CONFIDENTIAL

Copy
RM E51D25 C.1

NACA RM E51D25

NACA

RESEARCH MEMORANDUM

PRELIMINARY EVALUATION OF THE AIR AND FUEL SPECIFIC-IMPULSE CHARACTERISTICS OF SEVERAL POTENTIAL RAM-JET FUELS

III - DIBORANE, PENTABORANE, BORON, AND BORON - OCTENE-1 SLURRIES

By Benson E. Gammon

Lewis Flight Propulsion Laboratory
Cleveland, Ohio

CLASSIFIE[redacted]MENT

This document contains classified information a[redacted]he National Defense of the United States within the meaning of the Espionage Act, USC 50:31 and 3[redacted]ansmission or the revelation of its contents in any manner to an unauthorized person is prohibited [redacted].
Information so classified may be imparted [redacted] persons in the military and naval services of the United States, appropriate civilian officers and e[redacted] of the Federal Government who have a legitimate interest therein, and to United States citizens of kn[redacted]lity and discretion who of necessity must be informed thereof.

NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

WASHINGTON

July 9, 1951

CONFIDENTIAL

[redacted]

Errata No. 1

NACA RM E51D25

PRELIMINARY EVALUATION OF THE AIR AND FUEL SPECIFIC-IMPULSE CHARACTERISTICS OF SEVERAL POTENTIAL RAM-JET FUELS

III - DIBORANE, PENTABORANE, BORON, AND BORON - OCTENE-1 SLURRIES

By Benson E. Gammon

July 9, 1951

Page 14: The ordinate in figure 2(b) should read 90 to 190 instead of 140 to 190.

[redacted]

 [redacted]

NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

RESEARCH MEMORANDUM

PRELIMINARY EVALUATION OF THE AIR AND FUEL SPECIFIC-IMPULSE CHARACTERISTICS OF SEVERAL POTENTIAL RAM-JET FUELS

III - DIBORANE, PENTABORANE, BORON, AND BORON - OCTENE-1 SLURRIES

By Benson E. Gammon

SUMMARY

An analytical evalution of the air and fuel specific-impulse characteristics of diborane, pentaborane, boron, and boron - octene-1 slurries has been made.

Adiabatic constant-pressure combustion temperature, air specific impulse, and fuel specific impulse are given for each fuel. The specific-impulse data for octene-1, taken as representative of aviation-gasoline performance, are presented for comparison.

At an initial air temperature of 560° R and a pressure of 2 atmospheres, the adiabatic constant-pressure combustion temperatures for diborane, pentaborane, and boron were 4840°, 4990°, and 5320° R, respectively, for a fuel equivalence ratio of 1.0.

Diborane, pentaborane, boron, and boron - octene-1 slurries permit the attainment of air specific-impulse values beyond the octene-1 limit. At a fixed air specific impulse, the fuel-weight specific impulse of diborane is better than that for pentaborane, and pentaborane is better than boron. Boron gives a greater fuel-weight specific impulse than octene-1 at all air specific-impulse values less than 141 ((lb)(sec)/lb air). For air specific-impulse values between 141 and 172.8 ((lb)(sec)/lb air), octene-1 gives greater fuel-weight specific impulse values than boron; for air specific-impulse values greater than the 172.8 octene-1 limit, boron gives a fuel-weight specific impulse superior to octene-1.

The fuel-volume specific-impulse values of boron and pentaborane at a fixed value of air specific impulse are better than the values for the reference fuel, octene-1.

[redacted]

INTRODUCTION

An investigation to evaluate the performance characteristics of several proposed ram-jet fuels is being conducted at the NACA Lewis laboratory. As a part of this program an analytical evaluation of the air and fuel specific-impulse characteristics of aluminum, magnesium, boron, diborane, pentaborane, hydrogen, aviation gasoline, graphite carbon, α-methylnapthalene, and slurries of the above metals in aviation gasoline is being made. The performance characteristics obtainable with octene-1, taken as representative of aviation gasoline, were chosen as the reference standard with which the performance of the other fuels was to be compared. Data on the theoretical air and fuel specific-impulse characteristics of octene-1, aluminum, magnesium, and aluminum - octene-1 and magnesium - octene-1 slurries are presented in references 1 and 2. Experimental ram-jet combustion performance data for diborane, aluminum, and magnesium-hydrocarbon slurry blends are presented in references 3, 4, and 5, respectively.

At the present time boron and boron hydrides are expensive and relatively unavailable compared to aviation gasoline, aluminum, or magnesium. Boron and boron hydrides, however, exhibit thermodynamic or combustion characteristics that warrant an exploration of their ram-jet performance characteristics.

This report presents data for diborane, pentaborane, boron, and boron - octene-1 slurries in the following manner:

(a) Adiabatic combustion flame temperature as a function of equivalence ratio

(b) Air specific impulse as a function of equivalence ratio

(c) Fuel-weight specific impulse as a function of equivalence ratio

(d) Fuel-weight specific impulse as a function of air specific impulse

(e) Fuel-volume specific impulse as a function of air specific impulse.

The terms fuel equivalence ratio and stoichiometric fuel fraction are based on the oxygen available in the air and are used interchangeably.

SYMBOLS

The following symbols are used in this report:

A	area, (sq ft)
F	stream thrust, (lb)
f/a	fuel-air ratio
g	acceleration due to gravity, (ft/sec^2)
M	Mach number
m	mass, (slugs/sec)
p	pressure, (lb/sq ft)
R	gas constant, (ft-lb/(lb)($^{\circ}$R))
S_a	air specific impulse, ((lb)(sec)/lb air)
S_f	fuel-weight specific impulse, ((lb)(sec)/lb fuel)
S'_f	fuel-volume specific impulse, ((lb)(sec)/cu ft fuel)
T	static temperature, ($^{\circ}$R)
V	velocity, (ft/sec)
w	weight flow, (lb/sec)
X	weight fraction of solids in jet gases
ρ	density, (lb/cu ft)

Subscripts:

a	air
f	fuel
J	jet
3	nozzle throat station

THERMODYNAMIC DATA AND ANALYTICAL METHOD

Thermodynamic data. - Thermodynamic data for the constituents were taken from reference 6. Inasmuch as the thermodynamic data for boron nitride were inadequate, the possible reaction of boron with nitrogen was omitted.

Analytical method. - The analytical method used is presented in reference 1. The constituents considered to be present when either diborane or pentaborane was used as the sole fuel are solid, liquid, and gas B_2O_3; gaseous H_2, H_2O, N_2, NO, O_2, H, O, N, B, BH, and OH.

The constituents considered to be present when boron was used as the sole fuel are solid, liquid, and gas B_2O_3; gaseous N_2, NO, O_2, N, O, B, and BO.

When boron - octene-1 slurries were used as the fuel, the constituents considered to be present are solid, liquid, and gas B_2O_3; gaseous CO_2, NO, H_2O, O_2, H_2, N_2, CO, H, O, N, B, BO, BH, and OH.

Combustor inlet-air conditions were taken as 560° R and 2 atmospheres pressure throughout the analysis. An expansion ratio of 2 was used; gas composition was assumed fixed during the isentropic expansion to ambient pressure. These conditions were selected for convenience in making the specific-impulse calculations and to facilitate comparisons between the theoretical and experimental performance values. The calculations were made in intervals of 0.1 equivalence-ratio units, or less, over the equivalence-ratio range from 0 to 1.0 for boron and pentaborane; for diborane the equivalence-ratio range was from 0 to 1.3. For the boron - octene-1 slurries the total fuel equivalence ratio was fixed at 1.0 and the boron stoichiometric fraction was varied in regular steps from 0 to 1.0.

The air specific-impulse values were calculated from the equation:

$$S_a = \left(1 + \frac{f}{a}\right)\left[\frac{V_J}{g} + \frac{R\ T_3}{V_J}(1 - X)\right] \tag{1}$$

Equation (1) may be derived from the defining equation for air specific impulse at a flow state of Mach number 1.0:

$$S_a \equiv \frac{F_3}{w_a} \equiv \frac{m\ V_J + p_3 A_3}{w_a} \tag{2}$$

The fuel-weight specific impulse is defined as:

$$S_f \equiv (Sa)\ (a/f) \tag{3}$$

Fuel-volume specific impulse is defined as:

$$S'_f \equiv S_f\ \rho_f \tag{4}$$

The air specific impulse is a measure of the potential thrust; the fuel-weight specific impulse is a measure of the time 1 pound of fuel will maintain the given air specific impulse.

RESULTS AND DISCUSSION

Temperature. - The adiabatic constant-pressure-combustion temperature and the nozzle-exit gas temperature for diborane, pentaborane, boron, and boron - octene-1 slurries are shown in figures 1(a), 1(b), 1(c), and 1(d), respectively. The nozzle-exit gas temperatures represented are those used in deriving the air and fuel specific-impulse values; they are the static temperatures at the nozzle throat for a Mach 1.0 flow state.

At a stoichiometric fuel fraction of 1.0 and an initial air temperature of 560° R, the combustion temperatures for diborane, pentaborane, and boron are 4840°, 4990°, and 5320° R, respectively.

Air specific impulse. - The variation of air specific impulse with stoichiometric fuel fraction for diborane, pentaborane, and boron is presented in figures 2(a), 2(b), and 2(c), respectively. The irregular nature of these curves is due to the liquid-gas phase transition of boron sesquioxide, B_2O_3. At a fixed total stoichiometric fuel fraction of 1.0, the variation of air specific impulse with stoichiometric fraction of boron in a boron - octene-1 slurry is presented in figure 2(d).

Fuel-weight specific impulse. - The variation of fuel-weight specific impulse with stoichiometric fraction of diborane, pentaborane, and boron is presented in figures 3(a), 3(b), and 3(c), respectively. The variation of fuel-weight specific impulse with stoichiometric fraction of boron in octene-1 is presented in figure 3(d) for the case where the total stoichiometric fuel fraction is fixed at 1.0.

Relation between air and fuel specific impulse. - Comparisons of fuel-weight specific impulse for a series of fuels can best be made at the same air specific impulse, that is, at equivalent thrust levels. The variation of fuel-weight specific impulse with air specific impulse for diborane, pentaborane, boron, and boron - octene-1 slurries is presented in figures 4(a), 4(b), 4(c), and 4(d), respectively. These data were obtained by cross-plotting the data for air and fuel-weight specific impulse presented in figures 2 and 3. The data for boron are again shown in figure 4(d) for convenience of comparison with the data for boron - octene-1 slurries.

