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NACA RESEARCH MEMORANDUM

A REVIEW OF NACA RESEARCH THROUGH 1954 ON BORON COMPOUNDS AS FUELS FOR JET AIRCRAFT (PROJECT ZIP)

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NATIONAL ADVISORY COMMITTEE
FOR AERONAUTICS
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SUMMARY

This report reviews NACA work through 1954 on a project of the Bureau of Aeronautics, Department of the Navy, seeking a high-energy fuel suitable for turbojet-powered aircraft. This work includes thermal and combustion properties, experiments with combustors designed to use boron compounds, evaluation of boron fuels in full-scale turbojets with and without afterburners, and ram-jet flights on boron fuels. Satisfactory combustion of pentaborane has been demonstrated in a turbojet, an afterburner, and a ram jet. The anticipated reductions in specific fuel consumption have generally been obtained. Total running times have been quite brief.

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INTRODUCTION

The intention of this report is to review NACA participation in Project Zip, a Bureau of Aeronautics, Department of the Navy project on high-energy fuels for aircraft. Project Zip itself is a search for a turbojet fuel with a heating value at least 30 percent higher than current jet fuels. This fuel should have chemical, physical, and toxicological properties that make it applicable to aircraft. Prime contracts from the Navy to two chemical companies are intended to develop a suitable fuel and methods of producing it economically. The most promising candidate fuels in Project Zip, to date, are boron compounds.

The original purposes of NACA participation in Project Zip were, first, to assist in the measurement of properties, especially thermal and combustion properties, of candidate fuels for Project Zip, and second, to demonstrate principles for the design of turbojet combustors for high combustion efficiency, good outlet-temperature profile, and minimum boron oxide deposits. Later, two items were added: evaluation of boron fuels in full-scale turbojet engines including afterburners, and ram-jet flights on boron fuels.

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Since the ultimate fuel for Project Zip is not yet available, NACA research has proceeded with fuels that are available, as follows: diborane, pentaborane, borate esters, and small quantities of alkylated boron hydrides. Although borate esters actually have less heating value than ordinary hydrocarbon jet fuels, they provide boron in the fuel. Because they were available in much larger quantities than the other boron-containing fuels, they were useful in conducting preliminary research on boron oxide deposits.

The review presented here is based on an oral presentation to the NACA Subcommittee on Combustion at its December 9 and 10 meeting, 1954. 3641
It covers NACA work through the calendar year 1954. The material is presented under the following complete outline of the NACA participation in Project Zip:

I. THEORETICAL PERFORMANCE CALCULATIONS

II. FUEL PROPERTIES
- Heating Value
- Thermal Decomposition
- Spontaneous Ignition Temperature
- Ignition and Blowout in 2-Inch-Diameter Burner

III. APPLICATION IN TURBOJET PRIMARY COMBUSTOR
- Combustor Studies
  - Preliminary experiments
  - Combustor design features
  - Dual-fuel combustors
- Engine Tests with Substitute Fuels
- Engine Tests with Pentaborane Fuels

IV. APPLICATION IN TURBOJET AFTERBURNER

V. RAM-JET FLIGHTS

To keep this review brief, there is no discussion of apparatus, experimental procedure, or accuracy and precision of data. For these items, the original references should be consulted.

THEORETICAL PERFORMANCE CALCULATIONS

Theoretical performance calculations have appeared in references 1 to 4. Some information on pentaborane is summarized in figure 1, where fuel consumption of pentaborane relative to octene-1 (analogous to jet fuel) is plotted against air specific impulse. The combustion temperature of octene-1 required for the air specific impulse is also shown. Air specific impulse is the total jet thrust per pound of air per second at a station where the exhaust Mach number is unity. The figure shows that, at low combustion temperatures, the specific fuel consumption of pentaborane relative to the hydrocarbon fuel will be very nearly the inverse ratio of their heats of combustion, 0.65. At high combustion temperatures, vaporization of B_2O_3 and dissociation take so much enthalpy that this ratio is only 0.84. Experimental data are necessary to determine whether the composition of high-temperature products of boron fuels remains frozen in a rapid expansion.

FUEL PROPERTIES

Heating Value

Figure 2 lists the heating values and other properties of the principal fuels that have been under investigation by the NACA in its work for Project Zip. Several of these properties are estimates only. Further, the reaction products obtained by alkylating diborane with ethylene and subsequently cracking the material, or by alkylating decaborane with ethylene, are in a state of evolution in the research laboratories of the principal Navy contractors, the Callery Chemical Company and the Olin-Mathieson Chemical Company. Until processes have been worked out for making these candidate fuels for Project Zip, their properties cannot be known with certainty. Heating values of other materials have been measured (for example, refs. 5 and 6).

Thermal Decomposition

One of the important fuel properties is thermal decomposition. At high supersonic speeds, the temperature of fuels stored in aircraft will slowly rise, perhaps even to several hundred degrees, and will persist there for appreciable periods of time. Also, and particularly in high-speed flight, fuel may be subjected to 400° or 500° F temperatures for very short intervals of time as it flows through the fuel systems and into the engine, which is generally at a high temperature.

Laboratory data on thermal decomposition have been obtained by heating samples of fuel sealed in a 1/4-cubic-inch stainless-steel tube (ref. 7). The samples were held at elevated temperatures for fixed times, then cooled, and the volatile fuel was removed from the nonvolatile decomposition products. The weight of this residue was plotted against the time for the different temperatures as shown in figure 3. Further, when the log of the time, with 1 minute for initial heating subtracted, was plotted against the reciprocal of the absolute temperature, for different percentages of decomposition, straight lines were obtained (fig. 3). This result implies a simple reaction mechanism that is not altered by the presence of the products of decomposition.

Spontaneous Ignition Temperature

Another important property with fuels considered in Project Zip is spontaneous ignition temperature, which influences both the combustor performance and the relative ease with which the fuels may be handled. A low spontaneous ignition temperature assists rapid combustion in the engine. A high spontaneous ignition temperature permits easier handling.

There are many laboratory methods for measuring spontaneous ignition temperature. No one of these methods is completely to be preferred 3641
to another. The values of spontaneous ignition temperature for fuels are very much a function of the manner in which they are obtained and of the composition of the mixture.

For example, the lean limits for spontaneous ignition of pentaborane vapor-air mixtures at 77° F and in 6-centimeter-diameter bulbs were about 14 volume percent at 1 atmosphere and about 55 volume percent at 0.1 atmosphere (ref. 8). No rich limits were determined (ref. 8), but mixtures of 75 percent pentaborane ignited at 0.066 atmosphere. These data explain why explosions result when air is admitted to pentaborane. Combustible mixtures are at least momentarily formed.

Rich, explosive mixtures can be produced in other ways. For example, in reference 9, a liquid pool of pentaborane ignited spontaneously. Also, a spray of pentaborane in air ignited on a 110° F surface. An 80 percent blend of pentaborane in a hydrocarbon of similar volatility ignited when sprayed as a liquid on a 212° F surface, while a 50 percent blend required 420° F.

Ignition and Blowout in 2-Inch-Diameter Burner

Another property of fuels of interest for Project Zip is flame speed. Attempts to measure flame speed of alkyl borane fuels were not successful when using the conventional methods, because these fuels react slowly on exposure to air; subsequent flame-speed measurements are thus for oxygenated fuels rather than for the fuels themselves. A blowout velocity apparatus such as that shown in figure 4 has been substituted for flame-speed measurements. Data obtained with the apparatus give an idea of the difficulty that will be experienced in maintaining efficient combustion in a high-velocity system like a turbojet.

The apparatus in figure 4 atomizes the fuel with some air and intimately mixes this atomized fuel with all the combustion air in a 1-inch-diameter porous-wall section. The mixture is then ignited in the 2-inch-diameter burner section. Velocity and composition can be controlled independently to obtain blowout data, usually expressed as velocity against equivalence ratio.

Some illustrative data obtained with the blowout velocity apparatus in figure 4 are shown in figure 5. This figure, which is for data at an equivalence ratio of 1, shows the blowout velocity against the boron hydride concentration in JP-4 fuel for two boron hydride fuels. As noted in the figure, JP-4 fuel blows out at 50 feet per second in the apparatus at stoichiometric combustion. Propylene oxide, a good reference point because its flame speed is about twice that of JP-4 fuel, blows out at 100 feet per second.

3641 Pentaborane sprayed into a flowing stream of air at 400 feet per second required 500° F to ignite in a 14-inch length (ref. 10).

It is seen that pentaborane and ethylene decaborane are very reactive fuels, for their blends in only 30 percent concentration do not blow out except at velocities in excess of 100 feet per second in the apparatus of figure 4.

APPLICATION IN TURBOJET PRIMARY COMBUSTOR

Combustor Studies

Preliminary experiments. - The boron hydride fuels were next evaluated in turbojet combustors. This application brings together the previously discussed combustion and stability characteristics of the fuels. In addition, the problem of dealing with products of combustion containing a highly viscous, sticky fluid is introduced. One pound of pentaborane will produce 2.76 pounds of boron oxide (B_2O_3). This glass-like oxide has a high viscosity at normal turbojet operating temperatures. The viscosity characteristics of boron oxide are presented in figure 6 (ref. 11).

The first attempt to burn these fuels in a practical combustor was made with diborane fuel in a J33 combustor (ref. 12); the combustor-entry conditions were: pressure, 1/3 atmosphere; temperature, 245° F; velocity, 115 feet per second. The results of the exploratory tests with diborane fuel are shown in figure 7. Boron oxide mixed with decomposed fuel and formed large clinkers in the combustor. These clinkers seriously restricted the air flow in the combustor liner. Lower combustor-outlet temperatures than the 1080° F desired contributed to the excessive boron oxide deposits. Plugging of fuel lines with decomposed fuel prevented high combustor-outlet temperatures.

The liquid and solids resulting from combustion also presented problems at the combustor outlet or the entry to the turbine region. This is shown in figure 8 by photographs of two elements of the turbine nozzle diaphragm that were located at their normal station. These nozzles collected very heavy layers of boron oxide.

Subsequent to these early tests, a variety of combustion-chamber design changes were made, and pentaborane was used (refs. 13 to 16). A typical combustor liner used for evaluation of pentaborane fuel (ref. 14) is shown in figure 9. The upstream section of a standard J47 liner was modified by replacing the conventional dome with a porous wire cloth. This reduced the recirculation of the fuel-air mixture in the upstream part of the combustor.

The photograph of the combustor in figure 9 was taken immediately after operation. The tendency for deposits to collect in the combustor 3641
was reduced. Higher efficiency, flatter temperature profiles, and higher outlet temperatures apparently reduced the deposits. Also, better combustor performance apparently eased oxide-collection problems at the rear portion of the combustor. This is shown by the photograph of the transition section in figure 9.

A series of tests was made on special surfaces located at the rear of a J33 combustor in which diborane fuel was burned (ref. 12). These surfaces were tubes that spanned the outlet section. The tubes were kept at several temperatures, and variations in deposits on the surface were noted (fig. 10). Reading left to right, the first tube had no cooling or heating and approached equilibrium temperature. The second tube was cooled with water to about 80° F. The idea of a cooled surface was to make the boron oxide brittle so that it might break loose. The third tube was heated to 1750° F, well above the melting point of the boron oxide. This tube was the cleanest. The fourth tube was made of porous wire cloth. It was cooled by forcing air at 80° F through the pores of the wire cloth; it met with only partial success in this high-velocity location. Similar trends were experienced with the tubes downstream of a combustor fueled with pentaborane (ref. 15).

Further work on the development of combustor liners for use with pentaborane evolved in the design shown in figure 11 (ref. 14). This liner was shorter than the normal combustor by 4 inches. Wire cloth was used to form the combustor walls. This produced an air film on the inside walls of the combustor. Porous wire cloth was used in the combustor dome to reduce both recirculation and local fuel-air ratios. The deposits after a 13.3-minute run at 1/2-atmosphere pressure are shown in figure 11. The weight of the deposit in the combustor amounted to 27 grams, or 0.3 percent of the total boron oxide formed, assuming complete combustion of the fuel. The good performance of the combustor was again paralleled with reduced collection of oxide in the transition section, as seen in figure 11.

Some of the performance data are shown in figure 12. Pentaborane and a blend of 64 percent pentaborane with 36 percent JP-4 fuel were evaluated at altitudes ranging from 40,000 to 61,000 feet. Two engine conditions were simulated corresponding to cruise (85-percent) speed and maximum rated speed. The corresponding combustor inlet-air conditions are listed in the figure.

The combustion efficiency for the pentaborane fuel was over 90 percent at all conditions tested. The combustion efficiency of the 64 percent pentaborane blend was 89 percent. One feature of the combustor performance that was inferior to conventional combustor performance was the outlet temperature spread, that is, the maximum to minimum outlet temperature. This temperature spread at the rated engine speed condition was $\pm 450^{\circ}$ F as compared with about $\pm 200^{\circ}$ F for a standard combustor fueled with JP-4. Only small amounts of boron oxide deposited on the surfaces of the wire-cloth combustor. The heaviest deposit was 44 grams accumulated after 11 minutes operation at a combustor-outlet temperature of 1560° F. Because of the short test time, these results should not be overgeneralized. Duration of the tests was limited by the small quantities of pentaborane available.

Combustor design features. - Some of the desirable design features of a combustor for boron hydride fuel are shown in figure 13. These reflect some of the ideas that may have to be incorporated in a combustor for fuels containing boron, particularly one that must operate over a range of operating conditions. The main features are as previously indicated. A coolant protects the fuel as it enters the combustor. This coolant will reduce the tendency for thermal decomposition of the fuel in the fuel supply line and spray. If the coolant is air, it then can be utilized for atomizing and preparing a well-defined fuel spray.

It is important that the fuel spray does not impinge on the combustor walls, for thermal decomposition of the fuel may result at that point. The well-formed fuel spray is then mixed with air that passes through the upstream end of the combustor - for example, through a porous wire-cloth dome. Sufficient air comes through this dome to retard the normal recirculation that exists in most conventional combustors.

