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RESEARCH MEMORANDUM

THEORETICAL PERFORMANCE OF JP-4 FUEL AND LIQUID OXYGEN AS A ROCKET PROPELLANT

II - EQUILIBRIUM COMPOSITION

By Vearl N. Huff, Anthony Fortini, and Sanford Gordon

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NATIONAL ADVISORY COMMITTEE
FOR AERONAUTICS
WASHINGTON
September 7, 1956

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SUMMARY

Theoretical rocket performance for equilibrium composition during expansion was calculated for the propellant combination JP-4 fuel and liquid oxygen at two chamber pressures and several pressure ratios and oxidant-fuel ratios.

The parameters included are specific impulse, combustion-chamber temperature, nozzle-exit temperature, molecular weight, molecular-weight derivative, characteristic velocity, coefficient of thrust, ratio of nozzle-exit area to throat area, specific heat at constant pressure, isentropic exponent, viscosity, and thermal conductivity. A correlation is given for the effect of chamber pressure on several of the parameters.

INTRODUCTION

A continuing interest in hydrocarbon fuels and liquid oxygen as rocket propellants is assured by favorable logistics and relatively high specific impulse. Theoretical performance of several hydrocarbons with liquid oxygen is reported in the literature, for example, in references 1 to 3.

Additional computations were made for the propellant combination JP-4 fuel and liquid oxygen at the NACA Lewis laboratory between 1953 and 1955 as required for theoretical and experimental programs. These data were computed for both frozen and equilibrium composition during expansion.

The data for frozen composition during expansion are reported in reference 4. The subject report presents the data for equilibrium composition during expansion for two chamber pressures and a wide range of oxidant-fuel ratios and pressure ratios. A correlation is given that permits the determination of specific impulse, characteristic velocity, ratio of nozzle-exit area to throat area, combustion-chamber temperature, and nozzle-exit temperature for a wide range of chamber pressure. An equation is given that permits estimation of specific impulse for a change in heat of reaction of the propellant.

SYMBOLS

The following symbols are used in this report:

A	nozzle area, sq in.
a	local velocity of sound (velocity of flow at throat), ft/sec
C_F	coefficient of thrust; $C_F = g_c I/c^* = F/P_c A_t$
C_p^o	molar specific heat at constant pressure, cal/(mole)(°K)
c_p	specific heat at constant pressure, $(\partial h/\partial T)_P$, cal/(g)(°K)
c^*	characteristic velocity, $g_c P_c A_t/w$, ft/sec
F	thrust, lb
$f_1, f_2, \ldots$	functions
g_c	gravitational conversion factor, $32.174\left(\frac{\text{lb mass}}{\text{lb force}}\right)\left(\frac{\text{ft}}{\text{sec}^2}\right)$
H_T^o	sum of sensible enthalpy and chemical energy, cal/mole
h	sum of sensible enthalpy and chemical energy per unit mass $\frac{\sum_i n_i (H_T^o)_i}{M(1 - n_k)}$, cal/g
I	specific impulse, lb force-sec/lb mass
k	coefficient of thermal conductivity, cal/(sec)(cm)(°K)
M	molecular weight, $\frac{\sum_i n_i M_i}{1 - n_k}$, g/g-mole or lb/lb-mole

4040

CW-1 back

n	mole fraction
n_{c^*}	characteristic-velocity exponent, $\frac{\partial \ln c^*}{\partial \ln P_c}$
n_I	specific-impulse exponent for fixed pressure ratio, $\left(\frac{\partial \ln I}{\partial \ln P_c}\right)_{P_c/P}$
n_T	temperature exponent for fixed pressure ratio, $\left(\frac{\partial \ln T}{\partial \ln P_c}\right)_{P_c/P}$
n_ε	area-ratio exponent for fixed pressure ratio, $\left(\frac{\partial \ln \varepsilon}{\partial \ln P_c}\right)_{P_c/P}$
o/f	oxidant-to-fuel weight ratio
P	pressure, lb/sq in.
p	partial pressure, lb/sq in.
R	universal gas constant (consistent units)
r	equivalence ratio, ratio of four times the number of carbon atoms plus the number of hydrogen atoms to two times the number of oxygen atoms in propellant, $\frac{4(C) + (H)}{2(O)}$
S_T^o	entropy at pressure of 1 atmosphere, cal/(mole)(^{o}K)
s	entropy per unit mass, $\frac{\sum_i n_i(S_T^o)_i}{M(1 - n_k)} - \frac{R\sum_j p_j \ln(p_j/14.696)}{PM}$, cal/(g)(^{o}K)
T	temperature, ^{o}K
V	velocity, ft/sec
v	specific volume
w	mass-flow rate, lb/sec
γ	isentropic exponent, $\left(\frac{\partial \ln P}{\partial \ln \rho}\right)_s$

ε	ratio of nozzle area to throat area, A/A_t
μ	absolute viscosity, poises = g/(cm)(sec)
ξ	$\left(\frac{\partial \ln M}{\partial \ln T}\right)_s$, derivative of logarithm of molecular weight with respect to logarithm of temperature at constant entropy
ρ	density, lb/cu in.

Subscripts:

c	combustion chamber
e	nozzle exit
i	product of combustion including both gaseous and solid phases
inj	injector face
j	gaseous product of combustion
k	solid product of combustion (graphite)
o	conditions at 0° K
P	constant pressure
P_c/P	constant pressure ratio
s	constant entropy
t	nozzle throat
1	reference point

CALCULATION OF PERFORMANCE DATA

Performance data were obtained for two chamber pressures for a range of equivalence ratios and pressure ratios. Equilibrium composition during expansion was assumed.

The computations were carried out by means of the method described in reference 5 with modifications to adapt it for use with an IBM card-programmed electronic calculator. The machine was operated with floating-decimal-point notation and eight significant figures. The successive approximation process used in the calculations was continued until seven-figure accuracy was reached in the desired values of the assigned parameters (mass balance and pressure or entropy).

Assumptions

The calculations were based on the following usual assumptions: perfect gas law, adiabatic combustion at constant pressure, isentropic expansion, no friction, homogeneous mixing, and one-dimensional flow. The products of combustion were assumed to be graphite and the following ideal gases: atomic carbon C, methane CH_4, carbon monoxide CO, carbon dioxide CO_2, atomic hydrogen H, hydrogen H_2, water H_2O, atomic oxygen O, oxygen O_2, and the hydroxyl radical OH. The combustion products are assumed to be completely expanded within the exit nozzle; that is, ambient pressure equals exit pressure. Chemical equilibrium is assumed during the expansion process.

The graphite was assumed to be finely divided and to have the temperature and velocity of the gases during the flow process.

Initial Data

Thermodynamic data. - The thermodynamic data for all combustion products except graphite, methane, and water were taken from reference 5. Data for graphite were taken from reference 6, and for water from reference 7. Data for methane were determined by the rigid-rotator - harmonic-oscillator approximation using spectroscopic data from reference 8. The base used in this report for assigning absolute values to enthalpy is the same as in reference 5.

The heat of sublimation of graphite at 298.16° K was taken to be 171.698 kilocalories per mole (ref. 9).

Physical and thermochemical data. - The properties of the fuel used in these calculations are typical of the JP-4 fuel delivered to this laboratory over a period of 2 years. The JP-4 fuel was assumed to have a hydrogen-to-carbon weight ratio of 0.163 (atom ratio of 1.942), a lower heat of combustion value of 18,640 Btu per pound, and a specific gravity of 0.769. Additional properties of jet fuels may be found in reference 10.

Several properties of the oxidant taken from references 5, 9, and 11 are listed in table I.

Viscosity data. - The viscosity data for the individual combustion products were either taken from the literature when available or estimated.

The viscosity data for CO, CO_2, CH_4, H_2, and O_2 were calculated by the method of reference 12 using the values of the constants from table 1A of that reference.

The viscosities of C, O, H, and OH were calculated by the method of reference 13, which assumes that the logarithm of viscosity is a linear function of the logarithm of the temperature.

The viscosity of H_2O was calculated from the modified Sutherland equation given in reference 14.

Computation of Combustion Conditions

A combustion pressure was assigned (300 or 600 lb/sq in. abs). At this assigned pressure, the equilibrium composition n_i, enthalpy h (including both chemical and sensible energy), and entropy s were determined for three temperatures at 100° K intervals. The temperatures were chosen to band the value of enthalpy for the propellant mixture h_c. The formulas used to calculate h and s are

$$h = \frac{\sum_i n_i (H_T^0)_i}{M(1 - n_k)} \tag{1}$$

$$s = \frac{\sum_i n_i (S_T^0)_i}{M(1 - n_k)} - \frac{1.98718 \sum_j p_j \ln(p_j/14.696)}{PM} \tag{2}$$

Combustion composition corresponding to h_c was obtained by ordinary three-point interpolation of composition as a function of h. Entropy s_c corresponding to h_c was obtained by means of a three-point - three-slope interpolation of s as a function of h. The slope was obtained by means of the thermodynamic relation

$$\left(\frac{\partial s}{\partial h}\right)_P = \frac{1}{T} \tag{3}$$

It is convenient to treat the products of combustion (sometimes a mixture of solid graphite and ideal gases) as a single homogeneous fluid. Therefore, the molecular weight of the combustion products M is defined as the weight of a sample (including gases and solid graphite) divided by the number of moles of gas and was computed by

$$M = \frac{\sum_{i} n_i M_i}{1 - n_k} \tag{4}$$

4045

This value of M is suitable for use in the gas law

$$P = \frac{\rho R T}{M} \tag{5}$$

provided the solid phase is included in the density. Such a fluid will exhibit ideal properties as long as the volume of the gases is large with respect to the volume of the solid phase. The procedure is also consistent with the assumption that the solid particles are small enough to be considered gas molecules of extremely large molecular weight.

Computation of Exit Conditions

Calculation of parameters at assigned temperatures. - Exit temperatures were selected at 200°, 300°, or 400° K intervals to cover the range of pressure ratios from 1 to 1500. At these selected temperatures, the following data were computed assuming isentropic expansion and equilibrium composition: pressure, enthalpy, molecular weight, molecular-weight derivative, isentropic exponent, specific heat at constant pressure, absolute viscosity, thermal conductivity, nozzle-area ratio, coefficient of thrust, and specific impulse.

Interpolation of throat pressure. - A cubic equation in terms of $\ln P$ was derived from the following function and its first derivative using the data at two assigned temperatures:

$$\text{function, } f_1 = \ln f_2 = \ln\left(\frac{h}{R} + \frac{\gamma T}{2M} - \frac{h_o}{R}\right)$$

$$\text{first derivative, } \frac{df_1}{d \ln P} = \frac{T}{2Mf_2}\left(\gamma + 1 + \frac{d\gamma}{d \ln P}\right)$$

(Values for $d\gamma/d \ln P$ were found by a numerical method.)

The two temperatures were selected to band the throat temperature. The pressure at the throat was found by interpolating $\ln P$ as a function of f_1 for the point $f_1 = \ln (h_c/R - h_o/R)$. At this point the velocity of flow equals the velocity of sound.

Interpolation of enthalpy. - Enthalpies were interpolated for a series of pressures including the throat pressure by means of quartic equations in terms of ln P. Each of the quartic equations used was derived from data at two successive assigned temperatures and used to interpolate those points within the temperature interval. The data used in forming each quartic were the following function at one of the assigned temperatures and its first and second derivatives at both assigned temperatures:

$$\text{function, } f_3 = \frac{h}{R}$$

$$\text{first derivative, } \frac{df_3}{d \ln P} = \frac{T}{M}$$

$$\text{second derivative, } \frac{d^2 f_3}{(d \ln P)^2} = \frac{T}{M}\left(\frac{\gamma - 1}{\gamma}\right)$$

Interpolation of temperature. - Temperatures were interpolated for a series of pressures including the throat pressure by means of cubic equations in terms of ln P. Each of the cubic equations used was derived from data at two successive assigned temperatures and used to interpolate those points within the temperature interval. The data used in forming each cubic were the following function and its derivative at both assigned temperatures:

$$\text{function, } f_4 = \ln T$$

$$\text{first derivative, } f_5 = \frac{df_4}{d \ln P} = \left(\frac{\gamma - 1}{\gamma}\right)\left(\frac{1}{1 - \xi}\right)$$

Interpolation of molecular weight. - Molecular weights were interpolated similarly to temperatures using the following function and derivative:

$$\text{function, } f_6 = \ln M$$

$$\text{first derivative, } \frac{df_6}{d \ln P} = \xi f_5 = \left(\frac{\gamma - 1}{\gamma}\right)\left(\frac{\xi}{1 - \xi}\right)$$

Interpolation of specific heat, isentropic exponent, and molecular-weight derivative. - Specific heats were interpolated for a series of pressures including the throat pressure by means of cubic equations in terms of ln P. Each of the cubic equations used was derived from values of specific heat for four successive temperatures and used to interpolate those points within the interval of the two middle temperatures. Isentropic exponents and molecular-weight derivatives were interpolated in a manner similar to that for specific heats.

Accuracy of interpolation. - The errors due to interpolation were checked for several cases. The values presented for enthalpy, entropy, and specific impulse appear to be correctly computed to all figures tabulated. The temperature and molecular weight may in some cases be in error by a few figures in the last place tabulated. The derivatives may, in regions where they are changing rapidly, be in error by a few percent. However, because of uncertainties in thermodynamic data used, all values are probably tabulated to more places than are entirely significant.

Formulas

The formulas used in computing the various performance parameters as are follows:

Specific impulse, lb force-sec/lb mass

$$I = 294.98\sqrt{\frac{h_c - h_e}{1000}} \tag{6}$$

Throat area per unit mass-flow rate, (sq in.)(sec)/lb

$$\frac{A_t}{w} = \frac{2781.6\ T_t}{P_t M_t a} \tag{7}$$

Characteristic velocity, ft/sec

$$c^* = g_c P_c\left(\frac{A_t}{w}\right) = 32.174\ P_c\left(\frac{A_t}{w}\right) \tag{8}$$

Coefficient of thrust

$$C_F = \frac{g_c I}{c^*} = \frac{32.174\ I}{c^*} \tag{9}$$

Nozzle area per unit mass-flow rate, (sq in.)(sec)/lb

$$\frac{A}{w} = \frac{86.455\ T}{PMI} \tag{10}$$

Ratio of nozzle area to throat area

$$\varepsilon = \frac{A/w}{A_t/w} \tag{11}$$

Specific heat at constant pressure, cal/(g)(°K)

$$c_p = \left(\frac{\partial h}{\partial T}\right)_P = \frac{C_p^o}{M(1 - n_k)} \tag{12}$$

where C_p^o is given by equation (37) of reference 5.

Isentropic exponent

$$\gamma = \left(\frac{\partial \ln P}{\partial \ln \rho}\right)_s = \frac{a^2 M}{RT} \tag{13}$$

where a^2 is given by equation (32) of reference 5.

Absolute viscosity, poises

$$\mu = \frac{PM}{\sum\limits_j \dfrac{p_j}{\mu_j/M_j}} \tag{14}$$

Molecular-weight derivative

$$\xi = \left(\frac{\partial \ln M}{\partial \ln T}\right)_s = D_A - \frac{\sum\limits_i p_i D_i}{P} \tag{15}$$

where D_A and D_i have the definitions of ref. 5.

Coefficient of thermal conductivity, cal/(sec)(cm)(°K)

$$k = \mu\left(c_p + \frac{5}{4}\frac{R}{M}\right) \tag{16}$$

The values of viscosity and thermal conductivity for mixtures of combustion gases calculated by means of equations (14) and (16) are only approximate. When more reliable transport properties for the various products of combustion become available, a more rigorous procedure for computing the properties of mixtures may also be justified. When solid graphite was present among the combustion products, it was omitted from equation (14).