The data presented in figures 4(a), 4(b), and 4(c) are re-presented in figure 5 for comparison with the octene-1 reference curve. It is readily evident from figure 5 that diborane gives a better fuel-weight specific impulse at a given air specific impulse than pentaborane, boron, or octene-1. Pentaborane is better than boron on a fuel-weight specific-impulse basis. For air specific-impulse values below 141 ((lb)(sec)/lb air) boron is superior to octene-1 on a fuel-weight specific-impulse basis. Between the limits of 141 and 172.8 ((lb)(sec)/lb air) octene-1 has a better fuel-weight specific impulse than boron.

It follows from figure 5 that boron - octene-1 slurries are capable of giving better fuel-weight specific-impulse values than octene-1 alone for air specific-impulse values below 141 ((lb)(sec)/lb air). Consideration of figures 4(d) and 5 indicates that boron - octene-1 slurries are capable of giving better fuel-weight specific-impulse values than boron alone for values of air specific impulse greater than 141 ((lb)(sec)/lb air).

The limiting value of air specific impulse for octene-1 is 172.8 ((lb)(sec)/lb air). Limiting values of air specific impulse were not calculated for diborane, pentaborane, and boron. The calculations made to an equivalence ratio of 1.3, 1.0, and 1.0 for diborane, pentaborane, and boron, respectively, show that the limiting air specific impulse for each of these fuels is significantly greater than the octene-1 limit.

Pentaborane and boron show advantages over octene-1 with regard to fuel-volume specific impulse as well as the air and fuel-weight specific-impulse values previously shown. A comparison of the air and fuel-volume specific-impulse characteristics for diborane, pentaborane, boron, and octene-1 is shown in figure 6. This figure shows that the gains to be anticipated for boron on a volume basis are greater than those for pentaborane or diborane. On a volume basis, diborane shows advantages over octene-1 only for air specific-impulse values greater than the octene-1 limit of 172.8 ((lb)(sec)/lb air). The densities used for diborane, pentaborane, boron, and octene-1 were: 27.9, 38.1, 144.8, and 44.4 pounds per cubic foot, respectively. The density of liquid diborane is taken at approximately its normal boiling temperature, -134.5° F, whereas the density of liquid pentaborane is taken at 32° F. The densities of solid boron and liquid octene-1 are for approximately 60° F. All densities are quoted for 1-atmosphere pressure.

SUMMARY OF RESULTS

For the conditions of this preliminary analysis, the following results were obtained:

(1) At an initial air temperature of 560° R, the adiabatic constant-pressure combustion temperature for diborane, pentaborane, and boron were 4840°, 4990°, and 5320° R, respectively, at the stoichiometric point.

(2) Diborane, pentaborane, boron and boron - octene-1 slurries permit the attainment of air specific-impulse values beyond the 172.8 ((lb)(sec)/lb air) limit for octene-1.

(3) Pentaborane gives better values of air specific impulse, fuel-weight specific impulse, and fuel-volume specific impulse than octene-1. Boron gives better values of fuel-volume specific impulse and air specific impulse than octene-1; boron also gives better values of fuel-weight specific impulse than octene-1 for air specific-impulse values below 141 ((lb)(sec)/ft air) and for air specific-impulse values above 172.8 ((lb)(sec)/lb air). Diborane gives chiefly better values of air and fuel-weight specific impulse than octene-1.

(4) At air specific-impulse values between 141 and 185 ((lb)(sec)/lb air), boron - octene-1 slurries are capable of giving fuel-weight specific-impulse values superior to boron alone.

Lewis Flight Propulsion Laboratory,
National Advisory Committee for Aeronautics,
Cleveland, Ohio.

REFERENCES

1. Gammon, Benson E.: Preliminary Evaluation of the Air and Fuel Specific-Impulse Characteristics of Several Potential Ram-Jet Fuels. I - Octene-1, Aluminum, and Aluminum - Octene-1 Slurries. NACA RM E51C12, 1951.

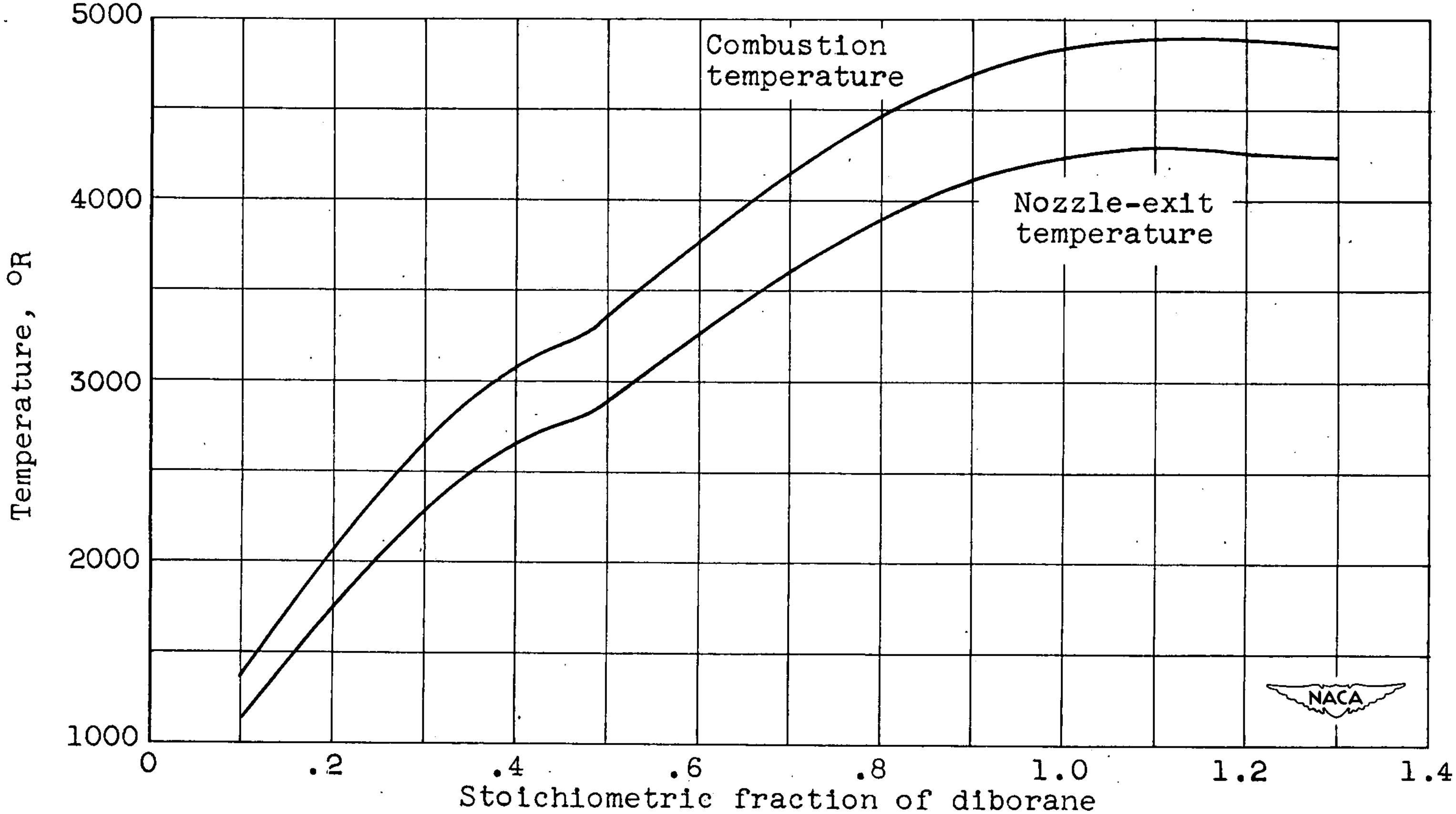
2. Gammon, Benson E.: Preliminary Evaluation of the Air and Fuel Specific-Impulse Characteristics of Several Potential Ram-Jet Fuels. II - Magnesium, and Magnesium - Octene-1 Slurries. NACA RM E51C23, 1951.

3. Gammon, Benson E., Genco, Russell S., and Gerstein, Melvin: A Preliminary Experimental and Analytical Evaluation of Diborane As a Ram-Jet Fuel. NACA RM E50J04, 1950.

4. Branstetter, J. Robert, Lord, Albert M., and Gerstein, Melvin: Combustion Properties of Aluminum As Ram-Jet Fuel. NACA RM E51B02, 1951.

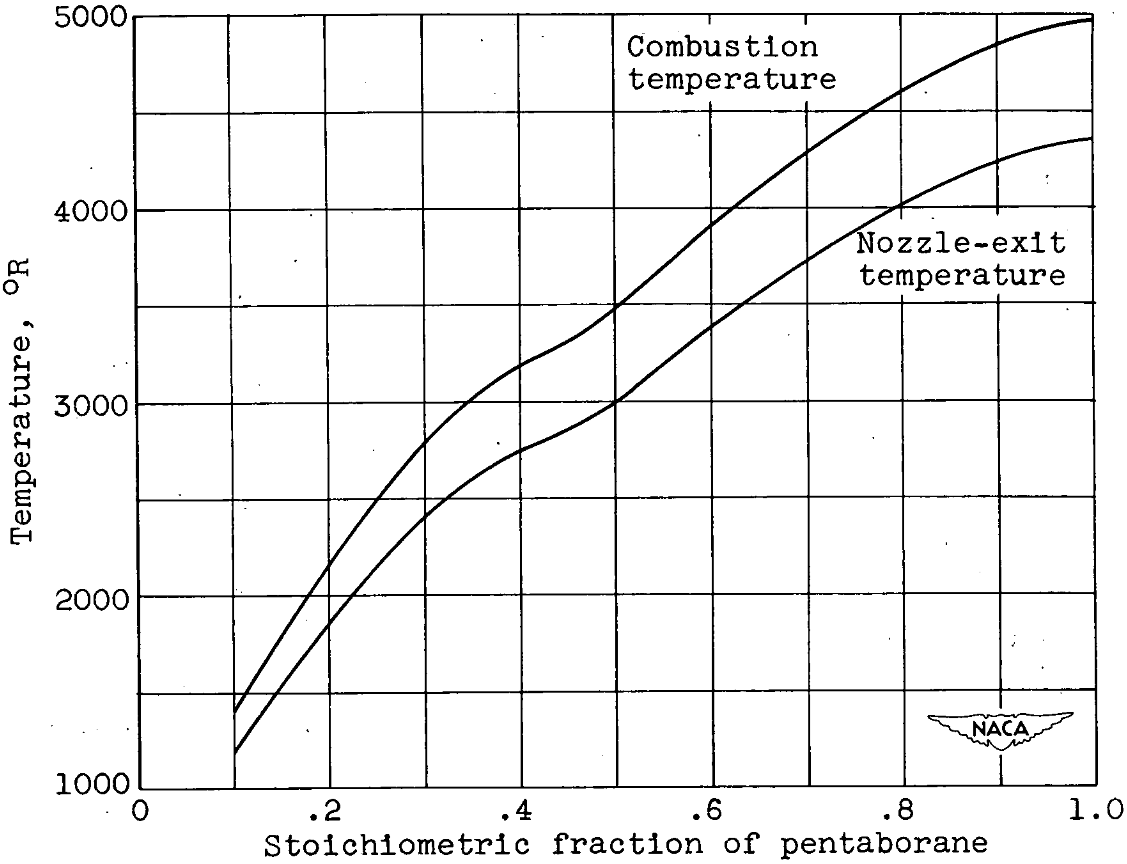
5. Tower, Leonard K., and Branstetter, J. Robert: Combustion Performance Evaluation of Magnesium-Hydrocarbon Slurry Blends in a Simulated Tail-Pipe Burner. NACA RM E51B26, 1951.

