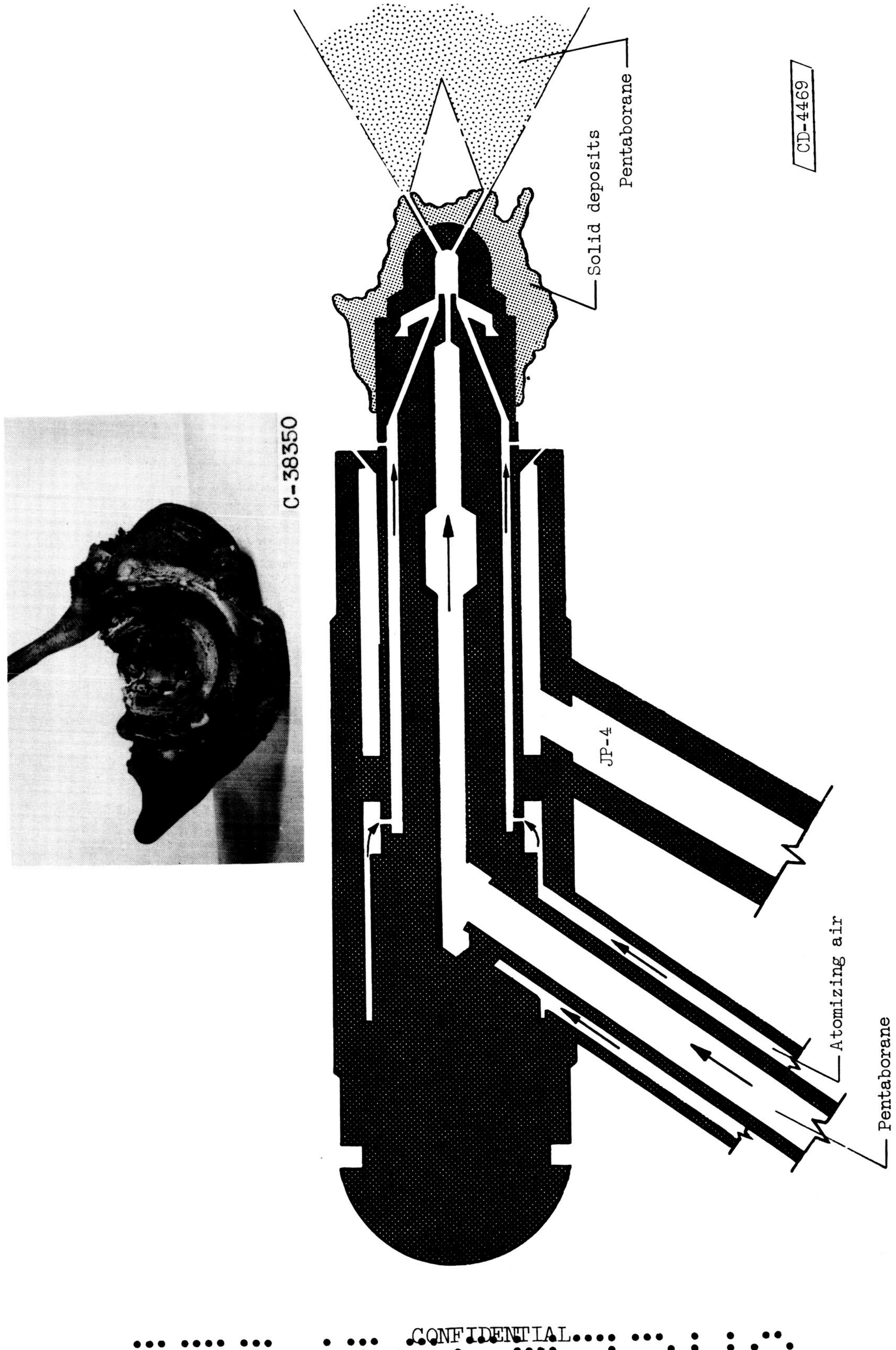


Figure 13. - Boron oxide deposits on turbojet-engine fuel nozzle after 22 minutes of operation with pentaborane.

