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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

## SUPPLEMENT I - INFLUENCE OF NEW BORIC-OXIDE VAPOR-PRESSURE DATA ON CALCULATED PERFORMANCE OF PENTABORANE

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NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

WASHINGTON

May 25, 1956

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## SUMMARY

The theoretical performance of pentaborane has been recalculated using recent data on the vapor pressure of boric oxide. Previous calculations were based upon vapor-pressure data obtained some years ago by a method not as accurate as that employed in current investigations. The recalculated performance data for pentaborane differ appreciably from previously published data and are considered more accurate for evaluation of the relative potentialities of boron-containing fuels.


## INTRODUCTION

As part of a general study of the performance of high-energy fuels in jet engines, theoretical calculations have been made to evaluate the relative performance potentialities of these fuels. Results of these calculations are reported in references 1 to 4. In making calculations for boron-containing fuels the accuracy of the predicted performance has been dependent upon the accuracy with which the properties of boric oxide have been known. All previous NACA references have based performance calculations on boric-oxide vapor-pressure data reported by Cole and Taylor (ref. 5) in 1935. Recent vapor-pressure data obtained by Speiser, Naiditch, and Johnston (ref. 6) and Soulen, Sthapitanonda, and Margrave (ref. 7) indicate that the earlier data (ref. 5) are considerably in error; consequently, previous performance calculations based upon reference 5 are also in error.

For this reason the present report has been prepared to show the recent vapor-pressure data on boric oxide (refs. 6 and 7) and to illustrate the effect of these data on performance calculations of boron-containing fuels. In addition data are presented to indicate corrections to be made to data for boric oxide previously reported in reference 8. For the performance calculations, pentaborane has been assumed to be the boron-containing fuel of interest. The calculated performance data for pentaborane supersede similar data reported in reference 3.

## SYMBOLS

| | |
|---|---|
| $g$ | acceleration due to gravity, 32.17 ft/sec$^2$ |
| $\Delta H^o/RT$ | enthalpy change due to formation of substance from its elements in atomic gas state divided by RT |
| $H_T^o$ | sum of sensible enthalpy and chemical energy at temperature T and at standard conditions, kcal/mole |
| $K$ | equilibrium constant for reaction $2B + 3O \rightarrow B_2O_3$ |
| $\overline{m}_g$ | mean molecular weight of gas mixture, exclusive of condensed $B_2O_3$ |
| $R$ | universal gas constant, $1545.33/\overline{m}_g$, (ft)(lb)/(lb)($^o$R) |
| $S_a$ | air specific impulse, (lb)(sec)/lb air |
| $T$ | temperature, $^o$K |
| $X$ | weight fraction of solids or liquids in exhaust gases |
| $\gamma$ | ratio of specific heats |
| $\varphi$ | equivalence ratio; ratio of actual to stoichiometric fuel-air ratio |

## DISCUSSION AND RESULTS

### Vapor Pressure of Boric Oxide

The vapor pressures obtained by Cole and Taylor (ref. 5) for boric oxide ($B_2O_3$) are compared with data from references 6 and 7 in figure 1. The more recent vapor-pressure data (refs. 6 and 7) are considerably lower than the previously available data (ref. 5). This difference in vapor pressure has a significant effect on computations of performance.

Slight adjustments have been made in the lower curve of figure 1 to make the data consistent with tabulations of properties of gaseous $B_2O_3$ contained in reference 8. These adjustments are such that entropy and specific-heat data for gaseous $B_2O_3$ in reference 8 are unchanged. The new values of vapor pressure shown in figure 1 render the tabulated values of log K and $H_T^o$ in reference 8 obsolete. Tabulated data of reference 8 can be corrected to the new standards by means of the following relations:

$$(H_T^o)_{new} = (H_T^o)_{old} + 12.2174 \text{ kcal/mole}$$

$$(-\Delta H^o/RT)_{new} = (-\Delta H^o/RT)_{old} - 6148.11/T$$

$$(\log_{10}K)_{new} = (\log_{10}K)_{old} - 2670.09/T$$

In these relations, conversions to Btu may be made by multiplying kilocalories by 1798.82. These corrections to the data of reference 8 should be regarded as interim values, which may be used until a formal revision of thermal data for the boron oxides is available.

## Heat of Vaporization of Boric Oxide

The Clausius Clapeyron equation was used to compute the variation of heat of vaporization with temperature. This relation is shown in figure 2 and is based on the recent vapor-pressure data (fig. 1, refs. 6 and 7).

