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RESEARCH MEMORANDUM

TABLES AND CHARTS FOR THERMODYNAMIC CALCULATIONS INVOLVING AIR AND FUELS CONTAINING BORON, CARBON, HYDROGEN, AND OXYGEN

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TABLES AND CHARTS FOR THERMODYNAMIC CALCULATIONS INVOLVING AIR AND FUELS CONTAINING BORON, CARBON, HYDROGEN, AND OXYGEN

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SUMMARY

Tables and charts of gas properties are presented for use in thermodynamic calculations for engine cycles involving the combustion of air and any fuel or combination of fuels containing carbon, boron, hydrogen, and oxygen.

Dissociation and phase changes may be accounted for with the method presented, which does not require the presentation of separate data for each fuel-air ratio. Calculations are limited to stoichiometric or lesser fuel-air ratios. With boron-containing fuels, either equilibrium or frozen expansion may be assumed with respect to phase changes.

Equations and examples are given illustrating calculations of combustion temperatures, expansion processes, and flow areas.

INTRODUCTION

Research in aircraft propulsion systems has, in recent years, focused increasing interest on the use of higher combustion temperatures and comparatively unconventional fuels (ref. 1).

In order to evaluate engine designs or to compare different fuels, estimates of engine performance must be derived by thermodynamic analyses of the engine cycles. The analyses are often quite sensitive to changes in the properties of the gases flowing through the engine. Different fuels may produce combustion products with widely different thermodynamic properties even at low temperatures. Some fuels may even produce solid products of combustion. In addition, with any fuel, high temperatures may significantly change the specific heats of the gases and even cause dissociation. Therefore, a need exists for methods of calculating thermodynamic processes that take into account variations in gas properties.

A straight-forward calculation of the cycle including dissociation, if done in the classical manner, requires information on such factors as equilibrium constants and specific heats that usually is not readily available to the engine researcher; in any case, an inordinate amount of work is required by this method. Simplifying methods and data are generally available for conventional hydrocarbon fuels of the gasoline type (e.g., refs. 2 and 3). Some reports, such as references 4 and 5, indicate performance trends with variations in operating conditions for certain fuels and can be used to compute engine performance with these fuels over limited ranges of conditions with reasonable accuracy. These reports are not adequate for the wide ranges of operating conditions and the variety of fuels proposed for future propulsion systems.

The purpose of the present report is to provide a practical method for calculating combustion temperatures and compression or expansion processes for all temperatures and pressures likely to be encountered in an air-breathing aircraft engine. Data are presented for air and water and for the combustion products of boron, carbon, hydrogen, and several other fuels of particular interest. A technique is presented for combining the given data in order to obtain similar data for fuels composed of boron, carbon, hydrogen, and oxygen in any proportion. Any fuel-air ratio not exceeding stoichiometric may be specified. Although not exact for all conditions, the accuracy of the presented method is suitable for most engine calculations.

Results for the given fuels are presented in the form of tables of specific heat, enthalpy, and entropy as functions of temperature for use when the effects of dissociation are negligible. Charts of enthalpy and entropy for ranges of both temperature and pressure are given for use when dissociation effects are large.

The method and basic data used to derive the presented tables and charts were taken from reference 6. Improved data for the properties of boron oxide B_2O_3 have recently been obtained and have been incorporated in the results of the present report. These results were derived over a period of years for use in cycle analyses at the NACA Lewis laboratory. They are being published now as an aid to others engaged in similar studies.

SYMBOLS

The following symbols are used in this report:

A	streamtube area, sq ft
c_p	specific heat at constant pressure, Btu/(lb)($^{\circ}$R)

D	function of fuel type
E	kinetic energy, $WV^2/2gJ$, Btu/sec
F_j	jet thrust, lb
G	function of fuel type
g	acceleration due to gravity, 32.174 ft/sec^2
H^o	total enthalpy, sensible plus chemical, Btu/lb
h	enthalpy, Btu/lb
J	mechanical equivalent of heat, ft-lb/Btu
K	function of pressure and temperature
k	ratio of gaseous moles to total moles in products of combustion
M	molecular weight
N	number of moles
P	static pressure, atm
p	partial pressure, atm
$p_{B_2O_3}$	equilibrium vapor pressure of saturated B_2O_3, atm
Q	heat transferred out of combustion chamber, Btu/lb
R	gas constant, 1545/M, ft-lb/(lb)(°R)
S	entropy, Btu/(lb)(°R)
T	temperature, °R
V	flow velocity, ft/sec
W	rate of flow, lb/sec
w	weight ratio of water (or water vapor) to air in unburned mixture, lb/lb
X(or Y)	equivalence ratio of fuel (fuel-air ratio divided by stoichiometric fuel-air ratio)
x(or y)	weight ratio of fuel to air

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CO-1 back

Z	constituents of air other than O_2
$\alpha,\beta,\gamma,\delta$	number of atoms of B, H, C, and O, respectively, in fuel molecule
ε	ratio of gaseous to total moles of B_2O_3 in combustion products
λ	proportionality factor
ρ	density, lb/cu ft
φ	constant-pressure entropy, $\int c_p \frac{dT}{T}$, Btu/(lb)(°R)
ψ	interpolation function

Subscripts:

a	air
c	condensed
e	exit
g	gas
o	ambient
P	products of stoichiometric combustion
p	constant pressure
s	stoichiometric
w	water or water vapor
x,y	fuels x and y, respectively
1,2,3,4	stations or states

Superscript:

'	estimated value

ANALYSIS

General Theory

The method of the present report is based on separate calculations of the thermodynamic properties (enthalpy, entropy, specific heat, and molecular weight) for (1) air and (2) the products of combustion of a stoichiometric fuel-air mixture. It is assumed that the properties of the combustion products for any fuel-air ratio less than the stoichiometric ratio may be obtained by linear interpolation between the two extreme cases. As explained in appendix A, the data for the elemental fuels boron, hydrogen, and carbon may be combined to provide data for more complex fuels of the form $B_\alpha H_\beta C_\gamma O_\delta$, where α, β, γ, and δ are arbitrary.

Results of the above method are exact for cases with no dissociation and for stoichiometric fuel-air ratios when stoichiometric data for the particular fuel are specifically presented. Essentially, the method amounts to obtaining data for less than stoichiometric fuel-air ratios by diluting the products of stoichiometric combustion with excess air. The results are not entirely correct when dissociation is present and (1) the fuel-air ratio is less than stoichiometric or (2) a complex fuel is synthesized from the elemental fuels. The error with dissociation arises because the method does not account for the change in the equilibrium composition of the gases when they are mixed. The error approaches zero for equivalence ratios near zero and 1, and is a maximum for equivalence ratios of about 0.5. However, comparison with more exact methods shows that the error is generally insignificant for engineering calculations (e.g., error of less than 1 percent in combustion temperature is expected).

Charts of thermodynamic data that include the effects of dissociation are given for air, water vapor, and the products of stoichiometric combustion of hydrogen, carbon, CH_2, and pentaborane B_5H_9. Tables of data that neglect dissociation are given for the above substances and also for the combustion products of CH, CH_3, CH_4, boron, diborane B_2H_6, and ethylene decaborane $B_{10}H_{13}C_2H_5$. Tabular data are also given for the properties of the constituents of air other than oxygen in order to facilitate the combining of data to derive the properties of other fuels (as further discussed in appendix A).

A large number of significant numbers have been retained in the tables to avoid inconsistencies and rounding-off errors. This is not meant to imply that the data are necessarily accurate to such high orders of precision.

Calculation of Gas Properties

Without dissociation. - The composition of the products of combustion was calculated for air and the stoichiometric quantity of each fuel with assumptions of no dissociation and complete combustion. The following composition was assumed for air:

Constituent	Percent by volume	Percent by weight
Nitrogen	78.09	75.525
Argon	.93	1.286
Carbon dioxide	.03	.046
Oxygen	20.95	23.143

Table I lists the stoichiometric fuel-air ratios for various fuels based on this composition of air. Other properties are also given, the use of which is given in following sections. For each fuel, the specific heat c_p, enthalpy h, and constant-pressure entropy φ were computed for temperatures from 350° to 6000° R by using the tables of thermodynamic properties for various pure substances given in reference 6. The results are presented in tables II to X for 50° increments of temperature up to 4000° R and 500° increments thereafter. Also tabulated are the interpolation functions defined as follows:

$$\psi(c_p) = \frac{1 + x_s}{x_s} (c_{p,P} - c_{p,a})$$

$$\psi(h) = \frac{1 + x_s}{x_s} (h_P - h_a)$$

$$\psi(\varphi) = \frac{1 + x_s}{x_s} (\varphi_P - \varphi_a)$$

Use of these functions is explained in a following section.

Fuels containing boron have the compound B_2O_3 as one of the combustion products. This compound may exist in either the gaseous or condensed (liquid or solid) phase. The relative proportions of each phase depend on the temperature and pressure. The tables of thermodynamic properties for boron fuels were obtained both for the case of gaseous B_2O_3 and for the case of condensed B_2O_3. In appendix B a method is derived for picking the proper case or combination for use in a cycle calculation.

With dissociation. - Equilibrium compositions of the products of stoichiometric combustion of various fuels were computed for a wide range of temperatures and pressures. The calculations were carried out on an IBM card-programmed computer by using a successive-approximation procedure presented in reference 6. The required values of equilibrium constants were also taken from reference 6.

Enthalpy, entropy, and molecular weight were then calculated for the dissociated products in the same manner as described for the undissociated products. For the calculations with dissociation, air was assumed to have the following composition:

Constituent	Percent by volume	Percent by weight
Nitrogen	79.050	76.764
Oxygen	20.950	23.236

Fewer constituents were assumed than for the undissociated case in order to simplify the calculations. Actually, the correct composition to use is somewhat indefinite since there is an appreciable variation with altitude. In any event, the presented data are insensitive to the exact composition of the air assumed, provided the proportion of oxygen does not change.

The calculations covered the range of temperatures from 360° to over 6000° R and pressures from 0.001 to 100 atmospheres. The data were computed at temperature intervals of approximately 500° R in the high-temperature region; pressure intervals were, in general, taken in powers of 10 (i.e., 0.001, 0.01, 0.1, etc.). Additional points were obtained in the regions of phase changes.

In contrast to the use of tables for the undissociated data, the data with dissociation are presented in the form of charts. Two independent variables, temperature and pressure, would otherwise result in very large tables requiring the use of double interpolation. Furthermore, the accuracy of the method probably does not warrant such precision. The data are plotted in figures 1 to 6 in the form enthalpy versus pressure, with lines of constant temperature and constant entropy. This arrangement has the advantages of minimizing waste space on the diagrams and of permitting linear interpolation for the most commonly occurring calculation requirements.

Molecular weights of the various substances are plotted in the last part of each figure as a function of the pressure with lines of constant temperature.

METHOD OF APPLICATION

Examples illustrating the use of the tables (i.e., without dissociation) and charts (with dissociation) by employing the equations presented in the following sections are given in appendix C. The equations are given for the general case of a mixture of two fuels plus water injection. Because the equations are general, they appear substantially more complicated than is normally required in calculations. As previously mentioned, the method is based on linear interpolation between the properties of air and the properties of the products of stoichiometric combustion to obtain data for equivalence ratios less than 1. Combustion is assumed to be complete in all cases.

Properties at Any State

This section presents equations relating to the calculation of the enthalpy, entropy, specific heat, pressure, temperature, density, and gas mass flow rate.

Enthalpy. - Enthalpy may be expressed as

$$h = X(1 + x_s)h_{P,x} + Y(1 + y_s)h_{P,y} + wh_w + (1 - X - Y)h_a \qquad \text{(Btu/lb air)} \qquad (1a)$$

or

$$h = \frac{X(1 + x_s)h_{P,x} + Y(1 + y_s)h_{P,y} + wh_w + (1 - X - Y)h_a}{1 + x + y + w} \qquad \text{(Btu/lb mixture)} \qquad (1b)$$

(In all cases where the unit of weight lb air is used, it signifies a pound of initial or reacting air before combustion occurs.) The enthalpy of the products of stoichiometric combustion h_P is obtained from tables II to X if dissociation can be neglected or from the charts (figs. 1 to 6), if dissociation is significant. Stoichiometric fuel-air ratios (x_s and y_s) for various fuels are given in table I or may be calculated with equation (A8) of appendix A (neglecting dissociation) and are obtained from the legends of figures 3 to 6 when dissociation is included.

A useful simplification may be made for the dissociation-neglected data. By algebraic manipulation, equation (1b) may be rewritten

$$h = h_a + \frac{x\psi(h_x) + y\psi(h_y) + wh_w}{1 + x + y + w} \qquad \text{(Btu/lb mixture)} \qquad (1c)$$

in which

$$\psi(h_x) = \frac{1 + x_s}{x_s} (h_{P,x} - h_a)$$

6K

$$\psi(h_y) = \frac{1 + y_s}{y_s} (h_{P,y} - h_a)$$

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The interpolation factors ψ are also given in tables II to X and their use is a time-saving technique in making calculations.

For the special case of boron-containing fuels, values of $\psi(h)$ are read from the tables for both gaseous and condensed B_2O_3 and then combined as follows:

$$\psi(h) = \varepsilon \cdot \psi(h_g) + (1 - \varepsilon)\psi(h_c) \qquad (1d)$$

CO-2

This result is then used in equation (1c) as though it had been obtained directly from the table. The value of ε must be computed by the following equation (derived in appendix B):

RATIO OF AIR TO O_2 by volume

$$\varepsilon = \frac{1}{P/p_{B_2O_3} - 1} \; \frac{XG_x + YG_y + 4.773}{\frac{\alpha_x}{2D_x} X + \frac{\alpha_y}{2D_y} Y} \qquad (1e)$$

$\frac{1.00}{20.95}$

in which P is the static pressure of the combustion products in atmospheres, $p_{B_2O_3}$ is a function of temperature only (given in table XI or fig. 7), and G, $\frac{\alpha}{2D}$, and D are functions of fuel type listed in table I (or calculated from eqs. of appendix B).

Entropy. - Equations for entropy to be used with the charts are similar to those for enthalpy. Entropy may be expressed by

$$S = X(1 + x_s)S_{P,x} + Y(1 + y_s)S_{P,y} + wS_w + (1 - X - Y)S_a$$

$$(\mathrm{Btu}/(\mathrm{lb\ air})(^{\circ}\mathrm{R})) \qquad (2a)$$

or

$$S = \frac{X(1 + x_s)S_{P,x} + Y(1 + y_s)S_{P,y} + wS_w + (1 - X - Y)S_a}{1 + x + y + w}$$

$$(\mathrm{Btu}/(\mathrm{lb\ mixture})(^{\circ}\mathrm{R})) \qquad (2b)$$

The tables of dissociation-neglected data give only that part of the entropy that is a function of temperature φ. That is,

$$\varphi = S + \frac{R}{J} \ln P$$

The value of φ for the products of combustion of a mixture of fuels and less than stoichiometric fuel-air ratio is given by

$$\varphi = \varphi_a + \frac{x\psi(\varphi_x) + y\psi(\varphi_y) + w\varphi_w}{1 + x + y + w} \quad \text{(Btu/(lb mixture)(}^{\circ}\text{R))} \quad (2c)$$

where

$$\psi(\varphi_x) = \frac{1 + x_s}{x_s} (\varphi_{P,x} - \varphi_a)$$

$$\psi(\varphi_y) = \frac{1 + y_s}{y_s} (\varphi_{P,y} - \varphi_a)$$

For the boron-containing fuels,

$$\psi(\varphi) = \varepsilon\psi(\varphi_g) + (1 - \varepsilon)\psi(\varphi_c) \quad (2d)$$

Specific heat at constant pressure. - The specific heat is not required for cycle calculations when the enthalpy and entropy are known. However, the specific heat is often useful in finding the temperature corresponding to a given enthalpy or entropy (as illustrated in one of the examples of appendix C). Interpolation factors $\psi(c_p)$ are given in the tables and the specific heat of the mixture of combustion gases is given by

$$c_p = c_{p,a} + \frac{x\psi(c_{p,x}) + y\psi(c_{p,y}) + wc_{p,w}}{1 + x + y + w} \quad \text{(Btu/(lb mixture)(}^{\circ}\text{R))} \quad (3a)$$

Again, for the boron-containing fuels, an equation similar to (1d) or (2d) may be used to find $\psi(c_p)$.

The specific heat for dissociated products is not specifically shown on the charts. However, by definition,

$$c_p = \left(\frac{\partial h}{\partial T}\right)_p$$

Therefore, the specific heat may be approximated by reading from the chart the change in enthalpy Δh corresponding to a small change in temperature ΔT (along a constant-pressure line) and forming the ratio of these two quantities. The ratio from each chart may be combined for less than stoichiometric fuel-air ratios as follows:

$$c_p = \frac{\Delta h}{\Delta T} = X\,(1 + x_s)\left(\frac{\Delta h}{\Delta T}\right)_{P,x} + Y(1 + y_s)\left(\frac{\Delta h}{\Delta T}\right)_{P,y} + w\left(\frac{\Delta h}{\Delta T}\right)_w + (1 - X - Y)\left(\frac{\Delta h}{\Delta T}\right)_a \qquad (\mathrm{Btu}/(\mathrm{lb\ air})(^{\circ}\mathrm{R})) \qquad (3b)$$

or

$$c_p = \frac{X(1 + x_s)\left(\frac{\Delta h}{\Delta T}\right)_{P,x} + Y(1 + y_s)\left(\frac{\Delta h}{\Delta T}\right)_{P,y} + w\left(\frac{\Delta h}{\Delta T}\right)_w + (1 - X - Y)\left(\frac{\Delta h}{\Delta T}\right)_a}{1 + x + y + w} \qquad (\mathrm{Btu}/(\mathrm{lb\ mixture})(^{\circ}\mathrm{R})) \qquad (3c)$$

Pressure. - The pressure of a mixture of gases is equal to the sum of the partial pressures of the constituents. Also, when dissociation is present, the composition of the mixture is a function of the pressure. Therefore, one way to approximate the composition and properties of the mixture of combustion products is to read data from the charts for air and for the stoichiometric products, each at the partial pressure it would have after being hypothetically mixed (according to the interpolation method of the present report). However, numerical calculations have shown that equally good or better results are usually obtained if the actual static pressure of the final mixture is used for reading each of the charts.

Pressure does not ordinarily affect the gas composition and thermodynamic properties when dissociation is not present and the tables are used. As previously mentioned, however, an exception must be made when B_2O_3 is present in the combustion products (as it always is when the fuel contains boron).

Temperature. - The equilibrium temperatures of all constituents in a mixture are equal.

Molecular weight. - The molecular weight of the combustion gases (not including any condensed B_2O_3 which may be present) is given by

$$M_g = \frac{W_g}{W}\frac{M}{k} \qquad (4)$$

where

$$\frac{W_g}{W} = 1 - (1 - \varepsilon)\,\frac{W_{B_2O_3}}{W} \tag{5a}$$

$$\frac{W_{B_2O_3}}{W} = \frac{69.64\left(\frac{\alpha_x}{2D_x}\,X + \frac{\alpha_y}{2D_y}\,Y\right)}{X\,\frac{M_x}{D_x} + Y\,\frac{M_y}{D_y} + 138.269} \tag{5b}$$

$$M = \frac{1 + x + y}{\frac{X(1 + x_s)}{M_{P,x}} + \frac{Y(1 + y_s)}{M_{P,y}} + \frac{1 - X - Y}{28.97}} \tag{5c}$$

$$k = \frac{\left(\dfrac{XG_x + YG_y + 4.773}{\frac{\alpha_x}{2D_x}\,X + \frac{\alpha_y}{2D_y}\,Y}\right) + \varepsilon}{\left(\dfrac{XG_x + YG_y + 4.773}{\frac{\alpha_x}{2D_x}\,X + \frac{\alpha_y}{2D_y}\,Y}\right) + 1} \tag{5d}$$

The value of ε is calculated from equation (1e). The quantities $\alpha/2D$, G, and the molecular weight of the fuel M are functions of the fuel type and are listed in table I. The quantity M_P is the molecular weight of the products of stoichiometric combustion and is given at the top of the table for each fuel for use when dissociation may be neglected. The last part of each of figures 1 to 6 gives the variation of M_P with temperature and pressure when dissociation is taken into account and the charts are used.

Gas flow per unit area. - The flow of gas per unit area is

$$\frac{W_g}{A} = \rho_g V \qquad \text{((lb/sec)/sq ft)} \tag{6}$$

where the density of the gases is given by

$$\rho_g = \frac{2116}{1545}\left(\frac{PM_g}{T}\right) \qquad \text{(lb/cu ft)}$$

in which P is the static gas pressure in atmospheres, T is the temperature in $^{\circ}R$, and M_g is calculated from equation (4). Combining equations (4) and (6) gives the total weight flow per unit area

$$\frac{W}{A} = \frac{2116}{1545}\left(\frac{M}{k}\right)\left(\frac{P}{T}\right)V \qquad ((\text{lb/sec})/\text{sq ft}) \qquad (7)$$

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Combustion

The equation for the combustion process follows directly from the equation for conservation of energy. The enthalpy of the gases after combustion is equal to the sum of the enthalpies of the entering constituents (including the chemical energy of the fuel) minus any energy lost through heat transfer and minus the increase in kinetic energy of the gases, as given by

enthalpy air
ϕ
.0292
enthalpy of product

$$xH_x^O + \cancel{yH_y^O} + \cancel{wh_{w,1}} + h_{a,1} + \cancel{E_1} = X(1 + x_s)h_{P,x_2} + Y(1 + y_s)h_{P,y,2} +$$

$$\cancel{wh_{w,2}} + (1 - X - Y)h_{a,2} + \cancel{Q} + \cancel{E_2} \qquad (8a)$$

f/a
Total enthalpy of fuel

(Btu/lb air)

where stations 1 and 2 represent the conditions before and after combustion, respectively. Values of initial fuel enthalpy, including the chemical energy (H_x^O or H_y^O) are listed in table I for various fuels.

When dissociation is sufficiently small to allow use of the data of tables II to X, equation (8a) may be rewritten in the form of equation (1c) as

$$xH_{x,1}^O + yH_{y,1}^O + wh_{w,1} + h_{a,1} + E_1 = (1 + x + y)h_{a,2} + x\psi(h_x)_2 +$$

$$y\psi(h_y)_2 + wh_{w,2} + Q + E_2 \qquad (\text{Btu/lb air}) \qquad (8b)$$

Equation (8a) or (8b) may be used to find the temperature after combustion or to find the required fuel-air ratio for a given combustion temperature.

Isentropic Processes

During an isentropic process the total entropy, that is, the sum of the entropies of all constituents, remains constant. Actual compression and expansion processes generally are only approximately isentropic but may be treated as isentropic if suitable efficiency factors are used.

$$f = \frac{h_{a_2} - h_{a_1}}{H_0 - h_{a_2} - \psi(h)}$$

compatible with TN 2021 ([illegible])
except H_0 (total fuel enthalpy) ≠ H (lower heating value of fuel)

For an isentropic compression or expansion,

$$S_2 = S_3 \tag{9a}$$

where stations 2 and 3 represent the conditions at the beginning and end of the process, and values of S are calculated according to equation (2a) or (2b). Although the total entropy remains constant, the entropy of any constituent (such as S_a) ordinarily does not. Differences in the specific heats of the various constituents cause heat to be transferred from one constituent to another with consequent changes in entropy if, as assumed, the final temperatures of all constituents are the same.

The constant-entropy process may be written as follows when the tables are used:

$$S_2 = S_3$$

$$\varphi_2 - \varphi_3 = \frac{1.987}{M}(K_2 - K_3) \tag{9b}$$

(final

where

$$K = \ln P \qquad (\text{for } \varepsilon \geqslant 1.0)$$

$$= \frac{k - \varepsilon}{1 - \varepsilon}\ln(P - p_{B_2O_3}) + \frac{\varepsilon(1 - k)}{1 - \varepsilon}\ln p_{B_2O_3} \qquad (\text{for } \varepsilon < 1.0)$$

and φ_2 and φ_3 are functions of temperature only and are calculated using equation (2c). Since no dissociation is assumed when the data of tables II to X are used, the values of ε are constant unless there are phase changes during the process. For the special case in which the B_2O_3 (if any) does not change phase throughout the process, equation (9b) reduces to

$$\varphi_2 - \varphi_3 = 1.987\frac{k}{M}\ln\frac{P_2}{P_3} \tag{9c}$$

An energy balance for the isentropic process is written as

$$h_2 + V_2^2/2gJ = h_3 + V_3^2/2gJ + Q_{output} + (\text{Work})_{output} \tag{10}$$

where h is evaluated from either equation (1b) or (1c) at both the initial and final conditions.

Expansion through a nozzle is an important process in jet engines which is approximately isentropic. From equation (10), the ideal nozzle-exit velocity is given by

$$V_3 = \sqrt{2gJ\,\Delta h + V_2^2} \qquad \text{(ft/sec)} \qquad (11)$$

where the units of Δh are Btu per pound of mixture. The actual exit velocity is usually defined by applying an efficiency factor or a velocity coefficient to the ideal velocity.

The jet thrust produced by a nozzle may be expressed as the sum of the fluid momentum and a pressure force acting on the exit area as follows:

$$F_j = \frac{W}{g} V_e + A_e(P_e - P_o) \qquad \text{(1b)} \qquad (12)$$

where station e is at the nozzle exit and station o is at ambient conditions. Complications arise in the use of the above equation when part of the combustion products is condensed. If the particles formed are small enough to be carried along and ejected at the same velocity as the remaining gases, the jet thrust is that computed by equation (12). If the particles are large and are therefore ejected at essentially zero velocity, equation (12) is approximately correct if the mass flow W is replaced with the gas mass flow W_g. The ratio W_g/W is given by equation (5a). In any case, when condensed products are present, the exit area A_e is computed using equation (7).

DISCUSSION

Representative examples of the use of the equations for applying the tables and charts for thermodynamic calculations are given in appendix C. Other uses, not illustrated herein, might include calculations involving reheat (e.g., turbojet afterburning) or water injection.

When substantial dissociation occurs in the combustion chamber of an engine, it is necessary to use the charts to calculate the correct gas temperature. Combustion temperatures calculated by using enthalpy values from the tables (i.e., without accounting for dissociation) may be too high by several hundred degrees. Nevertheless, engine calculations carried out at the NACA Lewis laboratory indicate that, for a given fuel-air ratio, nearly correct values of thrust and efficiency result from using the tables, despite the error in combustion temperatures. Whenever possible, use of the tables rather than the charts is suggested, since the former generally reduce the computational effort.

When the charts are used, it must be remembered that chemical equilibrium at all times was assumed in their derivation. This assumption may not be valid at some times, for example, during rapid expansion through a nozzle. When the tables are used, it is possible to assume frozen equilibrium with respect to phase changes (i.e., constant ε during the expansion).

It is previously pointed out that data for fuels other than those given in the present report may be derived by suitable combinations of the given tables or charts. An example of this technique, which is derived in appendix A, is also given in appendix C. A value of enthalpy calculated for CH_2 by this method agrees within 0.6 percent with the value read directly from the chart for this substance.

The authors of reference 6 point out that many of the basic data in that report are of uncertain accuracy. In fact, since the calculations were undertaken for the present report, significantly different data have been published for the properties of B_2O_3.[a] However, the tables and charts presented herein, which are otherwise based entirely on the data of reference 6, are believed sufficiently accurate for most practical studies of aircraft propulsion systems. Values of enthalpy for a given temperature and pressure can be estimated from the charts to within about 5 Btu per pound; the precision in reading entropy is about 0.005 Btu per pound per $^{\circ}R$. Maximum systematic errors in the use of the charts would occur at high combustion temperatures and equivalence ratios near 0.5, since the composition of the gases is approximated by diluting stoichiometric combustion products with air without accounting for the changes in equilibrium. A typical calculation, for the combustion of B_2H_6, resulted in an error in the calculated combustion temperature of 19° R out of 4470° R that is probably due to this effect. The error in calculating combustion temperatures by using the charts is not expected to exceed 1 percent in the worst cases.

CONCLUDING REMARKS

Tables and charts of gas properties are presented that allow thermodynamic calculations for engine cycles involving the combustion of air and any fuel containing carbon, boron, hydrogen, and oxygen.

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[a] The data given in reference 6 for B_2O_3 are based on those of reference 7. Recent work (ref. 8), however, tends to substantiate the appreciably different data presented in reference 9. The authors of reference 6 found that these revised data could easily be incorporated with acceptable accuracy by increasing the values of enthalpy (for gaseous B_2O_3) by 12.2174 kcal/mole and reducing the logarithm of the gaseous equilibrium constant by 2670.09/T (where T is in $^{\circ}K$).

Dissociation and phase changes may be accounted for with the method presented, which does not require the presentation of separate data for each fuel-air ratio. The method and data presented permit, with a minimum of error, calculations that would in many cases be otherwise very laborious.

Equations and examples are shown illustrating calculations for

(1) Combustion temperature or fuel-air ratio

(2) Isentropic processes

(3) Flow area

(4) Jet thrust

Lewis Flight Propulsion Laboratory
National Advisory Committee for Aeronautics
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APPENDIX A

SYNTHESIS OF DATA FOR OTHER FUELS

Data are given, in both tabular and chart form, for the thermodynamic properties of the products of stoichiometric combustion in air of boron (pentaborane), hydrogen, and carbon. These data, when suitably combined with the chart or table for water, may be used to calculate the specific heat, enthalpy, and entropy of the products of stoichiometric combustion in air of any other fuel containing boron, hydrogen, carbon, and oxygen in any proportion as follows:

(1) Write the stoichiometric reaction equation ignoring dissociation for the desired fuel in the form

$$B_\alpha H_\beta C_\gamma O_\delta + D(O_2 + 3.773Z) \rightarrow a(B_2O_3) + b(H_2O) + c(CO_2) + eZ \qquad (A1)$$

in which Z represents the nonreacting constituents of air (N_2, etc.). The numbers of moles D, a, b, c, and e are given by the following equations, which were obtained by equating the numbers of atoms of the various elements on each side of equation (A1):

$$\left.\begin{aligned} D &= \frac{3}{4}\alpha + \frac{1}{4}\beta + \gamma - \frac{1}{2}\delta \\ a &= \frac{1}{2}\alpha \\ b &= \frac{1}{2}\beta \\ c &= \gamma \\ e &= 3.773\ D \end{aligned}\right\} \qquad (A2)$$

$$3,773 = \frac{\text{Volume of inert gas}}{\text{Volume of } O_2} = \frac{1.0. - .20.95}{20.95}$$

(2) Combine the following stoichiometric reaction equations, which are for fuels that are presented in the tables or charts, so as to duplicate the right side of equation (A1). The duplication is achieved by multiplying the equations by suitable constants and then adding or subtracting one from another.

$$4B + 3(O_2 + 3.773Z) \rightarrow 2B_2O_3 + 3(3.773Z) \qquad (A3a)$$

$$2B_5H_9 + 12(O_2 + 3.773Z) \rightarrow 5B_2O_3 + 9H_2O + 12(3.773Z) \qquad (A3b)$$

3.773 is ratio by volume of the non-reacting parts of air to volume of O_2 in air $= \frac{79.05}{20.95}$

$$2H_2 + O_2 + 3.773Z \rightarrow 2H_2O + 3.773Z \qquad (A4)$$

$$C + O_2 + 3.773Z \rightarrow CO_2 + 3.773Z \qquad (A5)$$

$$H_2O \rightarrow H_2O \qquad (A6)$$

Note that, if dissociation is neglected, the products of stoichiometric combustion in air of any fuel containing only B, H, C, or O comprise (at the most) B_2O_3, H_2O, CO_2, and Z. It is possible to obtain the desired proportions of B_2O_3, H_2O, and CO_2 by combining equations (A3),[a] (A4), and (A5). In general, combinations of these three equations do not yield the correct number of moles of Z. However, it is observed that subtracting twice equation (A6) from equation (A4) leaves only Z in the products. This value can then be used to duplicate the number of moles of Z in (A1). It is necessary to perform this subtraction to obtain Z when using the charts, but a special table of the thermodynamic properties of 3.773Z is provided (table X) for convenience in combining the tables of undissociated data.