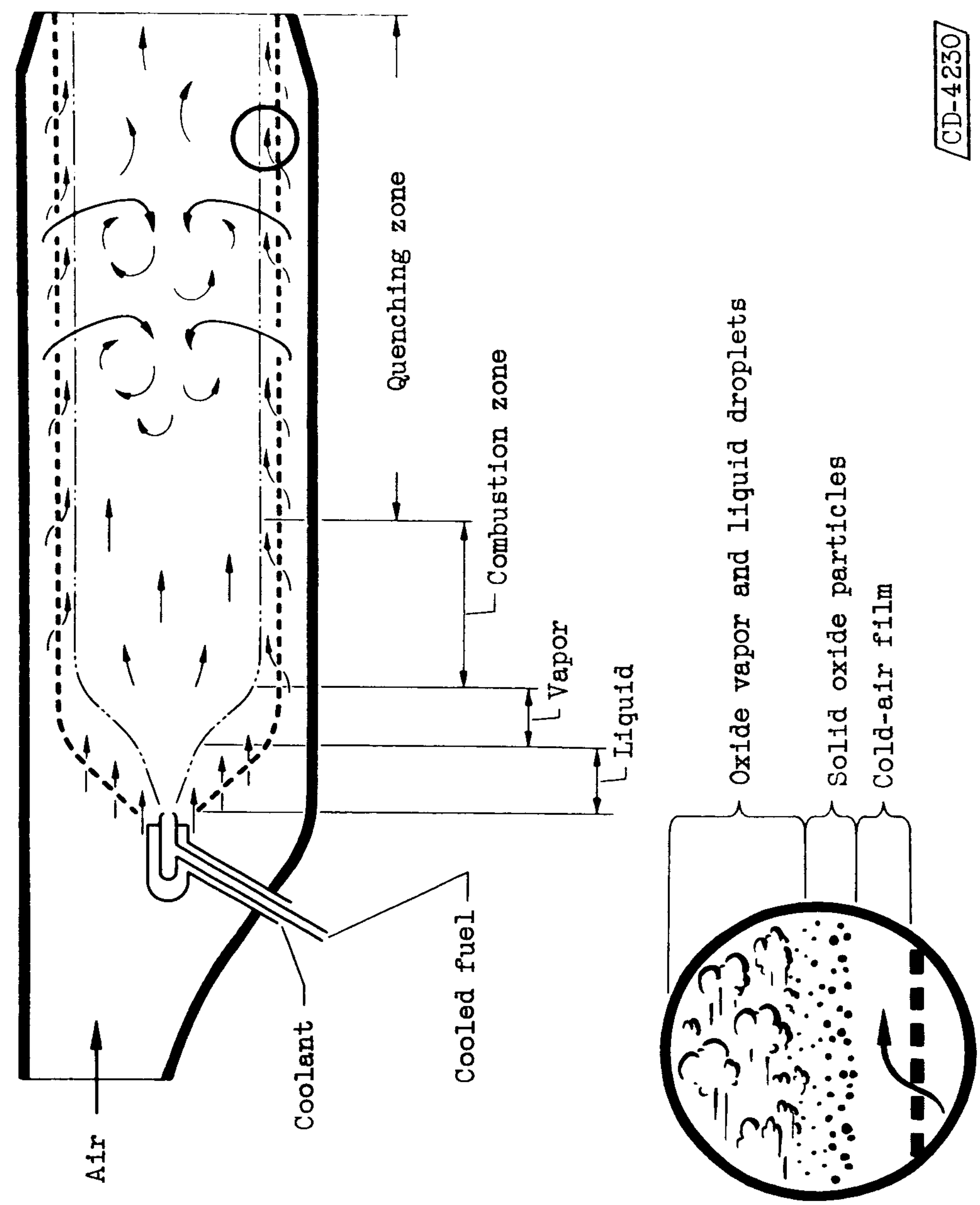


Figure 14. - Wire-cloth combustor design.

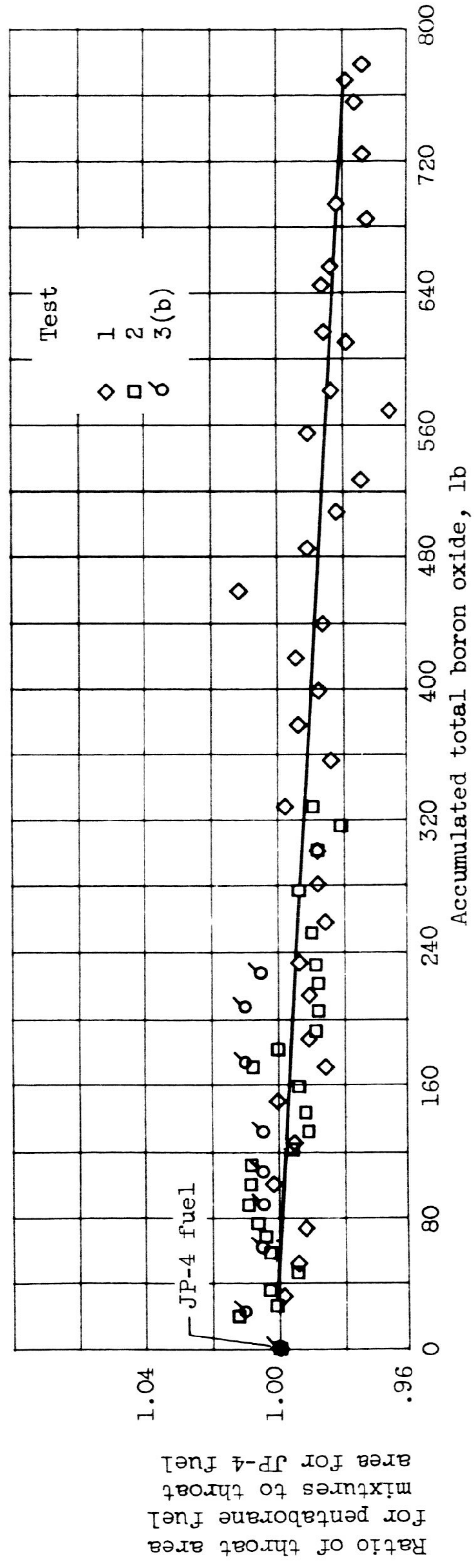
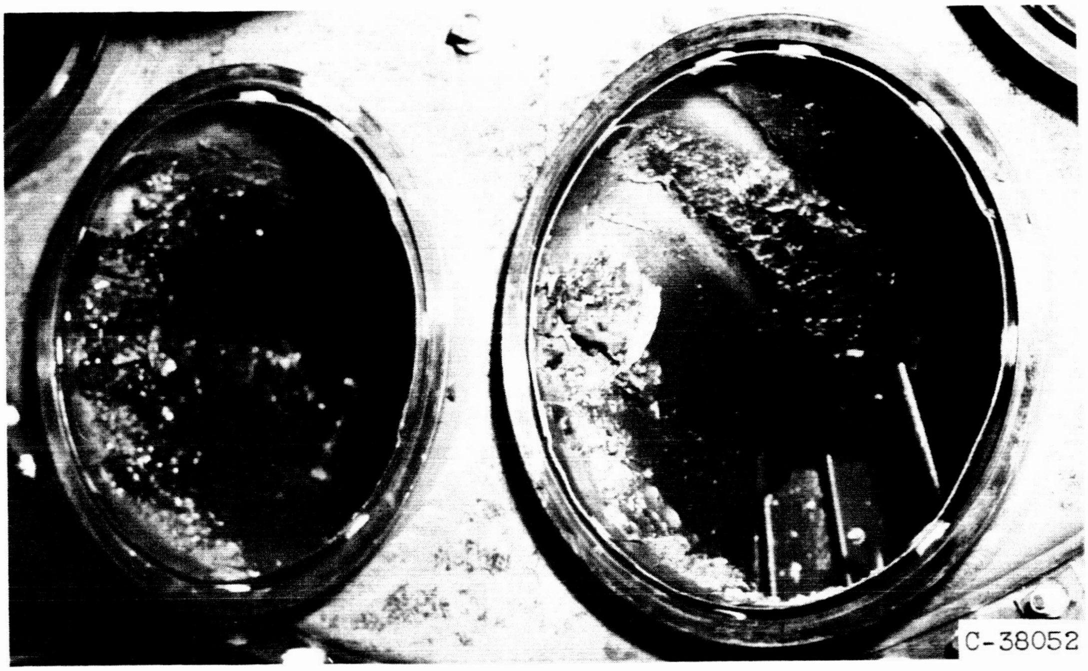


