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RESEARCH MEMORANDUM

ANALYTIC EVALUATION OF EFFECT OF INLET-AIR TEMPERATURE AND COMBUSTION PRESSURE ON COMBUSTION PERFORMANCE OF BORON SLURRIES AND BLENDS OF PENTABORANE IN OCTENE-1

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NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS
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SUMMARY

An analytic investigation of the theoretical combustion temperatures and the air-specific-impulse performance of slurries of boron in octene-1 and blends of pentaborane in octene-1 was conducted over a range of inlet-air temperatures, combustion pressures, equivalence ratios, and boron or pentaborane concentrations. Combustor inlet-air temperatures of 100°, 500°, and 900° F were considered at a combustion pressure of 2 atmospheres. A combustion pressure of 0.2 atmosphere was also considered at an inlet-air temperature of 100° F. Concentrations of boron or pentaborane in octene-1 varying from zero to 100 percent were considered. The air-specific-impulse data pertain to nozzle expansion at fixed composition. The effects of variation in inlet-air temperature, combustion pressure, and boron or pentaborane concentration on combustion performance were discussed.

Methods were devised for extrapolating or interpolating the data to inlet-air temperatures and combustion pressures other than those presented. Because of the vaporization of boric oxide, the data herein for combustion temperatures between 2400° and 3400° R and air specific impulse between 134 and 144 seconds are applicable only for a combustion pressure of 2 atmospheres. It was shown how the theoretical data herein could be employed in obtaining the combustion efficiency of experimental combustors. Likewise, it was shown how the relative consumption of boron slurries or pentaborane blends in various concentrations required for a fixed engine thrust level could be found. Data were presented by which combustion efficiencies obtained with a water-quench heat balance could be adjusted for the heat of dissociation of the combustion products.

INTRODUCTION

The demand for increased engine thrust or greater operating range in proposed aircraft has led to the consideration of special fuels for air-breathing engines. Fuels that promise gains in either jet thrust or range over conventional hydrocarbon fuels have become known

collectively as the high-energy jet-engine fuels. The suitability of some of these fuels for certain applications has been extensively investigated (refs. 1 to 4).

The theoretical combustion performance of a variety of high-energy fuels has been determined both as a guide in directing experimental research and as a means of evaluating the experimental data (refs. 5 and 6). In reference 5, the theoretical combustion performance of the high-energy fuels was considered over a range of fuel-air ratios for a single combustor inlet-air temperature and pressure. In reference 6, the theoretical combustion performance of many of these fuels was investigated over a range of inlet-air temperatures and pressures.

Two of the fuels investigated in these analytic studies, boron and pentaborane, have drawn attention because they offer gains over hydrocarbon fuels in fuel economy and aircraft range. The very high reactivity of pentaborane with air (ref. 4) has also directed interest toward new propulsive cycles and new combustor designs that have not been feasible with hydrocarbon fuels.

Because of the potentialities of both boron and pentaborane, the analytic investigation of their combustion performance over a range of inlet-air temperatures and combustion pressures (ref. 6) has been extended in the present report to include mixtures of any desired concentration of these materials in a hydrocarbon, octene-1.

Values of theoretical combustion temperature and air specific impulse are presented for a combustion pressure of 2 atmospheres, equivalence ratios from 0.1 to 1.0, and inlet-air temperatures of 100°, 500°, and 900° F. Combustion temperature and air-specific-impulse data are also shown for a combustion pressure of 0.2 atmosphere, an inlet-air temperature of 100° F, and equivalence ratios from 0.7 to 1.0. Charts are presented for extrapolating and interpolating to inlet-air temperatures and pressures other than those included in the calculations. The use of these charts in evaluating experimental data is shown.

ANALYTICAL METHODS

The combustion-temperature data reported herein were calculated by a method described in reference 7. Equations involving mass balance, heat balance, pressure, and chemical equilibriums of solid, liquid, and gaseous molecules were solved simultaneously. The necessary thermal data for the products of combustion were taken from tables in reference 7.

The determination of the combustion temperature was simplified by making the following assumptions: (1) All fuels were pure; (2) air was composed of 3.78 moles of nitrogen to every mole of oxygen; (3) combustor-outlet velocity was negligible so that the combustion static temperature

and the combustion total temperature were equal; (4) all gases were ideal; (5) combustion was adiabatic; (6) all products of combustion were in thermal and chemical equilibrium; and (7) the volume occupied by any solid or liquid combustion products was negligible.

Since the theoretical combustion-temperature data herein assume negligible combustor-outlet velocity, they may require adjustment before being compared with experimental data obtained in combustors having appreciable inlet or outlet velocities. In appendix B is discussed a method for making this adjustment.

In the following tabulation is presented the lower heat of combustion of each fuel component. From the heat of combustion, the enthalpy assigned to each fuel component was determined for use in the equations of heat balance:

Fuel	Formula	Phase	Lower heat of combustion,[a] ΔH_c, Btu/lb	Phase of combustion products	Enthalpy assigned, $(H_t^o)_f$, kcal/mole
Octene-1	C_8H_{16}	Liquid	[b]18,999	$(H_2O)_g$, $(CO_2)_g$	1263.28
Boron	B	Crystal	[c]25,104	$(B_2O_3)_{cr}$	173.38
Penta-borane	B_5H_9	Liquid	[c]29,127	$(H_2O)_g$, $(B_2O_3)_{cr}$	1187.18

[a]Both fuel and combustion products at 298.16° K.
[b]Heat of vaporization, 158 Btu/lb from ref. 8; heat of combustion of gaseous octene-1 from ref. 9.
[c]Computed from heat of formation in ref. 10.

Because the enthalpy assigned is consistent with the arbitrary base of the tables in reference 7, it gives no indication of the heat liberated in combustion.

The following substances were considered as possible combustion products in the computation of combustion temperature; they were gaseous except as noted:

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Fuel	Combustion product															
	O_2	N_2	CO_2	H_2O	H_2	CO	C	H	O	N	OH	NO	B_2O_3 (a)	B	BO	BH
Octene-1	x	x	x	x	x	x	x	x	x	x	x	x				
Boron	x	x							x	x		x	x	x	x	
Pentaborane	x	x		x	x			x	x	x	x	x	x	x	x	x
Pentaborane blends or boron slurries	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x

[a]Solid, liquid, and gas.

From the combustion temperature and conditions at the exhaust-nozzle throat, it is possible to compute a parameter that will express the theoretical thrust performance of the fuel. A suitable parameter that has been employed for both theoretical and actual jet-engine fuel performance is air specific impulse, or total stream momentum per pound of air, evaluated at the condition of sonic flow (symbols are defined in appendix A):

$$S_a = \frac{F^*}{w_a} = \frac{1}{w_a}\left(pA + \frac{wV}{g}\right)^* \tag{1}$$

where

$$w = w_a + w_f$$

or

$$S_a = \left(1 + \frac{w_f}{w_a}\right)\left[\frac{V^*}{g} + \frac{Rt^*}{V^*}(1 - X)\right] \tag{2}$$

Air specific impulse can also be expressed as

$$S_a = \left(1 + \frac{w_f}{w_a}\right)\sqrt{\frac{2(\bar{\gamma}+1)RT_3}{\bar{\gamma}g}(1 - X)} \tag{3}$$

where $\bar{\gamma}$ is an effective ratio of specific heats.

Another fuel performance parameter is fuel weight specific impulse, an index of fuel economy:

$$S_f = S_a \frac{w_a}{w_f} = \frac{1}{w_f}\left(pA + \frac{wV}{g}\right)^* \tag{4}$$

From the relation

$$F_{ni} = \varphi(M_5)\ w_a\ S_a - \left(pA + \frac{wV}{g}\right)_1 \tag{5}$$

the net internal thrust of an engine can be determined. The function $\varphi(M)$ relates stream thrust at any station to stream thrust at a station having a Mach number of unity (see appendix C). When the ratio p_5/P_3 or p_5/p_4 is specified for isentropic expansion within the nozzle, the value of M_5 can be determined as shown in appendix C.

An exhaust-nozzle-throat temperature t_4 was determined approximately by computing an isentropic expansion from the combustion temperature and pressure over a pressure ratio of 2. The following assumptions were made concerning the process of expansion in the nozzle: (1) Composition was fixed during expansion; (2) volume occupied by condensed materials was negligible; and (3) condensed materials were in thermal and velocity equilibrium with the gas phase. The following equation was then used to calculate the jet velocity V_4:

$$\frac{V_4}{g} = 294.98 \sqrt{\left(\frac{\Sigma n_i (H_t^o)_i}{\Sigma n_i m_i}\right)_3 - \left(\frac{\Sigma n_i (H_t^o)_i}{\Sigma n_i m_i}\right)_4} \tag{6}$$

The air specific impulse was then

$$S_a = \left(1 + \frac{w_f}{w_a}\right)\left[\frac{V_4}{g} + \frac{Rt_4}{V_4}(1 - X)\right] \tag{7}$$

Both the jet velocity V_4 and the exhaust-nozzle-outlet temperature t_4 determined for an expansion ratio of 2 differed slightly from those actually existing with sonic flow (V^* and t^*). The error introduced into the air specific impulse by assuming that the pressure ratio of 2 gave sonic flow was 0.5 percent or less (ref. 11). No correction was made to air specific impulse for this error.

The assumption of fixed or frozen composition during expansion results in values of air specific impulse which differ somewhat from those obtained by assuming chemical equilibrium during expansion. In appendix D, the performance resulting from expansion with fixed composition is compared with that obtained with equilibrium composition for a single fuel and inlet condition. The magnitude of the correction to air specific impulse for appreciable combustor-outlet velocity at a typical combustor-inlet condition is discussed in appendix B.

DISCUSSION

In figures 1 to 4 are presented the effects of combustor-inlet conditions on the theoretical combustion performance of the following fuels and fuel mixtures: octene-1, 30-percent-boron slurry, 60-percent-boron slurry, boron, 30-percent-pentaborane blend, 60-percent-pentaborane blend, and pentaborane.

Combustion Temperature

The variation in theoretical combustion temperature with equivalence ratio and inlet-air temperature for each of the fuels and fuel mixtures at a combustion pressure of 2 atmospheres is presented in figure 1. As can be seen in figure 1, there is a reduction in the rate of increase of combustion temperature as the equivalence ratio is increased. Also, the benefit to combustion temperature of an increase in inlet-air temperature diminishes at higher equivalence ratios. These effects are caused by increased specific heats and the presence of dissociated products at the higher temperatures. The inflection of the curves for the boron-containing fuels (figs. 1(b) to (g)) is due to the change of the boric oxide B_2O_3 from liquid to gaseous phase as the temperature is increased beyond approximately 3000° R.

The heat of combustion of boron has been redetermined since the beginning of this research program, which includes references 5 and 6 and the present report. In reference 12, a new value is given for the heat of formation of boric oxide, which results in a heat of combustion for boron of 25,382 Btu per pound. In the present report, however, an older heat of combustion of 25,104 Btu per pound has been used for boron in order to maintain consistency with previous NACA reports on the combustion performance of high-energy fuels for ram-jet engines. The combustion temperatures at equivalence ratios of 0.2 and 1.0, which result from the use of 25,382 Btu per pound for the heating value of boron, are shown in figure 1(d) for an inlet-air temperature of 100° F. At an equivalence ratio of 0.2, the combustion temperature is raised from 2405° to 2424° R by using 25,382 Btu per pound, and at an equivalence ratio of 1.0, from 5342° to 5365° R. The heating value for boron of 25,104 Btu per pound retained in this report thus gives combustion temperatures only a trifle lower than the temperature computed from more recent thermal data.

The variation in combustion temperature with combustion pressure for the various fuels and fuel blends at an inlet-air temperature of 100° F and equivalence ratios of 0.7, 0.8, 0.9, and 1.0 is presented on the semilogarithmic plots of figure 2. The data of figure 2 were calculated only for combustion pressures of 0.2 and 2 atmospheres. Straight lines of combustion temperature against the logarithm of combustion pressure

have been drawn between the points. In reference 13, it is shown that the theoretical impulse of a rocket, called V_e/g therein, varies nearly linearly with the logarithm of chamber pressure for fixed expansion ratios and fuel-oxidant ratios. The semilogarithmic relation is extended herein to combustion temperature against combustion pressure. As a check, additional combustion temperatures computed for octene-1 at combustion pressures of 0.6 and 10 atmospheres and an equivalence ratio of 1.0 are shown in figure 2(a). The data point at 0.6 atmosphere indicates that combustion temperature can be read quite accurately from the straight lines of combustion temperature against combustion pressure for combustion pressures between 0.2 and 2 atmospheres. When the straight line for an equivalence ratio of 1.0 was extended to 10 atmospheres pressure, an error in combustion temperature of 1/2 percent, or 20° R, resulted for octene-1. Linear extensions to pressures exceeding 2 atmospheres will therefore be less satisfactory in general than interpolation between 0.2 and 2 atmospheres.

It is shown in figure 2 that the combustion temperature decreases as the combustion pressure is lowered. Furthermore, the decrease in combustion temperature with decrease in combustion pressure is greatest at the higher equivalence ratios. A decrease in combustion pressure shifts the chemical equilibrium among the combustion products toward the condition of more dissociation. Since dissociation becomes greater at the higher temperatures, corresponding to higher equivalence ratios, the loss in combustion temperature with decrease in pressure becomes more pronounced.

The combustion temperature is also affected by the combustion pressure in the region of transition from liquid to gaseous boric oxide at about 3000° R. The region was investigated only at a pressure of 2 atmospheres, and no means of pressure adjustment was devised as was done for the higher equivalence ratios. The data in the region of boric oxide vaporization are directly applicable only for a combustion pressure of 2 atmospheres.

From the charts of figure 2, it is possible to determine the variation of combustion temperature with combustion pressure for inlet-air temperatures between 100° and 900° F. This determination is possible because combustion-product composition at a fixed combustion temperature is not greatly affected by the change in equivalence ratio resulting from the variation in inlet-air temperature between 100° and 900° F. For instance, the combustion temperature of pure boron at an equivalence ratio of 0.8, an inlet-air temperature of 800° F, and a combustion pressure of 0.3 atmosphere is sought. From figure 1(d), the combustion temperature at the conditions stated, but at a pressure of 2 atmospheres, is found to be 5250° R. This value is entered on figure 2(d) as point A, and a line of constant equivalence ratio is followed to a

pressure of 0.3 atmosphere (point B). The combustion temperature of 4980° R so determined agrees closely with the value of 4986° R found by direct computation.

Air Specific Impulse

The variation of theoretical air specific impulse with equivalence ratio and inlet-air temperature for each of the fuels and fuel mixtures at a combustion pressure of 2 atmospheres is shown in figure 3. Because air specific impulse is a function of combustion temperature (eq. (3)), the curves of figure 3 have forms similar to the curves of combustion temperature in figure 1. Comparison of the curves of air specific impulse against equivalence ratio for octene-1 (fig. 3(a)), 30-percent-boron slurry (fig. 3(b)), 60-percent-boron slurry (fig. 3(c)), and boron (fig. 3(d)) shows that, as boron concentration in the slurry is raised, the thrust performance increases at any inlet-air temperature and equivalence ratio. Similarly, in figures 3(e) (30-percent-pentaborane blend), 3(f) (60-percent-pentaborane blend), and 3(g) (pentaborane) it may be seen that raising the concentration of pentaborane in a blend increases the air specific impulse or thrust performance.

The variation of air specific impulse with combustion pressure is presented for the fuels and fuel mixtures on the semilogarithmic plots of figure 4 at an inlet-air temperature of 100° F and equivalence ratios of 0.7, 0.8, 0.9, and 1.0. Calculated air specific impulses in figure 4(a) for octene-1 at an equivalence ratio of 1.0 and pressures of 0.2, 0.6, and 2.0 atmospheres are fitted well by a straight line; the same line extended to 10 atmospheres gives an impulse which is 0.6 second or 0.35 percent higher than the computed value. The remaining data of figure 4 were computed only for combustion pressures of 0.2 and 2 atmospheres. It is apparent that linear extensions to pressures exceeding 2 atmospheres will be less satisfactory, in general, than interpolation between 0.2 and 2.0 atmospheres.

The charts of figure 4 can be used to determine the variation of air specific impulse with combustion pressure at inlet-air temperatures other than 100° F. Some examples for boron are presented in reference 6.

APPLICATION OF DATA

Determination of Combustion Temperature and Air Specific Impulse over a Wide Range of Conditions

The curves of figures 1 to 4 pertain to fixed concentrations of boron or pentaborane in octene-1. In many instances requiring the use of these data to predict engine performance or to evaluate experimental data, mixture concentrations other than those of figures 1 to 4 may

be considered. Means of interpolating and extrapolating the data readily to a wide range of mixture concentrations and combustor-inlet conditions are therefore presented.

In figure 5 is shown the effect of boron concentration and ram-jet combustor-inlet conditions on the theoretical combustion performance of boron slurries in such a manner as to facilitate the interpolation and extrapolation. In figure 5(a), combustion temperature is presented as a function of boron concentration for a range of equivalence ratios, inlet-air temperatures of 100°, 500°, and 900° F, and a pressure of 2 atmospheres. Simple linear interpolation to other inlet-air temperatures may be used, or for higher accuracy, the interpolation chart on the right may be employed as shown by the following example: The combustion temperature of a 50-percent-boron slurry is desired at an inlet-air temperature of 750° F, an equivalence ratio of 0.8, and a pressure of 2 atmospheres. The combustion temperatures at inlet-air temperatures of 100°, 500°, and 900° F are found to be 4250°, 4460°, and 4650° R, respectively. These values, entered in the interpolation chart as circled points on the proper vertical lines of inlet-air temperature, are connected by a faired curve. From this curve, a combustion temperature of 4580° R is determined for the condition stated. For this example, linear interpolation would have been satisfactory. At many conditions, it is essential that the interpolation chart be used because the variation of combustion temperature with inlet-air temperature is decidedly nonlinear.

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The combustion-temperature data of figure 5(a) for a combustion pressure of 2 atmospheres may be adjusted to other combustion pressures through the use of figure 5(b). Lines of combustion temperature against combustion pressure may be constructed on the semilogarithmic portion of figure 5(b) for a boron slurry of any concentration by means of the border chart on the right. For example, the combustion temperature of a 50-percent-boron slurry at an equivalence ratio of 0.8, an inlet-air temperature of 750° F, and a combustion pressure of 0.5 atmosphere is sought. At these conditions, but at a pressure of 2 atmospheres, a combustion temperature of 4580° R was found in the previous example. This is entered on figure 5(b) as point A. Point B is located on the border chart, along the 4580° R line at 50-percent-boron concentration. The line AB connecting these points is extended to a pressure of 0.5 atmosphere, determining point C, where the combustion temperature sought is found to be 4470° R.

In figure 5(c) is presented the variation of air specific impulse with equivalence ratio, concentration of boron in the slurry, and inlet-air temperature for a combustion pressure of 2 atmospheres. By means of figure 5(d), the air-specific-impulse data of figure 5(c) for 2 atmospheres combustion pressure can be adjusted to other combustion pressures. Figures 5(c) and (d) are read in the same manner as figures 5(a) and (b), respectively.

Figure 6 consists of a series of charts for pentaborane blends similar to those of figure 5 for boron slurries. A continuation of figure 6(a) (variation of combustion temperature with equivalence ratio, pentaborane concentration, and inlet-air temperature) is greatly expanded to improve the accuracy of reading temperatures below 2500° R. Likewise, a continuation of figure 6(c) (variation of air specific impulse with equivalence ratio, pentaborane concentration, and inlet-air temperature) has been enlarged to enable more accurate reading of low values of air specific impulse. In the continuations of both figures 6(a) and (c), the combustion temperatures are sufficiently low that neither dissociation of the combustion products nor vaporization of boric oxide is appreciable at combustion pressures at least down to 0.2 atmosphere. The curves of the expanded portions of figures 6(a) and (c) can therefore be employed for all combustion pressures exceeding 0.2 atmosphere without an adjustment for pressure.

The transition of boric oxide from liquid to gas at combustion temperatures between 2400° and 3400° R, or air specific impulse between 124 and 134 seconds, is affected by pressure. Since the data of figures 5 and 6 were determined only for 2 atmospheres pressure in this region, they are not directly applicable for other pressures within this range of temperatures.

Determination of Combustion Efficiency

Curves presented herein permit the determination of a combustion efficiency which is often useful in the evaluation of experimental data. It is defined as the ratio of the theoretical to the experimental equivalence ratio required to produce a given air specific impulse:

$$\eta = \left(\frac{\Phi_{th}}{\Phi_{exp}}\right) \quad \text{for the same air specific impulse} \qquad (8)$$

Fuel-air ratios may replace equivalence ratios. This definition is valid only for equivalence ratios of 1.0 or less. The determination of experimental air specific impulse is discussed in appendix C. In addition to thermal losses, this efficiency includes losses due to friction and nonuniform temperature and velocity distribution. When the experimental data are obtained at pressures other than 2 atmospheres and at temperatures above the region of vaporization of boric oxide, the theoretical equivalence ratio needed to produce the experimental air specific impulse S_a may be found by the use of figure 5(d) for boron and 6(d) for pentaborane. Assume, for example, that a 50-percent-boron slurry burned at an inlet-air temperature of 500° F, a combustion pressure of 0.5 atmosphere, and an equivalence ratio of 1.0 produces an experimental air specific impulse of 170 seconds. This value of air specific impulse is entered in figure 5(d) as point A. It is then necessary to find the air specific impulse at 2 atmospheres pressure that has the same theoretical equivalence ratio. Lines of constant but unspecified equivalence ratio are constructed for the 50-percent-boron slurry adjacent to point A. With these lines as

a guide, a line is extended from point A to point B at 2 atmospheres. The air specific impulse of 171.5 seconds at 2 atmospheres has the same theoretical equivalence ratio as 170 seconds at 0.5 atmosphere. When an air specific impulse of 171.5 seconds is entered in figure 5(c) for an inlet-air temperature of 500° F and a boron concentration of 50 percent, this theoretical equivalence ratio is found to be 0.81. The combustion efficiency is then 0.81 from equation (8).

It is also possible to find point B on figure 5(d) by the trial-and-error construction of line ABC. This method eliminates the construction of adjacent constant equivalence ratio lines.

In some instances, a combustion temperature may be determined from experimental data. This experimental combustion temperature can be used to determine combustion efficiency by a method analogous to that employing the experimental air specific impulse. The combustion efficiency is defined as:

$$\eta = \frac{\Phi_{th}}{\Phi_{exp}} \text{ for the same } (t_3)_{M_3=0} \tag{9}$$

Equation (9) may give a value of combustion efficiency which differs slightly from that yielded by equation (8), when both experimental combustion temperature and air specific impulse are available for a particular engine. When combustion efficiencies are reported, the definition used should be stated.

Determination of Relative Fuel-Consumption Requirements for a Given Engine

In many cases, it is of interest to know relative amounts of various boron slurries or pentaborane blends needed to obtain a given level of air specific impulse. This can be determined by means of air-specific-impulse data in figures 5 and 6 provided that the following assumptions are made: The combustion efficiency is the same and the pressure losses in the combustor are the same for all fuels at the same thrust level.

By the method outlined in the preceding section, the theoretical equivalence ratios of octene-1, boron slurries, and pentaborane blends giving the same level of thrust at any specified conditions of inlet-air temperature and combustion pressure can be found. These equivalence ratios can be converted to fuel-air ratios by means of the following expression:

$$w_f/w_a = \Phi(w_f/w_a)_{sto} \tag{10}$$

Curves of the stoichiometric fuel-air ratio $(w_f/w_a)_{sto}$ for pentaborane blends and boron slurries are presented in figure 7.

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The following table compares the relative flow rates required with a few typical fuels to produce an air specific impulse of 157.6 seconds at an inlet-air temperature of 100° F and pressure of 0.6 atmosphere:

Fuel	Theoretical equivalence ratio	Theoretical fuel-air ratio	Relative fuel consumption
Octene-1	0.8	0.0542	1.00
50-Percent-boron slurry	.69	.0568	1.05
50-Percent-pentaborane blend	.69	.0496	.915
Pentaborane	.6	.0458	.845

These results pertain to expansion at fixed composition and differ from the values that would be computed for expansion at equilibrium composition. At the level of air specific impulse chosen, the use of 50-percent-boron slurry results in an increase in fuel consumption, while the use of either 50-percent-pentaborane blend or pure pentaborane decreases fuel consumption materially. Reductions in fuel consumption through the use of boron slurry can be obtained only at lower levels of thrust, as discussed in references 5 and 6.

As an additional example, the data of figure 6 have been used in determining the ideal consumption of pentaborane relative to that of octene-1 required to obtain a given air specific impulse. Combustion pressures of 0.2 and 2 atmospheres were considered over a range of air specific impulse at an inlet-air temperature of 100° F. The results are shown in figure 8 as consumption of pentaborane relative to octene-1 against air specific impulse. The combustion temperature of octene-1 and pentaborane required to obtain any value of air specific impulse may be determined from additional abscissa scales. Data for pentaborane are not available from figure 6 at pressures other than 2 atmospheres in the range from about 2200° to 3400° F. Additional computations were therefore made for the burning of pentaborane at a pressure of 0.2 atmosphere in this region of combustion temperature.

At the very low air specific impulse of 87.5 seconds, the consumption of pentaborane relative to that of octene-1 is 0.667, whereas the inverse ratio of their heats of combustion is 18,999/29,127, or 0.652. It is apparent that a satisfactory comparison of the relative consumptions of fuels can be made at very low temperatures by comparing their lower heats of combustion.

The consumption of pentaborane relative to octene-1 rises as the level of air specific impulses is increased. At an air specific impulse of 120 seconds and a pressure of 0.2 atmosphere, the flow of pentaborane relative to octene-1 rises sharply because heat is absorbed by vaporization of the boric oxide. A combustion pressure of 2 atmospheres suppresses the vaporization of boric oxide so that the curve for this pressure rises less steeply. When all the boric oxide has vaporized, at an air specific impulse of 134 seconds for 0.2 atmosphere pressure or 144 seconds for 2 atmospheres pressure, the relative consumption of pentaborane is about 0.84. It declines slightly from this value with a further increase in air specific impulse.

It may be seen from figure 8 that the heating value of a fuel is an unsatisfactory index of fuel consumption at elevated temperatures or thrust levels because of marked differences in the thermal properties of combustion products. In the region where boric oxide begins to vaporize, the relative consumption of pentaborane is markedly affected by combustion pressure.

Adjustment of Combustion Efficiency Data from Heat Balance

A commonly used method of determining combustion efficiency is that of establishing heat balance. Water is sprayed into the hot exhaust gases in a quantity sufficient to cool them to temperatures of a few hundred degrees Fahrenheit. The enthalpy rise of the mixture of water and combustion products can be expressed as shown in reference 14 as

$$\Delta H_o = \Delta H_w + \Delta H_e + \Delta H_j \tag{11}$$

where

ΔH_o enthalpy rise (heat output), Btu/lb mixture

ΔH_w enthalpy rise of quench water, Btu/lb mixture

ΔH_e enthalpy rise of combustion mixture, Btu/lb mixture

ΔH_j enthalpy rise of jacket coolant, Btu/lb mixture

In reference 14, it is shown that the rapid quenching of the combustion products by the water froze the composition of the combustion products. The dissociation enthalpy was not recovered in the measured sensible enthalpy ΔH_o of the mixture. The combustion efficiencies were consequently too low when computed from the expression

$$\eta = \frac{(1 + w_f/w_a)\ \Delta H_o}{(w_f/w_a)\ \Delta H_c} \tag{12}$$

It was found that these combustion efficiencies could be adjusted by subtracting the energy required for dissociation of the combustion products from the heating value of the fuel. The equation for combustion efficiency then became

$$\eta = \frac{(1 + w_f/w_a)\,\Delta H_o}{(w_f/w_a)\,\Delta H_c\,(1 - x)} \qquad (13)$$

The energy required for dissociation was expressed as a fraction x of the fuel heating value. If quenching has not completely frozen the composition, the efficiency calculated from equation (13) will be in error by an amount dependent upon the change in composition during the quench.

Figure 9 presents the effect of boron concentration and combustor-inlet condition on the quantity x for boron slurries. In figure 9(a) is shown the variation of x with concentration of boron in a boron slurry at three inlet-air temperatures and a combustion pressure of 2 atmospheres for a range of equivalence ratios. Values of x for intermediate temperatures can be interpolated linearly. The data of figure 9(a) for a combustion pressure of 2 atmospheres can be adjusted to other combustion pressures by means of figure 9(b), which is read in the same manner as figure 5(b).

In figure 10 is shown the effect of pentaborane concentration and combustor-inlet conditions on the quantity x for pentaborane blends.

CONCLUDING REMARKS

The effect of inlet-air temperature, combustion pressure, and equivalence ratio upon the theoretical combustion temperature and air-specific-impulse performance was investigated for boron slurry fuels and pentaborane blends. Concentrations of boron or pentaborane in octene-1 varying from zero to 100 percent were considered. Inlet-air temperatures ranged from 100° to 900° F at a combustion pressure of 2 atmospheres. A combustion pressure of 0.2 atmosphere was also investigated at an inlet-air temperature of 100° F. It was assumed in computing air specific impulse that expansion in the nozzle occurred at fixed composition. The effects on combustion performance of variation in inlet-air temperature, combustion pressure, and boron or pentaborane concentration were observed.

Means were presented for extrapolating or interpolating the data to conditions of inlet-air temperature and combustion pressure other than those investigated. Because of the vaporization of boric oxide, the data herein for combustion temperatures between 2400° and 3400° R and air specific impulse between 134 and 144 seconds are applicable only for a combustion pressure of 2 atmospheres. The determination of combustion efficiency for experimental combustors by means of theoretical data herein was

described. A method was discussed for determining the relative amounts of fuels containing various concentrations of boron or pentaborane required by an engine operating at a fixed thrust level. Also presented were data enabling an adjustment for the heat of dissociation to be applied to combustion efficiency data obtained by a water-quench heat balance.