(3) In order that the result of the combination described above be on the basis of 1 pound of stoichiometric products of the new fuel, each equation used ((A3) to (A6)) must be multiplied by the ratio of the weight of the constituents of that equation to the weight of the constituents of equation (A1). The weights of the constituents of equations (A3) to (A6) are given in the following table:

Combustion products of -	Equation	Weight
4B	(A3a)	458.087
$2B_5H_9$	(A3b)	1785.571
$2H_2$	(A4)	142.301
C	(A5)	150.279
H_2O	(A6)	18.016
3.773Z	--	106.269

eq. molecular wt of product $= \frac{142.301}{2+3.773} = 24.648$

$-2H_2O + 106.269$

$\left[\frac{28.970}{6.704} - 1\right]32$

The weight of the constituents of equation (A1) is given by

$$\text{Weight} = 10.82\alpha + 1.008\beta + 12.01\gamma + 16\delta + 138.269D \qquad (A7)$$

---

[a] A chart is not given for the combustion products of B; therefore, equation (A3a) may be used only in conjunction with the tables of undissociated data. If dissociation is to be included, equation (A3b) may be used instead, since a chart is given for the products of B_5H_9.

wt = wt

volumes ≠ volume.

Mol wt ≠ mol wt

mol wt = $\frac{\text{Total wt}}{\text{No. of volumes or mols}}$

This procedure results in an expression that tells in what proportions to combine data from the charts or tables in order to obtain values of enthalpy, entropy, or specific heat for the stoichiometric combustion products of the new fuel. These calculated stoichiometric values are used for less than stoichiometric fuel-air ratios according to the equations in the main body of the report as though they had been read directly from one of the tables or charts. The stoichiometric fuel-air ratio needed for these equations is given by

$$x_s = \frac{10.82\alpha + 1.008\beta + 12.01\gamma + 16\delta}{138.269D} \qquad \text{(A8)}$$

(The constants used in this and the preceding equations are based on the composition of air assumed for the calculations neglecting dissociation but can also be used with the charts with little error.)

In calculating combustion processes it is also necessary to know the total fuel enthalpy H^o. Values of H^o for a number of fuels are given in table I. Values of the heat of formation of a large number of boron-hydrogen-carbon fuels may be found in reference 10. Other values are given in reference 6, which also explains the method for calculating the total fuel enthalpy from the heat of formation.

Example. - An example may make the above procedure more understandable. Suppose combustion of CO in air is desired. The properties of the stoichiometric combustion products of this fuel are not presented specifically in the tables, so it is necessary to derive the properties through combinations of the other tables (or charts). By writing the formula for the fuel in the form $B_\alpha H_\beta C_\gamma O_\delta$, it may be seen that

$$\alpha = 0$$

$$\beta = 0$$

$$\gamma = 1$$

$$\delta = 1$$

Substituting these values in equations (A2) gives

$$D = 1/2$$

$$a = 0$$

$$b = 0$$

$$c = 1$$

$$e = 1/2(3.773)$$

Equation (A1) then becomes, for this fuel,

$$CO + 1/2(O_2 + 3.773Z) \rightarrow CO_2 + 1/2(3.773)Z \tag{A9}$$

The right-hand side of equation (A5) is observed to equal the right-hand side of equation (A9) except for the inequality in moles of Z. Subtracting twice equation (A6) from (A4) gives

$$\left\{H_2\right\} - 2\left\{H_2O\right\} = 3.773Z \tag{A10}$$

and so,

$$\left\{C\right\} - 1/2\left[\left\{H_2\right\} - 2\left\{H_2O\right\}\right] = CO_2 + 1/2(3.773)Z = \left\{CO\right\} \tag{A11}$$

The braces used here and in following sections denote the products of combustion of each substance according to the reaction equations (A3) to (A6).

The weight of constituents of equation (A9) is found by substitution in equation (A7), which gives

$$\text{Weight} = 0 + 0 + 12.01(1) + 16(1) + 138.269(1/2) = 97.14$$

Equation (A11) is then rewritten on the basis of 1 pound of products of combustion as follows:

$$\left\{CO\right\} = \frac{150.279}{97.14}\left\{C\right\} - \frac{1}{2}\left[\frac{142.301}{97.14}\left\{H_2\right\} - 2\,\frac{18.016}{97.14}\left\{H_2O\right\}\right]$$

$$= 1.547\left\{C\right\} - 0.732\left\{H_2\right\} + 0.185\left\{H_2O\right\} \tag{A12}$$

Equation (A12) is the basic equation telling how to combine the values of thermodynamic properties of combustion products of C, H_2, and H_2O in order to obtain the thermodynamic properties of the stoichiometric combustion products of CO. If the tables are used, equation (A10) is unnecessary because the properties of 3.773Z are listed in table X, and

$$\left\{CO\right\} = 1.547\left\{C\right\} - 0.547\left\{Z\right\} \tag{A13}$$

The stoichiometric fuel-air ratio for CO as given by equation (A8) is

$$x_s = \frac{0 + 0 + 12.01(1) + 16(1)}{138.269(1/2)} = 0.4052$$

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APPENDIX B

BORON FUELS WITH CONDENSED B_2O_3

When a fuel containing boron is burned in air, the atoms of boron combine with oxygen to form B_2O_3, which under some conditions exists in the condensed phase (solid or liquid). The tables of thermodynamic data for boron-containing fuels were therefore prepared for the two cases: (1) all the B_2O_3 is gaseous and (2) all the B_2O_3 is condensed (crystalline for temperatures under 1301.7° R, and liquid for all higher temperatures). This appendix derives a method for selecting the proper case to use in engine calculations. In many situations both gaseous and condensed B_2O_3 is present, and both cases must be combined for a correct solution.

From equations (A1) and (A2) of appendix A, the reaction equation for stoichiometric combustion of a fuel containing arbitrary amounts of boron, hydrogen, carbon, and oxygen is

$$\frac{1}{D}\left(B_\alpha H_\beta C_\gamma O_\delta\right) + O_2 + 3.773Z \rightarrow \frac{1}{D}\left[\frac{1}{2}\alpha(B_2O_3) + \frac{1}{2}\beta(H_2O) + \gamma(CO_2)\right] + 3.773Z \tag{B1}$$

where

$$D = \frac{3}{4}\alpha + \frac{1}{4}\beta + \gamma - \frac{1}{2}\delta$$

For an equivalence ratio of less than 1.0, the reaction equation becomes

$$\frac{X}{D_x}\left(\beta_{\alpha_x} H_{\beta_x} C_{\gamma_x} O_{\delta_x}\right) + O_2 + 3.773Z \rightarrow$$

$$\frac{X}{D_x}\left[\frac{1}{2}\alpha_x(B_2O_3) + \frac{1}{2}\beta_x(H_2O) + \gamma_x(CO_2)\right] + (1 - X)O_2 + 3.773Z \tag{B2}$$

This equation may be expanded for the more general case of a mixture of two fuels to read

$$\frac{X}{D_x}\left(B_{\alpha_x} H_{\beta_x} C_{\gamma_x} O_{\delta_x}\right) + \frac{Y}{D_y}\left(B_{\alpha_y} H_{\beta_y} C_{\gamma_y} O_{\delta_y}\right) + O_2 + 3.773Z \rightarrow$$

$$\frac{X}{D_x}\left[\frac{1}{2}\alpha_x(B_2O_3) + \frac{1}{2}\beta_x(H_2O) + \gamma_x(CO_2)\right] + \frac{Y}{D_y}\left[\frac{1}{2}\alpha_y(B_2O_3) + \frac{1}{2}\beta_y(H_2O) + \gamma_y(CO_2)\right]$$

$$+ (1 - X - Y)O_2 + 3.773Z \tag{B3}$$

From equation (B3) the total number of gaseous moles of combustion products N_g is

$$N_g = N_{B_2O_{3,g}} + XG_x + YG_y + 4.773 \tag{B4}$$

where, for each fuel,

$$G = \frac{\frac{1}{2}\beta + \gamma}{D} - 1 = \frac{-3\alpha + \beta + 2\delta}{3\alpha + \beta + 4\gamma - 2\delta}$$

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Now define a factor λ such that

$$P = \lambda \cdot N_g$$

where P, the static pressure of the combustion products, is equal to the sum of the partial pressures of the constituents; that is,

$$P = p_{B_2O_3} + p_{H_2O} + p_{CO_2} + p_{O_2} + p_Z$$

Then, with the condensed B_2O_3 assumed to have essentially zero partial pressure,

$$p_{B_2O_3} = \lambda N_{B_2O_{3,g}}$$

so

$$N_g = \frac{P}{p_{B_2O_3}} N_{B_2O_{3,g}} \tag{B5}$$

Substituting equation (B5) in (B4) gives

$$N_{B_2O_{3,g}} = \frac{1}{P/p_{B_2O_3} - 1} (XG_x + YG_y + 4.773) \tag{B6}$$

Define a new term ε equal to the ratio of gaseous to total moles of B_2O_3;

$$\varepsilon = \frac{N_{B_2O_{3,g}}}{N_{B_2O_3}}$$

From equation (B3),

$$N_{B_2O_3} = \frac{\alpha_x X}{2D_x} + \frac{\alpha_y Y}{2D_y} \tag{B7}$$

Substituting equations (B6) and (B7) into the definition for ε gives, as a final result,

$$\varepsilon = \frac{1}{P/p_{B_2O_3} - 1} \frac{XG_x + YG_y + 4.773}{\frac{\alpha_x}{2D_x} X + \frac{\alpha_y}{2D_y} Y} \tag{B8}$$

The following similar expression may be derived for the ratio k of gaseous to total moles of the combustion products:

$$k = \frac{N_g}{N}$$

Since

$$N = N_g + N_{B_2O_3} - N_{B_2O_3,g}$$

k may also be written

$$k = \frac{N_g/N_{B_2O_3,g}}{N_g/N_{B_2O_3,g} + \frac{1}{\varepsilon} - 1} \tag{B9}$$

Combining equation (B9) with equations (B5) and (B8) gives

$$k = \frac{\left(\frac{XG_x + YG_y + 4.773}{\frac{\alpha_x}{2D_x} X + \frac{\alpha_y}{2D_Y} Y}\right) + \varepsilon}{\left(\frac{XG_x + YG_y + 4.773}{\frac{\alpha_x}{2D_x} X + \frac{\alpha_y}{2D_y} Y}\right) + 1} \tag{B10}$$

Expressions have thus been developed which give ε and k for any equivalence ratio, temperature, and pressure (where $p_{B_2O_3}$ is obtained from table XI or figure 7 as a function of the gas temperature, and G and $\alpha/2D$ are functions only of the fuel type, values of which may be calculated from the defining equations or read from table I).

Values of ε as calculated from equation (B8) are used to compute the thermodynamic properties of the combustion products when the tables are utilized. For example, for the stoichiometric products,

$$\psi(h) = \varepsilon\, \psi(h_{p,g}) + (1 - \varepsilon)\psi(h_{p,c})$$

where $\psi(h_{p,g})$ is read from the table for gaseous B_2O_3 and $\psi(h_{p,c})$ from the table for condensed B_2O_3. The enthalpy for less than stoichiometric mixtures is then calculated in the usual way from

$$h = h_a + \frac{x}{1 + x}\psi(h)$$

$c_p = c_{pa} + \frac{f}{1+f}(\psi c_p)$

Similar relations may be written for the specific heat and for φ.

Values of k as calculated from equation (B10) are used to calculate the molecular weight of the combustion gases, which in turn is required to compute gas densities and flow areas. An equation for the molecular weight of the gases (not including B_2O_3 that may be condensed) is derived as follows:

By definition,

$$M = \frac{W}{N}$$

$$M_g = \frac{W_g}{N_g}$$

$$k = \frac{N_g}{N}$$

Therefore,

$$M_g = \frac{1}{k}\frac{W_g}{W}M \tag{B11}$$

Now

$$\frac{W_g}{W} = 1 - \frac{W_{B_2O_3}}{W} + \frac{W_{B_2O_3,g}}{W}$$

$$= 1 - \left[1 - \left(\frac{W_{B_2O_3,g}}{W_{B_2O_3}}\right)\right]\frac{W_{B_2O_3}}{W}$$

$$\frac{W_{B_2O_3,g}}{W_{B_2O_3}} = \frac{N_{B_2O_3,g}\,M_{B_2O_3}}{N_{B_2O_3}\,M_{B_2O_3}} = \varepsilon$$

Also from equation (B3),

$$\frac{W_{B_2O_3}}{W} = \frac{\left(\frac{\alpha_x}{2D_x} X + \frac{\alpha_y}{2D_y} Y\right) M_{B_2O_3}}{\frac{X}{D_x} M_x + \frac{Y}{D_y} M_y + M_{O,Z}} \qquad \text{(B12)}$$

where M_x and M_y denote the molecular weight of fuels X and Y (given in table I), $M_{B_2O_3}$ is the molecular weight of B_2O_3 (69.64), and $M_{O,Z}$ is the weight of air per mole of O_2 (138.269).

The average molecular weight of all the combustion products is

$$M = \frac{1 + x + y}{\frac{X(1 + x_s)}{M_{P,x}} + \frac{Y(1 + y_s)}{M_{P,y}} + \frac{1 - X - Y}{M_a}} \qquad \text{(B13)}$$

where the values of M_P and M_a are given at the head of tables II to X for each fuel.

Equation (B11) can then be written

$$M_g = \left[1 - (1 - \varepsilon) \frac{W_{B_2O_3}}{W}\right] \frac{M}{k} \qquad \text{(B14)}$$

in which ε is given by equation (B8), k by (B10), $W_{B_2O_3}/W$ by (B12), and M by (B13).

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APPENDIX C

ILLUSTRATIVE EXAMPLES OF USE OF EQUATIONS AND DATA

Several examples are presented in this section illustrating the use of the equations and data presented in this report.

Combustion and Expansion of Pentaborane and Air with Dissociation

Assume the following conditions at the entrance to the combustion chamber:

Fuel, pentaborane B_5H_9 (liquid)

Equivalence ratio X, 0.8

Combustor inlet-air temperature, 560° R

Combustor inlet-air pressure, 2 atm

CO-4 back

First, calculate the combustor-outlet temperature. From figure 3 for B_5H_9,

$$x_s = 0.07645$$

From figure 1, for air at a temperature T of 560° R and a pressure P of 2 atmospheres,

$$h_{a,1} = 248 \text{ Btu/lb air}$$

Substituting in the left-hand side of equation (8a) yields

$$h_1 = (0.8)(0.07645)(33,828) + 248 = 2317 \text{ Btu/lb air}$$

where the value of H^o is obtained from table I.

For simplicity, the momentum-pressure drop due to heat release will be neglected so that the pressure after combustion is still 2 atmospheres. It is now possible to solve for the temperature after combustion. A trial-and-error procedure is required to find the temperature T_2 that will satisfy equation (8a).

Assume that $T_2 = 4400^\circ$ R. From figure 3, for B_5H_9 at a temperature T of 4400° R and a pressure P of 2 atmospheres,

$$h'_{p,2} = 2325$$

and from figure 1, for air at 4400° R and 2 atmospheres,

$$h'_{a,2} = 1370$$

Substituting in the right-hand side of equation (8a) gives

$$h'_2 = (0.8)(1.07645)(2325) + (0.2)(1370) = 2276 \text{ Btu/lb air}$$

which is slightly lower than the desired value of 2317. Assuming a combustion temperature of 4500° R gives for the enthalpy

$$h'_2 = 2332 \text{ Btu/lb air}$$

which is somewhat high. Linear interpolation then gives as the solution

$$T_2 = 4400 + \frac{4500 - 4400}{2332 - 2276}(2317 - 2276) = 4473^\circ \text{ R}$$

Now assume the combustion gases are expanded isentropically through a pressure ratio P_2/P_3 of 2 in the exhaust nozzle, which corresponds roughly to the nozzle throat. The entropy before expansion S_2 is calculated by substitution in equation (2a). From figure 3, at $T = 4473^\circ$ R and $P = 2$ atmospheres,

$$S_{P,2} = 2.227$$

and from figure 1, at $T = 4473^\circ$ R and $P = 2$ atmospheres,

$$S_{a,2} = 2.183$$

Then

$$S_2 = (0.8)(1.07645)(2.240) + (0.2)(2.183) = 2.355 \text{ Btu/(lb air)}(^\circ\text{R})$$

The temperature after expansion is found by satisfying equation (9a). As a first estimate of T_3, try

$$T'_3 = 4000^\circ \text{ R}$$

From figure 1 at 4000° R and 1 atmosphere,

$$S'_{a,3} = 2.191$$

and from figure 3 at 4000° R and 1 atmosphere,

$$S'_{P,3} = 2.222$$

The value of S'_3 corresponding to T'_3 is

$$S'_3 = (0.8)(1.07645)(2.222) + (0.2)(2.191) = 2.352 \text{ Btu/(lb air)(}^{\circ}\text{R)}$$

Estimating a temperature of 4100° yields

$$S'_3 = 2.362$$

The correct temperature is obtained by linear interpolation to be

$$T_3 = 4030^{\circ} \text{ R}$$

The enthalpy after expansion is obtained by substituting in equation (1a). From figure 1, for air at 4030° R and 1 atmosphere,

$$h_{a,3} = 1248$$

and from figure 3, for B_5H_9 at 4030° R and 1 atmosphere,

$$h_{P,3} = 2165$$

which gives

$$h_3 = 2114 \text{ Btu/lb air}$$

The enthalpy change during expansion, according to equation (10), is

$$\Delta h = h_2 - h_3 = 2317 - 2114 = 203 \text{ Btu/lb air}$$

or

$$\Delta h = \frac{h_2 - h_3}{1 + x} = \frac{203}{1 + (0.8)(0.07645)} = 191 \text{ Btu/lb mixture}$$

From equation (11), the gas velocity is given by

$$V_3 = \sqrt{(2)(32.2)(778)(191)} = 3093 \text{ ft/sec}$$

with no losses assumed. If the flow area is desired, it is first necessary to find the molecular weight of the gases by using equation (5c). The point on figure 3 corresponding to a temperature of 4030° R and a pressure of 1 atmosphere is still above the line for $k = 1$, so all the products are gaseous. From figure 1, for air at a temperature of 4030° R and a pressure of 1 atmosphere,

$$M_a = 28.85$$

and from figure 3 for B_5H_9

$$M_P = 29.90$$

By substitution in equation (5c),

$$M_{g,3} = \frac{1 + (0.8)(0.07645)}{\frac{0.8(1 + 0.07645)}{29.90} + \frac{0.2}{28.85}} = 29.67$$

From equation (7),

$$\frac{W}{A_3} = \frac{2116}{1545}\left(\frac{29.67}{1.0}\right)\left(\frac{1.0}{4030}\right) 3093 = 31.19 \text{ (lb/sec)/sq ft}$$

The preceding calculations for station 3 correspond roughly to the conditions at the nozzle throat. Suppose now a divergent section is added to the nozzle, which expands the gases to an exit pressure of 0.08 atmosphere (which is found at an altitude of approximately 60,000 ft).

As a first estimate, assume an exit temperature of 3100° R. At a temperature of 3100° R and a pressure of 0.08 atmosphere, figure 3 gives for the entropy of the stoichiometric products

$$S'_{P,4} = 2.190$$

and figure 1 gives the entropy of air at 3100° R and a pressure of 0.08 atmosphere as

$$S'_{a,4} = 2.284$$

Then the value of exit entropy at the estimated temperature of 3100° R, from equation (2a), is

$$S'_4 = 2.343$$

which is not equal to the value of S_2 as desired. Trying one or more other temperatures and interpolating yields the solution

$$T_4 = 3163^\circ \text{ R}$$

(Note that this point on figure 3 falls below the saturated vapor line.) The exit enthalpy calculated for the temperature of 3163° R is

$$h_4 = 1479 \text{ Btu/lb air}$$

Therefore,

$$\Delta h = 790 \text{ Btu/lb mixture}$$

$$V_4 = 6292 \text{ ft/sec}$$

The flow area at the exit may be calculated as before except that a value must be computed for k by use of equation (5d).

Combustion and Expansion of Pentaborane and Air without Dissociation

Assume the same initial conditions as in the preceding problem, but this time the tables are used. The value of total fuel enthalpy taken from table X as before is

$$H^o = 33{,}828 \text{ Btu/lb}$$

The stoichiometric fuel-air ratio is obtained from the headnote of table VI and is different from the value used previously because of the different assumptions for the composition of air:

$$x_s = 0.07615$$

$$x = (0.8)(0.07615) = 0.06092$$

At a temperature of 560° R, the enthalpy of air from table II(a) is

$$h_{a,1} = 243.0 \text{ Btu/lb}$$

By substitution in the left-hand side of equation (8b),

$$h_1 = (0.06092)(33{,}828) + 243.0 = 2303.8 \text{ Btu/lb air}$$

To get a first estimate for T_2, assume the combustion products are stoichiometric. Entering table VI at an enthalpy of 2303.8 Btu per pound gives approximately

$$T_2' = 4500^o \text{ R}$$

At this temperature, table VI gives

$$\psi(h)_2 = 13{,}192$$

and table II(a) gives

$$h_{a,2} = 1350.09$$

Substitution of these values in the right-hand side of equation (8b) yields

$$h_2 = (1.06092)(1350.1) + (0.06092)(13,192) = 2236.0 \text{ Btu/lb air}$$

The error in enthalpy is

$$\Delta h = 2303.8 - 2236.0 = 67.8 \text{ Btu/lb air}$$

$$= \frac{67.8}{1.06092} = 63.9 \text{ Btu/lb mixture}$$

For a better value of the combustion temperature, use the specific heat. From equation (3a), at a temperature of 4500° R,

$$c_{p,2} = 0.3051 + \left(\frac{0.06092}{1.06092}\right)(0.7112) = 0.3459$$

$$T_2 = 4500 + \frac{63.9}{0.3459} = 4685^{\circ} \text{ R}$$

This temperature is 200° R higher than the combustion temperature obtained in the previous example with dissociation taken into account. The temperature just found is far above that for condensation of the products to occur, so that the use of table VI(a), for gaseous B_2O_3, is justified.

Now calculate the expansion pressure ratio. The molecular weights of the stoichiometric products and of air are taken from the tops of tables VI and II(a), respectively;

$$M_P = 30.121$$

$$M_a = 28.967$$

The molecular weight of the mixture, from equation (5c), is

$$M_2 = \frac{1 + 0.06092}{\frac{(0.8)(1.07615)}{30.121} + \frac{0.2}{28.967}} = 29.90$$

From equation (9c),

$$\varphi_2 - \varphi_3 = \frac{(1.987)(1.0)}{29.90} \ln 2.0 = 0.0460$$

At a temperature of 4685° R,

$$\varphi_2 = 2.1830 + \left(\frac{0.06092}{1.06092}\right)(0.4061) = 2.2063$$

So

$$\varphi_3 = 2.2063 - 0.0460 = 2.1603$$

Assume that the temperature after expansion is 4000° R. At this temperature,

$$\varphi_3' = 2.1353 + \left(\frac{0.06092}{1.06092}\right)(0.2948) = 2.1522$$

For a better estimate, find $\Delta S/\Delta T$:

$$c_{p,3} = 0.3020 + \left(\frac{0.06092}{1.06092}\right)(0.7044) = 0.3424$$

$$\frac{\Delta S}{\Delta T} = \frac{c_p}{T} = \frac{0.3424}{4000} = 8.560\times10^{-5}$$

Then

$$T_3 = 4000 + \frac{2.1603 - 2.1522}{8.560\times10^{-5}} = 4095^\circ \text{ R}$$

The enthalpy at this temperature is

$$h_3 = 1227.0 + \left(\frac{0.06092}{1.06092}\right)(12,905) = 1968.0 \text{ Btu/lb mixture}$$

while

$$h_2 = \frac{2303.8}{1.06092} = 2171.6 \text{ Btu/lb mixture}$$

Hence,

$$\Delta H = 2171.6 - 1968.0 = 203.6 \text{ Btu/lb mixture}$$

which agrees reasonably well with the previous example, despite the erroneous combustion temperature.

The calculations up to this point are typical for fuels, such as hydrocarbons, that produce only gaseous products of combustion. The temperatures in the present problem have also been high enough to prevent condensation, even though the combustion products of B_5H_9 contain

B_2O_3. However, if the gases are now further expanded to a pressure of 0.08 atmosphere, there is a possibility of causing some of the B_2O_3 to condense. (It is noted that in the previous example at this condition k was less than 1.) Such a phase change requires use of the technique explained in appendix B.

Assume an exit temperature of 2700° R and check for the presence of condensed products. From equation (1e),

$$\varepsilon_4' = \frac{1}{\frac{0.08}{2.725\times10^{-5}} - 1}\left[\frac{0.8(-0.25) + 4.773}{(0.4167)(0.8)}\right]$$

$$= \frac{1}{2936 - 1}(13.72) = 0.004675$$

where the value of 2.725×10^{-5} for $p_{B_2O_3}$ is read from table XI and the values of -0.25 and 0.4167 for G and $\alpha/2D$ from table I. From equation (5d),

$$k_4' = \frac{13.72 + 0.004675}{13.72 + 1} = 0.9324$$

The change in φ during expansion is, from equation (9b),

$$\varphi_2 - \varphi_4 = \frac{1.987}{29.90}\left[\ln 2.0 - \frac{0.9324}{1.0}\ln 0.08\right] = 0.2025$$

$$\varphi_4 = 2.2063 - 0.2025 = 2.0038$$

Also, from the tables at 2700° R,

$$\psi(\varphi_g)_4' = 0.0271 \qquad \text{(gaseous } B_2O_3\text{)}$$

$$\psi(\varphi_c)_4' = -1.1988 \qquad \text{(condensed } B_2O_3\text{)}$$

So, from equation (2d),

$$\psi(\varphi)_4' = 0.004675(0.0271) + (1 - 0.004675)(-1.1988) = -1.1931$$

$$\varphi_4' = 2.0190 + \frac{0.06092}{1.06092}(-1.1931) = 1.9505$$

The value of φ_4' calculated from the assumed exit temperature is lower than the value of φ_4 calculated from the pressure ratio across the nozzle. (Note that φ_4 is also a function to some extent of the assumed exit temperature since k is not constant when condensation of B_2O_3 occurs.) It is not possible in this case to obtain a solution by calculating $\Delta S/\Delta T$ from c_p/T because c_p does not account for the heat of vaporization involved in the phase change. A solution is obtained by calculating φ_4 and φ_4' for several other assumed values of T_4. The intersection of φ_4 and φ_4' plotted against T_4' yields the answer

$$T_4 = 3084^\circ \text{ R}$$

$$\varepsilon_4 = 0.123$$

The enthalpy corresponding to this condition is calculated to be

$$h_4 = 1351.0 \text{ Btu/lb mixture}$$

and gives

$$\Delta h = 820.6 \text{ Btu/lb mixture}$$

$$V_4 = 6412 \text{ ft/sec}$$

which differs from the value obtained with the charts (including dissociation) by 2 percent.

Expansion with Frozen Phase Equilibrium

Recalculate the final expansion in the preceding problem assuming that the gaseous B_2O_3 in the exhaust products does not have sufficient time to condense during passage through the nozzle. Under these conditions,

$$\varepsilon = 1$$

$$k = 1$$

Using table VI(a)(for gaseous B_2O_3) leads to the following solution:

$$T_4 = 2477^\circ \text{ R}$$

$$\Delta h = 744.7 \text{ Btu/lb mixture}$$

$$V_4 = 6108 \text{ ft/sec}$$

If condensation does not take place, the thermal energy contained in the vaporized B_2O_3 is not recovered in the nozzle, and the jet velocity is therefore lower.

Combination of C and H_2 Charts to Obtain CH_2

Appendix A describes the procedure for combining the presented thermodynamic data to obtain data for other fuels that are not specifically presented. As a numerical example, suppose it is desired to calculate the enthalpy of the products of combustion for the following conditions:

Fuel, CH_2

Equivalence ratio, 0.9

Gas temperature, 4000° R

Gas pressure, 0.01 atm

The enthalpy will be calculated from the charts for the combustion products of C and H_2. Since CH_2 is one of the fuels for which a chart is presented, there can be a check on the calculation. By referring to equation (A1), it may be seen that

$$\alpha = 0$$

$$\beta = 2$$

$$\gamma = 1$$

$$\delta = 0$$

Substituting these values in equations (A2) gives

$$D = 1.5$$

$$a = 0$$

$$b = 1$$

$$c = 1$$

$$e = 3.773(1.5)$$

By substitution in equation (A1),

$$CH_2 + 1.5(O_2 + 3.773Z) \rightarrow H_2O + CO_2 + 1.5(3.773)Z$$

It is seen that 0.5 times the hydrogen reaction (eq. (A4)) gives for the combustion products

$$\frac{1}{2}\left\{H_2\right\} = H_2O + 0.5(3.773)Z$$

which, when added to the carbon reaction (eq. (A5)) yields

$$\frac{1}{2}\left\{H_2\right\} + \left\{C\right\} = H_2O + CO_2 + 1.5(3.773)Z$$

which contains the correct combustion products for the desired CH_2 reaction.

The weight of the CH_2 reactants is obtained from equation (A7) as follows:

$$\text{Weight} = (1.008)(2) + (12.01)(1) + (138.269)(1.5) = 221.428$$

and the table in appendix A gives the values 142.301 and 150.279 for the reactant weights in the H_2 and C reactions, respectively. The equation that defines the method of combining the charts (or tables) for the stoichiometric combustion products of H_2 and C in order to obtain CH_2 then is

$$\left\{CH_2\right\} = \left(\frac{1}{2}\right)\left(\frac{142.301}{221.428}\right)\left\{H_2\right\} + \frac{150.279}{221.428}\left\{C\right\}$$

$$= 0.3213\left\{H_2\right\} + 0.6787\left\{C\right\}$$

At a temperature of 4000° R and a pressure of 0.01 atmosphere, figure 4 (for carbon) gives

$$h = 1470 \text{ Btu/lb}$$

At a temperature of 4000° R and a pressure of 0.01 atmosphere, figure 5 (for hydrogen) gives

$$h = 2081 \text{ Btu/lb}$$

The enthalpy of the stoichiometric combustion products of CH_2 then is

$$h_p = (0.3213)(2081) + (0.6787)(1470) = 1666 \text{ Btu/lb}$$

At 1 atmosphere and a temperature of 4000° R, figure 1 (for air) gives

$$h_a = 1334 \text{ Btu/lb}$$

The stoichiometric fuel-air ratio from equation (A12) is

$$x_s = 0.06763$$

thus the enthalpy of the final mixture is

$$h = 0.9(1 + 0.06763)(1666) + (1 - 0.9)(1334) = 1734 \text{ Btu/lb air}$$

As a check on this result, calculate the enthalpy using the chart for CH_2. From figure 6 at a temperature of 4000° R and a pressure of 0.01 atmosphere,

$$h_p = 1654 \text{ Btu/lb}$$

so that the final enthalpy is

$$h = 0.9(1.06763)(1654) + (0.1)(1334) = 1723 \text{ Btu/lb air}$$

The error in calculating the enthalpy of CH_2 using the C and H_2 charts is 0.6 percent.