The combustor walls are protected by air filmed through the porous surfaces. This air prevents the impingement of fuel or boron oxide particles on the surfaces of the combustor. Many well-distributed louvers should also suffice.

The combustion gases are then mixed with dilution air and allowed to pass into the turbine section. It seems necessary to have the surfaces of the turbine-entry sections at temperatures of 1000° F or above to prevent accumulation of large deposits of boron oxide.

Dual-fuel combustors. - A more recent combustor design is one which burns two fuels. If operation with a boron-containing fuel is limited to conditions where the temperature of the combustor walls is high enough to keep the boron oxide molten, then less extensive ventilation of the combustor walls is needed. At conditions other than at high outlet temperature, a conventional fuel such as JP-4 can be used.

A fuel injector that resulted from this design approach is shown in figure 14 (ref. 16). Pentaborane fuel flows through a center annulus and is surrounded by atomizing air. This air both cools the fuel and controls the atomization and penetration of the pentaborane fuel spray. The JP-4 fuel flows through an external passage and is sprayed out through three small orifices. The spray from these orifices is broken up by a small quantity of the atomizing air directed to impinge on these fuel jets. Less than 0.4 percent of the engine air flow is used for atomization. These jets deflect the JP-4 fuel into the upstream portion of the combustor can, the normal location for fuel injection in a turbojet combustor. The pentaborane fuel is forcibly injected downstream of the recirculatory region by the atomizing air. The upstream deposits are considerably reduced by keeping the pentaborane fuel out of the recirculatory region.

One advantage of this dual-fuel system is that it involves a large degree of flexibility of engine operation. The engine can be started and brought up to test conditions with a standard fuel. The operation can be transferred to the pentaborane fuel at a constant set of engine conditions and a brief test of the pentaborane fuels made.

A summary of some of the combustion performance data obtained with this system is shown in figure 15 (ref. 16). The fuel was proportioned between the JP-4 and the pentaborane injector. A variety of fuel mixtures was evaluated over a range of altitudes, engine speeds, and combustor conditions, as shown in the table. One important observation was that the pentaborane operation was more efficient than that of the JP-4 fuel at the same conditions. Also, the outlet temperature spread, or the temperature profile at the combustor outlet, was better than for the wire-cloth combustor system.

One set of recent data (unpublished and unchecked) is included in figure 15 for a six-port air-atomizing fuel injector. The injector body is similar to the one shown in figure 14, except the pentaborane atomizing tip is changed. The tip with six ports gave better fuel atomization. The combustion efficiency was about the same as with the single-port fuel injector. The major improvement was in the outlet temperature profile. An acceptable temperature spread in a conventional combustor with JP-4 fuel is $\pm 200^{\circ}$ F.

Engine Tests with Substitute Fuels

A number of runs in full-scale engines, both J33 and J47, were conducted with borate ester fuels. Although these fuels are not high-energy fuels, they at least provide boron in the fuel. Thus, they serve as a research aid in the study of boron oxide deposits. A brief résumé of the heating value, the boron oxide per pound of fuel burned, and the boron oxide per 100,000 Btu from combustion of the fuel is given in the following table:

Fuel	ΔH_c, Btu/lb (a)	B_2O_3, lb/lb fuel	B_2O_3, lb/100,000 Btu
Tributylborate - 50 percent JP-4	16,220	0.075	0.46
Trimethylborate - 30 percent methanol	8,150	.235	2.9
Diborane	31,400	2.5	8.0
Pentaborane	29,130	2.76	9.5
Ethylene diborane product	[b]24,600	[b]1.7	[b]6.8
Ethylene decaborane product	[b]26,200	[b]2.3	[b]8.9

[a]$B_2O_3(s)$; $H_2O(g)$.

[b]Approximate.

Borate esters produce less boron oxide than do typical high-energy fuels of boron.

A summary of all the engine tests that have been conducted to date with borate ester fuels is shown in figure 16. Much of this work was done concurrently with the other combustor and engine studies described in this report. In test IA, tributylborate in 50 percent concentration by weight in JP-4 was run for $1\frac{1}{2}$ hours in a J33 engine on a sea-level static test stand (ref. 17). The engine ran satisfactorily. There was no change in thrust through the run. The specific fuel consumption of the engine was higher than with JP-4 because of the lower heating value of the borate ester blend. The engine consumed about 4760 pounds of fuel per hour and produced 360 pounds of boron oxide per hour. This was about 5 percent of the boron oxide rate of pentaborane.

In run IIA, the engine was run on trimethylborate azeotrope, a mixture which contains 30 percent methanol (ref. 18). During the first 45 minutes of the run, full engine speed and full thrust were maintained. Fuel flow was 10,300 pounds per hour, producing B_2O_3 at about three-eighths the rate of pentaborane. From 45 minutes to the end of the run at 1 hour 50 minutes, fuel flow, speed, and thrust decreased regularly. Some hydrolysis of the fuel from extraneous moisture in the system produced boron oxide that plugged fuel filter screens. The resulting lower fuel flow caused some of the performance loss, and perhaps all of it. Inspection of the engine for run IIA indicated that about 61 pounds of the more than 2 tons of boron oxide that went through the engine was retained in various parts of the engine.

In all the subsequent runs indicated in figure 16, such factors as techniques of instrumentation, fuel control, use of variable-area nozzle, engine starting on boron fuels, and engine operation over a range of temperatures, including low temperatures encountered at idling, were studied. A discussion of these results is beyond the scope of the present paper.

Figures 17 to 21 indicate the appearance of the engine deposits in two of the runs listed in figure 16, and these illustrations are typical of the observations made in all the runs of figure 16. Figure 17 (run IIA) is a view of the upstream end of the combustors with the dome removed. Very heavy deposits were seen after 1 hour 50 minutes of operation with trimethylborate. Figures 18 to 20 are from run IA, but are typical of other runs. Figure 18 is a view of the combustor exit just ahead of the nozzle diaphragm. Figure 19 shows the downstream side of the diaphragm, and deposits are observed on the convex side of the stator blades. Figure 20 shows the turbine rotor; only very light deposits were ever observed on the turbine rotor. The tailpipe is shown in figure 21 (run IIA), and here the deposits ranged from 1/8 to 1/2 inch thick and were a hard glassy material. Although the boron oxide deposits were frequently discolored as if by iron (reddish) or by nickel or cobalt (greenish), no evidence of serious corrosion was observed.

In conclusion, these engine runs on borate ester fuels, in addition to aiding in many test techniques, showed that the engine would start and run and would deliver full speed and full thrust with boron-containing fuels at the start of the test. Furthermore, the hot end of the engine looked as if it might tolerate boron oxide more readily than had been anticipated. Pressure loss across the combustors as they plugged with boron oxide decreased the engine speed. It must be remarked that the borate esters, at most, generated boron oxide at about three-eighths the rate of pentaborane.

Engine Tests with Pentaborane Fuel

The small-scale experiments indicated that reasonably high combustion efficiencies could be achieved with pentaborane fuels. The substitute fuels showed only minor losses in engine performance. The question remained: Could these high combustion efficiencies, and hence high heating values, of pentaborane fuel be translated into improvements in full-scale engine performance? A preliminary answer was obtained in a series of tests in a full-scale J47 engine. An outline of these tests is shown in figure 22. The flight condition simulated was a Mach number of 0.8 and an altitude of 50,000 feet. In all, there were three tests, corresponding to five test runs.

Test run IA was a preliminary test with pure pentaborane in an engine with wire-cloth combustors. Approximately 120 pounds of fuel was used. The second run of this test (IB) introduced modifications to the engine and operating technique. A 50 percent blend of pentaborane in JP-4 fuel was used and 40 pounds of fuel expended. In test runs IIA and IIB, a standard combustor and air-atomizing fuel nozzles were used. The engine was brought to starting conditions with JP-4 fuel, and in the two successive runs maximum concentrations of pentaborane of 33 and 42 percent were obtained. Quantities of fuel used were 25 and 80 pounds, respectively. For test III, a conventional combustor was used with two injectors located on each combustor wall at the station usually used for water injectors. Development of this configuration is discussed in reference 19. Pure pentaborane was used, and 120 pounds of fuel was expended.

The engine with the standard combustor and modifications to it is shown in figure 23. The upstream portion of the engine was conventional. The fuel injectors were modified as previously discussed. The cooling normally supplied through some of the hollow parts in the transition section between the combustor and turbine was reduced. A solid retaining ring blocked the cooling air that would normally have flowed around the combustor liner and through the hollow stator blades. The turbine shroud was tapered so that the forward clearance was the standard 0.09 inch and the aft was 0.019 inch. The tailpipe was wrapped with a reflective insulation to attain high surface temperatures. In the third test, a flap-type exhaust nozzle was used to give some control over engine speed and engine total-temperature ratio.

Tests II and III (fig. 22) of references 20 and 21 are most easily interpreted. The data for the last two series of tests are shown in figure 24. Specific fuel consumption is presented as a function of temperature ratio. The two engine configurations used in these tests were the engine with the air-atomizing injectors placed in the normal fuel injector position, and the one with the injectors located on the combustor wall. The series of tests in which the fuel injectors were located on the combustor wall was run with a variable-area exhaust nozzle, which permitted operation at a constant temperature ratio and a constant engine speed. The engine speed selected for both series was 95 to 100 percent of rated. As can be seen in figure 24, increasing the pentaborane concentration regularly from 11 to 42 percent decreased the fuel consumption.

The injectors located on the wall were fixed-area swirl-type nozzles. These injectors restricted the range of fuel flows so that only concentrations of 85 and 100 percent pentaborane could be conveniently evaluated. The data for both tests gave a consistent reduction of fuel consumption with increased pentaborane concentration.

Data are shown for the specific fuel consumption of pure pentaborane at 5 and $6\frac{1}{2}$ minutes of operation. As operation with pentaborane proceeded, the specific fuel consumption increased. This effect is explained in the subsequent figures.

Figure 25 (ref. 20, table II) illustrates the loss in engine performance with increased operating time of a 35 percent pentaborane mixture. These particular data were for the engine with a fixed-area exhaust nozzle and the air-atomizing fuel injector. A loss in engine performance in this set of data is reflected by a loss in engine speed, inasmuch as the temperature ratio was kept essentially constant. The corrected engine speed initially dropped as the engine was transferred from operation with JP-4 to pentaborane fuel. Speed continued to drop with increased operational time. Adjusted specific fuel consumption decreased from about 1.3 pounds per pound thrust per hour with JP-4 to about 1.1 pounds per pound thrust per hour with 35 percent pentaborane, and increased gradually thereafter.

A similar set of data for the series of tests in which the engine used a variable-area exhaust nozzle is shown in figure 26 (ref. 21, table I). Engine total-pressure ratio and specific fuel consumption are presented as functions of the time of operation in minutes. Since the speed was adjusted by changing the exhaust-nozzle area, the loss in total-pressure ratio reflects a loss in over-all engine performance. The pressure ratio of the engine dropped with the transfer from JP-4 to pentaborane operation. Increased operating time with pentaborane fuel further increased the loss in engine total-pressure ratio. Adjusted specific fuel consumption decreased from about 1.32 pounds per pound thrust per hour with JP-4 to about 0.86 pound per pound thrust per hour with 100 percent pentaborane, and increased thereafter.

Part of this loss in the performance of the engine, particularly the initial loss with pentaborane fuel, can be explained by the thermodynamic characteristics of the products of combustion. When pentaborane fuel was used, the amount of working fluid was reduced, because the lower specific fuel consumption reduced the mass of fuel-air mixture. The boron from the pentaborane combined with the oxygen present in the air to form a liquid combustion product that further reduced the mass of gas passing through the turbine. This, in turn, caused an initial loss in performance. Presumably, the continuing loss in performance with operating time was due to an accumulation of boron oxide on some critical component of the engine.

The influence of the boron oxide should be evident from engine component efficiencies. The instrumentation that was available in the engine measured combustion efficiency and turbine efficiency, which are presented as functions of time in figure 27 (ref. 21, table I). The combustion efficiency is shown for both 85 and 100 percent pentaborane concentrations. For all practical purposes, the combustion efficiency may be assumed to be 90 percent. The values above 90 percent were measured during the change in fuel concentration. The combustion efficiency increased slightly with the higher concentration of pentaborane, and no influence of operational time on combustion efficiency was apparent. In contrast, there was a definite loss in turbine efficiency with increased operating time. The turbine efficiency shown includes tailpipe losses, since the total-pressure measurements used for establishing turbine efficiency were those located upstream of the turbine nozzle and immediately upstream of the exhaust nozzle. The loss amounts to about 2 percent for the 10-minute test period.

Photographs of the engine (figs. 28 to 30) show some possible sources of performance loss. Figure 28 illustrates the type of deposits observed in the engine tests with the wire-cloth combustor and with the conventional combustor with injectors located on the wall. When the wire-cloth combustor was used, 110 pounds of boron oxide passed through the engine; and 330 pounds of boron oxide passed through the engine with the conventional combustor system. The photographs indicate that the wire-cloth combustor gave less deposit than the conventional combustor system. However, for the short-duration test with the conventional combustor system, the small amount of oxide present did not appear to affect any of the flow conditions or pressure drop in the combustor.

Views of the combustor systems in figure 29 indicate, again, the small amount of oxide that is collected in the short-duration test despite the fairly large amounts of boron oxide passed through. The two views are the conventional combustor with the air-atomizing nozzle and the conventional combustor with the injectors located on the wall. In each of these tests, operation with the pentaborane fuel was followed with JP-4 operation for the time indicated in the figure. The JP-4 operation did not clean out the thin deposits in the combustor to any appreciable extent, as can be seen by comparing figures 28 and 29.