Lewis Flight Propulsion Laboratory
National Advisory Committee for Aeronautics
Cleveland, Ohio, February 2, 1955

APPENDIX A

SYMBOLS

The following symbols are used in this report:

A	area, sq ft
F	stream thrust, lb
F_{ni}	net internal thrust, lb
g	acceleration due to gravity, 32.17 ft/sec^2
H_t^o	sum of sensible enthalpy and chemical energy at temperature t and at standard conditions, kcal/mole
ΔH_c	lower heating value of fuel, Btu/lb
h_T	sum of sensible enthalpy and chemical energy at total temperature T, Btu/lb
$(h_t)_3$	sum of sensible enthalpy and chemical energy of combustion products at static temperature t_3, Btu/lb
J	mechanical equivalent of heat, 778.16 (ft)(lb)/Btu
KE	kinetic energy, Btu/lb air
M	Mach number
m	molecular weight of a constituent
$\overline{m}_g$	mean molecular weight of gas mixture, exclusive of condensed B_2O_3
n	number of moles of a constituent
P	total pressure, lb/sq ft
p	static pressure, lb/sq ft
R	universal gas constant, $1545.33/\overline{m}_g$, (ft)(lb)/(lb)(^oR)
S_a	air specific impulse, (lb)(sec)/lb air
S_f	fuel weight specific impulse, (lb)(sec)/lb fuel

T	total temperature, ^{o}R
t	static temperature, ^{o}R
V	velocity, ft/sec
w	weight flow, lb/sec
X	weight fraction of solids or liquids in exhaust gases
x	fraction of fuel heating value required for dissociation
γ	ratio of specific heats
η	combustion efficiency
Φ	equivalence ratio; ratio of actual to stoichiometric fuel-air ratio
$\varphi(M)$	stream-thrust correction to $M = 1$

Subscripts:

a	air
cr	crystalline
exp	experimental
f	fuel
g	gas
i	denotes i^{th} constituent of combustion products
sto	stoichiometric
T	total
t	static
th	theoretical
1	engine inlet
2	combustor entrance
3	combustor outlet

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4 exhaust-nozzle throat

5 exhaust-nozzle outlet

Superscripts:

* denotes station having a Mach number of unity

' denotes effective value of combustor inlet-air total temperature or enthalpy where combustor-outlet velocity is appreciable

APPENDIX B

ADJUSTMENT OF THEORETICAL AIR SPECIFIC IMPULSE FOR APPRECIABLE COMBUSTOR-OUTLET VELOCITY

The theoretical air-specific-impulse and combustion-temperature data presented herein assume negligible combustor-outlet velocity. In actual combustors the high combustor-outlet velocity causes the kinetic energy to be an appreciable portion of the total energy possessed by the gases. The static combustor-outlet temperature for chemical equilibrium will then be less than that shown in the curves of this report. As a result of this decrease in combustor-outlet static temperature, there may be shifts in chemical and physical equilibriums in some cases. The static combustion temperature with appreciable velocity cannot then be related to the combustion temperature for zero combustor-outlet velocity by the conventional relation

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$$t_3 = \frac{(t_3)_{M_3=0}}{1 + \frac{\gamma_3 - 1}{2} M_3^2} \tag{B1}$$

Since this expression implies constant composition, it is unsuitable at temperatures where appreciable dissociation is present, above about 3600° R. It is also not appropriate in the region of phase transition from gaseous to liquid boric oxide. At these conditions it becomes necessary to allow for the kinetic energy of the combustion products when the theoretical static combustion temperature is determined for boron-containing fuels. An adjustment in the theoretical air specific impulse is then required also.

The data in this report permit approximate adjustments in theoretical combustor-outlet static temperature and air specific impulse to be made for appreciable combustor-outlet velocity over a range of pressures at temperatures above 3600° R, where dissociation becomes important. In the region of phase transition from gaseous to liquid boric oxide, the limited data presented are insufficient to enable these corrections to be determined.

The adjustment to combustion static temperature is made in the following manner. Conservation of energy across the combustor is expressed as

$$(h_T)_{a,2} + \frac{w_f}{w_a} (h_T)_f = \left(1 + \frac{w_f}{w_a}\right) \left[(h_t)_3\right] + KE \tag{B2}$$

By deducting the combustor-outlet kinetic energy from the inlet-air total enthalpy, an effective inlet-air total enthalpy can be obtained:

$$(h_T)'_{a,2} = (h_T)_{a,2} - KE \tag{B3}$$

The value of $(h_T)'_{a,2}$ is entered on figure 11, which shows the variation of $(h_T)_a$ with temperature to find an effective inlet-air total temperature T'_2. This value of T'_2 is then entered on a curve of combustion static temperature $(t_3)_{M_3=0}$ against combustor-inlet temperature at the proper equivalence ratio and combustion static pressure. The combustion static temperature so determined pertains to a combustor-inlet total temperature of T_2 and a combustor-outlet velocity V_3.

The procedure for approximating the combustor-outlet static temperature and air specific impulse will be illustrated by an example. An engine is operated with pentaborane at an equivalence ratio of 1.0 under the following combustor-inlet conditions:

Combustor inlet-air velocity, V_2, ft/sec	250
Combustor inlet-air total temperature, T_2, $^\circ$F	500
Combustor-outlet static pressure, p_3, atm	2

It is desired to know the theoretical combustion static temperature and air specific impulse for these conditions.

The combustor-outlet velocity must be calculated from the inlet conditions. For heat addition at constant area without friction, the Mach numbers at the combustor inlet and outlet are related by the following function, which can be solved graphically if desired:

$$\frac{\gamma_3 M_3^2 (1 + \gamma_2 M_2^2)^2}{\gamma_2 M_2^2 (1 + \gamma_3 M_3^2)^2} = \left(1 + \frac{w_f}{w_a}\right) \frac{(1 - X_3) R_3 t_3}{R_2 t_2} \tag{B4}$$

A first trial value of t_3 is estimated, and approximate values of γ_3 and R_3 ($R = 1545.33/\overline{m}_g$) are read from figure 12 (boron slurries) or 13 (pentaborane blends). In figure 11 may be found γ_2. For consistency with the data of figures 12 and 13, an R_2 of 53.57 foot-pounds per pound $^\circ$R should be used, although it is slightly larger than the value for actual air because only nitrogen and oxygen were assumed as constituents.

These values are substituted in equation (B4) and a first trial value of M_3 is found. The kinetic energy is then found from the expression

$$KE = \frac{M_3^2 \gamma_3 R_3 t_3}{2J} \left(1 + \frac{w_f}{w_a}\right) \tag{B5}$$

The first trial value of T_2' is determined by means of figure 11 and equation (B3). The corresponding second trial value of combustor-outlet static temperature t_3 can then be read from a curve of $(t_3)_{M_3=0}$ against inlet-air temperature for the stated combustor static pressure. If this second trial value of t_3 differs appreciably from the value assumed at the start, the calculation must be repeated. The following tabulation summarizes the results of the calculations for the example chosen; the first trial value of combustor-outlet static temperature t_3 was assumed to be that read from figure 6 for 500° F inlet-air temperature and zero inlet-air velocity, or 5080° R.

γ_2	1.38
R_2, (ft)(lb)/(lb)(°R)	53.57
w_f/w_a	0.0764
t_2, °R	955
M_2	0.166
$(h_T)_{a,2}$, Btu/lb	343

	First trial	Second trial
t_3, °R	5080	4990
γ_3	1.232	1.233
R_3, (ft)(lb)/(lb)(°R)	53.20	52.96
X_3	0	0
M_3	0.612	0.594
KE, Btu/lb air	86.1	79.4
$(h_T)'_{a,2}$, Btu/lb	256.9	263.6
T_2', °F	147	176
t_3', °R	4990	4998

Thus, the theoretical combustion static temperature with no combustor-outlet velocity is 5080° R, while with a reasonable outlet velocity it is 4998° R. The use of the curves of figure 6 without

adjustment for combustor-outlet-velocity results for this example in an error of about 80° F in theoretical combustion static temperature.

It is now desired to calculate the approximate air specific impulse at the exhaust-nozzle throat resulting from the appreciable combustor-outlet velocity. The assumption will be made that chemical equilibrium is frozen between the combustor outlet and the exhaust-nozzle throat. Because the appreciable combustor-outlet velocity lowers the combustion static temperature, less energy is required for dissociation than when there is no combustor-outlet velocity. This thermal energy thus made available as sensible energy causes the air specific impulse to be higher when there is appreciable combustor-outlet velocity.

Air specific impulse can be calculated from equation (3), provided a combustion total temperature T_3 can be defined. Where there is no combustor-outlet velocity,

$$T_3 = (t_3)_{M_3=0}$$

When there is appreciable combustor-outlet velocity, the combustion total temperature may be defined in the following manner: The gases moving with the combustion static temperature and combustor-outlet velocity are brought isentropically to rest with composition frozen. The resulting temperature,

$$T_3 = t_3\left(1 + \frac{\gamma_3 - 1}{2} M_3^2\right) \tag{B6}$$

is greater than $(t_3)_{M_3=0}$. When it is assumed that the quantities γ_3 and R_3 are the same for the nozzle-expansion process in both cases, the ratio of the air specific impulse for appreciable outlet velocity to that for no outlet velocity is

$$\frac{S_a}{(S_a)_{M_3=0}} = \sqrt{\frac{T_3}{(t_3)_{M_3=0}}} = \sqrt{\frac{t_3\left(1 + \frac{\gamma_3 - 1}{2} M_3^2\right)}{(t_3)_{M_3=0}}} \tag{B7}$$

For the example under consideration,

$$\frac{S_a}{(S_a)_{M_3=0}} = \sqrt{\frac{5204}{5080}} = 1.012$$

In the region of boric oxide vaporization, between about 2400° and 3400° R, the effect of appreciable combustor-outlet velocity may be greater than this because of rapid changes in the concentration of liquid boric oxide with temperature. Insufficient information on γ and R is published herein to permit the computation of this effect in the region of boric oxide vaporization.

APPENDIX C

COMPUTATION OF AIR SPECIFIC IMPULSE FROM EXPERIMENTAL DATA

By means of suitable thrust, drag, and pressure measurements on an experimental engine or combustor, stream thrust

$$F_5 = \left(pA + \frac{wV}{g}\right)_5 \tag{C1}$$

is determined. This can be related to the experimental air specific impulse thus:

$$S_a = \frac{F_5}{\varphi(M_5)w_a} \tag{C2}$$

where

$$\varphi(M_5) = \frac{1 + \gamma_5 M_5^2}{M_5\sqrt{2(\gamma_5+1)\left(1 + \frac{\gamma_5-1}{2} M_5^2\right)}} \tag{C3}$$

Values of $\varphi(M)$ may be found in tables 30 to 34 of reference 15 as the term F/F^* for γ of 1.0, 1.1, 1.2, 1.3, and 1.4. It happens that $\varphi(M)$ is quite insensitive to γ over a range of M from 0.7 to 1.3 and γ from 1.1 to 1.4 (ref. 6). A γ of 1.2 can therefore be employed with accuracy to obtain $\varphi(M_5)$ if M_5 lies within the region around unity. For M_5 greater or less than these values, the sensitivity of $\varphi(M_5)$ to γ increases rapidly, as shown in reference 15. Since V_5 can be determined from the thrust measurement by equations presented in reference 3, the Mach number at the exhaust-nozzle outlet can be estimated from the equation

$$M_5 = \sqrt{\frac{(w_f + w_a)\, V_5}{\gamma_5\, g\, p_5 A_5}} \tag{C4}$$

If the ratio P_3/p_5 is measured or specified and it is known that flow is essentially isentropic in the exhaust nozzle (small frictional and shock losses), M_5 can also be expressed as

$$M_5 = \sqrt{\frac{2}{\gamma-1}\left[\left(\frac{P_3}{p_5}\right)^{\frac{\gamma-1}{\gamma}} - 1\right]} \qquad (C5)$$

If the ratio p_4/p_5 is measured,

$$M_5 = \sqrt{\frac{2}{\gamma-1}\left[\frac{\gamma+1}{2}\left(\frac{p_4}{p_5}\right)^{\frac{\gamma-1}{\gamma}} - 1\right]} \qquad (C6)$$

The value of M_5 can be determined as a function of p_5/P_3 from tables 30 to 35 of reference 15, where the ratio herein designated as p_5/P_3 is shown as p/p_0.

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For greater accuracy in calculation, values of γ and the gas constant R may be found from figures 12 and 13. The γ presented is an effective γ for the process of expansion over a pressure ratio of 2. Values of T_3/t_4 determined for an isentropic expansion at frozen composition over a pressure ratio of 2 were substituted in the equation

$$\frac{\gamma}{\gamma - 1} = \frac{\log P_3/p_4}{\log T_3/t_4} \qquad (C7)$$

The value of R pertained to the combustion process. Because the composition during expansion was considered to be fixed, R is assumed to remain constant.

Where the pressure ratio P_3/p_4 across the nozzle greatly exceeds 2, these values of γ are in error. Because of the lack of knowledge as to change in composition within the nozzle (appendix D), it is believed that this error in γ will not greatly increase the uncertainty of calculations.

APPENDIX D

COMPARISON OF PERFORMANCE OBTAINED FROM EXPANSION AT FROZEN COMPOSITION WITH THAT AT EQUILIBRIUM COMPOSITION

It is assumed herein that expansion within the exhaust nozzle occurs at frozen composition. Low values of theoretical air specific impulse result because none of the heat of dissociation or vaporization is recovered. If equilibrium expansion occurs, the change in composition will cause a portion of this heat to be converted to sensible enthalpy and kinetic energy. The highest value of theoretical air specific impulse is thus produced. Intermediate values of air specific impulse will result from a partial shift in composition within the exhaust nozzle. Intermediate values will also result from appreciable combustor-outlet velocity as described in appendix B, with either fixed composition or partial recombination in the exhaust nozzle.

Little detailed information exists on the rate of adjustment in composition with change in pressure and temperature at elevated temperatures. Therefore, the degree of approach to equilibrium within various exhaust nozzles cannot be found. However, it is possible to indicate the extremes of performance by comparing an expansion at frozen composition with one at equilibrium composition.

The performance of pure pentaborane was computed both for nozzle expansion at equilibrium composition and at fixed composition. A range of equivalence ratios was considered at a combustor inlet-air temperature of 100° F and a combustion pressure of 2 atmospheres. Selecting the nozzle outlet Mach number as 1.0 made the nozzle pressure ratio comparable to that used throughout this report.

Figure 14(a) shows the nozzle-throat temperature as a function of equivalence ratio, both for fixed and equilibrium expansion. Also presented is the combustion temperature. In figure 14(b) is shown the corresponding air specific impulses for fixed and equilibrium expansion.

At an equivalence ratio of 0.3, there is little difference in either the nozzle-throat temperature or the air specific impulse obtained by frozen expansion compared with those obtained by equilibrium expansion. Under these conditions, there is virtually no dissociation at the combustion temperature, and very little boric oxide in the gaseous state. Equilibrium expansion then occurs essentially at fixed composition. At an equivalence ratio of 0.4, the air specific impulse is 2 seconds higher with equilibrium expansion than with frozen or fixed expansion. Combustion at this equivalence ratio results in the formation of considerable gaseous boric oxide. Expansion at equilibrium

composition from the combustion conditions results in the condensation of much of this gaseous boric oxide. The heat liberated by condensation prevents the throat temperature with equilibrium expansion from falling as low as the throat temperature with expansion at fixed composition, as may be seen in figure 14(a). The higher throat temperature with equilibrium expansion results in higher air specific impulse.

At an equivalence ratio of 0.6, the air specific impulse with both equilibrium and fixed expansion is about the same. Very little dissociation is present at the combustion temperature, and all the boric oxide is gaseous. Furthermore, the drop in temperature in expanding to $M = 1$ is insufficient to cause condensation of the boric oxide. Equilibrium expansion thus occurs virtually at fixed composition.

At an equivalence ratio of 1.0, the nozzle-throat temperature obtained with equilibrium expansion exceeds that with frozen expansion by 230° R. At these high combustion temperatures, considerable dissociation is encountered, and the boric oxide is entirely gaseous. When equilibrium expansion occurs, the recombination of dissociated products liberates considerable heat, although no boric oxide condenses. The nozzle-throat temperature is thus raised above that obtained by frozen expansion with a corresponding gain in air specific impulse.

If expansion were to occur to some other Mach number, the curves for equilibrium expansion would shift relative to those for frozen expansion.

Future research may show that the degree of chemical equilibrium attained in a nozzle can be influenced by varying the residence time within the nozzle. An increase in nozzle length will then increase the degree of equilibrium attained. The air specific impulse will be raised, provided the nozzle drag is not increased too much.

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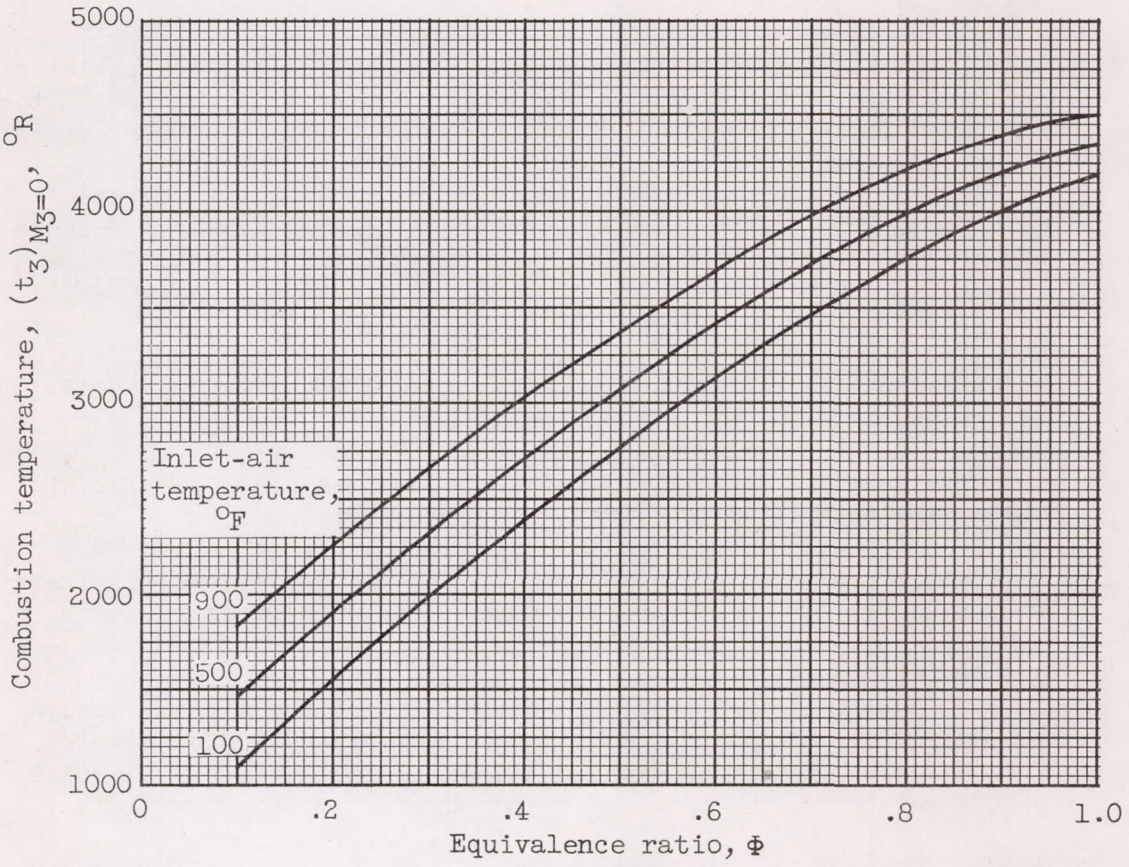
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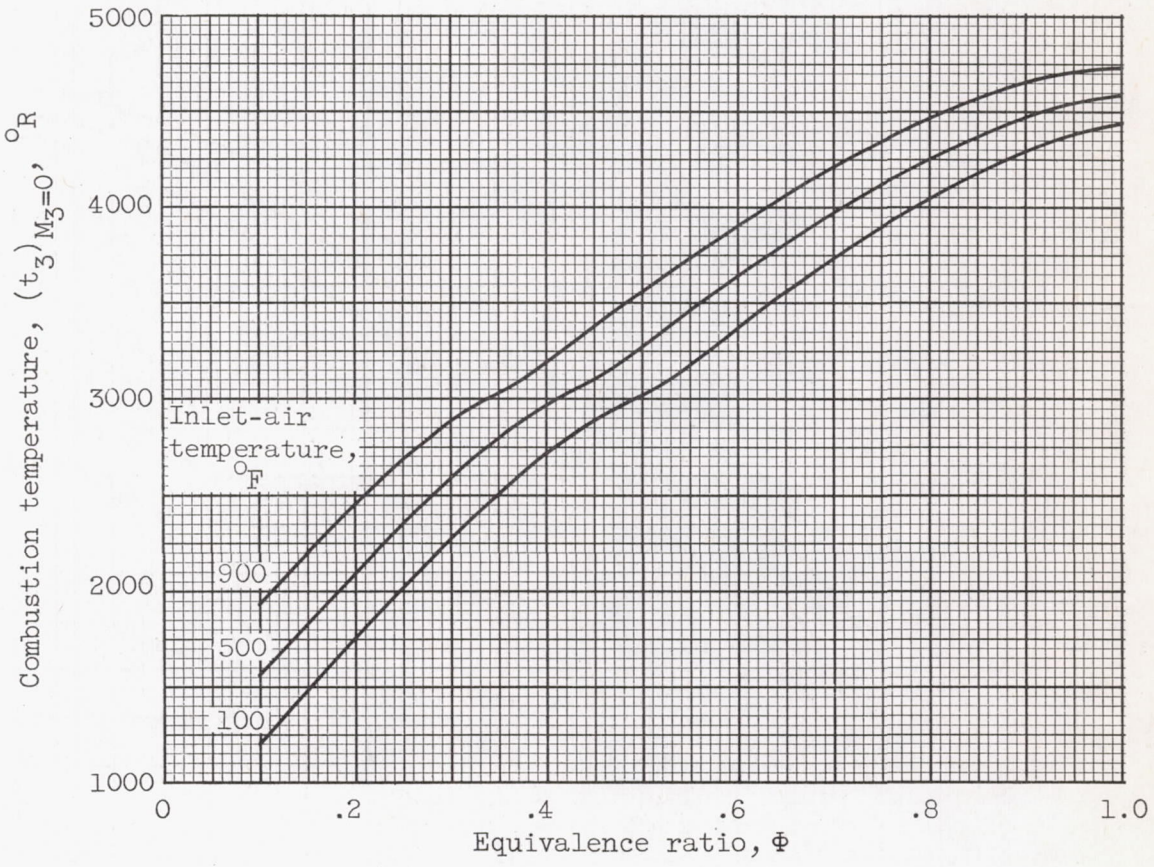
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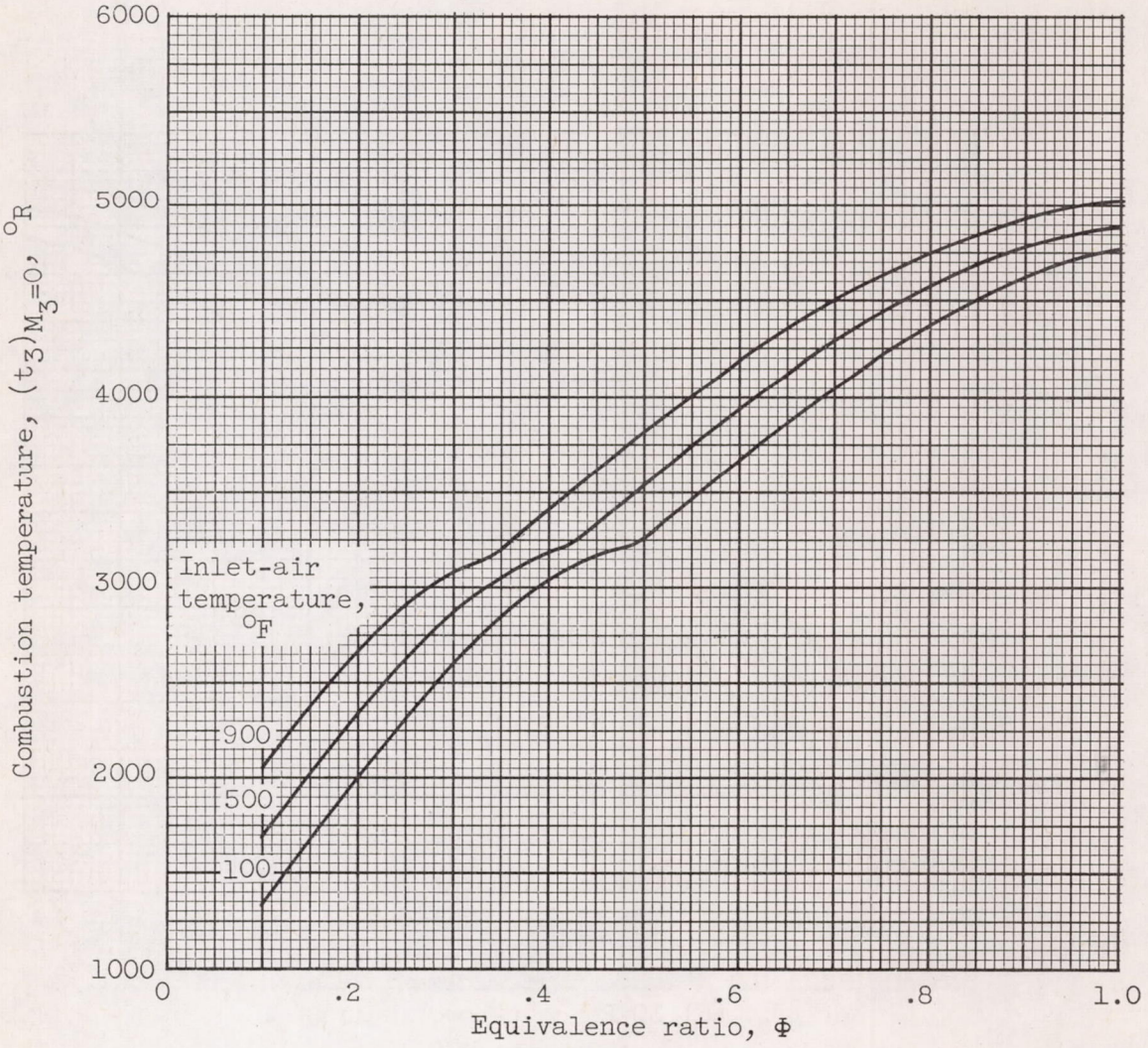
(a) Octene-1.

Figure 1. - Variation of theoretical combustion temperature with equivalence ratio and inlet-air temperature. Combustion pressure, 2 atmospheres.



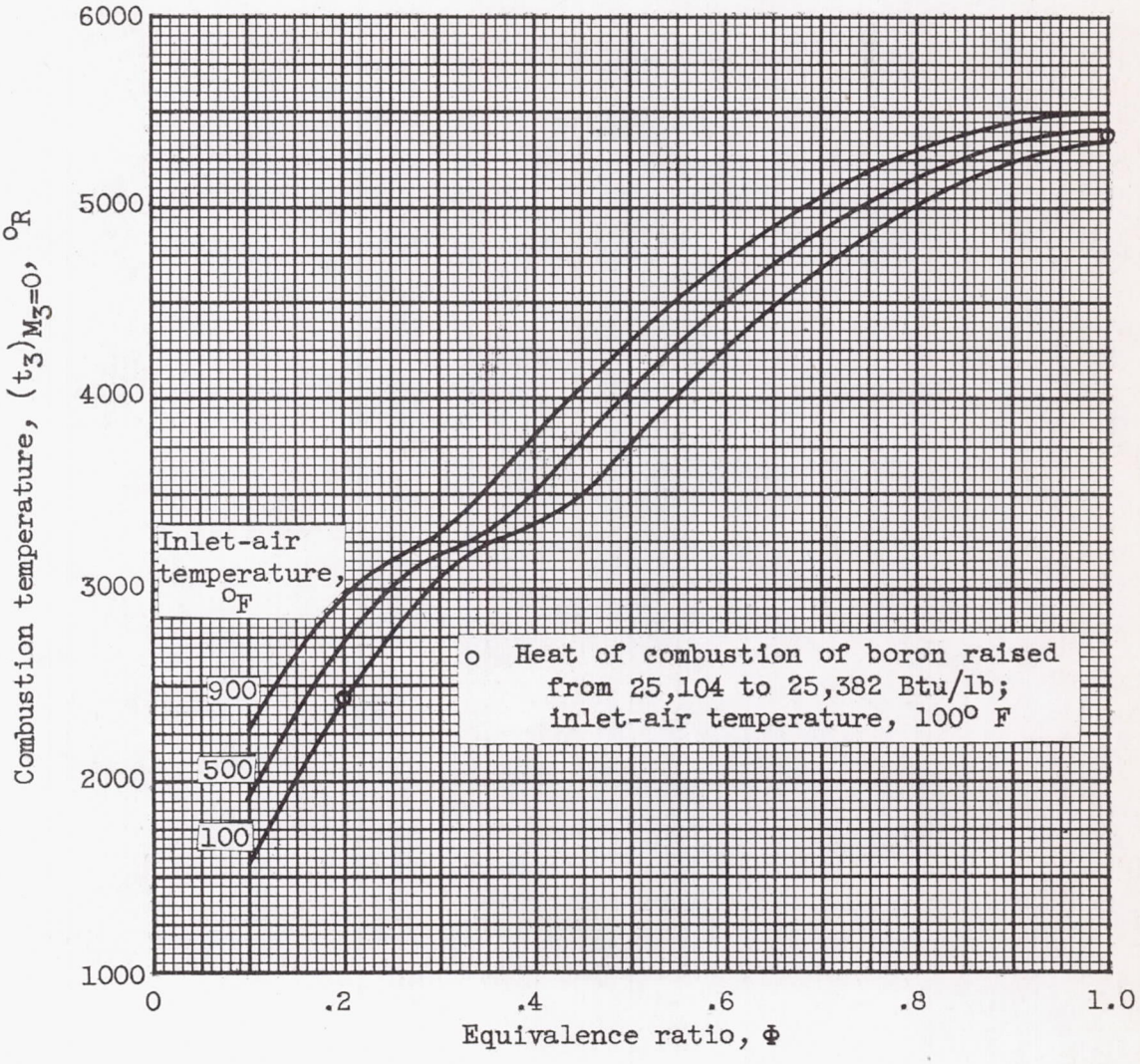
(b) 30-Percent-boron slurry.

Figure 1. - Continued. Variation of theoretical combustion temperature with equivalence ratio and inlet-air temperature. Combustion pressure, 2 atmospheres.