## Combustion Temperatures of Pentaborane

The data described in the preceding paragraphs were used to calculate the variation of combustion temperature with equivalence ratio for pentaborane ($B_5H_9$) in the region of $B_2O_3$ vaporization. The molecules considered as possible combustion products were: $B_2O_3$ (gas and liquid), $H_2O$, $N_2$, $O_2$, and NO. Because OH, BO, and other substances were overlooked, the calculations were limited to less than 4000° R. The variation of combustion temperature with equivalence ratio is shown in figure 3, and a comparison is shown of the results based on old and new vapor-pressure data for $B_2O_3$. At temperatures above 3900° R where vaporization is complete, the solid curve represents reasonably well the combustion temperature data using old and new vapor pressures.

## Air Specific Impulse of Pentaborane

From the combustion temperatures shown in figure 3 the air specific impulse of pentaborane was computed by the method described in reference

3, which assumes frozen composition during expansion. Necessary thermal properties $\gamma$, R, and X consistent with the combustion temperatures based on the new $B_2O_3$ vapor pressures are shown in figure 4. Figure 5 compares the variation of air specific impulse with equivalence ratio for both old and new vapor-pressure data.

## Consumption of Pentaborane

Of particular interest in the evaluation of boron-containing fuels is the consumption relative to hydrocarbons. A comparison of this type is reported in reference 3 for pentaborane; however, the calculation was based on the old vapor-pressure data for $B_2O_3$ as reported in reference 5. For this reason consumption data have been recalculated on the basis of the new vapor-pressure data reported in references 6 and 7. The results are shown in figure 6 for consumption of $B_5H_9$ relative to octene-1. The conditions chosen for this comparison were 560° R inlet-air temperature and a pressure of 2 atmospheres.

Use of the new data results in a significant decrease in relative fuel consumption at certain levels of air specific impulse. Also, the same level of relative fuel consumption is reached at higher air specific impulses. For example, the new data indicate that a relative fuel consumption of 0.838 is reached about 10 seconds higher than was previously estimated from the old vapor-pressure data.

The comparison of fuel consumption is based on frozen composition in the expansion process. If the composition adjusts during expansion, lower fuel consumptions can be attained with pentaborane fuel, particularly at high air specific impulse levels.

## CONCLUDING REMARKS

Small inconsistencies between figures 4 to 6 are largely a result of simplification in the calculations. Refined calculations will alter these figures some, although the general performance levels will not be greatly changed. Until better calculations are made, figures 4, 5, and 6 must be regarded as tentative. Further refinements in calculation may also alter the relative fuel consumption for pentaborane at elevated temperatures above the vaporization region.

A simplified method for obtaining approximate combustion temperatures and thrust performances of boron-containing fuels is presented in reference 9. The thermal data tabulated therein incorporate the new vapor pressures for boron oxide.

Lewis Flight Propulsion Laboratory
National Advisory Committee for Aeronautics
Cleveland, Ohio, April 3, 1956

[redacted]