Figure 16. - Influence of engine operation with pentaborane fuel mixtures on calculated turbine-nozzle-diaphragm throat area.

(a) Test 1.

Figure 17. - Turbine stator after pentaborane fuel tests.



(b) Test 2.

Figure 17. - Concluded. Turbine stator after pentaborane fuel tests.

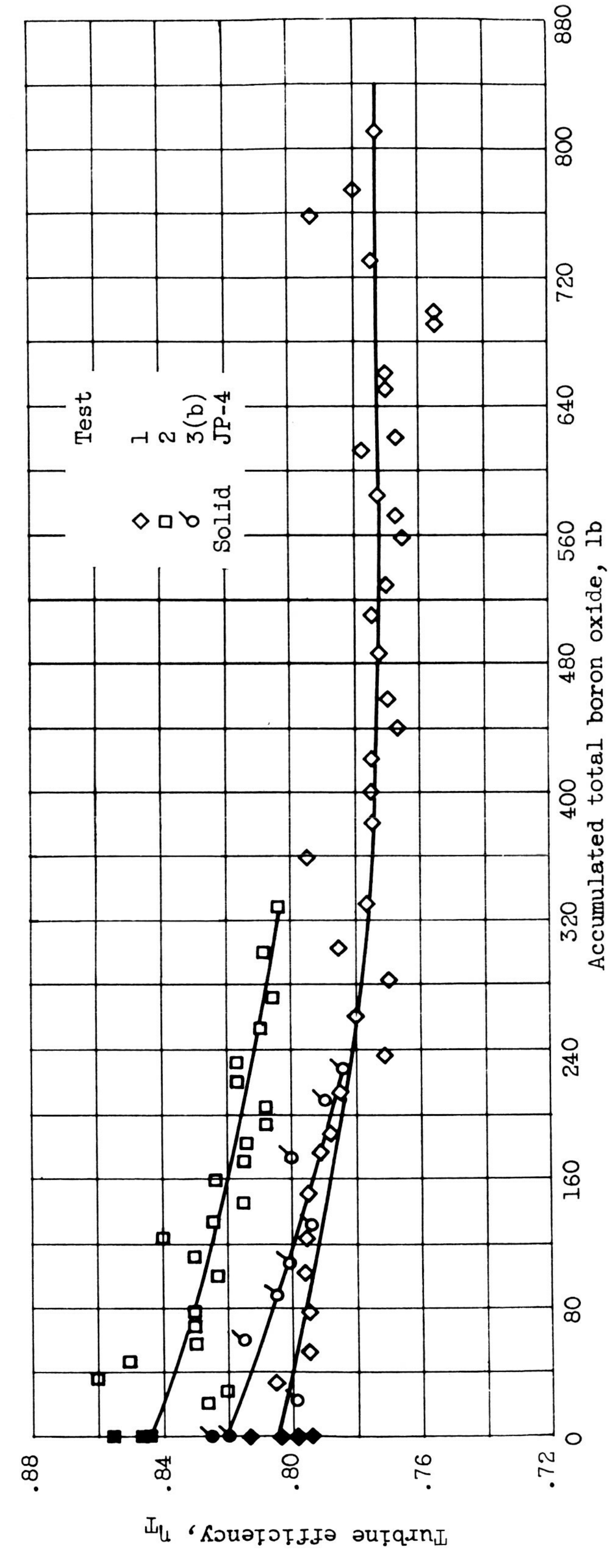
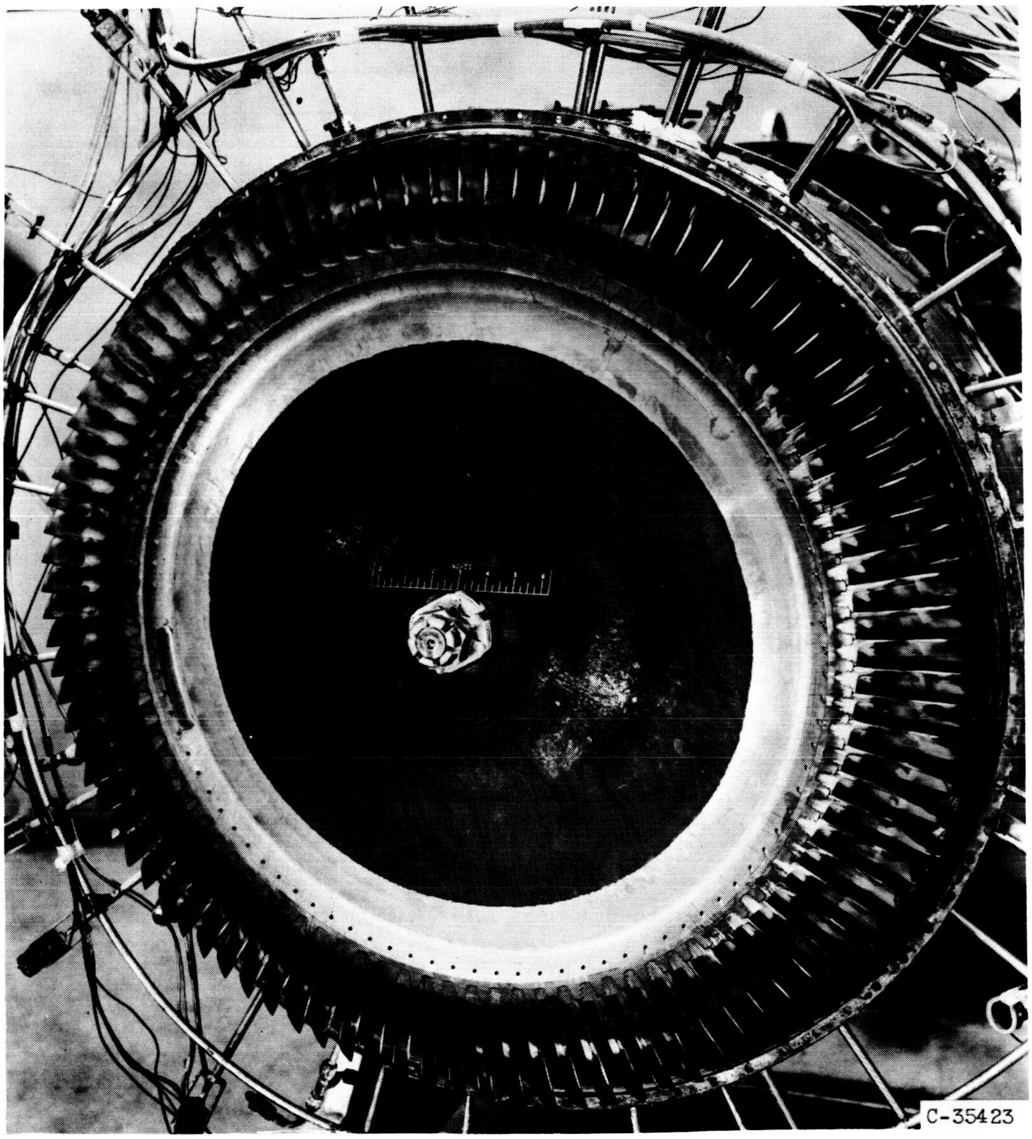