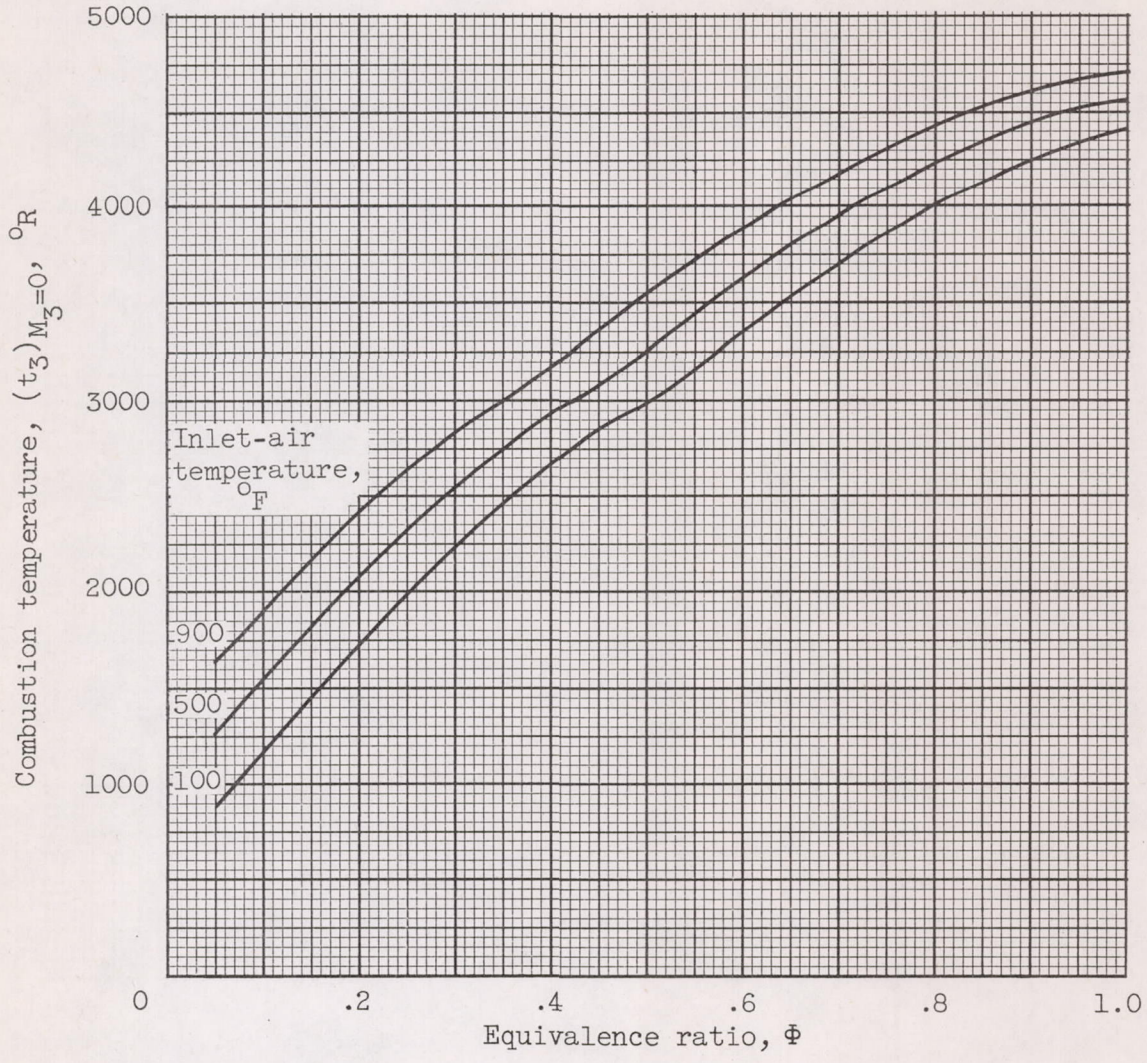
(c) 60-Percent-boron slurry.

Figure 1. - Continued. Variation of theoretical combustion temperature with equivalence ratio and inlet-air temperature. Combustion pressure, 2 atmospheres.



(d) Boron.

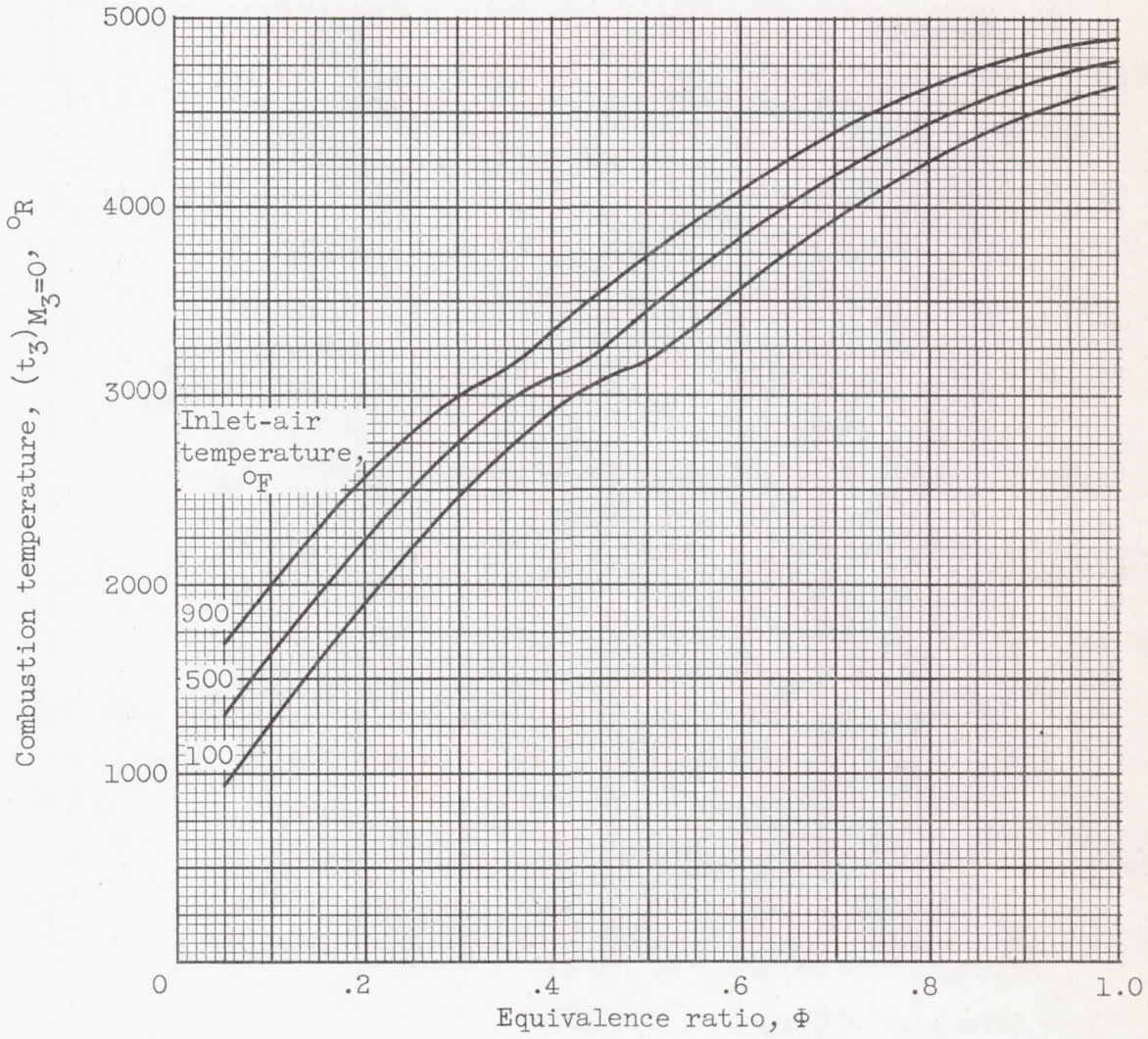
Figure 1. - Continued. Variation of theoretical combustion temperature with equivalence ratio and inlet-air temperature. Combustion pressure, 2 atmospheres.



(e) 30-Percent-pentaborane blend.

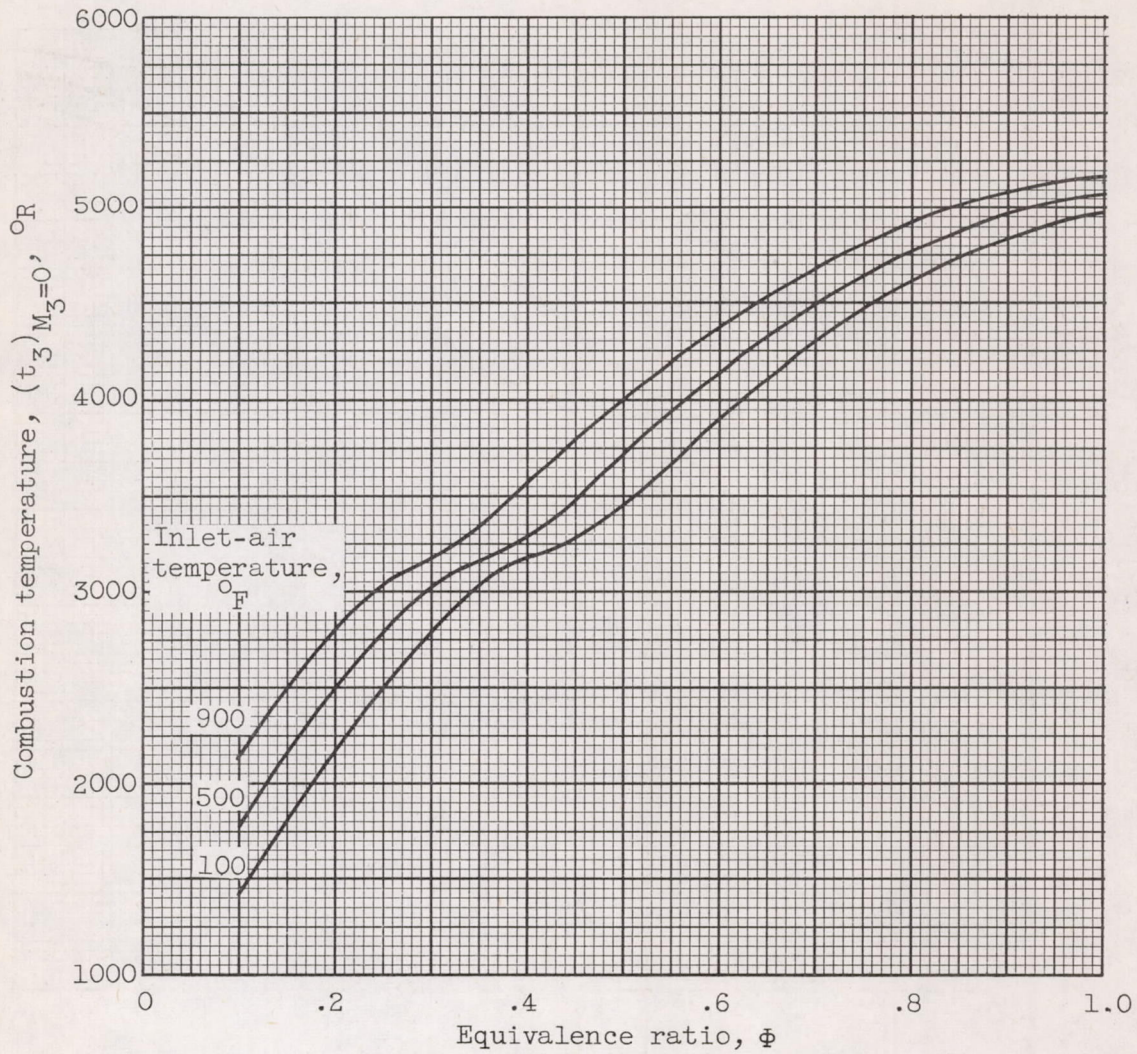
Figure 1. - Continued. Variation of theoretical combustion temperature with equivalence ratio and inlet-air temperature. Combustion pressure, 2 atmospheres.

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(f) 60-Percent-pentaborane blend.

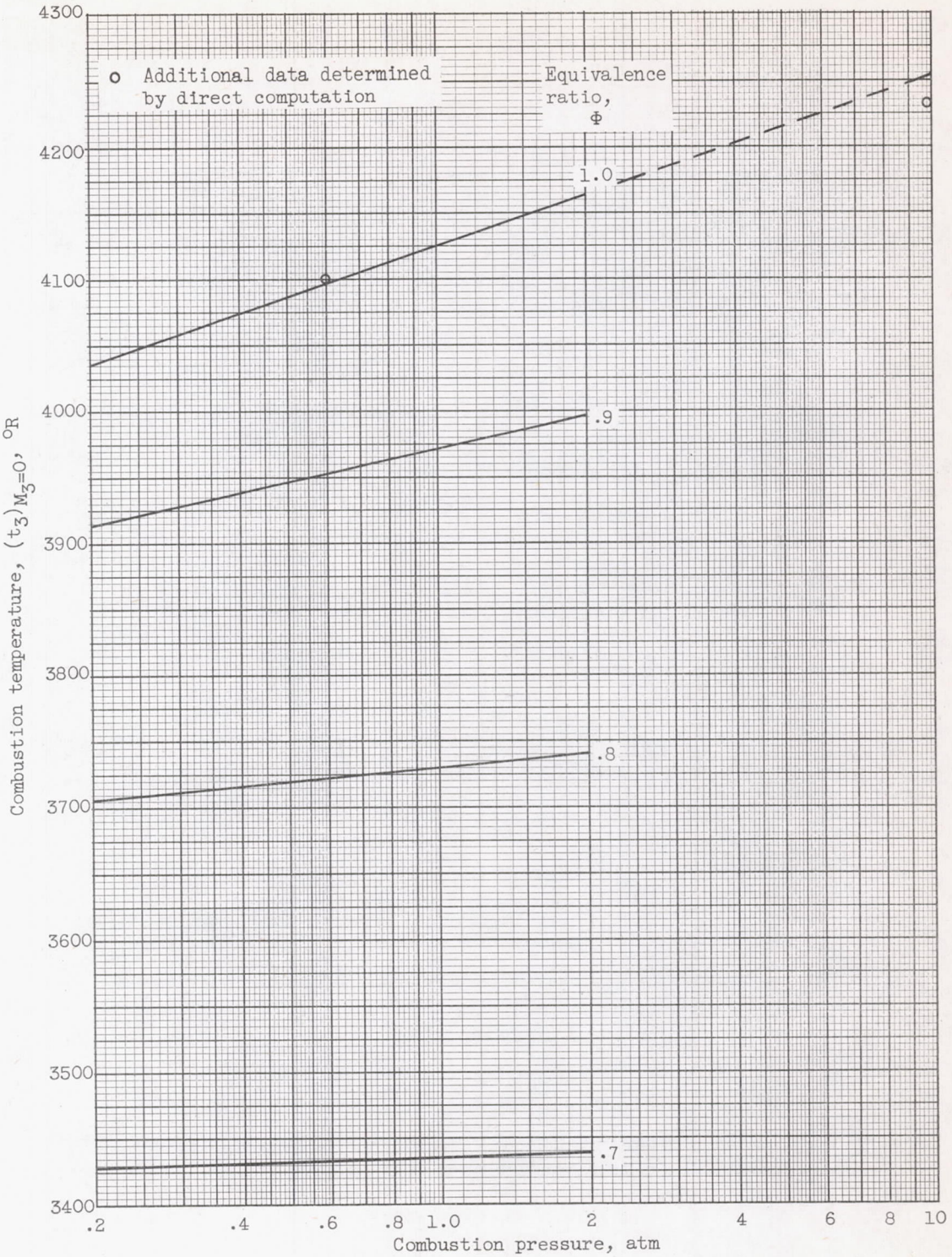
Figure 1. - Continued. Variation of theoretical combustion temperature with equivalence ratio and inlet-air temperature. Combustion pressure, 2 atmospheres.



(g) Pentaborane.

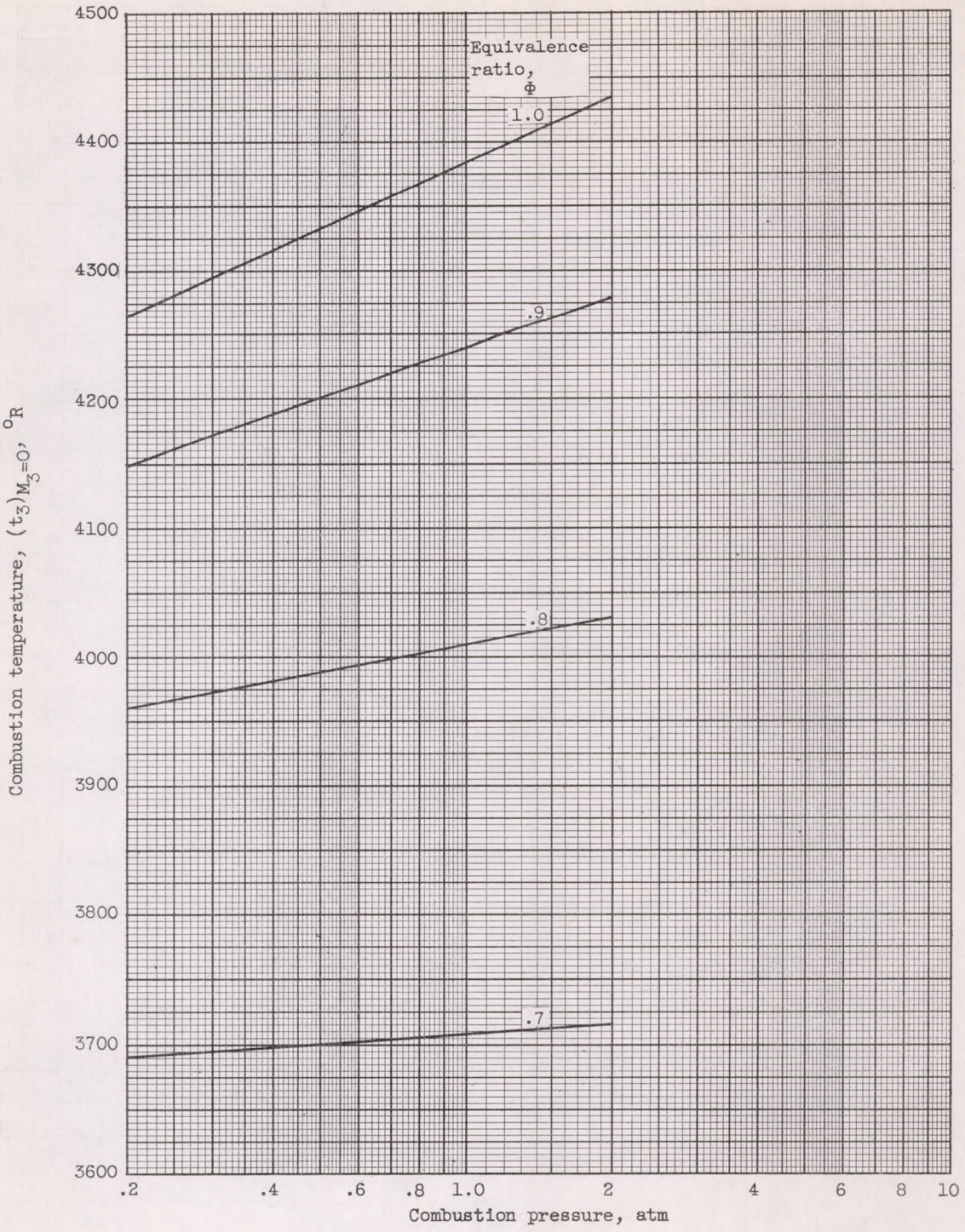
Figure 1. - Concluded. Variation of theoretical combustion temperature with equivalence ratio and inlet-air temperature. Combustion pressure, 2 atmospheres.

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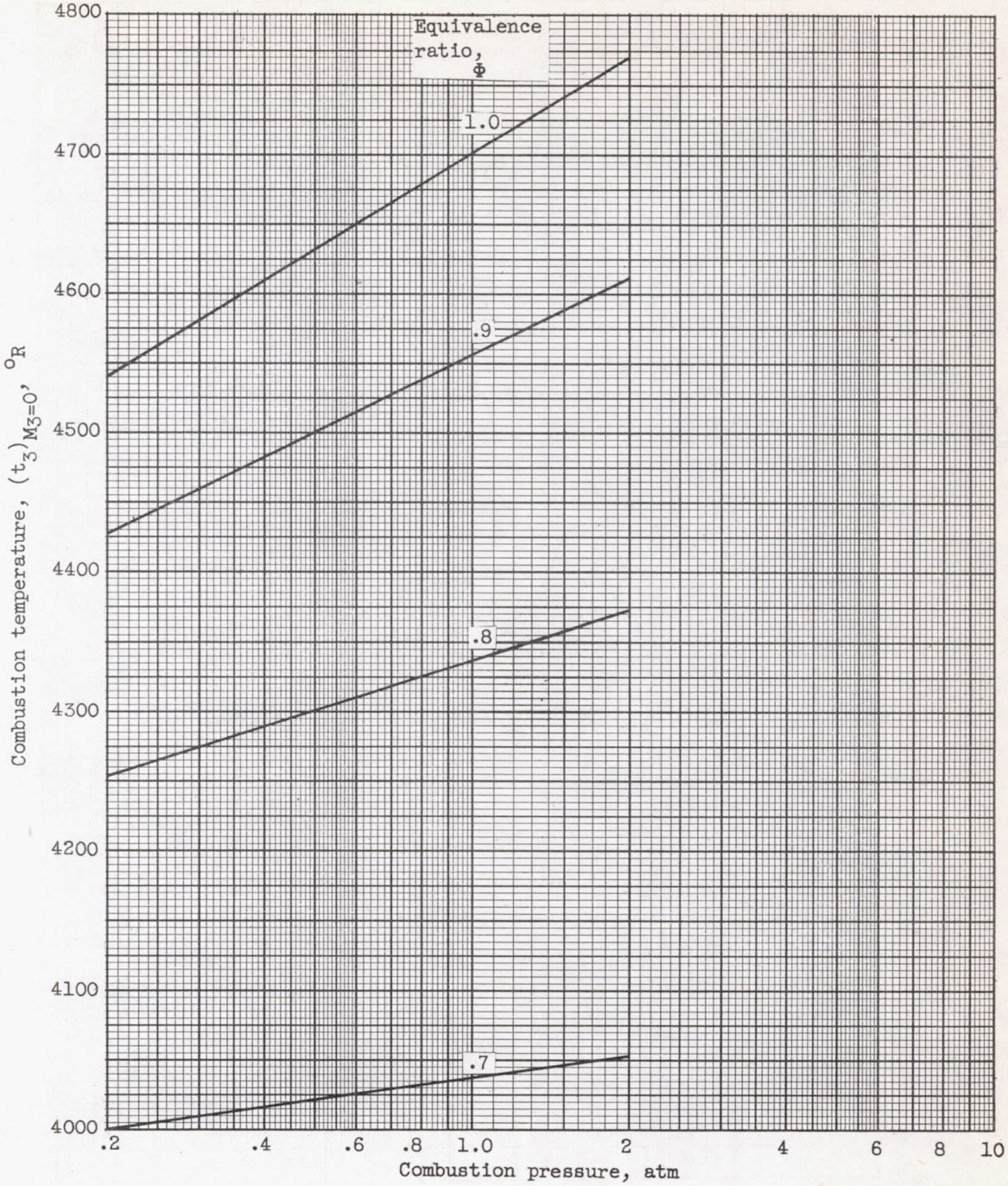
(a) Octene-1.

Figure 2. - Variation of theoretical combustion temperature with combustion pressure at selected equivalence ratios. Inlet-air temperature, 100° F.



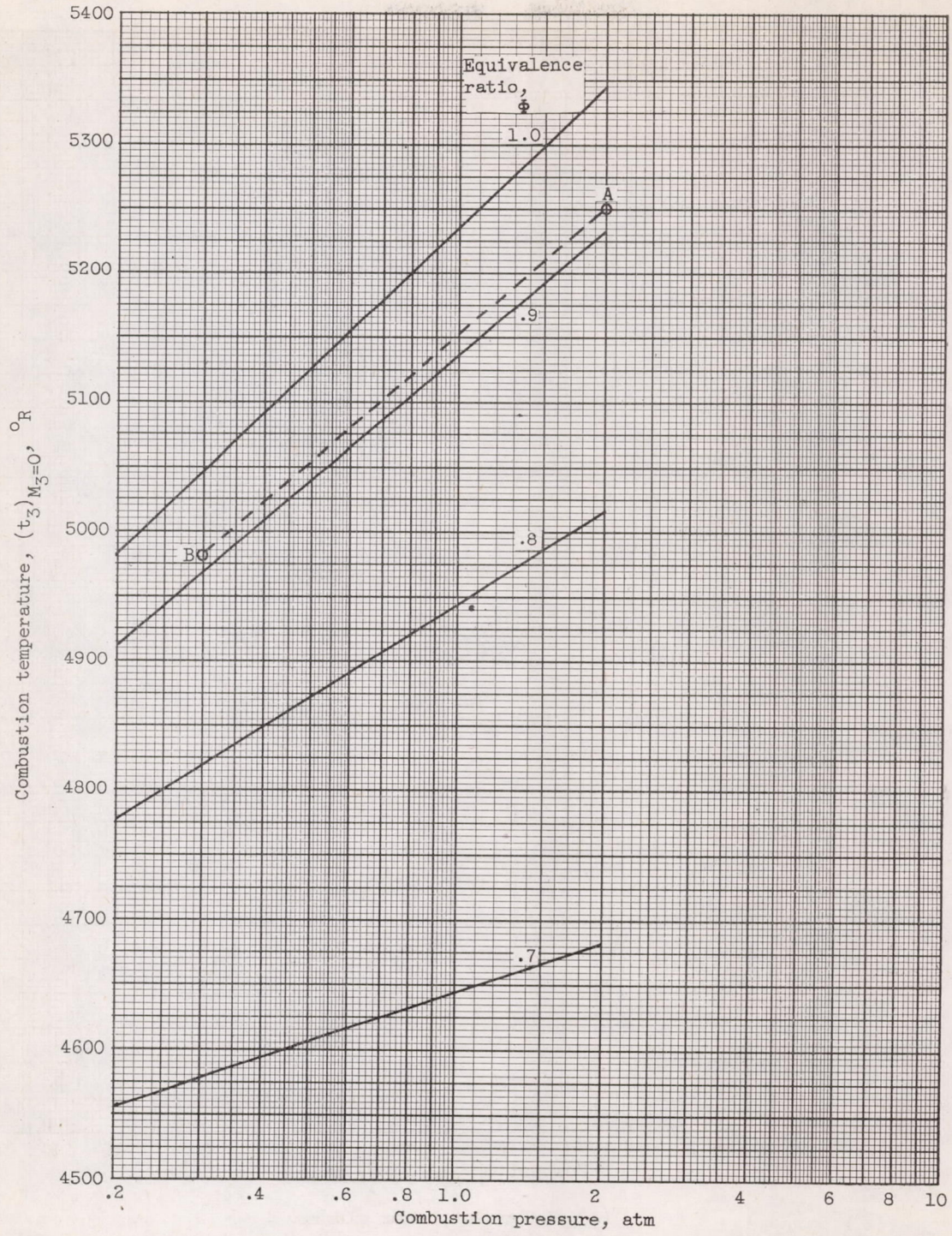
(b) 30-Percent-boron slurry.

Figure 2. - Continued. Variation of theoretical combustion temperature with combustion pressure at selected equivalence ratios. Inlet-air temperature, 100° F.



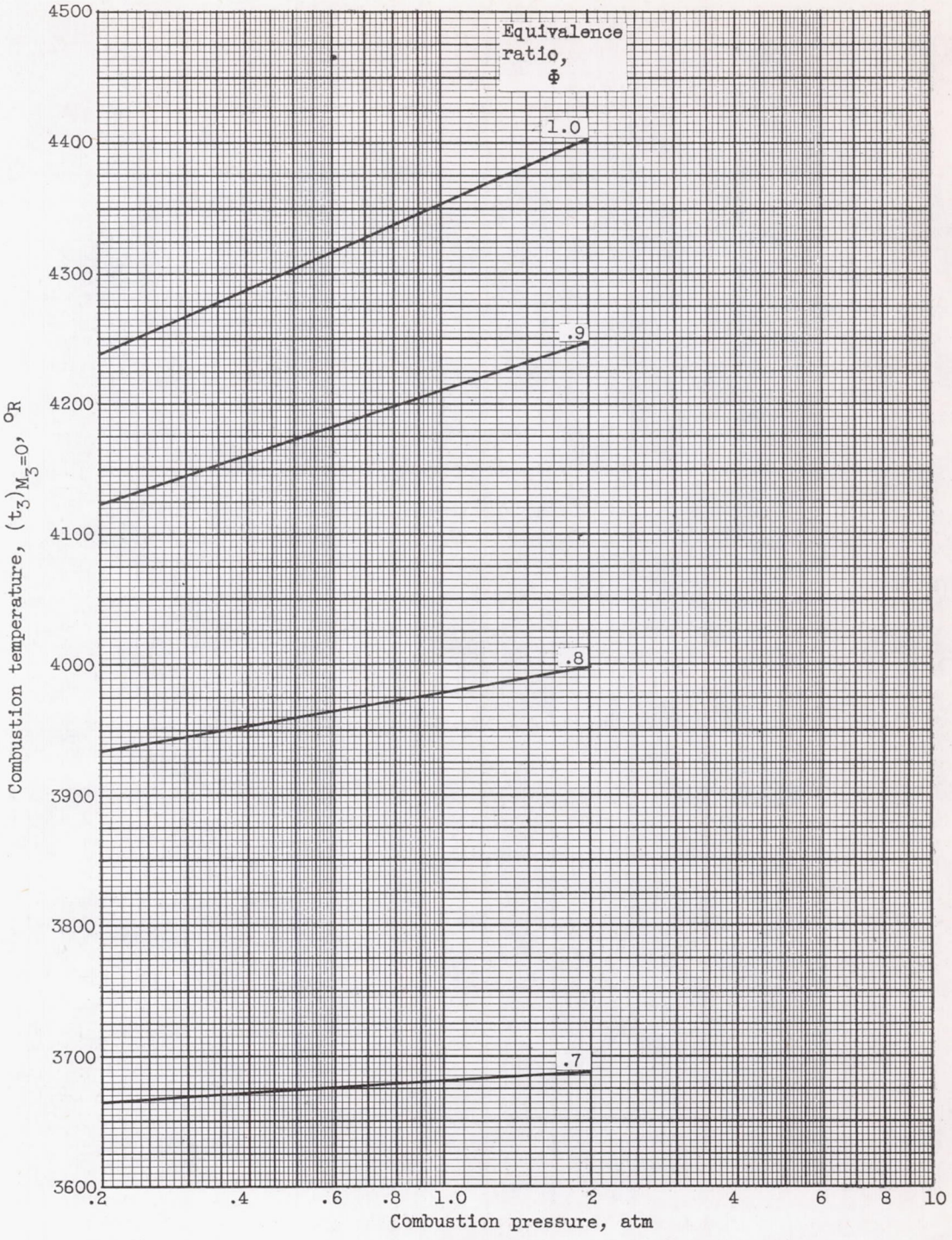
(c) 60-Percent-boron slurry.

Figure 2. - Continued. Variation of theoretical combustion temperature with combustion pressure at selected equivalence ratios. Inlet-air temperature, 100° F.