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3911

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TABLE I. - TOTAL ENTHALPY AND OTHER PROPERTIES OF SEVERAL FUELS

Fuel	Formula	Molecular weight	Phase	Assigned temperature, °R	Total enthalpy, H^o, Btu/lb	Stoichiometric fuel-air ratio, x_s (a)	G	D	$\frac{\alpha}{2D}$
Boron	B	10.82	Crystal	-----	28,843	0.1043	-1.0	0.75	0.6667
n-Butane	C_4H_{10}	58.12	Gas Liquid	536.7 470.8	21,249 21,064	.06467	.3846	6.5	0
Carbon	C	12.01	Graphite	536.7	13,815	.08686	0	1.0	0
Diborane	B_2H_6	27.688	Gas Liquid	536.7 325.1	36,575 36,263	.06675	0	3.0	.3333
Ethylene decaborane[b]	$B_{10}H_{13}C_2H_5$	150.364	Liquid	536.7	30,335	.07768	-.2143	14.0	.3571
Heptane	C_7H_{16}	100.198	Liquid	536.7	20,608	.06588	.3636	11.0	0
Hydrocarbon fuel	C_xH_{2x}	14.026x	Liquid	-----	[c]20,000	.06763	.3333	1.5	0
Hydrogen	H_2	2.016	Gas Liquid	536.7 36.7	62,000 60,309	.02916	1.0	.5	0
Methane	CH_4	16.042	Gas Liquid	536.7 201.0	23,919 23,531	.05800	.5	2.0	0
Methanol	CH_3OH	32.042	Liquid	536.7	9,892	.1545	1.0	1.5	0
n-Octane	C_8H_{18}	114.224	Liquid	536.7	20,528	.06608	.36	12.5	0
Pentaborane	B_5H_9	63.172	Liquid	536.7	33,828	.07615	-.25	6.0	.4167

[a] Air assumed to consist of the following mole fractions: N_2, 0.7809; O_2, 0.2095; A, 0.0093; CO_2, 0.0003. (For use in conjunction with the tables of undissociated data.)

[b] Pure.

[c] Interpolated.

CALLED WEBER FOR THESE

CH L 536.7 17,600

CH_2 " 20,000

CH_3 L " 22000

CH_4 L 201, 23,531

G 536.7 23,919

TABLE II. - THERMODYNAMIC DATA FOR AIR AND WATER VAPOR

[No dissociation assumed.]

(a) Air. Composition, percent by volume: nitrogen, 78.09; oxygen, 20.95; argon, 0.93; carbon dioxide, 0.03. Molecular weight, 28.97.

Temperature, T, °R	Enthalpy, h, Btu/lb	Constant-pressure entropy, φ, Btu/(lb)(°R)	Specific heat, c_p, Btu/(lb)(°R)
350	192.80	1.49849	0.2379
400	204.70	1.53031	.2385
450	216.65	1.55845	.2391
500	228.62	1.58368	.2396
550	240.62	1.60656	.2402
600	252.64	1.62748	.2408
650	264.70	1.64679	.2414
700	276.79	1.66471	.2419
750	288.88	1.68146	.2428
800	301.05	1.69717	.2439
850	313.27	1.71200	.2449
900	325.52	1.72598	.2460
950	337.86	1.73932	.2474
1000	350.27	1.75206	.2489
1050	362.75	1.76423	.2503
1100	375.29	1.77591	.2518
1150	387.92	1.78713	.2534
1200	400.63	1.79796	.2550
1250	413.42	1.80840	.2565
1300	426.28	1.81846	.2581
1350	439.24	1.82823	.2597
1400	452.26	1.83771	.2612
1450	465.38	1.84691	.2628
1500	478.56	1.85584	.2643
1550	491.81	1.86454	.2658
1600	505.14	1.87300	.2673
1650	518.56	1.88128	.2687
1700	532.02	1.88932	.2700
1750	545.56	1.89716	.2714
1800	559.17	1.90486	.2727
1850	572.84	1.91235	.2739
1900	586.57	1.91967	.2751
1950	600.35	1.92684	.2762
2000	614.20	1.93384	.2774
2050	628.10	1.94071	.2784
2100	642.04	1.94743	.2795
2150	656.04	1.95402	.2805
2200	670.09	1.96048	.2815
2250	684.20	1.96682	.2824
2300	698.35	1.97304	.2833
2350	712.53	1.97914	.2842
2400	726.76	1.98513	.2850
2450	741.03	1.99102	.2858
2500	755.35	1.99680	.2866
2550	769.70	2.00249	.2873
2600	784.08	2.00807	.2880
2650	798.50	2.01357	.2888
2700	812.96	2.01897	.2895
2750	827.45	2.02429	.2901
2800	841.98	2.02952	.2907
2850	856.53	2.03467	.2914
2900	871.12	2.03974	.2920
2950	885.73	2.04474	.2926
3000	900.38	2.04967	.2931
3050	915.05	2.05452	.2937
3100	929.75	2.05930	.2942
3150	944.48	2.06401	.2947
3200	959.23	2.06866	.2952
3250	974.00	2.07324	.2957
3300	988.80	2.07776	.2962
3350	1003.63	2.08222	.2967
3400	1018.48	2.08662	.2972
3450	1033.36	2.09096	.2976
3500	1048.25	2.09524	.2980
3550	1063.16	2.09948	.2985
3600	1078.09	2.10365	.2989
3650	1093.05	2.10778	.2993
3700	1108.03	2.11185	.2997
3750	1123.02	2.11588	.3001
3800	1138.04	2.11986	.3005
3850	1153.08	2.12379	.3008
3900	1168.13	2.12767	.3012
3950	1183.20	2.13151	.3016
4000	1198.29	2.13531	.3019
4500	1350.09	2.17106	.3051
5000	1503.36	2.20336	.3078
5500	1657.87	2.23281	.3101
6000	1813.44	2.25988	.3121

50 121.40 1.30757 .2343

0 0 0 0

$h - h_{KK} = 109.23$

$\Delta T = \frac{\Delta H}{c_p} = 459°$

(b) Water vapor. Molecular weight, 18.016.

Temperature, T, °R	Enthalpy, h, Btu/lb	Constant-pressure entropy, φ, Btu/(lb)(°R)	Specific heat, c_p, Btu(lb)(°R)
350	1286.33	2.3152	0.4362
400	1308.21	2.3737	.4386
450	1330.20	2.4255	.4411
500	1352.31	2.4721	.4436
550	1374.56	2.5145	.4460
600	1396.91	2.5534	.4484
650	1419.40	2.5894	.4509
700	1442.00	2.6229	.4533
750	1464.89	2.6546	.4564
800	1487.79	2.6842	.4600
850	1510.88	2.7121	.4635
900	1534.30	2.7389	.4671
950	1557.75	2.7643	.4711
1000	1581.42	2.7885	.4752
1050	1605.26	2.8118	.4792
1100	1629.54	2.8343	.4833
1150	1653.82	2.8559	.4877
1200	1678.32	2.8767	.4921
1250	1703.01	2.8969	.4964
1300	1728.70	2.9169	.5009
1350	1753.87	2.9358	.5055
1400	1779.26	2.9543	.5100
1450	1805.62	2.9726	.5146
1500	1831.45	2.9901	.5193
1550	1857.54	3.0072	.5240
1600	1883.86	3.0239	.5287
1650	1910.86	3.0404	.5334
1700	1937.64	3.0563	.5380
1750	1964.65	3.07200	.5427
1800	1992.14	3.08714	.5473
1850	2019.62	3.10220	.5517
1900	2047.32	3.11698	.5561
1950	2075.23	3.13148	.5605
2000	2103.36	3.14572	.5647
2050	2131.71	3.15971	.5688
2100	2160.26	3.17348	.5730
2150	2189.00	3.18701	.5771
2200	2217.96	3.20032	.5811
2250	2247.12	3.21343	.5850
2300	2276.47	3.22633	.5889
2350	2306.02	3.23904	.5928
2400	2335.71	3.25154	.5965
2450	2365.68	3.26380	.6003
2500	2395.78	3.27607	.6040
2550	2426.08	3.28807	.6076
2600	2456.34	3.29981	.6060
2650	2487.19	3.31157	.6145
2700	2517.99	3.32309	.6180
2750	2548.97	3.33446	.6212
2800	2580.12	3.34568	.6244
2850	2611.41	3.35676	.6276
2900	2642.88	3.36770	.6307
2950	2674.50	3.37851	.6337
3000	2706.27	3.38919	.6366
3050	2738.16	3.39973	.6396
3100	2770.21	3.41015	.6423
3150	2802.40	3.42045	.6450
3200	2834.72	3.43063	.6477
3250	2867.17	3.44070	.6503
3300	2899.74	3.45064	.6527
3350	2932.44	3.46048	.6552
3400	2965.26	3.47020	.6576
3450	2998.21	3.47982	.6599
3500	3031.26	3.48933	.6621
3550	3064.42	3.49874	.6643
3600	3097.69	3.50805	.6665
3650	3131.07	3.51726	.6685
3700	3164.55	3.52637	.6705
3750	3198.11	3.53538	.6725
3800	3231.79	3.54430	.6744
3850	3265.56	3.55313	.6762
3900	3299.43	3.56187	.6781
3950	3333.36	3.57052	.6799
4000	3367.41	3.57908	.6816
4500	3712.16	3.66027	.6968
5000	4063.70	3.73434	.7088
5500	4420.61	3.80236	.7184
6000	4781.77	3.86521	.7259

$h - h_{K-K} = 1132.8$

DRY AIR

$h - h_{KK} = 108.23$

$\Delta T = \frac{\Delta H}{C_P} = 453°$

TABLE III. - THERMODYNAMIC DATA FOR STOICHIOMETRIC COMBUSTION PRODUCTS OF BORON

[No dissociation assumed; molecular weight, 34.391; stoichiometric fuel-air ratio, 0.1043.]

(a) Gaseous boron oxide B_2O_3.

Temperature, T, °R	Enthalpy, h, Btu/lb	Constant-pressure entropy, φ, Btu/(lb)(°R)	Specific heat, c_p, Btu/(lb)(°R)	$\psi(h)$	$\psi(\varphi)$	$\psi(c_p)$
1750	-------	-------	------	--------	------	-----
1800	1611.24	1.70247	0.2943	11,135.4	-2.1421	0.229
1850	1626.00	1.71056	.2957	11,146.9	-2.1358	.230
1900	1640.82	1.71846	.2970	11,158.4	-2.1296	.232
1950	1655.71	1.72620	.2984	11,170.1	-2.1236	.234
2000	1670.66	1.73377	.2997	11,181.9	-2.1176	.236
2050	1685.68	1.74119	.3009	11,193.7	-2.1117	.237
2100	1700.75	1.74845	.3020	11,205.6	-2.1060	.238
2150	1715.88	1.75557	.3032	11,217.6	-2.1004	.239
2200	1731.07	1.76255	.3042	11,229.6	-2.0949	.240
2250	1746.31	1.76940	.3052	11,241.7	-2.0894	.241
2300	1761.60	1.77612	.3062	11,253.8	-2.0841	.242
2350	1776.94	1.78272	.3072	11,265.9	-2.0789	.243
2400	1792.31	1.78920	.3080	11,278.1	-2.0738	.243
2450	1807.74	1.79556	.3088	11,290.3	-2.0687	.243
2500	1823.21	1.80181	.3097	11,302.5	-2.0638	.244
2550	1838.71	1.80795	.3104	11,314.7	-2.0590	.244
2600	1854.25	1.81398	.3112	11,326.9	-2.0542	.244
2650	1869.83	1.81992	.3119	11,339.1	-2.0496	.244
2700	1885.44	1.82575	.3126	11,351.4	-2.0450	.244
2750	1901.09	1.83149	.3132	11,363.6	-2.0405	.244
2800	1916.77	1.83715	.3138	11,375.9	-2.0361	.244
2850	1932.48	1.84271	.3145	11,388.1	-2.0318	.244
2900	1948.23	1.84818	.3151	11,400.3	-2.0275	.244
2950	1963.99	1.85358	.3156	11,412.5	-2.0233	.244
3000	1979.79	1.85889	.3162	11,424.7	-2.0192	.243
3050	1995.61	1.86412	.3167	11,436.9	-2.0152	.243
3100	2011.46	1.86927	.3172	11,449.1	-2.0112	.243
3150	2027.34	1.87435	.3177	11,461.2	-2.0074	.242
3200	2043.24	1.87936	.3181	11,473.4	-2.0036	.242
3250	2059.15	1.88430	.3186	11,485.5	-1.9998	.241
3300	2075.10	1.88916	.3190	11,497.6	-1.9961	.241
3350	2091.06	1.89396	.3194	11,509.6	-1.9925	.240
3400	2107.05	1.89870	.3199	11,521.6	-1.9889	.240
3450	2123.05	1.90337	.3203	11,533.6	-1.9854	.239
3500	2139.08	1.90798	.3206	11,545.6	-1.9820	.239
3550	2155.12	1.91253	.3210	11,557.5	-1.9786	.238
3600	2171.18	1.91703	.3214	11,569.5	-1.9752	.237
3650	2187.26	1.92146	.3217	11,581.3	-1.9720	.237
3700	2203.36	1.92584	.3220	11,593.2	-1.9687	.236
3750	2219.46	1.93017	.3224	11,605.0	-1.9656	.235
3800	2235.59	1.93444	.3227	11,616.7	-1.9625	.235
3850	2251.74	1.93866	.3230	11,628.5	-1.9594	.234
3900	2267.90	1.94283	.3233	11,640.2	-1.9564	.233
3950	2284.07	1.94695	.3236	11,651.9	-1.9534	.233
4000	2300.26	1.95103	.3239	11,663.5	-1.9505	.232
4500	2462.85	1.98932	.3263	11,777.7	-1.9235	.224
5000	2626.50	2.02381	.3281	11,887.6	-1.9004	.215
5500	2790.97	2.05516	.3296	11,993.0	-1.8803	.206
6000	2956.10	2.08389	.3308	12,094.2	-1.8627	.198

TABLE III. - Concluded. THERMODYNAMIC DATA FOR STOICHIOMETRIC COMBUSTION PRODUCTS OF BORON

[No dissociation assumed; molecular weight, 34.391; stoichiometric fuel-air ratio, 0.1043.]

(b) Condensed boron oxide B_2O_3.

Temperature, T, °R	Enthalpy, h, Btu/lb	Constant-pressure entropy, φ, Btu/(lb)(°R)	Specific heat c_p, Btu/(lb)(°R)	$\psi(h)$	$\psi(\varphi)$	$\psi(c_p)$
350	524.33	1.08839	0.2186	3508.9	-4.3406	-0.204
400	535.37	1.11805	.2232	3499.8	-4.3634	-.162
450	546.65	1.14468	.2277	3492.7	-4.3794	-.119
500	558.15	1.16894	.2323	3487.8	-4.3897	-.077
550	569.88	1.19131	.2369	3485.0	-4.3951	-.034
600	581.84	1.21213	.2415	3484.3	-4.3961	.007
650	594.03	1.23166	.2461	3485.7	-4.3938	.049
700	606.46	1.25013	.2507	3489.3	-4.3880	.092
750	619.06	1.26750	.2548	3494.7	-4.3814	.126
800	631.90	1.28407	.2586	3501.8	-4.3723	.156
850	644.93	1.29989	.2625	3510.3	-4.3618	.185
900	658.19	1.31500	.2663	3521.0	-4.3499	.214
950	671.60	1.32949	.2697	3532.3	-4.3377	.236
1000	685.17	1.34343	.2732	3544.6	-4.3250	.257
1050	698.92	1.35685	.2767	3558.1	-4.3118	.279
1100	712.93	1.36990	.2801	3573.7	-4.2973	.299
1150	726.94	1.38235	.2834	3588.2	-4.2842	.317
1200	741.20	1.39449	.2868	3604.6	-4.2704	.336
1250	755.62	1.40628	.2901	3621.9	-4.2561	.355
1300	770.21	1.41769	.2934	3640.2	-4.2418	.373
1301.7	770.71	1.41803	.2935	3640.9	-4.2417	.374
1301.7	813.31	1.45078	.3205	4091.7	-3.8951	.659
1350	828.82	1.46249	.3214	4123.4	-3.8710	.653
1400	844.92	1.47420	.3224	4155.9	-3.7416	.646
1450	861.07	1.48553	.3232	4188.1	-3.8249	.639
1500	877.25	1.49649	.3238	4219.8	-3.8034	.629
1550	893.45	1.50713	.3244	4251.1	-3.7829	.620
1600	909.69	1.51743	.3249	4281.8	-3.7634	.610
1650	925.96	1.52745	.3255	4312.1	-3.7450	.601
1700	942.25	1.53719	.3260	4341.9	-3.7270	.592
1750	958.56	1.54664	.3265	4371.3	-3.7100	.583
1800	974.91	1.55588	.3269	4400.2	-3.6937	.574
1850	991.27	1.56485	.3275	4428.8	-3.6780	.567
1900	1007.67	1.57359	.3281	4457.0	-3.6630	.561
1950	1024.09	1.58212	.3287	4484.9	-3.6485	.555
2000	1040.54	1.59045	.3293	4512.5	-3.6345	.549
2050	1057.03	1.59859	.3299	4539.8	-3.6210	.544
2100	1073.53	1.60655	.3305	4567.0	-3.6079	.540
2150	1090.08	1.61434	.3312	4593.9	-3.5953	.535
2200	1106.65	1.62196	.3318	4620.6	-3.5830	.532
2250	1123.26	1.62942	.3324	4647.1	-3.5710	.529
2300	1139.90	1.63674	.3330	4673.5	-3.5594	.526
2350	1156.57	1.64391	.3337	4699.8	-3.5482	.523
2400	1173.26	1.65094	.3342	4725.9	-3.5372	.521
2450	1189.99	1.65783	.3348	4751.9	-3.5265	.518
2500	1206.76	1.66461	.3354	4777.8	-3.5160	.516
2550	1223.54	1.67126	.3359	4803.6	-3.5058	.514
2600	1240.35	1.67778	.3364	4829.2	-3.4958	.512
2650	1257.19	1.68420	.3370	4854.8	-3.4861	.510
2700	1274.05	1.69050	.3375	4880.2	-3.4765	.508
2750	1290.94	1.69670	.3379	4905.6	-3.4672	.506
2800	1307.85	1.70280	.3384	4930.9	-3.4581	.504
2850	1324.78	1.70879	.3389	4956.1	-3.4492	.502
2900	1341.75	1.71468	.3393	4981.2	-3.4405	.500
2950	1358.72	1.72049	.3397	5006.2	-3.4319	.499
3000	1375.72	1.72621	.3401	5031.1	-3.4236	.497
3050	1392.74	1.73183	.3406	5055.9	-3.4153	.495
3100	1409.78	1.73737	.3409	5080.7	-3.4073	.494
3150	1426.84	1.74283	.3413	5105.4	-3.3994	.492
3200	1443.91	1.74821	.3416	5129.9	-3.3917	.491
3250	1461.00	1.75351	.3420	5154.5	-3.3840	.489
3300	1478.11	1.75873	.3423	5178.9	-3.3766	.487
3350	1495.24	1.76388	.3426	5203.2	-3.3693	.486
3400	1512.38	1.76896	.3430	5227.5	-3.3621	.484
3450	1529.54	1.77397	.3433	5251.7	-3.3550	.483
3500	1546.71	1.77891	.3436	5275.8	-3.3481	.481
3550	1563.90	1.78379	.3438	5299.9	-3.3412	.480
3600	1581.10	1.78860	.3441	5323.9	-3.3345	.478
3650	1598.31	1.79335	.3444	5347.8	-3.3279	.477
3700	1615.54	1.79804	.3446	5371.6	-3.3215	.475
3750	1632.78	1.80267	.3449	5395.3	-3.3151	.474
3800	1650.03	1.80724	.3451	5419.0	-3.3088	.472
3850	1667.30	1.81175	.3454	5442.6	-3.3026	.471
3900	1684.58	1.81621	.3456	5466.1	-3.2966	.469
3950	1701.86	1.82061	.3458	5489.6	-3.2906	.468
4000	1719.16	1.82497	.3460	5513.0	-3.2847	.467
4500	1892.70	1.86584	.3479	5743.1	-3.2305	.453

TABLE IV. - THERMODYNAMIC DATA FOR STOICHIOMETRIC COMBUSTION PRODUCTS OF CARBON

[No dissociation assumed; molecular weight, 31.483; stoichiometric fuel-air ratio, 0.08686.]

Temperature, T, $^{\circ}R$	Enthalpy, h, Btu/lb	Constant-pressure entropy, φ, Btu/(lb)($^{\circ}R$)	Specific heat, c_p, Btu/(lb)($^{\circ}R$)	$\psi(h)$	$\psi(\varphi)$	$\psi(c_p)$
350	153.17	1.38826	0.2273	-495.8	-1.3792	-0.152
400	164.50	1.41861	.2277	-503.0	-1.3976	-.134
450	175.95	1.44588	.2297	-509.3	-1.4122	-.116
500	187.49	1.69912	.2317	-514.7	-1.4235	-.098
550	199.13	1.49210	.2338	-519.1	-1.4321	-.080
600	210.87	1.51253	.2358	-522.7	-1.4383	-.062
650	222.71	1.53149	.2378	-525.4	-1.4426	-.044
700	234.65	1.54922	.2398	-527.2	-1.4450	-.026
750	246.70	1.56590	.2418	-527.7	-1.4459	-.012
800	258.84	1.58157	.2438	-528.0	-1.4463	-.000
850	271.09	1.59643	.2458	-527.8	-1.4460	.011
900	283.43	1.61056	.2478	-526.6	-1.4442	.023
950	295.88	1.62402	.2499	-525.3	-1.4426	.031
1000	308.43	1.63690	.2520	-523.5	-1.4409	.039
1050	321.08	1.64925	.2541	-521.4	-1.4387	.047
1100	333.83	1.66106	.2561	-518.7	-1.4369	.054
1150	346.69	1.67260	.2582	-515.8	-1.4342	.060
1200	359.66	1.68354	.2603	-512.7	-1.4316	.066
1250	372.72	1.69421	.2623	-509.2	-1.4287	.072
1300	385.89	1.70452	.2643	-505.4	-1.4256	.077
1350	399.16	1.70788	.2662	-501.4	-1.4154	.081
1400	412.53	1.72425	.2682	-497.2	-1.4196	.086
1450	425.99	1.73369	.2701	-492.7	-1.4166	.091
1500	439.55	1.74288	.2719	-488.1	-1.4133	.094
1550	453.19	1.75183	.2737	-483.2	-1.4102	.098
1600	466.92	1.76055	.2754	-478.2	-1.4070	.102
1650	480.76	1.76909	.2771	-472.8	-1.4037	.105
1700	494.66	1.77738	.2787	-467.5	-1.4005	.108
1750	508.64	1.78549	.2803	-462.0	-1.3973	.112
1800	522.68	1.79343	.2819	-456.5	-1.3942	.115
1850	536.82	1.80118	.2833	-450.7	-1.3910	.117
1900	551.02	1.80875	.2847	-444.7	-1.3879	.120
1950	565.29	1.81617	.2861	-438.6	-1.3847	.123
2000	579.63	1.82343	.2874	-432.4	-1.3816	.125
2050	594.04	1.83054	.2886	-426.1	-1.3784	.127
2100	608.50	1.83752	.2898	-419.6	-1.3753	.129
2150	623.03	1.84435	.2911	-413.1	-1.3722	.132
2200	637.61	1.85105	.2922	-406.5	-1.3692	.133
2250	652.25	1.85763	.2932	-399.7	-1.3661	.135
2300	666.94	1.86409	.2943	-392.9	-1.3631	.137
2350	681.68	1.87043	.2953	-386.0	-1.3602	.138
2400	696.46	1.87663	.2962	-379.0	-1.3573	.140
2450	711.30	1.88270	.2971	-372.0	-1.3543	.141
2500	726.18	1.88879	.2980	-364.9	-1.3515	.143
2550	741.11	1.89470	.2989	-357.7	-1.3486	.144
2600	756.07	1.90051	.2996	-350.4	-1.3458	.145
2650	771.08	1.90623	.3005	-343.1	-1.3430	.146
2700	786.12	1.91185	.3012	-335.8	-1.3403	.147
2750	801.21	1.91739	.3020	-328.4	-1.3376	.148
2800	816.33	1.92284	.3027	-320.9	-1.3349	.149
2850	831.48	1.92820	.3034	-313.4	-1.3322	.150
2900	846.67	1.93348	.3041	-305.9	-1.3296	.151
2950	861.89	1.93869	.3047	-298.3	-1.3270	.151
3000	877.14	1.94381	.3053	-290.7	-1.3245	.152
3050	892.42	1.94887	.3059	-283.1	-1.3219	.153
3100	907.74	1.95384	.3065	-275.4	-1.3195	.153
3150	923.08	1.95876	.3071	-267.7	-1.3170	.154
3200	938.45	1.96360	.3076	-260.0	-1.3145	.154
3250	953.84	1.96837	.3082	-252.2	-1.3121	.155
3300	969.27	1.97308	.3086	-244.4	-1.3098	.155
3350	984.71	1.97773	.3091	-236.7	-1.3074	.155
3400	1000.19	1.98231	.3096	-228.9	-1.3051	.156
3450	1015.69	1.98683	.3101	-221.1	-1.3028	.156
3500	1031.20	1.99130	.3105	-213.2	-1.3006	.156
3550	1046.74	1.99571	.3110	-205.4	-1.2984	.156
3600	1062.30	2.00006	.3114	-197.6	-1.2962	.156
3650	1077.89	2.00436	.3118	-189.7	-1.2940	.156
3700	1093.49	2.00861	.3122	-181.9	-1.2919	.156
3750	1109.11	2.01280	.3126	-174.0	-1.2898	.156
3800	1124.75	2.01694	.3130	-166.2	-1.2874	.156
3850	1140.42	2.02104	.3134	-158.4	-1.2856	.156
3900	1156.10	2.02508	.3137	-150.5	-1.2836	.156
3950	1171.79	2.02908	.3141	-142.7	-1.2816	.156
4000	1187.51	2.03304	.3144	-134.9	-1.2797	.156
4500	1345.52	2.07026	.3174	-57.2	-1.2613	.154
5000	1504.88	2.10384	.3198	19.0	-1.2453	.150
5500	1665.33	2.13442	.3218	93.4	-1.2311	.146
6000	1826.70	2.16250	.3235	165.8	-1.2185	.143

TABLE V. - THERMODYNAMIC DATA FOR STOICHIOMETRIC COMBUSTION PRODUCTS OF HYDROGEN

[No dissociation assumed; molecular weight, 24.648; stoichiometric fuel-air ratio, 0.02916.]

Temperature, T, °R	Enthalpy, h, Btu/lb	Constant-pressure entropy, φ, Btu/(lb)(°R)	Specific heat c_p, Btu/(lb)(°R)	ψ(h)	ψ(φ)	ψ(c_p)
350	470.14	1.71863	0.2935	9,788.1	7.7696	1.963
400	484.84	1.75792	.2944	9,886.6	8.0331	1.972
450	499.58	1.79266	.2952	9,985.4	8.2662	1.982
500	514.37	1.82383	.2961	10,084.7	8.4756	1.991
550	529.19	1.85210	.2969	10,184.6	8.6659	2.001
600	544.06	1.87796	.2977	10,284.9	8.8401	2.010
650	558.97	1.90184	.2986	10,385.7	9.0014	2.019
700	573.93	1.92401	.2994	10,486.8	9.1515	2.029
750	588.95	1.94483	.3006	10,590.3	9.2951	2.041
800	604.02	1.96429	.3021	10,692.7	9.4274	2.056
850	619.17	1.98265	.3036	10,795.9	9.5521	2.070
900	634.40	2.00004	.3051	10,901.3	9.6726	2.085
950	649.71	2.01660	.3070	11,006.0	9.7860	2.103
1000	665.11	2.03240	.3090	11,111.6	9.8940	2.121
1050	680.61	2.04753	.3109	11,218.1	9.9984	2.139
1100	696.24	2.06204	.3130	11,327.4	10.0984	2.159
1150	711.95	2.07601	.3152	11,435.9	10.1954	2.182
1200	727.77	2.08948	.3174	11,545.7	10.2886	2.204
1250	743.69	2.10249	.3196	11,656.3	10.3795	2.227
1300	759.92	2.11514	.3220	11,775.0	10.4707	2.253
1350	776.09	2.12031 2.12731	.3243	11,888.3	10.5635	2.280
1400	792.36	2.13918	.3266	12,003.1	10.6397	2.306
1450	808.95	2.15075	.3289	~~12,125.5~~ 12119.5	10.7233	2.334
1500	825.45	2.16194	.3313	12,242.9	10.8034	2.364
1550	842.08	2.17285	.3336	12,361.9	10.8811	2.394
1600	858.82	2.18348	.3360	12,482.5	10.9577	2.424
1650	875.81	2.19390	.3382	~~12,608.3~~ 12608.3	11.0333	2.455
1700	~~829.77~~ 892.77	2.20403	.3405	12,731.8	11.1070	2.487
1750	909.85	2.21393	.3427	12,856.9	11.1797	2.519
1800	927.12	2.22360	.3450	12,985.8	11.2491	2.551
1850	944.42	2.23308	.3470	13,114.1	11.3194	2.581
1900	961.83	2.24237	.3491	13,244.0	11.3888	2.612
1950	979.33	2.25146	.3511	13,375.4	11.4570	2.643
2000	996.95	2.26038	.3531	13,508.3	11.5243	2.674
2050	1014.66	2.26912	.3550	13,642.8	11.5907	2.704
2100	1032.46	2.27771	.3569	13,778.8	11.6563	2.733
2150	1050.35	2.28613	.3588	13,916.2	11.7209	2.763
2200	1068.33	2.29439	.3606	14,055.0	11.7847	2.792
2250	1086.42	2.30252	.3623	14,195.5	11.8478	2.821
2300	1104.58	2.31050	.3640	14,337.2	11.9102	2.850
2350	1122.83	2.31836	.3658	14,480.6	11.9718	2.879
2400	1141.14	2.32607	.3673	14,624.7	12.0325	2.906
2450	1159.56	2.33366	.3689	14,771.2	12.0929	2.934
2500	1178.05	2.34113	.3705	14,918.5	12.1525	2.961
2550	1196.62	2.34849	.3720	15,067.4	12.2114	2.988
2600	1215.26	2.35560	.3735	15,117.5	12.2689	3.014
2650	1233.97	2.36286	.3749	15,368.8	12.3274	3.040
2700	1252.75	2.36987	.3763	15,521.4	12.3844	3.066
2750	1271.60	2.37679	.3776	15,675.3	12.4409	3.089
2800	1290.52	2.38361	.3790	15,830.4	12.4968	3.114
2850	1309.50	2.39033	.3803	15,986.6	12.5521	3.137
2900	1328.56	2.39695	.3816	16,144.2	12.6068	3.160
2950	1347.67	2.40349	.3827	16,302.8	12.6611	3.182
3000	1366.84	2.40993	.3839	16,462.5	12.7147	3.204
3050	1386.06	2.41629	.3851	16,623.1	12.7679	3.225
3100	1405.34	2.42256	.3862	16,785.0	12.8202	3.245
3150	1424.69	2.42875	.3873	16,947.8	12.8726	3.265
3200	1444.08	2.43486	.3883	17,111.6	12.9242	3.284
3250	1463.52	2.44089	.3894	17,276.3	12.9753	3.304
3300	1483.01	2.44684	.3903	17,441.9	13.0258	3.321
3350	1502.55	2.45272	.3913	17,608.3	13.0759	3.338
3400	1522.15	2.45852	.3923	17,775.7	13.1255	3.355
3450	1541.79	2.46425	.3932	17,943.9	13.1746	3.371
3500	1561.47	2.46992	.3940	18,113.0	13.2232	3.387
3550	1581.19	2.47551	.3949	18,282.6	13.2714	3.402
3600	1600.95	2.48104	.3957	18,453.2	13.3194	3.418
3650	1620.77	2.48651	.3965	18,624.5	13.3664	3.431
3700	1640.62	2.49191	.3973	18,796.4	13.4131	3.445
3750	1660.50	2.49725	.3981	18,969.0	13.4595	3.459
3800	1680.42	2.50253	.3989	19,142.2	13.5054	3.472
3850	1700.39	2.50775	.3996	19,316.2	13.5509	3.484
3900	1720.39	2.51291	.4003	19,490.8	13.5959	3.496
3950	1740.42	2.51801	.4010	19,665.8	13.6405	3.508
4000	1760.49	2.52306	.4016	19,841.6	13.6847	3.519
4500	1962.86	2.57072	.4075	21,626.5	14.1050	3.615
5000	2167.87	2.61392	.4122	23,452.3	14.4897	3.684
5500	2374.95	2.65339	.4159	25,307.9	14.8434	3.735
6000	2583.71	2.68971	.4189	27,184.9	15.1700	3.770
50	381.94	1.48289	.2881	9183.3	6.1886	1.909
0	0	0	0	0	0	0

TABLE VI. - THERMODYNAMIC DATA FOR STOICHIOMETRIC COMBUSTION PRODUCTS OF PENTABORANE B_5H_9

[No dissociation assumed; molecular weight, 30.121; stoichiometric fuel-air ratio, 0.07615.]