Deposits in the engine at the turbine and tailcone positions are shown in figure 30. The top photograph was taken immediately after the engine was shut down after operation with pentaborane fuel. The engine was subsequently restarted and run for $1\frac{1}{2}$ hours with JP-4 fuel, after which the same section was photographed. Operation with JP-4 apparently cleaned the tailcone and tailpipe rather well. The turbine rotor was clean even after immediate shut-down with pentaborane fuel; the turbine stator was not completely clean (see fig. 19). These observations were consistent with the results with the trimethylborate fuels.

A summary of the performance of pentaborane fuel is shown in figure 31. The performance is presented in terms of a range index as established by the Breguet range equation:

$$\text{Range} = H\eta_i \eta_b \eta_e \frac{L}{D} \ln \frac{W_G}{W_e}$$

where

H	heating value of fuel
η_i	efficiency term correcting for thermodynamic characteristics of exhaust
η_b	combustion efficiency
η_e	engine efficiency
L/D	lift-drag ratio of aircraft
W_G	gross weight of aircraft
W_e	empty weight of aircraft

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The lift-drag and weight ratios are assumed constant.

The range index for a variety of pentaborane concentrations from 0 to 100 percent are shown in three columns (fig. 31). The first column is the range index that would be predicted on the basis of heating value alone, assuming constant engine component efficiencies. The second column modifies the range index by accounting for the thermodynamic characteristics of the exhaust. Thus, the specific heats and condensed phases are accounted for. The third column shows the range index as determined by the specific fuel consumption data in the actual engine. The actual performance closely matches the theoretical values based upon the impulse of the fuel. The range index in figure 31 is higher at the 100-percent pentaborane concentration than those values predicted by analysis ($H\eta_i$) because of the higher combustion efficiencies of pentaborane fuel compared with JP-4.

APPLICATION IN TURBOJET AFTERBURNER

A single test was made with pentaborane with a full-scale afterburner (ref. 22). The objectives of this work were similar to the previous ones; namely, to see if the higher heating value of the fuel can be translated into improved engine specific fuel consumption, and to determine the nature of the problems that might arise from the use of these fuels. The standard afterburner tailpipe (fig. 32) from the J47-17 engine was used in these tests. Slight modifications were made to the tailcone. The flameholders normally present for hydrocarbon operation were removed. The only flameholding surface present was a bluff end to the tail cone. Thirty air-cooled fuel injectors were located around the perimeter of the afterburner. The same cooling air was used for atomization and penetration of the fuel. The air and fuel jets were located at right angles to the stream.

The data obtained in this afterburner are shown in figure 33. The conditions of operation were almost the same as for the previous engine tests: an altitude of 50,000 feet and a Mach number of 0.6. The JP-4 fuel was used in the primary combustors; pentaborane, in the afterburner. The data are presented in terms of net and jet augmented thrust ratios as functions of augmented liquid ratio. The value of unity represents operation of the engine at rated-speed conditions without afterburning. Included in the figure are theoretical curves for pentaborane and JP-4 fuel assuming 100-percent combustion efficiency. Actual data for JP-4 in an afterburner using the flameholder system of about 30 percent blocked area is shown (ref. 23). The actual pentaborane performance is higher than the ideal for JP-4 fuel. The maximum combustion efficiency at an augmented thrust level of 1.46 was about 88 percent. JP-4 operating at this condition gives a maximum combustion efficiency of about 82 percent. The ratio of improvement of the actual performance of pentaborane fuel to that of the JP-4 fuel was approximately in proportion to their heating values. Part of this improvement was due to the higher combustion efficiency of the pentaborane fuel.

Another encouraging feature can be seen in figure 34, in which a view of the tailpipe from the exhaust-nozzle station is shown. The tailpipe after afterburning with pentaborane is compared with a similar view of the tailpipe in which pentaborane was run at the same altitude and engine speed conditions with primary combustion alone. The same quantity of fuel, 120 pounds, was used in each test. Both tests were followed with short periods of operation on JP-4 in the primary combustor. The photograph shows that operation of only the afterburner with pentaborane resulted in much cleaner tailpipe surfaces than operation of only the primary combustor system with pentaborane. This is probably attributable to the higher surface temperatures of the tailpipe with afterburning. The run was too brief to permit observations on possible corrosion from molten boron oxide.

Thus, with the afterburner, high combustion efficiencies have been achieved and the combustion system appears to be only slightly affected by the presence of the boron oxide products of combustion. The simplicity of the afterburner makes application of this fuel to it look easy.

RAM-JET FLIGHTS

A ram-jet-powered vehicle to test pentaborane was assembled. It had to be small enough to use a minimum of fuel that was scarce, yet large enough to carry eight channels of telemetering of the sort already developed by NACA. The telemetering, together with the theodolite and radar observations, was just enough to give the thrust, altitude, speed, and acceleration of the vehicle, and also the essential flow, pressure, and performance characteristics of the diffuser and combustor.

Figure 35 illustrates the particular vehicle that was developed. 3641
It weighed 156 pounds, including 9 pounds of fuel. The combustor diameter was $9\frac{3}{4}$ inches. The diffuser was a simple conical type with a single oblique shock; it was designed for Mach number 1.8. A manned aircraft launched the test vehicle by dropping it at about 35,000 feet over the Atlantic Ocean.

The combustion system and the fuel-spray system were developed in a direct-connect duct. Typical data from these tests are given in figure 36. In this figure, combustion efficiencies over a range of equivalence ratios are shown for pressures from 1/4 to 2 atmospheres. The conditions cover most of those to be met in flight. The combustion efficiencies ranged from 85 to 100 percent (ref. 24).

Results from three flights are depicted in figure 37. The plot shows the Mach number throughout the flight as the vehicle falls and accelerates from the launching point of 35,000 feet.

In the first flight (ref. 25), violent acceleration surges and large bursts of flame from the engine occurred at about 31 or 32 seconds. Details of the data indicated that the diffuser ejected its normal shock and buzzed as a result of high temperatures in the combustor. These high temperatures resulted from unanticipated very high combustion efficiencies and fairly rich operation.

In flight 2 (ref. 26), the engine was run at an equivalence ratio of 0.23 as contrasted to the 0.55 of the first flight. This time, however, the engine did not use all the fuel before reaching the ocean. The data showed that the fuel ejection bar plugged. It was deduced that the flame somehow reached this injection bar. Designs to eliminate this problem were tested in the direct-connect duct and incorporated into the next flight engine.

In flight 3 all the fuel was consumed at about 35 seconds and before the engine reached sea level. A flight Mach number of 2, which is in excess of the design value, was achieved.

Figure 38 is a résumé of the performance achieved in these ram-jet flights with pentaborane. A range index is used in which a Breguet flight path is assumed and the index of unity is taken for ideal performance, including 100 percent combustion efficiency, with JP-4. The heights of the pentaborane bars are the ideal curves for the same flight conditions. The shaded parts of the bars represent the relative range multiplied by the combustion efficiency as experimentally observed. The combustion efficiencies used for the shaded bars with JP-4 are average values from 16-inch-diameter flight engines. A 47-percent increase in potential aircraft range over that theoretically possible with JP-4 may be said to have been actually demonstrated in ram-jet flights with pentaborane.

FINAL SUMMARY

A final summary of the experimental data obtained with pentaborane in the several programs is shown in figure 39. The heights of the bars in figure 39 correspond to the range calculated from the equation shown at the bottom of the figure. The basis is unity for ideal performance with JP-4. The cross-hatched parts of the bars represent the experimental data obtained on the average for research with the various engines noted. In the case of the pentaborane experiments, with the three types of engines noted, the cross-hatched data were obtained and averaged for the period shown immediately under the bars; that is, 5 minutes for the primary combustor in the turbojet, 5 minutes for the afterburner, and 1/3 minute for the ram jet. The total experience with pentaborane in which experimental ranges greater than that theoretically possible with JP-4 were obtained is also listed in figure 39: 25 minutes for the primary combustors of the turbojet, 5 minutes for the afterburner, and 3 flights with the ram jet. Total test time on pentaborane fuel is noted as well.

To emphasize the relatively small amount of experimental test time with pentaborane to date, a table of the approximate quantities of fuel used for the various kinds of work follows:

Item	Fuel quantity, lb
2-Inch-diameter ignition and blowout test	50
Turbojet combustors	240
Turbojet engine	390
Turbojet afterburner	120
Ram-jet combustor	100
Ram-jet flights	30

CONCLUSIONS

1. Satisfactory combustion of pentaborane and high-concentration blends of pentaborane has been demonstrated in a turbojet, an afterburner, and a ram jet. The anticipated reductions in specific fuel consumption have generally been obtained.

2. Deposits in the turbine engine have been troublesome. Fuel tests have been too few and too brief to reveal the full magnitude of this problem.

3. The one run made in an afterburner indicated that it might be fairly easy to apply a boron compound to this component. 3641

4. Most of the work done to date should be applicable to final candidate fuels for Project Zip, fuels like ethylene diborane and ethylene decaborane compounds that are planned for pilot-plant production. However, much more engine operation will be required. This work must be largely on the final fuels both to determine their suitability for use and to solve engine problems encountered in their use. Aircraft and engine fuel systems will present problems, and there are the many problems of fuel supply, storage, and handling.

Lewis Flight Propulsion Laboratory
National Advisory Committee for Aeronautics
Cleveland, Ohio, February 4, 1955

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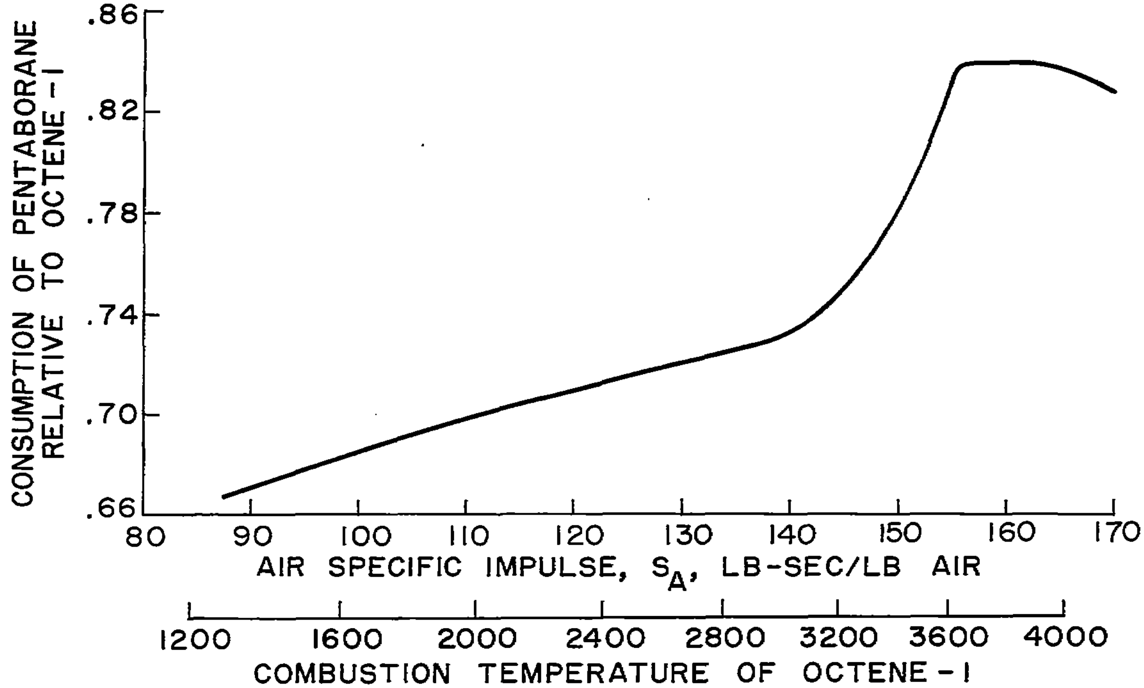

Figure 1. - Consumption of pentaborane relative to octene-1 against air specific impulse for combustion pressure of 2 atmospheres. Frozen composition; Mach number in combustor, 2.

FUEL	BOILING POINT, °F	FREEZING POINT, °F	SPECIFIC GRAVITY	ΔH_c, BTU/LB	SPONTANEOUS IGNITION TEMPERATURE, °F
JP-4	220-420 (10%-90%)	<-76	0.777	18,600	484
DIBORANE	-134.6	-165.5	0.210	31,400	---
PENTABORANE	140	-52	0.623	29,130	116
50-PERCENT PENTABORANE IN JP-4	140-420	<-76	0.692	23,950	284
ETHYLENE DIBORANE	55-110* (260 mm Hg)	----	0.70-0.75	24,600	150-200*
ETHYLENE DECABORANE	530*	-76	0.815-.835*	25,500-26,900*	253*

*ESTIMATED.

Figure 2. - Fuel properties.

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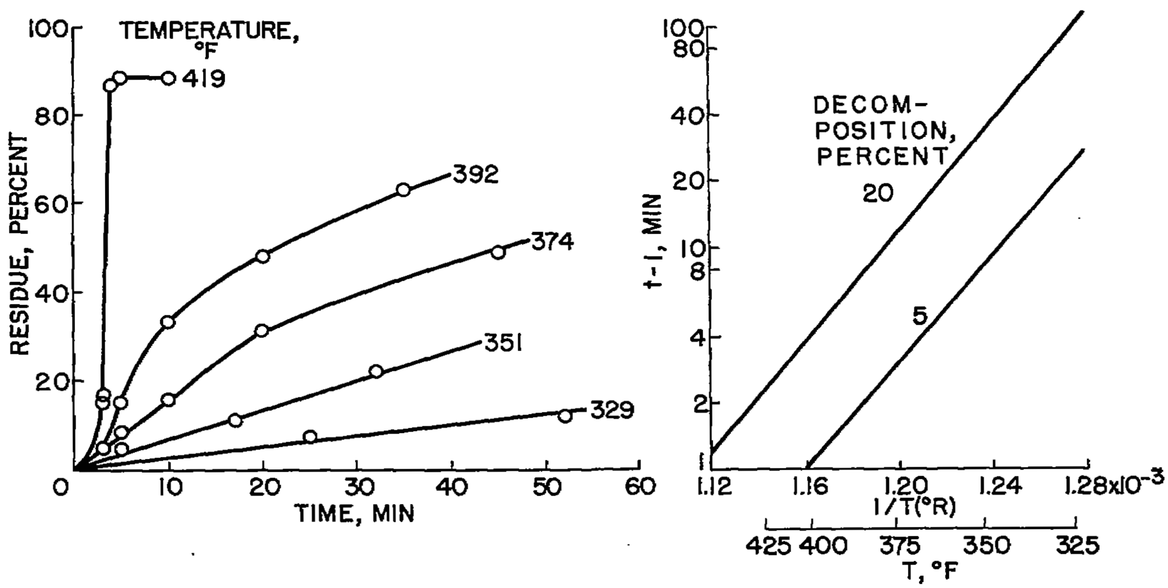

Figure 3. - Thermal decomposition of pentaborane.