6. Huff, Vearl N., and Gordon, Sanford: Tables of Thermodynamic Functions For Analysis of Aircraft-Propulsion Systems. NACA TN 2161, 1950.



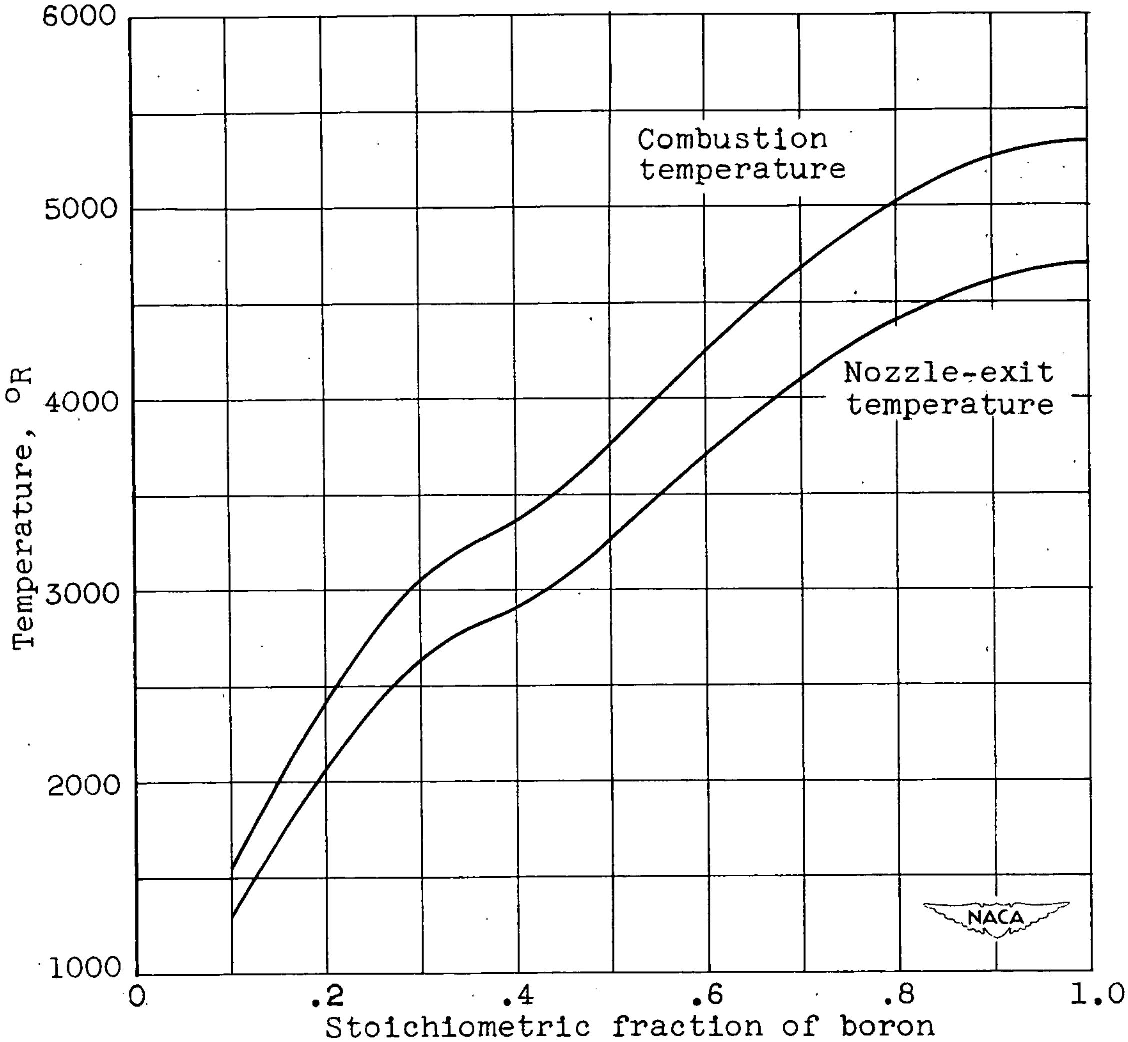
(a) Diborane.

Figure 1. - Theoretical variation of combustion and nozzle-exit temperature with stoichiometric fraction of fuel. Combustor inlet-air temperature, 560° R; inlet-air pressure, 2 atmospheres; expansion ratio, 2.0.



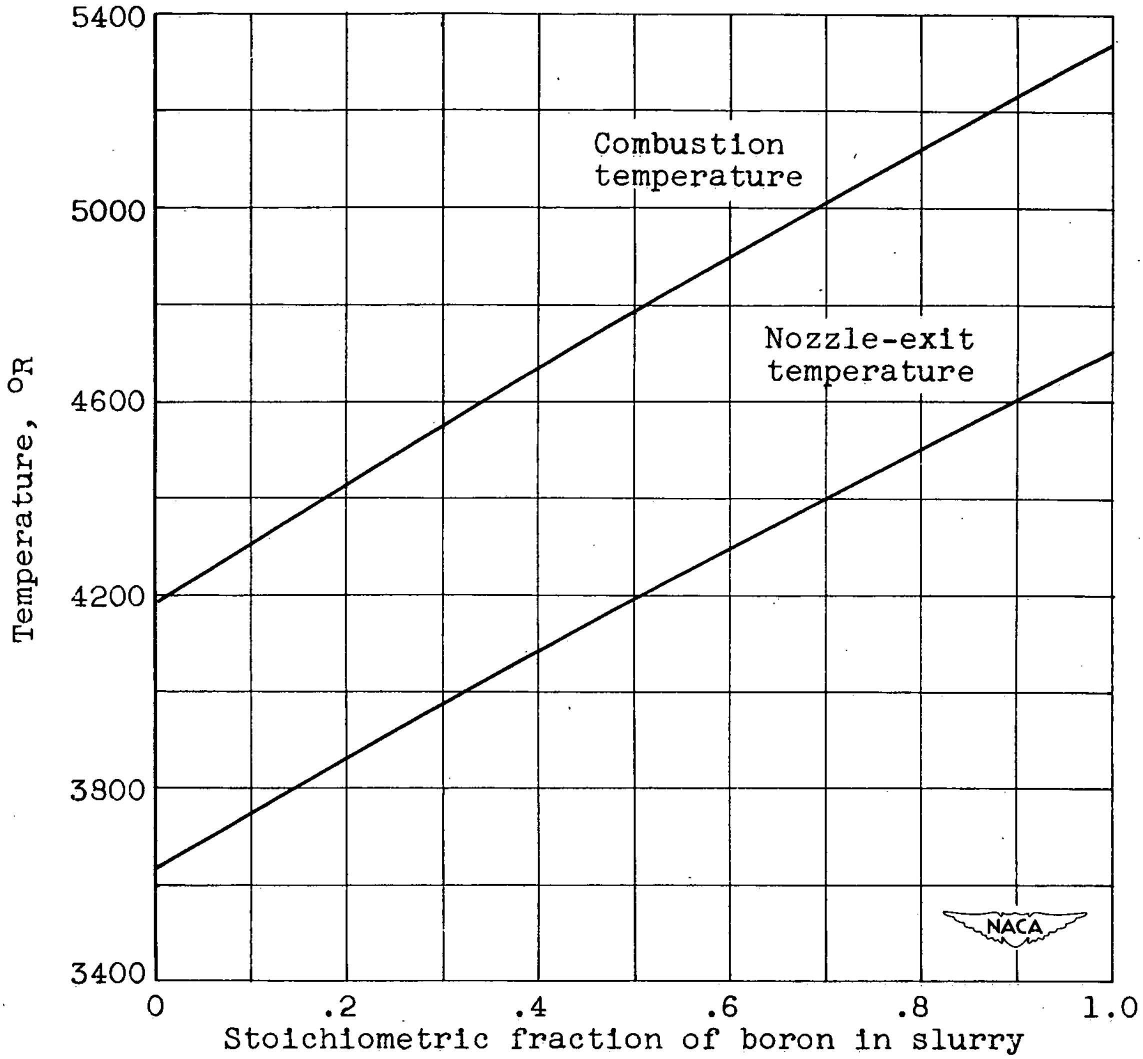
(b) Pentaborane.

Figure 1. - Continued. Theoretical variation of combustion and nozzle-exit temperature with stoichiometric fraction of fuel. Combustor inlet-air temperature, 560° R; inlet-air pressure, 2 atmospheres; expansion ratio, 2.0.