(a) Gaseous boron oxide B_2O_3.

Temperature, T, °R	Enthalpy, h, Btu/lb	Constant-pressure entropy, φ, Btu/(lb)(°R)	Specific heat, c_p, Btu/(lb)(°R)	ψ(h)	ψ(φ)	ψ(c_p)
1750	-------	-------	------	--------	------	-----
1800	1365.90	1.88936	0.3125	11,401.1	-0.2190	0.562
1850	1381.56	1.89795	.3141	11,429.4	-.2035	.568
1900	1397.32	1.90635	.3157	11,458.0	-.1883	.574
1950	1413.14	1.91457	.3173	11,486.8	-.1733	.580
2000	1429.05	1.92263	.3189	11,516.0	-.1585	.586
2050	1445.03	1.93052	.3203	11,545.5	-.1439	.591
2100	1461.08	1.93826	.3217	11,575.2	-.1296	.596
2150	1477.21	1.94584	.3231	11,605.2	-.1155	.602
2200	1493.40	1.95329	.3244	11,635.4	-.1016	.607
2250	1509.66	1.96059	.3257	11,665.9	-.0879	.612
2300	1525.98	1.96777	.3269	11,696.6	-.0744	.616
2350	1542.36	1.97482	.3282	11,727.6	-.0611	.621
2400	1558.89	1.98173	.3293	11,758.8	-.0480	.625
2450	1575.28	1.98854	.3304	11,790.2	-.0350	.630
2500	1591.84	1.99522	.3315	11,821.8	-.0222	.634
2550	1608.44	2.00180	.3325	11,853.6	-.0096	.638
2600	1625.09	2.00827	.3335	11,885.6	.0028	.642
2650	1641.79	2.01463	.3345	11,917.9	.0150	.646
2700	1658.54	2.02089	.3355	11,950.3	.0271	.650
2750	1675.34	2.02705	.3363	11,982.9	.0391	.653
2800	1692.18	2.03313	.3372	12,015.6	.0509	.656
2850	1709.06	2.03910	.3381	12,048.5	.0625	.659
2900	1726.00	2.04499	.3389	12,081.6	.0740	.663
2950	1742.96	2.05079	.3397	12,114.9	.0854	.665
3000	1759.97	2.05651	.3405	12,148.2	.0966	.668
3050	1777.01	2.06214	.3412	12,181.7	.1077	.671
3100	1794.09	2.06769	.3419	12,215.4	.1186	.674
3150	1811.21	2.07317	.3426	12,249.2	.1294	.676
3200	1828.36	2.07858	.3433	12,283.1	.1401	.679
3250	1845.54	2.08390	.3440	12,317.1	.1507	.681
3300	1862.76	2.08916	.3446	12,351.3	.1611	.683
3350	1880.01	2.09435	.3452	12,385.5	.1714	.685
3400	1897.29	2.09947	.3458	12,419.8	.1816	.687
3450	1914.60	2.10452	.3464	12,454.2	.1916	.689
3500	1931.93	2.10951	.3470	12,488.8	.2016	.691
3550	1949.29	2.11443	.3475	12,523.4	.2114	.692
3600	1966.68	2.11930	.3480	12,558.1	.2211	.694
3650	1984.10	2.12410	.3485	12,592.8	.2307	.695
3700	2001.54	2.12885	.3490	12,627.6	.2401	.697
3750	2019.00	2.13354	.3495	12,662.5	.2495	.698
3800	2036.50	2.13817	.3500	12,697.5	.2588	.700
3850	2054.01	2.14275	.3504	12,732.6	.2679	.701
3900	2071.55	2.14728	.3509	12,767.6	.2770	.702
3950	2089.10	2.15175	.3513	12,802.8	.2860	.703
4000	2106.68	2.15617	.3518	12,838.0	.2948	.704
4500	2283.54	2.19783	.3554	13,192.1	.3782	.711
5000	2462.02	2.23544	.3583	13,548.4	.4533	.713
5500	2641.78	2.26970	.3606	13,905.2	.5213	.713
6000	2822.55	2.30116	.3624	14,261.4	.5833	.711

TABLE VI. - Concluded. THERMODYNAMIC DATA FOR STOICHIOMETRIC COMBUSTION PRODUCTS OF PENTABORANE B_5H_9

[No dissociation assumed; molecular weight, 30.121; stoichiometric fuel-air ratio, 0.07615.]

(b) Condensed boron oxide B_2O_3.

Temperature, T, °R	Enthalpy, h, Btu/lb	Constant-pressure entropy, φ, Btu/(lb)(°R)	Specific heat, c_p, Btu/(lb)(°R)	ψ(h)	ψ(φ)	ψ(c_p)
350	504.90	1.31441	0.2454	4410.7	-2.6014	0.106
400	517.25	1.34752	.2487	4417.0	-2.5832	.144
450	529.77	1.37706	.2519	4425.2	-2.5634	.182
500	542.45	1.40380	.2552	4435.2	-2.5421	.219
550	555.29	1.42829	.2584	4447.1	-2.5194	.257
600	568.30	1.45091	.2617	4461.0	-2.4953	.295
650	581.46	1.47200	.2649	4476.6	-2.4701	.332
700	594.79	1.49180	.2681	4494.2	-2.4436	.370
750	608.26	1.51041	.2712	4513.7	-2.4173	.401
800	621.90	1.52801	.2742	4534.5	-2.3905	.429
850	635.69	1.54474	.2772	4556.6	-2.3637	.456
900	649.66	1.56067	.2802	4580.9	-2.3362	.483
950	663.75	1.57590	.2831	4605.6	-2.3094	.504
1000	677.98	1.59651	.2860	4631.4	-2.2831	.525
1050	692.35	1.60454	.2890	4658.1	-2.2567	.546
1100	706.95	1.61807	.2919	4687.2	-2.2306	.566
1150	721.57	1.63111	.2948	4715.2	-2.2048	.585
1200	736.39	1.64373	.2978	4745.0	-2.1796	.604
1250	751.34	1.65596	.3007	4775.7	-2.1543	.624
1300	766.52	1.66781	.3037	4808.4	-2.1290	.644
1301.7	767.04	1.66818	.3037	4809.6	-2.1284	.644
1301.7	794.36	1.68918	.3210	5195.6	-1.8316	.888
1350	809.91	1.70092	.3225	5238.5	-1.7992	.886
1400	826.07	1.71267	.3239	5282.8	-1.7670	.885
1450	842.38	1.72409	.3253	5328.0	-1.7357	.882
1500	858.68	1.73514	.3265	5372.0	-1.7057	.879
1550	875.03	1.74587	.3277	5415.9	-1.6770	.875
1600	891.45	1.75629	.3289	5459.5	-1.6493	.871
1650	907.98	1.76645	.3301	5503.5	-1.6227	.867
1700	924.50	1.77633	.3312	5546.8	-1.5967	.864
1750	941.10	1.78595	.3323	5589.9	-1.5717	.861
1800	957.77	1.79534	.3334	5633.2	-1.5478	.858
1850	974.47	1.80450	.3345	5676.1	-1.5243	.857
1900	991.23	1.81343	.3356	5718.9	-1.5014	.856
1950	1008.04	1.82217	.3367	5761.7	-1.4792	.854
2000	1024.91	1.83071	.3378	5804.4	-1.4576	.854
2050	1041.83	1.83906	.3389	5847.1	-1.4365	.854
2100	1058.80	1.84725	.3400	5889.9	-1.4158	.855
2150	1075.83	1.85526	.3411	5932.7	-1.3957	.855
2200	1092.91	1.86311	.3421	5975.5	-1.3760	.857
2500	1110.05	1.87081	.3431	6018.4	-1.3567	.858
2300	1127.24	1.87837	.3441	6061.3	-1.3379	.860
2350	1144.47	1.88578	.3452	6104.4	-1.3193	.861
2400	1161.75	1.89306	.3461	6147.5	-1.3012	.863
2450	1179.08	1.90021	.3471	6190.8	-1.2834	.865
2500	1196.46	1.90723	.3480	6234.1	-1.2658	.867
2550	1213.89	1.91413	.3489	6277.6	-1.2486	.869
2600	1241.36	1.92091	.3498	6321.2	-1.2318	.871
2650	1248.86	1.92759	.3506	6364.7	-1.2151	.873
2700	1266.41	1.93414	.3514	6408.5	-1.1988	.875
2750	1284.01	1.94060	.3522	6452.3	-1.1827	.877
2800	1301.64	1.94696	.3529	6496.2	-1.1668	.879
2850	1319.30	1.95321	.3537	6540.2	-1.1513	.881
2900	1337.02	1.95936	.3545	6584.3	-1.3598	.882
2950	1354.76	1.96543	.3551	6628.5	-1.1208	.884
3000	1372.54	1.97141	.3558	6672.8	-1.1059	.886
3050	1390.34	1.97730	.3565	6717.1	-1.0913	.887
3100	1408.19	1.98310	.3572	6761.6	-1.0768	.889
3150	1426.07	1.98882	.3578	6806.1	-1.0626	.890
3200	1443.97	1.99446	.3584	6850.6	-1.0486	.892
3250	1461.91	2.00002	.3590	6895.3	-1.0347	.893
3300	1479.87	2.00551	.3595	6940.0	-1.0210	.894
3350	1497.86	2.01092	.3601	6984.8	-1.0076	.895
3400	1515.88	2.01626	.3606	7029.6	-.9943	.896
3450	1533.93	2.02153	.3612	7074.5	-.9812	.898
3500	1552.00	2.02673	.3617	7119.4	-.9683	.898
3550	1570.10	2.03186	.3621	7164.4	-.9556	.899
3600	1588.22	2.03693	.3626	7209.4	-.9429	.900
3650	1606.37	2.04193	.3631	7254.5	-.9305	.901
3700	1624.53	2.04688	.3635	7299.5	-.9182	.902
3750	1642.72	2.05176	.3640	7344.6	-.9061	.902
3800	1660.93	2.05659	.3644	7389.8	-.8941	.903
3850	1679.17	2.06135	.3648	7435.0	-.8823	.904
3900	1697.42	2.06606	.3652	7480.2	-.8706	.904
3950	1715.69	2.07072	.3656	7525.5	-.8591	.905
4000	1733.98	2.07532	.3660	7570.7	-.8477	.905
4500	1917.87	2.11863	.3693	8024.1	-.7409	.907

TABLE VII. - THERMODYNAMIC DATA FOR PRODUCTS OF STOICHIOMETRIC COMBUSTION OF DIBORANE B_2H_6

[No dissociation assumed; molecular weight, 28.883; stoichiometric fuel-air ratio, 0.06675.]

(a) Gaseous boron oxide B_2O_3.

Temperature, T, °R	Enthalpy, h, Btu/lb	Constant-pressure entropy, φ, Btu/(lb)(°R)	Specific heat, c_p, Btu/(lb)(°R)	ψ(h)	ψ(φ)	ψ(c_p)
1750	--------	--------	-------	--------	---------	--------
1800	1281.23	1.95385	0.3187	11,539.5	0.7829	0.736
1850	1297.21	1.96261	.3204	11,576.5	.8032	.744
1900	1313.29	1.97118	.3222	11,613.9	.8232	.752
1950	1329.44	1.97958	.3239	11,651.8	.8428	.760
2000	1345.67	1.98779	.3255	11,690.0	.8622	.768
2050	1361.99	1.99585	.3270	11,728.6	.8812	.776
2100	1378.38	2.00375	.3285	11,767.6	.9001	.783
2150	1394.84	2.01150	.3300	11,807.0	.9186	.791
2200	1411.38	2.01910	.3314	11,846.7	.9368	.798
2250	1427.99	2.02657	.3328	11,886.8	.9548	.805
2300	1444.67	2.03390	.3341	11,927.2	.9726	.812
2350	1461.41	2.04110	.3354	11,968.1	.9902	.818
2400	1478.20	2.04817	.3366	12,009.0	1.0074	.825
2450	1495.07	2.05513	.3378	12,050.6	1.0246	.831
2500	1512.00	2.06197	.3390	12,092.3	1.0414	.837
2550	1528.98	2.06869	.3401	12,134.4	1.0580	.843
2600	1546.01	2.07529	.3412	12,176.8	1.0744	.849
2650	1563.10	2.08182	.3423	12,219.3	1.0908	.855
2700	1580.24	2.08823	.3433	12,262.2	1.1068	.861
2750	1597.44	2.09454	.3443	12,305.4	1.1226	.866
2800	1614.68	2.10075	.3453	12,348.8	1.1383	.871
2850	1631.97	2.10687	.3462	12,392.5	1.1538	.876
2900	1649.31	2.11290	.3471	12,436.5	1.1690	.881
2950	1666.69	2.11884	.3480	12,480.7	1.1842	.885
3000	1684.11	2.12470	.3488	12,525.1	1.1991	.890
3050	1701.58	2.13048	.3497	12,569.7	1.2138	.894
3100	1719.08	2.13617	.3505	12,614.6	1.2284	.899
3150	1736.63	2.14178	.3512	12,659.6	1.2428	.902
3200	1754.21	2.14732	.3520	12,704.9	1.2571	.906
3250	1771.83	2.15278	.3527	12,750.3	1.2712	.910
3300	1789.49	2.15818	.3534	12,796.0	1.2851	.914
3350	1807.17	2.16350	.3541	12,841.7	1.2989	.917
3400	1824.90	2.16875	.3548	12,887.7	1.3125	.920
3450	1842.66	2.17393	.3554	12,933.8	1.3260	.923
3500	1860.45	2.17905	.3560	12,980.1	1.3393	.926
3550	1878.26	2.18410	.3566	13,026.5	1.3524	.929
3600	1896.11	2.18910	.3572	13,073.0	1.3655	.932
3650	1913.99	2.19403	.3578	13,119.7	1.3784	.934
3700	1931.90	2.19890	.3583	13,166.5	1.3911	.937
3750	1949.83	2.20372	.3589	13,213.5	1.4037	.939
3800	1967.79	2.20847	.3594	13,260.5	1.4162	.942
3850	1985.78	2.21318	.3599	13,307.7	1.4285	.944
3900	2003.79	2.21782	.3603	13,355.0	1.4407	.946
3950	2021.82	2.22242	.3609	13,402.3	1.4528	.948
4000	2039.88	2.22696	.3614	13,449.8	1.4647	.950
4500	2221.67	2.26978	.3655	13,929.0	1.5776	.964
5000	2405.26	2.30846	.3687	14,413.7	1.6797	.972
5500	2590.29	2.34373	.3712	14,901.4	1.7727	.977
6000	2776.47	2.37613	.3733	15,390.5	1.8577	.978

TABLE VII. - Concluded. THERMODYNAMIC DATA FOR PRODUCTS OF STOICHIOMETRIC COMBUSTION OF DIBORANE B_2H_6

[No dissociation assumed; molecular weight, 28.883; stoichiometric fuel-air ratio, 0.06675.]

(b) Condensed boron oxide B_2O_3.

Temperature, T, °R	Enthalpy, h, Btu/lb	Constant-pressure entropy, φ, Btu/(lb)(°R)	Specific heat, c_p, Btu/(lb)(°R)	ψ(h)	ψ(φ)	ψ(c_p)
350	498.19	1.39240	0.2547	4880.5	-1.6953	0.268
400	510.99	1.42671	.2575	4894.8	-1.6556	.303
450	523.94	1.45725	.2603	4910.9	-1.6171	.339
500	537.03	1.48484	.2631	4928.7	-1.5794	.374
550	550.25	1.51006	.2690	4948.3	-1.5421	.409
600	563.62	1.53331	.2686	4969.7	-1.5049	.449
650	577.12	1.55494	.2714	4992.8	-1.4678	.480
700	590.76	1.57519	.2742	5017.7	-1.4305	.515
750	604.53	1.59423	.2769	5044.5	-1.3939	.545
800	618.45	1.61219	.2796	5072.4	1.3580	.571
850	632.50	1.62924	.2823	5101.7	-1.3226	.597
900	646.71	1.64545	.2850	5133.1	-1.2869	.623
950	661.03	1.66094	.2877	5164.8	-1.2526	.644
1000	675.49	1.67577	.2905	5197.5	-1.2191	.664
1050	690.08	1.69002	.2932	5231.2	-1.1859	.685
1100	704.88	1.70377	.2959	5267.3	-1.1528	.705
1150	719.71	1.71695	.2988	5302.3	-1.1214	.725
1200	734.72	1.72974	.3016	5339.1	-1.0902	.744
1250	749.86	1.74211	.3043	5376.8	-1.0592	.764
1300	765.25	1.75412	.3072	5417.1	-1.0281	.784
1301.7	765.77	1.75450	.3073	5418.4	-1.0273	.784
1301.7	787.82	1.77145	.3212	5770.8	-.7565	1.008
1350	803.38	1.78320	.3228	5819.5	-.7196	1.008
1400	819.57	1.79497	.3244	5870.0	-.6830	1.009
1450	835.92	1.80641	.3260	5921.8	-.6471	1.009
1500	852.26	1.81749	.3274	5972.2	-.6127	1.008
1550	868.67	1.82825	.3288	6022.7	-.5798	1.007
1600	885.15	1.83872	.3303	6073.0	-.5478	1.006
1650	901.76	1.84893	.3316	6124.1	-.5169	1.006
1700	918.38	1.85885	.3300	6174.4	-.4868	1.006
1750	935.06	1.86853	.3343	6224.7	-.4576	1.006
1800	951.85	1.87797	.3356	6275.5	-.4297	1.006
1850	968.67	1.88719	.3369	6325.8	-.4021	1.007
1900	985.55	1.89619	.3328	6376.3	-.3752	1.009
1950	1002.50	1.90500	.3395	6426.8	-.3490	1.011
2000	1019.51	1.91361	.3408	6477.4	-.3233	1.013
2050	1036.58	1.92204	.3420	6528.1	-.2983	1.016
2100	1053.71	1.93030	.3432	6579.0	-.2737	1.019
2150	1070.91	1.93839	.3445	6630.1	-.2497	1.022
2200	1088.16	1.94632	.3457	6681.3	-.2262	1.026
2250	1105.48	1.95411	.3468	6732.7	-.2031	1.030
2300	1122.86	1.96175	.3480	6784.3	-.1804	1.034
2350	1140.29	1.96925	.3491	6836.1	-.1581	1.038
2400	1157.76	1.97660	.3502	6888.0	-.1362	1.042
2450	1175.31	1.98384	.3513	6940.3	-.1146	1.046
2500	1192.91	1.99095	.3523	6992.7	-.0935	1.050
2550	1210.55	1.99794	.3533	7045.4	-.0726	1.054
2600	1228.24	2.00482	.3543	7098.3	-.0520	1.058
2650	1245.98	2.01157	.3553	7151.3	-.0319	1.063
2700	1263.77	2.01822	.3562	7204.5	-.0120	1.067
2750	1281.61	2.02476	.3571	7258.0	.0075	1.070
2800	1299.49	2.03121	.3580	7311.6	.0268	1.074
2850	1317.40	2.03755	.3588	7365.4	.0459	1.078
2900	1335.38	2.04379	.3597	7419.4	.0647	1.081
2950	1353.38	2.04995	.3605	7473.6	.0832	1.085
3000	1371.43	2.05602	.3612	7528.0	.1015	1.088
3050	1389.51	2.06200	.3620	7582.5	.1195	1.092
3100	1407.63	2.06789	.3628	7637.2	.1373	1.095
3150	1425.79	2.07370	.3635	7692.0	.1548	1.098
3200	1443.99	2.07943	.3641	7747.0	.1721	1.101
3250	1462.21	2.08508	.3648	7802.2	.1893	1.104
3300	1480.47	2.09066	.3655	7857.4	.2061	1.106
3350	1498.76	2.09616	.3661	7912.2	.2228	1.109
3400	1517.09	2.10159	.3667	7968.3	.2392	1.111
3450	1535.44	2.10695	.3673	8024.0	.2555	1.114
3500	1553.82	2.11224	.3679	8079.8	.2715	1.116
3550	1572.23	2.11746	.3684	8135.6	.2874	1.118
3600	1590.67	2.12262	.3690	8191.6	.3031	1.120
3650	1609.14	2.12771	.3695	8247.2	.3185	1.122
3700	1627.63	2.13275	.3700	8303.9	.3338	1.124
3750	1646.14	2.13772	.3706	8360.1	.3489	1.126
3800	1664.69	2.14263	.3710	8416.5	.3638	1.127
3850	1683.25	2.14748	.3715	8472.9	.3786	1.129
3900	1701.85	2.15228	.3720	8529.4	.3932	1.131
3950	1720.45	2.15702	.3724	8586.0	.4076	1.132
4000	1739.09	2.16171	.3729	8642.7	.4219	1.133
4500	1926.54	2.20586	.3767	9212.4	.5561	1.144

TABLE VIII. - THERMODYNAMIC DATA FOR STOICHIOMETRIC COMBUSTION PRODUCTS OF VARIOUS HYDROCARBONS

[No dissociation assumed.]

(a) Hydrogen-carbon ratio, 1 (CH); molecular weight, 29.896; stoichiometric fuel-air ratio, 0.07532.

Temperature, T, $^{\circ}R$	Enthalpy, h, Btu/lb	Constant-pressure entropy, φ, Btu/(lb)($^{\circ}R$)	Specific heat, c_p, Btu/(lb)($^{\circ}R$)	$\psi(h)$	$\psi(\varphi)$	$\psi(c_p)$
350	213.84	1.45149	0.2387	300.4	-0.6708	0.011
400	225.82	1.48356	.2405	301.4	-.6674	.028
450	237.89	1.51202	.2423	303.3	-.6628	.045
500	250.06	1.53765	.2440	306.0	-.6570	.063
550	262.31	1.56101	.2458	309.6	-.6502	.080
600	274.64	1.58248	.2476	314.1	-.6424	.097
650	287.07	1.60238	.2494	319.4	-.6339	.115
700	299.59	1.62096	.2512	325.5	-.6245	.132
750	312.21	1.63843	.2531	333.1	-.6142	.146
800	324.92	1.65483	.2550	340.7	-.6044	.158
850	337.72	1.67036	.2569	349.0	-.5944	.170
900	350.61	1.68511	.2588	358.2	-.5834	.182
950	363.60	1.69916	.2608	367.5	-.5732	.191
1000	376.70	1.71260	.2629	377.3	-.5632	.200
1050	389.90	1.72548	.2649	387.5	-.5531	.209
1100	403.20	1.73782	.2670	398.5	-.5437	.217
1150	416.61	1.74974	.2691	409.5	-.5337	.224
1200	430.12	1.76124	.2712	420.9	-.5241	.231
1250	443.73	1.77236	.2733	432.7	-.5144	.239
1300	457.49	1.78312	.2753	445.4	-.5045	.245
1350	471.31	1.78682	.2773	457.8	-.4878	.252
1400	485.23	1.80367	.2793	470.6	-.4858	.258
1450	499.30	1.81352	.2813	484.2	-.4765	.264
1500	513.42	1.82310	.2832	497.6	-.4674	.270
1550	527.63	1.83242	.2851	511.3	-.4585	.276
1600	541.93	1.84150	.2870	525.2	-.4496	.282
1650	556.38	1.85040	.2888	540.0	-.4407	.287
1700	570.86	1.85905	.2905	554.5	-.4320	.293
1750	585.44	1.86750	.2923	569.2	-.4234	.298
1800	600.10	1.87577	.2940	584.3	-.4152	.303
1850	614.84	1.88385	.2955	599.6	-.4069	.308
1900	629.66	1.89175	.2970	615.1	-.3985	.313
1950	651.27	1.89949	.2985	726.9	-.3903	.322
2000	659.51	1.90707	.3000	646.7	-.3822	.327
2050	674.55	1.91449	.3013	663.2	-.3742	.331
2100	689.65	1.92177	.3027	679.7	-.3662	.335
2150	704.82	1.92891	.3040	696.3	-.3584	.339
2200	720.06	1.93592	.3053	713.2	-.3506	.339
2250	735.36	1.94279	.3064	730.3	-.3430	.343
2300	750.71	1.94954	.3076	747.6	-.3354	.347
2350	766.12	1.95617	.3088	765.1	-.3279	.351
2400	781.06	1.96268	.3098	773.0	-.3205	.354
2450	797.60	1.96908	.3109	800.5	-.3131	.357
2500	812.68	1.97538	.3119	818.5	-.3058	.361
2550	843.97	1.98764	.3129	854.9	-.2916	.367
2600	843.95	1.98764	.3135	854.8	-.2916	.364
2650	859.68	1.99364	.3147	873.4	-.2845	.370
2700	875.44	1.99952	.3156	892.0	-.2775	.373
2750	891.25	2.00532	.3164	910.7	-.2707	.376
2800	907.09	2.01104	.3173	929.6	-.2639	.379
2850	922.98	2.01663	.3181	948.6	-.2571	.381
2900	938.91	2.02220	.3189	967.7	-.2505	.384
2950	954.87	2.02766	.3196	987.0	-.2439	.386
3000	970.88	2.03304	.3204	1006.4	-.2374	.388
3050	986.91	2.03834	.3211	1025.9	-.2309	.391
3100	1002.98	2.04356	.3218	1045.5	-.2246	.393
3150	1019.10	2.04872	.3224	1065.2	-.2183	.395
3200	1035.24	2.05380	.3231	1085.1	-.2120	.397
3250	1051.40	2.05862	.3237	1105.0	-.2058	.399
3300	1067.60	2.06377	.3243	1124.9	-.1997	.400
3350	1083.83	2.06865	.3249	1145.0	-.1937	.402
3400	1100.10	2.07346	.3255	1165.1	-.1877	.403
3450	1116.39	2.07822	.3260	1185.4	-.1818	.405
3500	1132.70	2.08291	.3265	1205.7	-.1760	.406
3550	1149.04	2.08755	.3270	1226.0	-.1702	.407
3600	1165.41	2.09213	.3276	1246.5	-.1645	.409
3650	1181.80	2.09665	.3280	1267.0	-.1588	.410
3700	1198.22	2.10112	.3285	1287.5	-.1532	.411
3750	1214.65	2.10553	.3290	1308.1	-.1477	.412
3800	1231.12	2.10989	.3294	1324.8	-.1422	.413
3850	1247.60	2.11420	.3299	1349.5	-.1368	.414
3900	1264.11	2.11846	.3303	1370.2	-.1315	.415
3950	1280.64	2.12267	.3307	1391.0	-.1262	.416
4000	1297.18	2.12684	.3311	1411.9	-.1209	.416
4500	1463.69	2.16605	.3347	1621.7	-.0715	.422
5000	1631.78	2.20147	.3375	1833.4	-.2694	.424
5500	1801.16	2.23376	.3398	2045.8	.0135	.424
6000	1971.60	2.26341	.3418	2258.0	.0504	.423

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TABLE VIII. - Continued. THERMODYNAMIC DATA FOR STOICHIOMETRIC COMBUSTION PRODUCTS OF VARIOUS HYDROCARBONS

[No dissociation assumed.]

(b) Hydrogen-carbon ratio, 2 (CH_2); molecular weight, 28.907; stoichiometric fuel-air ratio, 0.06763.