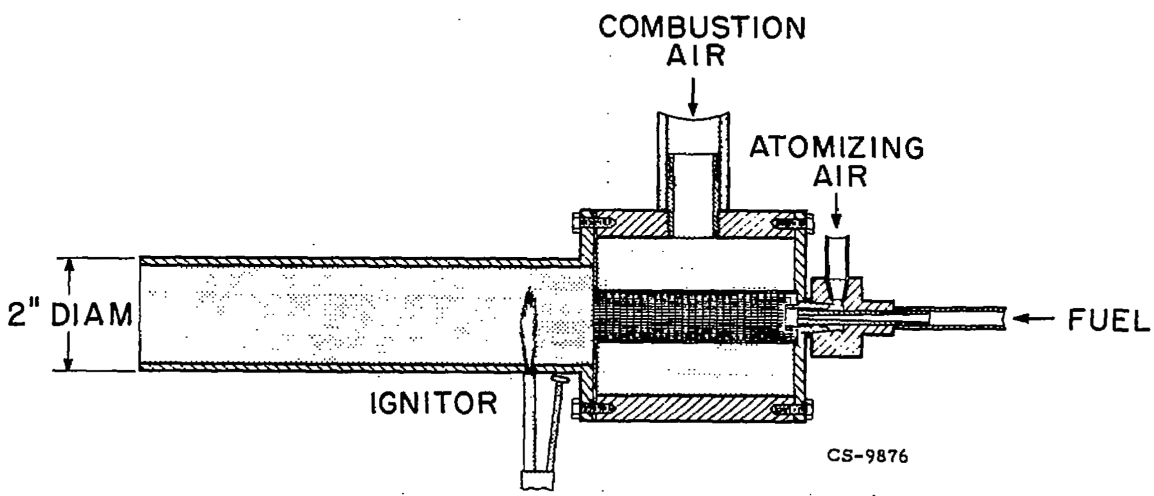

Figure 4. - Blowout-velocity apparatus.

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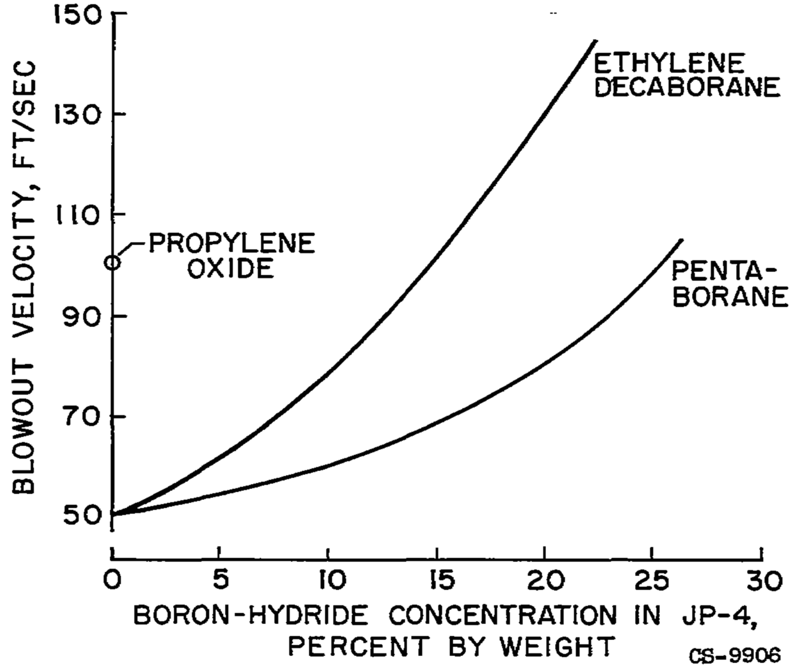

Figure 5. - Blowout velocities of boron hydride - JP-4 fuel mixtures. Equivalence ratio, 1.0.

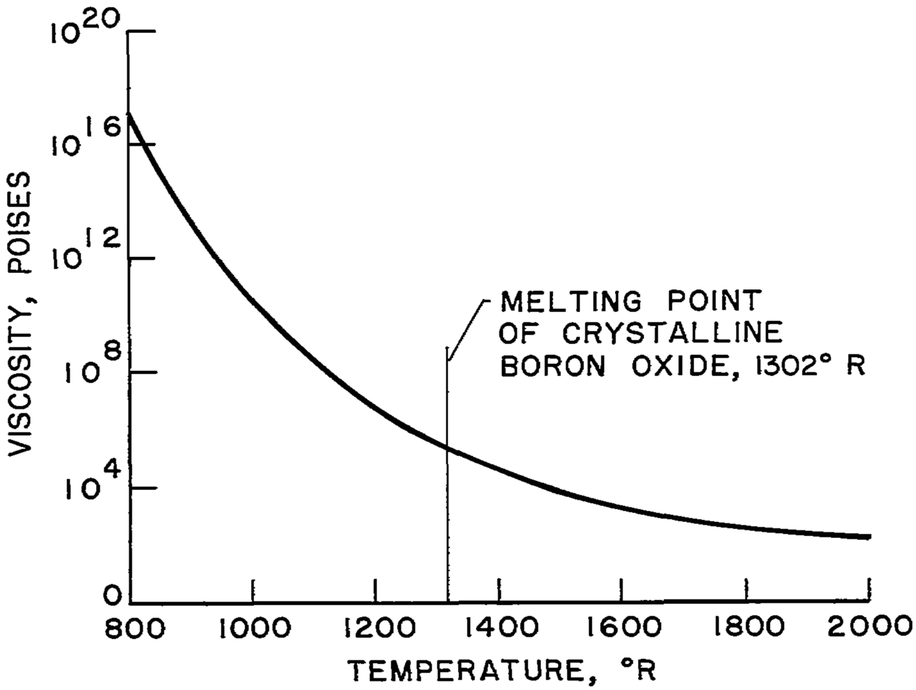

Figure 6. - Viscosity of vitreous boron oxide B_2O_3 (ref. 11).

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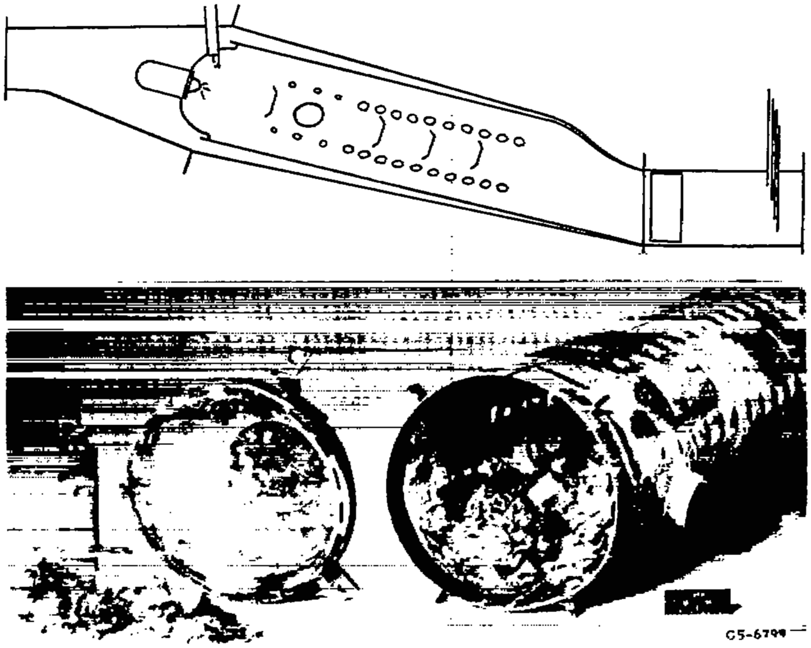

Figure 7. - Boron oxide deposits from diborane in combustor configuration 1.

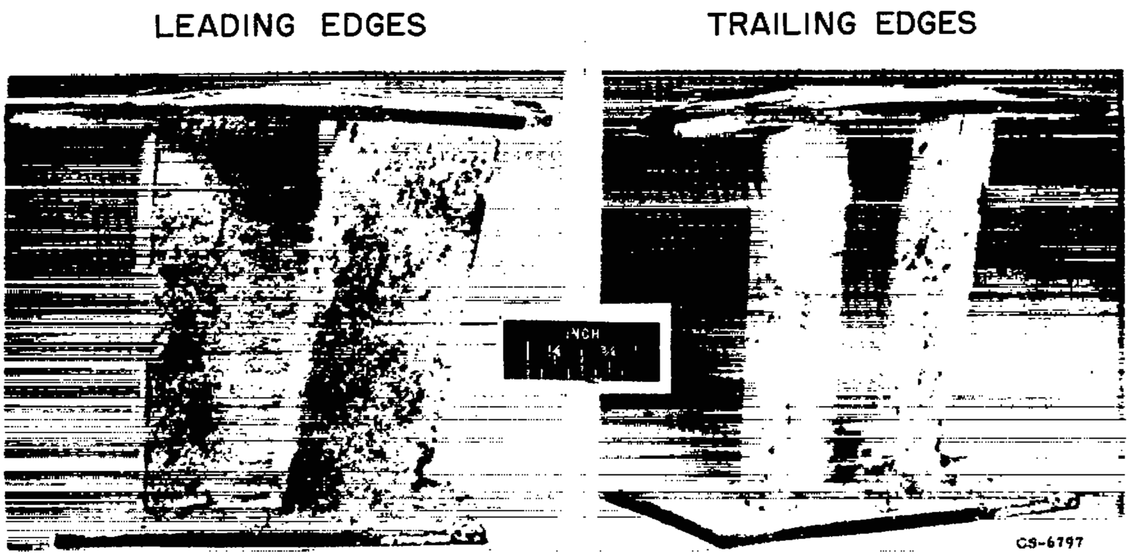

Figure 8. - Boron oxide deposits from diborane on turbine stator blades.

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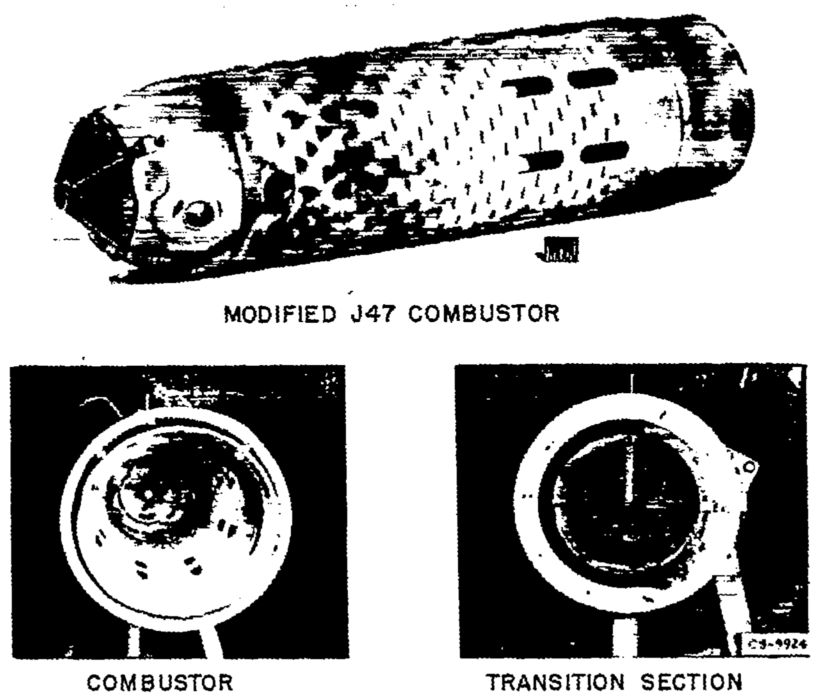

Figure 9. - Experimental combustor liner for pentaborane. Operating time, 6 minutes; pressure, 1/2 atmosphere; outlet temperature, 925° F.

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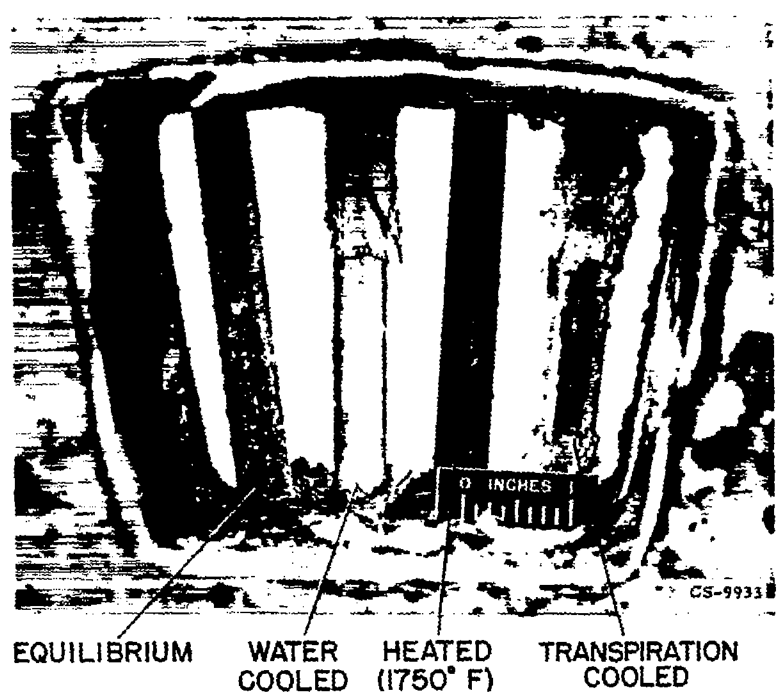

Figure 10. - Deposits on special tubes at combustor outlet. Gas temperature, 1380° F.