THEORETICAL PERFORMANCE DATA

Tables. - The calculated values of the performance parameters and equilibrium composition of the combustion products are given in tables II to VII. The properties of gases in the combustion chamber and the characteristic velocity are given in table II for each chamber pressure and equivalence ratio. Table III presents the values of performance parameters at assigned temperatures and constant entropy. These values were computed directly and used to interpolate properties for assigned pressure ratios. The values of viscosity and thermal conductivity of the mixture are also given in this table as a function of temperature.

4045

The performance parameters for small pressure ratios from 1 to 8 are given in table IV. These properties permit computations within the rocket nozzle and for finite combustion-chamber diameters. Properties at the throat may be found where $\varepsilon = 1.000$. The values adjacent to the throat correspond to pressures 1.2 and 0.8 times the throat pressure.

CW-2 back

The performance parameters for pressure ratios from 10 to 1500 are given in table V. This table gives sufficient data to permit interpolation of complete data for any pressure ratio within the range tabulated.

The performance parameters are summarized in table VI for expansion from chamber pressure to 1 atmosphere. The maximum values calculated for specific impulse for chamber pressures of 600 and 300 pounds per square inch absolute are 284.9 and 260.8, respectively.

Table VII presents the composition of the combustion products at the combustion temperature and various assigned temperatures at constant entropy.

Curves. - The performance parameters are plotted in figures 1 to 6 for chamber pressures of 600 and 300 pounds per square inch absolute.

Curves of specific impulse are presented in figure 1 for pressure ratios from 10 to 1500 as functions of weight percent fuel. The location of the maximum values shifts from about 31 percent fuel at the low pressure ratios to about 26 percent fuel at the higher pressure ratios. The exponent n_I is also shown.

Curves of combustion-chamber temperature and nozzle-exit temperature for pressure ratios from 10 to 1500 are plotted in figure 2 as functions of weight percent fuel. The exponent n_T is also shown.

Curves of the ratio of nozzle area to throat area are plotted in figure 3 for pressure ratios from 10 to 1500 as functions of weight percent fuel. The exponent n_ε is also shown.

Figures 4 and 5 give the curves for coefficient of thrust and molecular weight, respectively, for pressure ratios from 10 to 1500 as functions of weight percent fuel.

Figure 6 presents curves of characteristic velocity as functions of weight percent fuel. Also shown is the exponent n_{c*}.

Effect of solid graphite. - The theoretical calculations of equilibrium composition in the combustion chamber showed that solid graphite was not present for the equivalence ratios of 1 to 2 (weight percent fuel, 22.71 to 37.01) and was present for an equivalence ratio of 3. The appearance of solid graphite affected the values of the thermodynamic parameters and resulted in a break in the performance data in the region of equivalence ratios between 2 and 3. The performance at an equivalence ratio of 3 was not plotted in figures 1 to 6 but is presented in tables II to VII.

Effect of assuming frozen or equilibrium composition. - The assumption of whether the composition remains constant during the expansion process (frozen) or is in continuous equilibrium affects the values of the performance parameters. Figure 7 compares the values of specific impulse assuming equilibrium composition (this report) and frozen composition (ref. 4). The maximum value of specific impulse for a chamber pressure of 600 pounds per square inch absolute and a pressure ratio of 40.83 is 284.9 for equilibrium composition and 271.8 for frozen composition, a difference of 4.8 percent. The maximum specific impulse occurs at about 29 and 32 percent fuel for equilibrium and frozen composition, respectively.

An example of the large effect of change of composition on specific heat and isentropic exponent is given in figures 8(a) and (b). For the stoichiometric equivalence ratio, the value for specific heat assuming equilibrium composition is, at the higher temperatures, almost four times the value assuming frozen composition. This large difference in specific heat is due primarily to the chemical energy associated with the change of composition with temperature. The value for isentropic exponent at the higher temperatures is about 5 to 10 percent greater for frozen composition than for equilibrium composition.

Chamber-pressure effect. - By use of suitable derivatives, performance parameters can be estimated with good accuracy at chamber pressures other than those given in this report. Derivatives which permit the calculation of I, T, ε, and $c*$ at various chamber pressures for fixed pressure ratios and equivalence ratios were obtained from the following equations:

$$n_I = \left(\frac{\partial \ln I}{\partial \ln P_c}\right)_{P_c/P} = 86.4554 \frac{T}{I^2}\left(\frac{1}{M_c} - \frac{1}{M}\right) \qquad (17)$$

$$n_T = \left(\frac{\partial \ln T}{\partial \ln P_c}\right)_{P_c/P} = \left(\frac{\gamma - 1}{\gamma}\right)\left(\frac{1}{1 - \xi}\right) - \frac{R}{M_c c_p} \tag{18}$$

$$n_\varepsilon = \left(\frac{\partial \ln \varepsilon}{\partial \ln P_c}\right)_{P_c/P} = (n_{A/w})_e - (n_{A/w})_t \tag{19}$$

where $n_{A/w} = \left(\frac{\partial \ln A/w}{\partial \ln P_c}\right)_{P_c/P} = -\left(\frac{M}{M_c}\right)\left(\frac{\gamma - 1}{\gamma}\right)\left(\frac{1}{1 - \xi}\right) - \frac{1}{\gamma} - n_I$

$$n_{c*} = \frac{\partial \ln c^*}{\partial \ln P_c} = 1 + (n_{A/w})_t \tag{20}$$

These equations, which were derived analytically from thermodynamic relations, are valid only for chemical equilibrium during expansion. The equations may be written in the approximate form:

$$I = I_1\left(\frac{P_c}{P_{c,1}}\right)^{n_{I,1}} \tag{21}$$

$$T = T_1\left(\frac{P_c}{P_{c,1}}\right)^{n_{T,1}} \tag{22}$$

$$\varepsilon = \varepsilon_1\left(\frac{P_c}{P_{c,1}}\right)^{n_{\varepsilon,1}} \tag{23}$$

$$c^* = c^*_1\left(\frac{P_c}{P_{c,1}}\right)^{n_{c^*,1}} \tag{24}$$

where $P_{c,1}$ may be selected to be either 300 or 600 pounds per square inch absolute provided that I_1, T_1, ε_1, c^*_1, and their derivatives are the corresponding values for the chamber pressure selected.

The derivatives obtained by means of equations (17) to (20) are shown in tables II to V and are plotted in figures 1, 2, 3, and 6.

To illustrate the use of these derivatives, suppose it is desired to obtain the value of specific impulse for a chamber pressure of 450 pounds per square inch absolute and a pressure ratio of 30.62 (exit pressure, 1 atm) for an equivalence ratio r of 1.4 (29.15 weight percent fuel). From figure 1(b) and table V, the value of I at this pressure ratio and equivalence ratio (but for a chamber pressure of 300 lb/sq in. abs) is 274.5 and the value of n_I is 0.0084. From equation (21),

$$
\begin{aligned}
I &= 274.5\left(\frac{450}{300}\right)^{0.0084} \\
&= 274.5\ (1.0034) \\
&= 275.4
\end{aligned}
$$

4045

A comparison of the parameters obtained by means of the chamber-pressure correlation and by a direct calculation for two examples is given in the following table ($r = 1.4$ (29.15 weight percent fuel)):

Parameter	P_c = 450 lb/sq in. abs P_e = 1 atm			P_c = 1200 lb/sq in. abs P_e = 1 atm		
	Estimated by correlation	Direct calculation	Error	Estimated by correlation	Direct calculation	Error
I	275.44	275.43	0.01	304.98	304.91	0.07
T_c	3537.6	3536.8	.8	3672.2	3670.5	1.7
T_e	2472.9	2470.6	2.3	2111.9	2112.8	.9
ε	5.383	5.374	.009	10.900	10.894	.006
c^*	5886.1	5885.3	.8	5948.9	5946.3	2.6

It is expected that values estimated for other equivalence ratios and pressure ratios for any chamber pressure from about 150 to 1200 pounds per square inch absolute will have small errors of the order of magnitude shown in the previous table. A possible exception might occur when the value of the exponent is changing rapidly, such as in the region where solid graphite first appears.

Estimated performance of JP-4 fuel with ozone or oxygen-ozone mixtures. - The change in specific impulse due to a change in the heat content of the propellants or combustion products may be estimated from the following equation:

$$
I^2 = I_1^2 + B\,\Delta h_c + C(\Delta h_c)^2 \tag{25}
$$

where Δh_c is the change in the heat content,

$$B = 87.0132 \left(1 - \frac{T_e}{T_c}\right)_1$$

$$C = \frac{87.0132}{2}\left(\frac{T_e}{T_c^2}\right)_1 \left[\frac{1}{(c_p)_c} - \frac{1}{(c_p)_e}\right]_1$$

and the subscript 1 indicates the values of the parameters before the change is made. For example, assume that the performance is desired for JP-4 fuel and a mixture of 20 percent liquid ozone and 80 percent liquid oxygen by weight at an equivalence ratio of 1.4, a combustion pressure of 600 pounds per square inch absolute, and a pressure ratio of 40. The reaction may be written

$$CH_{1.942} + 0.8489\ O_2 + 0.1415\ O_3 \tag{26}$$

From reference 5, the difference in heat content between oxygen and ozone is 34,853 calories per mole of ozone. Therefore, Δh_c is 102.9 calories per gram of propellant (fuel plus oxidant).

From tables II and V(a) or figures 1(a) and 2(a), the values of the parameters are

$$I_1 = 284.3$$

$$T_{c,1} = 3576$$

$$T_{e,1} = 2378$$

$$(c_p)_{c,1} = 1.520$$

$$(c_p)_{e,1} = 0.580$$

These values yield the following:

$$I_1^2 = 80,826$$

$$B = 29.15$$

$$C = -0.00863$$

By equation (25),

$$I^2 = 80{,}826 + 29.15(102.9) + (-0.00863)(10{,}588)$$

$$= 80{,}826 + 3000 - 91 = 83{,}735$$

$$I = 289.37$$

This compares to a value of 289.39 obtained by a direct calculation. It is expected that estimates made for higher percentages of ozone in the oxidant mixture will have somewhat higher errors.

Equation (25) was used to obtain the variation of specific impulse with percent ozone in the oxidant for an equivalence ratio of 1.4, a chamber pressure of 600 pounds per square inch absolute, and an exit pressure of 1 atmosphere. The results are shown in figure 9.

Use of derivatives. - The derivatives of the fundamental thermodynamic quantities have many useful applications. Equations (21) to (25) are examples of these applications.

All the relations between the first derivatives may be expressed in terms of three arbitrary first derivatives in addition to the fundamental quantities (ref. 15). Reference 15 presents a convenient scheme for expressing all first derivatives in terms of $(\partial v/\partial T)_P$, $(\partial v/\partial P)_T$, and $(\partial h/\partial T)_P = c_p$. In order to make use of the tables in reference 15, $(\partial v/\partial T)_P$ and $(\partial v/\partial P)_T$ can be obtained from the data in this report by means of the following equations:

$$\left(\frac{\partial v}{\partial T}\right)_P = \left(\frac{c_p}{P}\right)\left(\frac{\gamma - 1}{\gamma}\right)\left(\frac{1}{1 - \xi}\right) \tag{27}$$

$$\left(\frac{\partial v}{\partial P}\right)_T = -\frac{T}{c_p}\left(\frac{\partial v}{\partial T}\right)_P^2 - \frac{v}{\gamma P} \tag{28}$$

The dimensions of specific volume v in equations (27) and (28) which result from using the dimensions assigned to the other variables in this report are (cal)(sq in.)/(g)(lb force). For certain applications involving these derivatives, the dimensions of v are unimportant inasmuch as they will cancel. However, a conversion factor may be used, when desired, to obtain any dimension for v. For example, 1(cal)(sq in.)/(g)(lb force) equals 606.84 cu cm/g.

Effect of finite chamber area. - The use of a combustion chamber of finite cross-sectional area leads to a pressure change across the combustion process. For a cylindrical chamber, the injector face pressure P_{inj} may be found from the following equation for conservation of momentum.

$$P_{inj} = P_1 + \frac{w}{A_1 g_c} (V_1 - V_{inj}) \tag{29}$$

where P_1 and V_1 are the static pressure and velocity at the nozzle entrance, respectively, and V_{inj} is the average velocity of propellant (liquid or gas) in the axial direction when injected. Equation (29) may be written

$$P_{inj} = P_c\left(\frac{P_1}{P_c}\right) + \frac{P_c}{c^* \varepsilon} (I_1 g_c - V_{inj}) \tag{30}$$

where P_c is the stagnation pressure in the nozzle.

The data tabulated in tables II and IV may be used to evaluate this expression. For example, the pressure at the face of the injector of a rocket operating at the stoichiometric ratio with a nozzle stagnation pressure of 600 pounds per square inch absolute and a chamber-to-throat area ratio of 1.24 with V_{inj} equal to 100 feet per second is

$$\begin{aligned} P_{inj} &= 600 \frac{1}{1.2} + \frac{600}{5622(1.24)} (66.5 \times 32.2 - 100) \\ &= 500 + 0.0861\ (2041) \\ &= 500 + 175.7 \\ &= 675.7 \text{ lb/sq in. abs} \end{aligned}$$

SUMMARY OF RESULTS

A theoretical investigation of the performance of JP-4 fuel with liquid oxygen as an oxidant was made for the following conditions: (1) equivalence ratios from 1 to 3, (2) chamber pressures of 300 and 600 pounds per square inch, (3) pressure ratios from 1 to 1500, and (4) equilibrium composition during expansion.

The results of the investigation are as follows:

1. The maximum values of specific impulse for chamber pressures of 600 and 300 pounds per square inch absolute (40.83 and 20.41 atm) and an exit pressure of 1 atmosphere were 284.9 and 260.8, respectively.

2. The data presented in this report permit interpolation of complete performance data for equivalence ratios from 1 to 2, chamber pressures from 150 to 1200 pounds per square inch absolute, and pressure ratios up to 1500.

Lewis Flight Propulsion Laboratory
National Advisory Committee for Aeronautics
Cleveland, Ohio, May 17, 1956

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TABLE I. - PROPERTIES OF LIQUID OXYGEN

Molecular weight, M	32.00
Density, g/cc	[a]1.1415
Freezing point, °C	[b]-218.76
Boiling point, °C	[b]-182.97
Enthalpy required to convert liquid at boiling point to gas at 25° C, kcal/mole	[c]3.080
Enthalpy of vaporization, kcal/mole	[d]1.630
Enthalpy of fusion, kcal/mole	[e]0.106

[a] At -182.0° C; ref. 11.

[b] Ref. 9.

[c] Ref. 5.

[d] At -182.97° C; ref. 9.

[e] At -218.76° C; ref. 9.