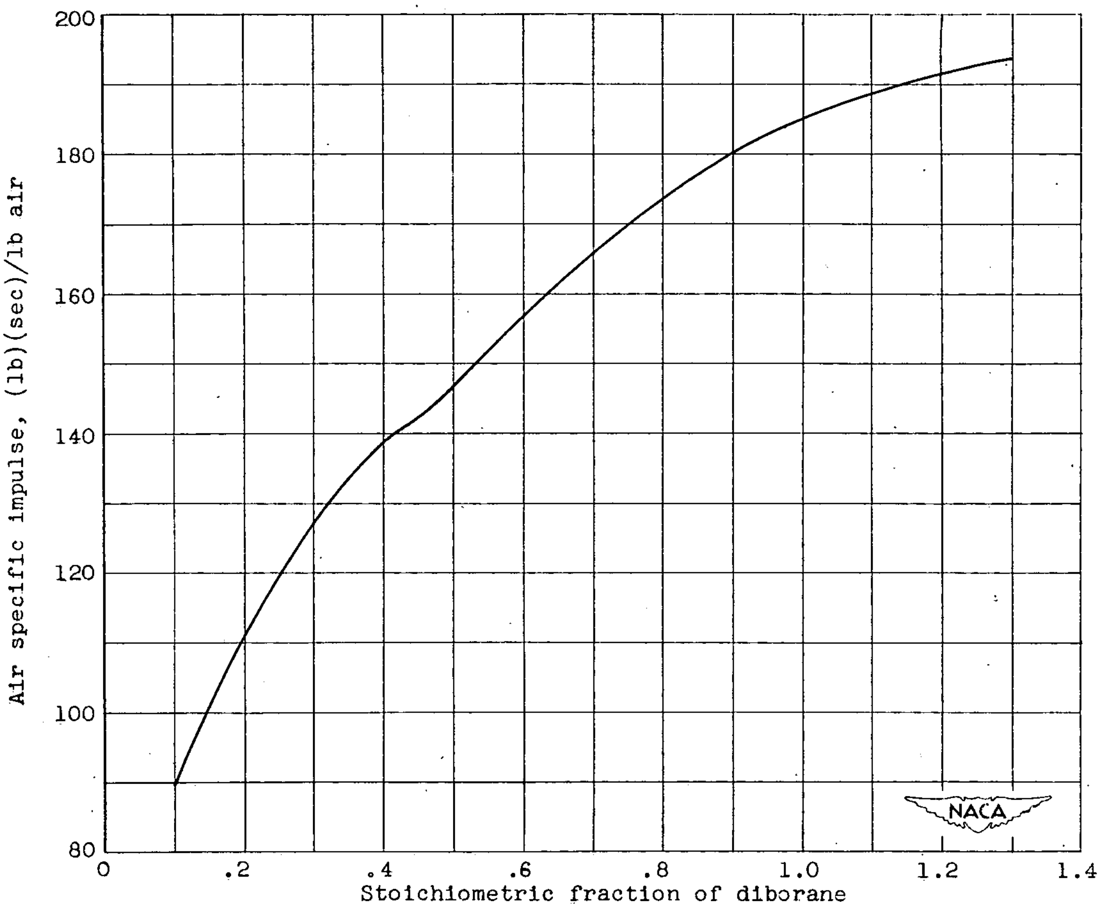
(c) Boron.

Figure 1. - Continued. Theoretical variation of combustion and nozzle-exit temperature with stoichiometric fraction of fuel. Combustor inlet-air temperature, 560° R; inlet-air pressure, 2 atmospheres; expansion ratio 2.0.



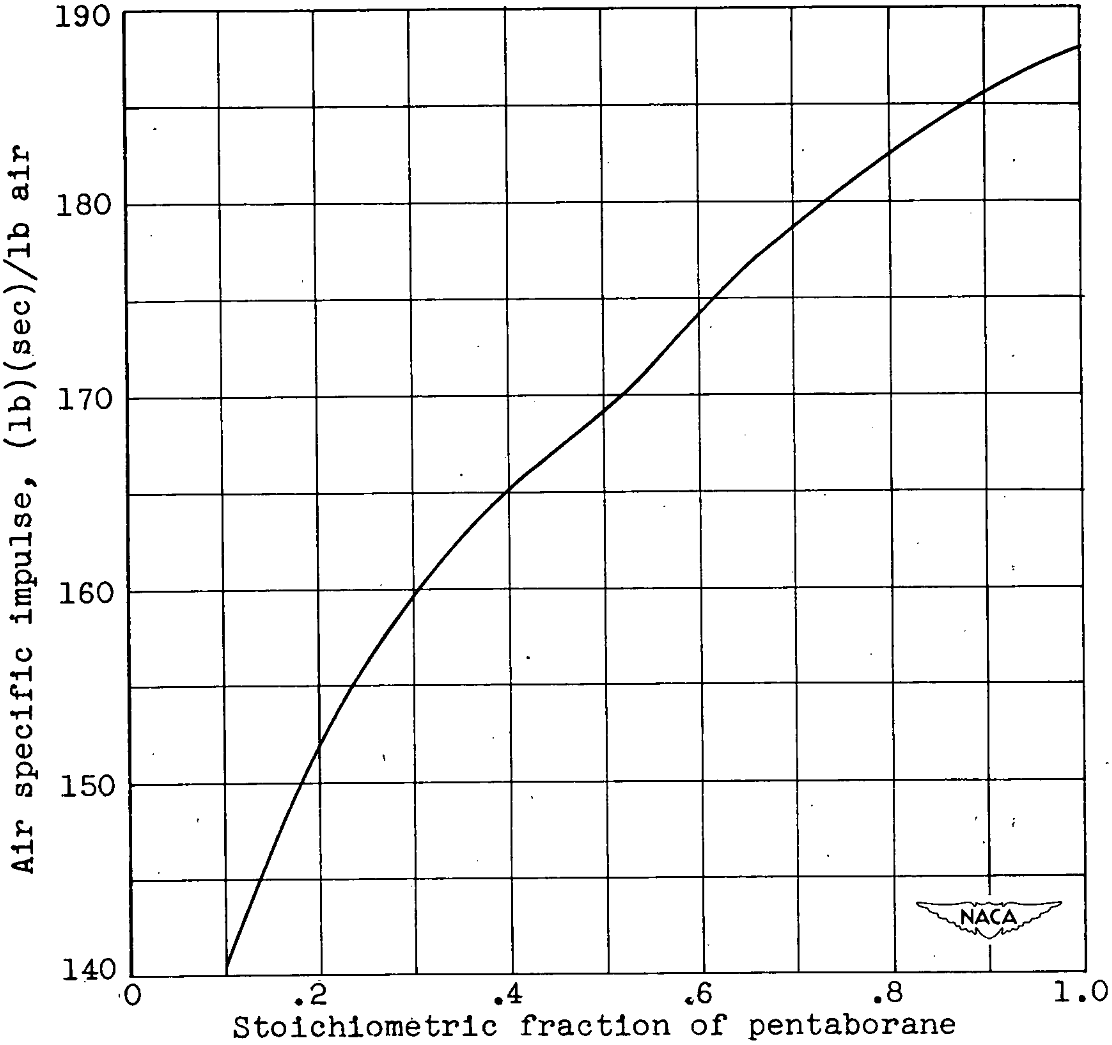
(d) Boron - octene-1 slurries; total stoichiometric fuel fraction fixed at 1.0.

Figure 1. - Concluded. Theoretical variation of combustion and nozzle-exit temperature with stoichiometric fraction of fuel. Combustor inlet-air temperature, 560° R; inlet-air pressure, 2 atmospheres; expansion ratio, 2.0.



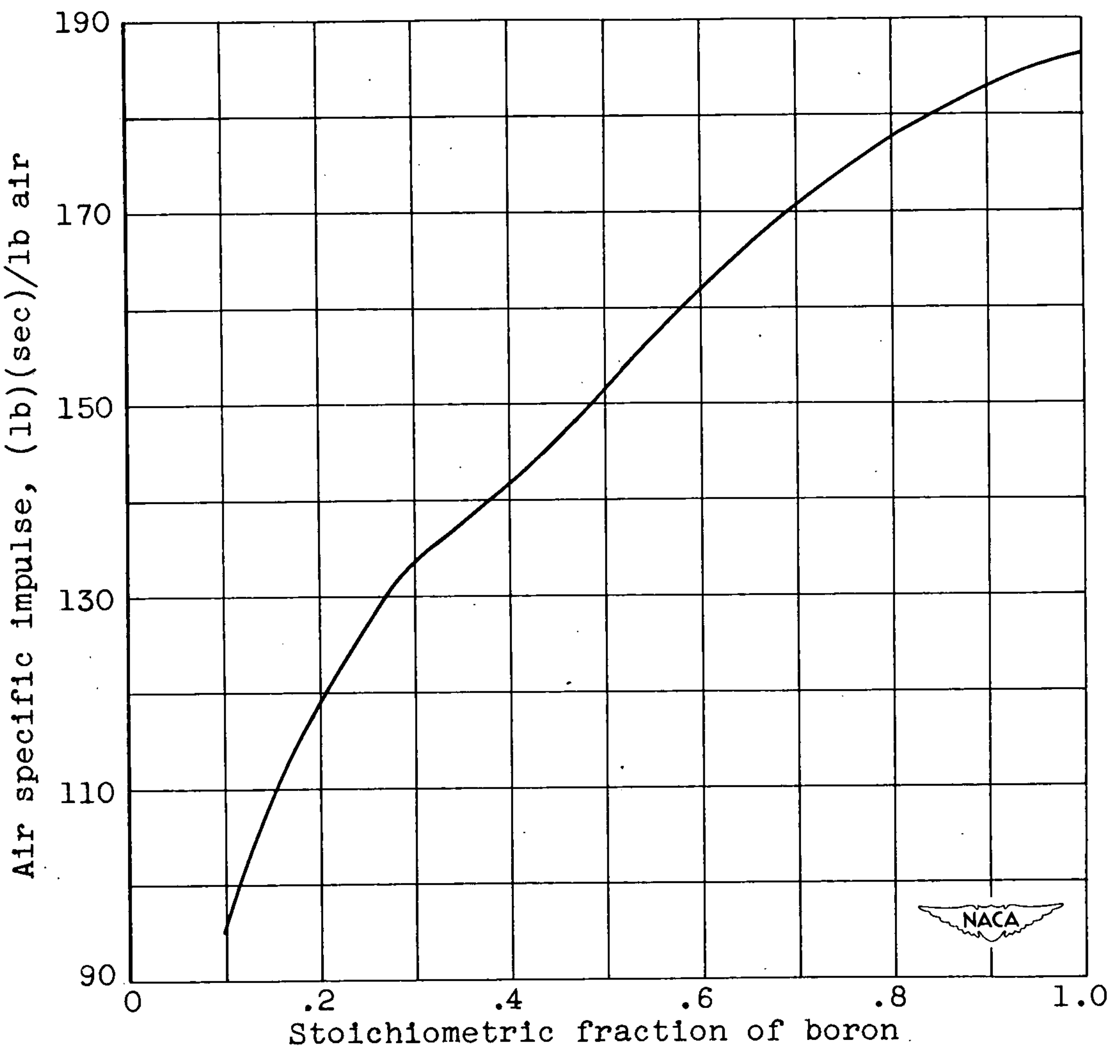
(a) Diborane.

Figure 2. - Variation of air specific impulse with stoichiometric fraction of fuel. Combustor inlet-air temperature, 560° R; inlet-air pressure, 2 atmospheres.