Temperature, T, °R	Enthalpy, h, Btu/lb	Constant-pressure entropy, φ, Btu/(lb)(°R)	Specific heat, c_p, Btu/(lb)(°R)	ψ(h)	ψ(φ)	ψ(c_p)
350	255.02	1.49442	0.2475	982.3	-0.0642	0.151
400	267.44	1.52764	.2491	990.3	-.0421	.168
450	279.94	1.55711	.2508	999.1	-.0210	.184
500	292.52	1.58363	.2524	1008.7	-.0006	.201
550	305.19	1.60778	.2541	1019.3	.0193	.218
600	317.93	1.62995	.2557	1030.6	.0390	.235
650	330.76	1.65050	.2573	1042.8	.0585	.251
700	343.67	1.66965	.2590	1055.8	.0780	.268
750	356.68	1.68766	.2607	1070.3	~~.0979~~ .0923	.282
800	369.76	1.70455	.2625	1084.7	.1165	.295
850	382.94	1.72053	.2644	1099.8	.1347	.307
900	396.21	1.73571	.2662	1115.9	.1537	.319
950	409.57	1.75017	.2683	1132.1	.1713	.328
1000	423.04	1.76398	.2703	1148.8	.1883	.338
1050	436.60	1.77723	.2723	1165.9	.2052	.347
1100	450.28	1.78991	.2744	1183.9	.2210	.356
1150	464.06	1.80216	.2765	1202.0	.2373	.365
1200	477.94	1.81398	.2786	1220.4	.2529	.373
1250	491.92	1.82540	.2807	1239.3	.2685	.381
1300	506.08	1.83646	.2828	1259.6	.2842	.389
1350	520.28	1.84040	.2849	1279.3	.3063	.397
1400	534.58	1.85758	.2869	1299.4	.3137	.405
1450	549.05	1.86770	.2890	1320.9	.3283	.413
1500	563.55	1.87754	.2910	1341.7	.3426	.421
1550	578.15	1.88711	.2929	1363.0	.3564	.428
1600	592.85	1.89645	.2949	1384.6	.3702	.436
1650	607.70	1.90559	.2968	1407.3	.3838	.443
1700	622.58	1.91448	.2986	1429.6	.3972	.450
1750	637.56	1.92316	.3004	1452.3	.4104	.458
1800	652.64	1.93166	.3022	1475.5	.4230	.465
1850	667.79	1.93996	.3038	1499.0	.4358	.471
1900	683.02	1.94809	.3054	1522.7	.4485	.478
1950	698.33	1.95604	.3070	1546.8	.4610	.485
2000	713.73	1.96383	.3085	1571.3	.4734	.491
2050	729.20	1.97147	.3100	1596.0	.4856	.498
2100	744.73	1.97896	.3114	1621.1	.4977	.504
2150	760.34	1.98631	.3128	1646.4	.5097	.510
2200	776.01	1.99351	.3142	1672.1	.5214	.515
2250	791.76	2.00059	.3154	1698.0	.5331	.521
2300	867.57 807.67	2.00754	.3167	1724.2	.5446	.527
2350	823.43	2.01436	.3179	1750.8	.5560	.532
2400	839.35	2.02107	.3191	1777.4	.5673	.537
2450	855.34	2.02766	.3202	1804.5	.5785	.542
2500	871.38	2.03414	.3213	1831.8	.5895	.548
2550	887.48	2.04052	.3224	1859.4	.6004	.553
2600	903.60	2.04678	.3230	1886.9	.6407 .6111	.551 .558
2650	919.82	2.05296	.3244	1915.1	.6218	.562
2700	936.06	2.05903	.3254	1943.4	.6324	.567
2750	952.36	2.06501	.3263	1971.8	.6428	.571
2800	968.70	2.07090	.3272	2000.5	.6532	.575
2850	985.08	2.07670	.3281	2029.4	.6634	.579
2900	1001.51	2.08241	.3290	2058.5	.6735	.583
2950	1017.98	2.08804	.3298	2087.7	.6835	.587
3000	1034.49	2.09359	.3306	2117.2	.6934	.591
3050	1051.04	2.09907	.3314	2146.8	.7032	.594
3100	1067.63	2.10446	.3321	2176.7	.7129	.598
3150	1084.26	2.10978	.3328	2206.7	.7225	.601
3200	1100.92	2.11503	.3335	2236.8	.7320	.604
3250	1117.62	2.12021	.3343	2267.2	.7414	.607
3300	1134.35	2.12531	.3349	2297.6	.7507	.610
3350	1151.11	2.13036	.3355	2328.2	.7599	.613
3400	1167.91	2.13533	.3362	2358.9	.7690	.615
3450	1184.74	2.14024	.3368	2389.8	.7780	.618
3500	1201.59	2.14509	.3374	2420.8	.7869	.620
3550	1218.47	2.14988	.3379	2451.9	.7957	.623
3600	1235.39	2.15461	.3385	2483.1	.8045	.625
3650	1252.33	2.15929	.3391	2514.5	.8131	.627
3700	1269.30	2.16391	.3396	2545.9	.8217	.629
3750	1286.29	2.16847	.3401	2577.4	.8302	.631
3800	1303.31	2.17298	.3406	2609.0	.8385	.633
3850	1320.35	2.17743	.3411	2640.7	.8468	.635
3900	1337.42	2.18184	.3415	2672.5	.8550	.636
3950	1354.51	2.18619	.3420	2704.4	.8632	.638
4000	1371.62	2.19050	.3424	2736.4	.8712	.639
4500	1543.89	2.23107	.3464	3059.5	.9473	.659
5000	1717.92	2.26774	.3495	3387.2	1.0163	.658
5500	1893.35	2.30118	.3521	3717.6	1.0793	.662
6000	2069.95	2.33191	.3542	4049.5	1.1371	.664
50	180.50	1.29510	.2379	934.3	-.1968	.049
0	0	0	0	0	0	0

TABLE VIII. - Continued. THERMODYNAMIC DATA FOR STOICHIOMETRIC COMBUSTION PRODUCTS OF VARIOUS HYDROCARBONS

[No dissociation assumed.]

(c) Hydrogen-carbon ratio, 3 (CH_3); molecular weight, 28.232; stoichiometric fuel-air ratio, 0.06213.

Temperature, T, °R	Enthalpy, h, Btu/lb	Constant-pressure entropy, φ, Btu/(lb)(°R)	Specific heat, c_p, Btu/(lb)(°R)	$\psi(h)$	$\psi(\varphi)$	$\psi(c_p)$
350	284.80	1.52545	0.2539	1572.7	0.4609	0.272
400	297.53	1.55951	.2554	1586.8	.4992	.289
450	310.34	1.58971	.2569	1601.6	.5345	.305
500	323.23	1.61688	.2584	1617.3	.5676	.321
550	336.19	1.64160	.2600	1633.8	.5990	.338
600	349.23	1.66428	.2615	1651.1	.6291	.354
650	362.35	1.68528	.2630	1669.2	.6581	.370
700	375.54	1.70486	.2646	1688.1	.6863	.386
750	388.83	1.72326	.2662	1708.5	.7145	.400
800	402.18	1.74050	.2680	1728.9	.7408	.413
850	415.63	1.75681	.2698	1749.9	.7661	.425
900	429.18	1.77230	.2716	1771.9	.7918	.437
950	442.81	1.78704	.2736	1794.1	.8159	.447
1000	456.55	1.80114	.2757	1816.7	.8390	.457
1050	470.38	1.81464	.2777	1839.9	.8618	.467
1100	484.33	1.82758	.2797	1864.0	.8832	.477
1150	498.37	1.84006	.2819	1888.1	.9049	.486
1200	512.52	1.85211	.2840	1912.7	.9258	.496
1250	526.77	1.86376	.2861	1937.7	.9463	.505
1300	541.21	1.87503	.2882	1964.7	.9672	.514
1350	555.68	1.87915	.2903	1990.6	.9940	.523
1400	570.26	1.89656	.2924	2017.1	1.0060	.532
1450	585.02	1.90688	.2945	2045.3	1.0252	.542
1500	599.80	1.91690	.2965	2072.6	1.0439	.551
1550	614.68	1.92666	.2986	2100.4	1.0620	.560
1600	629.66	1.93618	.3006	2128.7	1.0800	.569
1650	644.81	1.94550	.3025	2158.3	1.0979	.578
1700	659.98	1.95455	.3044	3187.4	1.1152	.587
1750	675.25	1.96341	.3062	2217.0	1.1324	.596
1800	690.63	1.97207	.3081	2247.2	1.1488	.605
1850	706.08	1.98053	.3097	2277.7	1.1655	.613
1900	721.62	1.98882	.3114	2308.6	1.1820	.621
1950	737.23	1.99693	.3131	2339.9	1.1983	.630
2000	752.93	2.00488	.3147	2371.6	1.2143	.638
2050	768.71	2.01267	.3162	2403.7	1.2302	.646
2100	784.56	2.02031	.3177	2436.2	1.2458	.653
2150	800.48	2.02781	.3192	2469.1	1.2613	.661
2200	816.47	2.03516	.3206	2502.3	1.2766	.668
2250	832.55	2.04238	.3219	2535.9	1.2917	.675
2300	848.68	2.04947	.3232	2569.9	1.3066	.683
2350	864.87	2.05644	.3246	2604.3	1.3214	.690
2400	881.12	2.06328	.3257	2638.8	1.3360	.696
2450	897.46	2.07001	.3269	2673.9	1.3504	.703
2500	913.83	2.07663	.3281	2709.2	1.3647	.710
2550	930.27	2.08314	.3292	2744.9	1.3788	.716
2600	946.71	2.08954	.3303	2781.1	1.3928	.722
2650	963.30	2.09585	.3314	2817.2	1.4066	.728
2700	979.89	2.10205	.3324	2853.7	1.4203	.734
2750	996.55	2.10816	.3334	2890.6	1.4338	.740
2800	1013.24	2.11418	.3343	2927.8	1.4472	.745
2850	1029.98	2.12011	.3353	2965.2	1.4604	.751
2900	1046.78	2.12594	.3362	3002.8	1.4735	.756
2950	1063.62	2.13170	.3371	3040.8	1.4865	.761
3000	1080.50	2.13738	.3379	3079.0	1.4993	.766
3050	1097.41	2.14297	.3388	3117.4	1.5121	.771
3100	1114.38	2.14849	.3396	3156.1	1.5247	.775
3150	1131.38	2.15393	.3404	3195.0	1.5371	.780
3200	1148.42	2.15930	.3411	3234.1	1.5494	.784
3250	1165.49	2.16459	.3419	3273.5	1.5616	.788
3300	1182.61	2.16982	.3426	3313.0	1.5737	.792
3350	1199.75	2.17497	.3432	3352.7	1.5856	.795
3400	1216.94	2.18006	.3440	3392.6	1.5974	.799
3450	1234.16	2.18509	.3446	3432.7	1.6091	.803
3500	1251.40	2.19005	.3452	3472.9	1.6207	.806
3550	1268.68	2.19496	.3458	3513.3	1.6322	.809
3600	1285.99	2.19980	.3464	3553.9	1.6435	.812
3650	1303.33	2.20458	.3470	3594.6	1.6541	.815
3700	1320.69	2.20931	.3475	3635.4	1.6659	.818
3750	1338.08	2.21398	.3481	3676.4	1.6769	.821
3800	1355.51	2.21859	.3487	3717.5	1.6878	.823
3850	1372.96	2.22315	.3491	3758.8	1.6986	.826
3900	1390.43	2.22766	.3497	3800.1	1.7093	.828
3950	1407.92	2.23212	.3502	3841.6	1.7198	.830
4000	1425.45	2.23653	.3506	3883.2	1.7303	.832
4500	1601.88	2.27808	.3548	4304.3	1.8294	.850
5000	1780.20	2.31566	.3582	4732.5	1.9196	.861
5500	1960.01	2.34993	.3609	5165.1	2.0021	.868
6000	2141.06	2.38143	.3631	5600.6	2.0779	.872

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TABLE VIII. - Concluded. THERMODYNAMIC DATA FOR STOICHIOMETRIC COMBUSTION PRODUCTS OF VARIOUS HYDROCARBONS

[No dissociation assumed.]

(d) Hydrogen-carbon ratio, 4 (CH_4); molecular weight, 27.741; stoichiometric fuel-air ratio, 0.05801.

H = 23919.
HS = 23199
TF = 536

Temperature, T, °R	Enthalpy, h, Btu/lb	Constant-pressure entropy, φ, Btu/(lb)(°R)	Specific heat, c_p, Btu/(lb)(°R)	ψ(h)	ψ(φ)	ψ(c_p)
350	307.33	1.54894	0.2587	2088.9	0.9202	0.379
400	320.30	1.58364	.2601	2108.3	.9726	.394
450	333.35	1.61439	.2616	2128.4	1.0203	.410
500	346.47	1.64204	.2630	2149.3	1.0645	.426
550	359.66	1.66719	.2645	2171.1	1.1059	.442
600	372.92	1.69026	.2659	2193.6	1.1450	.458
650	386.25	1.71162	.2673	2216.9	1.1824	.474
700	399.66	1.73150	.2688	2241.0	1.2183	.489
750	413.16	1.75020	.2704	2266.6	1.2537	.503
800	426.73	1.76771	.2722	2292.1	1.2866	.516
850	440.38	1.78427	.2739	2318.3	1.3182	.528
900	454.13	1.79999	.2757	2345.6	1.3499	.541
950	467.97	1.81496	.2777	2372.9	1.3795	.551
1000	481.91	1.82926	.2797	2400.8	1.4080	.562
1050	495.94	1.84296	.2817	2429.1	1.4359	.572
1100	510.10	1.85608	.2338	2458.6	1.4623	.583
1150	524.34	1.86875	.2859	2488.0	1.4887	.593
1200	538.70	1.88097	.2881	2518.0	1.5141	.603
1250	553.15	1.89279	.2902	2548.4	1.5391	.613
1300	567.81	1.90423	.2923	2581.1	1.5643	.624
1350	582.48	1.90847	.2945	2612.6	1.5953	.634
1400	597.27	1.92606	.2966	2644.5	1.6113	.644
1450	612.25	1.93653	.2987	2678.7	1.6346	.654
1500	627.24	1.94670	.3008	2711.7	1.6572	.665
1550	642.33	1.95660	.3028	2745.2	1.6790	.675
1600	657.53	1.96625	.3049	2779.3	1.7007	.686
1650	672.90	1.97570	.3069	2814.9	1.7221	.696
1700	688.29	1.98489	.3087	2850.0	1.7430	.706
1750	703.78	1.99387	.3107	2885.5	1.7637	.717
1800	719.39	2.00265	.3126	2922.0	1.7835	.727
1850	735.06	2.01124	.3143	2958.6	1.8035	.737
1900	750.82	2.01965	.3160	2995.7	1.8233	.746
1950	766.67	2.02788	.3177	3033.3	1.8429	.756
2000	782.60	2.03595	.3194	3071.4	1.8621	.766
2050	798.61	2.04385	.3209	3109.9	1.8812	.775
2100	814.70	2.05161	.3225	3148.9	1.9000	.784
2150	830.86	2.05922	.3240	3188.3	1.9185	.793
2200	847.10	2.06668	.3254	3228.2	1.9369	.802
2250	863.42	2.07401	.3268	3268.6	1.9550	.810
2300	879.79	2.08121	.3282	3309.3	1.9729	.819
2350	896.24	2.08829	.3296	3350.5	1.9906	.827
2400	912.74	2.09524	.3308	3392.0	2.0081	.835
2450	929.32	2.10207	.3320	3434.0	2.0254	.843
2500	945.96	2.10880	.3333	3476.4	2.0426	.851
2550	962.65	2.11541	.3344	3519.2	2.0595	.859
2600	979.40	2.12191	.3355	3562.5	2.0762	.867
2650	996.21	2.12832	.3367	3605.8	2.0928	.873
2700	1013.07	2.13462	.3378	3649.7	2.1092	.881
2750	1029.99	2.14083	.3388	3693.9	2.1254	.887
2800	1046.96	2.14694	.3398	3738.5	2.1415	.894
2850	1063.97	2.15296	.3408	3783.3	2.1574	.901
2900	1081.04	2.15890	.3418	3828.6	2.1731	.907
2950	1098.15	2.16475	.3426	3874.1	2.1887	.913
3000	1115.31	2.17052	.3435	3926.0	2.2041	.919
3050	1132.51	2.17621	.3444	3966.1	2.2193	.925
3100	1149.55	2.18181	.3453	4012.5	2.2344	.930
3150	1167.05	2.18734	.3461	4059.2	2.2494	.936
3200	1184.37	2.19280	.3467	4106.1	2.2641	.941
3250	1201.73	2.19819	.3477	4153.3	2.2788	.946
3300	1219.13	2.20350	.3484	4200.8	2.2933	.951
3350	1236.57	2.20875	.3491	4248.4	2.3076	.955
3400	1254.05	2.21392	.3498	4296.3	2.3218	.960
3450	1271.56	2.21903	.3505	4344.5	2.3358	.964
3500	1289.10	2.22408	.3512	4392.8	2.3498	.968
3550	1306.68	2.22907	.3518	4441.3	2.3635	.972
3600	1324.28	2.23399	.3524	4490.1	2.3772	.976
3650	1341.93	2.23886	.3530	4539.0	2.3907	.979
3700	1359.59	2.24367	.3536	4588.1	2.4040	.983
3750	1377.29	2.24842	.3542	4637.3	2.4172	.986
3800	1395.01	2.25311	.3548	4686.7	2.4303	.990
3850	1412.77	2.25776	.3553	4736.3	2.4433	.993
3900	1430.55	2.26234	.3558	4786.1	2.4561	.996
3950	1448.35	2.26688	.3563	4835.9	2.4689	.999
4000	1466.18	2.27137	.3568	4886.0	2.4815	1.001
4500	1645.77	2.31367	.3612	5392.7	2.6008	1.024
5000	1827.33	2.35192	.3648	5908.7	2.7095	1.038
5500	2010.47	2.38683	.3676	6430.8	2.8090	1.048
6000	2194.88	2.41892	.3699	6956.8	2.9005	1.054
50	229.51	1.34074	.2503	1972.5	.6058	.289
0	0	0	0	0	0	0

TABH4. TABPHS TABPSH TABPSP

TABLE IX. - THERMODYNAMIC DATA FOR STOICHIOMETRIC COMBUSTION PRODUCTS OF ETHYLENE DECABORANE $B_{10}H_{13}C_2H_5$

[No dissociation assumed; molecular weight, 30.756; stoichiometric fuel-air ratio, 0.07768.]

(a) Gaseous boron oxide B_2O_3.

Temperature, T, °R	Enthalpy, h, Btu/lb	Constant-pressure entropy, φ, Btu/(lb)(°R)	Specific heat, c_p, Btu/(lb)(°R)	ψ(h)	ψ(φ)	ψ(c_p)
1750	-------	-------	------	-------	-------	-----
1800	1244.41	1.87554	0.3081	9,506.9	-0.4067	0.491
1850	1259.86	1.88401	.3096	9,531.5	-.3932	.496
1900	1275.39	1.89229	.3112	9,556.5	-.3799	.501
1950	1290.99	1.90040	.3128	9,581.7	-.3668	.507
2000	1306.67	1.90833	.3143	9,607.2	-.3539	.512
2050	1322.43	1.91611	.3157	9,633.0	-.3412	.517
2100	1338.25	1.92374	.3171	9,659.0	-.3286	.522
2150	1354.14	1.93122	.3185	9,685.2	-.3163	.527
2200	1370.10	1.93856	.3198	9,711.7	-.3041	.531
2250	1386.13	1.94576	.3210	9,738.4	-.2921	.535
2300	1402.21	1.95283	.3222	9,765.3	-.2803	.540
2350	1418.36	1.95978	.3234	9,792.5	-.2686	.544
2400	1434.63	1.96659	.3245	9,820.9	-.2572	.548
2450	1450.81	1.97329	.3256	9,847.3	-.2459	.552
2500	1467.12	1.97989	.3267	9,875.0	-.2346	.556
2550	1483.48	1.98637	.3277	9,902.9	-.2236	.559
2600	1499.88	1.99275	.3287	9,930.9	-.2127	.562
2650	1516.35	1.99901	.3296	9,959.2	-.2019	.566
2700	1532.85	2.00518	.3305	9,987.6	-.1912	.569
2750	1549.40	2.01125	.3314	10,016.1	-.1808	.572
2800	1565.99	2.01724	.3322	10,044.9	-.1704	.575
2850	1582.63	2.02312	.3331	10,073.7	-.1602	.578
2900	1599.31	2.02892	.3339	10,102.7	-.1501	.581
2950	1616.02	2.03464	.3346	10,131.8	-.1401	.583
3000	1632.78	2.04027	.3354	10,161.1	-.1303	.586
3050	1649.56	2.04582	.3361	10,190.5	-.1206	.588
3100	1666.39	2.05129	.3368	10,220.0	-.1110	.591
3150	1683.26	2.05669	.3375	10,249.6	-.1015	.593
3200	1700.15	2.06201	.3381	10,279.3	-.0922	.595
3250	1717.07	2.06726	.3388	10,309.2	-.0829	.597
3300	1734.03	2.07244	.3394	10,339.1	-.0738	.599
3350	1751.02	2.07755	.3400	10,369.1	-.0648	.601
3400	1768.04	2.08259	.3406	10,399.2	-.0558	.602
3450	1785.09	2.08756	.3412	10,429.4	-.0470	.604
3500	1802.16	2.09248	.3417	10,459.6	-.0383	.605
3550	1819.26	2.09733	.3422	10,489.9	-.0297	.607
3600	1836.38	2.10212	.3428	10,520.3	-.0212	.608
3650	1853.54	2.10685	.3433	10,550.8	-.0128	.609
3700	1870.72	2.11153	.3437	10,581.3	-.0045	.610
3750	1887.91	2.11614	.3442	10,611.9	.0036	.612
3800	1905.14	2.12071	.3447	10,642.5	.0117	.613
3850	1922.39	2.12522	.3451	10,673.2	.0197	.614
3900	1939.66	2.12967	.3455	10,704.0	.0277	.615
3950	1956.94	2.13408	.3460	10,734.8	.0355	.616
4000	1974.25	2.13843	.3464	10,765.6	.0433	.616
4500	2148.40	2.17945	.3499	11,075.5	.1163	.622
5000	2324.12	2.21648	.3527	11,387.1	.1819	.623
5500	2501.09	2.25021	.3550	11,698.8	.2413	.622
6000	2679.08	2.28118	.3568	12,009.7	.2954	.620

TABLE IX. - Concluded. THERMODYNAMIC DATA FOR STOICHIOMETRIC COMBUSTION PRODUCTS OF ETHYLENE DECABORANE $B_{10}H_{13}C_2H_5$

[No dissociation assumed; molecular weight, 30.756; stoichiometric fuel-air ratio, 0.07768.]

(b) Condensed boron oxide B_2O_3.

Temperature, T, °R	Enthalpy, h, Btu/lb	Constant-pressure entropy, φ, Btu/(lb)(°R)	Specific heat, c_p, Btu/(lb)(°R)	ψ(h)	ψ(φ)	ψ(c_p)
350	454.22	1.32505	0.2428	3626.9	-2.4062	0.068
400	466.43	1.35776	.2457	3631.0	-2.3938	.099
450	478.79	1.38698	.2487	3636.9	-2.3789	.134
500	491.31	1.41332	.2518	3644.4	-2.3634	.168
550	503.98	1.43748	.2549	3653.8	-2.3457	.203
600	516.80	1.45979	.2579	3664.8	-2.3265	.237
650	529.77	1.48057	.2610	3677.5	-2.3059	.272
700	542.90	1.50007	.2641	3692.0	-2.2841	.306
750	556.17	1.51840	.2670	3708.3	-2.2621	.335
800	569.59	1.53573	.2698	3725.7	-2.2397	.360
850	583.16	1.55219	.2727	3744.4	-2.2171	.385
900	596.90	1.56786	.2755	3765.0	-2.1937	.409
950	610.75	1.58284	.2783	3786.0	-2.1709	.428
1000	624.74	1.60233	.2811	3807.9	-2.0773	.447
1050	638.86	1.61098	.2839	3830.7	-2.1260	.466
1100	653.19	1.62426	.2867	3855.5	-2.1038	.484
1150	667.56	1.63708	.2895	3879.6	-2.0817	.501
1200	682.11	1.64947	.2924	3905.1	-2.0601	.518
1250	696.79	1.66147	.2951	3931.4	-2.0384	.535
1300	711.68	1.67310	.2980	3959.5	-2.0166	.553
1301.7	712.19	1.67343	.2981	3960.5	-2.0166	.553
1301.7	735.57	1.69141	.3129	4284.9	-1.7672	.759
1350	750.73	1.70173	.3144	4321.6	-1.7523	.758
1400	766.49	1.71434	.3158	4359.5	-1.7115	.757
1450	782.39	1.72547	.3173	4398.1	-1.6847	.756
1500	798.29	1.73626	.3186	4435.9	-1.6590	.753
1550	814.25	1.74673	.3199	4473.5	-1.6344	.751
1600	830.29	1.75691	.3212	4511.0	-1.6106	.748
1650	846.43	1.76683	.3224	4548.8	-1.5877	.745
1700	862.57	1.77648	.3236	4586.0	-1.5654	.743
1750	878.79	1.78572	.3248	4623.1	-1.5462	.741
1800	895.09	1.79507	.3260	4660.4	-1.5232	.739
1850	911.41	1.80402	.3271	4697.3	-1.5030	.739
1900	927.81	1.81276	.3283	4734.3	-1.4833	.738
1950	944.25	1.82130	.3294	4771.2	-1.4641	.738
2000	960.75	1.82966	.3306	4808.1	-1.4454	.738
2050	977.32	1.83784	.3317	4845.0	-1.4272	.738
2100	993.93	1.84584	.3328	4882.0	-1.4094	.739
2150	1010.59	1.85369	.3339	4918.9	-1.3920	.740
2200	1027.31	1.86137	.3349	4955.9	-1.3749	.741
2250	1044.09	1.86891	.3359	4993.1	-1.3582	.743
2300	1060.92	1.87631	.3370	5030.3	-1.3419	.744
2350	1077.79	1.88357	.3380	5067.6	-1.3259	.746
2400	1094.71	1.89069	.3389	5104.9	-1.3102	.748
2450	1111.69	1.89768	.3399	5142.4	-1.2949	.749
2500	1128.71	1.90457	.3408	5179.9	-1.2795	.751
2550	1162.87	1.9180	.3426	5255.1	-1.2501	.755
2600	1162.86	1.91796	.3421	5255.1	-1.2501	.750
2650	1180.03	1.92451	.3434	5293.1	-1.2355	.757
2700	1197.21	1.93093	.3442	5331.1	-1.2214	.759
2750	1214.45	1.93726	.3450	5369.0	-1.2074	.761
2800	1231.72	1.94348	.3457	5407.2	-1.1937	.762
2850	1249.02	1.94961	.3465	5445.3	-1.1802	.764
2900	1266.37	1.95563	.3472	5483.6	-1.1669	.766
2950	1283.75	1.96158	.3479	5521.9	-1.1538	.767
3000	1301.16	1.96743	.3486	5560.4	-1.1409	.769
3050	1318.61	1.97320	.3492	5598.8	-1.1281	.770
3100	1336.08	1.97888	.3499	5637.4	-1.1156	.771
3150	1353.60	1.98449	.3505	5676.0	-1.1032	.773
3200	1371.14	1.99001	.3511	5714.7	-1.0910	.774
3250	1388.71	1.99546	.3517	5753.5	-1.0790	.775
3300	1406.30	2.00084	.3522	5792.3	-1.0672	.776
3350	1423.93	2.00614	.3527	5831.1	-1.0555	.777
3400	1441.59	2.01137	.3533	5870.0	-1.0440	.778
3450	1459.27	2.01653	.3538	5909.0	-1.0326	.779
3500	1476.97	2.02162	.3543	5948.0	-1.0214	.780
3550	1494.70	2.02665	.3548	5987.0	-1.0103	.781
3600	1512.45	2.03162	.3553	6026.1	-.9994	.781
3650	1530.23	2.03652	.3557	6065.2	-.9886	.782
3700	1548.02	2.04137	.3561	6104.4	-.9779	.783
3750	1565.84	2.04615	.3566	6143.5	-.9674	.783
3800	1583.68	2.05087	.3570	6182.7	-.9570	.784
3850	1601.55	2.05555	.3574	6222.0	-.9467	.784
3900	1619.43	2.06016	.3578	6261.2	-.9366	.785
3950	1637.33	2.06472	.3582	6300.5	-.9266	.785
4000	1655.25	2.06923	.3586	6339.8	-.9167	.785
4500	1835.41	2.11166	.3618	6733.2	-.8241	.787

TABLE X. - THERMODYNAMIC DATA FOR STOICHIOMETRIC COMBUSTION PRODUCTS OF CONSTITUENTS OF AIR OTHER THAN OXYGEN

[No dissociation assumed.]