TABLE II. - THERMODYNAMIC PROPERTIES OF COMBUSTION GASES FOR JP-4 FUEL AND LIQUID OXYGEN

Equivalence ratio, r, $\frac{4(C) + (H)}{2(O)}$	Percent fuel by weight	Oxidant to fuel weight ratio, o/f	Temperature, T, °K	Temperature exponent, n_T	Molecular weight, M	Enthalpy, h, cal/g (a)	Entropy, s, $\frac{cal}{(g)(°K)}$	Specific heat, c_p, $\frac{cal}{(g)(°K)}$ (b)	Isentropic exponent, γ (b)	Characteristic velocity exponent, n_{c^*} (b)	Characteristic velocity, c^*, ft/sec (b)
Combustion-chamber pressure, 600 lb/sq in. abs											
1.00	22.71	3.403	3612	0.0426	25.48	2531.6	2.5729	1.845	1.128	0.0127	5622
1.20	26.07	2.836	3628	.0422	24.03	2901.1	2.6815	1.818	1.131	.0125	5795
1.30	27.64	2.618	3612	.0408	23.36	3074.1	2.7297	1.700	1.134	.0119	5859
1.40	29.15	2.431	3576	.0382	22.70	3239.9	2.7740	1.520	1.139	.0110	5904
1.50	30.59	2.269	3518	.0344	22.05	3399.0	2.8146	1.283	1.146	.0092	5924
1.60	31.98	2.127	3436	.0290	21.41	3551.6	2.8515	1.089	1.156	.0069	5918
1.80	34.59	1.891	3205	.0187	20.17	3839.4	2.9142	.798	1.184	.0031	5832
2.00	37.01	1.702	2923	.0099	19.03	4105.8	2.9627	.653	1.215	.0009	5679
3.00	46.85	1.134	1657	.0264	15.49	5188.4	3.0102	.701	1.285	.0114	4674
Combustion-chamber pressure, 300 lb/sq in. abs											
1.00	22.71	3.403	3507	0.0432	25.24	2531.6	2.6273	2.012	1.124	0.0129	5572
1.20	26.07	2.836	3523	.0425	23.80	2901.1	2.7391	1.996	1.127	.0128	5745
1.30	27.64	2.618	3511	.0418	23.14	3074.1	2.7889	1.887	1.131	.0124	5810
1.40	29.15	2.431	3482	.0396	22.50	3239.9	2.8349	1.707	1.135	.0116	5859
1.50	30.59	2.269	3433	.0360	21.88	3399.0	2.8773	1.472	1.140	.0100	5886
1.60	31.98	2.127	3363	.0315	21.27	3551.6	2.9160	1.233	1.149	.0080	5888
1.80	34.59	1.891	3160	.0215	20.09	3839.4	2.9826	.880	1.176	.0040	5818
2.00	37.01	1.702	2900	.0123	18.99	4105.8	3.0351	.696	1.207	.0014	5674

[a] The base used for enthalpy is given in ref. 5.

[b] Parameter includes energy due to change in composition.

TABLE III. - THEORETICAL ROCKET PERFORMANCE AT ASSIGNED TEMPERATURES FOR JP-4 FUEL AND LIQUID OXYGEN

[Equilibrium composition during isentropic expansion or compression from combustion conditions.]

(a) Combustion-chamber pressure, 600 pounds per square inch absolute

Temperature, T, °K	Pressure, P, lb/sq in. abs	Enthalpy, h, cal/g	Molecular weight, M	Partial derivative, $\left(\frac{\partial \ln M}{\partial \ln T}\right)_s$	Isentropic exponent, γ, $\left(\frac{\partial \ln P}{\partial \ln \rho}\right)_s$	Specific heat, c_p, $\frac{cal}{(g)(^\circ K)}$	Absolute viscosity, μ, micropoises	Thermal conductivity, k, cal/(sec)(cm)(°K)	Area ratio, ϵ	Thrust coefficient, C_F	Specific impulse, I, $\frac{lb\text{-}sec}{lb}$
r = 1.0; O/F = 3.403; percent fuel = 22.71											
4000	1898.3	2878.7	24.649	-.3198	1.1389	1.7578	997	0.00185	----------	-------	--------
3600	576.23	2520.2	25.513	-.3333	1.1272	1.8470	921	.00179	2.312	0.180	31.4
3200	134.29	2142.8	26.547	-.3397	1.1158	1.8910	843	.00167	1.449	1.053	183.9
2800	22.297	1749.4	27.769	-.3307	1.1057	1.8292	763	.00146	5.146	1.493	260.9
2400	2.497	1352.6	29.139	-.2870	1.0992	1.5619	680	.00118	30.570	1.833	320.3
2000	.211	990.5	30.422	-.1753	1.1055	1.0305	596	.00066	258.02	2.096	366.2
1600	.022	728.9	31.099	-.0376	1.1498	.5328	504	.00031	1718.1	2.267	396.0
900	.001	444.4	31.204	-.0000	1.2171	.3571	339	.00015	33282.	2.439	426.2
r = 1.2; o/f = 2.836; percent fuel = 26.07											
4000	1755.7	3244.6	23.302	-.3133	1.1413	1.7758	981	0.00185	----------	-------	--------
3600	548.54	2874.4	24.095	-.3206	1.1302	1.8191	907	.00174	1.626	0.268	48.3
3200	135.33	2489.9	25.017	-.3139	1.1202	1.7656	831	.00155	1.439	1.050	189.2
2800	25.883	2104.0	26.026	-.2687	1.1150	1.4847	753	.00119	4.545	1.468	263.4
2400	4.562	1764.7	26.866	-.1290	1.1324	.8586	675	.00064	17.934	1.746	314.5
2000	1.102	1534.3	27.150	-.0160	1.1820	.4929	597	.00035	55.823	1.915	344.9
1600	.276	1352.3	27.183	-.0009	1.1995	.4405	514	.00027	167.59	2.038	367.1
1200	.049	1177.6	27.184	-.0000	1.2007	.4373	421	.00022	664.14	2.150	387.3
900	.009	1044.5	27.184	-.0000	1.1924	.4530	342	.00019	2757.3	2.231	401.9
r = 1.3; o/f = 2.618; percent fuel = 27.64											
4000	1787.0	3432.6	22.646	-.3015	1.1438	1.7138	974	0.00177	----------	-------	--------
3600	578.52	3063.0	23.379	-.3006	1.1337	1.6977	901	.00162	2.431	0.171	31.2
3200	153.69	2686.9	24.194	-.2759	1.1264	1.5375	827	.00136	1.335	1.008	183.6
2800	35.125	2329.3	24.985	-.1949	1.1295	1.1272	751	.00092	3.570	1.398	254.6
2400	8.693	2043.0	25.478	-.0654	1.1610	.6547	676	.00050	10.305	1.645	299.5
2000	2.543	1832.7	25.617	-.0097	1.1959	.4840	599	.00035	26.609	1.805	328.7
1600	.676	1648.3	25.637	-.0007	1.2075	.4517	511	.00028	74.711	1.934	352.2
1200	.127	1467.8	25.638	-.0000	1.2050	.4557	418	.00023	281.81	2.053	373.9
900	.022	1327.5	25.638	-.0000	1.1902	.4849	343	.00020	1154.1	2.141	389.8
r = 1.4; o/f = 2.431; percent fuel = 29.15											
3600	642.97	3261.7	22.655	-.2714	1.1391	1.5265	897	0.00147	----------	-------	--------
3200	188.86	2902.1	23.338	-.2265	1.1361	1.2826	824	.00115	1.197	0.934	171.5
2800	52.357	2578.4	23.912	-.1320	1.1482	.8869	751	.00074	2.635	1.307	239.9
2400	15.960	2323.1	24.212	-.0410	1.1806	.5898	678	.00047	6.217	1.539	282.4
2000	5.113	2118.2	24.298	-.0070	1.2066	.4852	601	.00035	14.567	1.703	312.4
1600	1.425	1930.8	24.312	-.0005	1.2154	.4617	517	.00029	38.681	1.839	337.5
1200	.279	1745.5	24.313	-.0000	1.2104	.4702	423	.00024	138.72	1.965	360.6
900	.050	1599.7	24.313	-.0000	1.1917	.5082	345	.00021	551.39	2.059	377.8
r = 1.6; o/f = 2.127; percent fuel = 31.98											
3600	906.91	3687.1	21.218	-.2007	1.1554	1.1842	893	0.00116	----------	-------	--------
3200	328.53	3367.2	21.653	-.1407	1.1613	.9387	823	.00087	1.001	0.689	126.7
2800	118.890	3089.4	21.956	-.0707	1.1804	.7005	753	.00061	1.508	1.090	200.6
2400	44.037	2856.5	22.104	-.0238	1.2062	.5547	680	.00045	2.827	1.337	245.9
2000	15.629	2652.2	22.151	-.0043	1.2248	.4936	603	.00037	5.823	1.521	279.8
1800	8.837	2555.1	22.157	-.0014	1.2294	.4822	562	.00033	8.804	1.601	294.5
1600	4.710	2459.3	22.159	-.0003	1.2312	.4780	517	.00030	14.022	1.676	308.3
1400	2.310	2363.6	22.160	-.0001	1.2297	.4801	474	.00028	23.985	1.748	321.5
1200	1.005	2266.7	22.160	-.0000	1.2236	.4907	426	.00026	45.468	1.818	334.4
1000	.362	2166.4	22.160	-.0000	1.2104	.5159	374	.00024	101.28	1.887	347.2
r = 1.8; o/f = 1.891; percent fuel = 34.59											
3600	1413.2	4128.5	19.890	-.1437	1.1748	0.9704	891	0.00098	----------	-------	--------
3200	593.22	3835.8	20.170	-.0941	1.1847	.7954	824	.00076	4.333	0.097	17.7
2800	245.81	3576.7	20.357	-.0468	1.2033	.6452	754	.00058	1.059	.834	151.2
2400	100.02	3349.2	20.449	-.0160	1.2249	.5488	682	.00046	1.626	1.139	206.5
2000	37.910	3142.3	20.479	-.0031	1.2407	.5036	605	.00038	2.993	1.359	246.3
1600	12.164	2944.6	20.485	-.0002	1.2466	.4906	521	.00032	6.585	1.539	279.0
1200	2.808	2746.9	20.485	-.0000	1.2388	.5032	428	.00027	19.363	1.701	308.3
900	.594	2590.2	20.492	-.0069	1.2131	.5617	350	.00024	64.211	1.819	329.7
r = 3.0; o/f = 1.134; percent fuel = 46.85											
1800	883.10	5274.2	15.429	-.0384	1.2932	0.6508	567	0.00046	----------	-------	--------
1600	506.25	5152.9	15.527	-.0735	1.2787	.7384	526	.00047	1.309	0.382	55.5
1400	247.22	5016.7	15.752	-.1491	1.2385	1.0099	484	.00056	1.050	.841	122.2
1200	82.492	4840.6	16.278	-.2808	1.1771	1.8389	443	.00088	1.834	1.197	174.0
1000	12.191	4593.8	17.350	-.4051	1.1270	3.5681	407	.00151	7.421	1.566	227.5
900	2.931	4442.5	18.143	-.4369	1.1099	4.4190	389	.00177	23.717	1.754	254.8

TABLE III. - Concluded. THEORETICAL ROCKET PERFORMANCE AT ASSIGNED TEMPERATURES FOR JP-4 FUEL AND LIQUID OXYGEN

[Equilibrium composition during isentropic expansion or compression from combustion conditions.]

(b) Combustion-chamber pressure, 300 pounds per square inch absolute

Temperature, T, °K	Pressure, P, lb/sq in. abs	Enthalpy, h, cal/g	Molecular weight, M	Partial derivative, $\left(\frac{\partial \ln M}{\partial \ln T}\right)_s$	Isentropic exponent, γ, $\left(\frac{\partial \ln P}{\partial \ln \rho}\right)_s$	Specific heat, c_p, $\frac{cal}{(g)(^{\circ}K)}$	Absolute viscosity, μ, micropoises	Thermal conductivity, k, $\frac{cal}{(sec)(cm)(^{\circ}K)}$	Area ratio, ε	Thrust coefficient, C_F	Specific impulse, I, $\frac{lb\text{-}sec}{lb}$
r = 1.0; o/f = 3.403; percent fuel = 22.71											
3600	411.50	2620.4	25.006	-.3494	1.1272	1.9919	927	0.00193	———	———	———
3200	93.808	2229.9	26.072	-.3579	1.1153	2.0566	847	.00182	1.209	0.936	162.0
2800	14.956	1820.8	27.345	-.3526	1.1044	2.0155	766	.00161	4.123	1.436	248.7
2600	5.088	1612.1	28.057	-.3397	1.0999	1.9216	725	.00146	9.644	1.633	282.9
2400	1.547	1404.2	28.804	-.3150	1.0966	1.7550	682	.00125	25.752	1.808	313.2
2200	.427	1202.6	29.553	-.2722	1.0958	1.5029	640	.00102	76.793	1.964	340.1
2000	.112	1016.4	30.239	-.2062	1.0999	1.1757	597	.00075	242.59	2.097	363.1
1800	.031	857.5	30.767	-.1283	1.1139	.8327	554	.00051	736.55	2.204	381.7
r = 1.2; o/f = 2.836; percent fuel = 26.07											
3600	386.48	2976.7	23.630	-.3403	1.1296	1.9913	912	0.00191	———	———	———
3200	92.217	2575.8	24.598	-.3386	1.1187	1.9710	834	.00173	1.218	0.942	168.2
3000	40.364	2371.2	25.134	-.3284	1.1142	1.8919	795	.00158	2.000	1.203	214.7
2800	16.420	2167.4	25.692	-.3056	1.1112	1.7317	755	.00138	3.816	1.415	252.7
2600	6.328	1970.4	26.240	-.2599	1.1116	1.4551	716	.00111	7.993	1.594	284.6
2400	2.451	1792.3	26.711	-.1785	1.1206	1.0620	676	.00078	17.147	1.740	310.6
2200	1.052	1648.4	27.009	-.0810	1.1456	.6975	637	.00050	34.054	1.849	330.2
2000	.512	1537.2	27.133	-.0247	1.1753	.5191	597	.00036	60.727	1.929	344.5
1800	.258	1442.0	27.171	-.0064	1.1919	.4608	556	.00031	104.66	1.996	356.3
1600	.126	1352.4	27.182	-.0014	1.1990	.4419	509	.00027	185.65	2.056	367.1
r = 1.3; o/f = 2.618; percent fuel = 27.64											
3600	399.84	3162.2	22.953	-.3248	1.1324	1.8925	906	0.00181	———	———	———
3200	101.18	2765.8	23.832	-.3090	1.1234	1.7702	830	.00156	1.164	0.907	163.8
2800	20.851	2378.5	24.744	-.2419	1.1219	1.3671	753	.00111	3.168	1.362	246.0
2400	4.404	2057.8	25.402	-.0959	1.1484	.7576	677	.00057	10.361	1.647	297.4
2200	2.253	1937.5	25.546	-.0405	1.1729	.5788	638	.00043	17.454	1.741	314.5
2000	1.198	1834.5	25.607	-.0143	1.1919	.4978	599	.00036	28.501	1.819	328.4
1800	.630	1739.7	25.630	-.0042	1.2024	.4650	558	.00031	47.007	1.887	340.8
1600	.315	1648.4	25.637	-.0009	1.2071	.4527	511	.00028	80.848	1.950	352.2
1200	.059	1467.8	25.638	-.0000	1.2049	.4557	418	.00023	305.17	2.070	373.9
r = 1.4; o/f = 2.431; percent fuel = 29.15											
3600	432.87	3354.7	22.278	-.3015	1.1366	1.7397	901	0.00166	———	———	———
3200	118.87	2970.2	23.045	-.2670	1.1307	1.5171	827	.00134	1.086	0.841	153.2
2800	29.320	2613.7	23.751	-.1753	1.1376	1.0652	752	.00088	2.454	1.282	233.4
2400	7.971	2332.5	24.166	-.0592	1.1705	.6475	678	.00050	6.316	1.543	281.0
2000	2.446	2119.5	24.292	-.0100	1.2036	.4947	601	.00036	15.355	1.715	312.2
1800	1.322	2023.9	24.307	-.0031	1.2116	.4714	560	.00032	24.529	1.786	325.3
1600	.676	1930.9	24.312	-.0007	1.2151	.4625	517	.00029	41.059	1.853	337.5
1400	.318	1838.6	24.313	-.0001	1.2149	.4621	471	.00027	73.793	1.918	349.2
1200	.132	1745.5	24.313	-.0000	1.2104	.4702	420	.00024	147.33	1.980	360.6
r = 1.5; o/f = 2.269; percent fuel = 30.59											
3600	487.38	3554.9	21.607	-.2717	1.1424	1.5605	898	0.00150	———	———	———
3200	147.83	3187.6	22.252	-.2210	1.1407	1.2820	825	.00115	1.017	0.741	135.6
2800	43.040	2861.0	22.780	-.1270	1.1545	.8860	753	.00075	1.871	1.183	216.4
2400	13.644	2601.9	23.061	-.0423	1.1866	.6041	679	.00048	4.106	1.440	263.4
2000	4.498	2392.1	23.149	-.0078	1.2136	.4963	602	.00036	9.202	1.618	296.0
1800	2.486	2295.5	23.160	-.0025	1.2203	.4779	561	.00033	14.305	1.694	309.9
1600	1.299	2200.9	23.164	-.0006	1.2231	.4710	518	.00030	23.352	1.765	322.9
1400	.624	2106.8	23.165	-.0001	1.2222	.4719	473	.00027	40.935	1.833	335.3
1200	.265	2011.6	23.165	-.0000	1.2167	.4817	425	.00025	79.651	1.899	347.4
900	.050	1861.7	23.165	-.0000	1.1956	.5244	346	.00022	304.18	1.999	365.7
r = 1.6; o/f = 2.127; percent fuel = 31.98											
3600	569.87	3761.9	20.948	-.2389	1.1497	1.3866	895	0.00135	———	———	———
3200	190.72	3413.4	21.477	-.1799	1.1521	1.1045	825	.00101	1.010	0.599	109.7
2800	63.150	3109.5	21.876	-.0965	1.1696	.7889	753	.00068	1.465	1.072	196.1
2400	22.043	2862.0	22.081	-.0327	1.1992	.5842	680	.00047	2.653	1.339	245.0
2000	7.647	2653.0	22.148	-.0062	1.2227	.4996	603	.00037	5.985	1.528	279.6
1800	4.309	2555.3	22.156	-.0020	1.2286	.4842	562	.00034	9.076	1.609	294.4
1600	2.294	2459.3	22.159	-.0004	1.2309	.4785	519	.00031	14.471	1.685	308.3
1400	1.125	2363.6	22.160	-.0001	1.2297	.4802	474	.00028	24.759	1.757	321.5
1200	.489	2266.7	22.160	-.0000	1.2236	.4907	426	.00026	46.938	1.827	334.4
900	.095	2113.9	22.160	-.0001	1.2013	.5353	347	.00022	171.22	1.933	353.7
r = 1.8; o/f = 1.891; percent fuel = 34.59											
3200	329.31	3868.7	20.059	-.1233	1.1747	0.9029	824	0.00085	———	———	———
2800	128.46	3590.7	20.307	-.0640	1.1939	.7008	755	.00062	1.047	0.813	147.1
2400	50.322	3353.2	20.435	-.0223	1.2193	.5690	682	.00047	1.628	1.138	205.7
2000	18.787	3142.9	20.477	-.0044	1.2390	.5079	605	.00038	3.029	1.361	246.2
1800	10.924	3043.1	20.483	-.0014	1.2443	.4957	564	.00035	4.383	1.456	263.2
1600	6.009	2944.6	20.485	-.0003	1.2464	.4910	521	.00032	6.682	1.543	279.0
1400	3.056	2846.3	20.485	-.0001	1.2451	.4928	476	.00029	10.913	1.626	293.9
1200	1.387	2746.9	20.485	-.0000	1.2388	.5032	428	.00027	19.650	1.705	308.3
900	.294	2590.5	20.487	-.0017	1.2158	.5489	350	.00023	64.937	1.823	329.6
r = 2.0; o/f = 1.702; percent fuel = 37.01											
3200	564.28	4308.2	18.852	-.0908	1.1942	0.8085	824	0.00078	———	———	———
2800	242.31	4042.2	19.023	-.0468	1.2128	.6643	756	.00060	1.200	0.422	74.4
2400	101.28	3807.6	19.110	-.0165	1.2357	.5659	684	.00048	1.125	.913	161.1
2200	64.740	3699.2	19.130	-.0079	1.2458	.5359	645	.00043	1.389	1.066	188.1
2000	40.098	3594.8	19.140	-.0032	1.2536	.5169	606	.00039	1.817	1.196	210.9
1600	13.512	3392.3	19.145	-.0003	1.2613	.5012	521	.00033	3.650	1.413	249.2
1400	7.093	3292.1	19.145	-.0001	1.2607	.5020	478	.00030	5.698	1.509	266.1
1200	3.348	3191.0	19.145	-.0001	1.2552	.5106	428	.00027	9.758	1.600	282.1
900	.765	3031.7	19.166	-.0241	1.2214	.6071	352	.00026	29.541	1.733	305.7