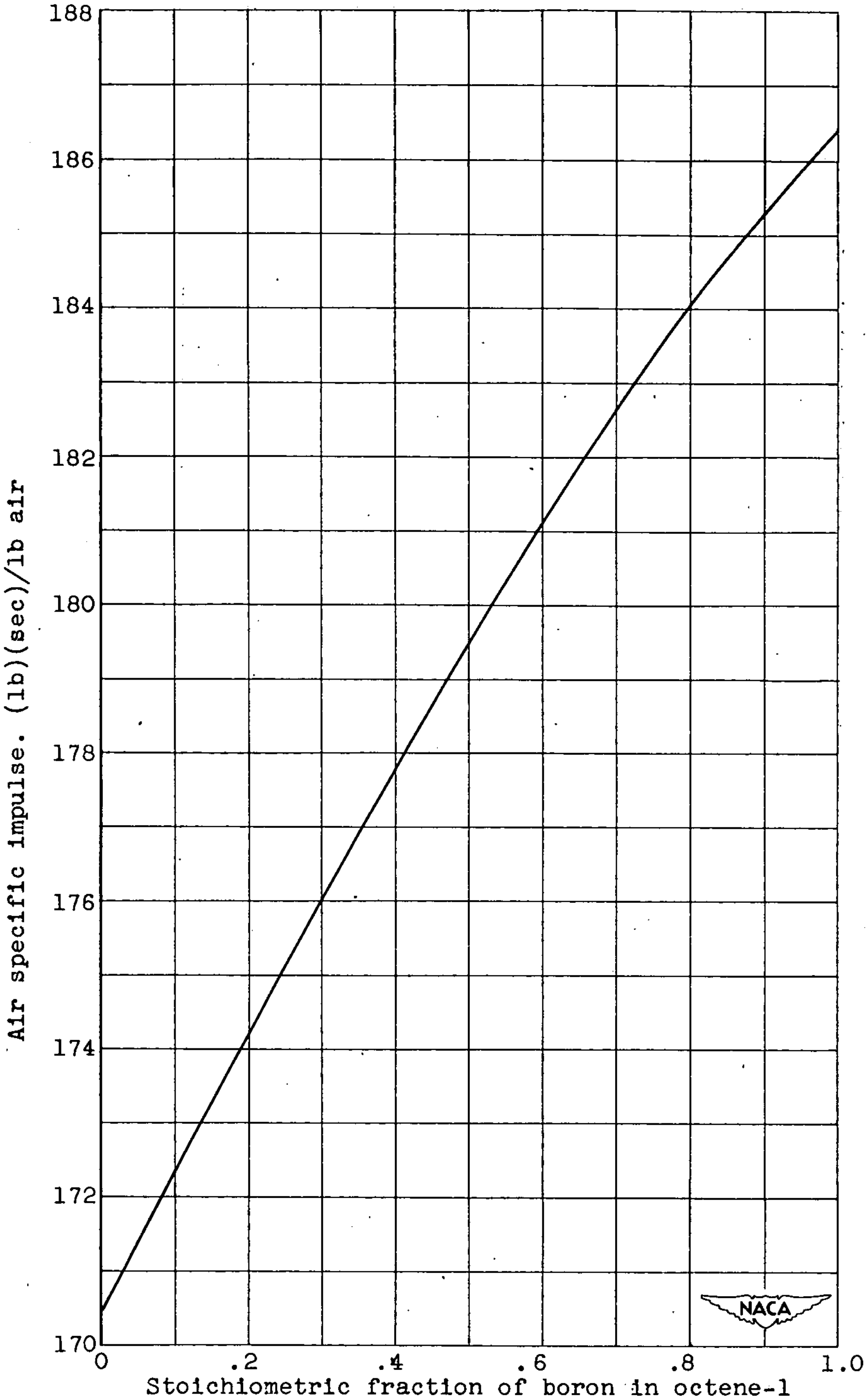
(b) Pentaborane.

Figure 2. - Continued. Variation of air specific impulse with stoichiometric fraction of fuel. Combustor inlet-air temperature, 560° R; inlet-air pressure, 2 atmospheres.



(c) Boron.

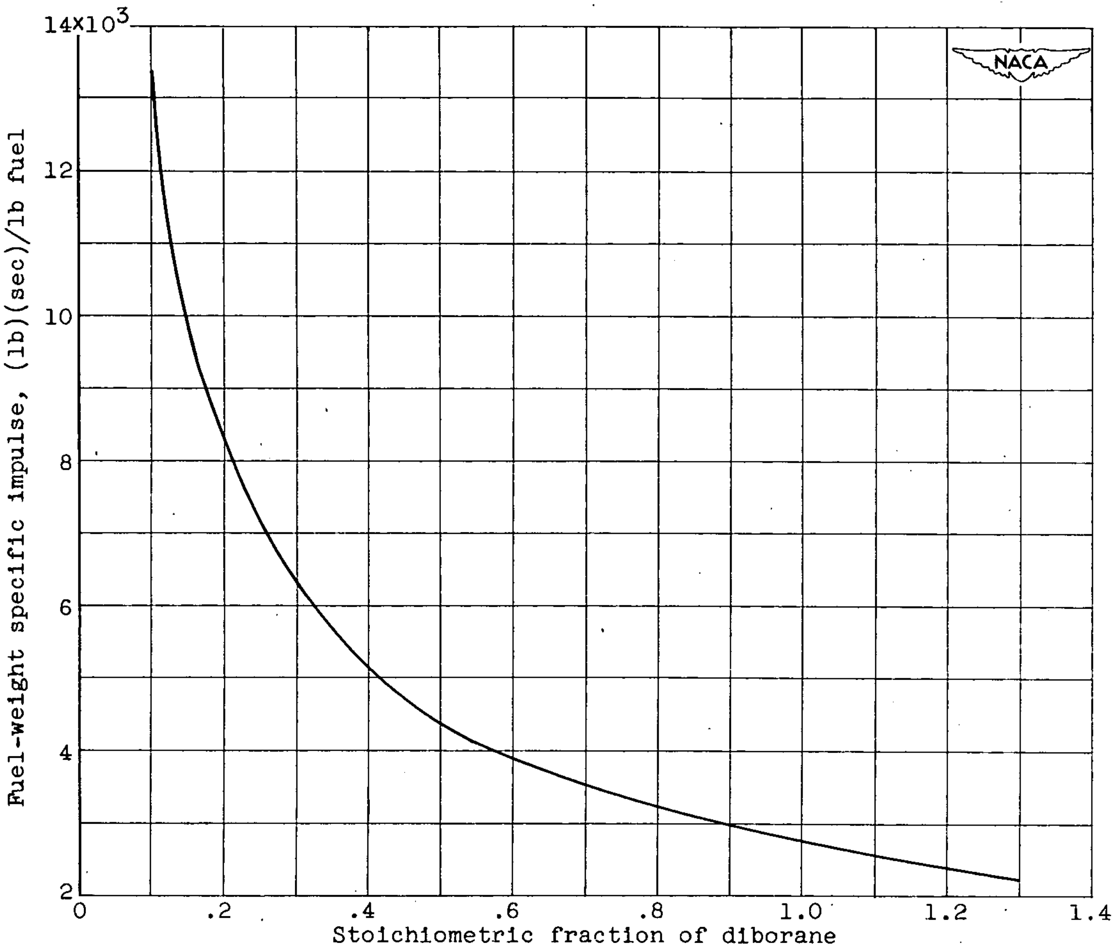
Figure 2. - Continued. Variation of air specific impulse with stoichiometric fraction of fuel. Combustor inlet-air temperature, 560° R; inlet-air pressure, 2 atmospheres.



(d) Boron - octene-1 slurries; total stoichiometric fuel fraction fixed at 1.0.

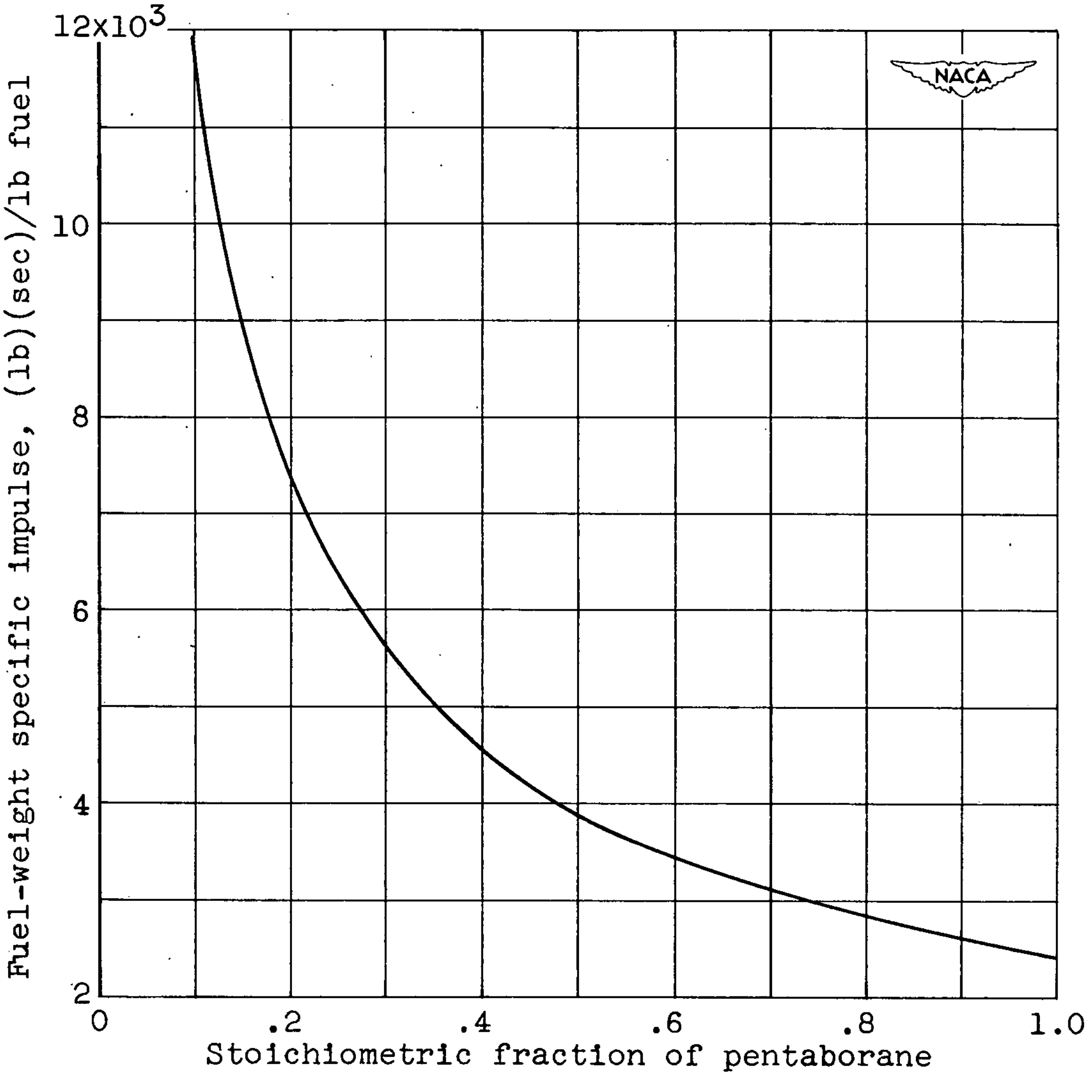
Figure 2. - Concluded. Variation of air specific impulse with stoichiometric fraction of fuel. Combustor inlet-air temperature, 560° R; inlet-air pressure, 2 atmospheres.