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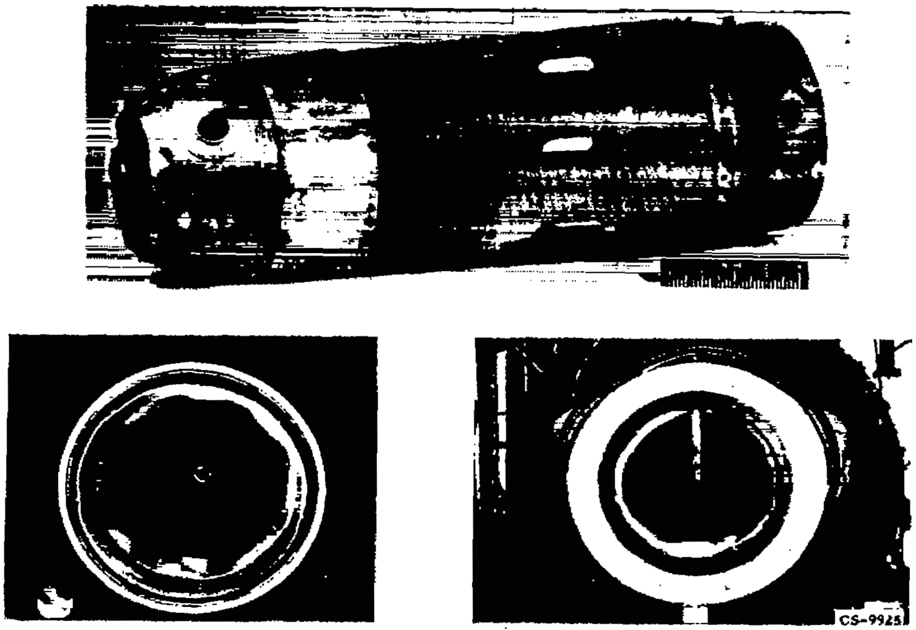

COMBUSTOR TRANSITION SECTION

Figure 11. - Wire-cloth combustor liner for pentaborane. Operating time, 13.3 minutes; pressure, 1/2 atmosphere; outlet temperature, 925° F.

FUEL	ALTITUDE, FT	MACH NUMBER	PERCENT RATED ENGINE SPEED	ACTUAL COMBUSTOR CONDITIONS				η_b	OUTLET TEMPERATURE SPREAD, °F	B_2O_3, g	TIME, MIN
				P, LB/SQ IN.	V, FPS	T, °F	ΔT, °F				
PENTABORANE	40,000	0.6	85	16.2	107	271	504	94	±230	33	8
	44,000	.6	100	15.7	103	354	1203	91	±450	36	4
	57,000	.6	85	7.0	107	279	738	92	±155	27	13
	61,000	.6	100	7.1	100	370	1187	93	±280	44	11
64% PENTABORANE 36% JP-4 FUEL	61,000	0.6	100	7.15	100	370	1162	89	±320	32	7

Figure 12. - Performance of wire-cloth combustor.

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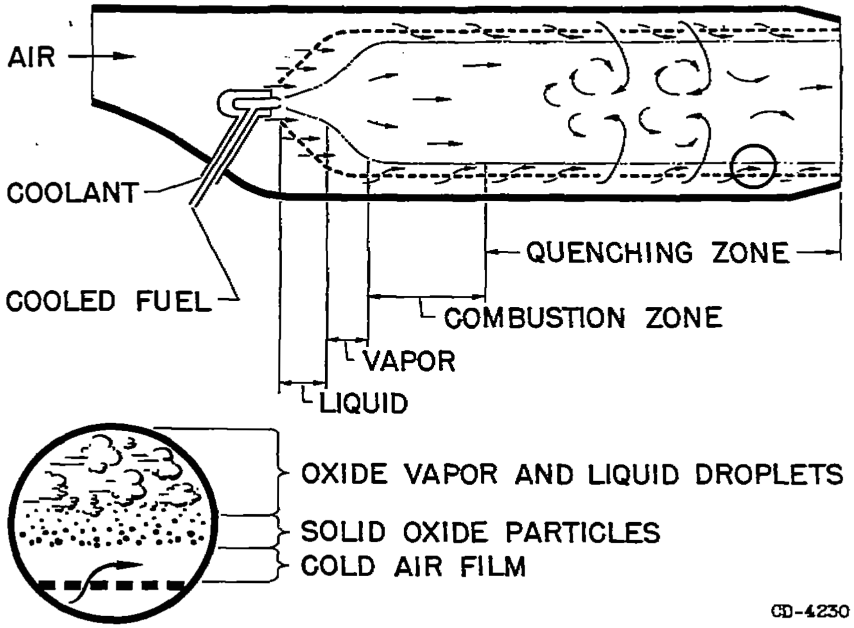

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Figure 13. - Desirable design features of a combustor for boron hydride fuels.

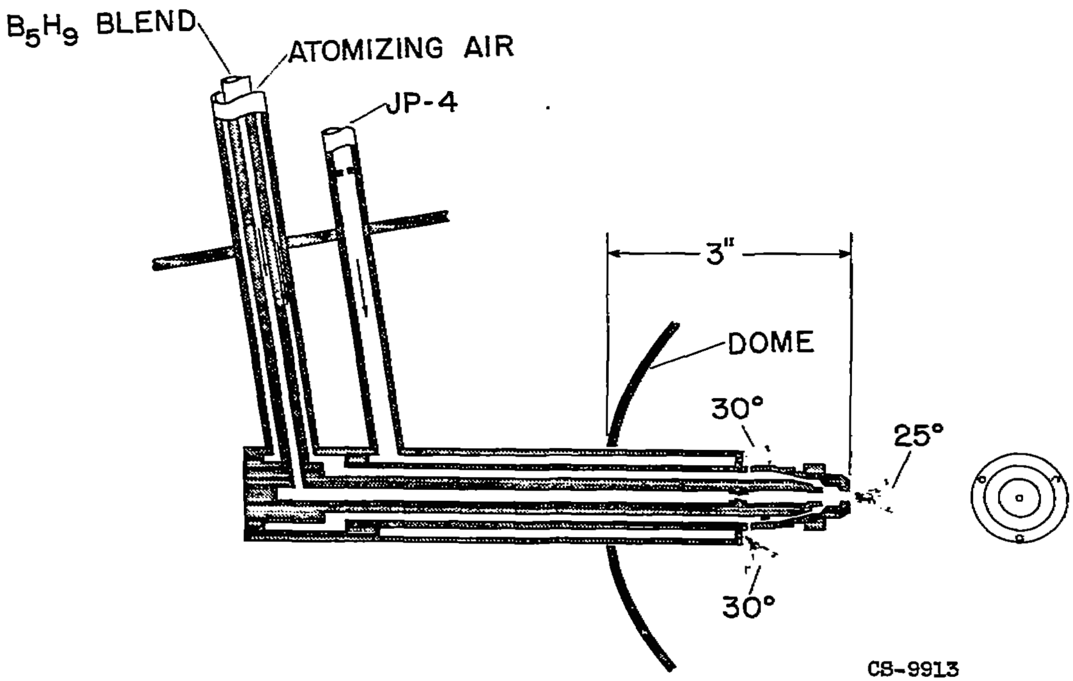

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Figure 14. - Dual-fuel injector.

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FUEL, % B_5H_9 IN JP-4	ALTITUDE, FT	PERCENT RATED ENGINE SPEED	MACH NUMBER	ACTUAL COMBUSTOR CONDITIONS P, LB/SQ IN.	V, FPS	T, °F	ΔT, °F	η_b	OUTLET TEMPERATURE SPREAD, °F
0	44,000	100	0.6	16.1	100	359	1204	93.5	±150
28	↓	↓	↓	16.1	100	356	1196	95.7	±200
66.8	↓	↓	↓	15.8	101	367	1309	95.6	±200
0	61,000	100	0.6	6.95	108	382	1254	80.9	±150
27	↓	↓	↓	6.95	108	378	1204	79.3	±225
66.8	↓	↓	↓	6.90	106	372	1288	84.2	±220
0	48,000	95	0.8	15.4	107	408	1282	93.4	±130
31	↓	↓	↓	14.8	108	408	1242	100	±170
6-PORT AIR-ATOMIZING FUEL INJECTOR									
0	44,000	100	0.6	15.9	101	370	1202	92	±160
40	↓	↓	↓	15.9	101	367	1177	93	±130
100	↓	↓	↓	15.9	101	367	1148	99	±125

Figure 15. - Performance of combustor using air-atomizing fuel injectors.

DATE	TEST	FUEL	TEST TIME, MIN	ENGINE	REMARKS
FALL '52	IA	$(C_4H_9)_3BO_3$ JP-4	90	J33	SEA LEVEL
SPRING '53	IIA	$(CH_3)_3BO_3$ CH_3OH	90	J33	SEA LEVEL
WINTER '53	IIIA	$(CH_3)_3BO_3$ CH_3OH	120	J47	SEA LEVEL
	IVA	$(CH_3)_3BO_3$ CH_3OH	30	J47	SEA LEVEL
SPRING '54	VA	$(CH_3)_3BO_3$ CH_3OH	59	J47	MACH 0.8, 50,000 FT
SUMMER '54	IB	$(CH_3)_3BO_3$ CH_3OH	120	J47	SEA LEVEL; VARIABLE-AREA NOZZLE FROZE, SPEED DROPPED
	IIB	$(CH_3)_3BO_3$ CH_3OH	100	↓	SEA LEVEL; VARIABLE-AREA NOZZLE OPERABLE
	IIIB	$(CH_3)_3BO_3$ CH_3OH	130	↓	SEA LEVEL; LOW TEMPERATURE RATIO TEST
	IVB	$(CH_3)_3BO_3$ CH_3OH	130	↓	SEA LEVEL; COMBUSTOR ALTERATION
	VB	$(CH_3)_3BO_3$ CH_3OH	15	↓	SEA LEVEL; ENGINE START AND IDLE TESTS-2 CYCLES
	VIB	$(CH_3)_3BO_3$ CH_3OH	100	↓	ENGINE START AND HIGH-TEMPERATURE TEST

Figure 16. - Engine tests with substitute fuels. Total test time, approximately 16 hours.

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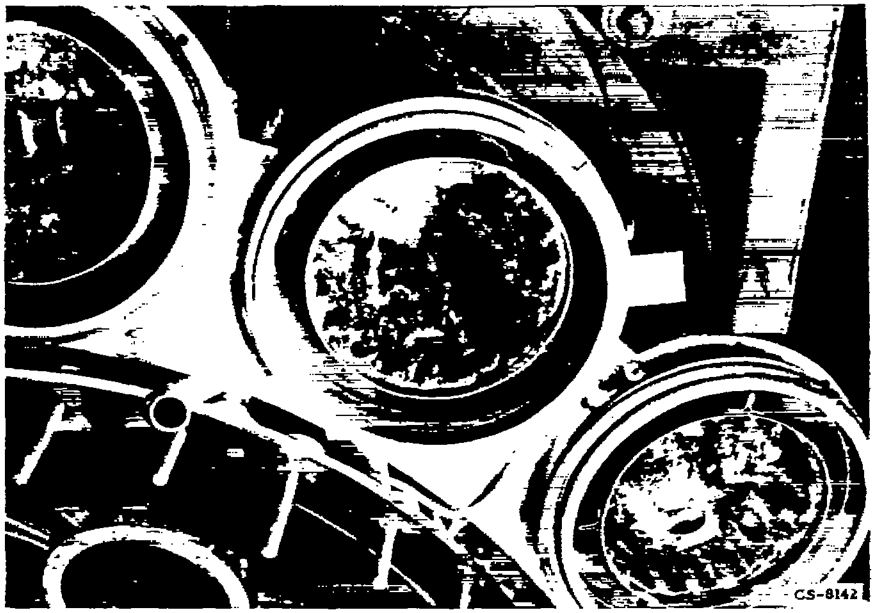

Figure 17. - Deposits from trimethylborate in upstream end of combustor. Domes have been removed.

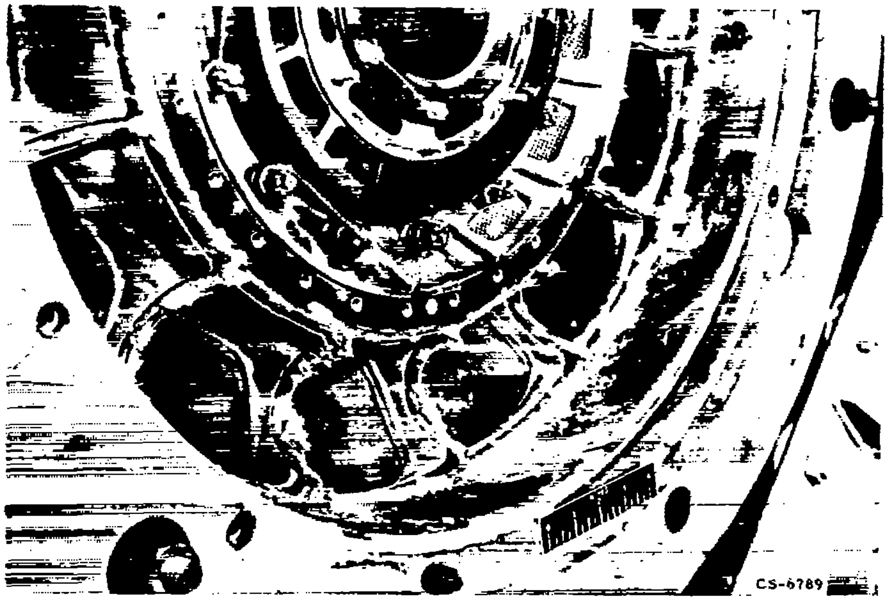

Figure 18. - Buildup of deposits at combustor exit.