TABLE IV. - THEORETICAL ROCKET PERFORMANCE AT ASSIGNED PRESSURE RATIOS FROM 1 TO 8 FOR JP-4 FUEL AND LIQUID OXYGEN

[Equilibrium composition during isentropic expansion.]

(a) Combustion-chamber pressure, 600 pounds per square inch absolute

Pressure ratio, P_o/P	Pressure, P, lb/sq in. abs	Temperature, T, °K	Temperature exponent, n_T, $\left(\frac{\partial \ln T}{\partial \ln P_o}\right)_{\frac{P_o}{P}}$	Enthalpy, h, cal/g	Molecular weight, M	Partial derivative, $\left(\frac{\partial \ln M}{\partial \ln T}\right)_s$	Isentropic exponent, γ, $\left(\frac{\partial \ln P}{\partial \ln \rho}\right)_s$	Specific heat, c_p, $\frac{cal}{(g)(^\circ K)}$	Area ratio, ε	Area-ratio exponent, n_ε, $\left(\frac{\partial \ln \varepsilon}{\partial \ln P_o}\right)_{\frac{P_o}{P}}$	Thrust coefficient, C_F	Specific-impulse exponent, n_I, $\left(\frac{\partial \ln I}{\partial \ln P_o}\right)_{\frac{P_o}{P}}$	Specific impulse, I, $\frac{\text{lb-sec}}{\text{lb}}$
r = 1.0; o/f = 3.403; percent fuel = 22.71													
1.000	600.00	3612	0.0426	2531.6	25.48	-.333	1.128	1.845	-------	-------	-------	-------	-------
1.020	588.24	3606	.0425	2526.0	25.50	-.334	1.127	1.846	3.242	0.0013	0.126	0.0141	22.0
1.040	576.92	3600	.0424	2520.5	25.51	-.333	1.127	1.847	2.345	.0013	.177	.0141	31.0
1.200	500.00	3557	.0418	2480.7	25.62	-.335	1.126	1.855	1.240	.0009	.381	.0140	66.5
1.437	417.60	3504	.0410	2431.5	25.74	-.336	1.124	1.863	1.037	.0004	.534	.0138	93.3
[a]1.724	348.00	3452	.0402	2382.7	25.87	-.336	1.123	1.871	1.000	.0000	.651	.0136	113.8
2.155	278.40	3390	.0393	2324.3	26.03	-.339	1.121	1.879	1.034	-.0006	.769	.0135	134.3
4.000	150.00	3228	.0367	2169.4	26.47	-.339	1.117	1.890	1.359	-.0021	1.016	.0129	177.5
8.000	75.00	3061	.0339	2007.3	26.95	-.340	1.112	1.886	2.105	-.0039	1.222	.0124	213.6
r = 1.2; o/f = 2.836; percent fuel = 26.07													
1.000	600.00	3628	0.0422	2901.1	24.03	-.320	1.131	1.818	-------	-------	-------	-------	-------
1.020	588.24	3622	.0421	2895.2	24.05	-.321	1.131	1.818	3.245	0.0016	0.126	0.0140	22.7
1.040	576.92	3616	.0420	2889.4	24.06	-.320	1.131	1.819	2.347	.0015	.177	.0140	32.0
1.200	500.00	3571	.0413	2847.0	24.16	-.321	1.129	1.820	1.241	.0009	.381	.0139	68.6
1.439	417.07	3516	.0404	2794.3	24.28	-.321	1.128	1.819	1.037	.0006	.535	.0137	96.4
[a]1.726	347.56	3461	.0395	2742.4	24.40	-.321	1.126	1.817	1.000	-.0001	.653	.0135	117.5
2.158	278.05	3397	.0384	2680.2	24.55	-.320	1.125	1.810	1.034	-.0007	.770	.0133	138.6
4.000	150.00	3227	.0354	2516.2	24.95	-.316	1.121	1.775	1.357	-.0024	1.016	.0127	183.0
8.000	75.00	3051	.0314	2344.5	25.39	-.305	1.117	1.696	2.096	-.0046	1.222	.0121	220.1
r = 1.3; o/f = 2.618; percent fuel = 27.64													
1.000	600.00	3612	0.0408	3074.1	23.36	-.302	1.134	1.700	-------	-------	-------	-------	-------
1.020	588.24	3605	.0407	3068.1	23.37	-.301	1.134	1.699	3.249	0.0018	0.126	0.0136	23.0
1.040	576.92	3599	.0406	3062.1	23.38	-.300	1.134	1.698	2.350	.0017	.178	.0136	32.3
1.200	500.00	3553	.0397	3018.7	23.47	-.300	1.133	1.688	1.242	.0012	.381	.0135	69.5
1.441	416.51	3495	.0386	2964.3	23.59	-.298	1.131	1.674	1.037	.0005	.537	.0133	97.7
[a]1.729	347.09	3439	.0375	2911.2	23.70	-.296	1.130	1.656	1.000	-.0000	.654	.0131	119.1
2.161	277.68	3371	.0362	2847.7	23.84	-.291	1.129	1.630	1.033	-.0007	.771	.0128	140.4
4.000	150.00	3193	.0324	2680.5	24.21	-.276	1.126	1.532	1.353	-.0031	1.016	.0122	185.1
8.000	75.00	3003	.0269	2505.7	24.60	-.244	1.125	1.359	2.085	-.0063	1.221	.0114	222.4
r = 1.4; o/f = 2.431; percent fuel = 29.15													
1.000	600.00	3576	0.0382	3239.9	22.70	-.271	1.139	1.520	-------	-------	-------	-------	-------
1.020	588.24	3569	.0381	3233.7	22.71	-.270	1.139	1.518	3.254	0.0020	0.127	0.0129	23.2
1.040	576.92	3563	.0380	3227.7	22.72	-.271	1.138	1.515	2.353	.0019	.178	.0129	32.7
1.200	500.00	3514	.0370	3183.5	22.80	-.268	1.138	1.497	1.243	.0015	.382	.0127	70.1
1.444	415.57	3453	.0356	3127.4	22.91	-.264	1.137	1.468	1.036	.0008	.539	.0125	98.9
[a]1.733	346.31	3393	.0343	3073.4	23.01	-.258	1.136	1.433	1.000	-.0000	.656	.0122	120.4
2.166	277.05	3321	.0326	3008.9	23.13	-.248	1.136	1.383	1.033	-.0009	.773	.0119	141.8
4.000	150.00	3128	.0274	2840.2	23.45	-.212	1.137	1.216	1.348	-.0043	1.016	.0111	186.5
8.000	75.00	2913	.0200	2664.0	23.77	-.161	1.143	.999	2.064	-.0088	1.220	.0100	223.9
r = 1.6; o/f = 2.127; percent fuel = 31.98													
1.000	600.00	3436	0.0290	3551.6	21.41	-.180	1.156	1.089	-------	-------	-------	-------	-------
1.020	588.24	3428	.0288	3545.3	21.42	-.179	1.156	1.084	3.275	0.0033	0.127	0.0102	23.4
1.040	576.92	3420	.0286	3539.2	21.42	-.179	1.156	1.079	2.368	.0033	.179	.0102	32.9
1.200	500.00	3364	.0271	3494.2	21.49	-.169	1.157	1.044	1.249	.0024	.384	.0099	70.7
1.457	411.91	3288	.0252	3434.7	21.57	-.157	1.159	.996	1.035	.0012	.548	.0096	100.9
[a]1.748	343.27	3217	.0233	3380.1	21.64	-.144	1.161	.950	1.000	.0001	.664	.0092	122.2
2.185	274.61	3130	.0210	3315.2	21.72	-.128	1.164	.894	1.032	-.0015	.780	.0088	143.4
4.000	150.00	2892	.0135	3149.3	21.90	-.086	1.175	.750	1.327	-.0058	1.017	.0075	187.1
8.000	75.00	2615	.0051	2976.7	22.04	-.045	1.192	.622	1.994	-.0106	1.216	.0061	223.7
r = 1.8; o/f = 1.891; percent fuel = 34.59													
1.000	600.00	3205	0.0187	3839.4	20.17	-.095	1.184	0.798	-------	-------	-------	-------	-------
1.020	588.24	3196	.0185	3833.1	20.17	-.093	1.185	.794	3.307	0.0036	0.129	0.0067	23.3
1.040	576.92	3187	.0183	3827.0	20.18	-.093	1.185	.790	2.390	.0035	.181	.0067	32.8
1.200	500.00	3128	.0167	3782.6	20.21	-.083	1.188	.763	1.258	.0025	.388	.0063	70.3
1.475	406.86	3028	.0144	3720.4	20.26	-.072	1.192	.726	1.033	.0011	.561	.0059	101.8
[a]1.770	339.05	2946	.0124	3667.0	20.30	-.062	1.196	.695	1.000	-.0000	.676	.0055	122.5
2.212	271.24	2845	.0098	3603.8	20.34	-.052	1.201	.660	1.031	-.0013	.790	.0051	143.2
4.000	150.00	2578	.0042	3447.3	20.42	-.028	1.215	.585	1.304	-.0044	1.019	.0040	184.7
8.000	75.00	2277	-.0004	3283.8	20.46	-.010	1.231	.530	1.931	-.0069	1.213	.0029	219.9
r = 3.0; o/f = 1.134; percent fuel = 46.85													
1.000	600.00	1657	0.0264	5188.4	15.49	-.060	1.285	0.701	-------	-------	-------	-------	-------
1.020	588.24	1650	.0267	5184.2	15.50	-.061	1.285	.705	3.381	-.0053	0.132	0.0064	19.1
1.040	576.92	1644	.0271	5180.1	15.50	-.063	1.284	.709	2.442	-.0049	.185	.0064	26.9
1.200	500.00	1596	.0295	5150.4	15.53	-.075	1.278	.741	1.276	-.0036	.396	.0068	57.5
1.504	399.00	1526	.0334	5105.4	15.59	-.096	1.267	.807	1.031	-.0016	.585	.0074	85.0
[a]1.805	332.50	1475	.0365	5070.6	15.65	-.115	1.257	.874	1.000	-.0001	.697	.0079	101.2
2.256	266.00	1418	.0397	5029.7	15.78	-.141	1.243	.973	1.030	.0017	.809	.0085	117.5
4.000	150.00	1296	.0475	4938.4	15.97	-.210	1.210	1.341	1.294	.0045	1.027	.0098	149.2
8.000	75.00	1187	.0478	4826.7	16.33	-.290	1.173	1.923	1.950	.0047	1.221	.0108	177.4

[a] At throat.

4045

TABLE IV. - Concluded. THEORETICAL ROCKET PERFORMANCE AT ASSIGNED PRESSURE RATIOS FROM 1 TO 8 FOR JP-4 FUEL AND LIQUID OXYGEN

[Equilibrium composition during isentropic expansion.]