Temperature, T, °R	Enthalpy, h, Btu/lb	Constant-pressure entropy, φ, Btu/(lb)(°R)	Specific heat, c_p, Btu/(lb)(°R)
350	193.40	1.51637	0.2452
400	205.66	1.54914	.2455
450	217.95	1.57809	.2458
500	230.25	1.60401	.2461
550	242.56	1.62749	.2464
600	254.89	1.64894	.2467
650	267.23	1.66870	.2470
700	279.60	1.68703	.2473
750	291.95	1.70418	.2478
800	304.37	1.72020	.2486
850	316.82	1.73530	.2494
900	329.28	1.74952	.2502
950	341.82	1.76309	.2514
1000	354.43	1.77602	.2527
1050	367.09	1.78838	.2539
1100	379.80	1.80021	.2552
1150	392.60	1.81159	.2567
1200	405.48	1.82255	.2582
1250	418.43	1.83313	.2597
1300	431.45	1.84331	.2613
1350	444.56	1.85320	.2629
1400	457.75	1.86279	.2644
1450	471.01	1.87209	.2660
1500	484.36	1.88114	.2675
1550	497.77	1.88994	.2691
1600	511.27	1.89851	.2706
1650	524.86	1.90690	.2721
1700	538.49	1.91504	.2735
1750	552.21	1.92300	.2750
1800	566.01	1.93080	.2764
1850	579.86	1.93840	.2776
1900	593.78	1.94582	.2789
1950	607.76	1.95308	.2802
2000	621.80	1.96019	.2814
2050	635.91	1.96716	.2825
2100	650.06	1.97398	.2837
2150	664.27	1.98067	.2848
2200	678.54	1.98723	.2858
2250	692.87	1.99366	.2868
2300	707.24	1.99998	.2878
2350	721.65	2.00618	.2888
2400	736.11	2.01227	.2896
2450	750.61	2.01825	.2905
2500	765.17	2.02413	.2913
2550	779.76	2.02991	.2922
2600	794.38	2.03559	.2929
2650	809.05	2.04118	.2937
2700	823.75	2.04668	.2944
2750	838.49	2.05208	.2951
2800	853.27	2.05741	.2957
2850	868.07	2.06265	.2964
2900	882.92	2.06781	.2971
2950	897.78	2.07290	.2976
3000	912.69	2.07790	.2982
3050	927.61	2.08284	.2988
3100	942.56	2.08770	.2993
3150	957.55	2.09250	.2999
3200	972.56	2.09723	.3004
3250	987.59	2.10189	.3009
3300	1002.65	2.10649	.3013
3350	1017.73	2.11102	.3018
3400	1032.84	2.11550	.3023
3450	1047.97	2.11991	.3027
3500	1063.11	2.12427	.3031
3550	1078.28	2.12857	.3035
3600	1093.47	2.13282	.3039
3650	1108.68	2.13702	.3043
3700	1123.91	2.14116	.3047
3750	1139.15	2.14526	.3051
3800	1154.41	2.14930	.3054
3850	1169.70	2.15329	.3057
3900	1185.00	2.15724	.3061
3950	1200.31	2.16114	.3064
4000	1215.64	2.16500	.3067
4500	1369.74	2.20130	.3095
5000	1525.06	2.33402	.3116
5500	1681.34	2.26381	.3134
6000	1838.42	2.29115	.3148

TABLE XI. - VAPOR PRESSURE OF SATURATED BORON OXIDE B_2O_3

Temperature, °R	Vapor pressure, $p_{B_2O_3}$, atm	Temperature, °R	Vapor pressure, $p_{B_2O_3}$, atm
1800	0.4384×10^{-10}	3000	36.52×10^{-5}
1850	1.318	3050	53.38
1900	3.730	3100	77.00
1950	9.959	3150	109.8
		3200	154.7
2000	25.25		
2050	61.31	3250	215.7
2100	142.2	3300	297.3
2150	315.9	3350	406.3
2200	676.6	3400	54.79×10^{-4}
		3450	73.45
2250	1399		
2300	2797	3500	97.41
2350	5423	3550	128.1
2400	$.1021\times10^{-5}$	3600	167.3
2450	.1875	3650	216.6
		3700	278.7
2500	.3350		
2550	.5845	3750	355.4
2600	.9963	3800	450.6
2650	1.662	3850	567.5
2700	2.725	3900	710.4
		3950	883.3
2750	4.379		
2800	6.912	4000	1092
2850	10.70	4500	6900
2900	16.37		
2950	24.63		

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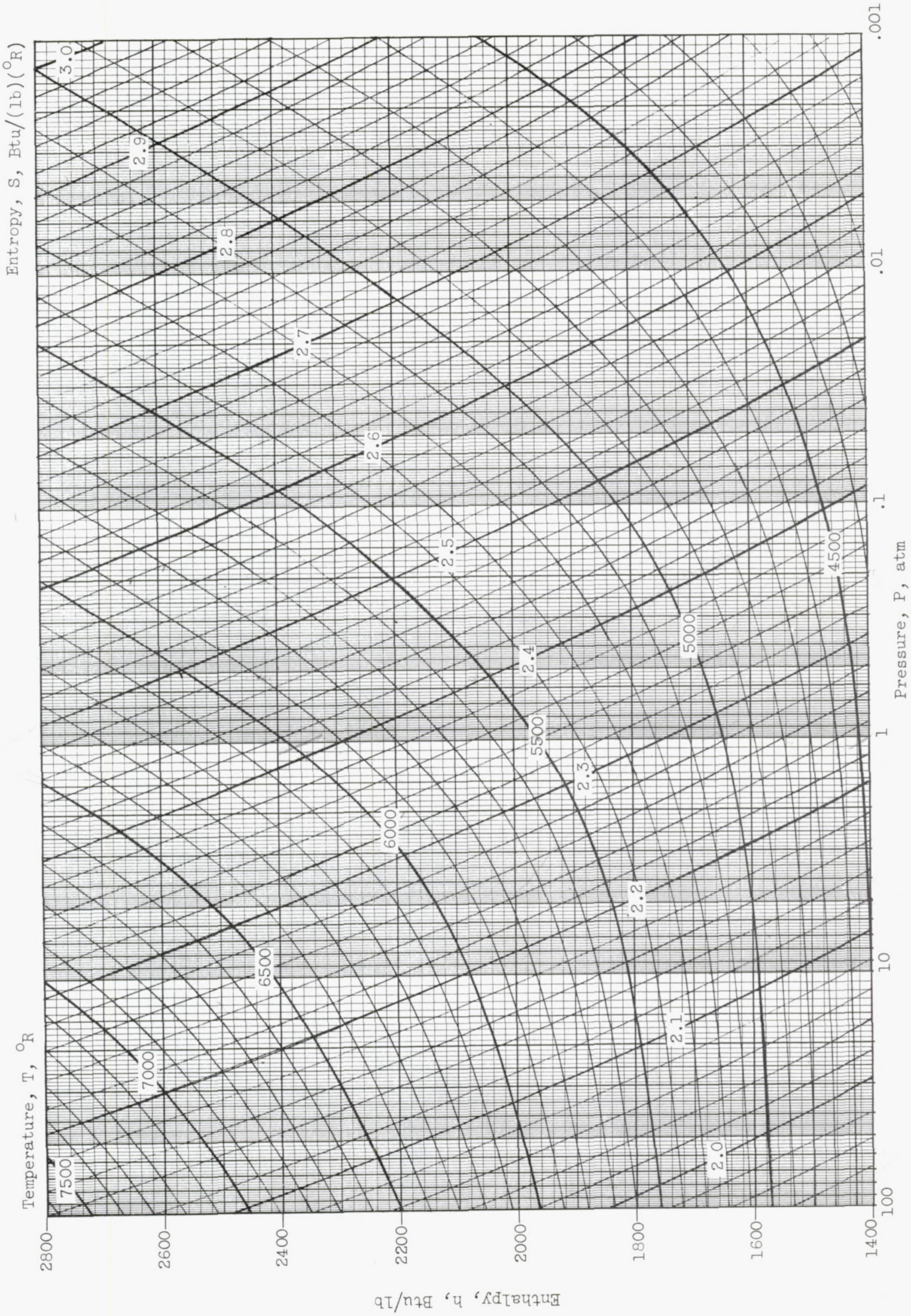
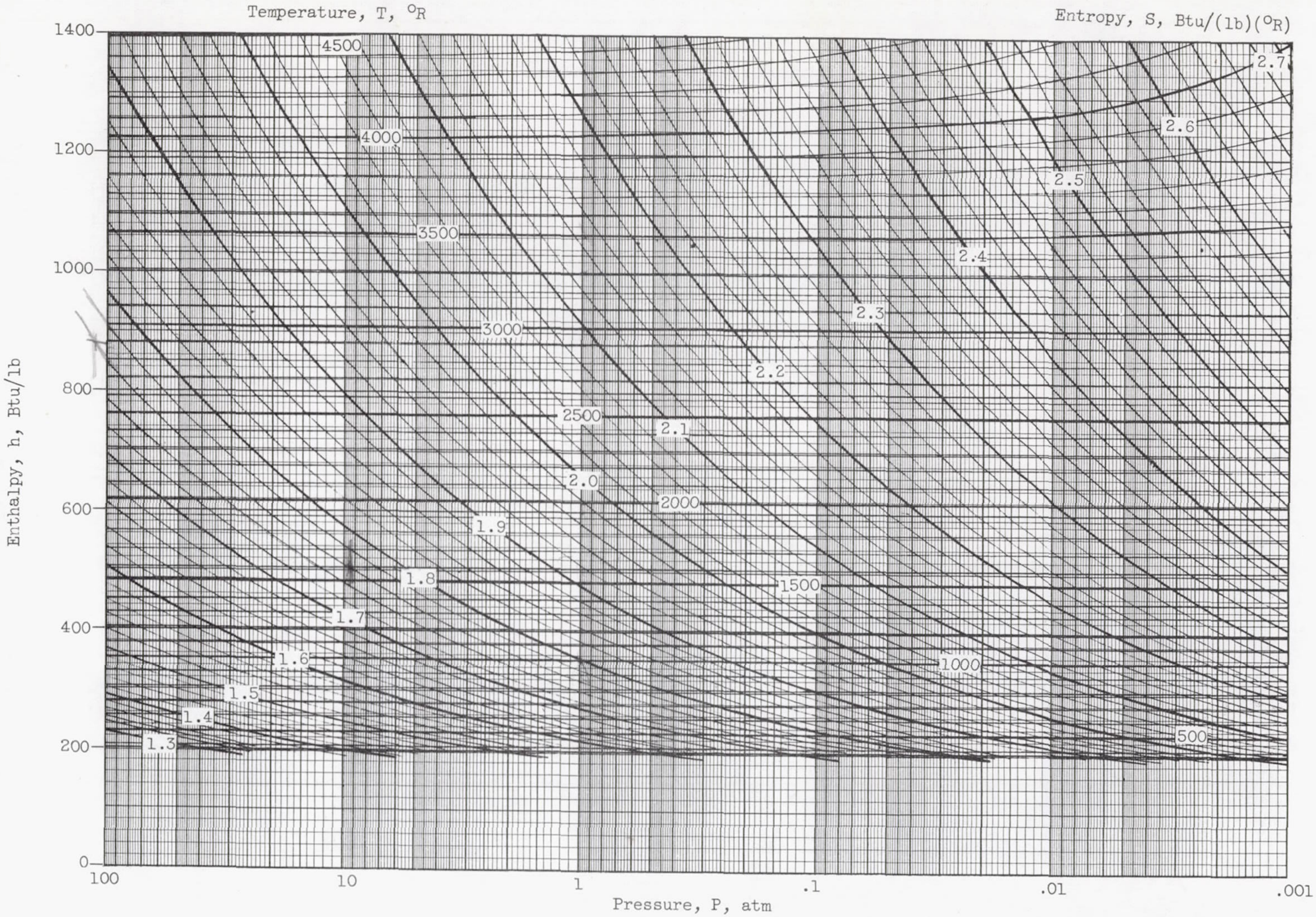


(b) Enthalpy, 1400 to 2800 Btu per pound.



(a) Enthalpy, 0 to 1400 Btu per pound.

Figure 1. - Thermodynamic data for air, including effects of dissociation. Composition, percent by volume: nitrogen, 79.050; oxygen, 20.950.

3911

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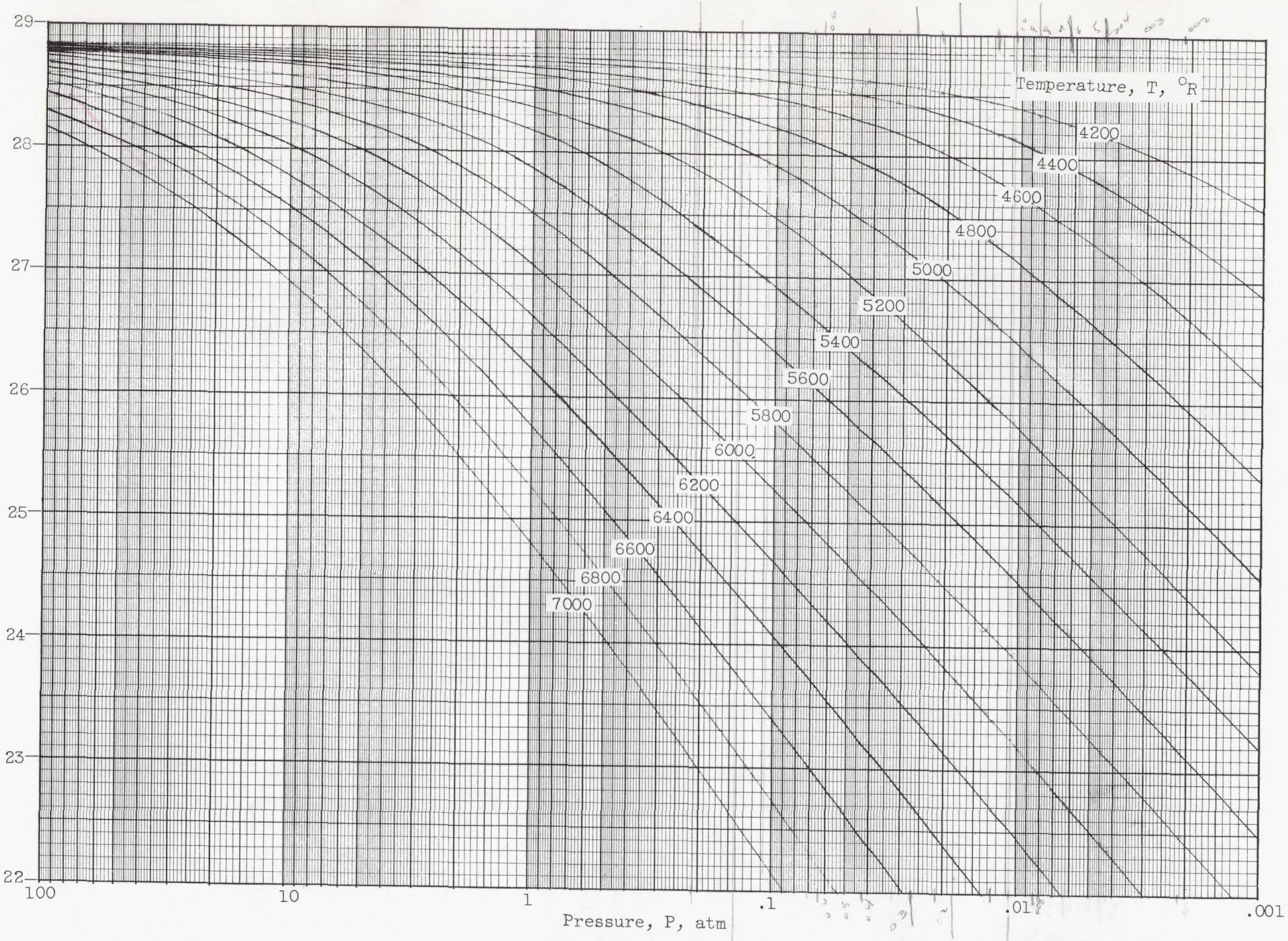

(c) Molecular weight.

Figure 1. - Concluded. Thermodynamic data for air, including effects of dissociation. Composition, percent by volume: nitrogen, 79.050; oxygen, 20.950.

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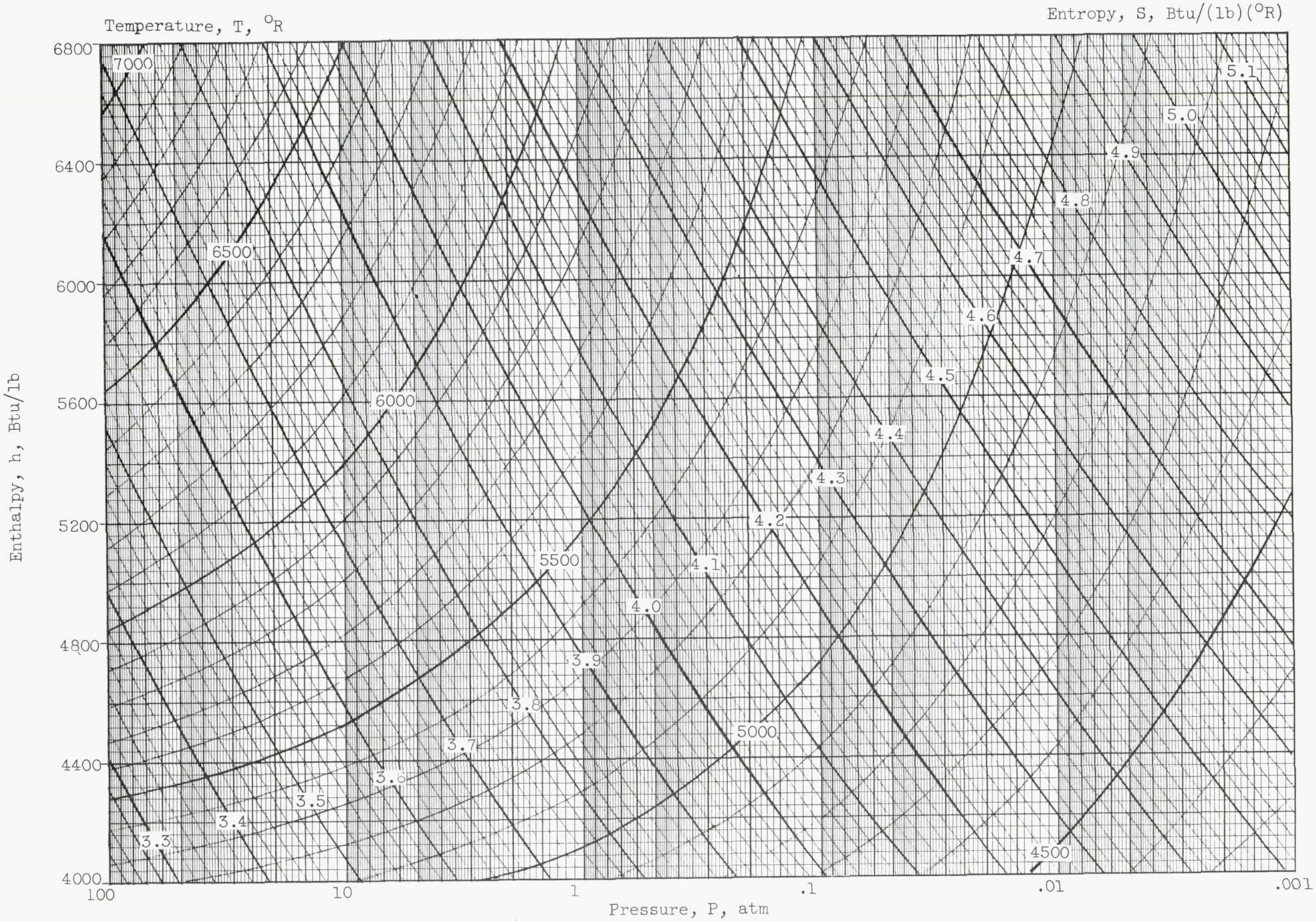

(b) Enthalpy, 4000 to 6800 Btu per pound.

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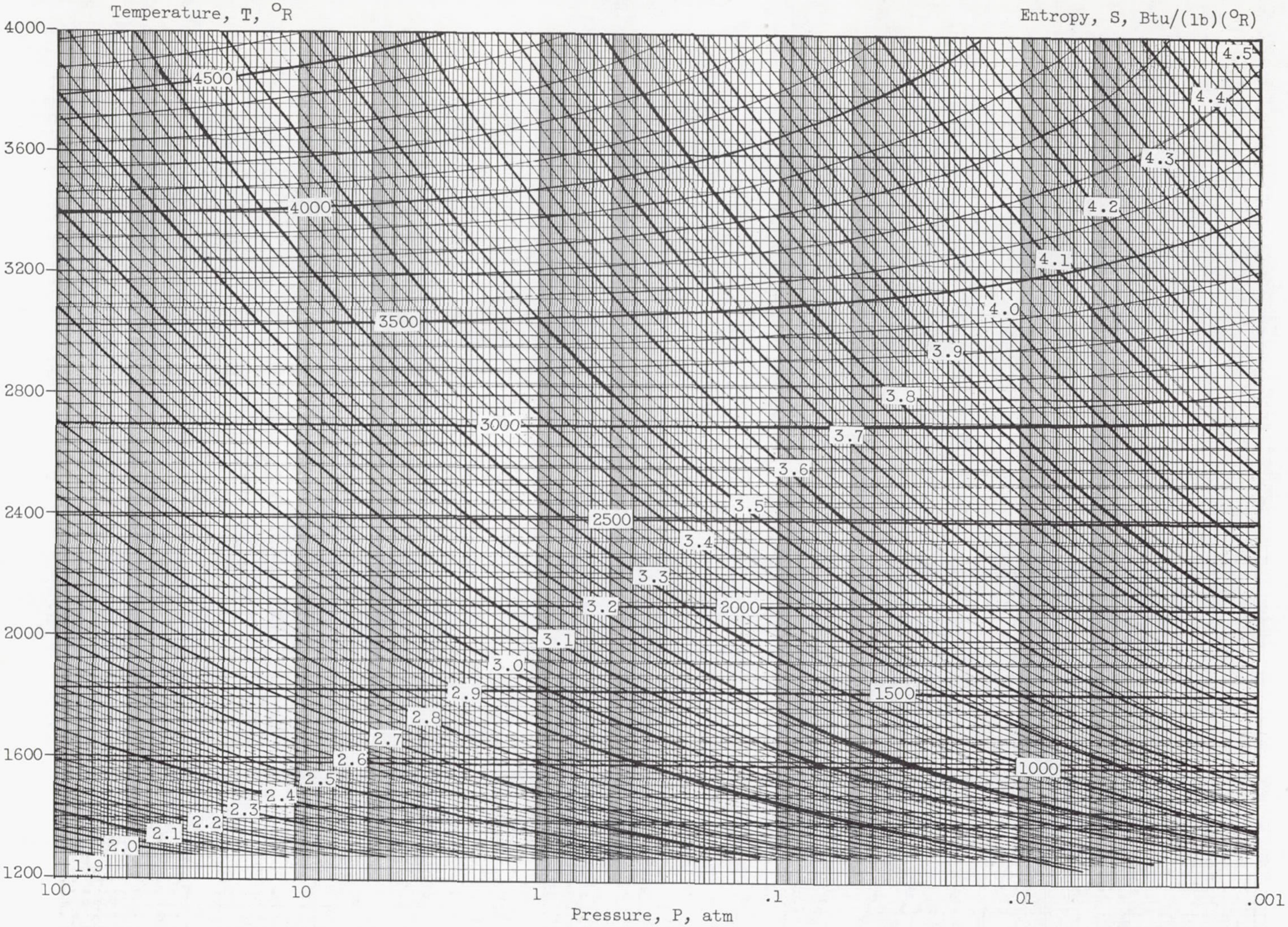
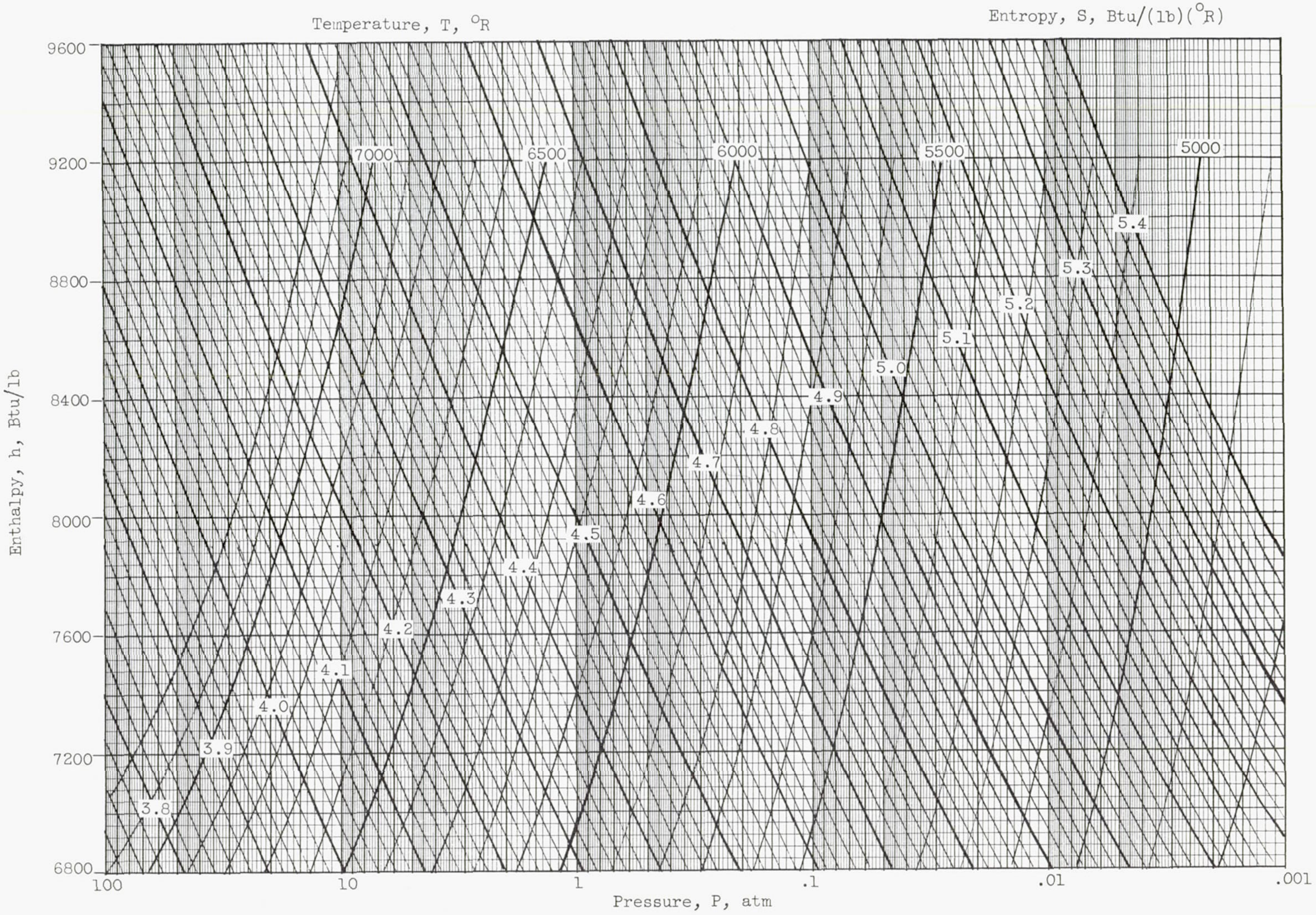
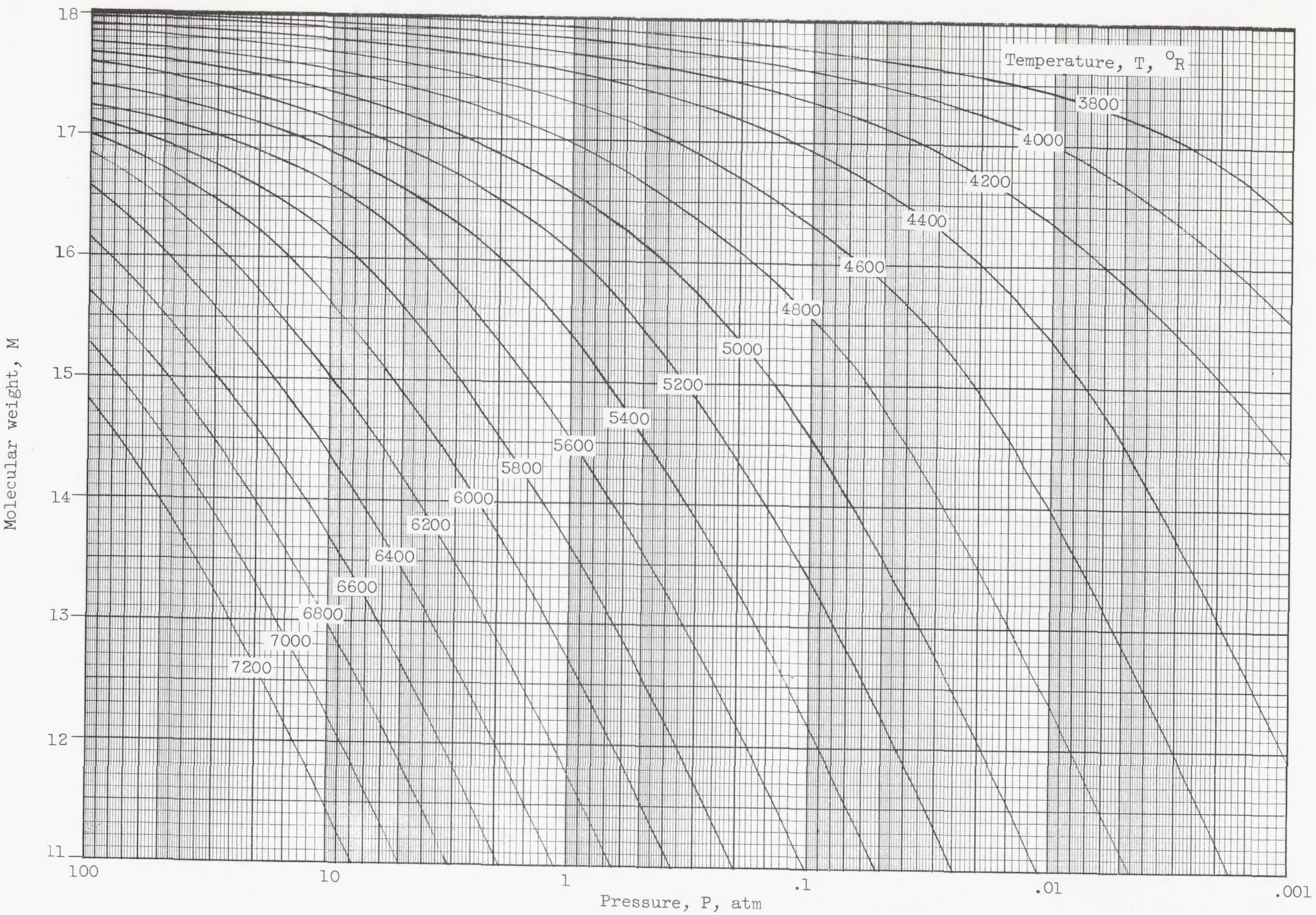


(a) Enthalpy, 1200 to 4000 Btu per pound.

Figure 2. - Thermodynamic data for water vapor, including effects of dissociation.

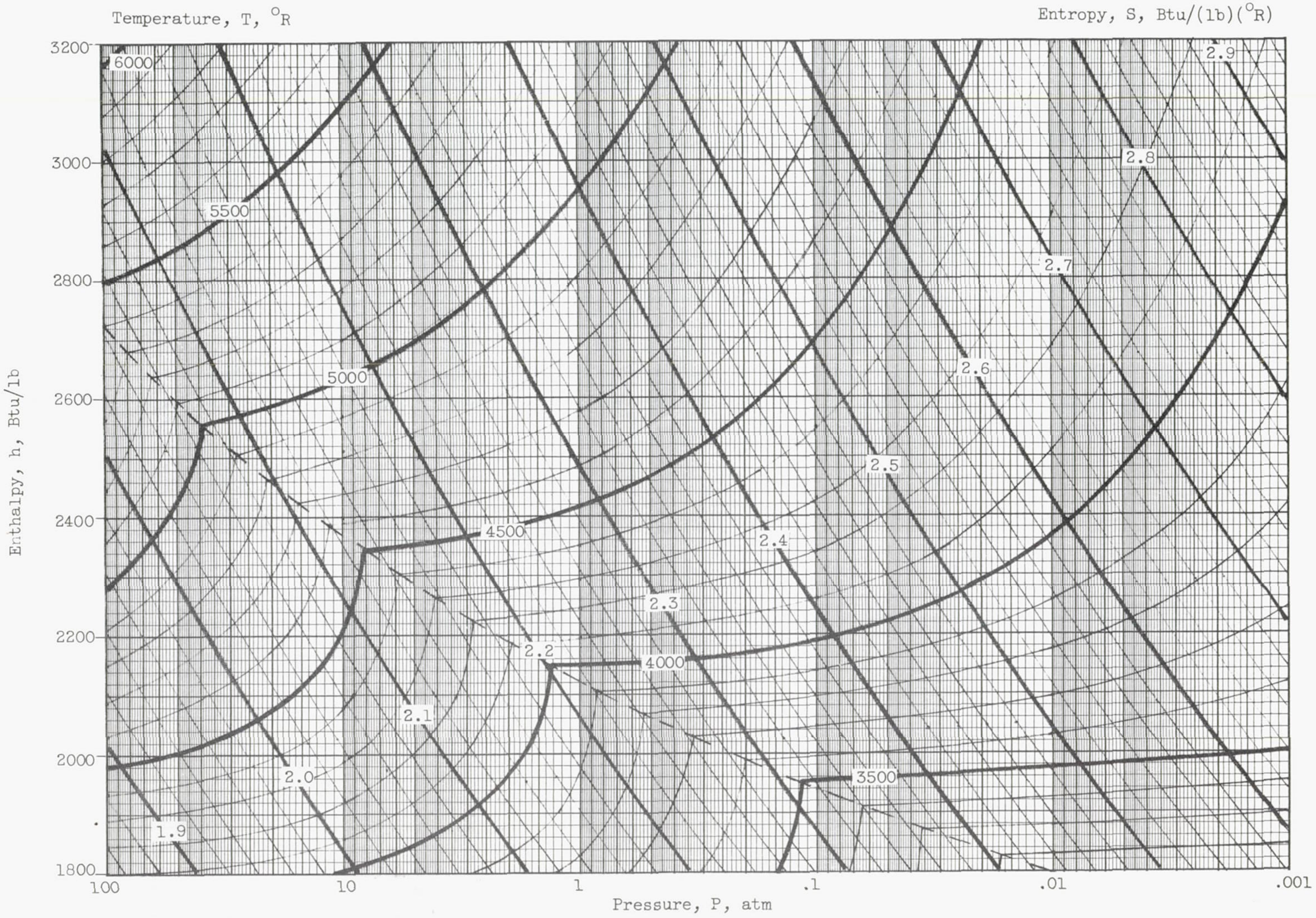


(c) Enthalpy, 6800 to 9600 Btu per pound.