[redacted]



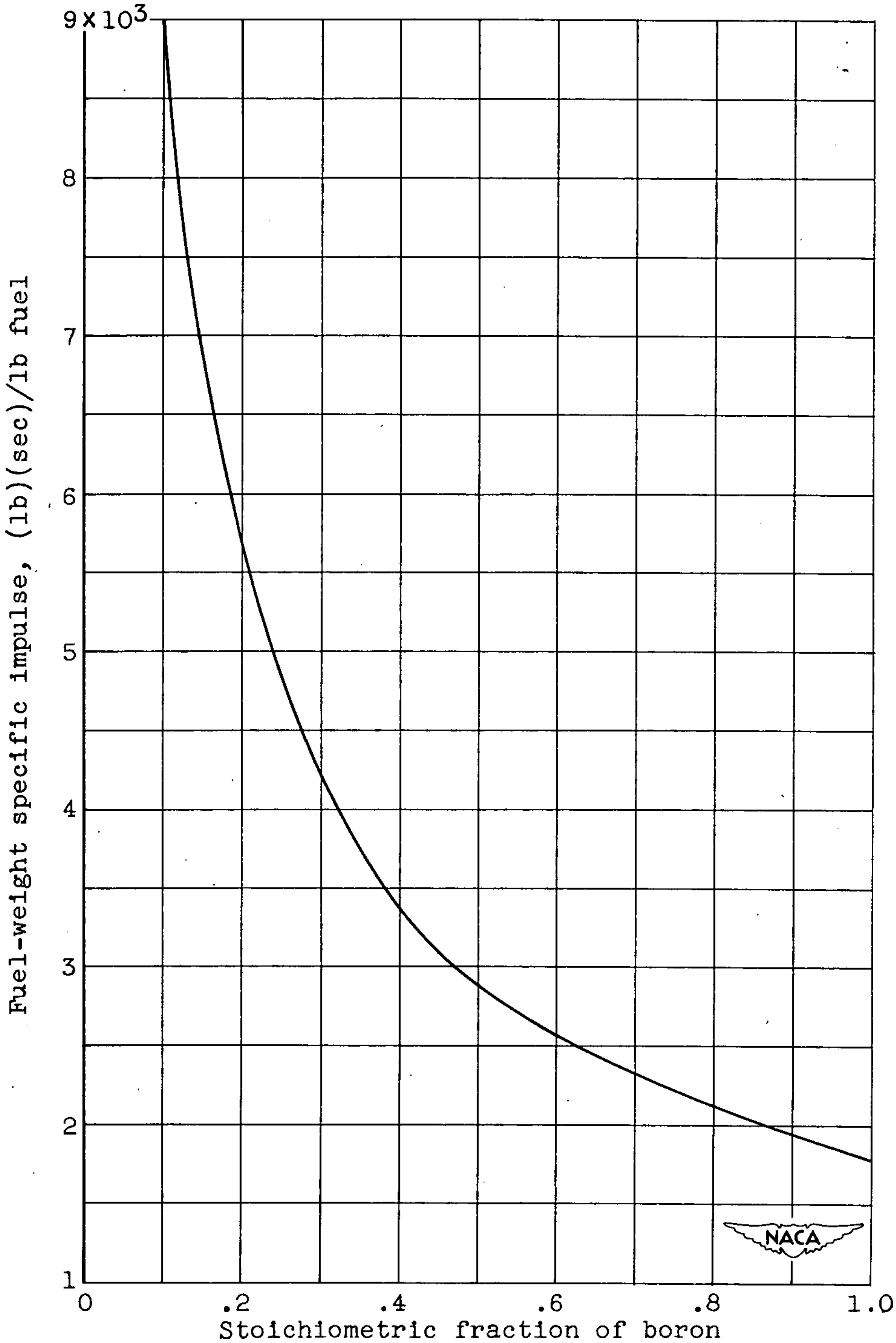
(a) Diborane.

Figure 3. - Variation of fuel-weight specific impulse with stoichiometric fraction of fuel. Combustor inlet-air temperature, 560° R; inlet-air pressure, 2 atmospheres.



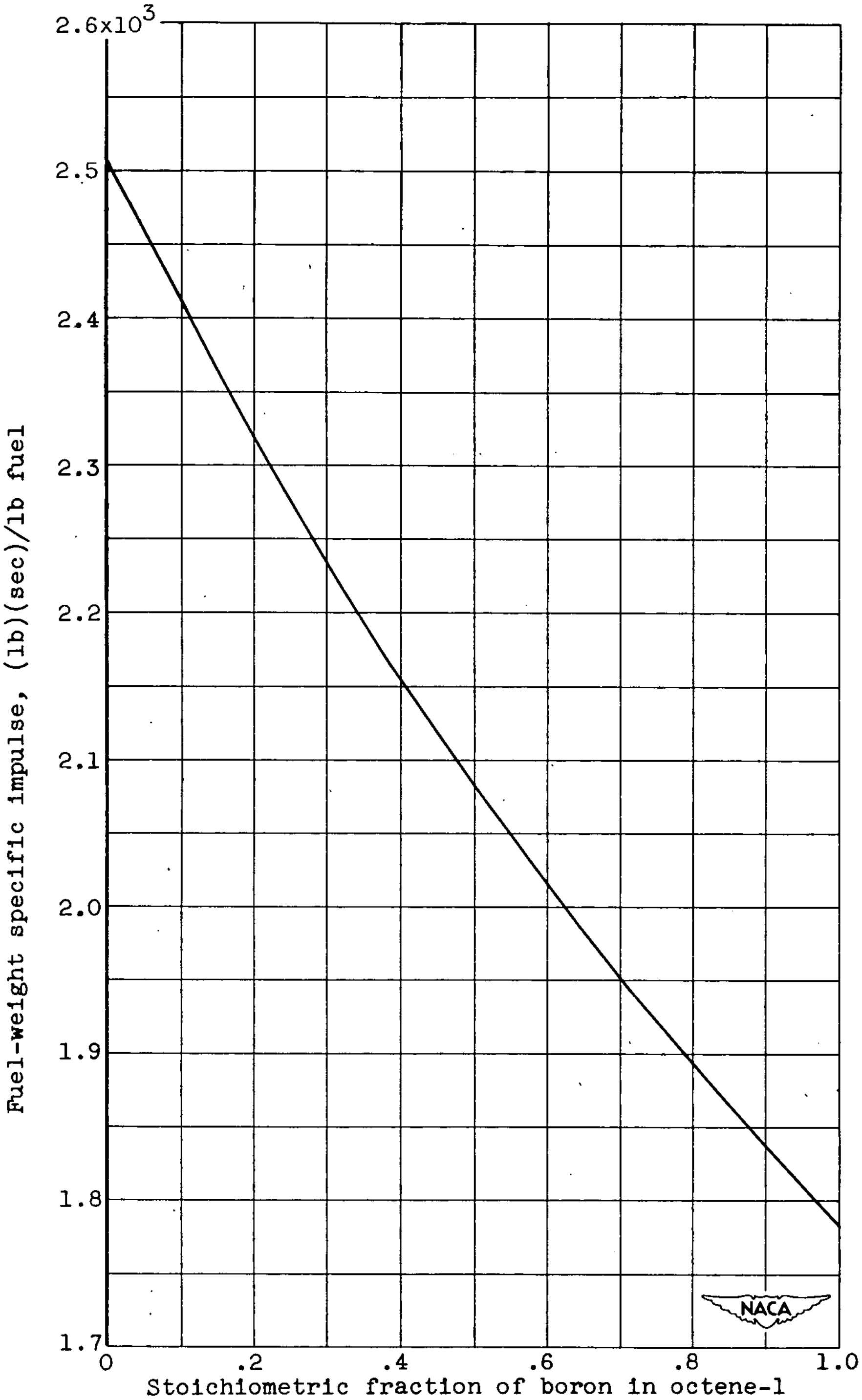
(b) Pentaborane.

Figure 3. - Continued. Variation of fuel-weight specific impulse with stoichiometric fraction of fuel. Combustor inlet-air temperature, 560° R; inlet-air pressure, 2 atmospheres.



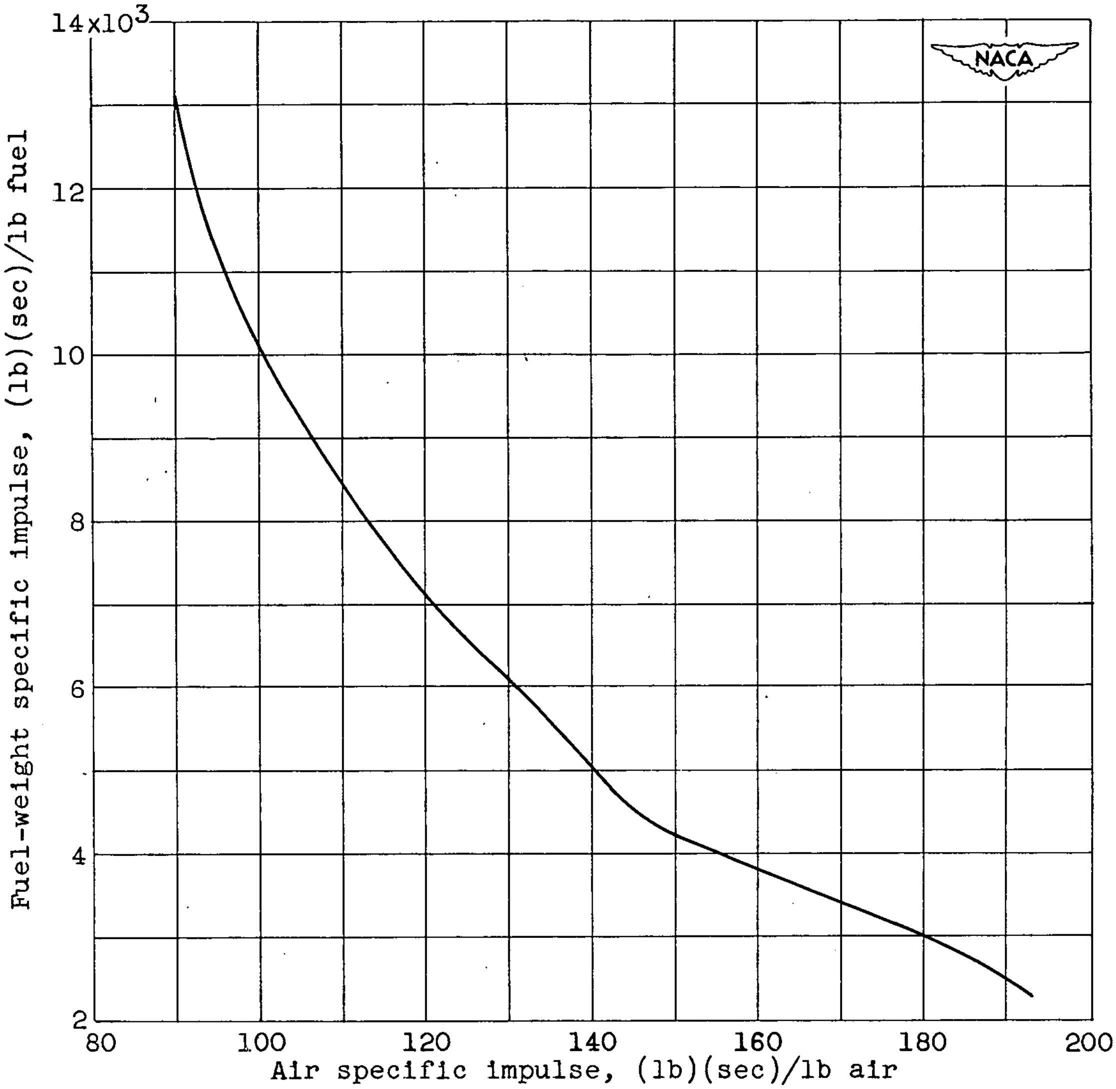
(c) Boron.