(b) Combustion-chamber pressure, 300 pounds per square inch absolute

Pressure ratio, P_c/P	Pressure, P, lb/sq in. abs	Temperature, T, $^{\circ}K$	Temperature exponent, n_T, $\left(\frac{\partial \ln T}{\partial \ln P_c}\right)_{\frac{P_c}{P}}$	Enthalpy, h, cal/g	Molecular weight, M	Partial derivative, $\left(\frac{\partial \ln M}{\partial \ln T}\right)_s$	Isentropic exponent, γ, $\left(\frac{\partial \ln P}{\partial \ln \rho}\right)_s$	Specific heat, c_p, $\frac{cal}{(g)(^{\circ}K)}$	Area ratio, ε	Area-ratio exponent, n_ε, $\left(\frac{\partial \ln \varepsilon}{\partial \ln P_c}\right)_{\frac{P_c}{P}}$	Thrust coefficient, C_F	Specific-impulse exponent, n_I, $\left(\frac{\partial \ln I}{\partial \ln P_c}\right)_{\frac{P_c}{P}}$	Specific impulse, I, $\frac{\text{lb-sec}}{\text{lb}}$
r = 1.0; o/f = 3.403; percent fuel = 22.71													
1.000	300.00	3507	0.0427	2531.6	25.24	-.352	1.124	2.018	------	------	------	------	------
1.020	294.11	3501	.0426	2526.1	25.25	-.352	1.124	2.014	3.238	0.0014	0.126	0.0144	21.8
1.040	288.47	3496	.0425	2520.8	25.26	-.352	1.124	2.015	2.343	.0013	.177	.0144	30.7
1.200	250.00	3456	.0419	2481.7	25.37	-.353	1.123	2.023	1.239	.0009	.380	.0142	65.9
1.435	209.04	3406	.0412	2433.8	25.50	-.354	1.121	2.032	1.037	.0004	.533	.0141	92.3
[a]1.728	174.19	3357	.0404	2385.8	25.63	-.355	1.120	2.039	1.000	.0000	.650	.0139	118.6
2.153	139.35	3299	.0395	2328.4	25.79	-.356	1.118	2.047	1.034	-.0006	.768	.0137	133.0
4.000	75.00	3146	.0369	2175.9	26.23	-.358	1.114	2.059	1.361	-.0022	1.016	.0132	175.9
8.000	37.50	2989	.0342	2016.4	26.72	-.358	1.109	2.054	2.110	-.0039	1.223	.0127	211.7
r = 1.2; o/f = 2.836; percent fuel = 26.07													
1.000	300.00	3523	0.0425	2901.1	23.80	-.340	1.127	1.996	------	------	------	------	------
1.020	294.11	3517	.0424	2895.3	23.82	-.341	1.127	1.997	3.242	0.0015	0.126	0.0144	22.5
1.040	288.47	3512	.0423	2889.6	23.83	-.340	1.127	1.997	2.345	.0015	.177	.0143	31.6
1.200	250.00	3470	.0416	2848.1	23.93	-.341	1.126	1.998	1.240	.0011	.381	.0142	68.0
1.437	208.79	3418	.0408	2796.7	24.05	-.341	1.125	1.998	1.037	.0007	.534	.0140	95.3
[a]1.724	173.99	3368	.0399	2745.7	24.17	-.341	1.123	1.996	1.000	-.0000	.651	.0139	116.3
2.155	139.19	3307	.0389	2684.7	24.32	-.341	1.122	1.990	1.034	-.0005	.769	.0136	137.2
4.000	75.00	3148	.0360	2523.0	24.73	-.337	1.117	1.957	1.359	-.0025	1.016	.0131	181.4
8.000	37.50	2983	.0327	2353.9	25.18	-.327	1.114	1.882	2.103	-.0044	1.222	.0124	218.2
r = 1.3; o/f = 2.618; percent fuel = 27.64													
1.000	300.00	3511	0.0418	3074.1	23.14	-.323	1.131	1.887	------	------	------	------	------
1.020	294.11	3504	.0418	3068.2	23.15	-.322	1.131	1.886	3.245	0.0018	0.126	0.0141	22.8
1.040	288.47	3499	.0417	3062.3	23.17	-.323	1.130	1.885	2.347	.0017	.177	.0140	32.0
1.200	250.00	3456	.0410	3019.7	23.26	-.321	1.129	1.878	1.241	.0010	.381	.0139	68.8
1.439	208.55	3402	.0400	2966.8	23.38	-.320	1.128	1.864	1.037	.0006	.535	.0137	96.7
[a]1.726	173.79	3350	.0389	2914.6	23.49	-.318	1.127	1.846	1.000	.0001	.652	.0135	117.8
2.158	139.03	3287	.0375	2852.1	23.63	-.314	1.125	1.819	1.034	-.0008	.770	.0133	139.0
4.000	75.00	3121	.0333	2687.2	24.02	-.301	1.122	1.714	1.356	-.0030	1.016	.0126	183.5
8.000	37.50	2945	.0285	2514.8	24.42	-.275	1.120	1.546	2.093	-.0057	1.222	.0119	220.6
r = 1.4; o/f = 2.431; percent fuel = 29.15													
1.000	300.00	3481	0.0396	3239.9	22.50	-.299	1.135	1.707	------	------	------	------	------
1.020	294.11	3475	.0395	3233.8	22.51	-.298	1.134	1.704	3.250	0.0020	0.126	0.0135	23.0
1.040	288.47	3469	.0394	3227.9	22.53	-.297	1.134	1.702	2.350	.0019	.178	.0135	32.4
1.200	250.00	3424	.0385	3184.5	22.61	-.294	1.134	1.680	1.242	.0015	.381	.0133	69.5
1.441	208.14	3367	.0373	3129.9	22.72	-.289	1.133	1.648	1.037	.0009	.537	.0130	97.8
[a]1.730	173.46	3312	.0360	3076.8	22.83	-.283	1.132	1.610	1.000	.0000	.654	.0128	119.1
2.162	138.76	3245	.0343	3013.3	22.96	-.274	1.131	1.557	1.033	-.0010	.771	.0125	140.4
4.000	75.00	3067	.0292	2846.4	23.30	-.242	1.131	1.382	1.351	-.0040	1.016	.0117	185.0
8.000	37.50	2871	.0226	2672.2	23.64	-.194	1.135	1.151	2.075	-.0081	1.221	.0108	222.3
r = 1.5; o/f = 2.269; percent fuel = 30.59													
1.000	300.00	3433	0.0360	3399.0	21.88	-.259	1.140	1.472	------	------	------	------	------
1.020	294.11	3426	.0358	3392.8	21.89	-.258	1.140	1.468	3.257	0.0036	0.127	0.0125	23.2
1.040	288.47	3420	.0357	3386.8	21.90	-.258	1.140	1.463	2.356	.0036	.178	.0125	32.6
1.200	250.00	3372	.0345	3342.7	21.98	-.252	1.140	1.429	1.244	.0019	.382	.0123	69.9
1.446	207.48	3310	.0330	3286.6	22.08	-.241	1.140	1.380	1.036	.0009	.541	.0120	98.9
[a]1.735	172.90	3251	.0315	3232.8	22.17	-.232	1.140	1.329	1.000	.0001	.657	.0117	120.2
2.169	138.32	3179	.0296	3168.7	22.28	-.217	1.141	1.262	1.033	-.0012	.774	.0114	141.5
4.000	75.00	2982	.0234	3001.7	22.57	-.178	1.146	1.064	1.343	-.0051	1.016	.0103	185.9
8.000	37.50	2754	.0148	2827.6	22.83	-.116	1.158	.846	2.046	-.0103	1.219	.0091	223.0
r = 1.6; o/f = 2.127; percent fuel = 31.98													
1.000	300.00	3363	0.0315	3551.6	21.27	-.210	1.149	1.233	------	------	------	------	------
1.020	294.11	3356	.0313	3545.4	21.28	-.210	1.149	1.227	3.268	0.0038	0.127	0.0112	23.3
1.040	288.47	3349	.0312	3539.3	21.29	-.208	1.149	1.222	2.363	.0030	.179	.0112	32.7
1.200	250.00	3297	.0299	3495.0	21.36	-.199	1.150	1.182	1.247	.0023	.384	.0109	70.2
1.453	206.52	3229	.0281	3437.1	21.44	-.185	1.151	1.128	1.035	.0011	.545	.0105	99.8
[a]1.743	172.10	3163	.0263	3383.2	21.52	-.172	1.153	1.074	1.000	-.0000	.661	.0102	121.0
2.179	137.68	3083	.0240	3319.0	21.61	-.156	1.156	1.009	1.032	-.0015	.777	.0098	142.3
4.000	75.00	2863	.0164	3153.8	21.83	-.109	1.166	.835	1.332	-.0059	1.017	.0085	186.1
8.000	37.50	2604	.0078	2981.9	22.00	-.062	1.184	.674	2.009	-.0111	1.217	.0071	222.7
r = 1.8; o/f = 1.891; percent fuel = 34.59													
1.000	300.00	3161	0.0215	3839.4	20.09	-.116	1.176	0.880	------	------	------	------	------
1.020	294.11	3152	.0213	3833.2	20.09	-.116	1.176	.875	3.298	0.0038	0.128	0.0078	23.2
1.040	288.47	3144	.0210	3827.1	20.10	-.114	1.177	.870	2.384	.0036	.180	.0078	32.6
1.200	250.00	3083	.0191	3783.1	20.14	-.104	1.179	.837	1.256	.0026	.387	.0074	69.9
1.470	204.04	2997	.0166	3722.3	20.20	-.092	1.183	.792	1.033	.0013	.558	.0070	100.9
[a]1.764	170.03	2920	.0145	3669.3	20.25	-.081	1.187	.754	1.000	.0001	.673	.0066	121.6
2.205	136.03	2824	.0121	3606.5	20.30	-.067	1.192	.711	1.031	-.0015	.787	.0061	142.4
4.000	75.00	2570	.0059	3449.7	20.39	-.038	1.209	.616	1.309	-.0051	1.018	.0049	184.1
8.000	37.50	2277	.0000	3286.3	20.45	-.014	1.226	.544	1.941	-.0082	1.213	.0036	219.4
r = 2.0; o/f = 1.702; percent fuel = 37.01													
1.000	300.00	2900	0.0123	4105.8	18.99	-.057	1.207	0.696	------	------	------	------	------
1.020	294.11	2891	.0120	4099.8	18.99	-.056	1.208	.693	3.331	0.0032	0.130	0.0046	22.9
1.040	288.47	2882	.0118	4093.9	18.99	-.055	1.208	.690	2.407	.0029	.182	.0046	32.1
1.200	250.00	2815	.0104	4051.3	19.02	-.049	1.212	.669	1.264	.0022	.390	.0043	68.9
1.489	201.53	2714	.0083	3989.1	19.05	-.038	1.218	.639	1.032	.0010	.571	.0038	100.8
[a]1.786	167.95	2629	.0067	3938.4	19.07	-.032	1.223	.616	1.000	.0000	.684	.0035	120.7
2.233	134.35	2526	.0048	3878.5	19.09	-.024	1.229	.598	1.030	-.0011	.797	.0031	140.7
4.000	75.00	2264	.0011	3733.3	19.13	-.011	1.243	.544	1.289	-.0030	1.021	.0023	180.0
8.000	37.50	1973	-.0010	3581.0	19.14	-.003	1.254	.515	1.892	-.0039	1.212	.0016	213.7

[a] At throat.

TABLE V. - THEORETICAL ROCKET PERFORMANCE AT ASSIGNED PRESSURE RATIOS FROM 10 TO 1500 FOR JP-4 FUEL WITH LIQUID OXYGEN

[Equilibrium composition during isentropic expansion.]