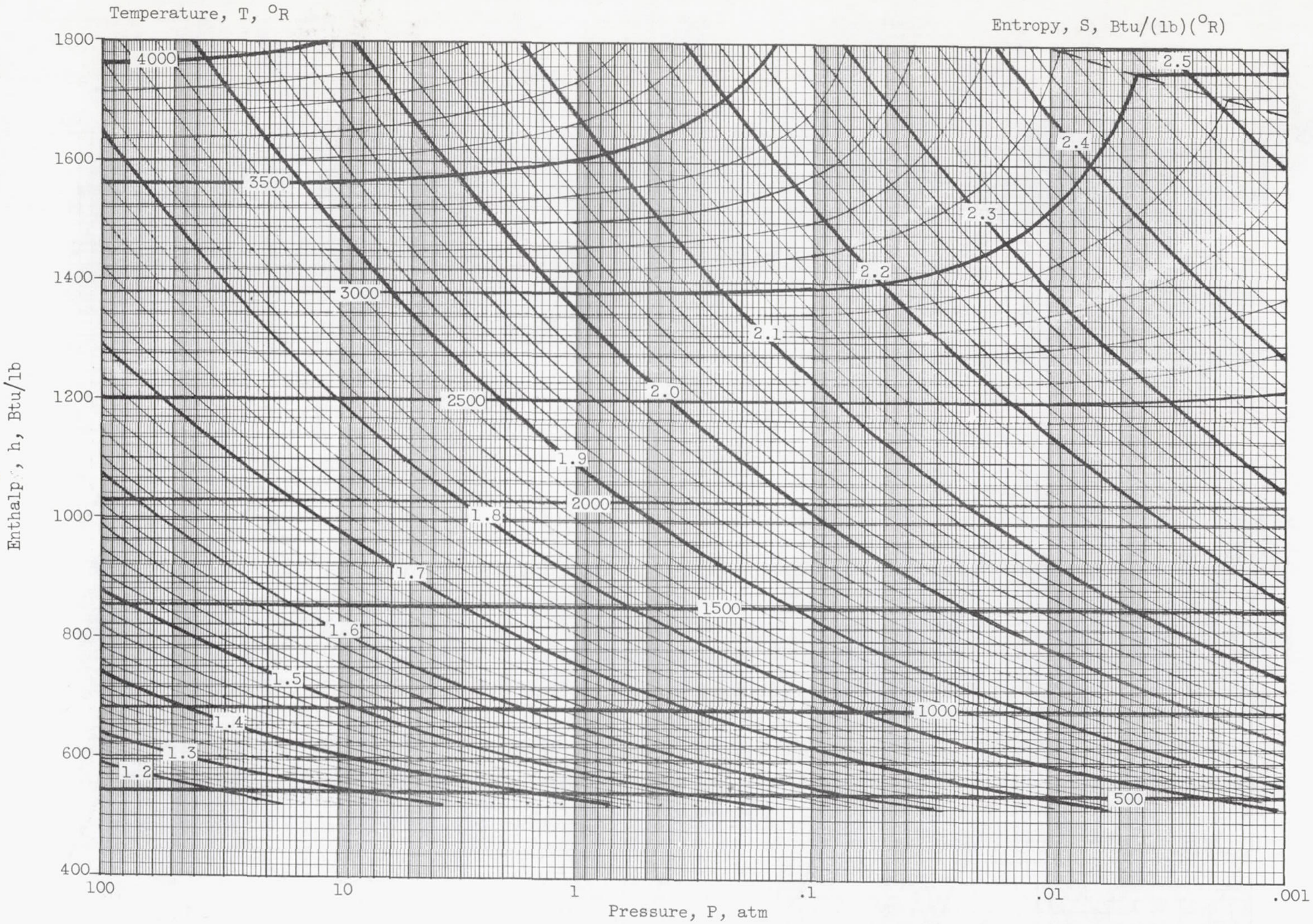


(d) Molecular weight.

Figure 2. - Concluded. Thermodynamic data for water vapor, including effects of dissociation.



(b) Enthalpy, 1800 to 3200 Btu per pound.



(a) Enthalpy, 400 to 1800 Btu per pound.

Figure 3. - Thermodynamic data for pentaborane B_5H_9, including effects of dissociation. Fuel-air ratio (stoichiometric), 0.07645.

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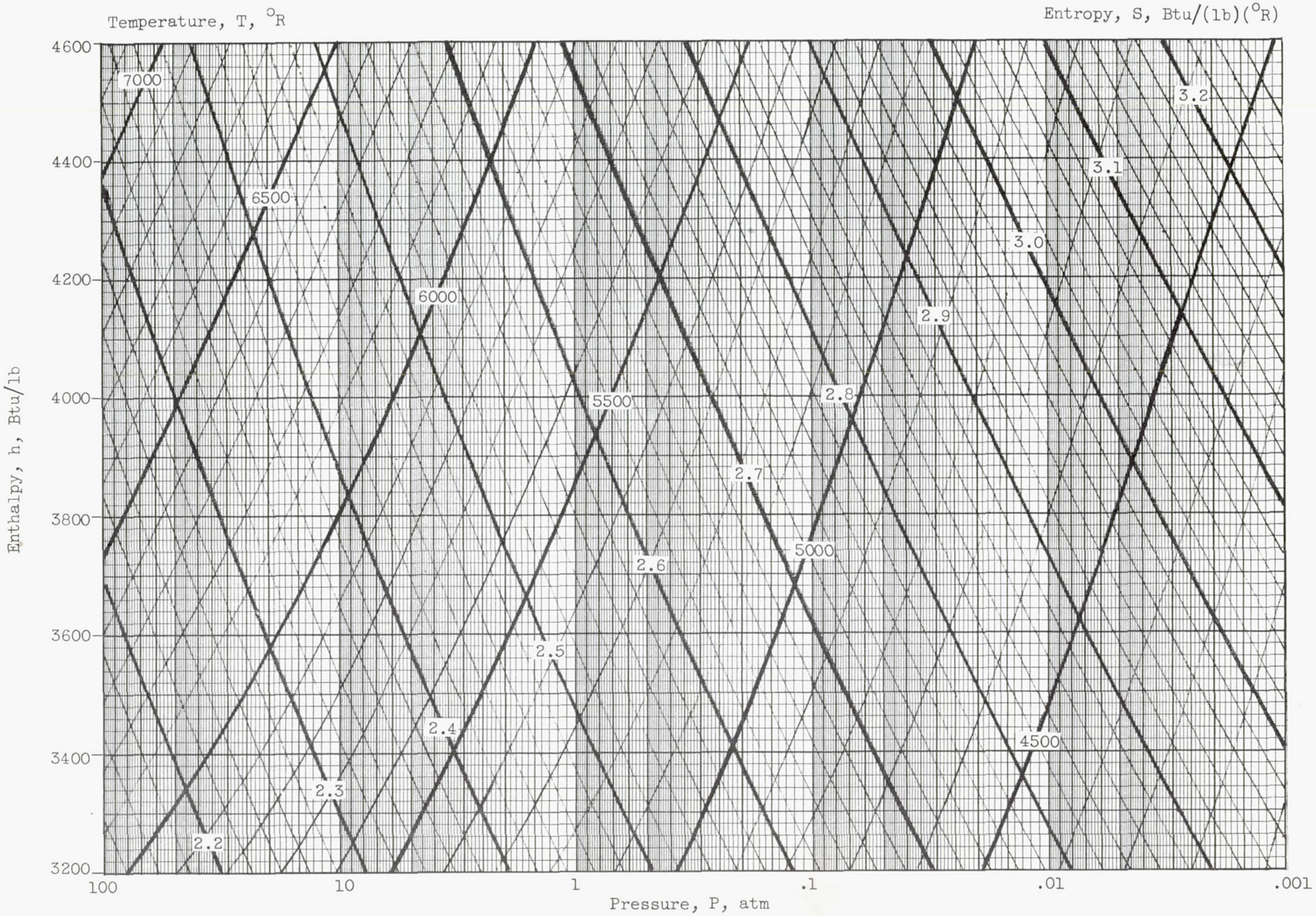

(c) Enthalpy, 3200 to 4600 Btu per pound.

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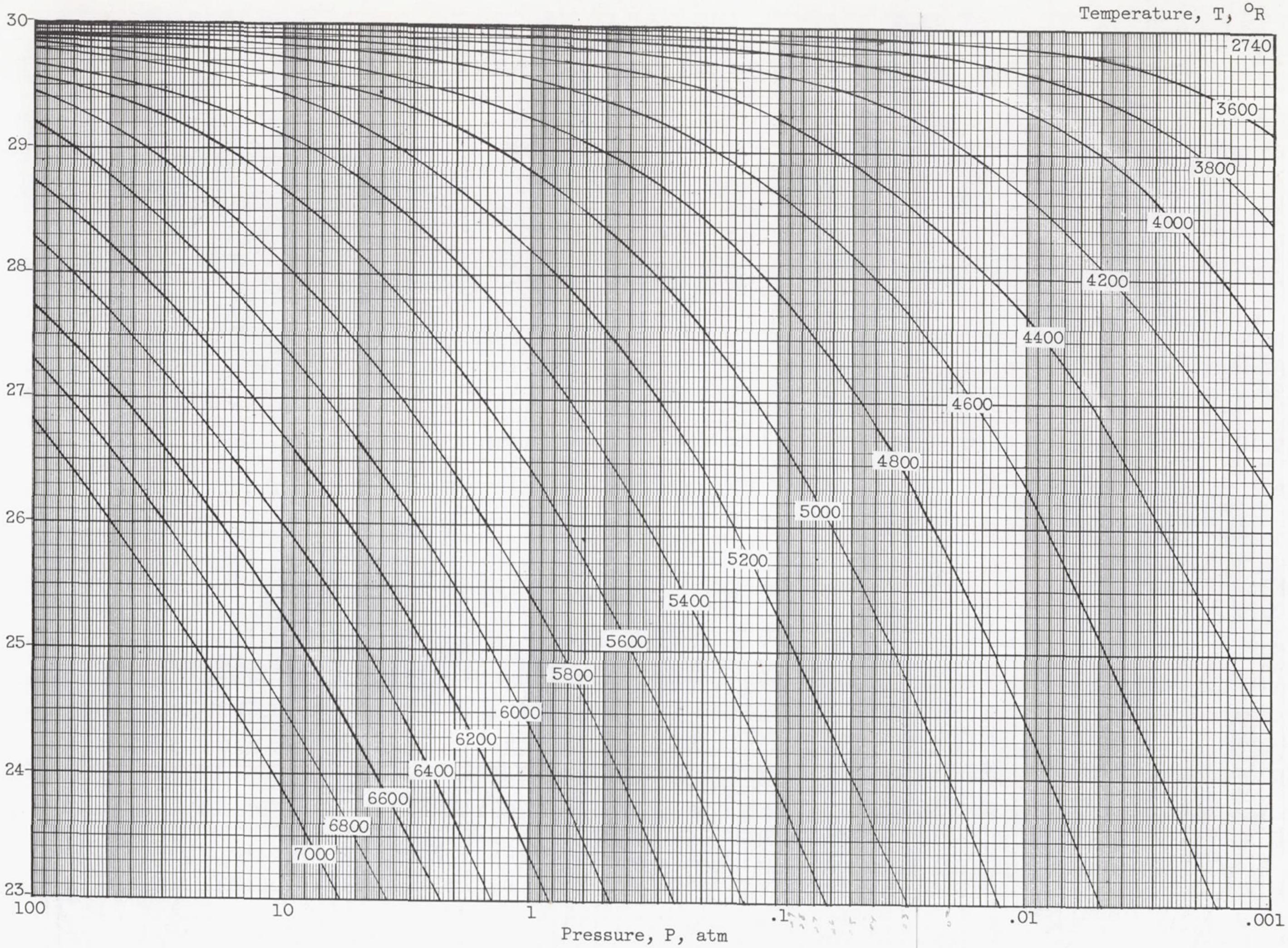
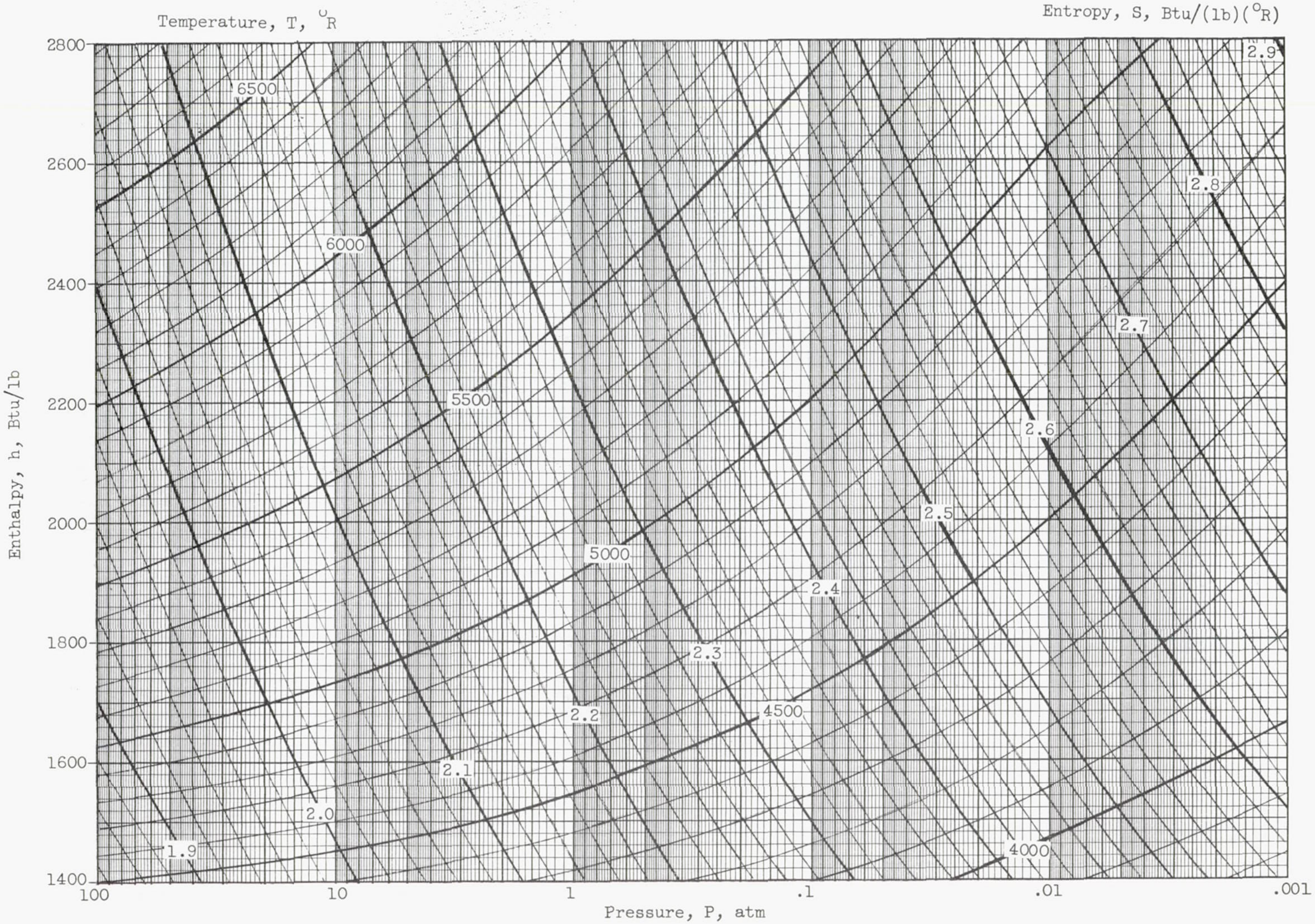
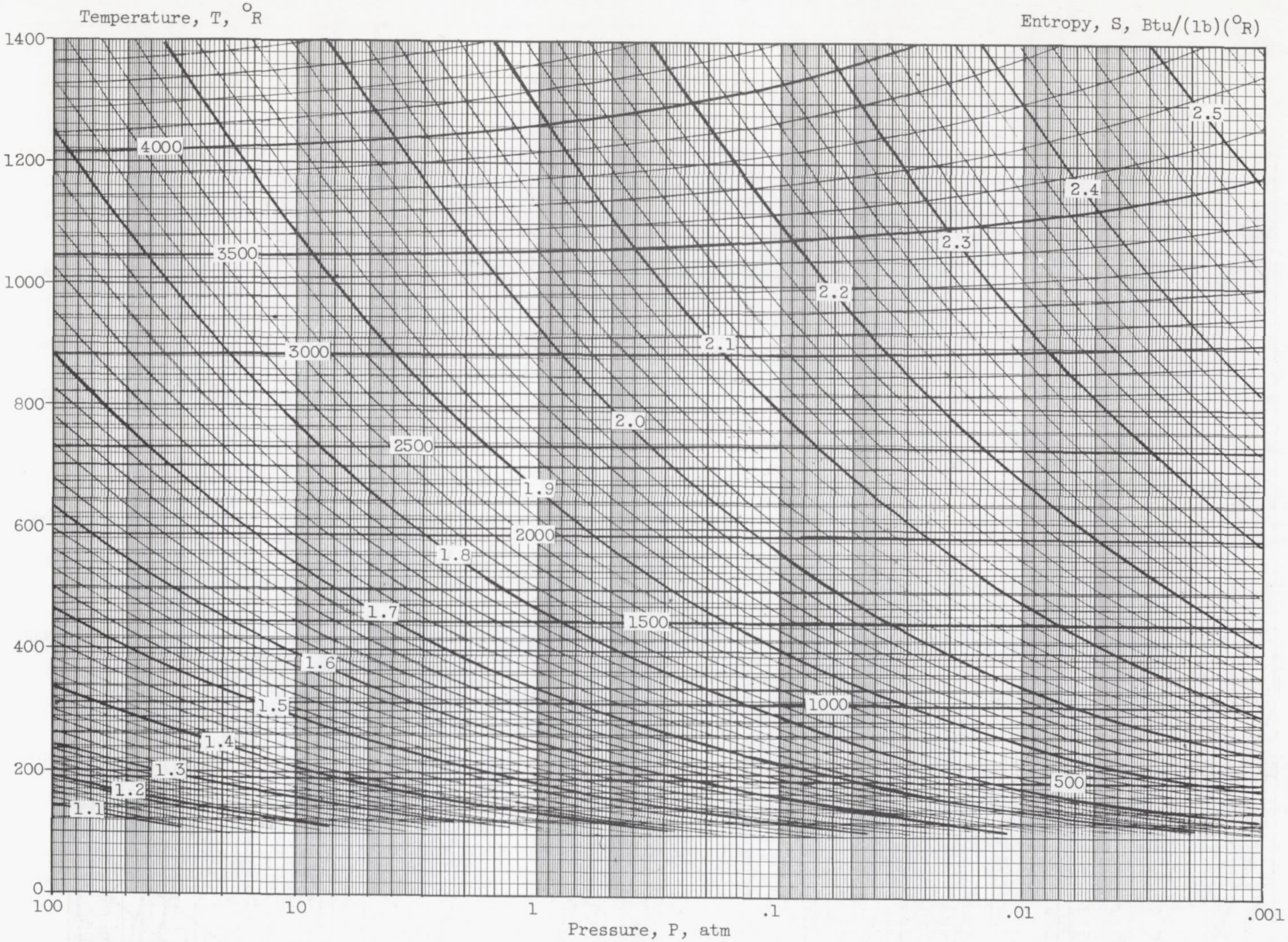


(d) Molecular weight.

Figure 3. - Concluded. Thermodynamic data for pentaborane B_5H_9, including effects of dissociation. Fuel-air ratio (stoichiometric), 0.07645.



(b) Enthalpy, 1400 to 2800 Btu per pound.



(a) Enthalpy, 0 to 1400 Btu per pound.

Figure 4. - Thermodynamic data for stoichiometric combustion products of carbon, including effects of dissociation. Fuel-air ratio (stoichiometric), 0.08721.

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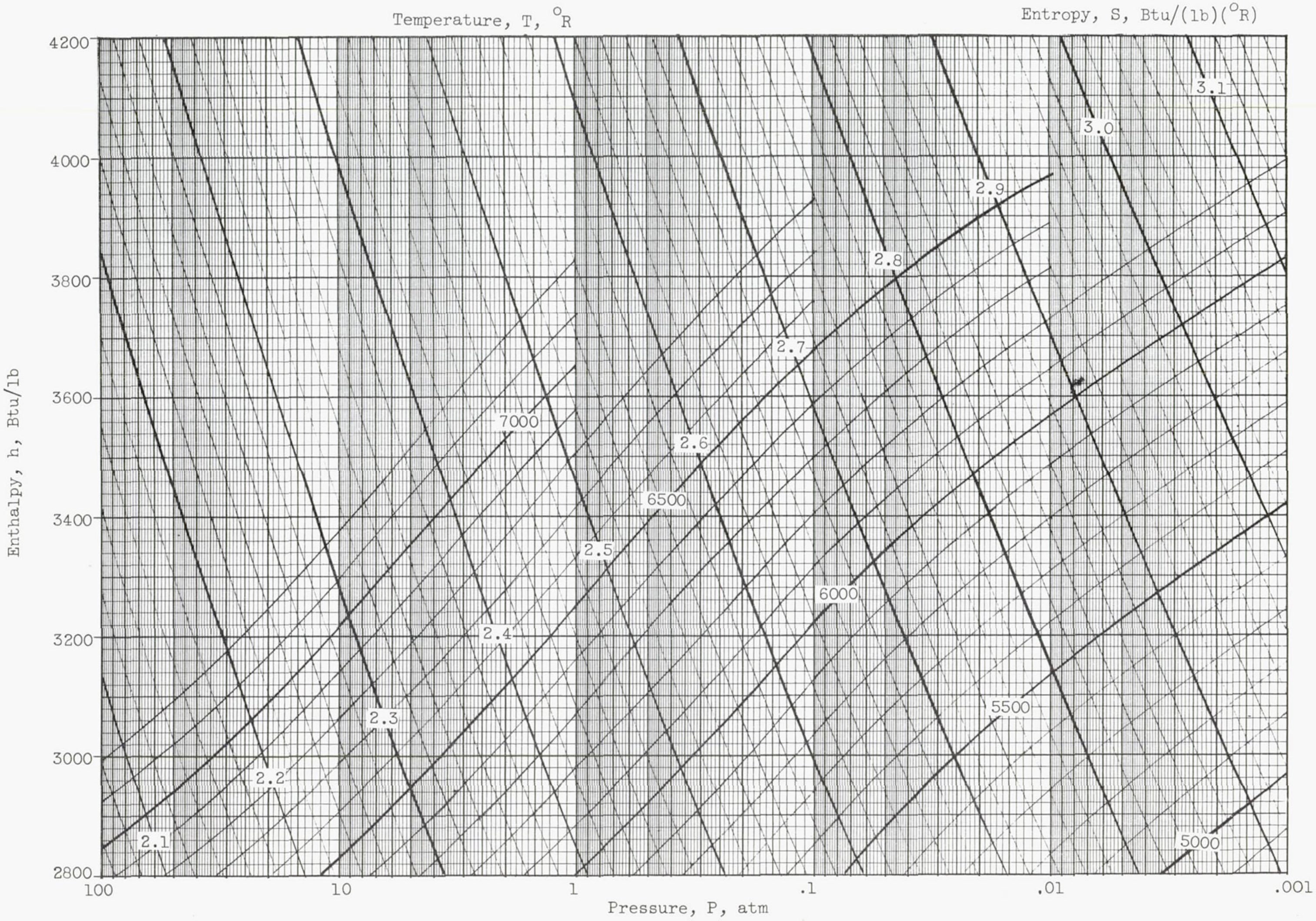

(c) Enthalpy, 2800 to 4200 Btu per pound.

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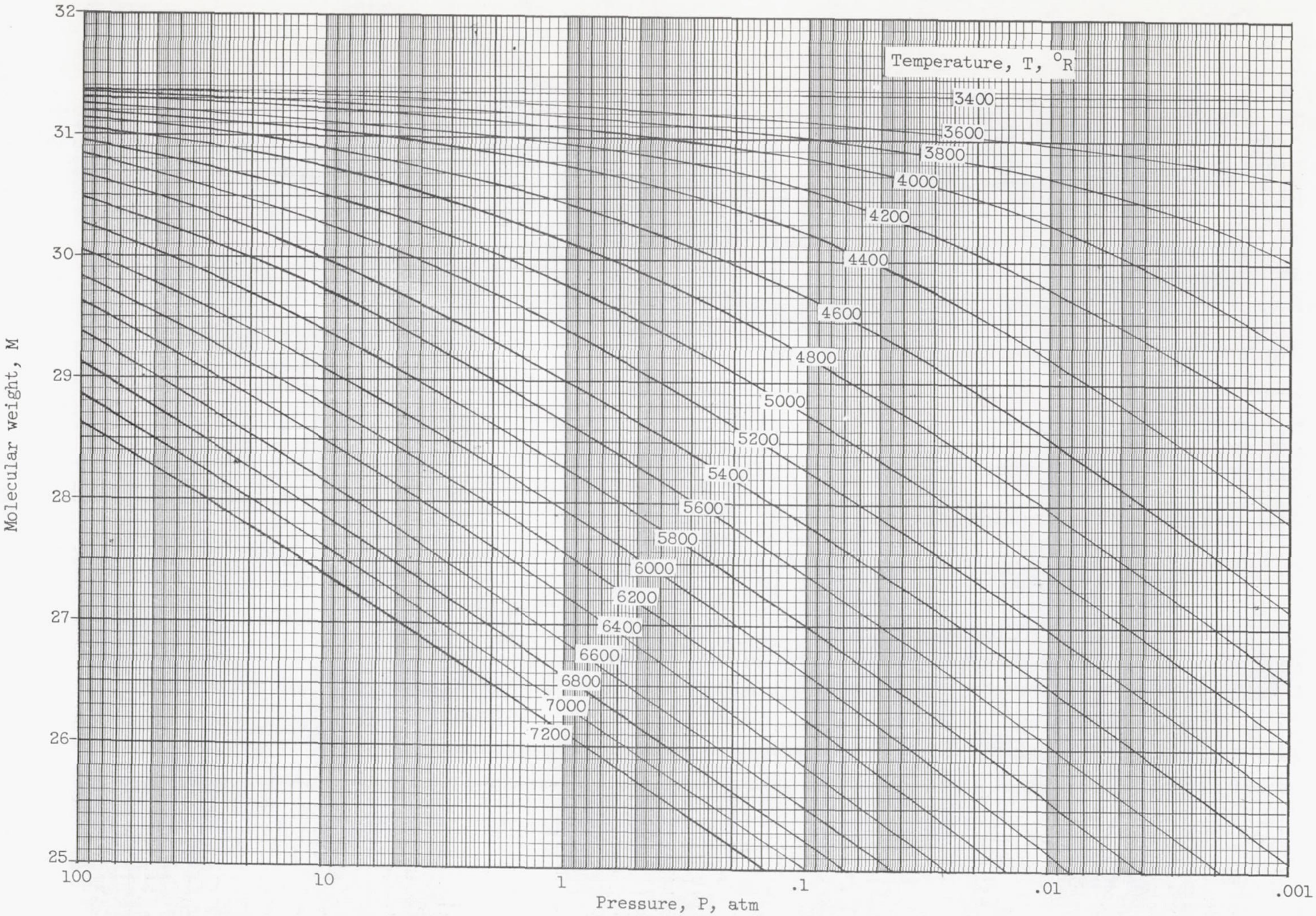
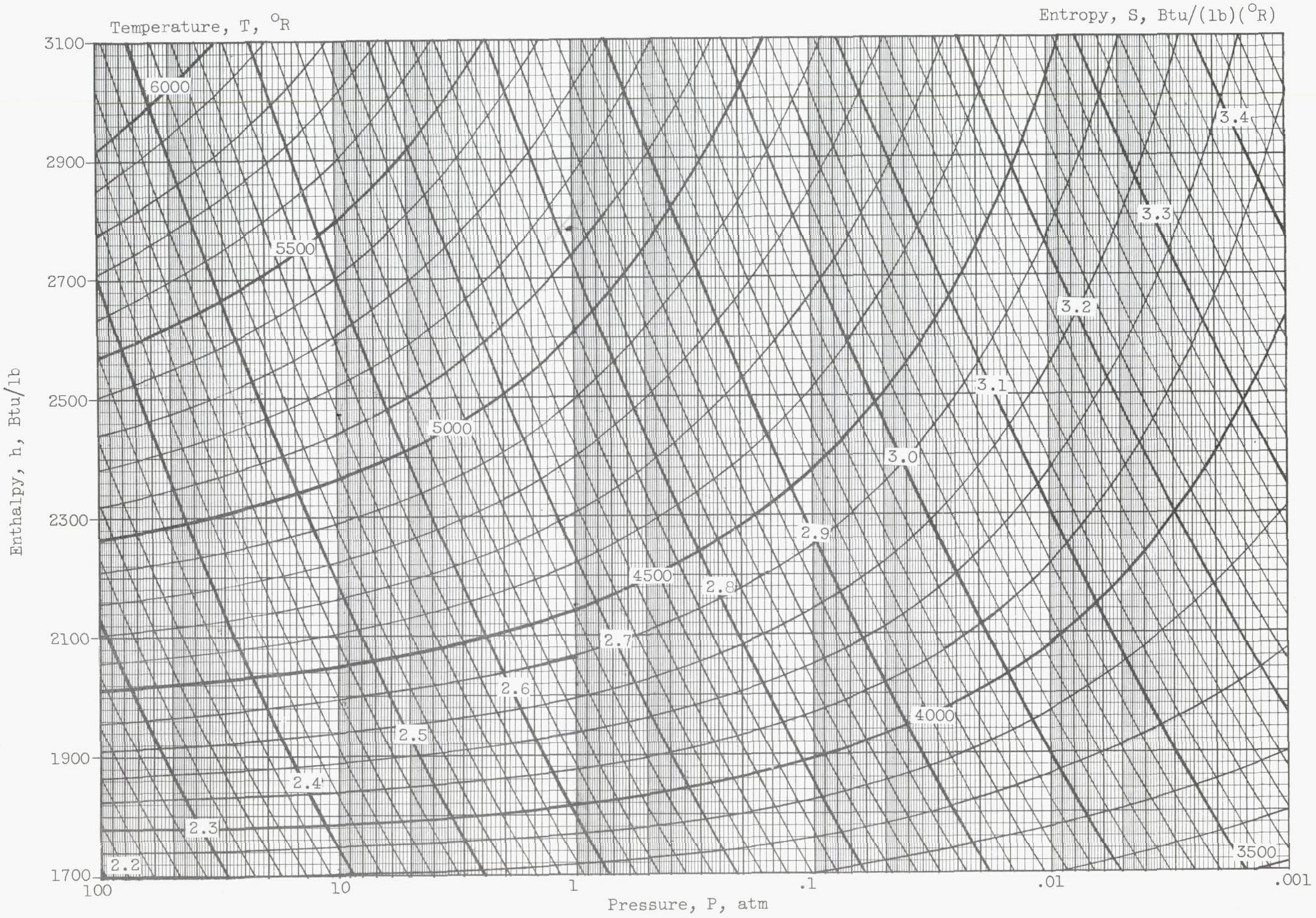
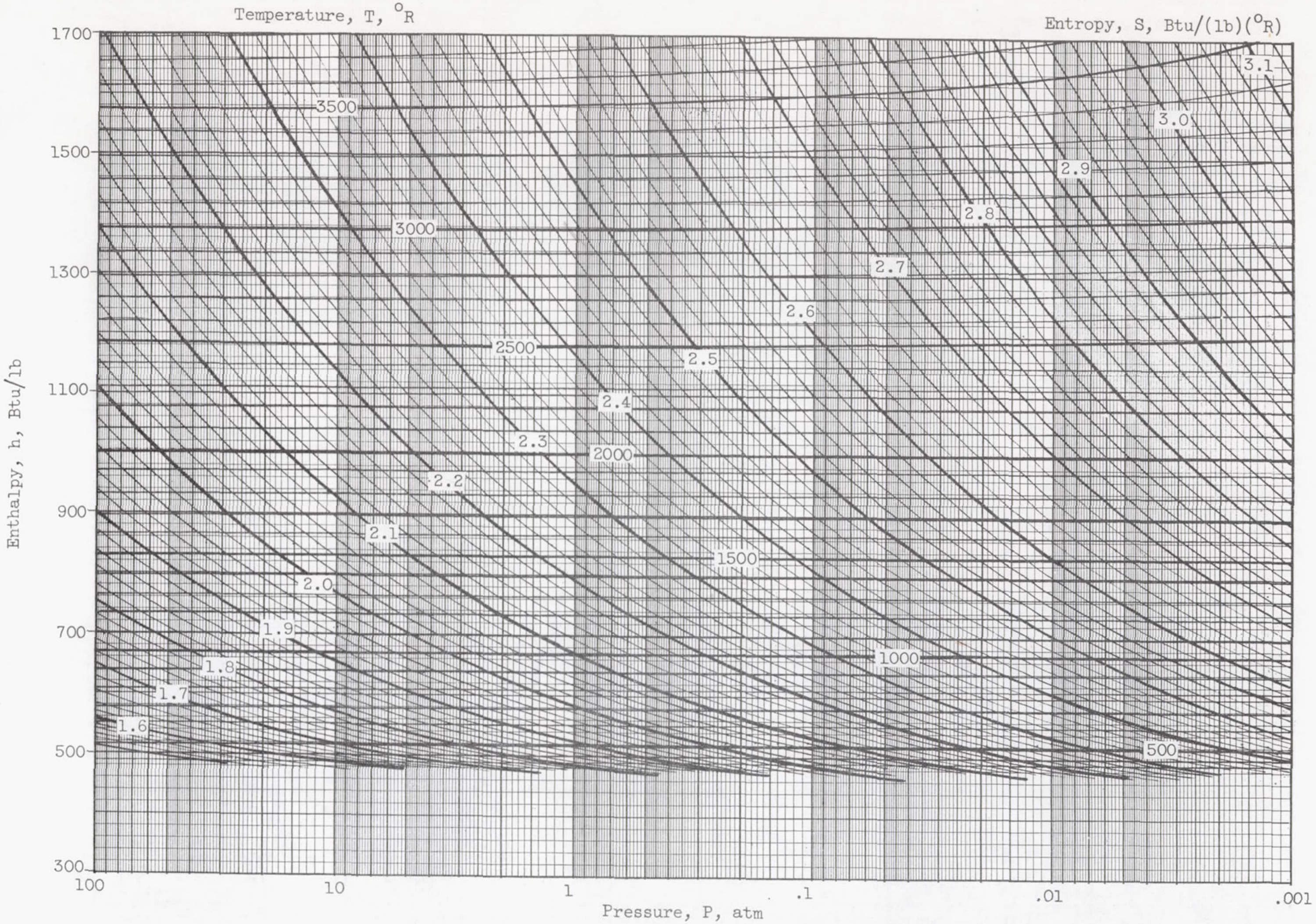


(d) Molecular weight.