Figure 3. - Continued. Variation of fuel-weight specific impulse with stoichiometric fraction of fuel. Combustor inlet-air temperature, 560° R; inlet-air pressure, 2 atmospheres.



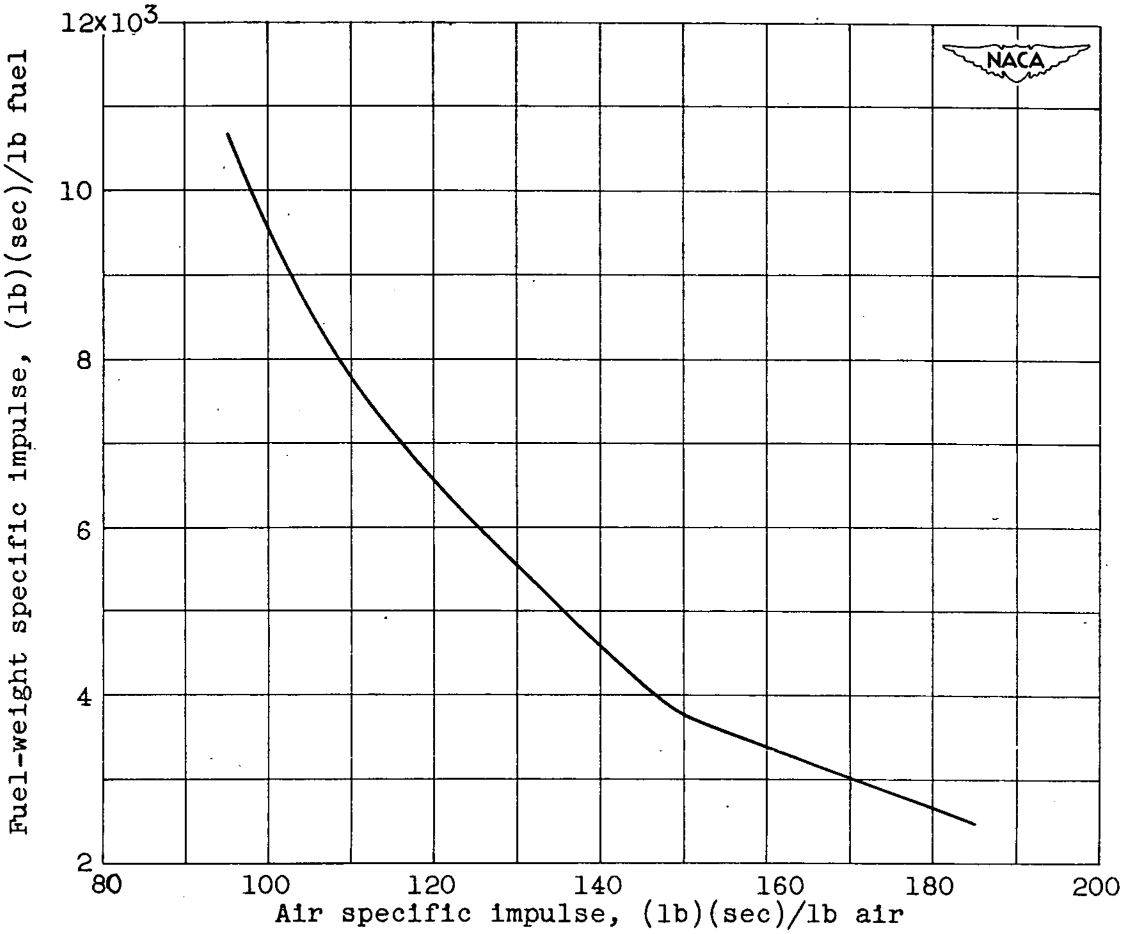
(d) Boron - octene-1 slurries; total stoichiometric fuel fraction fixed at 1.0.

Figure 3. - Concluded. Variation of fuel-weight specific impulse with stoichiometric fraction of fuel. Combustor inlet-air temperature, 560° R; inlet-air pressure, 2 atmospheres.



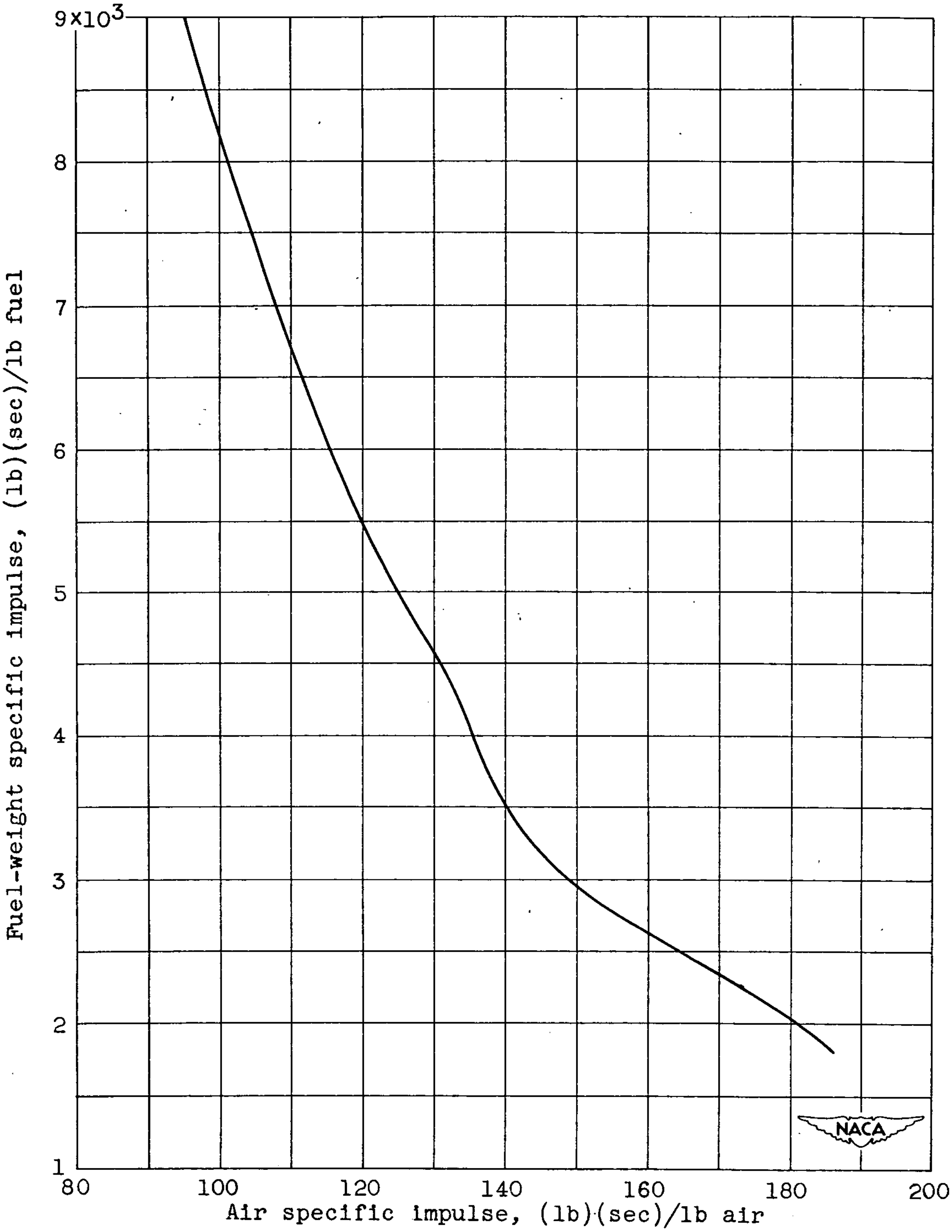
(a) Diborane.

Figure 4. - Variation of fuel-weight specific impulse with air specific impulse for several fuels. Combustor inlet-air temperature, 560° R; inlet-air pressure, 2 atmospheres.



(b) Pentaborane.