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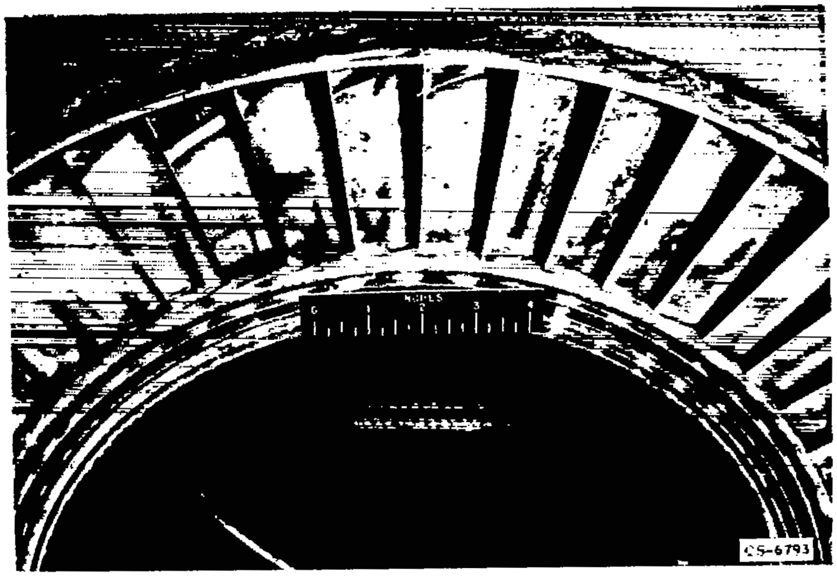

Figure 19. - Buildup of deposits on nozzle diaphragm. Downstream view.

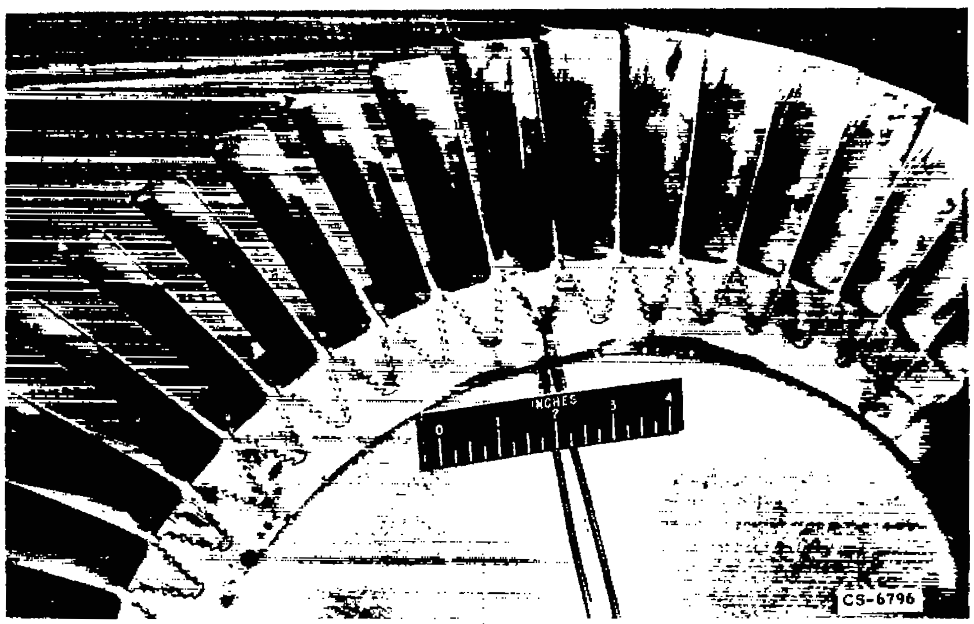

Figure 20. - Buildup of deposits on turbine rotor. Downstream view.

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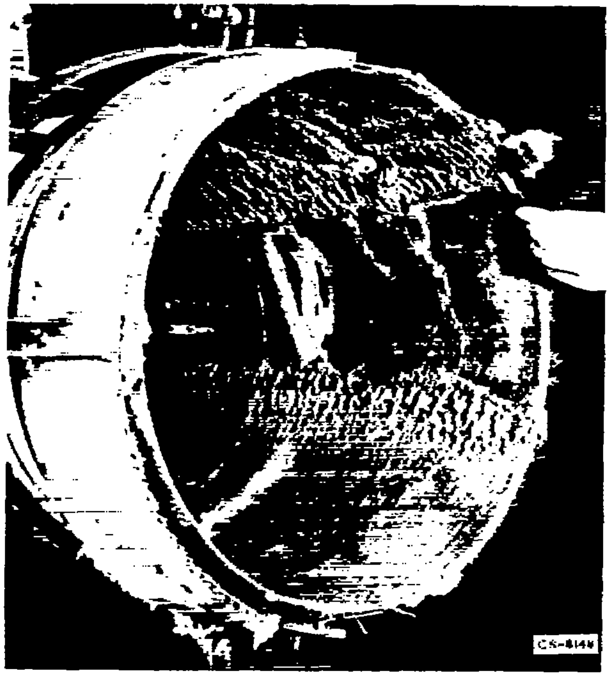

Figure 21. - Deposits on tailpipe.

SERIES	CONFIGURATION	MAX.% B_5H_9	QUANTITY OF PENTABORANE USED, LB
IA	WIRE-CLOTH COMBUSTOR	100	120
IB	WIRE-CLOTH COMBUSTOR WITH MODIFIED TURBINE	50	40
IIA	STANDARD COMBUSTOR WITH JP-4 AND B_5H_9 AIR-ATOMIZING FUEL INJECTOR	33	25
IIB	STANDARD COMBUSTOR WITH MODIFIED AIR-ATOMIZING FUEL INJECTOR	42	80
III	STANDARD COMBUSTOR WITH B_5H_9 INJECTORS LOCATED ON COMBUSTOR WALL	100	120

Figure 22. - Primary-combustor tests with pentaborane in full scale engine. Simulated flight condition: Mach number, 0.8; altitude, 50,000 feet.

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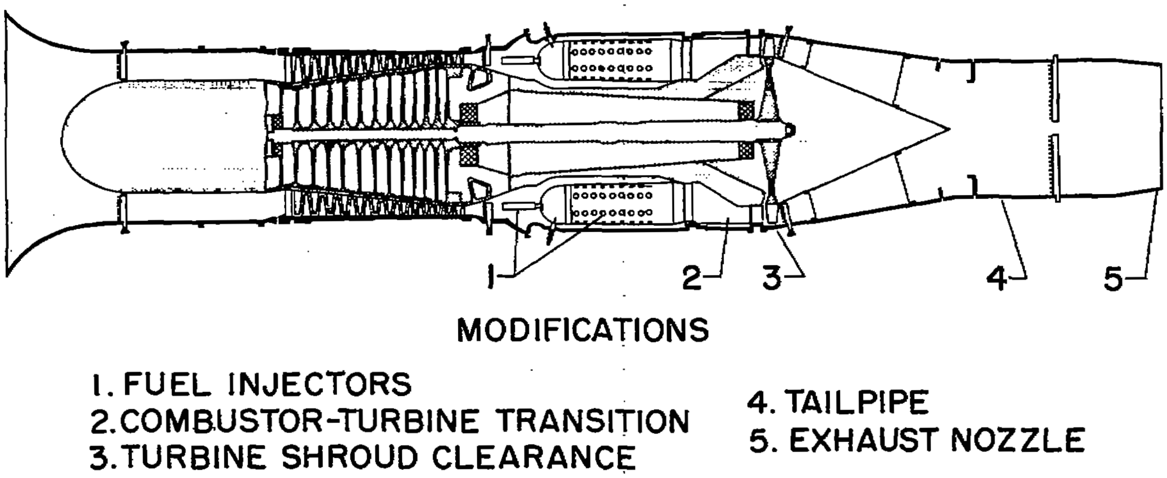

Figure 23. - Engine used with pentaborane fuel.

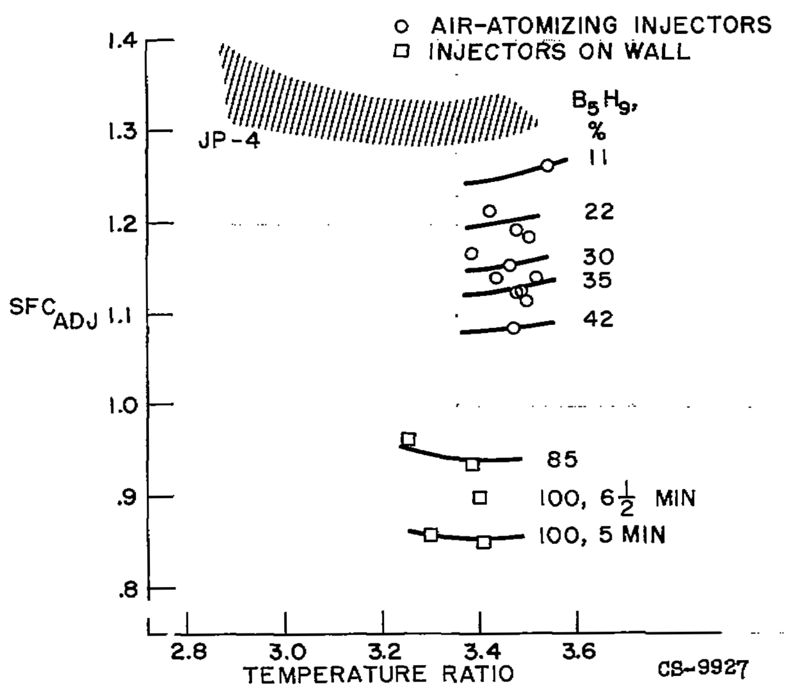

Figure 24. - Engine performance of pentaborane and JP-4 fuel mixtures. Altitude, 50,000 feet; Mach number, 0.8.

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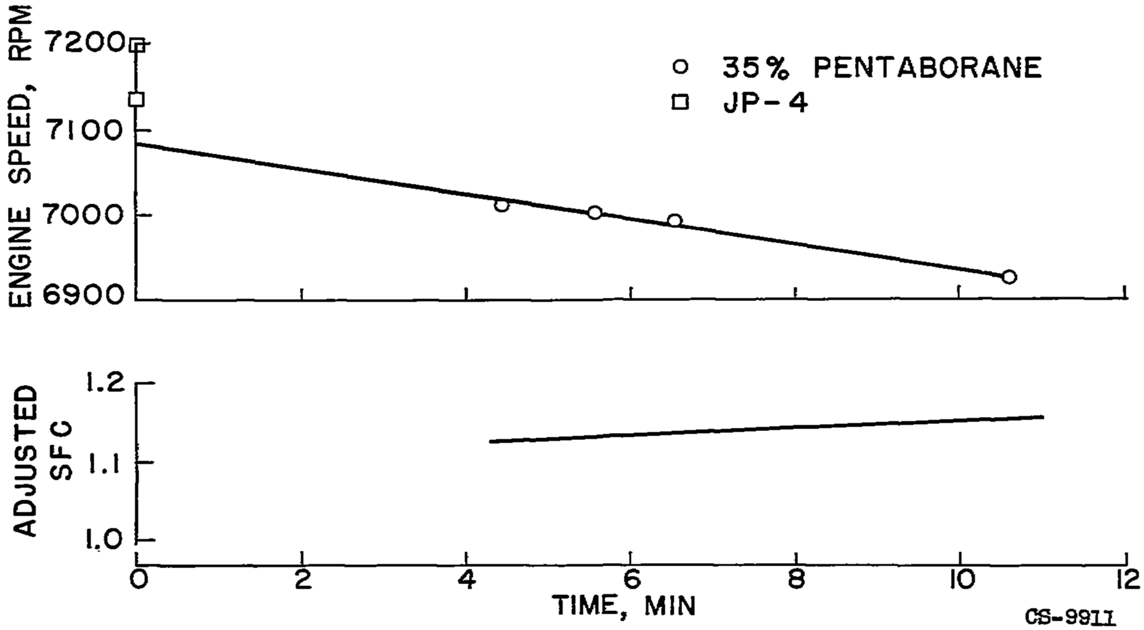

Figure 25. - Effect of operating time on engine performance. Fixed-area exhaust nozzle; altitude, 50,000 feet; Mach number, 0.8.

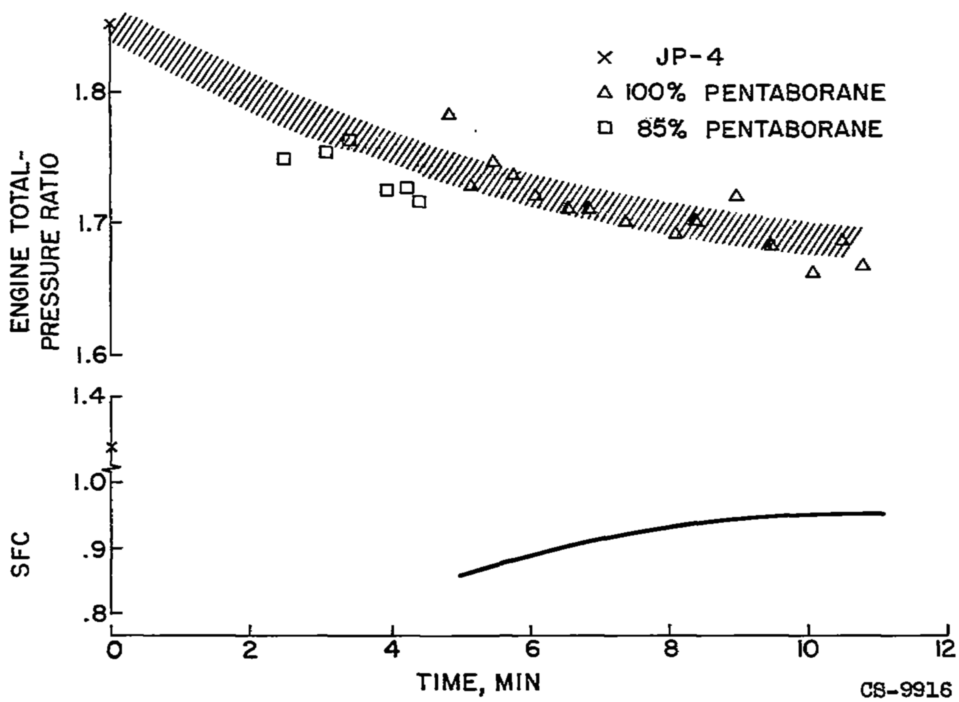

Figure 26. - Effect of operating time on engine performance. Variable-area exhaust nozzle; altitude, 50,000 feet; Mach number, 0.8.