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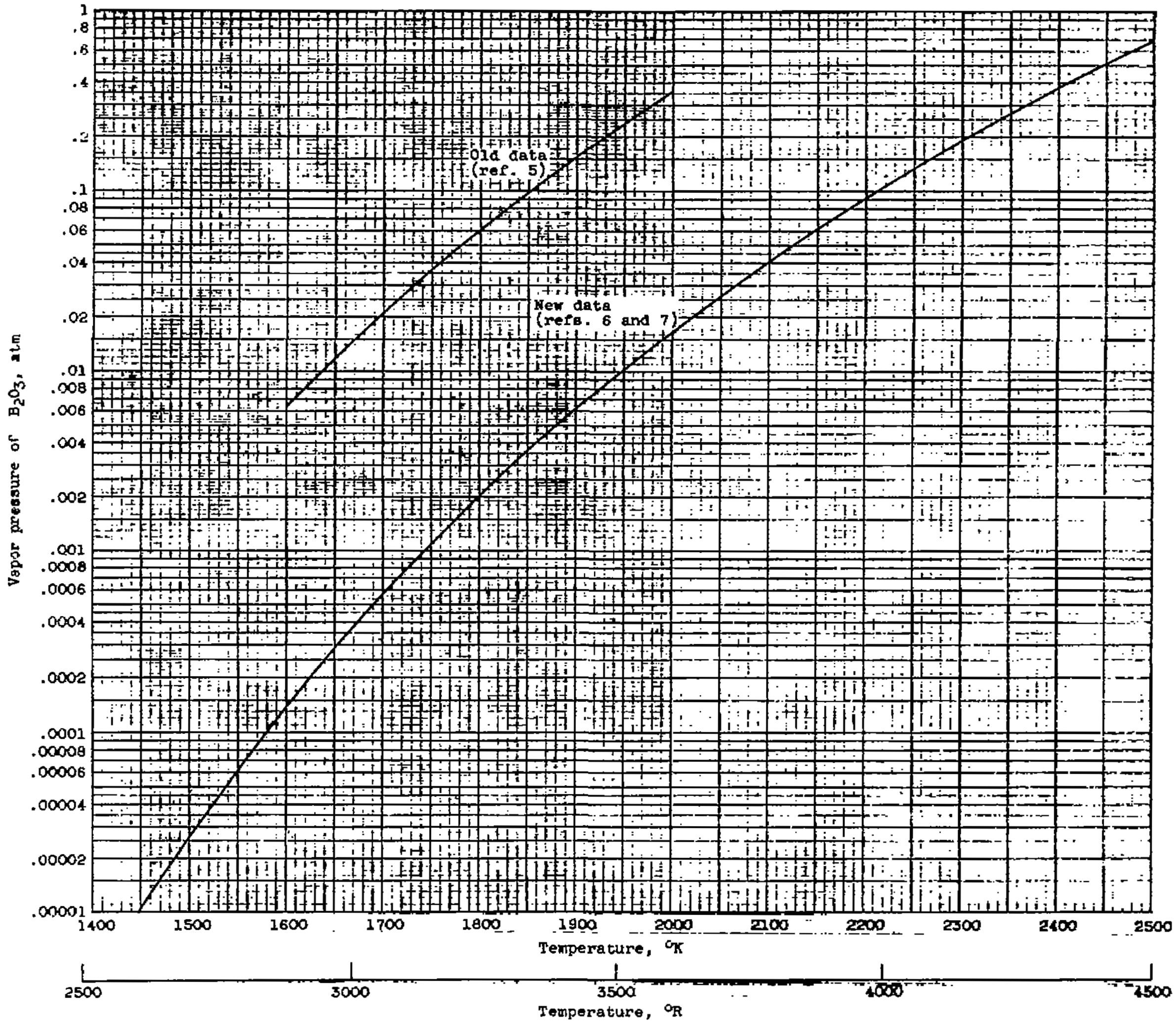


Figure 1. - Vapor pressure of boric oxide ($B_2O_3$).