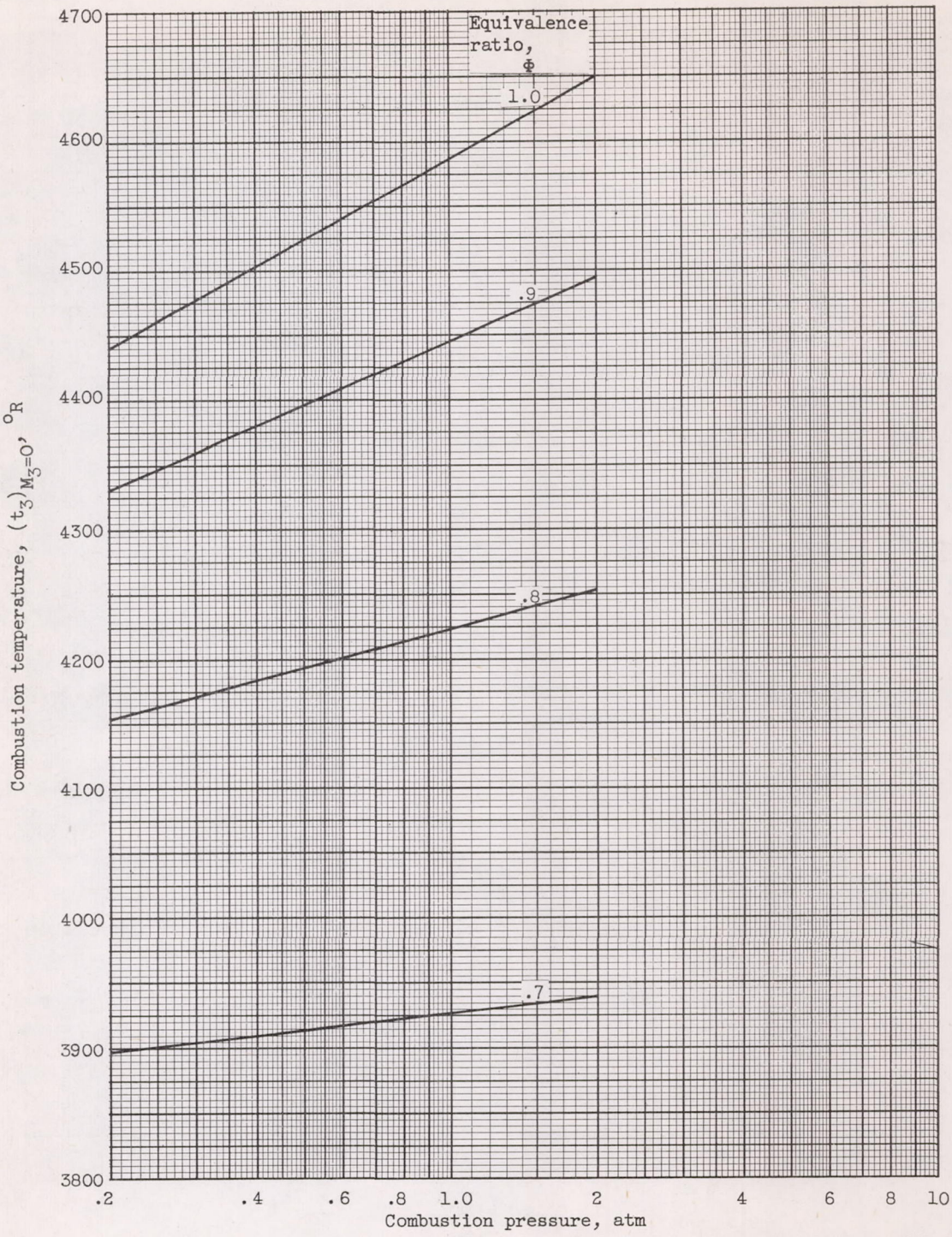
(d) Boron.

Figure 2. - Continued. Variation of theoretical combustion temperature with combustion pressure at selected equivalence ratios. Inlet-air temperature, 100° F.



(e) 30-Percent-pentaborane blend.

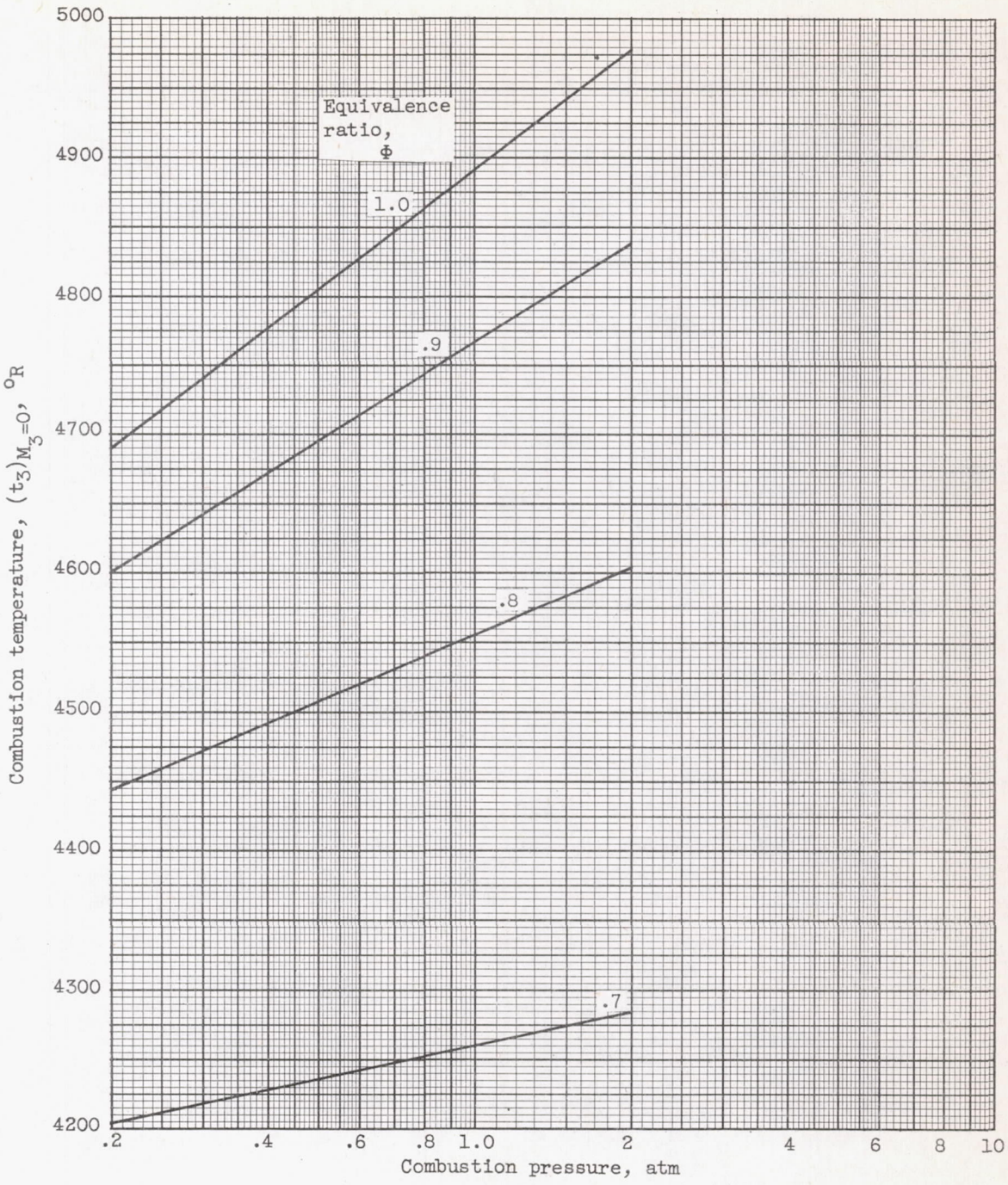
Figure 2. - Continued. Variation of theoretical combustion temperature with combustion pressure at selected equivalence ratios. Inlet-air temperature, 100° F.



(f) 60-Percent-pentaborane blend.

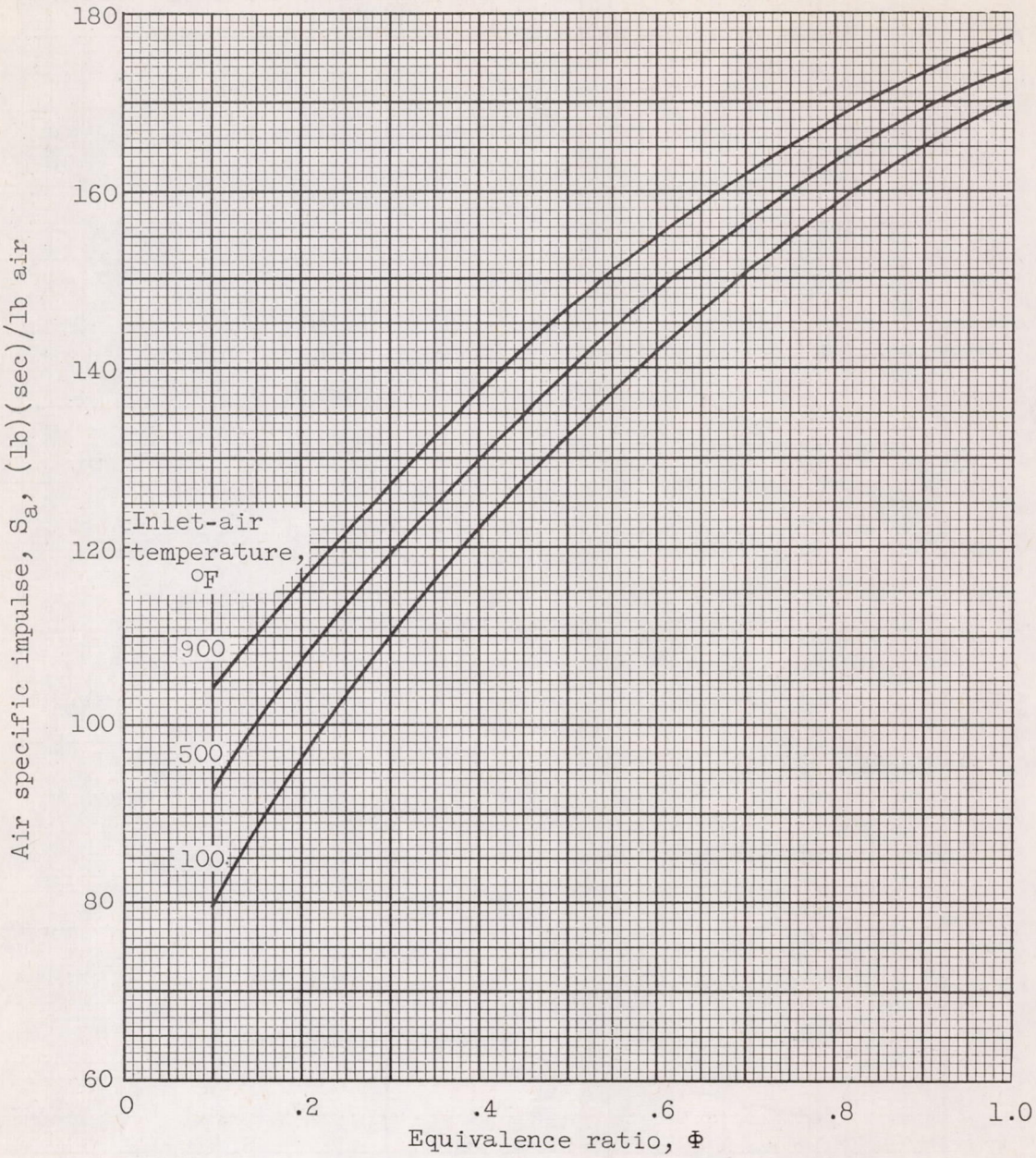
Figure 2. - Continued. Variation of theoretical combustion temperature with combustion pressure at selected equivalence ratios. Inlet-air temperature, 100° F.

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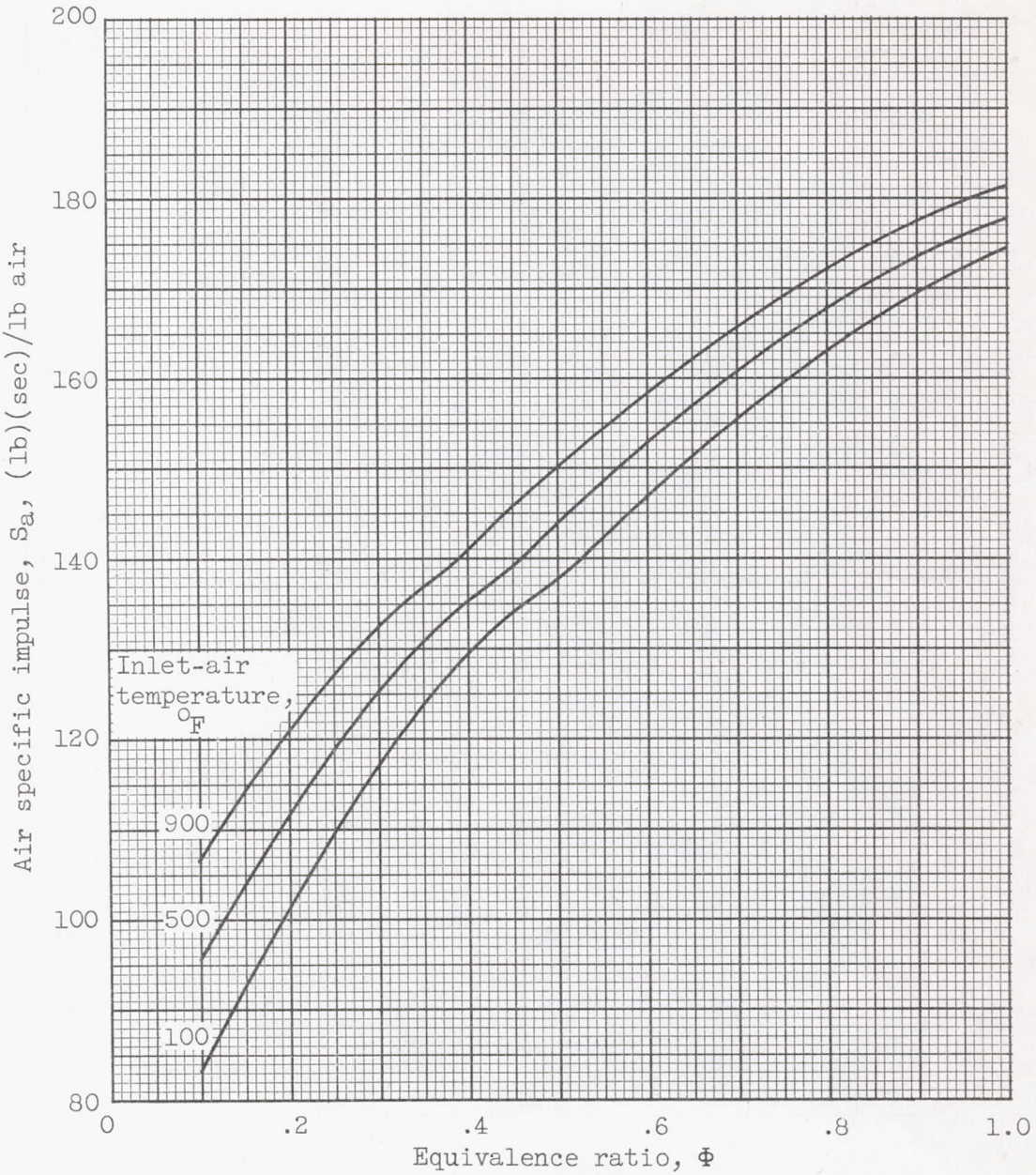
(g) Pentaborane.

Figure 2. - Concluded. Variation of theoretical combustion temperature with combustion pressure at selected equivalence ratios. Inlet-air temperature, 100° F.



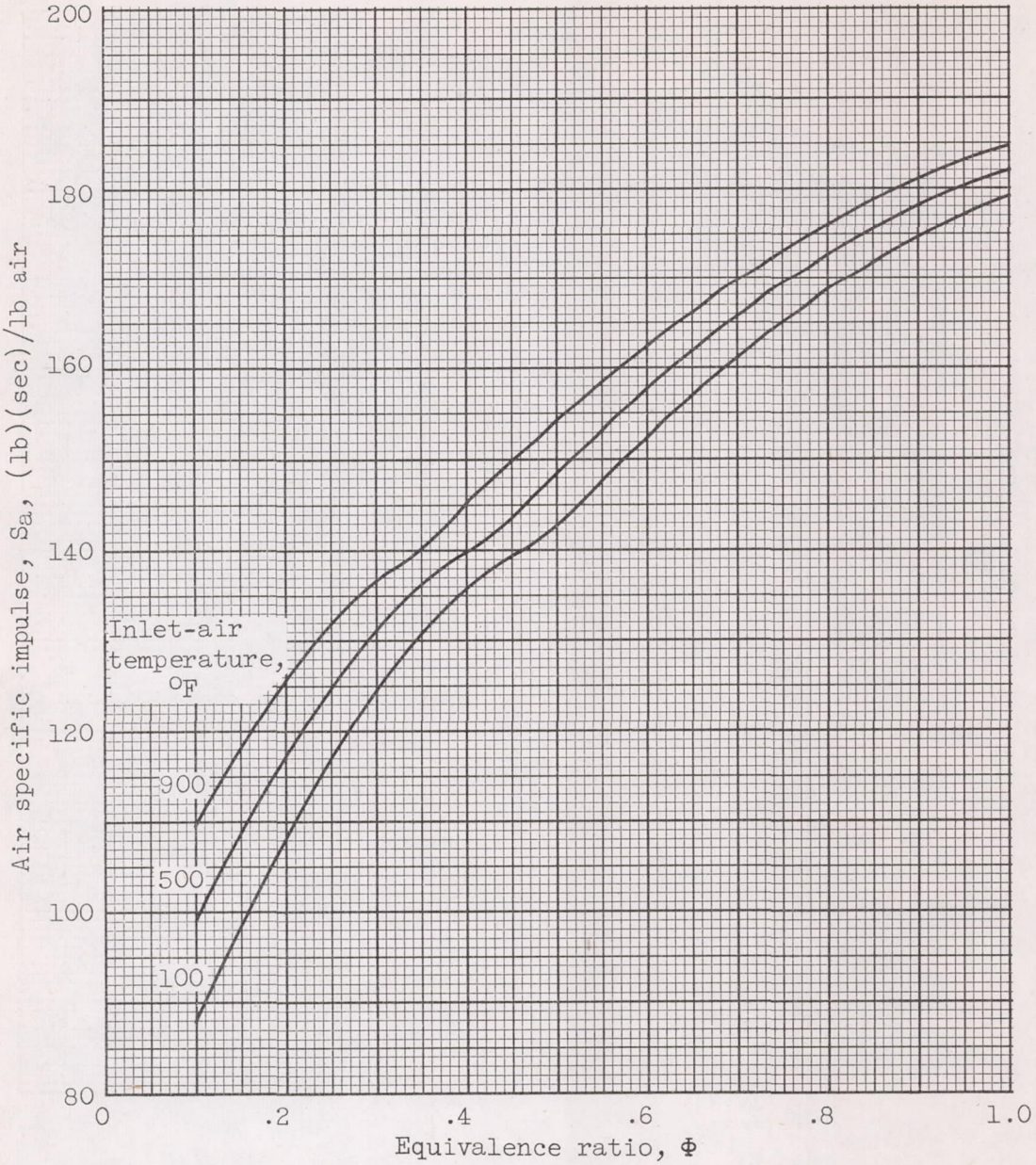
(a) Octene-1.

Figure 3. - Variation of theoretical air specific impulse with equivalence ratio and inlet-air temperature. Combustion pressure, 2 atmospheres.



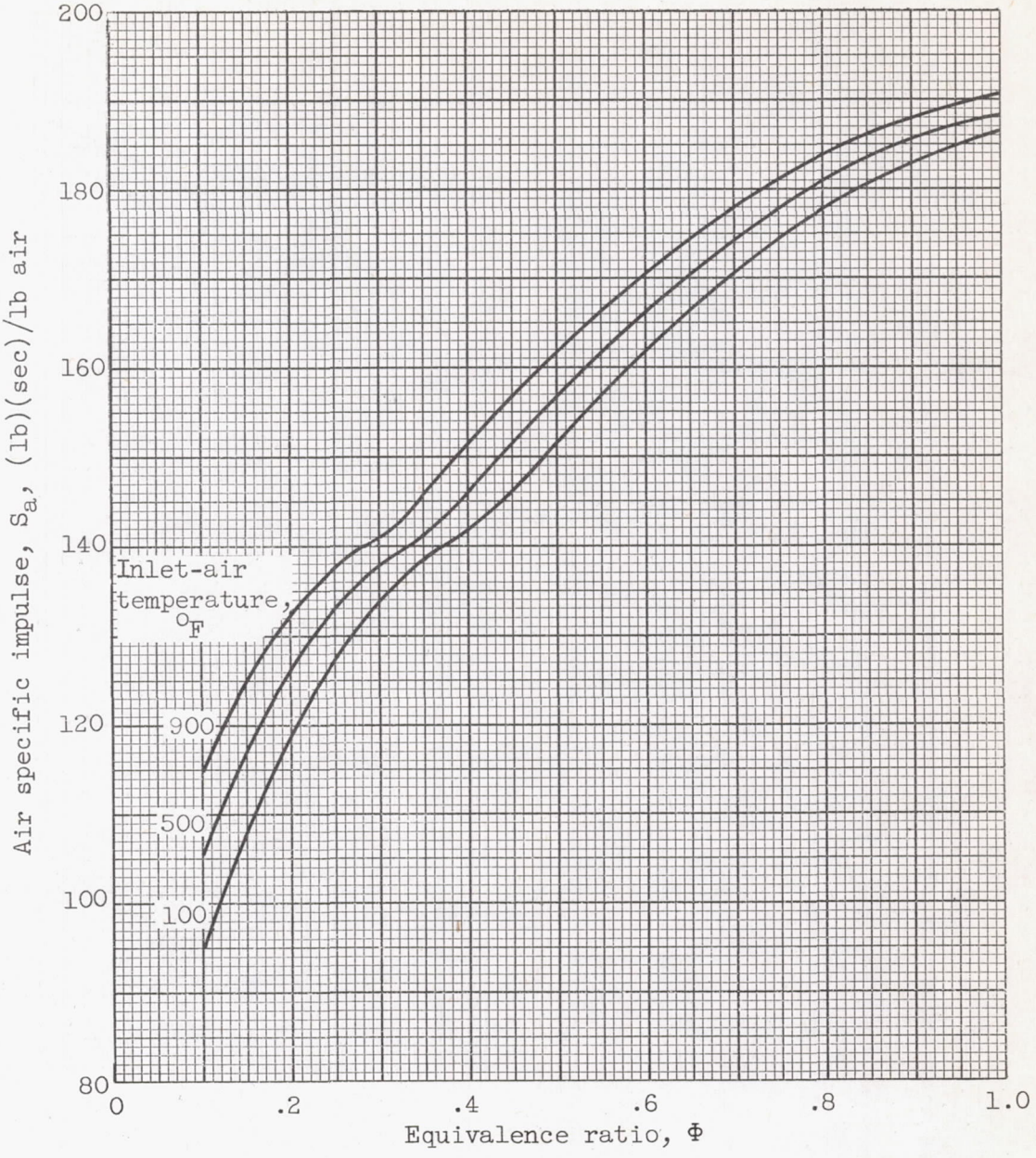
(b) 30-Percent-boron slurry.

Figure 3. - Continued. Variation of theoretical air specific impulse with equivalence ratio and inlet-air temperature. Combustion pressure, 2 atmospheres.



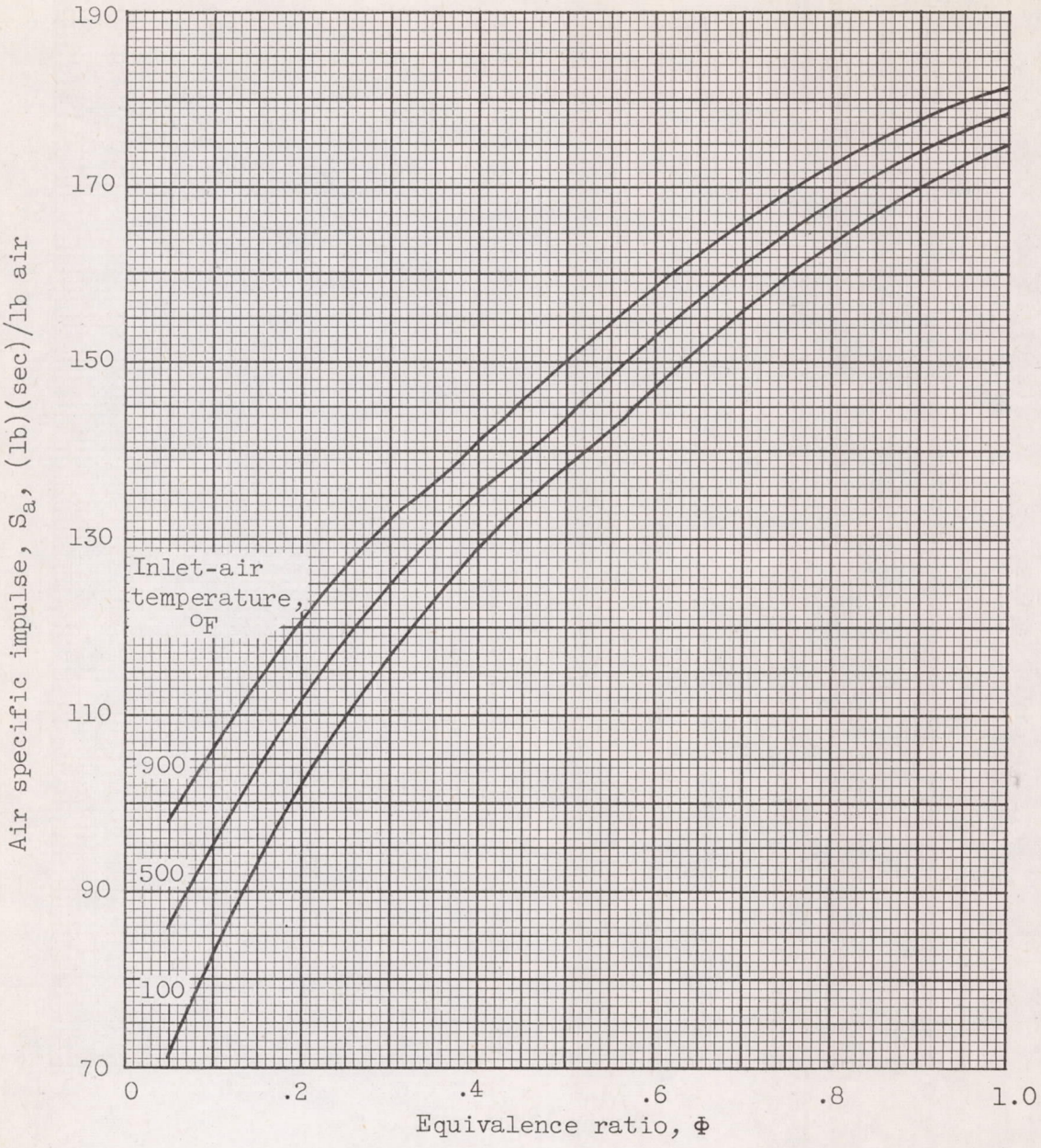
(c) 60-Percent-boron slurry.

Figure 3. - Continued. Variation of theoretical air specific impulse with equivalence ratio and inlet-air temperature. Combustion pressure, 2 atmospheres.



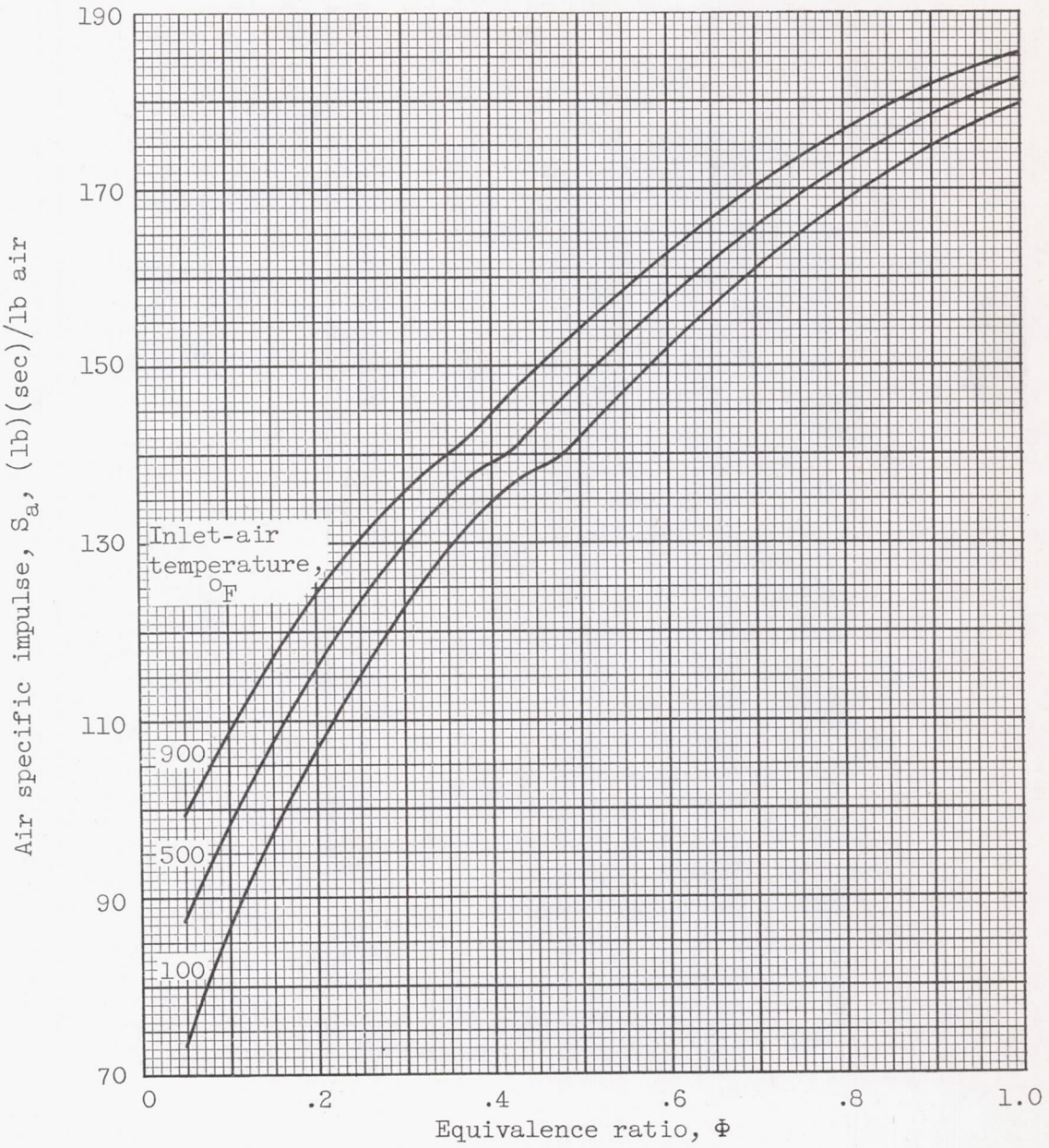
(d) Boron.