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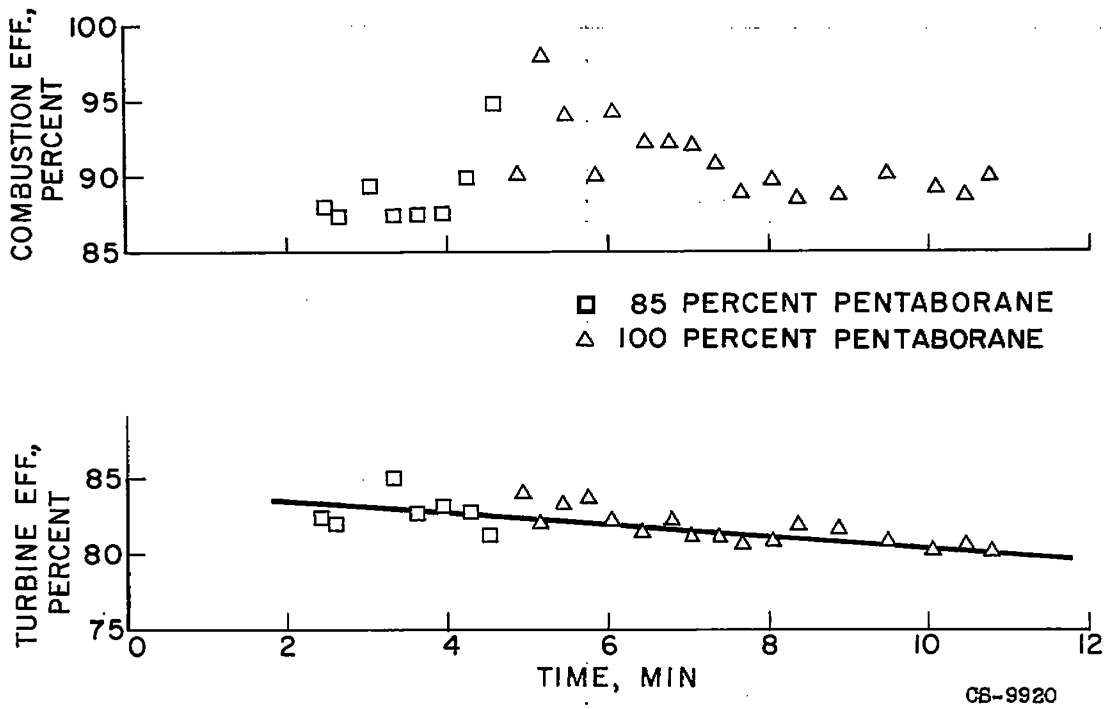

Figure 27. - Effect of operating time on component performance. Variable-area exhaust nozzle; injectors located on combustor wall; altitude, 50,000 feet; Mach number, 0.8.

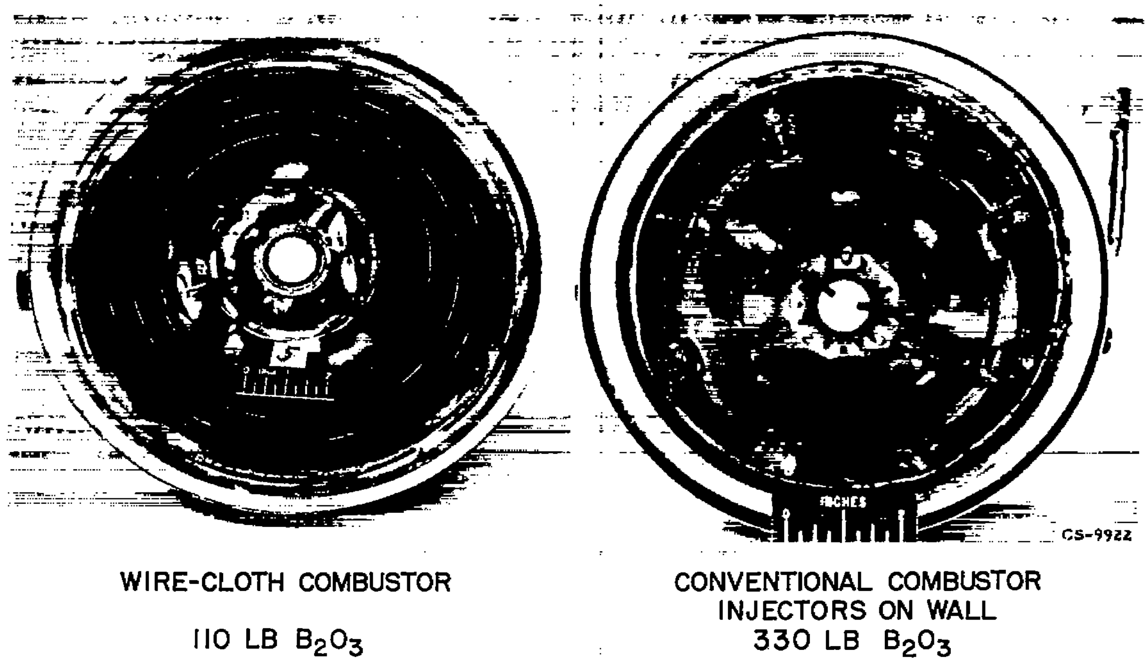

Figure 28. - Deposits in combustors immediately after operation with pentaborane fuel.

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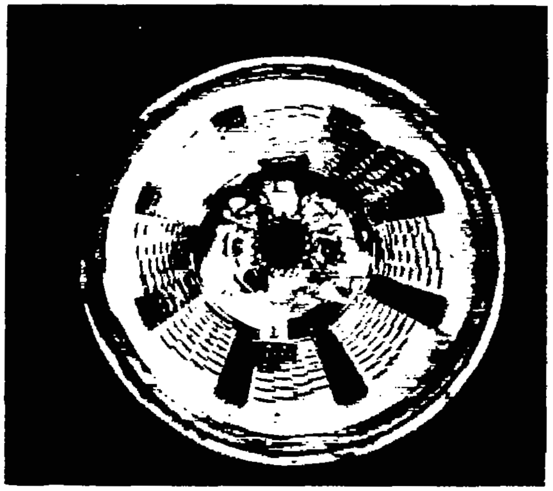
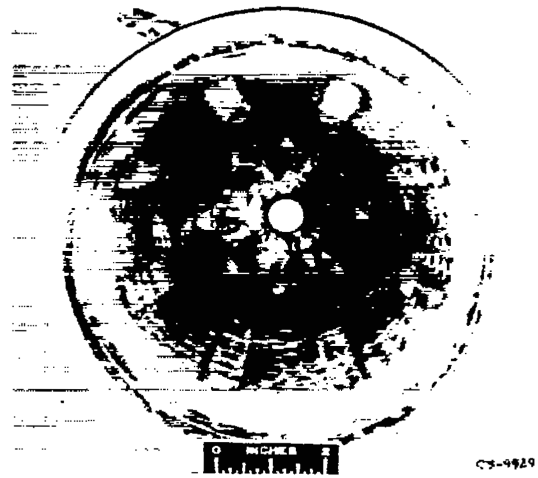


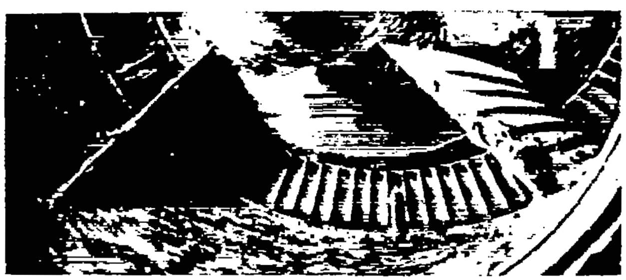
AIR-ATOMIZING FUEL INJECTOR
220 LB B_2O_3
8 MIN OPERATION WITH JP-4



FUEL INJECTOR ON WALL
330 LB B_2O_3
$1\frac{1}{2}$ HR OPERATION WITH JP-4

Figure 29. - Deposits in combustor with pentaborane fuel followed by JP-4 operation.

CD-5 back



IMMEDIATE SHUT DOWN

RESTART AND 1 1/2 HR RUN WITH JP-4

Figure 30. - Deposits in turbine and tailcone. Injectors at wall; 330 pounds of boron oxide formed.

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PENTABORANE, PERCENT	RANGE INDEX		
	H	$H(\eta_i)$	$H\eta_i\eta_b\eta_e$
0	1.00	1.00	1.00
20	1.115	1.09	1.085-1.065
40	1.225	1.19	1.178-1.16
60	1.34	1.285	1.28-------
80	1.45	1.4	1.4-1.35
100	1.56	1.48	1.49-1.54

$$R = H\eta_i\eta_b\eta_e \frac{L}{D} \ln \frac{W_G}{W_e}$$

Figure 31. - Influence of performance of pentaborane in engine on range.

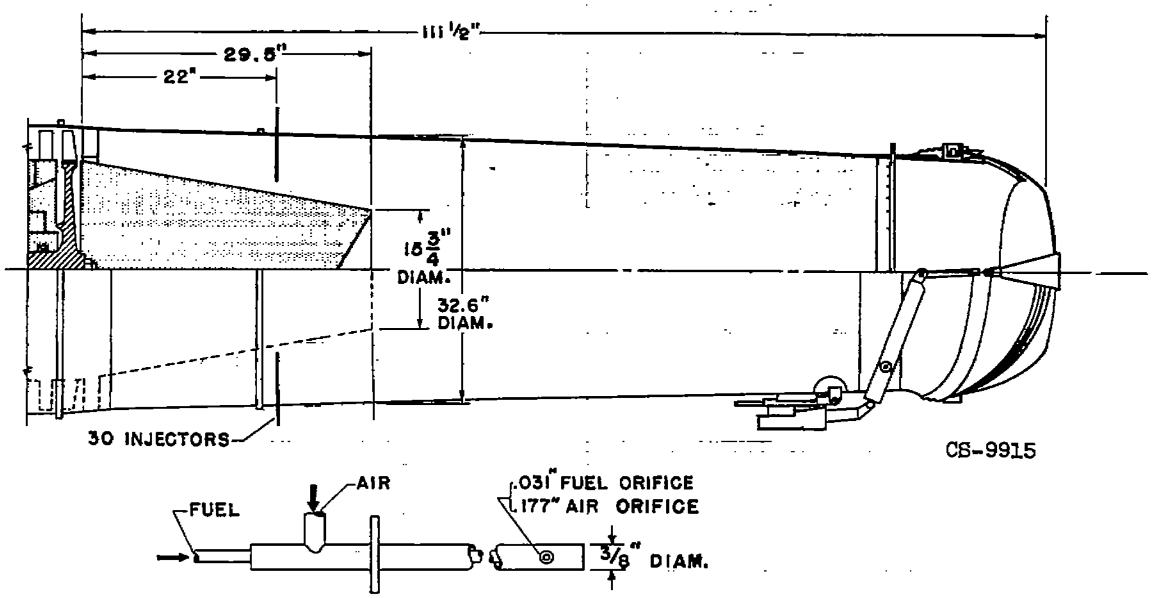

Figure 32. - Pentaborane afterbu_ner.

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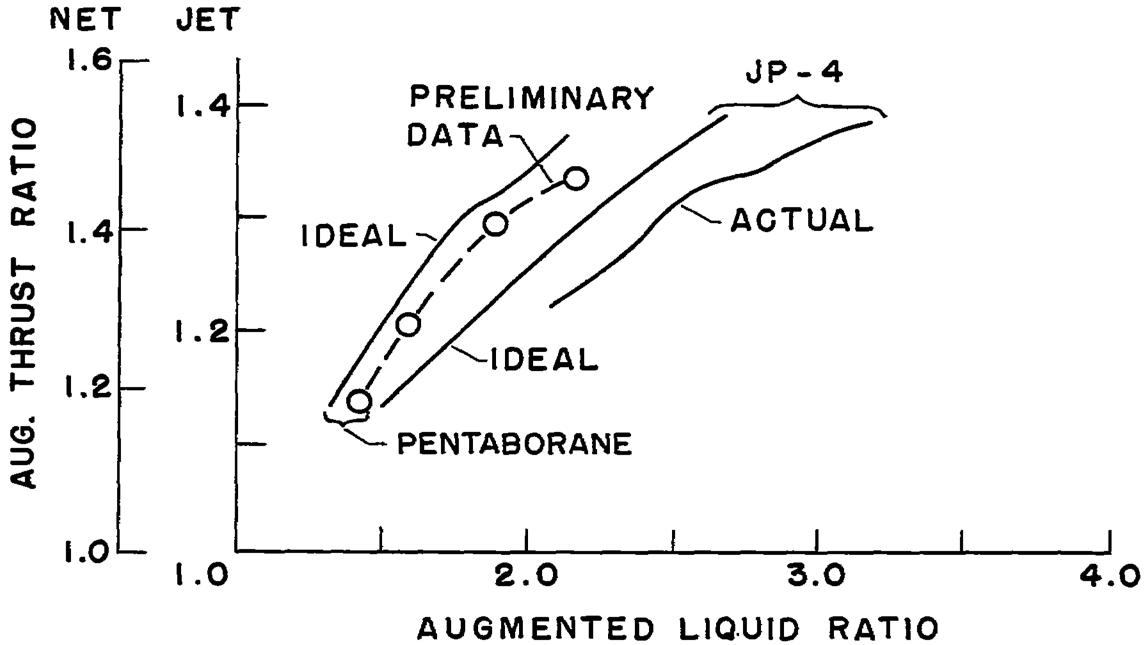

Figure 33. - Afterburner performance. Altitude, 50,000 feet; Mach number, 0.6.