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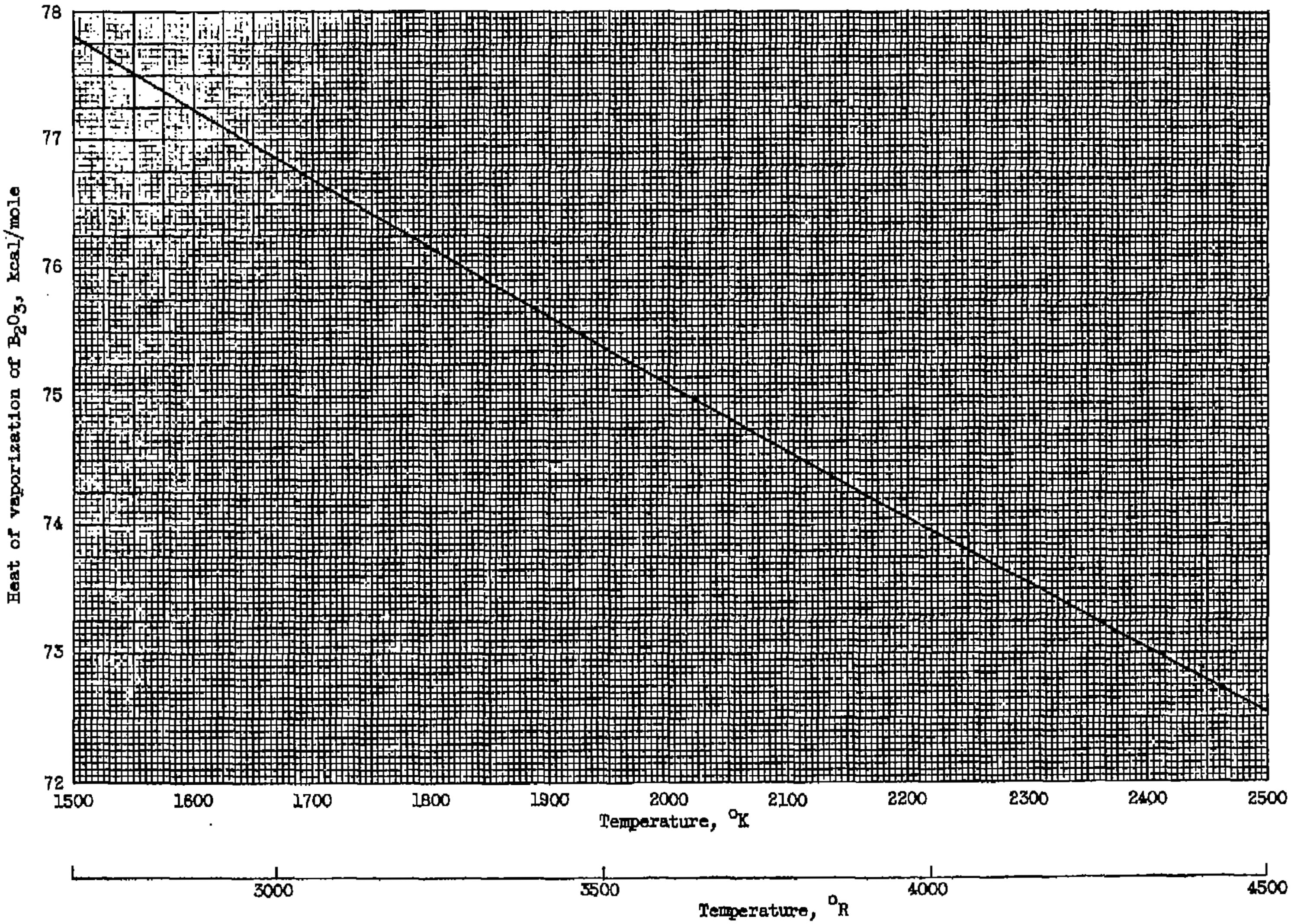


Figure 2. - Heat of vaporization of boric oxide ($B_2O_3$). (Data based on refs. 6 and 7.)

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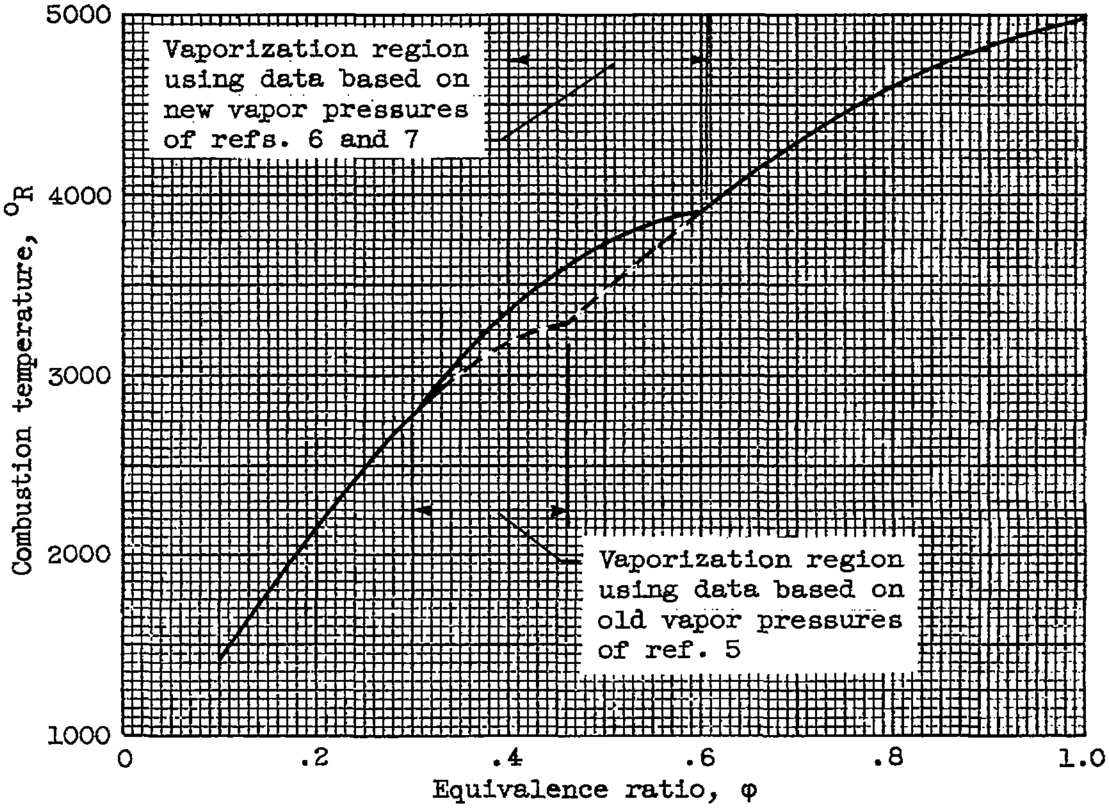