Figure 4. - Concluded. Thermodynamic data for stoichiometric combustion products of carbon, including effects of dissociation. Fuel-air ratio (stoichiometric), 0.08721.



(b) Enthalpy, 1700 to 3100 Btu per pound.



(a) Enthalpy, 300 to 1700 Btu per pound.

Figure 5. - Thermodynamic data for stoichiometric combustion products of hydrogen, including effects of dissociation. Fuel-air ratio (stoichiometric), 0.02928.

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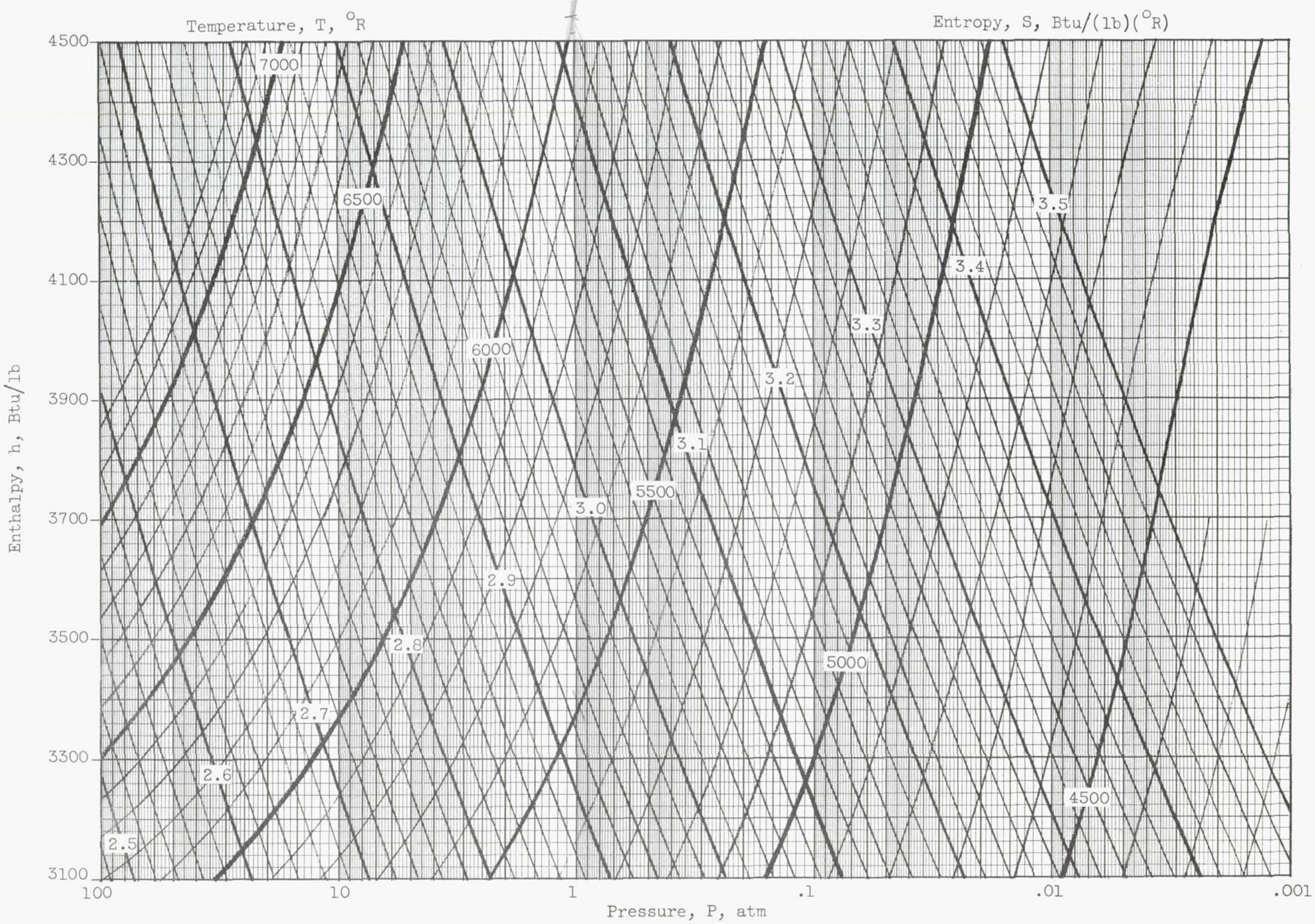

(c) Enthalpy, 3100 to 4500 Btu per pound.

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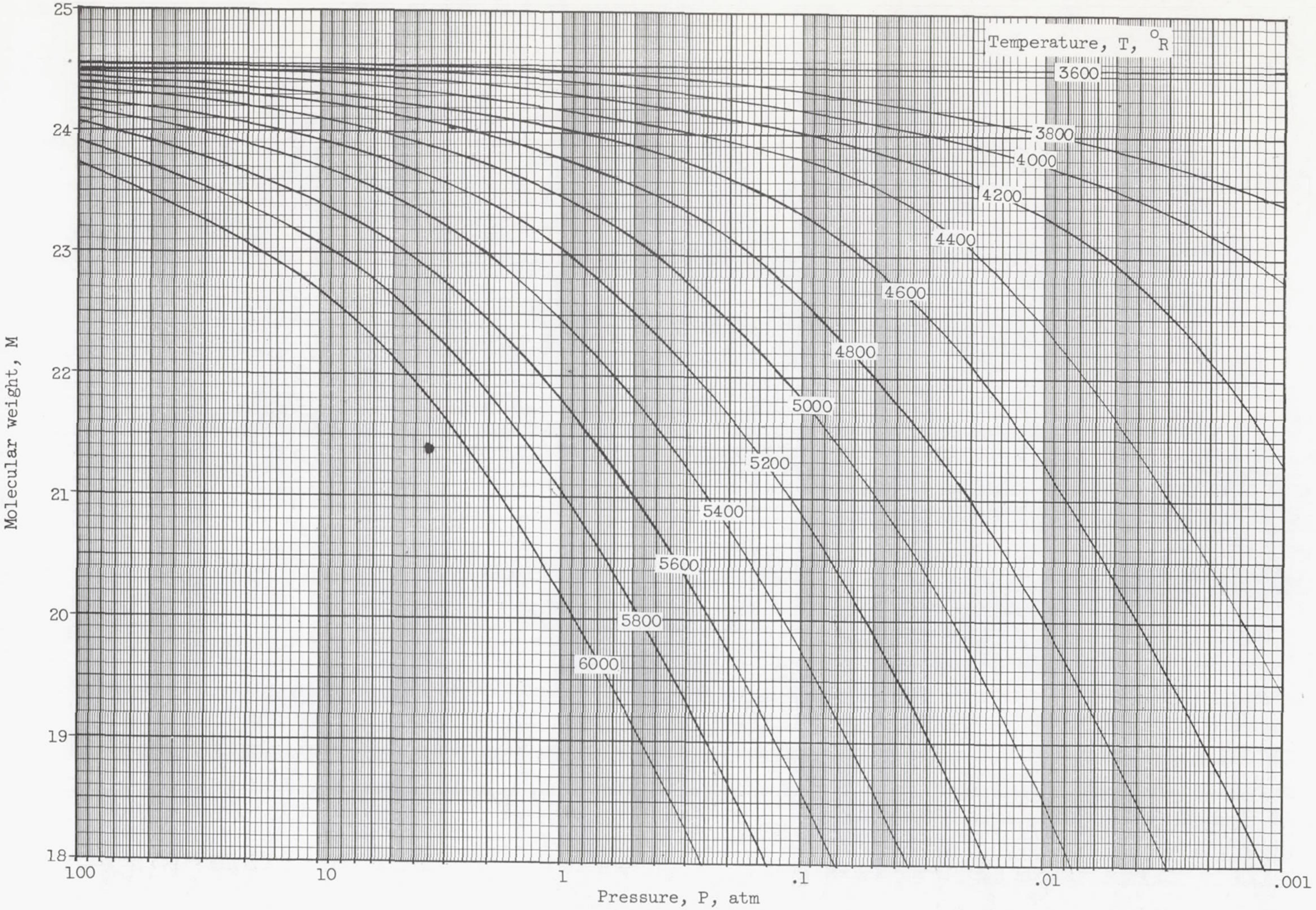

(d) Molecular weight.

Figure 5. - Concluded. Thermodynamic data for stoichiometric combustion products of hydrogen, including effects of dissociation. Fuel-air ratio (stoichiometric), 0.02928.

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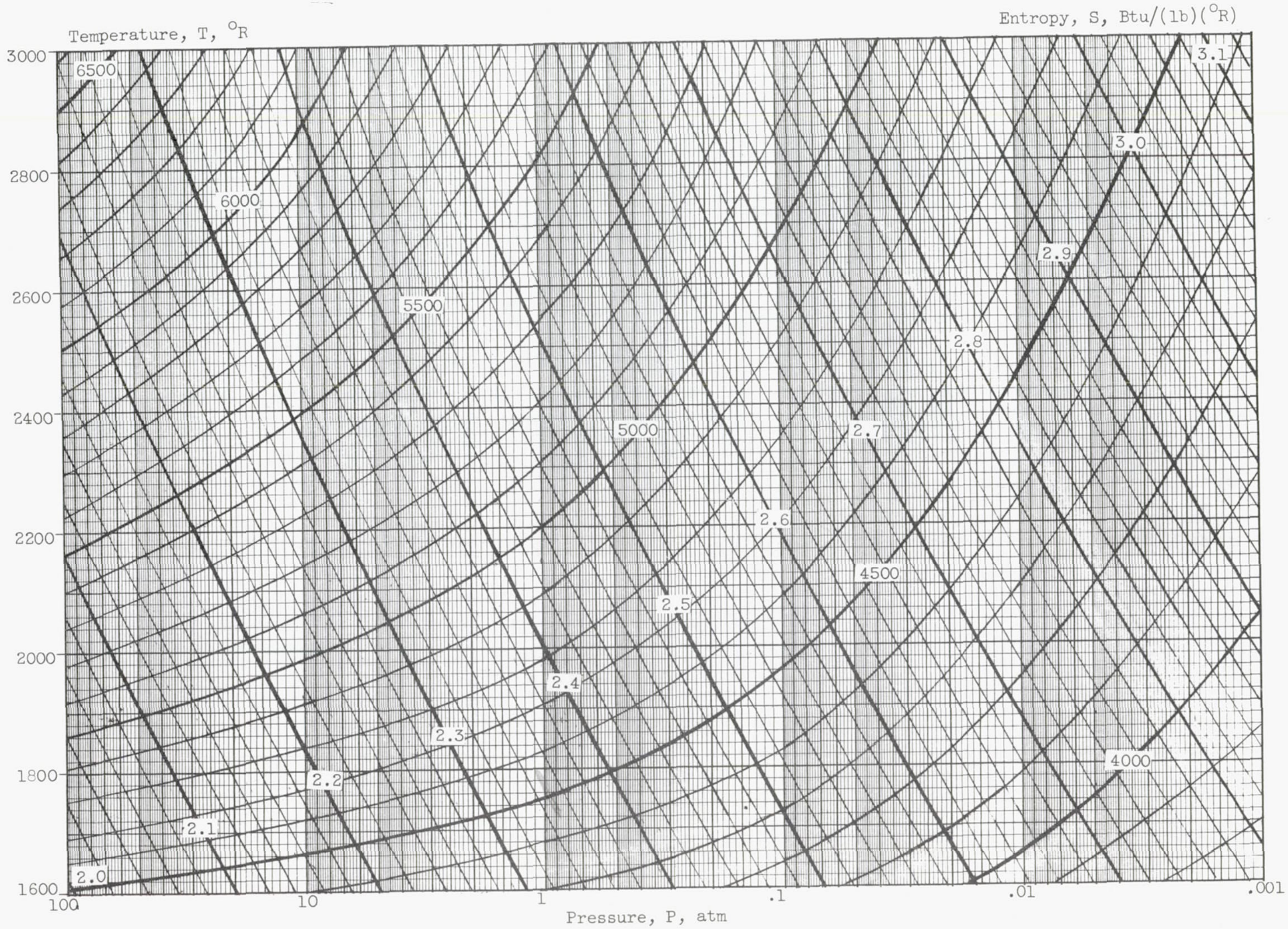
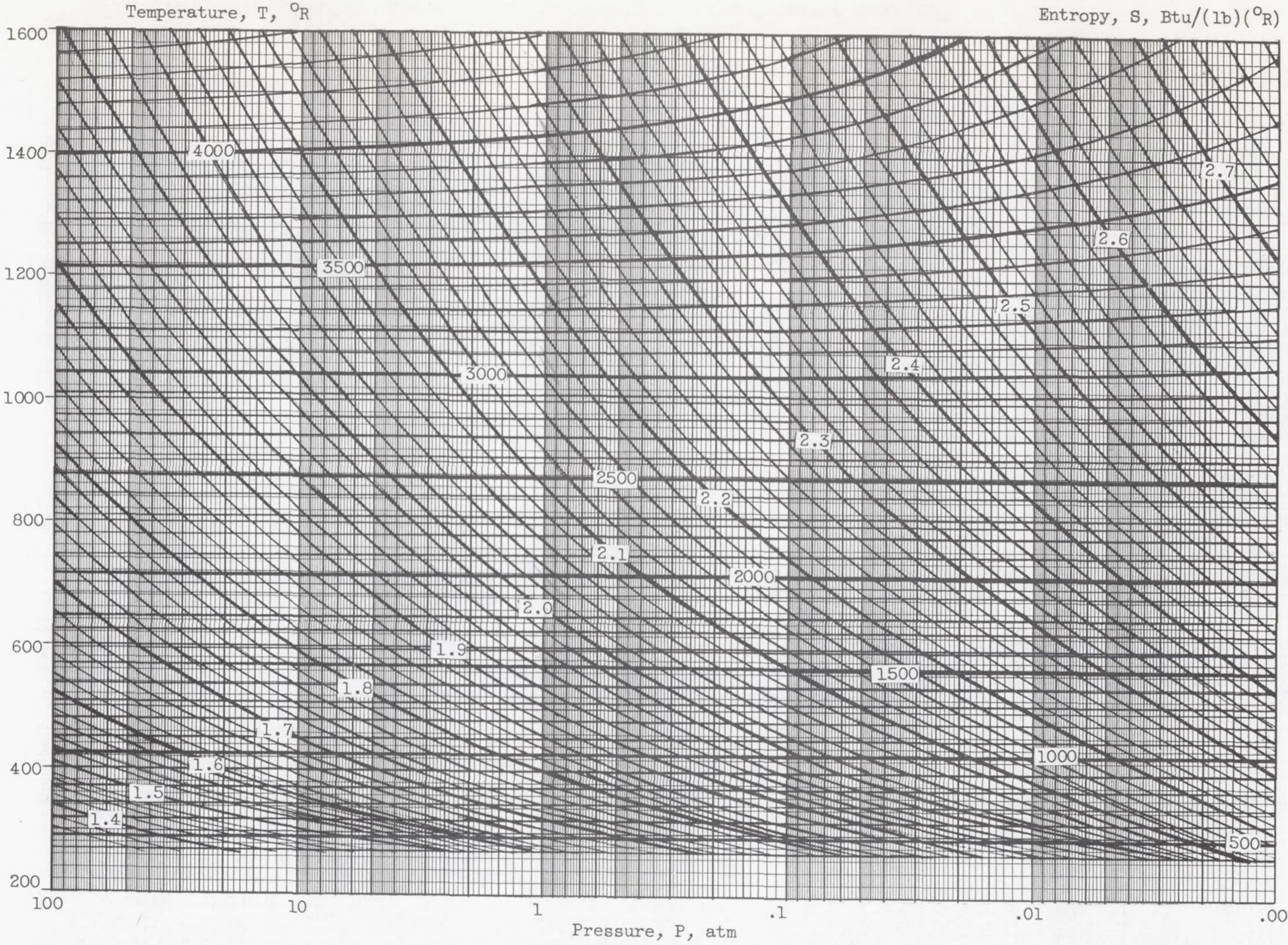


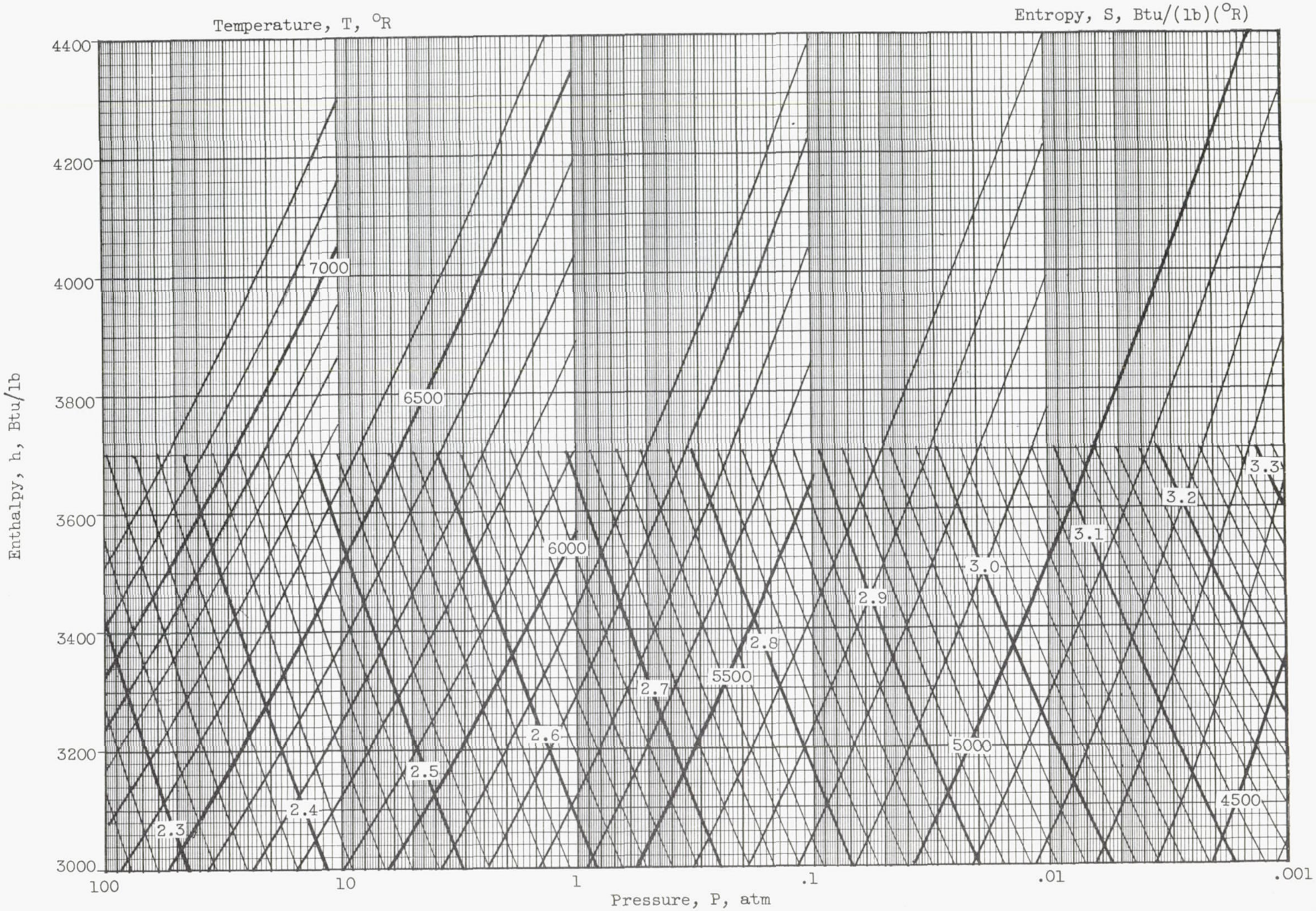
(b) Enthalpy, 1600 to 3000 Btu per pound.

Figure 6. - Continued. Thermodynamic data for stoichiometric combustion products of hydrocarbon with hydrogen-carbon ratio of 2 (CH_2), including effects of dissociation. Fuel-air ratio (stoichiometric), 0.06790.

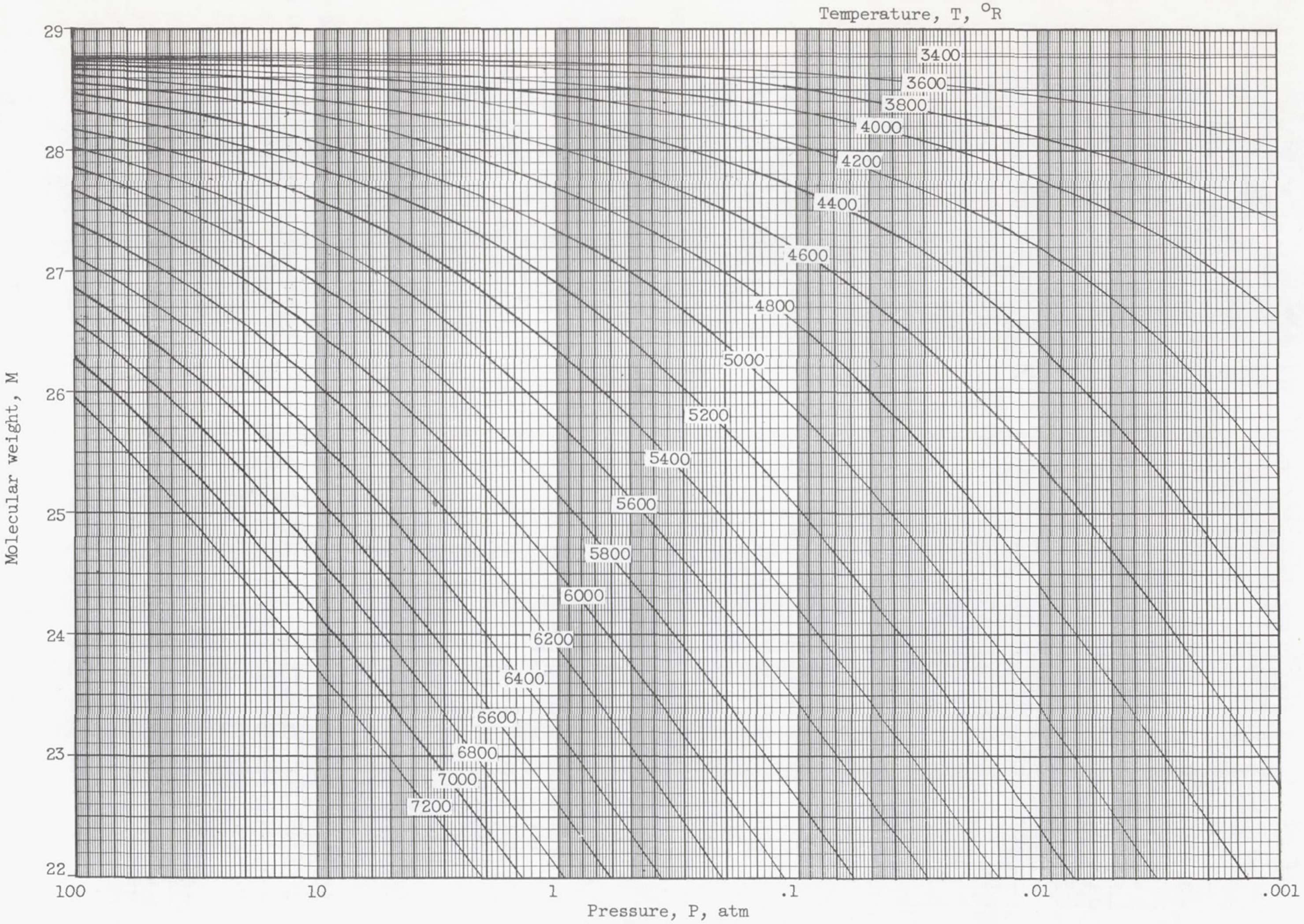


(a) Enthalpy, 200 to 1600 Btu per pound.

Figure 6. - Thermodynamic data for stoichiometric combustion products of hydrocarbon with hydrogen-carbon ratio of 2 (CH_2), including effects of dissociation. Fuel-air ratio (stoichiometric), 0.06790.



(c) Enthalpy, 3000 to 4400 Btu per pound.



(d) Molecular weight.

Figure 6. - Concluded. Thermodynamic data for stoichiometric combustion products of hydrocarbon with hydrogen-carbon ratio of 2 (CH_2), including effects of dissociation. Fuel-air ratio (stoichiometric), 0.06790.

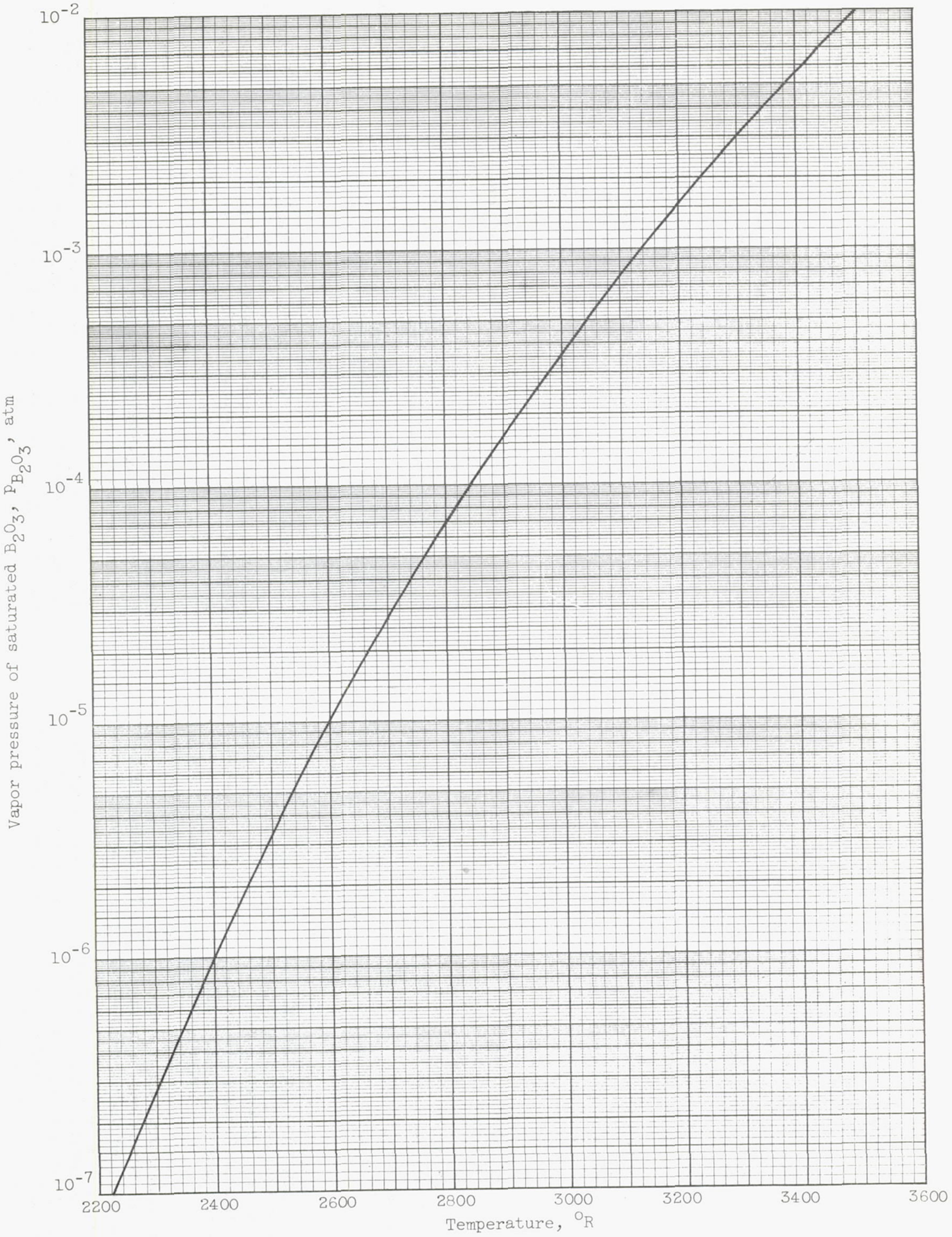


Figure 7. - Vapor pressure of saturated boron oxide B_2O_3.

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