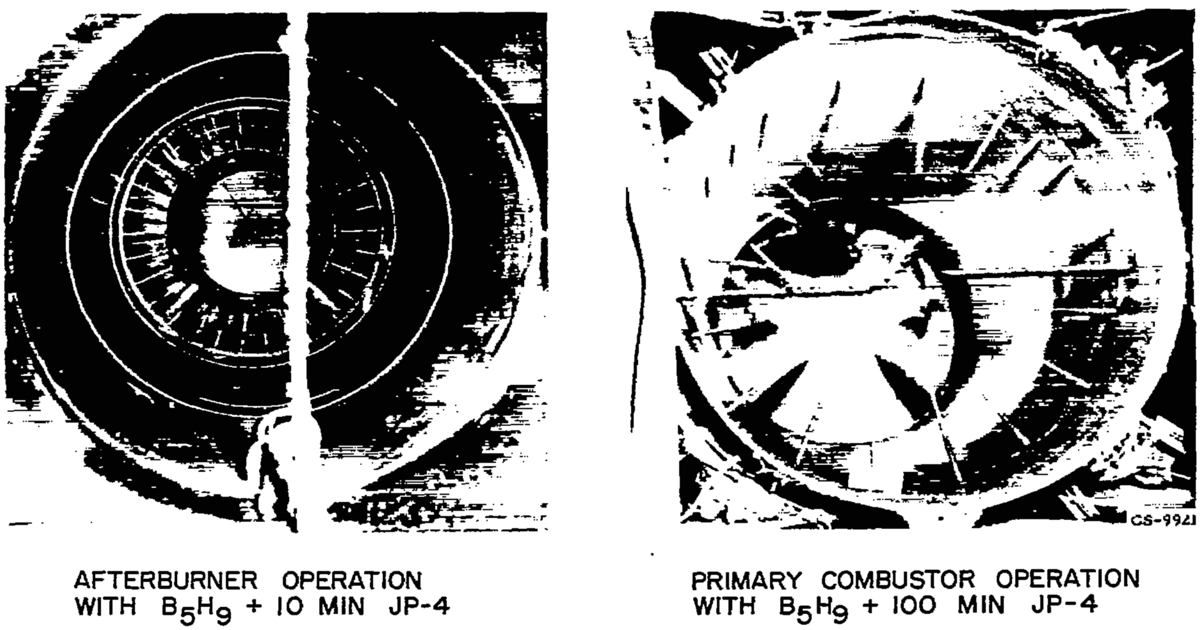

Figure 34. - Comparison of tailpipe deposits. Altitude, 50,000 feet; 330 pounds of boron oxide formed.

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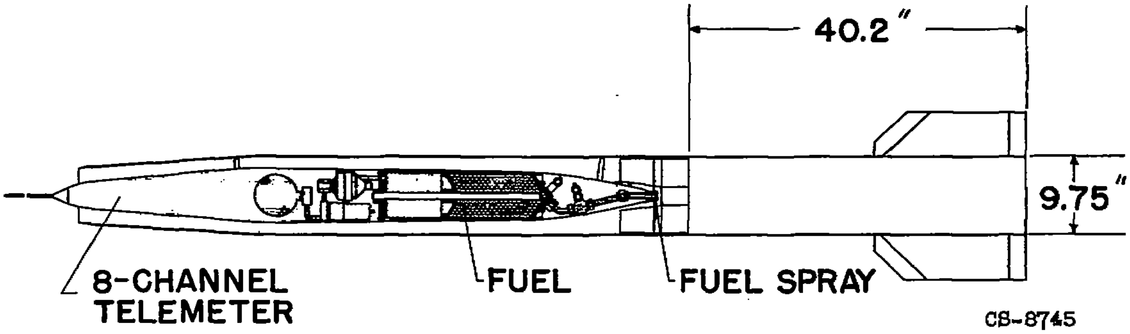

Figure 35. - Free-flight ram jet.

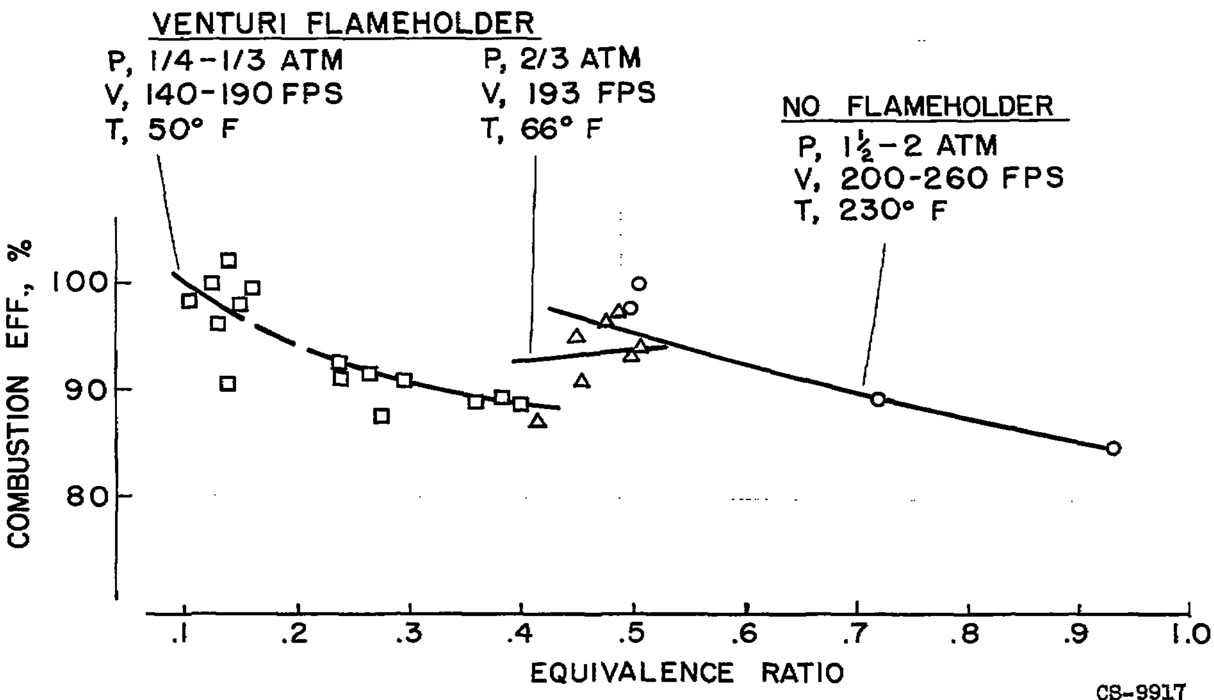

Figure 36. - Pentaborane performance in connected-pipe combustor.

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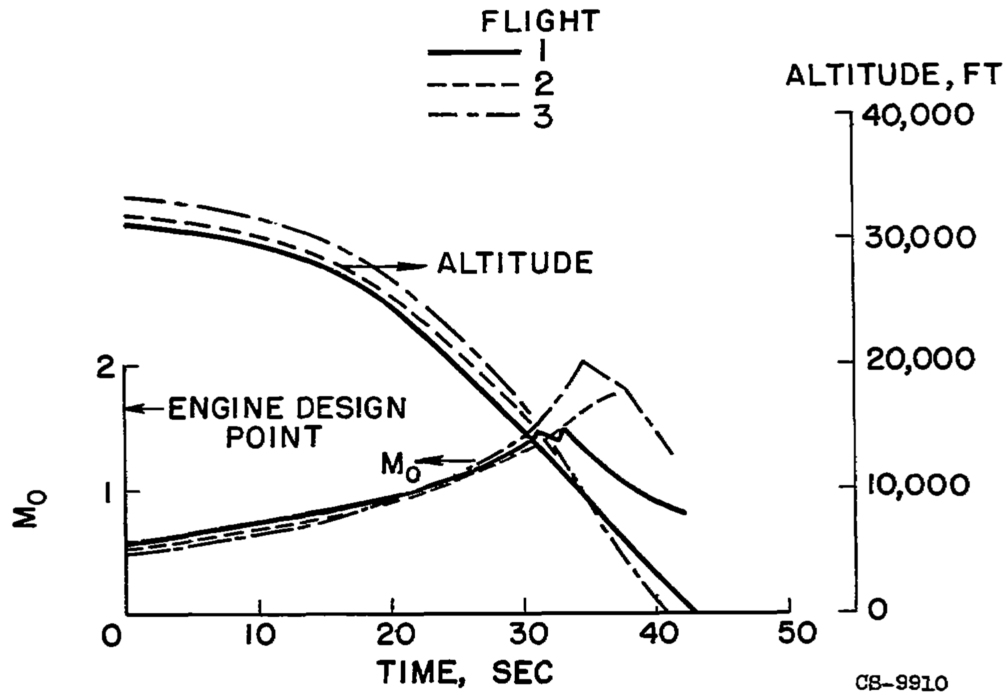

Figure 37. - Ram-jet flights with pentaborane.

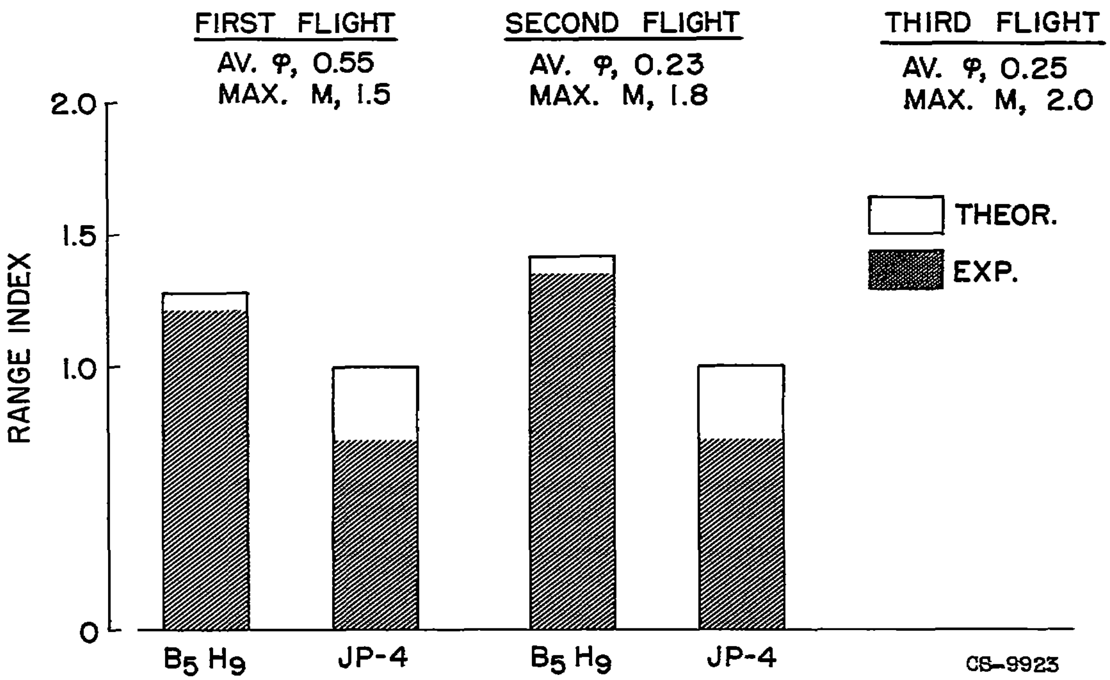

Figure 38. - Relative performance of pentaborane and JP-4 in ram-jet flights.

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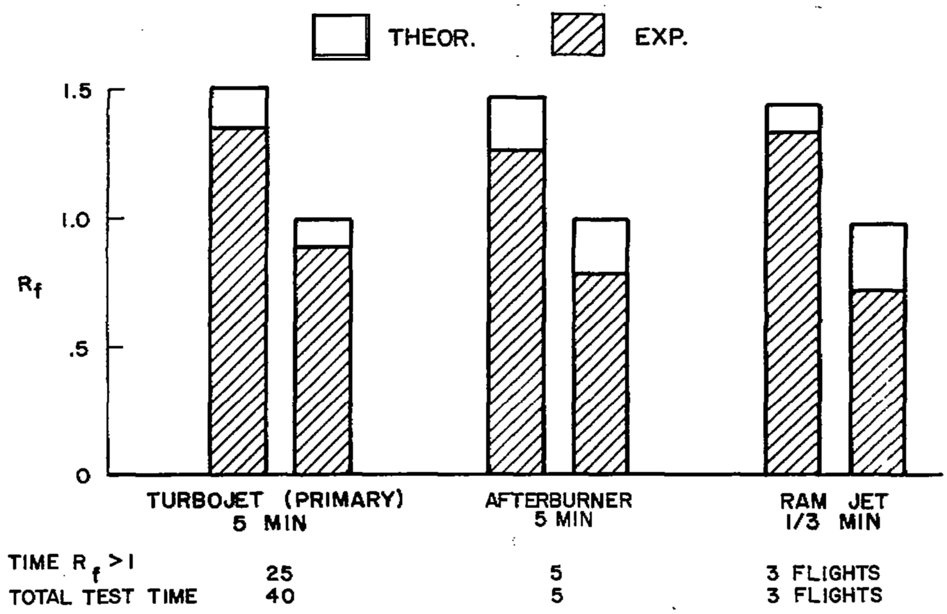

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$$R = H\eta \frac{L}{D} \ln \frac{W_G}{W_e}$$

Figure 39. - Summary of pentaborane data.

NACA - Langley Field, Va.

[redacted]

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