Figure 3. - Combustion temperature of pentaborane ($B_5H_9$) at 560° R inlet-air temperature and 2 atmospheres pressure.

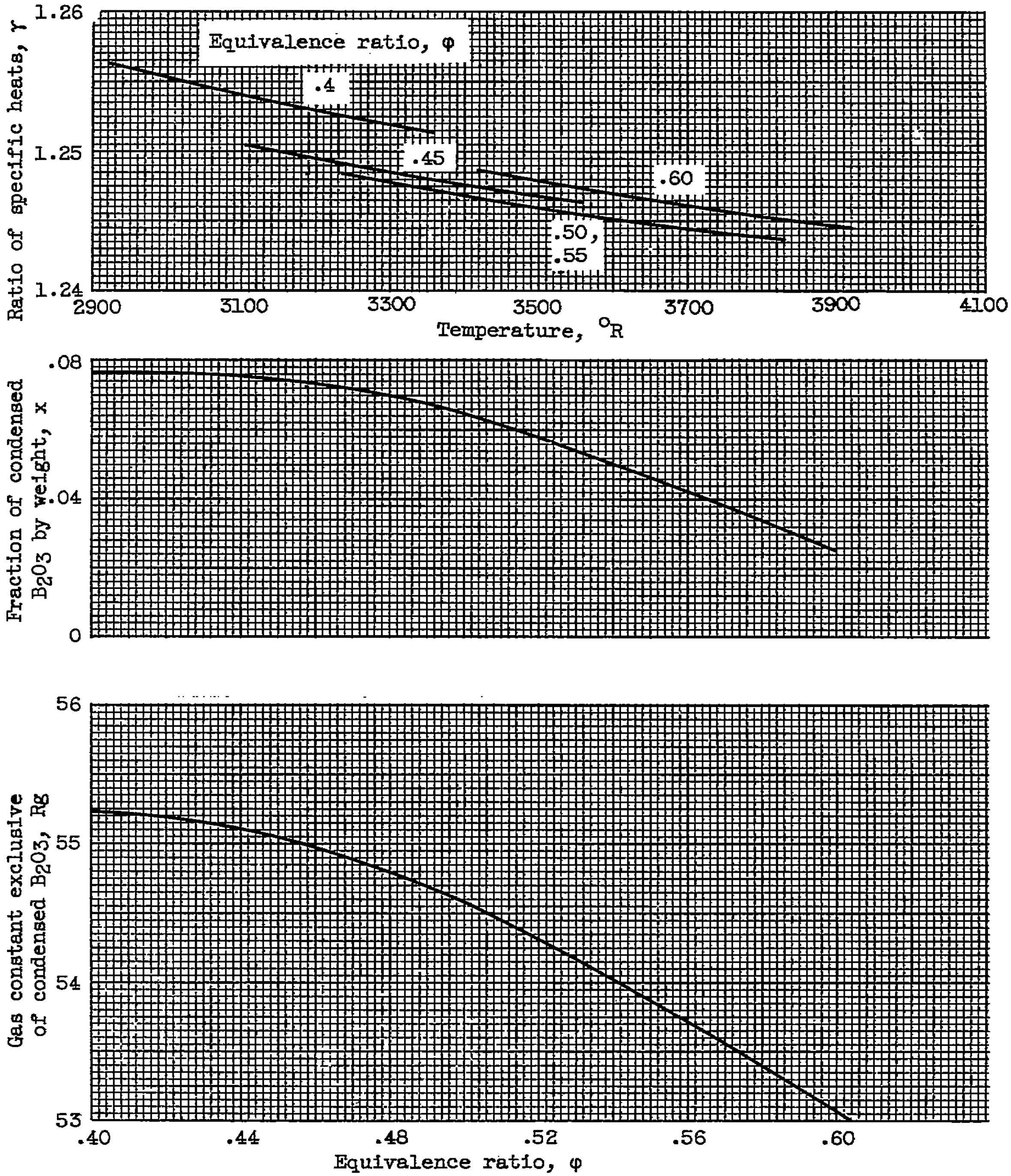


Figure 4. - Thermal properties of pentaborane ($B_5H_9$) combustion products in region of