(a) Combustion-chamber pressure, 600 pounds per square inch absolute

Pressure ratio, P_c/P	Pressure, P, lb/sq in. abs	Temperature, T, °K	Temperature exponent, n_T, $\left(\frac{\partial \ln T}{\partial \ln P_c}\right)_{\frac{P_c}{P}}$	Enthalpy, h, cal/g	Molecular weight, M	Partial derivative, $\left(\frac{\partial \ln M}{\partial \ln T}\right)_s$	Isentropic exponent, γ, $\left(\frac{\partial \ln P}{\partial \ln \rho}\right)_s$	Specific heat, c_p, $\frac{cal}{(g)(°K)}$	Area ratio, ε	Area-ratio exponent, n_ϵ, $\left(\frac{\partial \ln \epsilon}{\partial \ln P_c}\right)_{\frac{P_c}{P}}$	Thrust coefficient, C_F	Specific-impulse exponent, n_I, $\left(\frac{\partial \ln I}{\partial \ln P_c}\right)_{\frac{P_c}{P}}$	Specific impulse, I, $\frac{lb-sec}{lb}$
r = 1.0; o/f = 3.403; percent fuel = 22.71													
10	60.00	3010	0.0330	1957.5	27.10	-.339	1.111	1.880	2.46	-.0043	1.279	0.0122	223.5
15	40.00	2921	.0314	1869.8	27.38	-.336	1.109	1.864	3.30	-.0054	1.373	.0119	240.0
20	30.00	2861	.0303	1809.7	27.57	-.334	1.107	1.849	4.10	-.0061	1.434	.0117	250.6
30	20.00	2778	.0287	1727.7	27.84	-.329	1.105	1.821	5.60	-.0071	1.514	.0114	264.5
40	15.00	2722	.0276	1671.4	28.03	-.326	1.104	1.796	7.03	-.0078	1.566	.0112	273.6
60	10.00	2645	.0259	1594.6	28.29	-.320	1.102	1.755	9.72	-.0089	1.634	.0109	285.5
80	7.50	2592	.0247	1541.9	28.47	-.315	1.101	1.722	12.28	-.0096	1.679	.0107	293.5
100	6.00	2552	.0238	1501.9	28.61	-.310	1.101	1.693	14.74	-.0101	1.713	.0106	299.3
150	4.00	2480	.0221	1431.4	28.86	-.301	1.100	1.636	20.62	-.0112	1.771	.0103	309.4
200	3.00	2431	.0209	1382.9	29.03	-.298	1.099	1.592	26.21	-.0121	1.809	.0101	316.1
300	2.00	2363	.0190	1316.6	29.27	-.279	1.099	1.521	36.86	-.0133	1.861	.0098	325.1
400	1.50	2316	.0173	1271.1	29.43	-.269	1.098	1.465	47.01	-.0142	1.895	.0096	331.2
600	1.00	2250	.0150	1208.8	29.66	-.253	1.098	1.381	66.38	-.0157	1.942	.0093	339.3
800	.75	2203	.0133	1166.0	29.81	-.239	1.099	1.320	84.87	-.0167	1.973	.0091	344.7
1000	.60	2168	.0120	1133.6	29.93	-.230	1.099	1.270	102.75	-.0176	1.996	.0090	348.8
1500	.40	2103	.0095	1076.3	30.13	-.209	1.101	1.178	145.56	-.0193	2.037	.0087	355.8
r = 1.2; o/f = 2.836; percent fuel = 26.07													
10	60.00	2996	0.0301	2291.8	25.53	-.300	1.116	1.661	2.45	-.0053	1.278	0.0119	230.3
15	40.00	2900	.0279	2199.2	25.77	-.288	1.115	1.585	3.28	-.0067	1.372	.0115	247.1
20	30.00	2834	.0264	2135.8	25.94	-.275	1.115	1.521	4.06	-.0079	1.433	.0113	258.1
30	20.00	2742	.0237	2049.6	26.17	-.251	1.115	1.400	5.54	-.0099	1.511	.0109	272.2
40	15.00	2677	.0213	1990.6	26.33	-.230	1.117	1.298	6.94	-.0116	1.563	.0106	281.5
60	10.00	2586	.0175	1910.4	26.53	-.197	1.120	1.148	9.56	-.0143	1.630	.0102	293.6
80	7.50	2520	.0143	1855.5	26.67	-.172	1.124	1.040	12.03	-.0164	1.675	.0098	301.6
100	6.00	2467	.0114	1814.2	26.76	-.153	1.127	.957	14.39	-.0182	1.707	.0096	307.5
150	4.00	2367	.0064	1741.6	26.91	-.116	1.137	.816	19.93	-.0218	1.763	.0090	317.6
200	3.00	2291	.0040	1692.2	26.99	-.089	1.147	.728	25.12	-.0250	1.801	.0086	324.3
300	2.00	2177	-.0019	1625.6	27.08	-.055	1.162	.618	34.74	-.0298	1.850	.0079	333.2
400	1.50	2093	-.0081	1580.5	27.12	-.034	1.178	.551	43.70	-.0333	1.882	.0075	339.0
600	1.00	1971	-.0180	1520.2	27.16	-.013	1.184	.482	60.29	-.0372	1.924	.0068	346.6
800	.75	1884	-.0223	1479.6	27.17	-.007	1.189	.458	75.72	-.0383	1.953	.0063	351.7
1000	.60	1818	-.0241	1449.4	27.18	-.003	1.193	.447	90.36	-.0391	1.973	.0060	355.4
1500	.40	1702	-.0242	1397.3	27.18	-.001	1.197	.439	124.62	-.0391	2.008	.0054	361.7
r = 1.3; o/f = 2.618; percent fuel = 27.64													
10	60.00	2943	0.0251	2452.3	24.72	-.231	1.126	1.295	2.43	-.0072	1.277	0.0111	232.6
15	40.00	2835	.0216	2358.5	24.92	-.205	1.128	1.169	3.25	-.0095	1.370	.0106	249.5
20	30.00	2757	.0194	2294.5	25.06	-.179	1.132	1.070	4.01	-.0116	1.430	.0102	260.5
30	20.00	2646	.0156	2207.9	25.23	-.139	1.140	.984	5.44	-.0151	1.508	.0096	274.5
40	15.00	2564	.0117	2149.0	25.33	-.112	1.147	.824	6.78	-.0178	1.558	.0092	283.7
60	10.00	2443	.0037	2069.5	25.45	-.077	1.157	.694	9.25	-.0220	1.624	.0085	295.7
80	7.50	2353	-.0019	2015.7	25.51	-.056	1.165	.624	11.55	-.0246	1.666	.0080	303.5
100	6.00	2282	-.0050	1975.4	25.54	-.043	1.172	.584	13.71	-.0266	1.698	.0076	309.2
150	4.00	2148	-.0098	1905.6	25.59	-.024	1.184	.526	18.75	-.0295	1.751	.0068	318.9
200	3.00	2054	-.0124	1858.7	25.61	-.014	1.192	.497	23.42	-.0312	1.786	.0063	325.2
300	2.00	1923	-.0157	1796.2	25.63	-.006	1.200	.470	32.05	-.0327	1.831	.0057	333.5
400	1.50	1833	-.0173	1754.3	25.63	-.003	1.203	.459	40.07	-.0329	1.861	.0052	338.9
600	1.00	1711	-.0177	1698.6	25.64	-.001	1.206	.452	54.96	-.0331	1.900	.0047	346.0
800	.75	1629	-.0170	1661.4	25.64	-.001	1.207	.451	68.83	-.0329	1.925	.0044	350.6
1000	.60	1568	-.0168	1633.8	25.64	-.001	1.208	.451	82.00	-.0327	1.944	.0041	354.0
1500	.40	1462	-.0172	1586.2	25.64	-.000	1.208	.449	112.86	-.0324	1.976	.0037	359.8
r = 1.4; o/f = 2.431; percent fuel = 29.15													
10	60.00	2843	0.0172	2610.4	23.86	-.143	1.146	0.929	2.40	-.0105	1.275	0.0097	234.0
15	40.00	2713	.0126	2516.9	24.00	-.109	1.155	.809	3.18	-.0138	1.367	.0089	250.8
20	30.00	2618	.0091	2453.5	24.08	-.085	1.162	.731	3.91	-.0164	1.426	.0084	261.6
30	20.00	2479	.0027	2368.4	24.17	-.055	1.174	.635	5.26	-.0199	1.501	.0076	275.4
40	15.00	2378	-.0023	2311.0	24.22	-.038	1.182	.580	6.51	-.0224	1.549	.0071	284.3
60	10.00	2234	-.0070	2234.3	24.26	-.022	1.193	.531	8.80	-.0247	1.612	.0063	295.8
80	7.50	2133	-.0091	2182.9	24.28	-.014	1.199	.507	10.91	-.0259	1.653	.0058	303.3
100	6.00	2055	-.0101	2144.7	24.29	-.009	1.204	.493	12.91	-.0267	1.682	.0054	308.7
150	4.00	1918	-.0118	2078.9	24.30	-.004	1.210	.475	17.54	-.0273	1.732	.0048	317.8
200	3.00	1824	-.0127	2034.9	24.31	-.002	1.212	.467	21.84	-.0274	1.765	.0044	323.8
300	2.00	1699	-.0130	1976.5	24.31	-.001	1.215	.462	29.79	-.0274	1.807	.0039	331.6
400	1.50	1615	-.0126	1937.6	24.31	-.001	1.215	.462	37.18	-.0270	1.835	.0036	336.6
600	1.00	1503	-.0128	1885.9	24.31	-.000	1.216	.460	50.90	-.0269	1.871	.0032	343.2
800	.75	1428	-.0129	1851.5	24.31	-.000	1.215	.461	63.69	-.0266	1.894	.0030	347.6
1000	.60	1373	-.0129	1825.9	24.31	-.000	1.215	.462	75.83	-.0264	1.912	.0028	350.8
1500	.40	1278	-.0127	1782.0	24.31	-.000	1.213	.465	104.30	-.0261	1.941	.0026	356.2

TABLE V. - Continued. THEORETICAL ROCKET PERFORMANCE AT ASSIGNED PRESSURE RATIOS FROM 10 TO 1500 FOR JP-4 FUEL WITH LIQUID OXYGEN

[Equilibrium composition during isentropic expansion.]

(a) Concluded. Combustion-chamber pressure, 600 pounds per square inch absolute

Pressure ratio, P_c/P	Pressure, P, lb/sq in. abs	Temperature, T, °K	Temperature exponent, n_T, $\left(\frac{\partial \ln T}{\partial \ln P_c}\right)_{\frac{P_c}{P}}$	Enthalpy, h, cal/g	Molecular weight, M	Partial derivative, $\left(\frac{\partial \ln M}{\partial \ln T}\right)_s$	Isentropic exponent, γ, $\left(\frac{\partial \ln P}{\partial \ln \rho}\right)_s$	Specific heat, c_p, $\frac{cal}{(g)(°K)}$	Area ratio, ε	Area-ratio exponent, n_ε, $\left(\frac{\partial \ln \varepsilon}{\partial \ln P_c}\right)_{\frac{P_c}{P}}$	Thrust coefficient, C_F	Specific-impulse exponent, n_I, $\left(\frac{\partial \ln I}{\partial \ln P_c}\right)_{\frac{P_c}{P}}$	Specific impulse, I, $\frac{lb\text{-}sec}{lb}$
r = 1.6; o/f = 2.127; percent fuel = 31.98													
10	60.00	2525	0.0028	2925.0	22.07	-.035	1.198	0.591	2.30	-.0118	1.269	0.0056	233.5
15	40.00	2362	-.0011	2835.9	22.11	-.020	1.208	.546	3.02	-.0139	1.357	.0049	249.5
20	30.00	2248	-.0031	2776.4	22.13	-.013	1.214	.524	3.68	-.0149	1.412	.0044	259.7
30	20.00	2092	-.0048	2697.4	22.15	-.007	1.221	.502	4.88	-.0158	1.482	.0038	272.6
40	15.00	1985	-.0054	2644.8	22.15	-.004	1.225	.492	6.00	-.0158	1.527	.0034	280.9
60	10.00	1842	-.0061	2575.3	22.16	-.002	1.229	.484	8.04	-.0161	1.585	.0030	291.5
80	7.50	1746	-.0063	2529.0	22.16	-.001	1.230	.480	9.93	-.0160	1.622	.0027	298.3
100	6.00	1674	-.0065	2494.8	22.16	-.001	1.231	.479	11.71	-.0158	1.649	.0025	303.2
150	4.00	1552	-.0066	2436.2	22.16	-.000	1.231	.478	15.85	-.0157	1.694	.0022	311.5
200	3.00	1470	-.0066	2397.2	22.16	-.000	1.231	.479	19.68	-.0155	1.723	.0020	316.9
300	2.00	1363	-.0065	2345.7	22.16	-.000	1.229	.481	26.77	-.0153	1.761	.0018	323.9
400	1.50	1292	-.0065	2311.5	22.16	-.000	1.227	.484	33.37	-.0150	1.786	.0016	328.5
600	1.00	1199	-.0064	2266.2	22.16	-.000	1.224	.491	45.62	-.0149	1.818	.0015	334.4
800	.75	1138	-.0063	2236.1	22.16	-.000	1.220	.497	57.07	-.0146	1.839	.0014	338.3
1000	.60	1093	-.0063	2213.8	22.16	-.000	1.218	.502	67.96	-.0145	1.855	.0013	341.2
1500	.40	1018	-.0061	2175.4	22.16	-.000	1.212	.513	93.56	-.0143	1.881	.0012	346.0
r = 1.8; o/f = 1.891; percent fuel = 34.59													
10	60.00	2184	-.0013	3235.4	20.47	-.007	1.234	0.519	2.22	-.0071	1.265	0.0026	229.2
15	40.00	2021	-.0022	3152.8	20.48	-.003	1.240	.505	2.89	-.0076	1.348	.0022	244.4
20	30.00	1911	-.0027	3097.9	20.48	-.002	1.243	.498	3.50	-.0076	1.401	.0019	254.0
30	20.00	1765	-.0032	3025.7	20.48	-.001	1.246	.492	4.63	-.0076	1.468	.0017	266.1
40	15.00	1668	-.0032	2977.8	20.48	-.000	1.246	.491	5.67	-.0077	1.511	.0015	273.8
60	10.00	1539	-.0032	2914.7	20.48	-.000	1.247	.490	7.58	-.0075	1.565	.0013	283.6
80	7.50	1454	-.0035	2873.0	20.48	-.000	1.246	.491	9.34	-.0073	1.600	.0011	290.0
100	6.00	1392	-.0036	2842.2	20.49	-.000	1.245	.492	11.00	-.0073	1.625	.0011	294.6
150	4.00	1285	-.0035	2789.6	20.49	-.000	1.242	.497	14.85	-.0071	1.667	.0009	302.2
200	3.00	1215	-.0031	2754.7	20.49	-.000	1.240	.502	18.42	-.0071	1.695	.0009	307.2
300	2.00	1124	-.0027	2708.6	20.48	-.001	1.235	.512	25.04	-.0067	1.730	.0008	313.7
400	1.50	1065	-.0023	2678.0	20.48	-.002	1.231	.521	31.20	-.0063	1.754	.0007	317.9
600	1.00	988	-.0017	2637.6	20.48	-.004	1.224	.536	42.68	-.0058	1.784	.0006	323.4
800	.75	938	-.0012	2610.8	20.49	-.005	1.218	.550	53.43	-.0055	1.804	.0006	327.0
1000	.60	902	-.0010	2591.1	20.49	-.007	1.213	.561	63.68	-.0053	1.818	.0006	329.6
1500	.40	841	-.0007	2557.3	20.51	-.010	1.204	.585	87.88	-.0048	1.843	.0005	334.0
r = 3.0; o/f = 1.134; percent fuel = 46.85													
10	60.00	1158	0.0476	4795.0	16.45	-.310	1.165	2.125	2.26	0.0044	1.273	0.0110	185.0
15	40.00	1110	.0469	4739.9	16.68	-.341	1.152	2.501	3.01	.0033	1.360	.0113	197.5
20	30.00	1080	.0463	4702.5	16.84	-.360	1.144	2.770	3.71	.0025	1.415	.0114	205.6
30	20.00	1042	.0453	4652.1	17.07	-.383	1.135	3.142	5.04	.0012	1.487	.0115	216.0
40	15.00	1017	.0447	4617.8	17.23	-.397	1.130	3.395	6.30	.0004	1.534	.0116	222.8
60	10.00	984	.0438	4571.3	17.46	-.412	1.124	3.725	8.69	-.0007	1.595	.0115	231.7
80	7.50	963	.0432	4539.6	17.62	-.421	1.121	3.935	10.95	-.0014	1.635	.0115	237.6
100	6.00	947	.0426	4515.7	17.75	-.426	1.118	4.081	13.13	-.0022	1.665	.0115	241.9
150	4.00	920	.0413	4473.6	17.97	-.434	1.114	4.299	18.32	-.0033	1.717	.0114	249.4
200	3.00	901	.0400	4444.8	18.13	-.436	1.110	4.412	23.26	-.0044	1.751	.0113	254.4
300	2.00	877	.0376	4405.5	18.35	-.438	1.105	4.502	32.69	-.0059	1.796	.0112	261.0

TABLE V. - Continued. THEORETICAL ROCKET PERFORMANCE AT ASSIGNED PRESSURE RATIOS FROM 10 TO 1500 FOR JP-4 FUEL WITH LIQUID OXYGEN

[Equilibrium composition during isentropic expansion.]