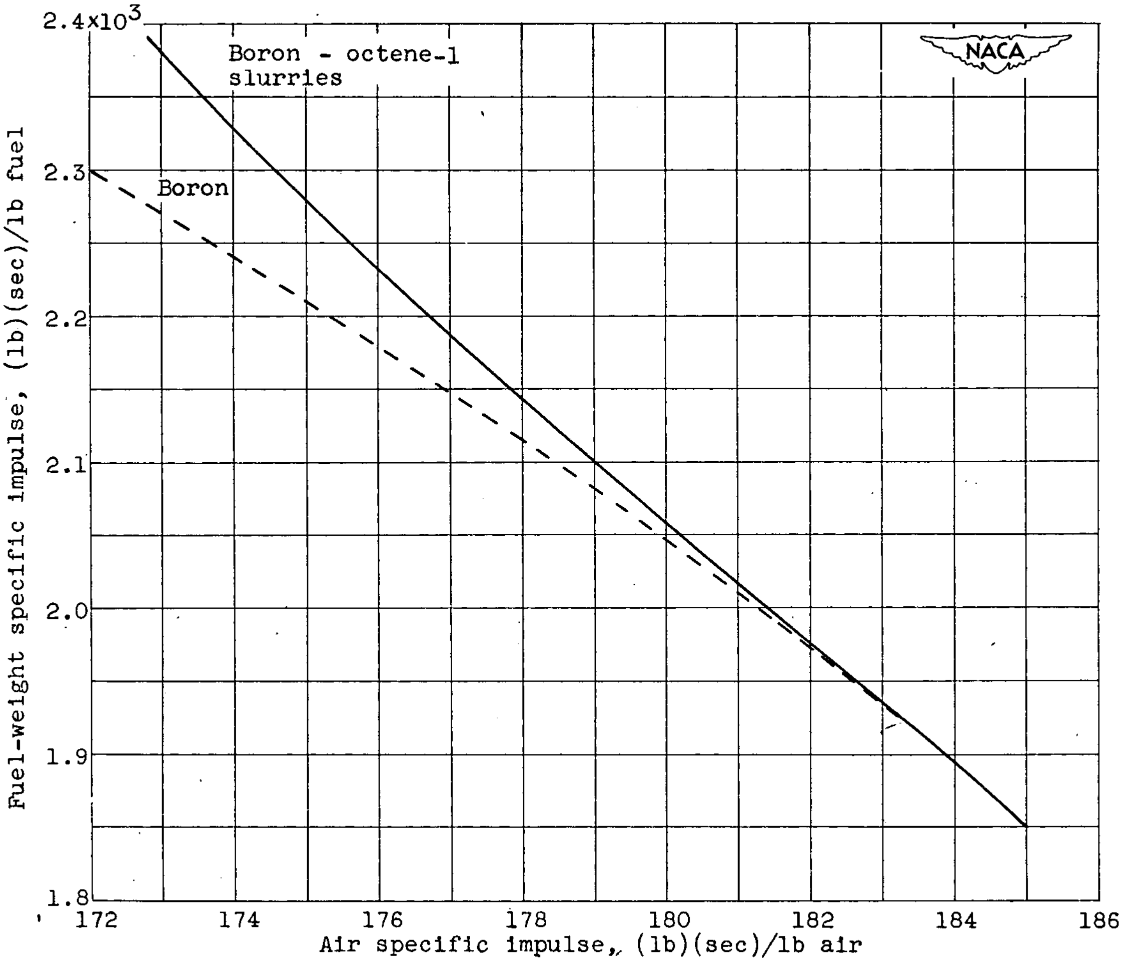
Figure 4. - Continued. Variation of fuel-weight specific impulse with air specific impulse for several fuels. Combustor inlet-air temperature, 560° R; inlet-air pressure, 2 atmospheres.



(c) Boron.

Figure 4. - Continued. Variation of fuel-weight specific impulse with air specific impulse for several fuels. Combustor inlet-air temperature, 560° R; inlet-air pressure, 2 atmospheres.

[redacted]



(d) Boron - octene-1 slurries; total stoichiometric fuel fraction fixed at 1.0.

Figure 4. - Concluded. Variation of fuel-weight specific impulse with air specific impulse for several fuels. Combustor inlet-air temperature, 560° R; inlet-air pressure, 2 atmospheres.

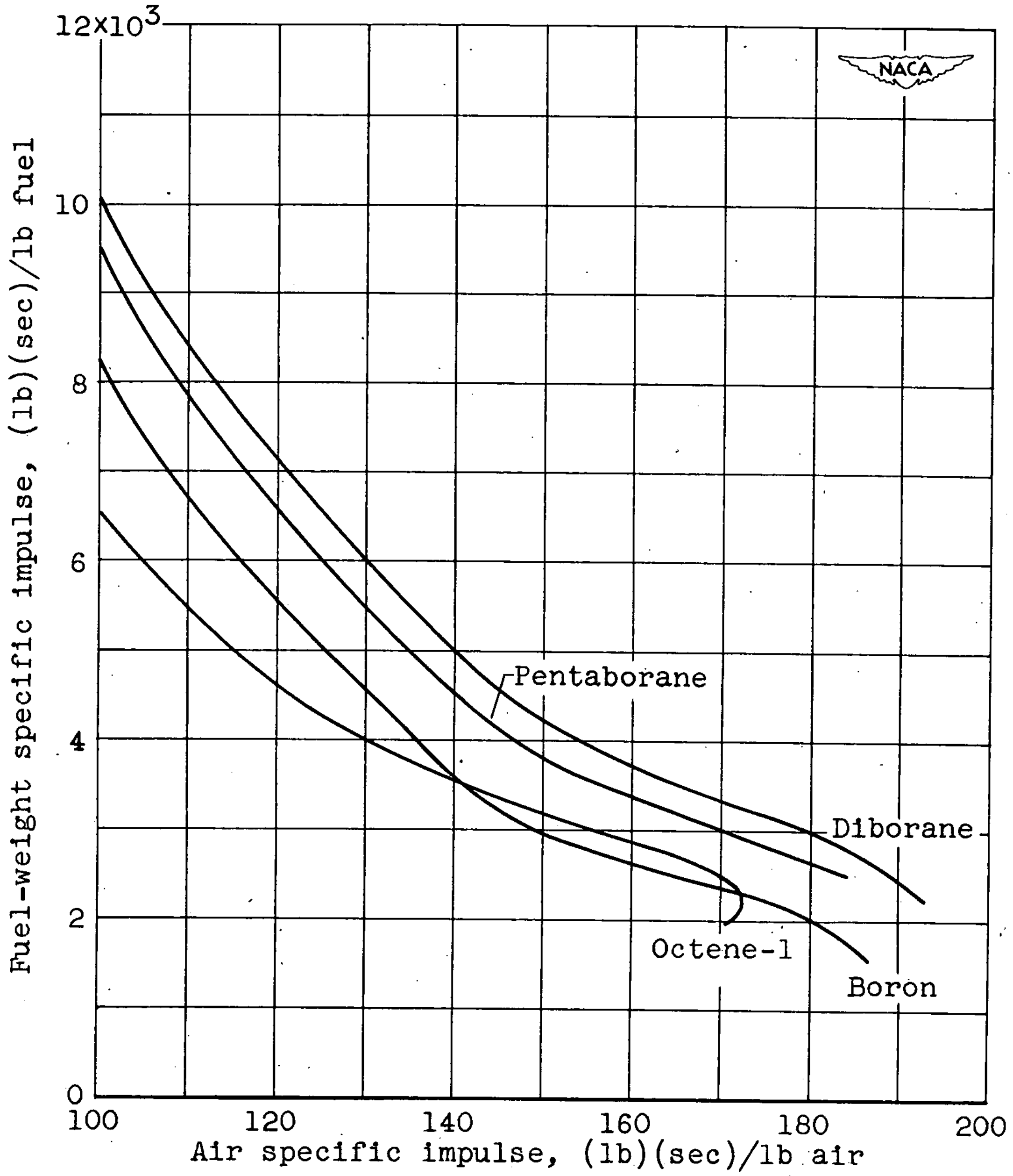


Figure 5. - Comparison of air- and fuel-weight specific impulse characteristics for diborane, pentaborane, boron, and octene-1.

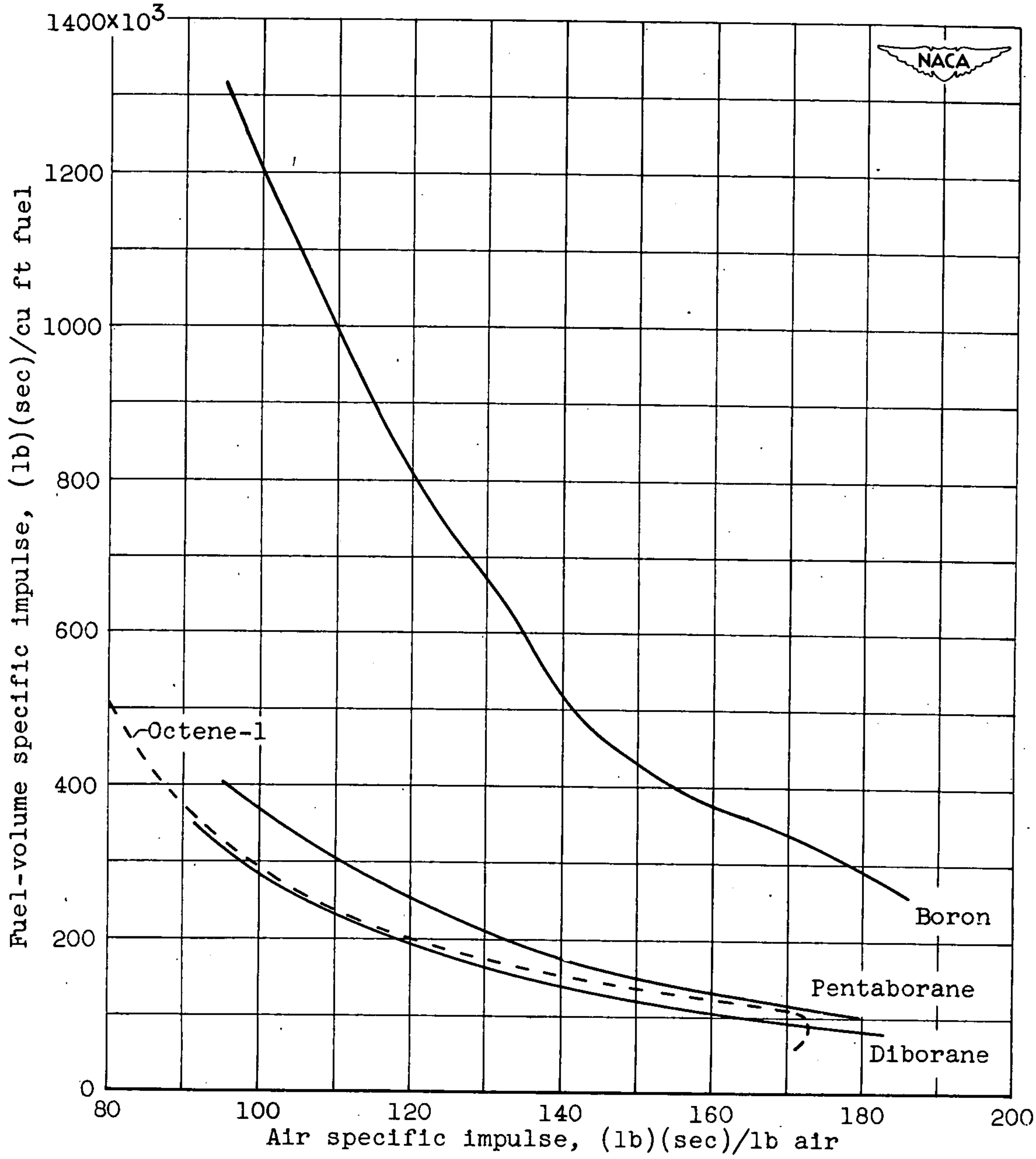


Figure 6. - Comparison of air- and fuel-volume specific impulse characteristics of diborane, pentaborane, boron, and octene-1.

[redacted]

[redacted]

[redacted]