Figure 18. - Effect of boron oxide on turbine efficiency. Altitude, 50,000 feet; flight Mach number, 0.8; corrected engine speed, 90 to 98 percent of rated speed.

(a) Test 1.

Figure 19. - Turbine wheel after operation with pentaborane.



(b) Test 3.

Figure 19. - Concluded. Turbine wheel after operation with pentaborane.

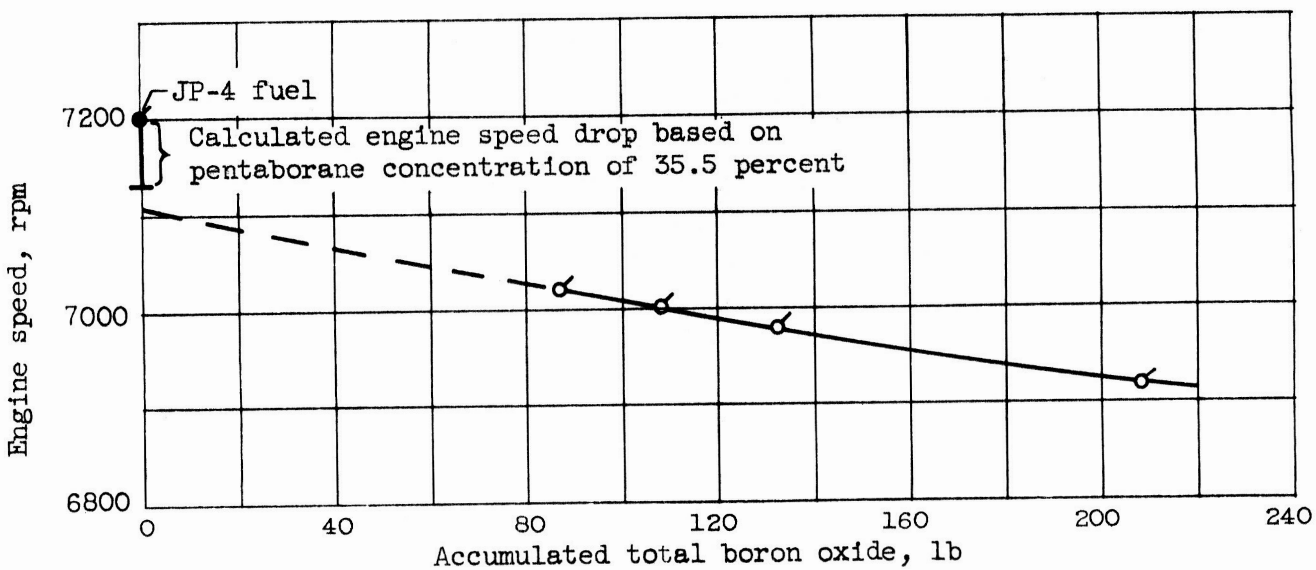


Figure 20. - Engine speed variation resulting from operation with pentaborane - JP-4 mixture in a turbojet engine having a fixed-area exhaust nozzle, test 3(b). Altitude, 50,000 feet; flight Mach number, 0.8; engine total-temperature ratio, 3.48; pentaborane concentration, 35.5 percent.