(b) Combustion-chamber pressure, 300 pounds per square inch absolute

Pressure ratio, P_c/P	Pressure, P, lb/sq in. abs	Temperature, T, °K	Temperature exponent, n_T, $\left(\frac{\partial \ln T}{\partial \ln P_c}\right)_{\frac{P_c}{P}}$	Enthalpy, h, cal/g	Molecular weight, M	Partial derivative, $\left(\frac{\partial \ln M}{\partial \ln T}\right)_s$	Isentropic exponent, γ, $\left(\frac{\partial \ln P}{\partial \ln \rho}\right)_s$	Specific heat, c_p, $\frac{cal}{(g)(^\circ K)}$	Area ratio, ε	Area-ratio exponent, n_ε, $\left(\frac{\partial \ln \varepsilon}{\partial \ln P_c}\right)_{\frac{P_c}{P}}$	Thrust coefficient, C_F	Specific-impulse exponent, n_I, $\left(\frac{\partial \ln I}{\partial \ln P_c}\right)_{\frac{P_c}{P}}$	Specific impulse, I, $\frac{\text{lb-sec}}{\text{lb}}$
r = 1.0; o/f = 3.403; percent fuel = 22.71													
10	30.00	2942	0.0334	1967.3	26.87	-.357	1.108	2.048	2.47	-.0044	1.279	0.0125	221.6
15	20.00	2858	.0319	1880.8	27.15	-.355	1.106	2.032	3.31	-.0054	1.374	.0122	238.0
20	15.00	2801	.0308	1821.4	27.34	-.353	1.104	2.016	4.11	-.0061	1.435	.0120	248.6
30	10.00	2723	.0293	1740.5	27.61	-.349	1.103	1.987	5.63	-.0071	1.515	.0117	262.4
40	7.50	2670	.0282	1684.8	27.80	-.345	1.101	1.962	7.06	-.0078	1.567	.0115	271.4
60	5.00	2597	.0268	1608.9	28.07	-.340	1.100	1.920	9.78	-.0087	1.636	.0112	283.3
80	3.75	2547	.0256	1556.7	28.25	-.335	1.099	1.885	12.36	-.0094	1.682	.0110	291.3
100	3.00	2509	.0247	1517.1	28.39	-.331	1.098	1.856	14.85	-.0099	1.716	.0108	297.1
150	2.00	2442	.0232	1447.2	28.65	-.322	1.097	1.796	20.78	-.0110	1.774	.0106	307.8
200	1.50	2395	.0220	1399.1	28.82	-.314	1.097	1.750	26.43	-.0118	1.813	.0104	313.9
300	1.00	2331	.0202	1333.3	29.07	-.302	1.096	1.677	37.19	-.0129	1.864	.0101	322.9
400	.75	2286	.0189	1288.0	29.23	-.293	1.096	1.622	47.47	-.0137	1.899	.0099	328.9
600	.50	2224	.0171	1226.1	29.47	-.278	1.096	1.538	67.07	-.0149	1.946	.0096	337.0
800	.37	2180	.0156	1183.5	29.62	-.267	1.096	1.473	85.82	-.0159	1.978	.0094	342.5
1000	.30	2147	.0145	1151.2	29.74	-.257	1.096	1.421	103.96	-.0168	2.001	.0093	346.6
1500	.20	2086	.0123	1094.0	29.96	-.237	1.097	1.323	147.45	-.0184	2.042	.0090	353.7
r = 1.2; o/f = 2.836; percent fuel = 26.07													
10	30.00	2932	0.0316	2301.9	25.32	-.323	1.113	1.848	2.46	-.0050	1.279	0.0122	228.3
15	20.00	2843	.0295	2210.5	25.57	-.312	1.112	1.774	3.29	-.0064	1.373	.0119	245.1
20	15.00	2781	.0279	2147.9	25.75	-.302	1.111	1.710	4.09	-.0075	1.434	.0116	256.0
30	10.00	2695	.0254	2062.6	25.98	-.285	1.111	1.602	5.58	-.0090	1.513	.0113	270.1
40	7.50	2635	.0235	2004.1	26.15	-.270	1.111	1.513	6.99	-.0103	1.565	.0110	279.4
60	5.00	2551	.0202	1924.5	26.37	-.243	1.113	1.364	9.64	-.0123	1.633	.0106	291.5
80	3.75	2491	.0174	1870.0	26.51	-.219	1.115	1.246	12.15	-.0142	1.678	.0103	299.5
100	3.00	2444	.0150	1828.8	26.62	-.198	1.117	1.150	14.55	-.0159	1.711	.0101	305.5
150	2.00	2355	.0103	1756.5	26.80	-.155	1.125	.968	20.22	-.0196	1.768	.0096	315.6
200	1.50	2288	.0057	1707.0	26.90	-.120	1.134	.839	25.55	-.0231	1.805	.0092	322.3
300	1.00	2187	-.0030	1640.1	27.02	-.076	1.148	.681	35.49	-.0284	1.855	.0086	331.2
400	.75	2109	-.0082	1594.7	27.08	-.051	1.160	.599	44.73	-.0324	1.888	.0082	337.2
600	.50	1993	-.0156	1533.8	27.14	-.024	1.176	.516	61.87	-.0373	1.932	.0075	344.9
800	.37	1909	-.0193	1492.7	27.16	-.013	1.184	.483	77.78	-.0393	1.961	.0070	350.1
1000	.30	1844	-.0208	1462.1	27.17	-.009	1.189	.468	92.86	-.0403	1.982	.0066	353.9
1500	.20	1728	-.0214	1409.1	27.18	-.004	1.195	.453	128.13	-.0412	2.018	.0060	360.3
r = 1.3; o/f = 2.618; percent fuel = 27.64													
10	30.00	2889	0.0271	2462.0	24.55	-.264	1.120	1.482	2.44	-.0068	1.278	0.0116	230.8
15	20.00	2790	.0243	2369.2	24.77	-.239	1.122	1.351	3.27	-.0087	1.371	.0111	247.7
20	15.00	2719	.0218	2305.8	24.91	-.213	1.125	1.235	4.04	-.0107	1.432	.0108	258.6
30	10.00	2618	.0175	2219.8	25.10	-.174	1.130	1.069	5.50	-.0139	1.510	.0103	272.7
40	7.50	2545	.0137	2161.1	25.22	-.146	1.135	.953	6.86	-.0164	1.561	.0099	281.9
60	5.00	2436	.0070	2081.8	25.36	-.108	1.145	.801	9.39	-.0202	1.627	.0092	293.8
80	3.75	2354	.0023	2027.9	25.45	-.080	1.154	.708	11.74	-.0234	1.671	.0087	301.7
100	3.00	2288	-.0014	1987.5	25.50	-.061	1.163	.645	13.97	-.0262	1.703	.0084	307.5
150	2.00	2163	-.0084	1917.3	25.56	-.034	1.177	.558	19.15	-.0302	1.757	.0076	317.3
200	1.50	2071	-.0119	1870.0	25.59	-.021	1.186	.519	23.94	-.0325	1.792	.0071	323.7
300	1.00	1943	-.0152	1806.8	25.62	-.010	1.196	.485	32.80	-.0345	1.839	.0064	332.1
400	.75	1853	-.0166	1764.5	25.63	-.006	1.200	.471	41.02	-.0351	1.869	.0059	337.6
600	.50	1731	-.0178	1708.1	25.63	-.003	1.205	.459	56.28	-.0355	1.909	.0053	344.8
800	.37	1649	-.0182	1670.4	25.64	-.001	1.206	.454	70.48	-.0355	1.935	.0049	349.5
1000	.30	1587	-.0183	1642.5	25.64	-.001	1.207	.452	83.96	-.0354	1.954	.0046	353.0
1500	.20	1480	-.0180	1594.3	25.64	-.001	1.208	.452	115.52	-.0350	1.987	.0042	358.8
r = 1.4; o/f = 2.431; percent fuel = 29.15													
10	30.00	2807	0.0203	2619.1	23.74	-.177	1.137	1.073	2.41	-.0094	1.276	0.0104	232.4
15	20.00	2688	.0167	2526.1	23.90	-.138	1.146	.930	3.21	-.0128	1.369	.0097	249.2
20	15.00	2601	.0132	2463.0	24.00	-.112	1.153	.833	3.96	-.0154	1.428	.0092	260.0
30	10.00	2474	.0062	2378.0	24.12	-.077	1.164	.708	5.34	-.0195	1.504	.0085	273.9
40	7.50	2380	.0003	2320.6	24.18	-.055	1.172	.635	6.61	-.0222	1.553	.0079	282.8
60	5.00	2243	-.0049	2243.6	24.24	-.033	1.185	.566	8.95	-.0253	1.617	.0071	294.4
80	3.75	2145	-.0079	2191.9	24.27	-.022	1.193	.531	11.12	-.0271	1.658	.0066	302.0
100	3.00	2069	-.0098	2153.4	24.28	-.015	1.199	.510	13.16	-.0288	1.689	.0062	307.5
150	2.00	1933	-.0122	2087.1	24.30	-.007	1.207	.484	17.89	-.0294	1.739	.0055	316.7
200	1.50	1840	-.0131	2042.7	24.31	-.004	1.210	.474	22.27	-.0297	1.773	.0050	322.8
300	1.00	1714	-.0138	1983.8	24.31	-.001	1.214	.466	30.38	-.0300	1.816	.0045	330.6
400	.75	1629	-.0140	1944.5	24.31	-.001	1.215	.463	37.91	-.0297	1.844	.0041	335.7
600	.50	1517	-.0142	1892.4	24.31	-.001	1.216	.461	51.90	-.0294	1.881	.0037	342.4
800	.37	1441	-.0142	1857.6	24.31	-.000	1.215	.462	64.92	-.0292	1.905	.0034	346.8
1000	.30	1385	-.0142	1831.9	24.31	-.000	1.215	.462	77.29	-.0290	1.922	.0032	350.0
1500	.20	1290	-.0141	1787.5	24.31	-.000	1.213	.466	106.28	-.0286	1.952	.0029	355.5

TABLE V. - Concluded. THEORETICAL ROCKET PERFORMANCE AT ASSIGNED PRESSURE RATIOS FROM 10 TO 1500 FOR JP-4 FUEL WITH LIQUID OXYGEN

[Equilibrium composition during isentropic expansion.]

(b) Concluded. Combustion-chamber pressure, 300 pounds per square inch absolute

Pressure ratio, P_c/P	Pressure, P, lb/sq in. abs	Temperature, T, °K	Temperature exponent, n_T, $\left(\frac{\partial \ln T}{\partial \ln P_c}\right)_{\frac{P_c}{P}}$	Enthalpy, h_s, cal/g	Molecular weight, M	Partial derivative, $\left(\frac{\partial \ln M}{\partial \ln T}\right)_s$	Isentropic exponent, γ, $\left(\frac{\partial \ln P}{\partial \ln \rho}\right)_s$	Specific heat, c_p, $\frac{cal}{(g)(°K)}$	Area ratio, ε	Area-ratio exponent, n_ε, $\left(\frac{\partial \ln \varepsilon}{\partial \ln P_c}\right)_{\frac{P_c}{P}}$	Thrust coefficient, C_F	Specific-impulse exponent, n_I, $\left(\frac{\partial \ln I}{\partial \ln P_c}\right)_{\frac{P_c}{P}}$	Specific impulse, I, $\frac{lb\text{-}sec}{lb}$
r = 1.5; o/f = 2.269; percent fuel = 30.59													
10	30.00	2678	0.0124	2774.9	22.89	-.097	1.164	0.784	2.37	-.0121	1.274	0.0086	233.0
15	20.00	2537	.0069	2683.3	22.99	-.066	1.175	.683	3.13	-.0156	1.364	.0078	249.5
20	15.00	2434	.0022	2621.6	23.05	-.048	1.184	.622	3.84	-.0182	1.422	.0072	260.1
30	10.00	2287	-.0030	2539.2	23.10	-.029	1.195	.561	5.13	-.0207	1.495	.0064	273.5
40	7.50	2182	-.0056	2483.9	23.12	-.019	1.203	.531	6.32	-.0220	1.543	.0058	282.2
60	5.00	2037	-.0080	2410.4	23.15	-.010	1.212	.502	8.51	-.0235	1.603	.0051	293.3
80	3.75	1937	-.0091	2361.4	23.15	-.006	1.216	.489	10.53	-.0239	1.643	.0047	300.5
100	3.00	1862	-.0097	2325.0	23.16	-.003	1.219	.482	12.43	-.0243	1.671	.0043	305.7
150	2.00	1731	-.0103	2262.5	23.16	-.001	1.222	.474	16.84	-.0241	1.719	.0038	314.5
200	1.50	1643	-.0105	2220.9	23.16	-.001	1.223	.472	20.93	-.0241	1.750	.0035	320.2
300	1.00	1525	-.0107	2165.8	23.16	-.000	1.223	.470	28.50	-.0238	1.791	.0031	327.6
400	.75	1448	-.0107	2129.2	23.16	-.000	1.223	.471	35.54	-.0236	1.817	.0029	332.4
600	.50	1345	-.0106	2080.6	23.16	-.000	1.221	.474	48.60	-.0232	1.851	.0026	338.7
800	.37	1277	-.0106	2048.3	23.16	-.000	1.219	.477	60.78	-.0229	1.874	.0024	342.8
1000	.30	1227	-.0105	2024.3	23.16	-.000	1.218	.480	72.36	-.0227	1.891	.0022	345.8
1500	.20	1141	-.0103	1983.2	23.16	-.000	1.214	.487	99.52	-.0223	1.919	.0020	351.0
r = 1.6; o/f = 2.127; percent fuel = 31.98													
10	30.00	2519	0.0049	2930.3	22.04	-.048	1.190	0.633	2.32	-.0128	1.271	0.0066	232.5
15	20.00	2362	-.0001	2841.2	22.09	-.029	1.202	.572	3.05	-.0153	1.359	.0058	248.6
20	15.00	2252	-.0027	2781.5	22.12	-.019	1.209	.542	3.72	-.0167	1.415	.0052	258.9
30	10.00	2099	-.0051	2702.3	22.14	-.010	1.218	.513	4.94	-.0179	1.486	.0045	271.8
40	7.50	1993	-.0061	2649.5	22.15	-.006	1.223	.499	6.07	-.0184	1.531	.0041	280.2
60	5.00	1850	-.0071	2579.7	22.15	-.003	1.227	.487	8.14	-.0187	1.589	.0035	290.8
80	3.75	1754	-.0074	2533.2	22.16	-.002	1.229	.482	10.05	-.0186	1.627	.0032	297.7
100	3.00	1682	-.0076	2498.8	22.16	-.001	1.230	.480	11.85	-.0186	1.654	.0030	302.7
150	2.00	1559	-.0078	2439.9	22.16	-.000	1.231	.478	16.03	-.0185	1.700	.0026	311.0
200	1.50	1477	-.0078	2400.7	22.16	-.000	1.231	.479	19.91	-.0183	1.729	.0024	316.5
300	1.00	1370	-.0078	2349.0	22.16	-.000	1.229	.481	27.08	-.0179	1.768	.0021	323.5
400	.75	1298	-.0078	2314.6	22.16	-.000	1.227	.484	33.75	-.0177	1.793	.0020	328.1
600	.50	1205	-.0076	2269.1	22.16	-.000	1.224	.490	46.14	-.0175	1.826	.0018	334.1
800	.37	1143	-.0075	2238.8	22.16	-.000	1.221	.496	57.70	-.0172	1.847	.0016	338.0
1000	.30	1099	-.0074	2216.4	22.16	-.000	1.218	.501	68.71	-.0170	1.863	.0015	340.9
1500	.20	1022	-.0073	2177.9	22.16	-.000	1.213	.511	94.57	-.0167	1.889	.0014	345.7
r = 1.8; o/f = 1.891; percent fuel = 34.59													
10	30.00	2185	-.0012	3238.0	20.46	-.011	1.231	0.529	2.23	-.0087	1.265	0.0033	228.8
15	20.00	2024	-.0025	3155.1	20.48	-.005	1.238	.510	2.91	-.0096	1.349	.0028	244.0
20	15.00	1915	-.0032	3100.2	20.48	-.003	1.242	.502	3.53	-.0097	1.403	.0025	253.6
30	10.00	1769	-.0036	3027.8	20.48	-.001	1.245	.494	4.66	-.0097	1.470	.0021	265.7
40	7.50	1672	-.0038	2979.7	20.48	-.001	1.246	.492	5.71	-.0095	1.513	.0019	273.5
60	5.00	1543	-.0039	2916.6	20.48	-.000	1.246	.491	7.63	-.0094	1.567	.0016	283.4
80	3.75	1458	-.0039	2874.7	20.48	-.000	1.246	.492	9.39	-.0092	1.602	.0014	289.7
100	3.00	1395	-.0039	2843.8	20.48	-.000	1.245	.493	11.06	-.0091	1.628	.0013	294.3
150	2.00	1288	-.0039	2791.1	20.49	-.000	1.242	.497	14.93	-.0091	1.670	.0012	302.0
200	1.50	1218	-.0038	2756.1	20.49	-.000	1.240	.502	18.52	-.0089	1.698	.0011	307.0
300	1.00	1127	-.0037	2710.0	20.48	-.000	1.235	.510	25.18	-.0087	1.734	.0010	313.5
400	.75	1068	-.0036	2679.4	20.48	-.001	1.231	.517	31.37	-.0084	1.757	.0009	317.7
600	.50	990	-.0034	2639.0	20.48	-.001	1.225	.530	42.91	-.0081	1.787	.0008	323.2
800	.37	940	-.0032	2612.1	20.49	-.001	1.220	.540	53.70	-.0080	1.807	.0007	326.8
1000	.30	903	-.0031	2592.2	20.49	-.002	1.216	.548	63.97	-.0078	1.822	.0007	329.4
1500	.20	841	-.0028	2557.9	20.49	-.002	1.209	.565	88.18	-.0075	1.847	.0006	333.9
r = 2.0; o/f = 1.702; percent fuel = 37.01													
10	30.00	1886	-.0013	3536.3	19.14	-.002	1.257	0.510	2.17	-.0039	1.262	0.0014	222.6
15	20.00	1735	-.0016	3460.1	19.14	-.001	1.260	.503	2.81	-.0039	1.344	.0011	237.0
20	15.00	1635	-.0017	3409.8	19.14	-.000	1.261	.502	3.40	-.0040	1.395	.0010	246.1
30	10.00	1503	-.0017	3343.8	19.15	-.000	1.261	.501	4.48	-.0039	1.460	.0008	257.5
40	7.50	1416	-.0017	3300.3	19.15	-.000	1.261	.502	5.48	-.0039	1.501	.0008	264.8
60	5.00	1303	-.0020	3243.1	19.15	-.000	1.259	.504	7.30	-.0037	1.553	.0006	274.0
80	3.75	1228	-.0019	3205.3	19.15	-.000	1.256	.508	8.99	-.0037	1.587	.0006	279.9
100	3.00	1174	-.0015	3177.5	19.15	-.001	1.254	.513	10.57	-.0035	1.611	.0005	284.2
150	2.00	1081	-.0004	3130.1	19.14	-.004	1.247	.529	14.25	-.0026	1.652	.0005	291.4
200	1.50	1021	.0009	3098.7	19.14	-.008	1.241	.545	17.67	-.0017	1.678	.0004	296.0
300	1.00	945	.0031	3057.4	19.15	-.017	1.230	.578	24.03	-.0008	1.713	.0004	302.0
400	.75	897	.0047	3029.9	19.17	-.025	1.221	.609	29.99	.0009	1.735	.0004	306.0
600	.50	838	.0062	2993.5	19.22	-.039	1.204	.667	41.22	.0025	1.764	.0005	311.1

4045

TABLE VI. - THEORETICAL ROCKET PERFORMANCE FOR COMPLETE EXPANSION TO EXIT PRESSURE OF 1 ATMOSPHERE FOR JP-4 FUEL AND LIQUID OXYGEN

[Equilibrium composition during isentropic expansion.]