Figure 3. - Continued. Variation of theoretical air specific impulse with equivalence ratio and inlet-air temperature. Combustion pressure, 2 atmospheres.



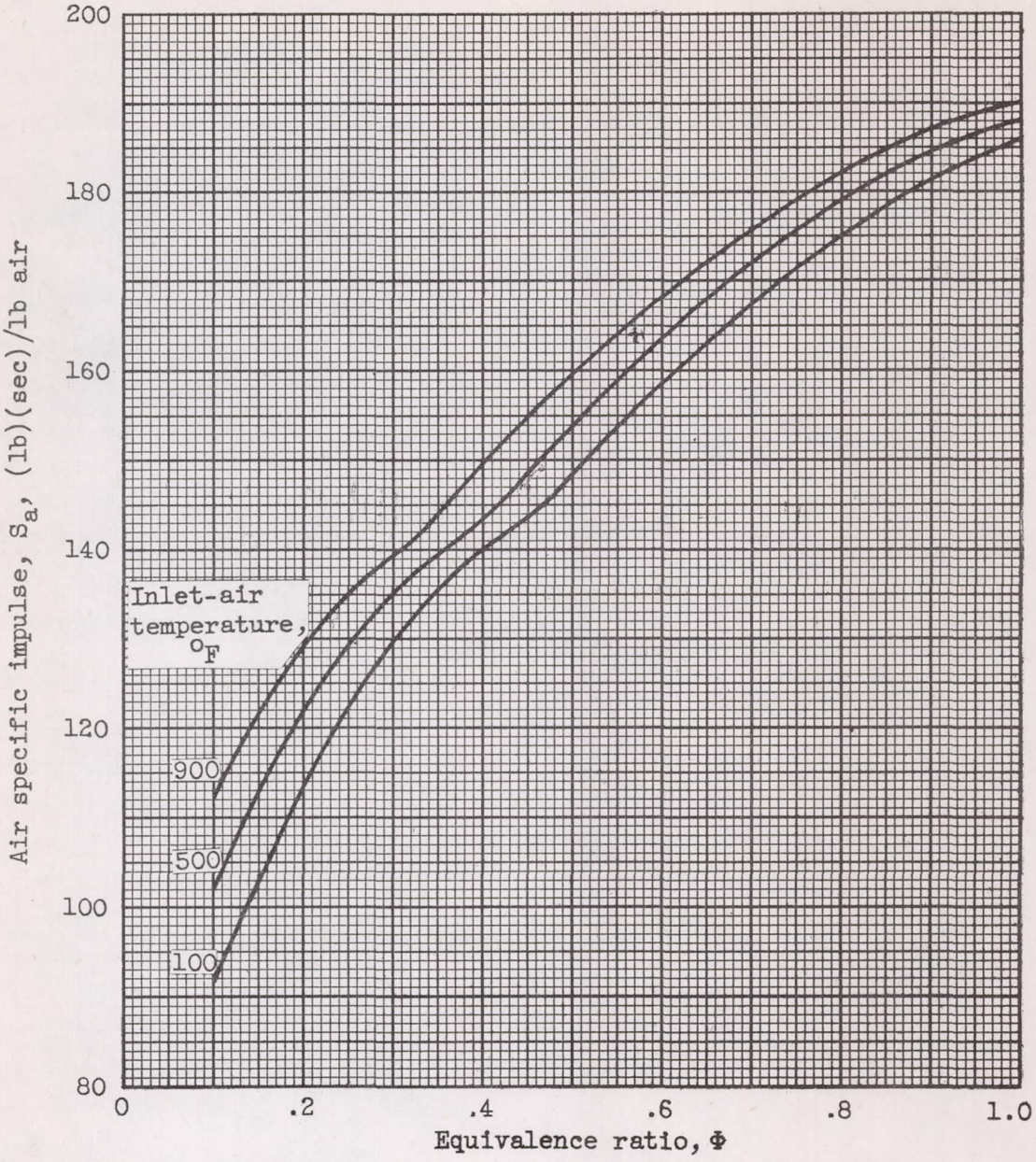
(e) 30-Percent-pentaborane blend.

Figure 3. - Continued. Variation of theoretical air specific impulse with equivalence ratio and inlet-air temperature. Combustion pressure, 2 atmospheres.



(f) 60-Percent-pentaborane blend.

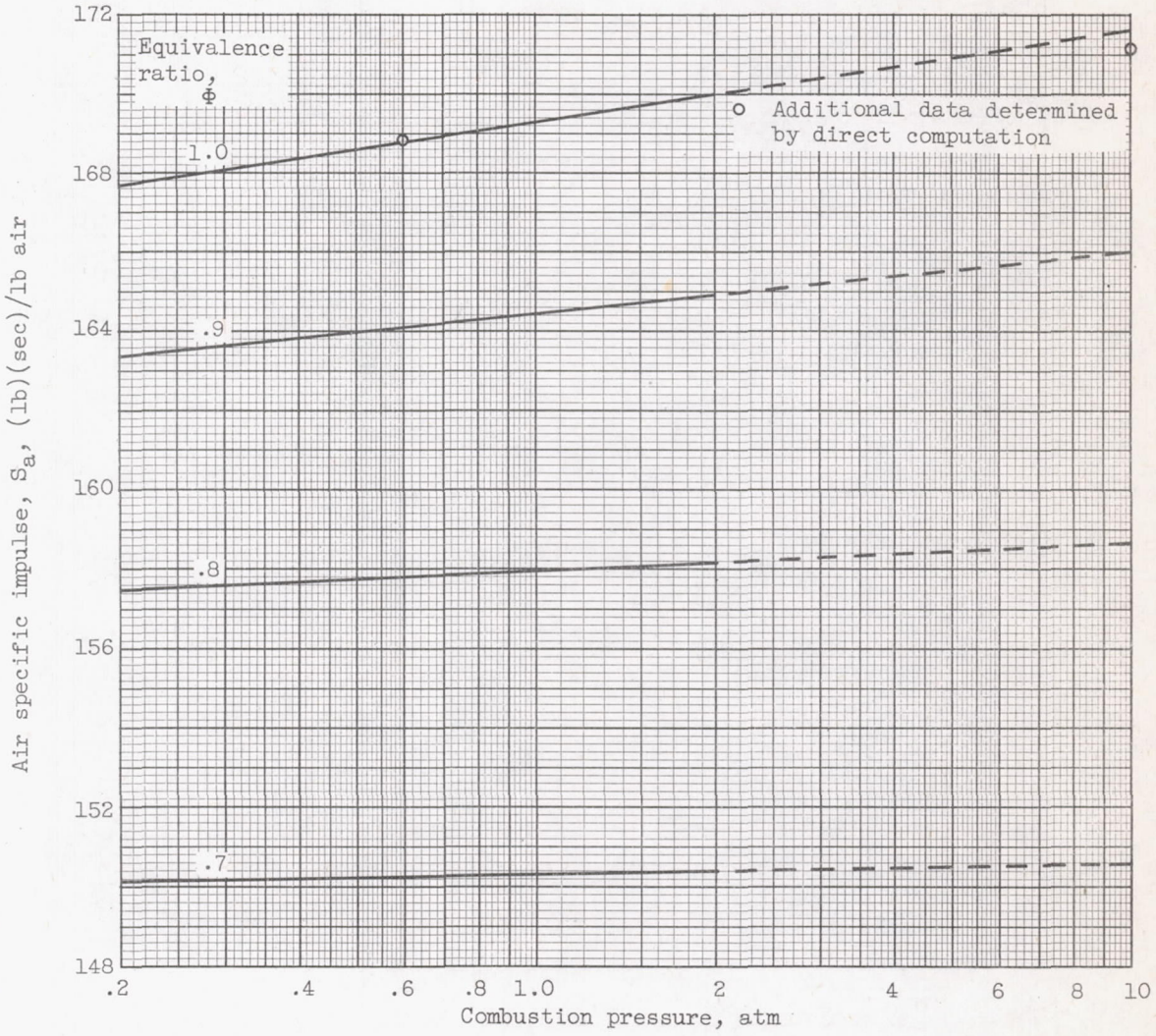
Figure 3. - Continued. Variation of theoretical air specific impulse with equivalence ratio and inlet-air temperature. Combustion pressure, 2 atmospheres.



(g) Pentaborane.

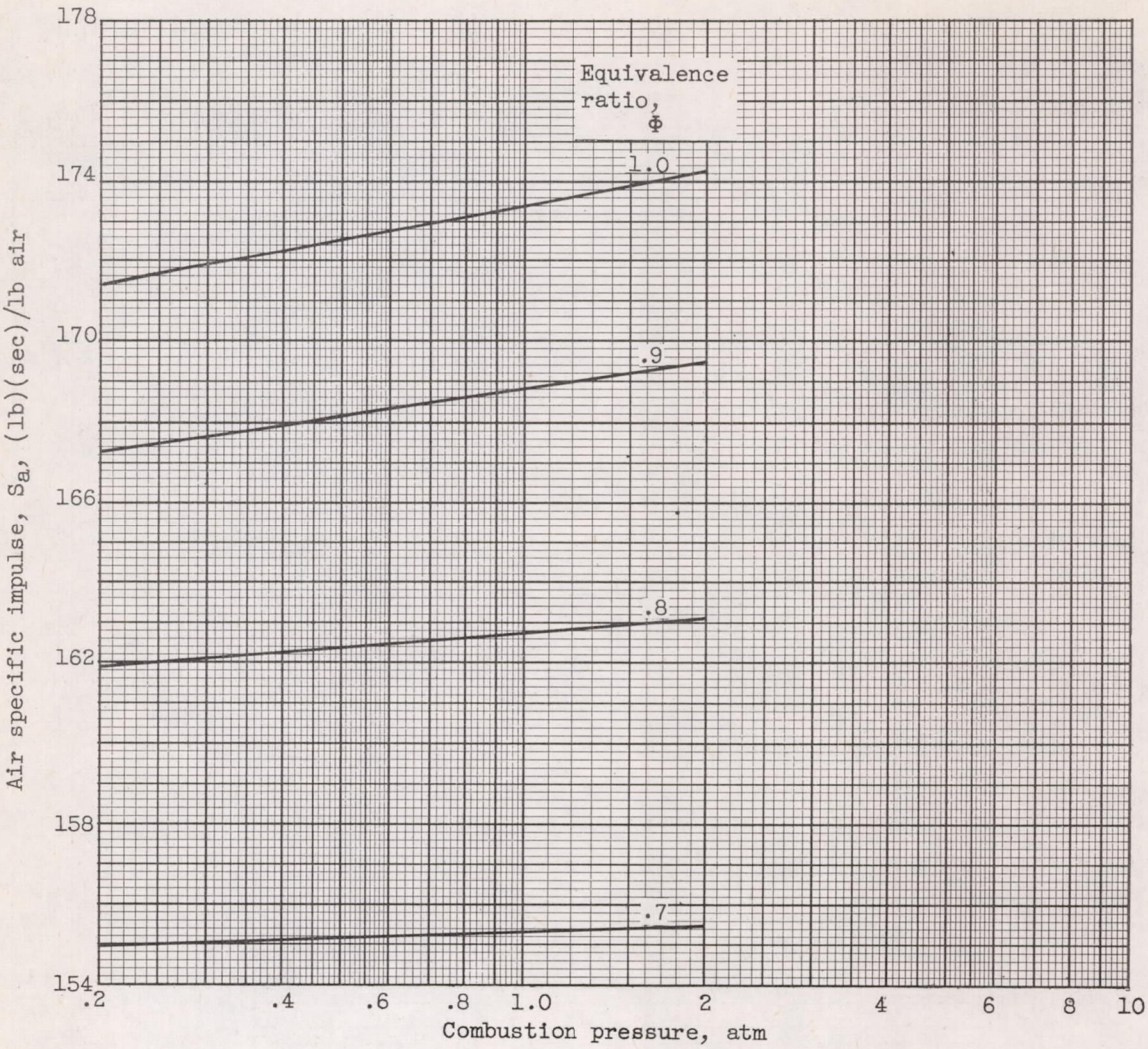
Figure 3. - Concluded. Variation of theoretical air specific impulse with equivalence ratio and inlet-air temperature. Combustion pressure, 2 atmospheres.

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(a) Octene-1.

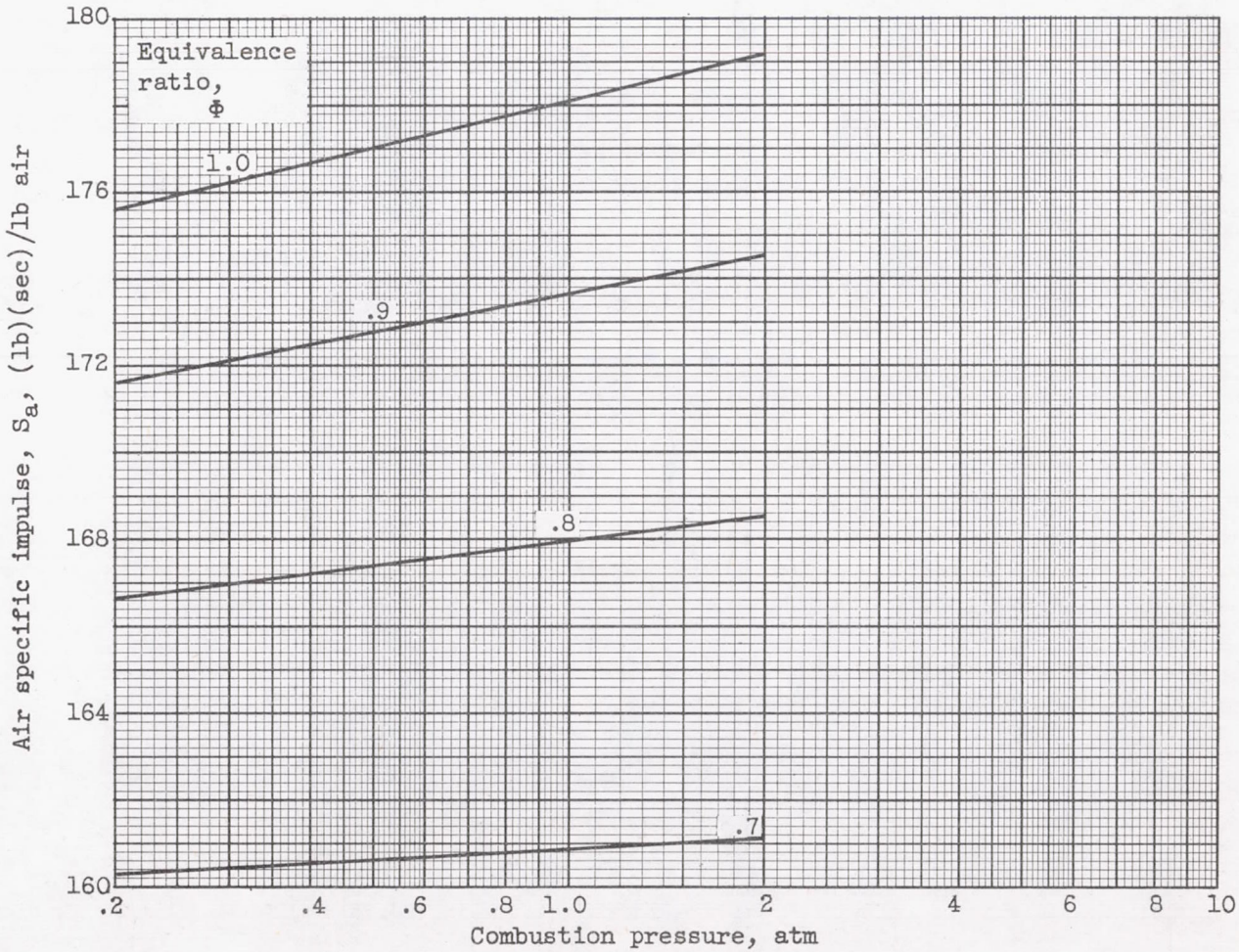
Figure 4. - Variation of theoretical air specific impulse with combustion pressure at selected equivalence ratios. Inlet-air temperature, 100° F.



(b) 30-Percent-boron slurry.

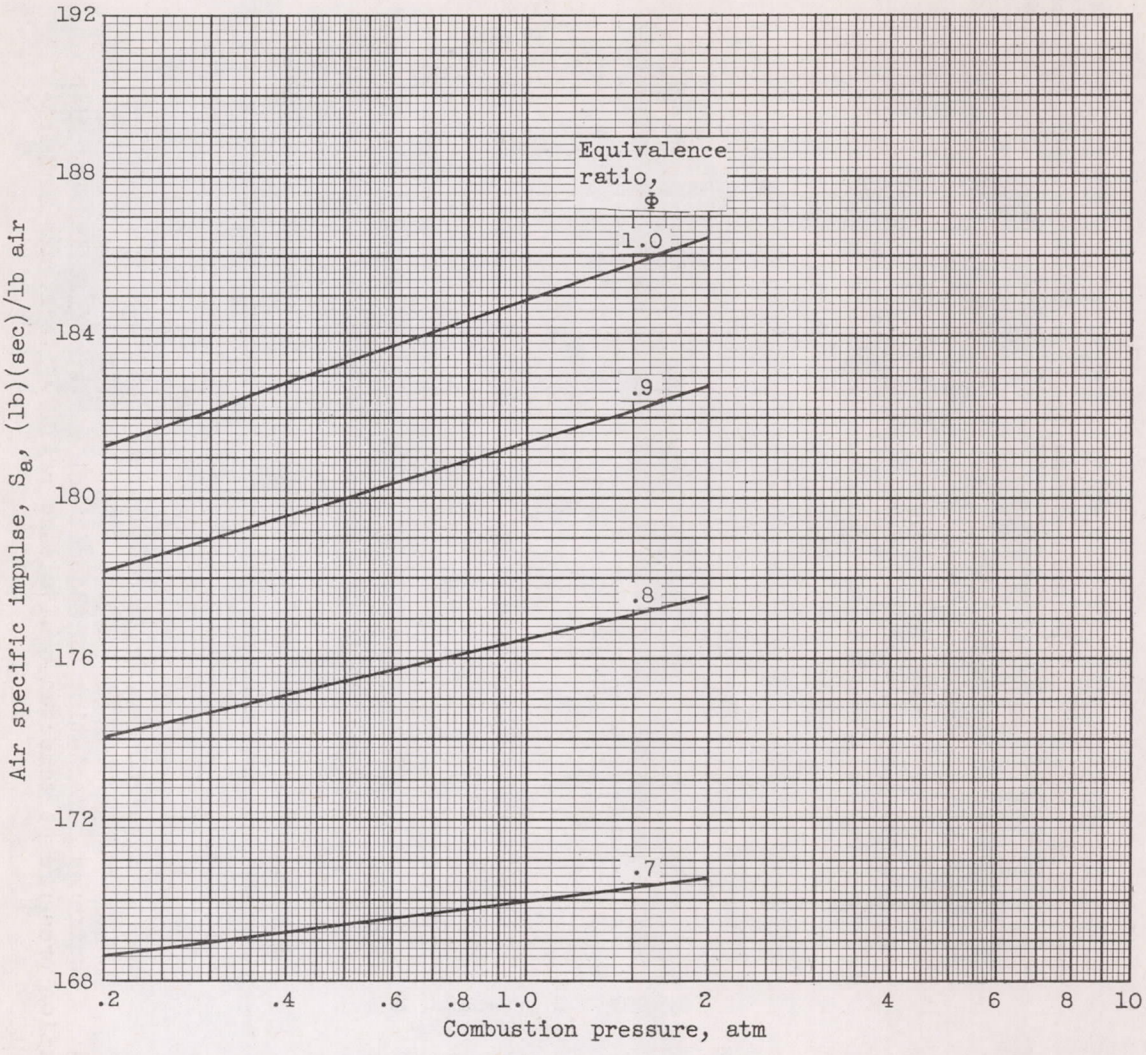
Figure 4. - Continued. Variation of theoretical air specific impulse with combustion pressure at selected equivalence ratios. Inlet-air temperature, 100° F.

CC-7 back



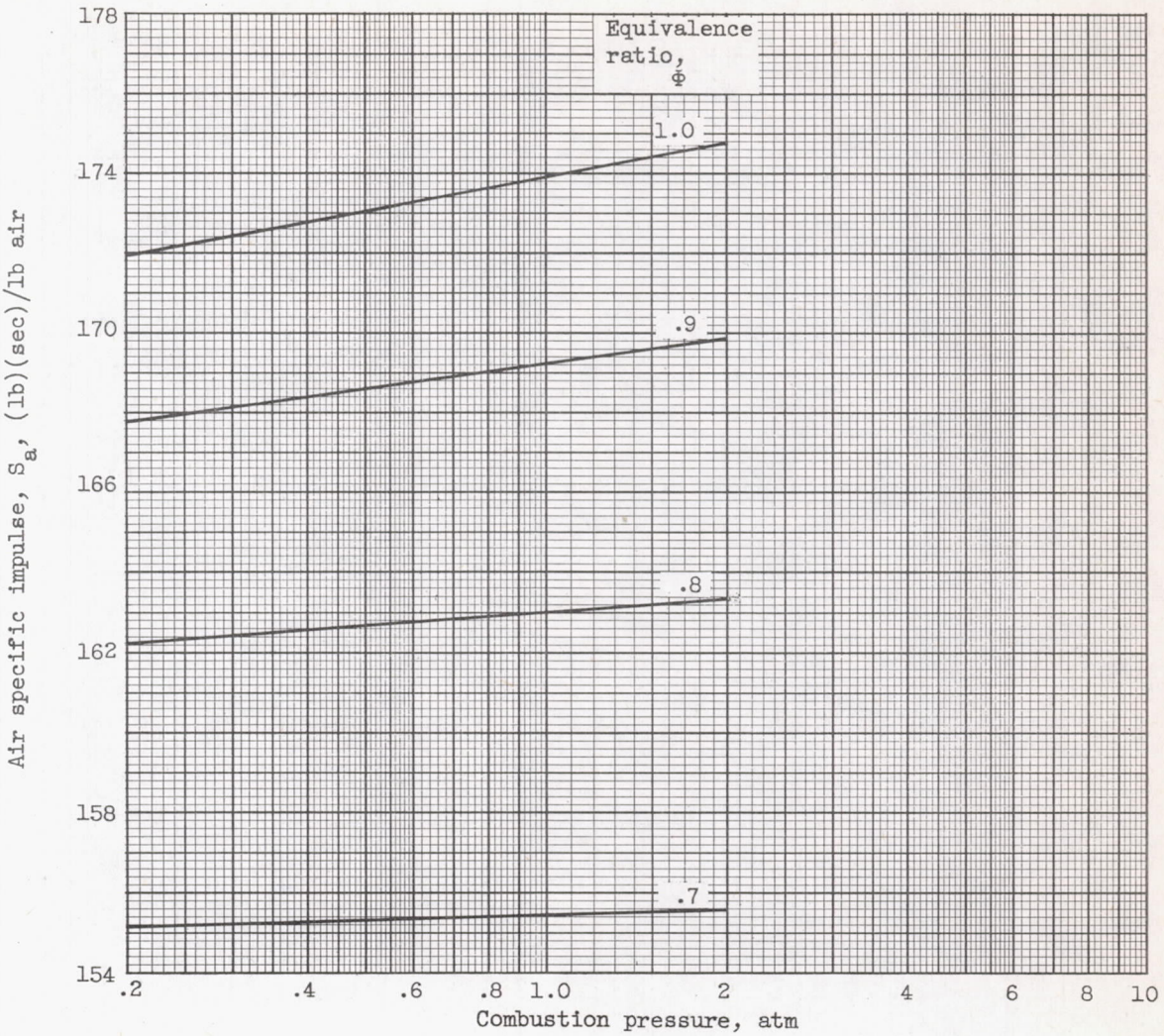
(c) 60-Percent-boron slurry.

Figure 4. - Continued. Variation of theoretical air specific impulse with combustion pressure at selected equivalence ratios. Inlet-air temperature, 100° F.



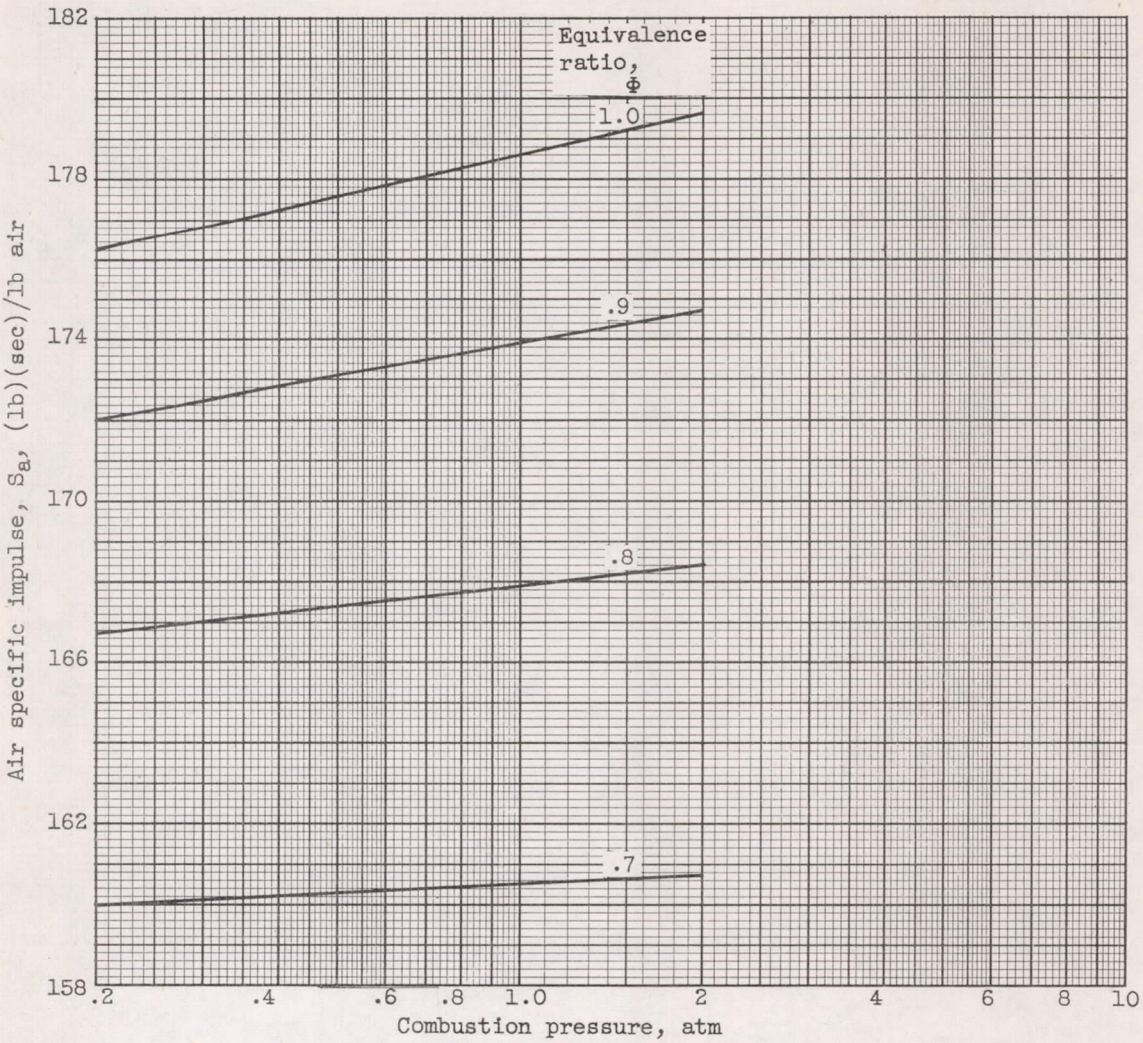
(d) Boron.

Figure 4. - Continued. Variation of theoretical air specific impulse with combustion pressure at selected equivalence ratios. Inlet-air temperature, 100° F.



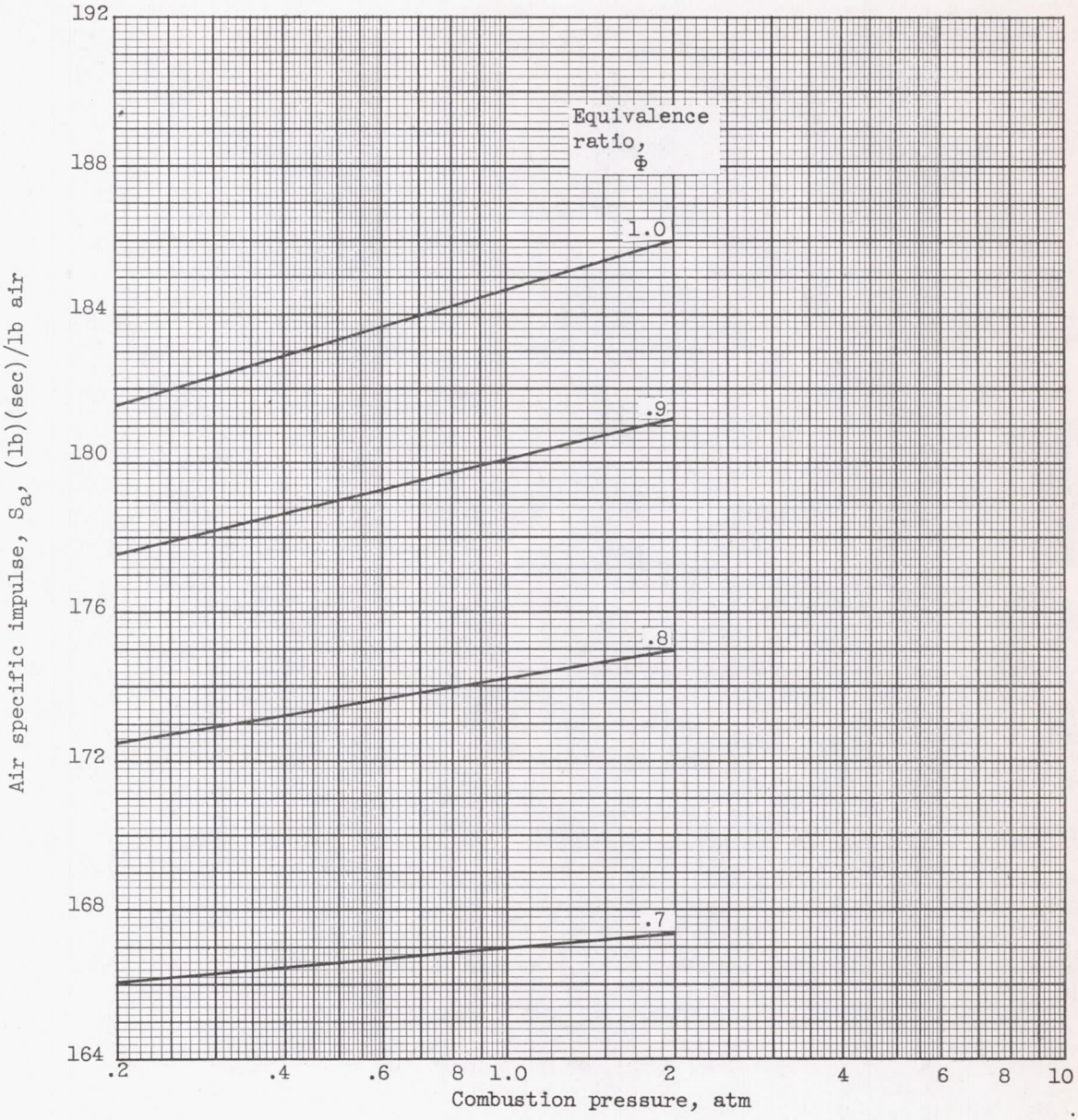
(e) 30-Percent-pentaborane blend

Figure 4. - Continued. Variation of theoretical air specific impulse with combustion pressure at selected equivalence ratios. Inlet-air temperature, 100° F.