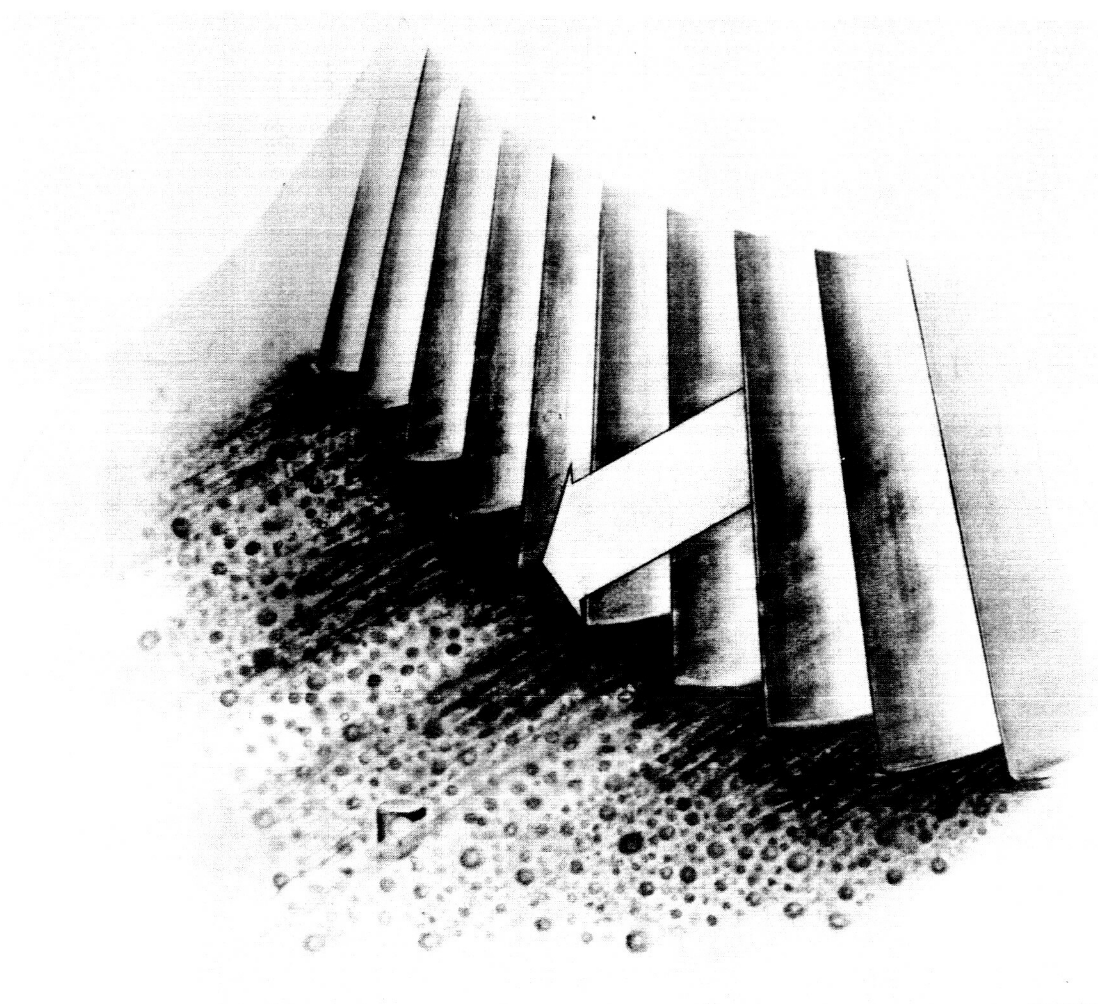


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Figure 21. - Boron oxide flowing through turbine rotor section into turbojet-engine tailpipe.