boric oxide ($B_2O_3$) vaporization for ideal combustion using data of references 6 and 7.

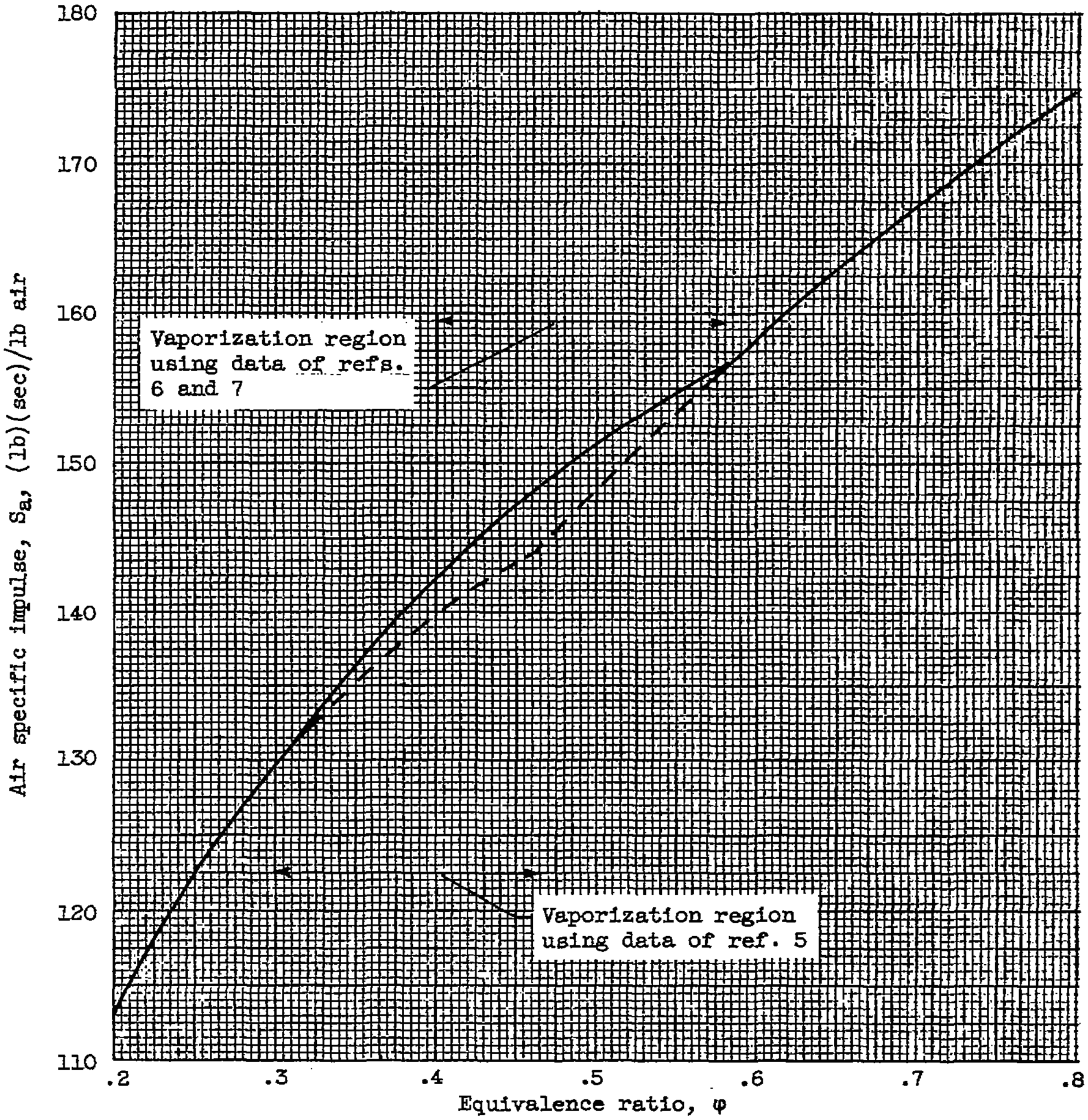


Figure 5. - Air specific impulse of pentaborane ($B_5H_9$) at 560° R inlet-air temperature and 2 atmospheres pressure.