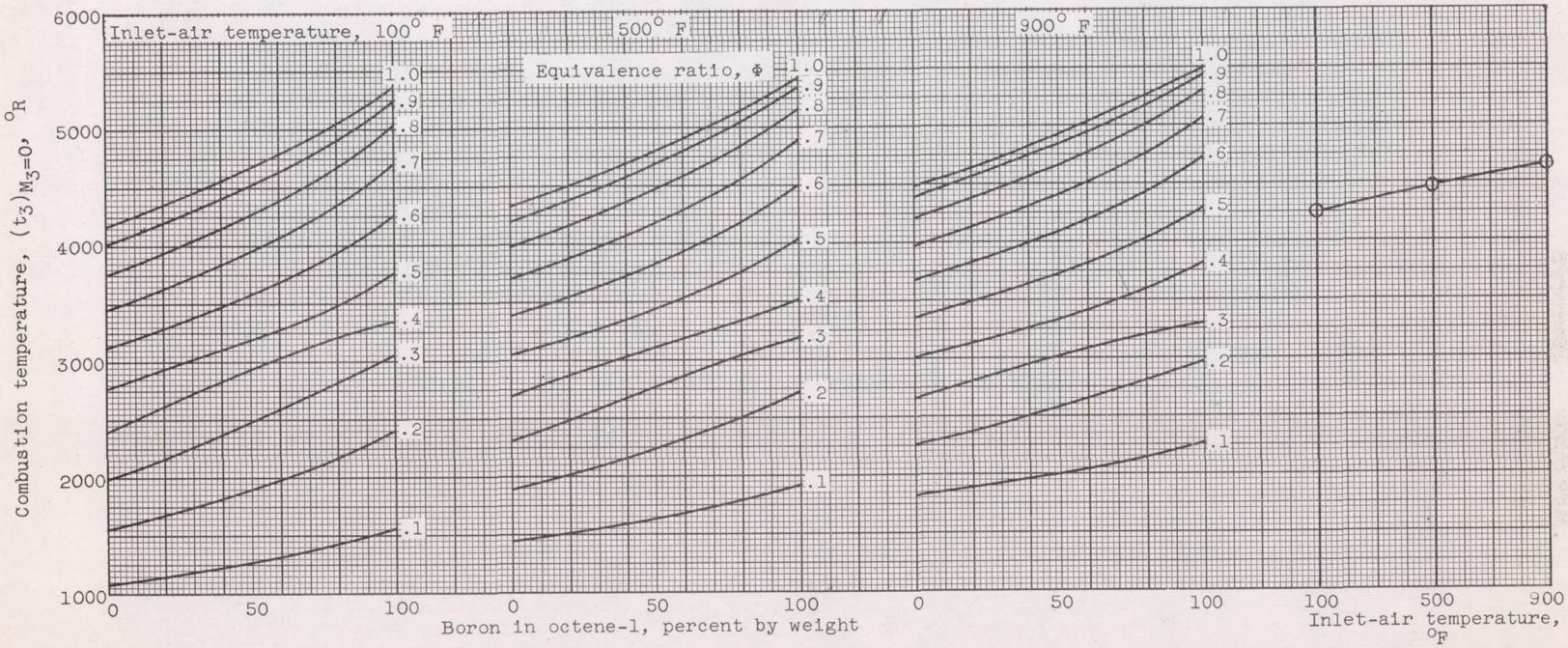
(f) 60-Percent-pentaborane blend.

Figure 4. - Continued. Variation of theoretical air specific impulse with combustion pressure at selected equivalence ratios. Inlet-air temperature, 100° F.



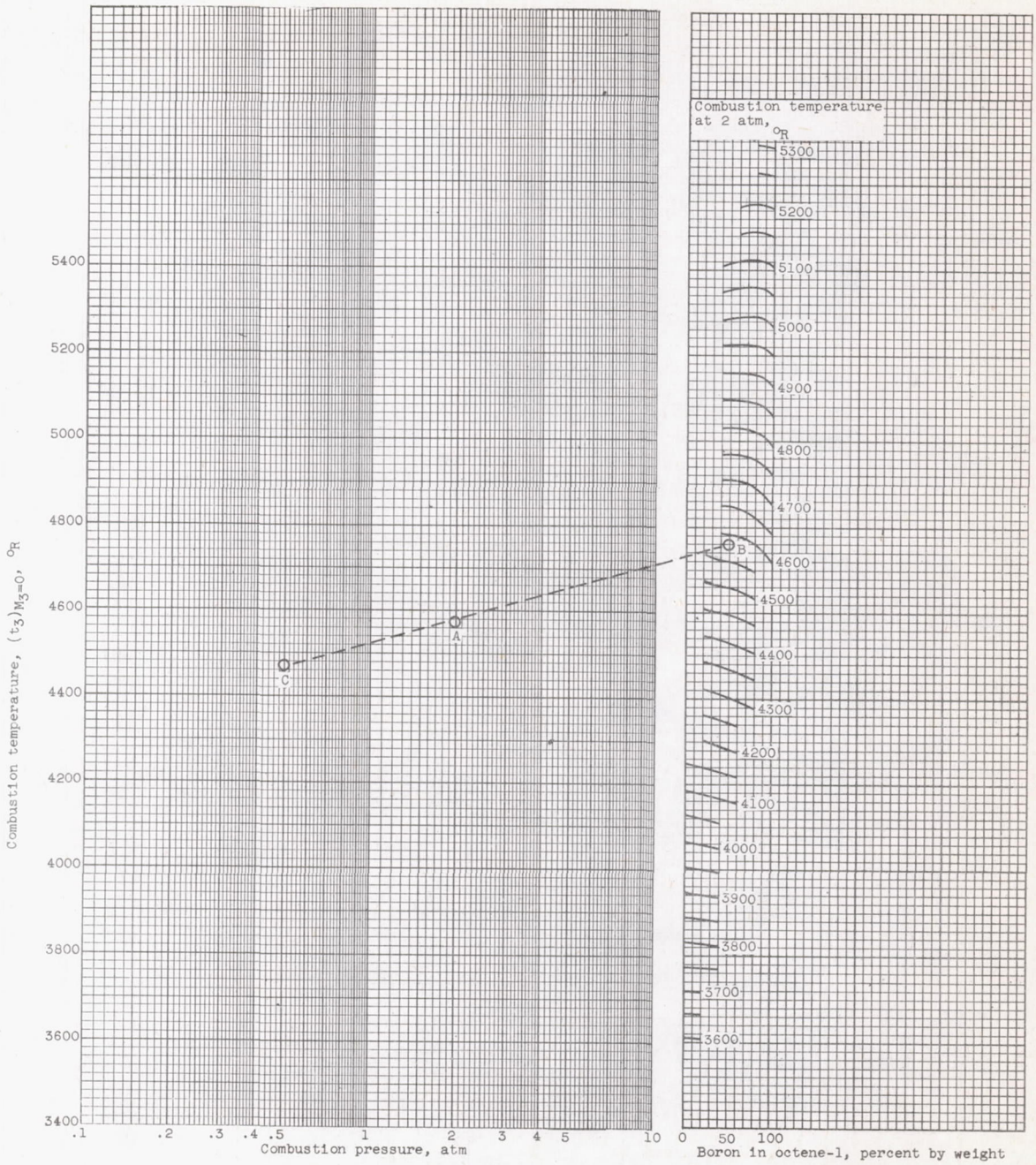
(g) Pentaborane.

Figure 4. - Concluded. Variation of theoretical air specific impulse with combustion pressure at selected equivalence ratios. Inlet-air temperature, 100° F.



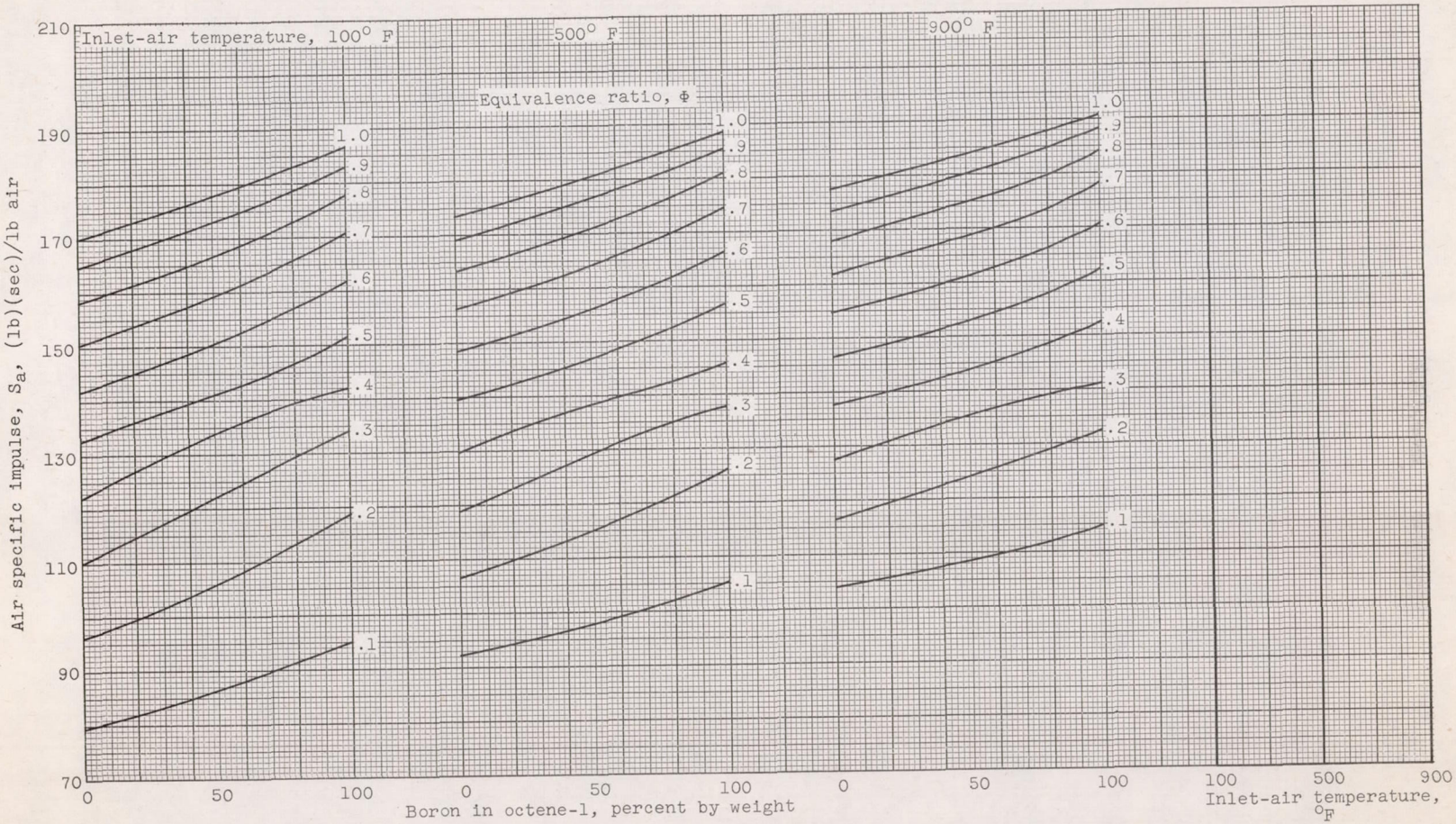
(a) Variation of combustion temperature with boron concentration and equivalence ratio at three inlet-air temperatures. Combustion pressure, 2 atmospheres.

Figure 5. - Effect of boron concentration and ram-jet combustor-inlet conditions on theoretical combustion performance of boron slurries.



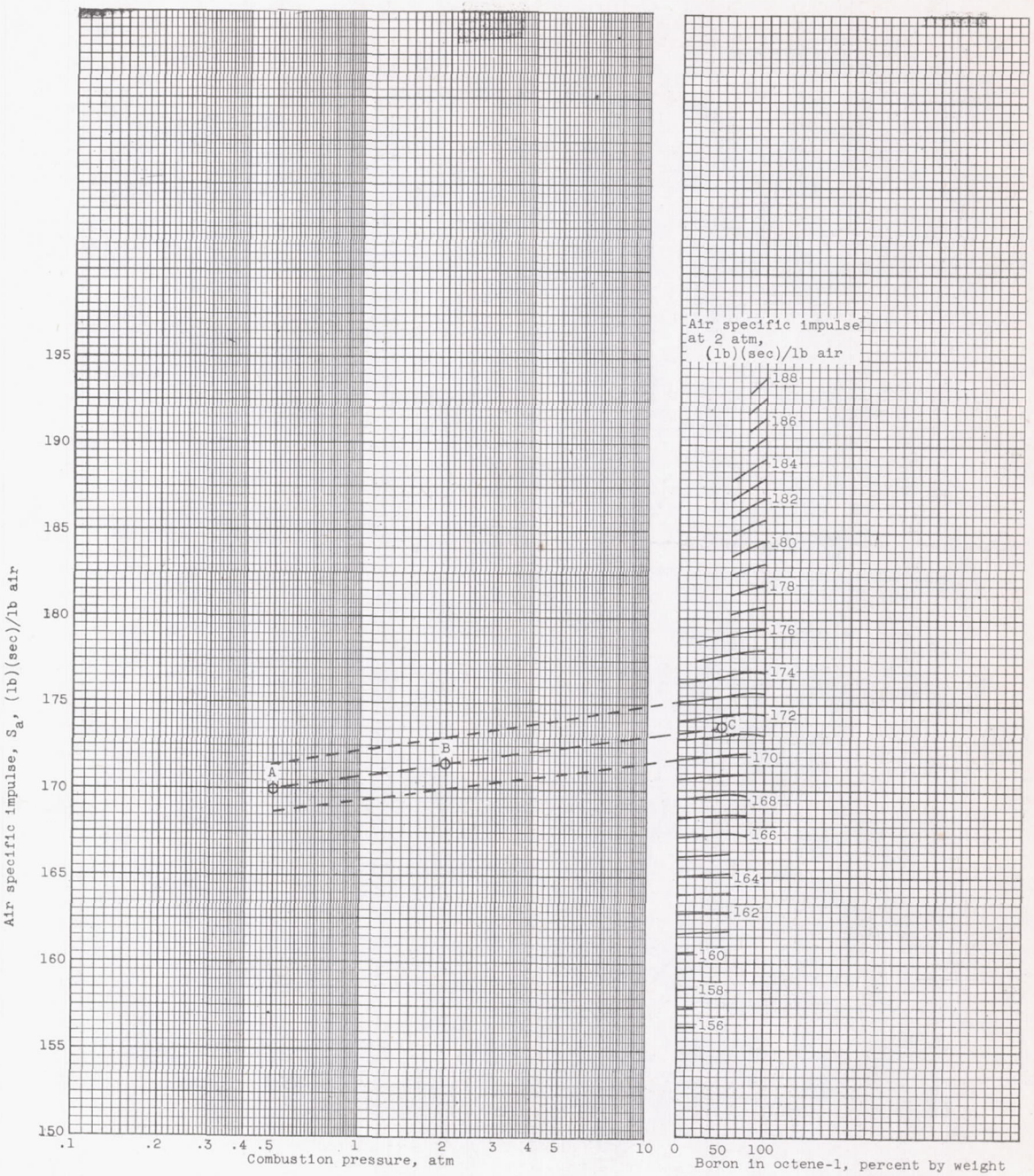
(b) Chart for determining variation of combustion temperature with combustion pressure and boron concentration.

Figure 5. - Continued. Effect of boron concentration and ram-jet combustor-inlet conditions on theoretical combustion performance of boron slurries.



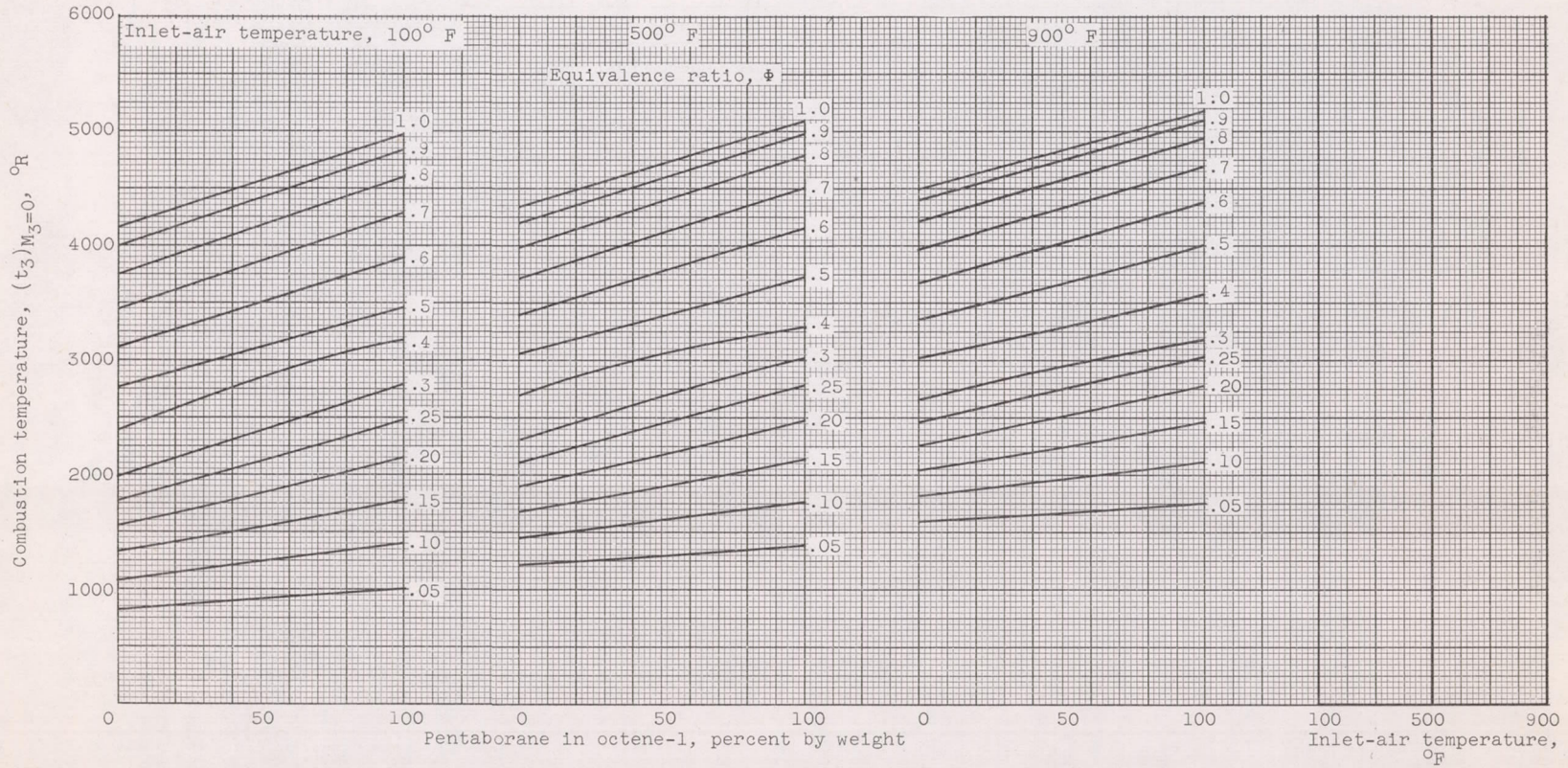
(c) Variation of air specific impulse with boron concentration and equivalence ratio at three inlet-air temperatures. Combustion pressure, 2 atmospheres.

Figure 5. - Continued. Effect of boron concentration and ram-jet combustor-inlet conditions on theoretical combustion performance of boron slurries.



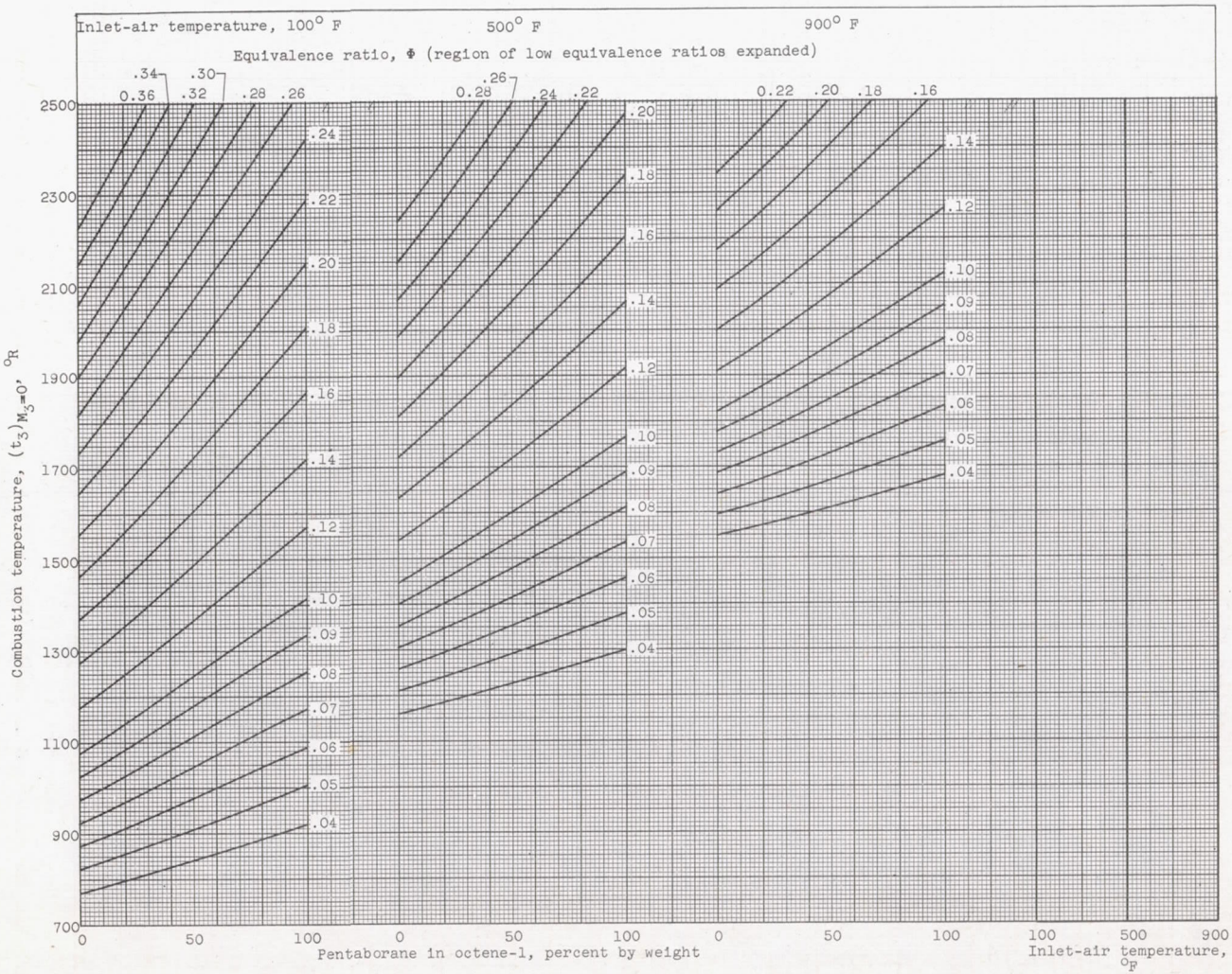
(d) Chart for determining variation of air specific impulse with combustion pressure and boron concentration.

Figure 5. - Concluded. Effect of boron concentration and ram-jet combustor-inlet conditions on theoretical combustion performance of boron slurries.



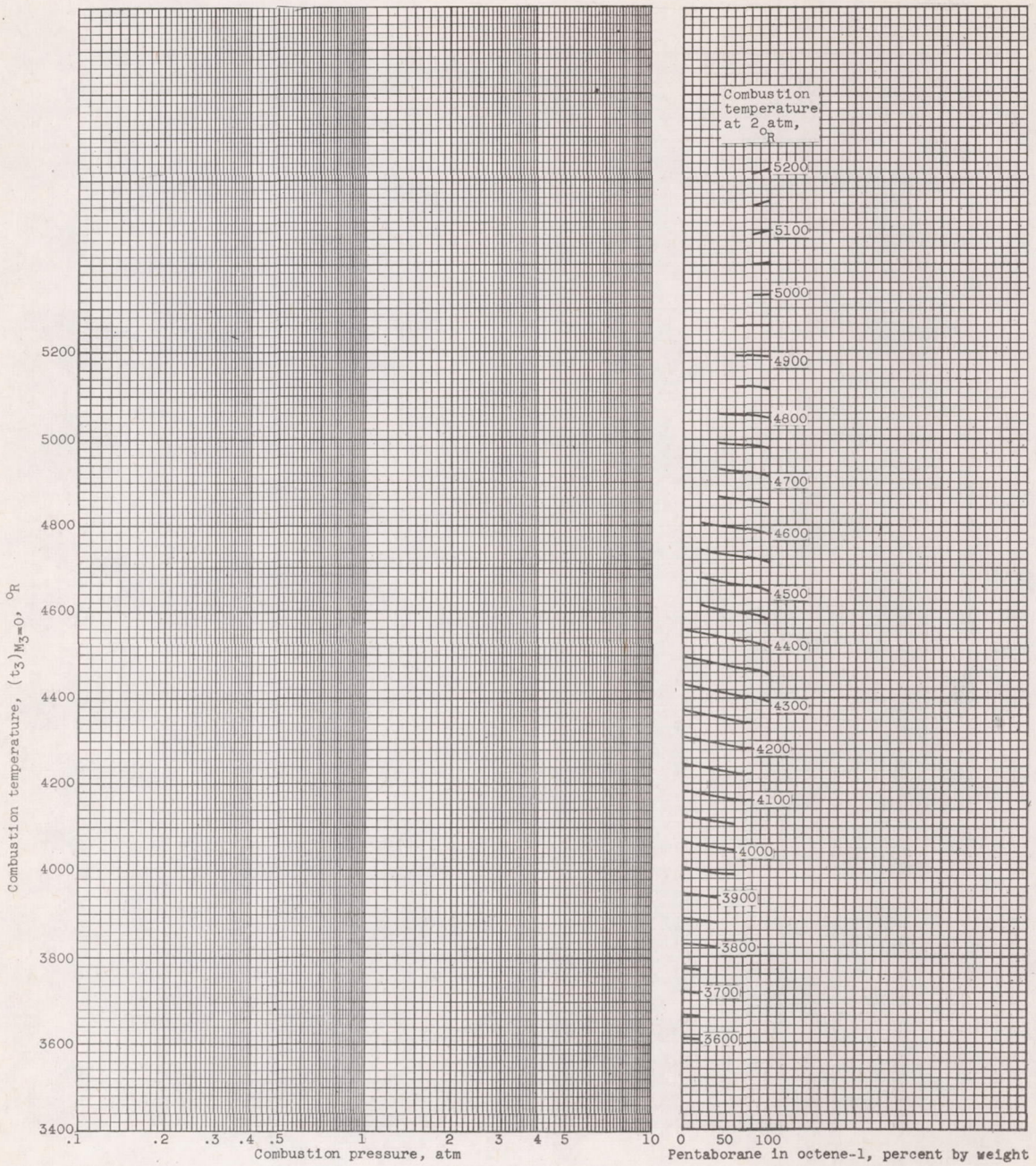
(a) Variation of combustion temperature with pentaborane concentration and equivalence ratio at three inlet-air temperatures. Combustion pressure, 2 atmospheres.

Figure 6. - Effect of pentaborane concentration and ram-jet combustor-inlet conditions on theoretical combustion performance of pentaborane blends.