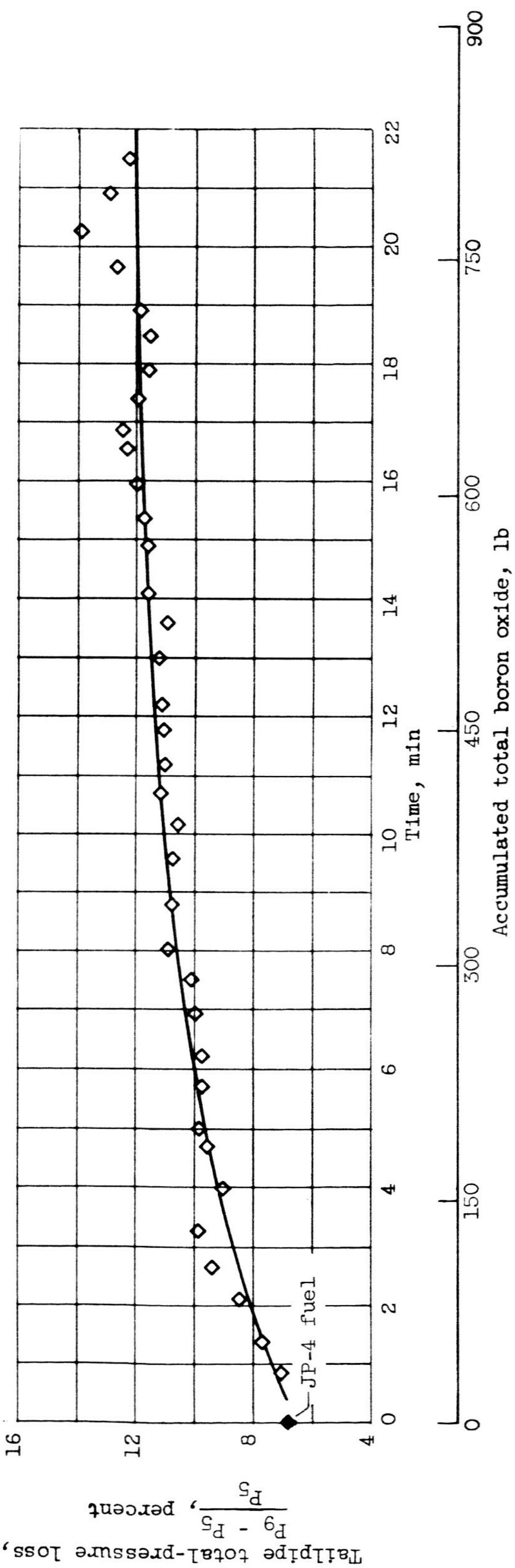
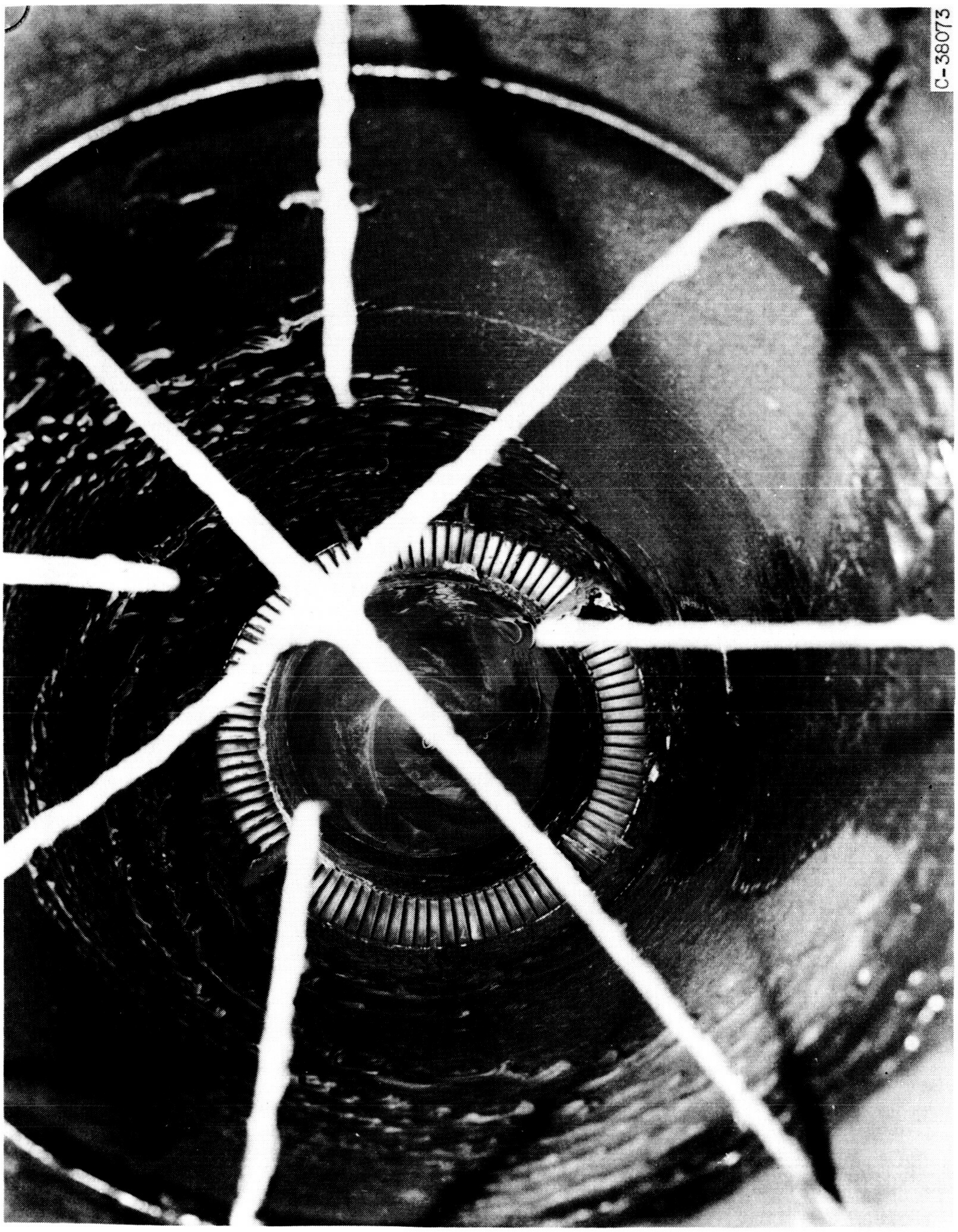