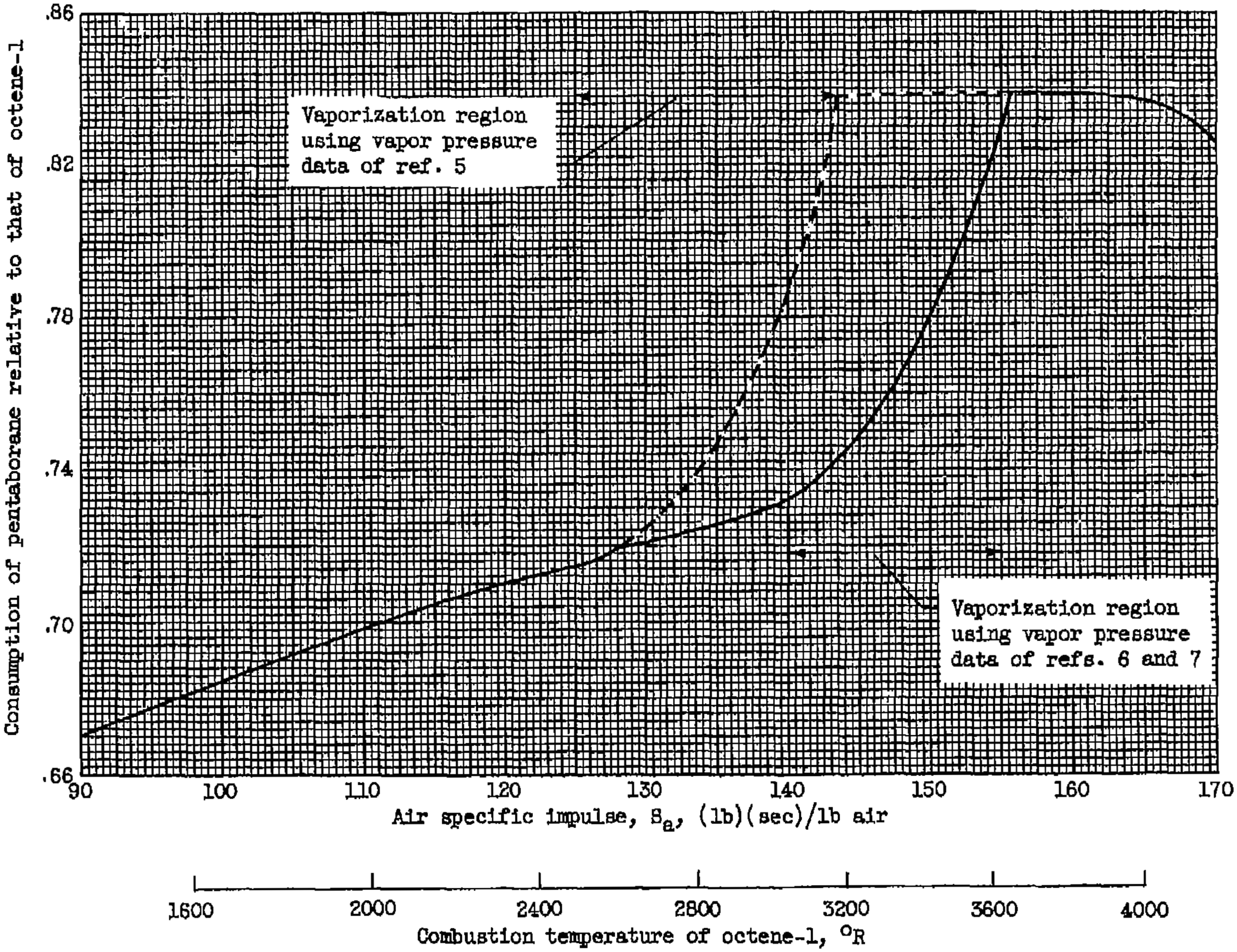


Figure 6. - Consumption of pentaborane relative to that of octene-1 against air specific impulse for 2 atmospheres combustion pressure and 560° R inlet-air temperature.

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