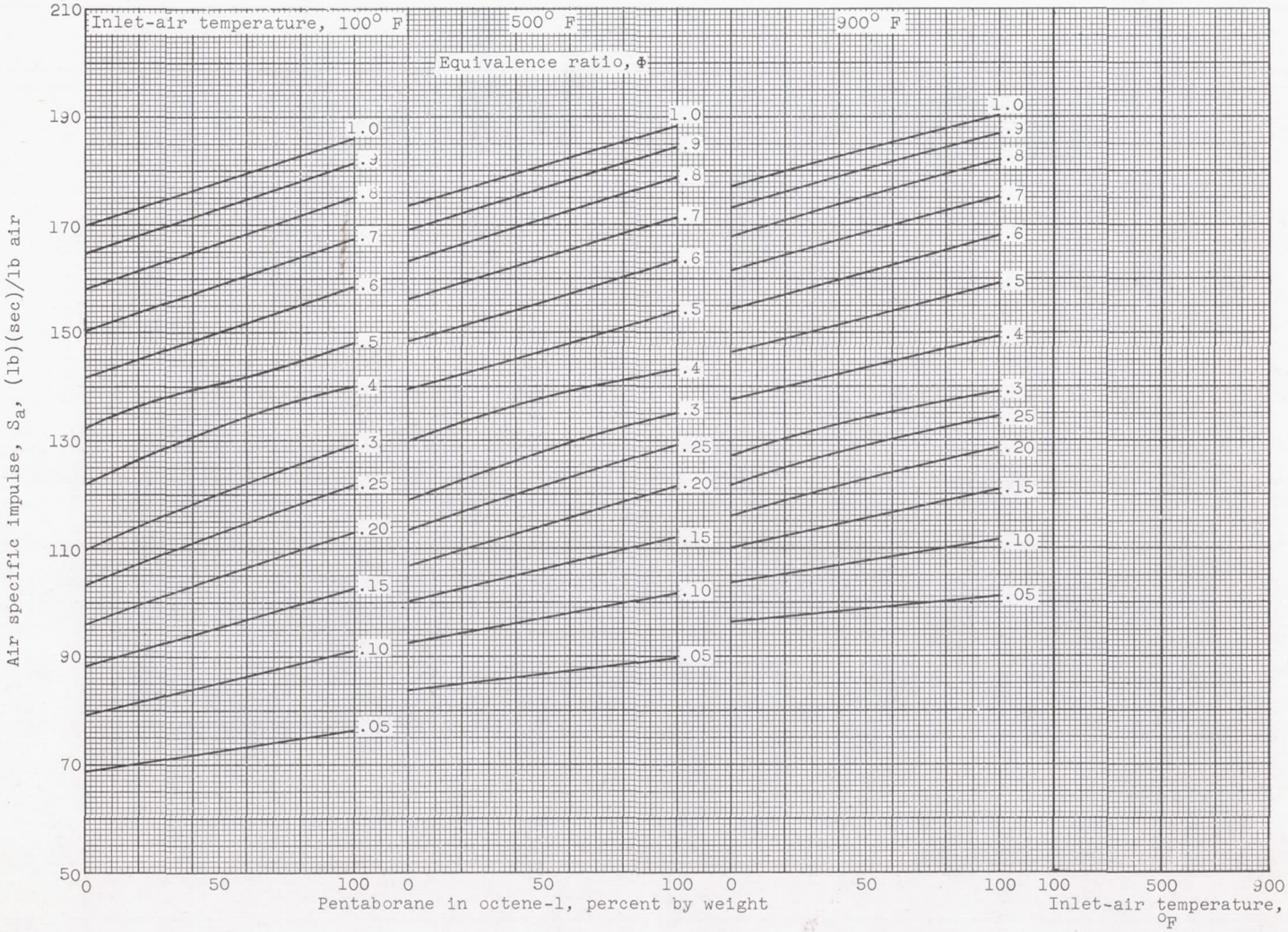
(a) Concluded. Variation of combustion temperature with pentaborane concentration and equivalence ratio at three inlet-air temperatures. Combustion pressure, 2 atmospheres.

Figure 6. - Continued. Effect of pentaborane concentration and ram-jet combustor-inlet conditions on theoretical combustion performance of pentaborane blends.



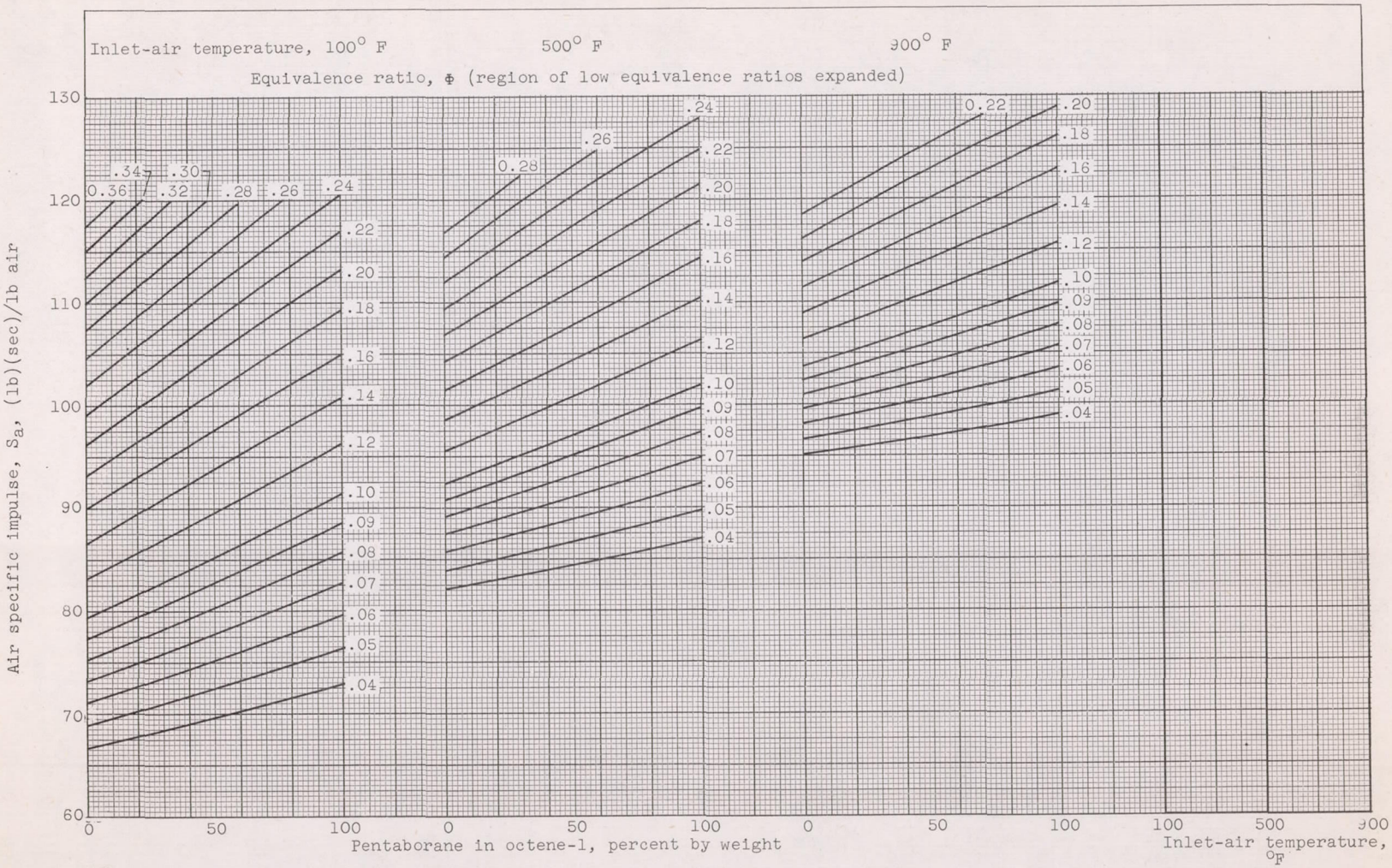
(b) Chart for determining variation of combustion temperature with combustion pressure and pentaborane concentration.

Figure 6. - Continued. Effect of pentaborane concentration and ram-jet combustor-inlet conditions on theoretical combustion performance of pentaborane blends.



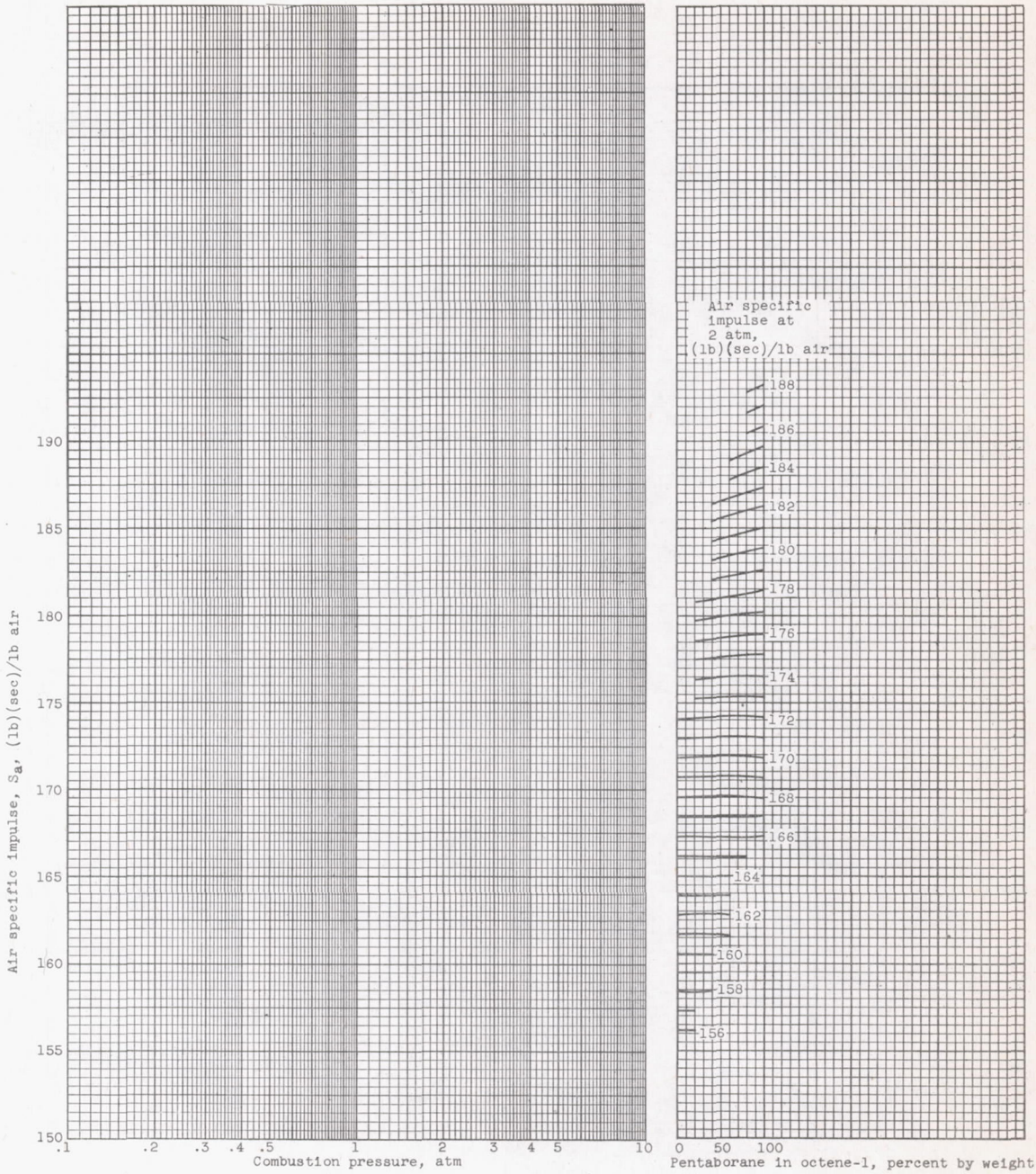
(c) Variation of air specific impulse with pentaborane concentration and equivalence ratio at three inlet-air temperatures. Combustion pressure, 2 atmospheres.

Figure 6. - Continued. Effect of pentaborane concentration and ram-jet combustor-inlet conditions on theoretical combustion performance of pentaborane blends.



(c) Concluded. Variation of air specific impulse with pentaborane concentration and equivalence ratio at three inlet-air temperatures. Combustion pressure, 2 atmospheres.

Figure 6. - Continued. Effect of pentaborane concentration and ram-jet combustor-inlet conditions on theoretical combustion performance of pentaborane blends.



(d) Chart for determining variation of air specific impulse with combustion pressure and pentaborane concentration.

Figure 6. - Concluded. Effect of pentaborane concentration and ram-jet combustor-inlet conditions on theoretical combustion performance of pentaborane blends.

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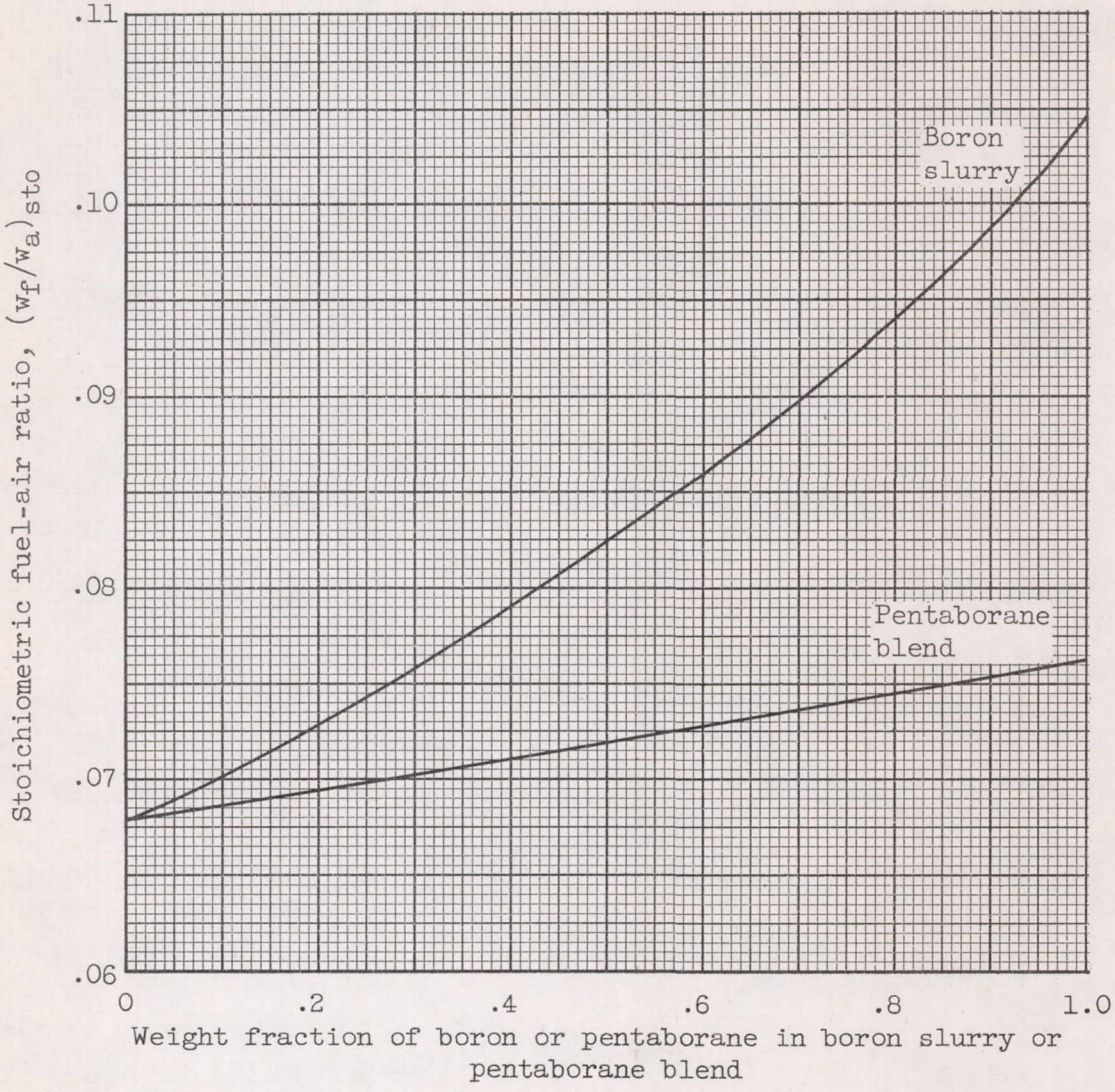


Figure 7. - Variation of stoichiometric fuel-air ratio with weight fraction of boron or pentaborane in boron slurry or pentaborane blend.

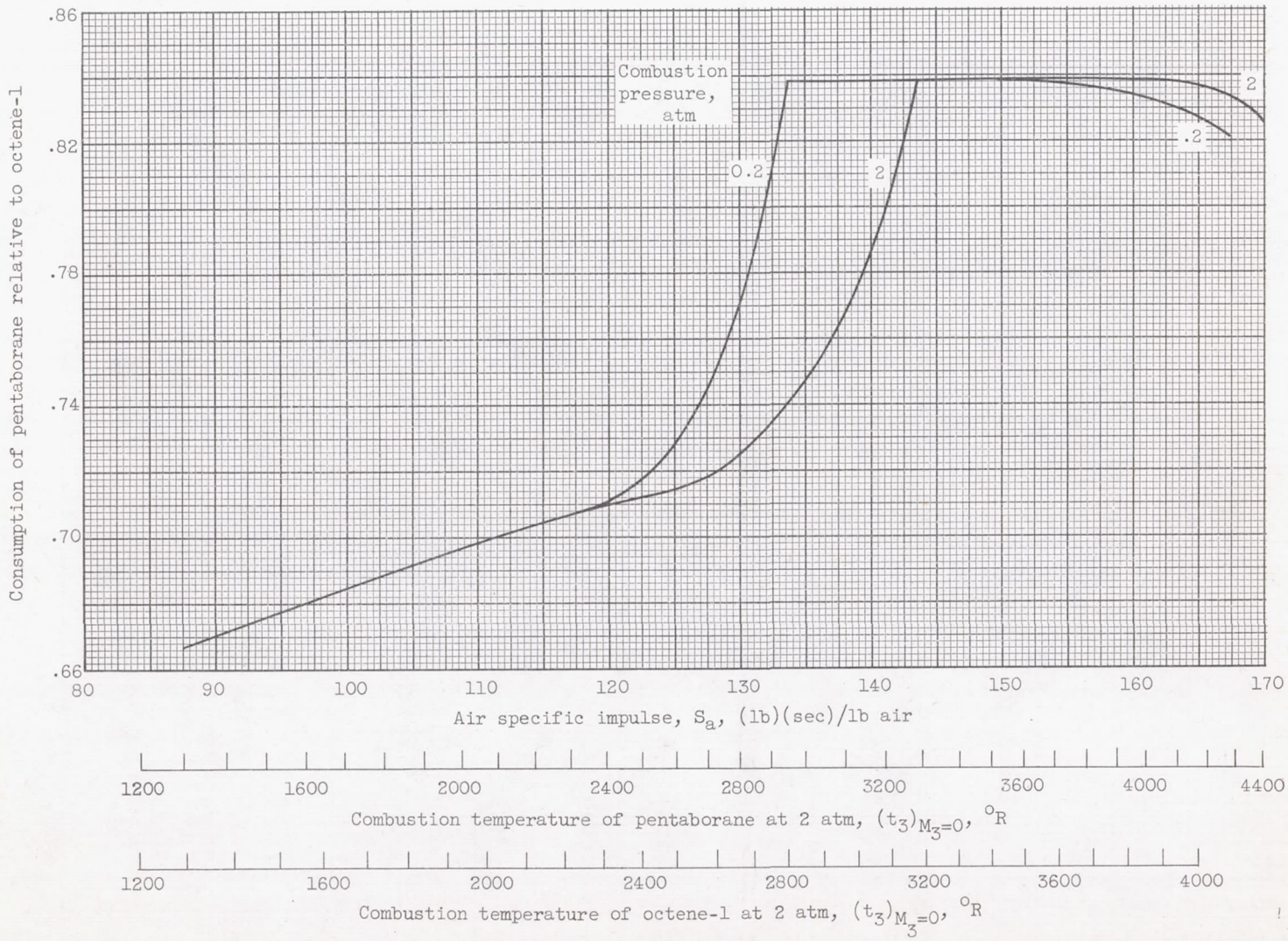
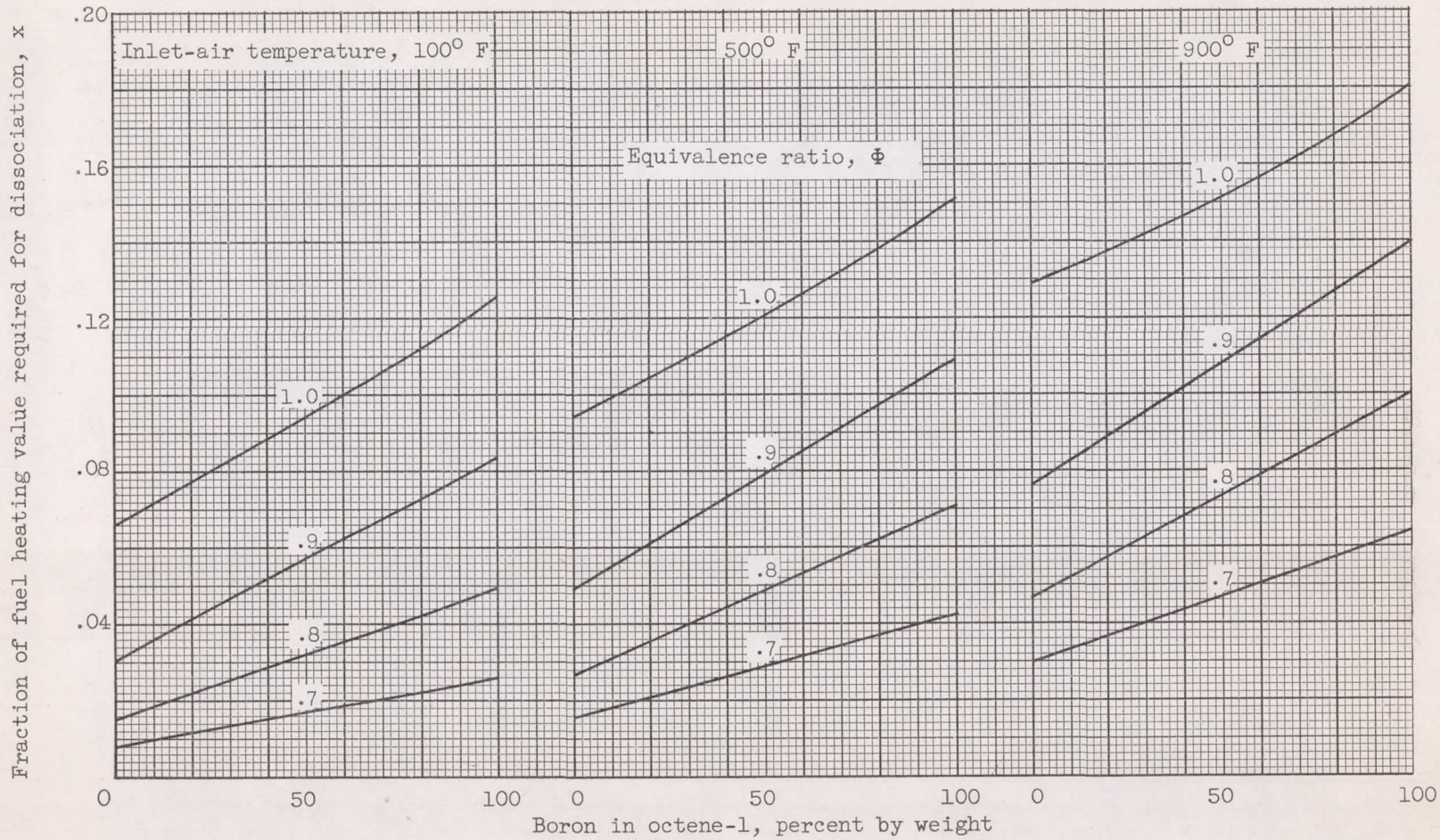
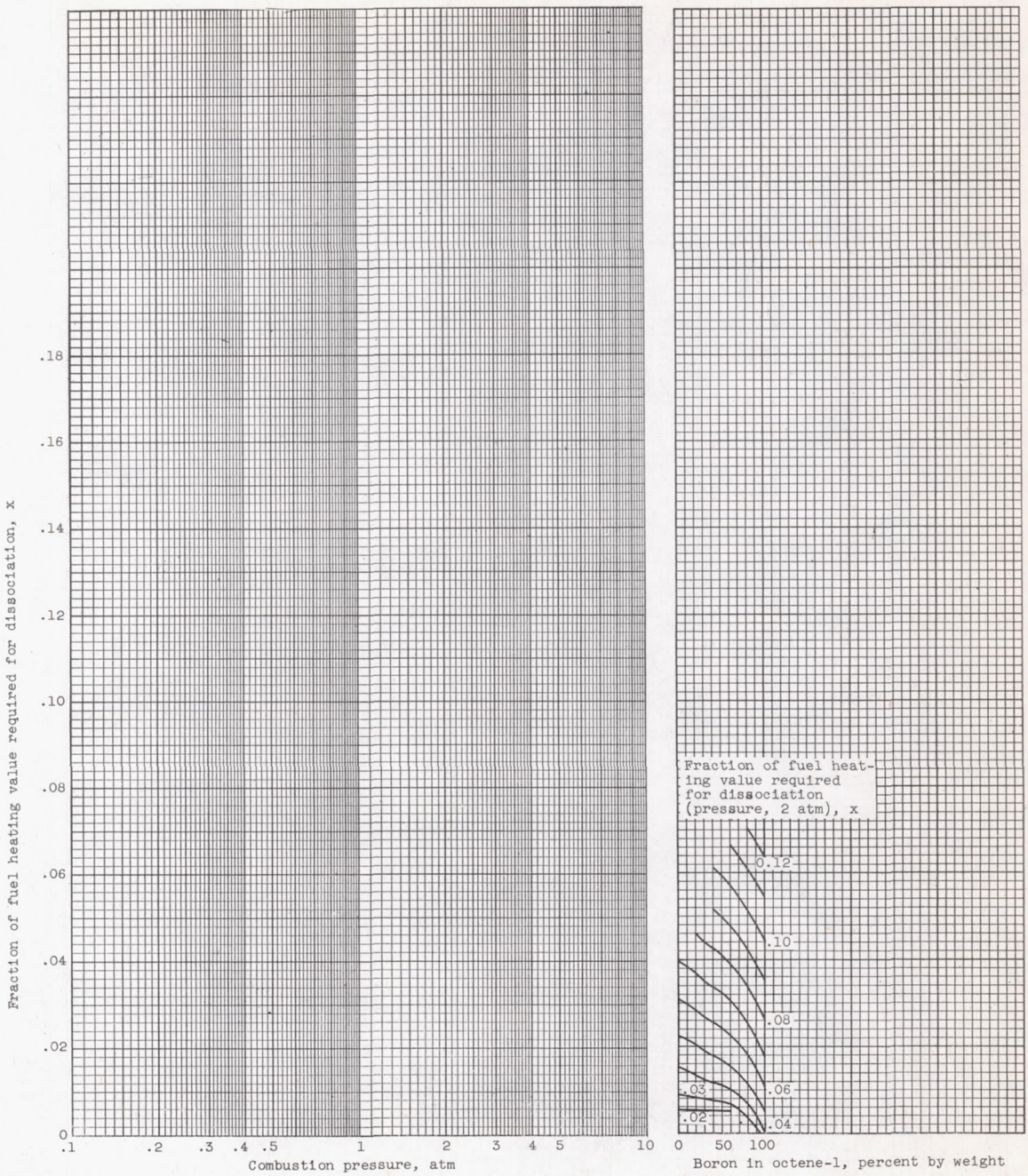


Figure 8. - Consumption of pentaborane relative to octene-1 against air specific impulse for combustion pressures of 0.2 and 2 atmospheres. Inlet-air temperature, 100° F.



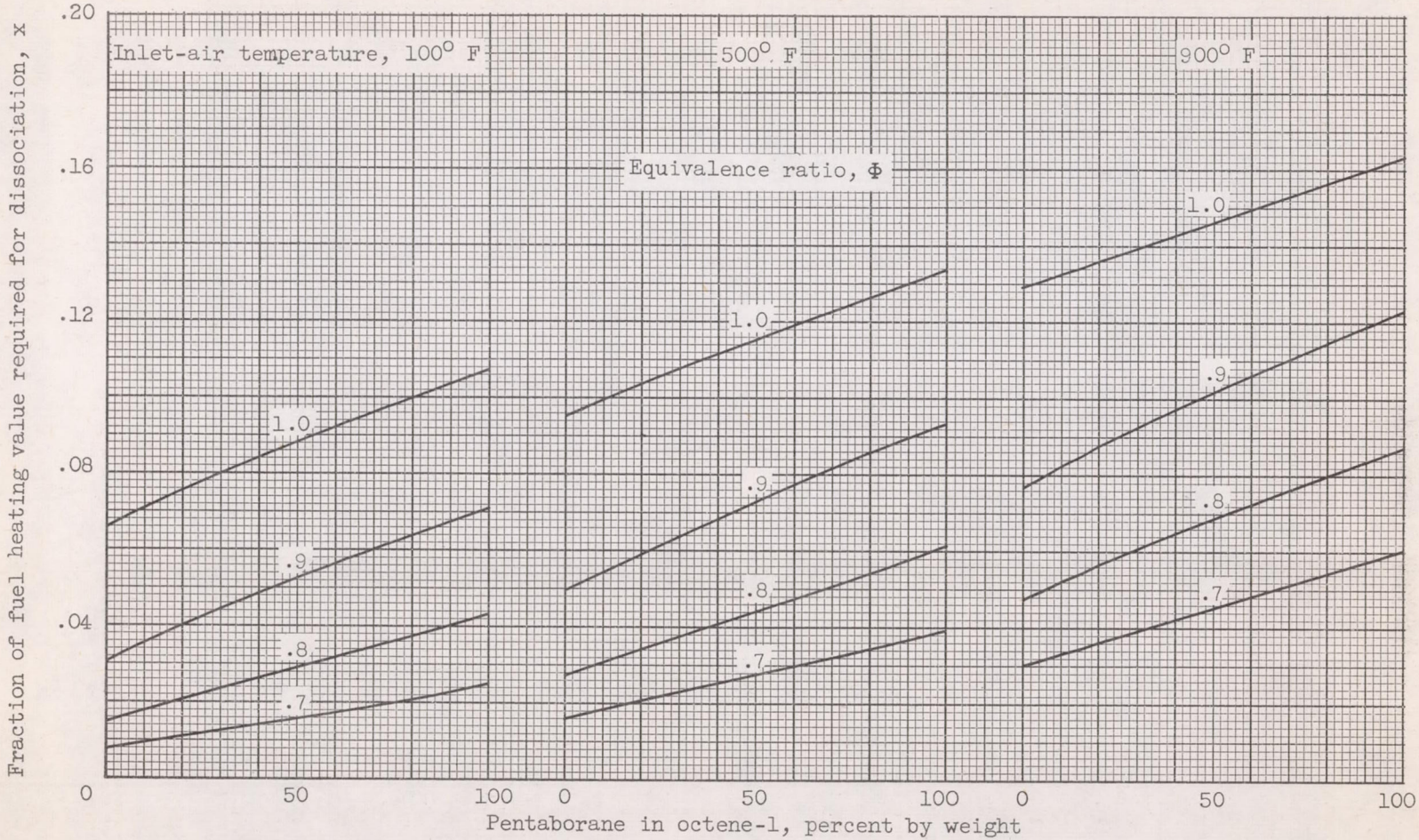
(a) Variation of x with boron concentration at three inlet-air temperatures. Combustion pressure, 2 atmospheres.

Figure 9. - Effect of ram-jet combustor-inlet conditions and boron concentration in slurry on fraction of fuel heating value required for dissociation.