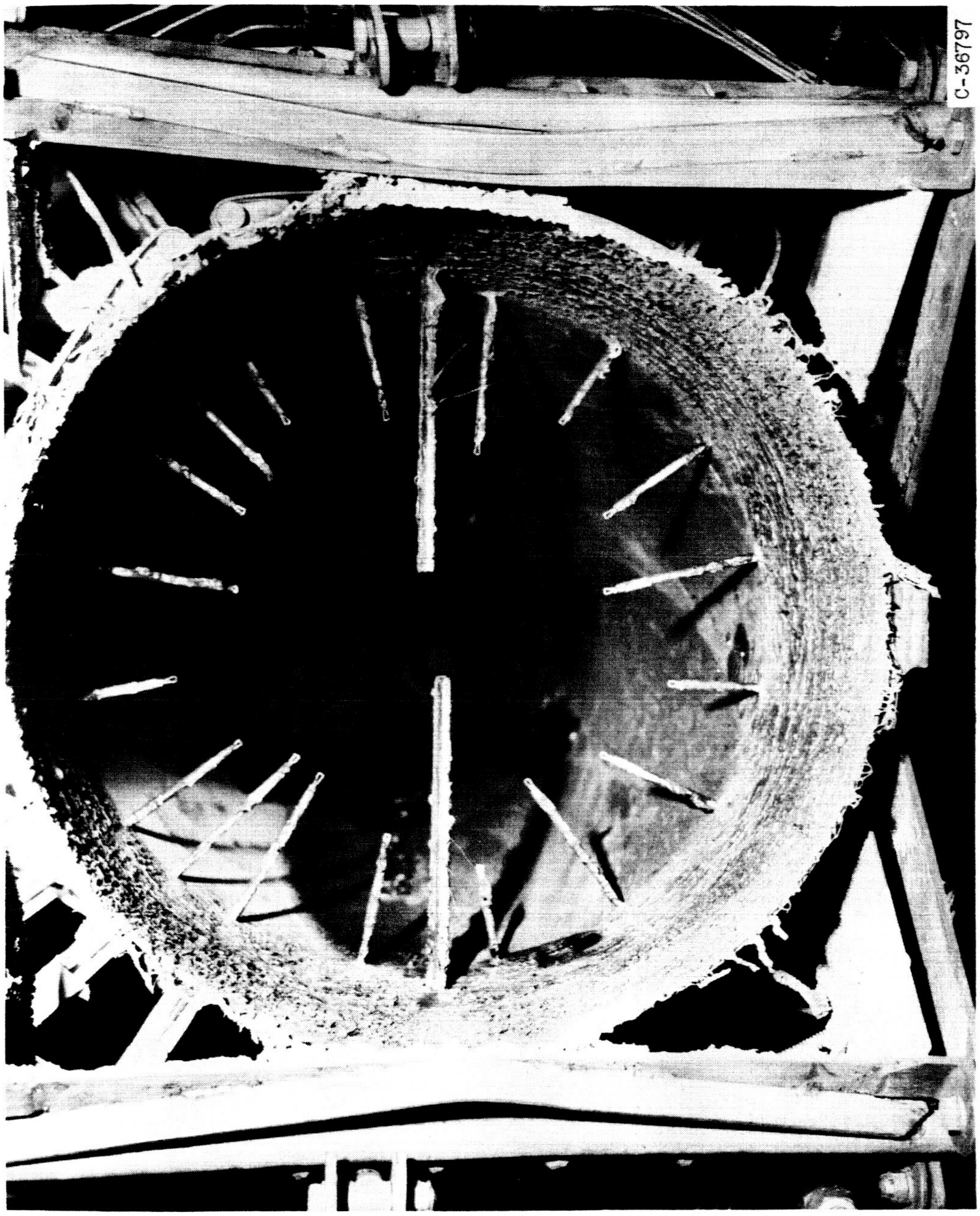