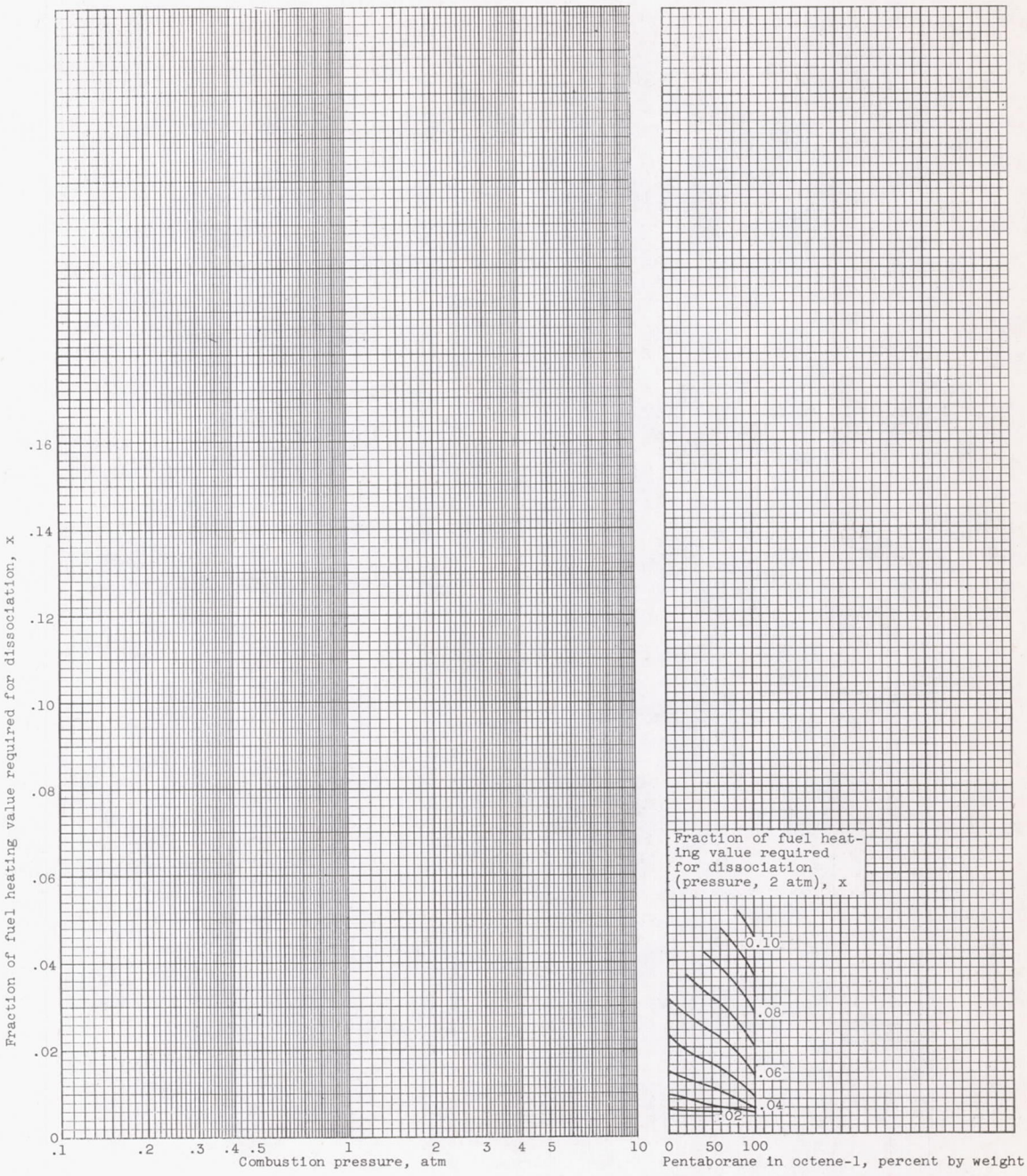
(b) Variation of x with combustion pressure and boron concentration.

Figure 9. - Concluded. Effect of ram-jet combustor-inlet conditions and boron concentration in slurry on fraction of fuel heating value required for dissociation.



(a) Variation of x with pentaborane concentration at three inlet-air temperatures. Combustion pressure, 2 atmospheres.

Figure 10. - Effect of ram-jet combustor-inlet conditions and pentaborane concentration in blend on fraction of fuel heating value required for dissociation.



(b) Variation of x with combustion pressure and pentaborane concentration.

Figure 10. - Concluded. Effect of ram-jet combustor-inlet conditions and pentaborane concentration in blend on fraction of fuel heating value required for dissociation.

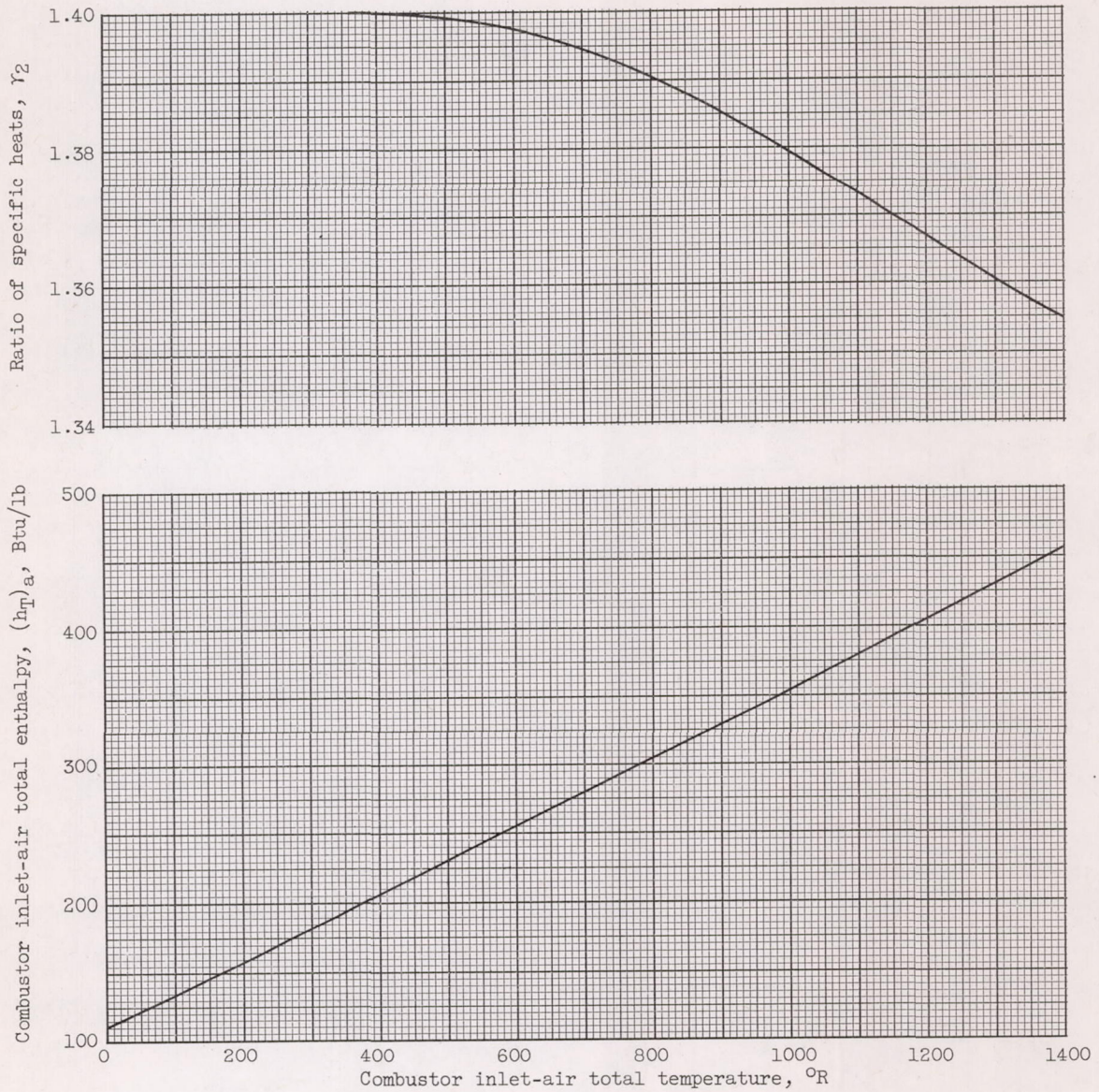
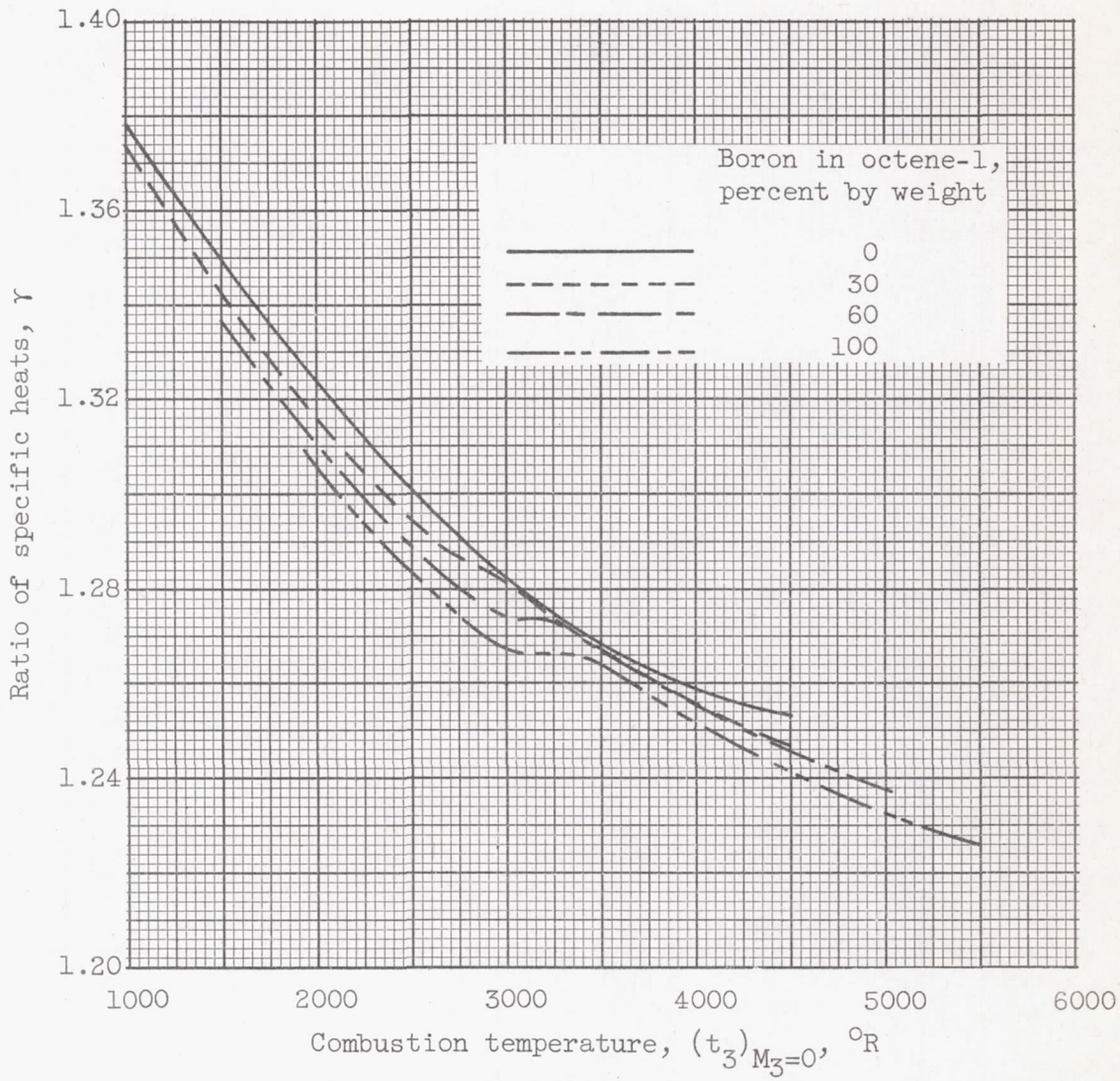


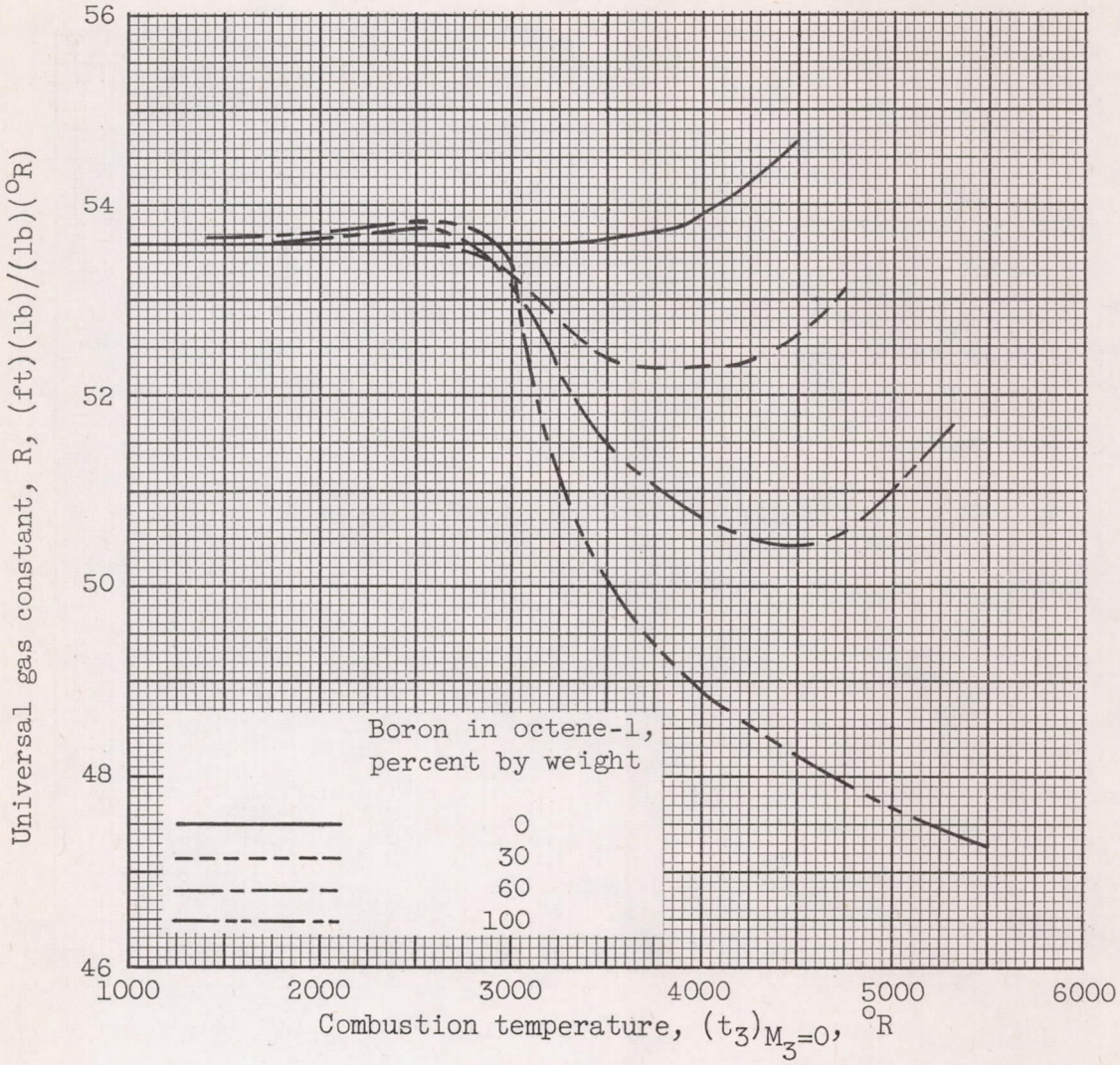
Figure 11. - Variation of ratio of specific heats γ_2 and combustor inlet-air total enthalpy $(h_T)_a$ with combustor inlet-air total temperature.

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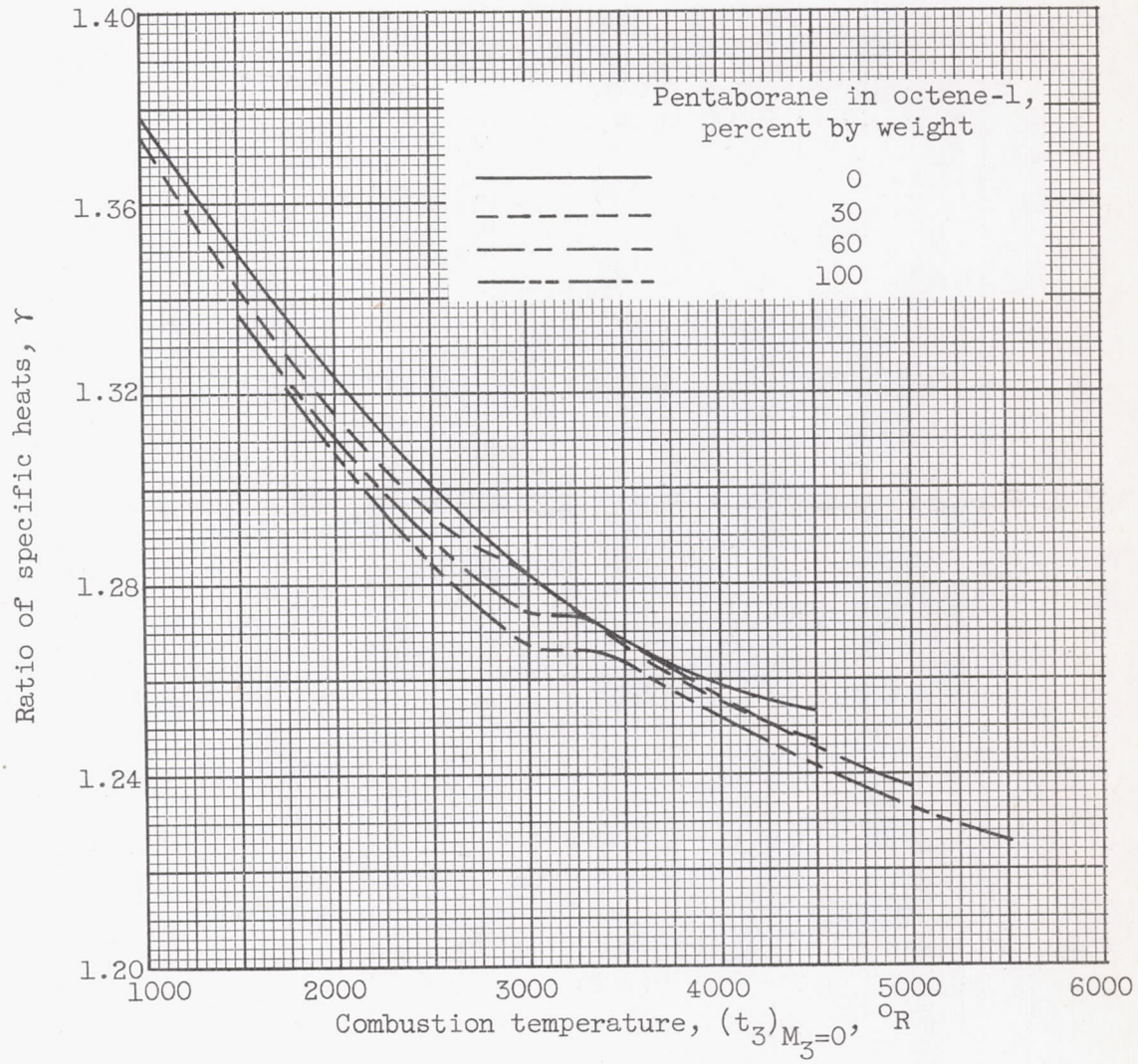
(a) Ratio of specific heats.

Figure 12. - Effect of combustion temperature on thermal properties of products formed in combustion of boron slurries.



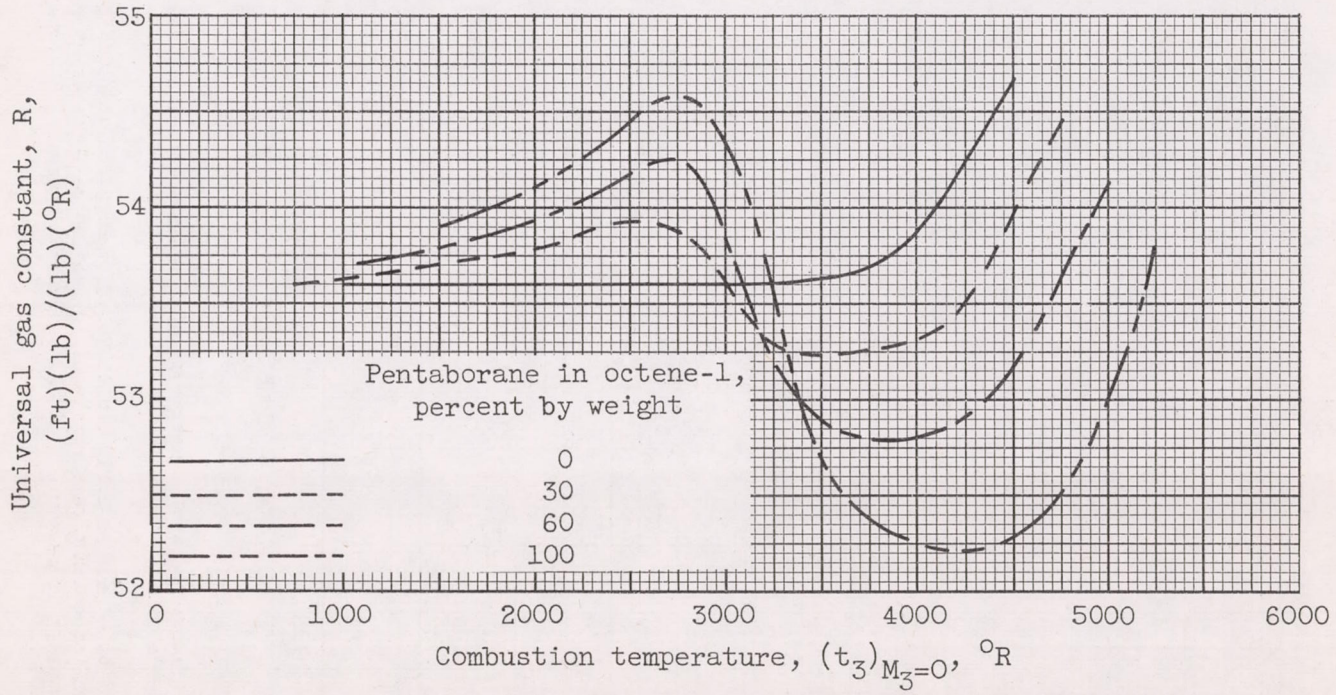
(b) Universal gas constant.

Figure 12. - Concluded. Effect of combustion temperature on thermal properties of products formed in combustion of boron slurries.



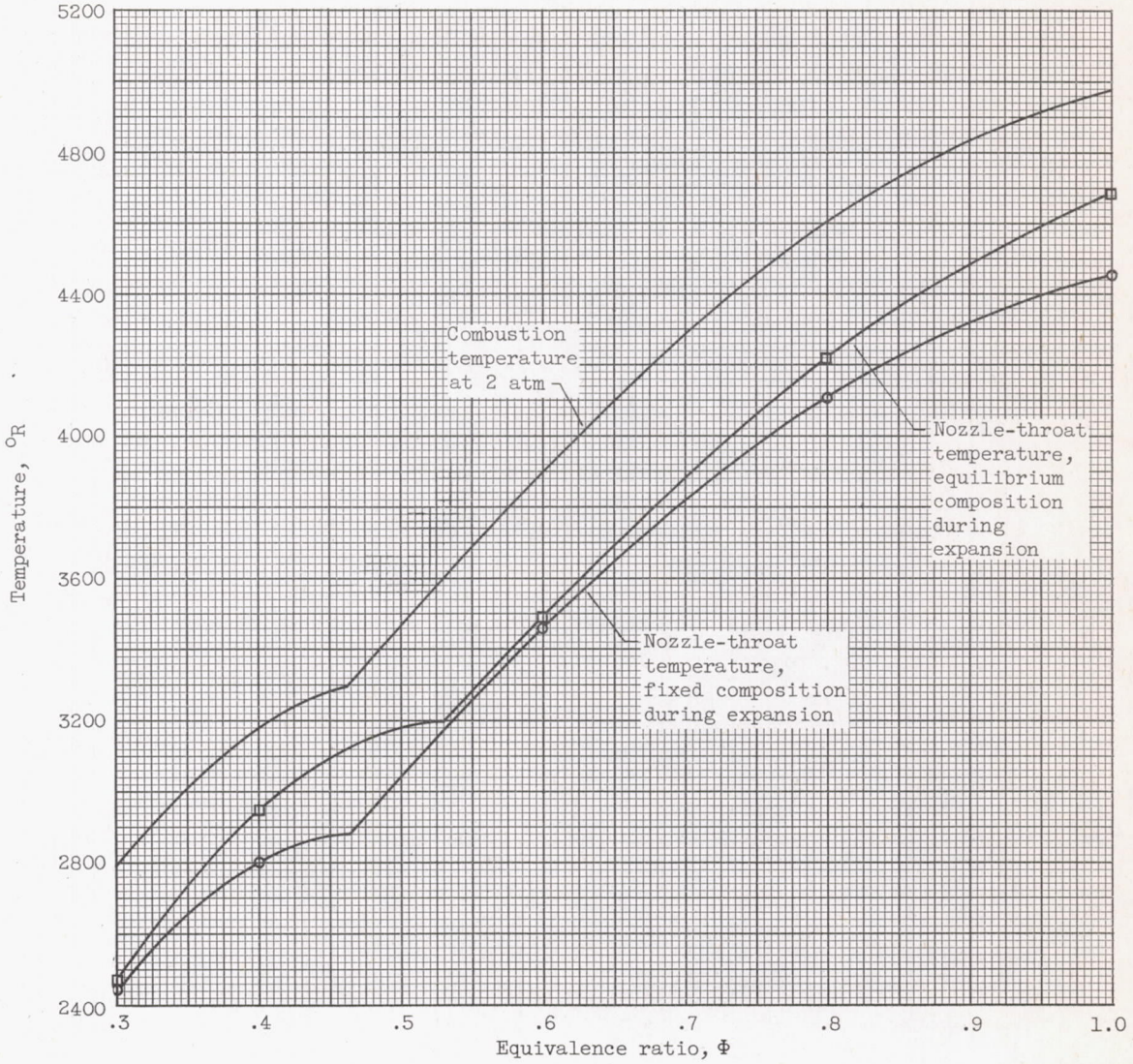
(a) Ratio of specific heats.

Figure 13. - Effect of combustion temperature on thermal properties of products formed in combustion of pentaborane blends.



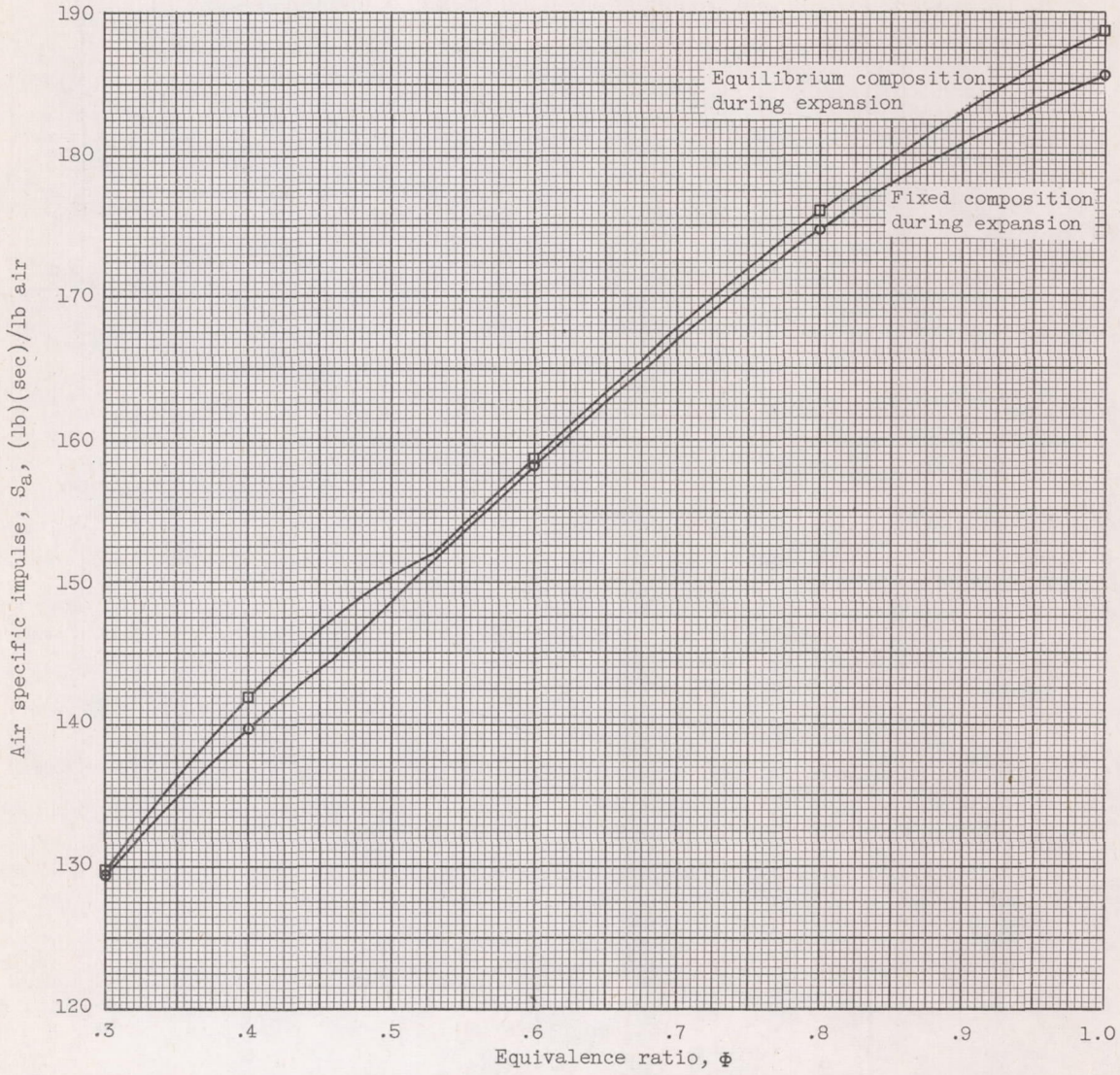
(b) Universal gas constant.

Figure 13. - Concluded. Effect of combustion temperature on thermal properties of products formed in combustion of pentaborane blends.



(a) Variation of nozzle-throat temperature at fixed and at equilibrium composition with equivalence ratio.

Figure 14. - Effect of nozzle expansion at fixed composition compared with expansion at equilibrium composition on theoretical combustion performance of pentaborane. Combustor inlet-air temperature, 100° F; combustion pressure, 2 atmospheres.



(b) Variation of air specific impulse at fixed and at equilibrium composition with equivalence ratio.

Figure 14. - Concluded. Effect of nozzle expansion of fixed composition compared with expansion at equilibrium composition on theoretical combustion performance of pentaborane. Combustor inlet-air temperature, 100° F; combustion pressure, 2 atmospheres.