Figure 22. - Variation of tailpipe total-pressure loss during operation with pentaborane fuel in test 1.



(a) Test 1.

Figure 23. - Photograph of tailpipe after operation with pentaborane fuel.



(b) Test 2.

Figure 23. - Concluded. Photograph of tailpipe after operation with pentaborane fuel.

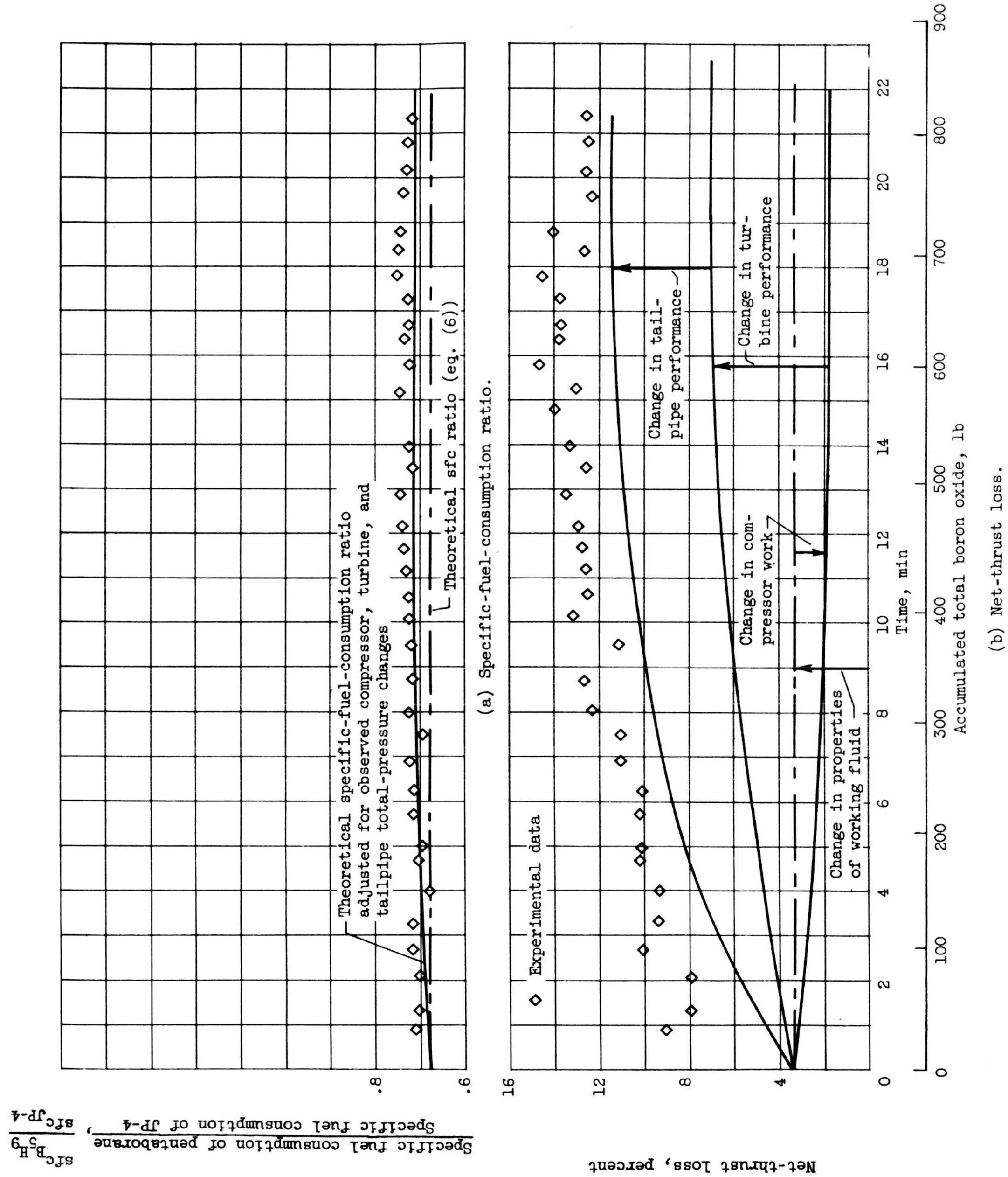
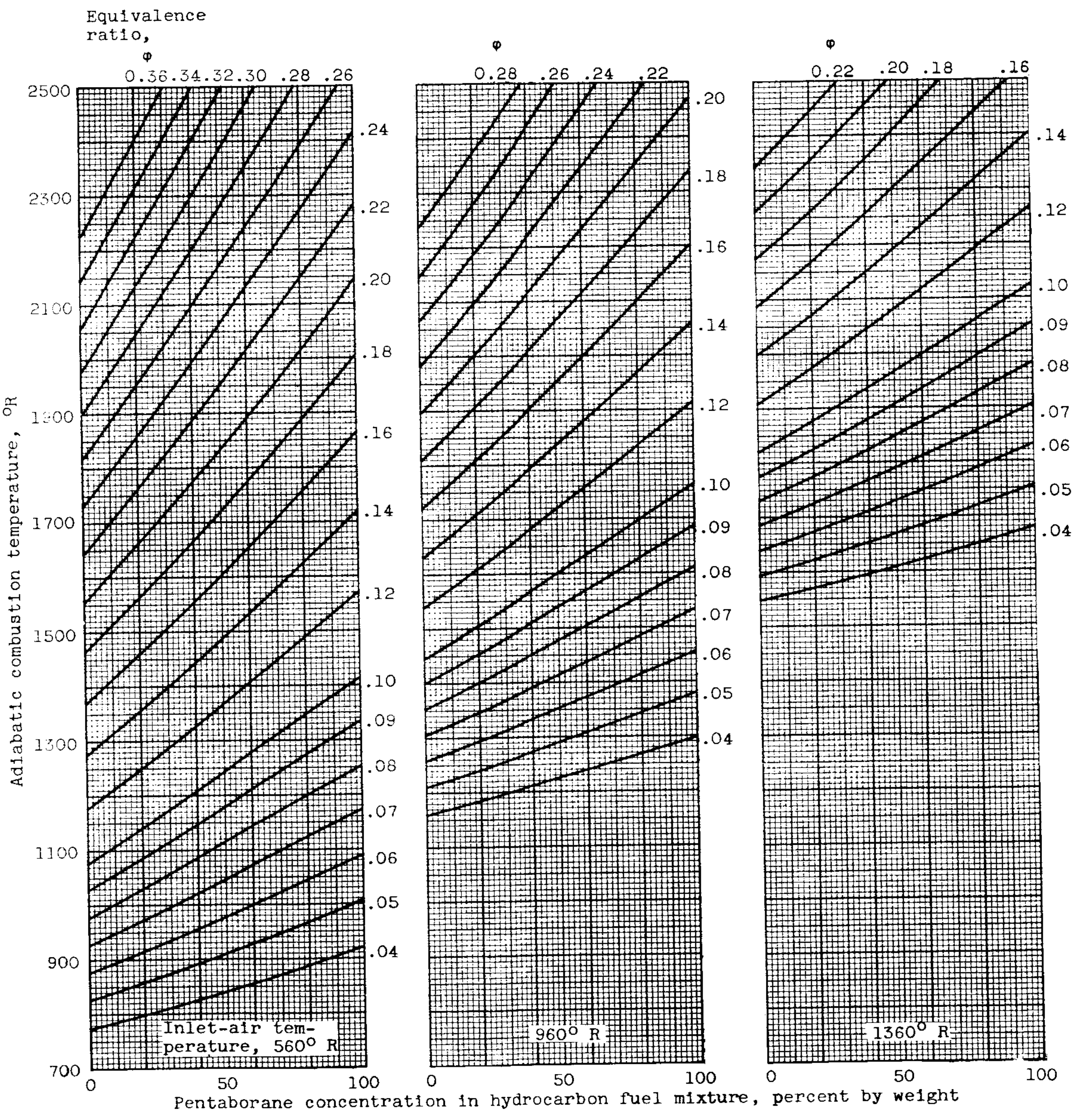


Figure 24. - Engine performance loss encountered with use of pentaborane fuel for test 1. Altitude, 50,000 feet; flight Mach number, 0.8.



(b) Adiabatic combustion temperature.

Figure 29. - Concluded. Air specific impulse and combustion temperature values for pentaborane-hydrocarbon fuel mixtures at several inlet-air temperatures. Hydrogen-carbon ratio for hydrocarbon fuel, 0.168.