Equivalence ratio, r, $\frac{4(C) + (H)}{2(O)}$	Percent fuel by weight	Oxidant-to-fuel weight ratio, o/f	Combustion temperature, T_c, °K	Exit temperature, T_e, °K	Characteristic velocity, c*, ft/sec	Thrust coefficient, C_F	Area ratio, ε	Specific impulse, I, $\frac{\text{lb-sec}}{\text{lb}}$
Combustion-chamber pressure, 600 lb/sq in. abs								
1.00	22.71	3.403	3612	2718	5622	1.569	7.14	274.2
1.20	26.07	2.836	3628	2673	5795	1.566	7.05	282.1
1.30	27.64	2.618	3612	2558	5859	1.561	6.88	284.4
1.40	29.15	2.431	3576	2371	5904	1.553	6.61	284.9
1.50	30.59	2.269	3518	2167	5924	1.541	6.32	283.8
1.60	31.98	2.127	3436	1978	5918	1.530	6.09	281.5
1.80	34.59	1.891	3205	1661	5832	1.513	5.76	274.3
2.00	37.01	1.702	2923	1409	5679	1.503	5.55	265.4
3.00	46.85	1.134	1657	1015	4674	1.537	6.42	223.3
Combustion-chamber pressure, 300 lb/sq in. abs								
1.00	22.71	3.403	3507	2797	5572	1.440	4.18	249.3
1.20	26.07	2.836	3523	2776	5745	1.438	4.15	256.8
1.30	27.64	2.618	3511	2714	5810	1.436	4.10	259.3
1.40	29.15	2.431	3482	2595	5859	1.432	4.02	260.7
1.50	30.59	2.269	3433	2427	5886	1.426	3.90	260.8
1.60	31.98	2.127	3363	2244	5888	1.418	3.77	259.6
1.80	34.59	1.891	3160	1907	5818	1.406	3.57	254.3
2.00	37.01	1.702	2900	1628	5674	1.399	3.45	246.7

TABLE VII. - EQUILIBRIUM COMPOSITION OF PRODUCTS OF REACTION AT ASSIGNED TEMPERATURES FOR JP-4 FUEL AND LIQUID OXYGEN

[Isentropic expansion or compression from combustion conditions.]

(a) Combustion-chamber pressure, 600 pounds per square inch absolute

Mole fraction[a] at temperature T, °K										
r = 1.0; o/f = 3.403; percent fuel = 22.71										
T, °K	4000	[b]3612	3600	3200	2800	2400	2000	1600	900	
CO	0.23473	0.21540	0.21467	0.18574	0.14517	0.09229	0.03652	0.00482	--------	
CO_2	.16604	.19895	.20015	.24590	.30633	.38148	.45811	.50082	0.50734	
H	.02986	.02369	.02349	.01701	.01069	.00505	.00180	.00005	--------	
H_2	.04573	.04043	.04025	.03374	.02609	.01723	.00790	.00151	--------	
H_2O	.27686	.30785	.30892	.34566	.38672	.43007	.46877	.48919	.49265	
O	.04324	.03303	.03270	.02223	.01259	.00499	.00088	.00002	--------	
O_2	.10025	.09621	.09603	.08726	.07187	.04842	.02055	.00303	--------	
OH	.10329	.08444	.08380	.06246	.04055	.02046	.00607	.00056	--------	
r = 1.2; o/f = 2.836; percent fuel = 26.07										
T, °K	4000	[b]3628	3600	3200	2800	2400	2000	1600	1200	900
CO	0.29586	0.28284	0.28163	0.26076	0.23308	0.20684	0.19393	0.17833	0.14424	0.09103
CO_2	.13902	.16572	.16805	.20614	.25264	.29456	.31277	.32898	.36310	.41631
H	.03879	.03125	.03067	.02235	.01406	.00636	.00141	.00011	--------	--------
H_2	.07136	.06578	.06534	.05869	.05235	.04993	.05688	.07284	.10698	.16019
H_2O	.28698	.31844	.32097	.35902	.39859	.42933	.43399	.41973	.38568	.33246
O	.03105	.02262	.02198	.01317	.00557	.00094	.00002	--------	--------	--------
O_2	.04783	.04189	.04132	.03088	.01634	.00315	.00007	--------	--------	--------
OH	.08912	.07146	.07004	.04900	.02739	.00888	.00092	.00002	--------	--------
r = 1.3; o/f = 2.618; percent fuel = 27.64										
T, °K	4000	[b]3612	3600	3200	2800	2400	2000	1600	1200	900
CO	0.32446	0.31453	0.31416	0.29939	0.28220	0.26944	0.25858	0.23870	0.19676	0.13234
CO_2	.12367	.14764	.14847	.17937	.21222	.23474	.24835	.26862	.31059	.37501
H	.04264	.03378	.03350	.02399	.01432	.00574	.00116	.00008	--------	--------
H_2	.08777	.08240	.08223	.07682	.07374	.07736	.08865	.10909	.15109	.21551
H_2O	.28633	.31891	.31995	.35615	.38953	.40691	.40280	.38349	.34157	.27714
O	.02475	.01675	.01651	.00879	.00285	.00030	.00001	--------	--------	--------
O_2	.03091	.02480	.02458	.01562	.00579	.00062	.00001	--------	--------	--------
OH	.07947	.06119	.06060	.03987	.01936	.00490	.00045	.00001	--------	--------
r = 1.4; o/f = 2.431; percent fuel = 29.15										
T, °K	3600	[b]3576	3200	2800	2400	2000	1600	1200	900	
CO	0.34489	0.34444	0.33630	0.32751	0.31995	0.30849	0.28626	0.24044	0.17069	
CO_2	.12785	.12914	.15070	.17146	.18527	.19855	.22106	.26690	.33665	
H	.03552	.03488	.02465	.01371	.00501	.00096	.00007	--------	--------	
H_2	.10270	.10247	.09966	.10074	.10824	.12157	.14436	.19023	.25998	
H_2O	.31341	.31534	.34559	.37047	.37843	.37018	.34824	.30243	.23268	
O	.01165	.01124	.00535	.00133	.00011	--------	--------	--------	--------	
O_2	.01360	.01324	.00711	.00188	.00015	--------	--------	--------	--------	
OH	.05038	.04923	.03064	.01290	.00284	.00025	.00001	--------	--------	
r = 1.6; o/f = 2.127; percent fuel = 31.98										
T, °K	3600	[b]3436	3200	2800	2400	2000	1600	1200		
CO	0.39683	0.39669	0.39624	0.39430	0.38899	0.37740	0.35488	0.30879		
CO_2	.08894	.09344	.09949	.10838	.11709	.12975	.15246	.19856		
H	.03660	.03118	.02344	.01160	.00382	.00068	.00004	--------		
H_2	.15384	.15462	.15681	.16359	.17355	.18735	.21034	.25647		
H_2O	.28388	.29328	.30468	.31587	.31540	.30473	.28228	.23619		
O	.00499	.00343	.00172	.00031	.00002	--------	--------	--------		
O_2	.00353	.00248	.00128	.00023	.00001	--------	--------	--------		
OH	.03139	.02488	.01633	.00573	.00113	.00009	--------	--------		
r = 1.8; o/f = 1.891; percent fuel = 34.59										
T, °K	3600	[b]3205	3200	2800	2400	2000	1600	1200	900	
CH_4	--------	--------	--------	--------	--------	--------	--------	--------	0.00016	
CO	0.43331	0.43518	0.43519	0.43472	0.43042	0.42044	0.40078	0.35968	.29689	
CO_2	.05929	.06430	.06436	.06945	.07604	.08676	.10656	.14766	.21046	
H	.03447	.02080	.02064	.00952	.00296	.00050	.00003	--------	--------	
H_2	.21259	.21932	.21942	.22779	.23713	.24907	.26912	.31024	.37262	
H_2O	.23949	.25101	.25111	.25566	.25293	.24317	.22351	.18241	.11987	
O	.00196	.00057	.00056	.00009	.00001	--------	--------	--------	--------	
O_2	.00084	.00025	.00025	.00004	--------	--------	--------	--------	--------	
OH	.01805	.00857	.00847	.00273	.00051	.00004	--------	--------	--------	
r = 3.0; o/f = 1.134; percent fuel = 46.85										
T, °K	2000	[b]1657	1600	1200	900					
GRAPHITE	--------	0.00130	0.00213	0.03684	0.14454					
CH_4	0.00838	.01146	.01219	.01828	.01304					
CO	.50682	.50434	.50303	.45006	.27290					
CO_2	.00062	.00187	.00236	.02072	.09009					
H	.00011	.00001	.00001	--------	--------					
H_2	.48128	.47514	.47333	.44478	.41695					
H_2O	.00279	.00588	.00695	.02932	.06247					

[a] Mole fractions were computed for all 11 substances considered in this report but are omitted if less than 5×10^{-6}.

[b] Combustion temperature.

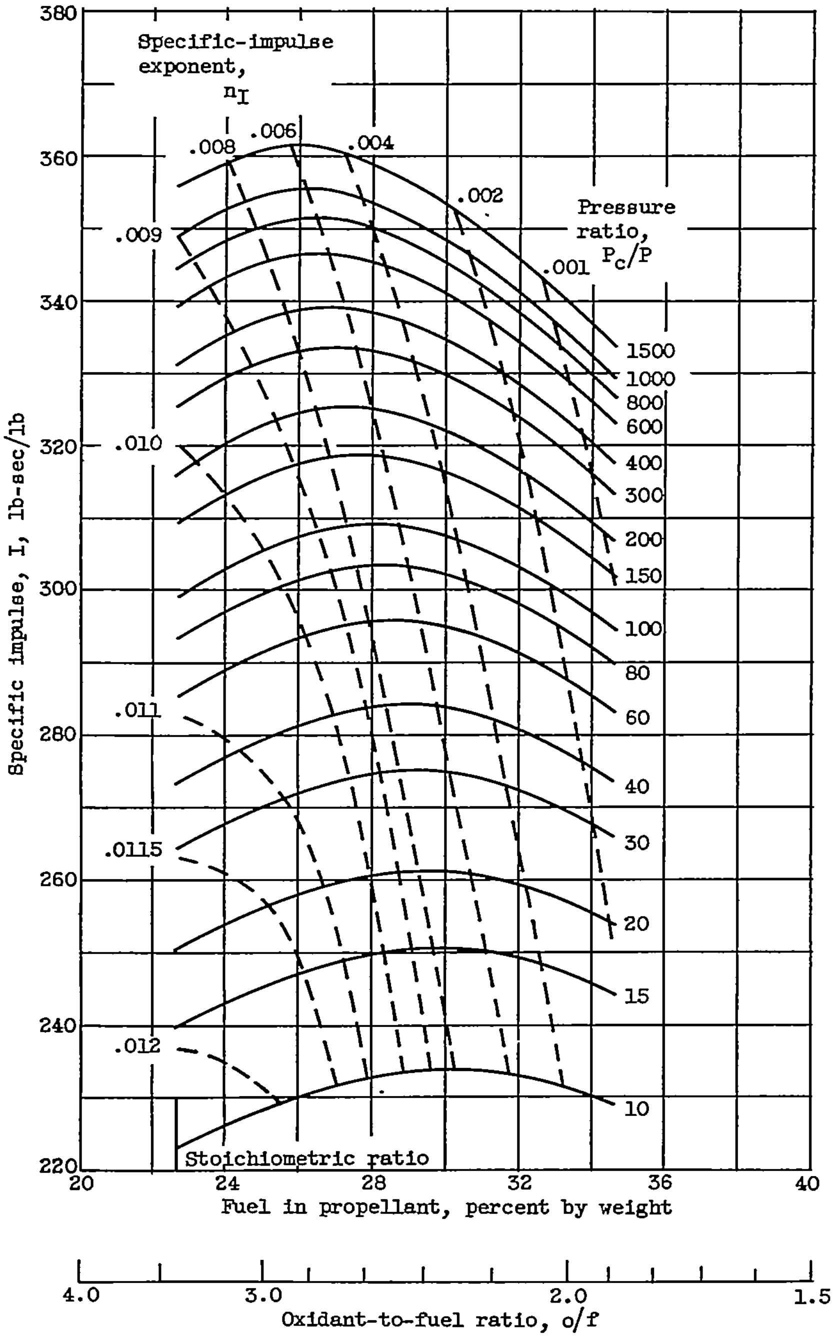
TABLE VII. - Concluded. EQUILIBRIUM COMPOSITION OF PRODUCTS OF REACTION AT ASSIGNED TEMPERATURES FOR JP-4 FUEL AND LIQUID OXYGEN

[Isentropic expansion or compression from combustion conditions.]

(b) Combustion-chamber pressure, 300 pounds per square inch absolute

Mole fraction[a] at temperature T, °K									
r = 1.0; o/f = 3.403; percent fuel = 22.71									
T, °K	3600	[b]3507	3200	2800	2400	2000			
CO	0.28541	0.22000	0.19815	0.15861	0.10488	0.04436			
CO_2	.18116	.19031	.22575	.28599	.36345	.44730			
H	.02908	.02731	.02143	.01387	.00692	.00183			
H_2	.04405	.04262	.03740	.02944	.02005	.00971			
H_2O	.29149	.29989	.32967	.37288	.41950	.46309			
O	.03947	.03664	.02738	.01604	.00675	.00132			
O_2	.09991	.09868	.09251	.07824	.05494	.02497			
OH	.08943	.08455	.06771	.04494	.02351	.00742			
r = 1.2; o/f = 2.836; percent fuel = 26.07									
T, °K	3600	[b]3523	3200	2800	2400	2000	1600		
CO	0.28836	0.28519	0.26864	0.24059	0.20999	0.19390	0.17831		
CO_2	.15264	.15906	.19043	.23890	.28851	.31249	.32898		
H	.03763	.03578	.02790	.01813	.00877	.00207	.00016		
H_2	.06930	.06802	.06236	.05522	.05097	.05682	.07282		
H_2O	.30201	.30933	.34204	.38516	.42281	.43320	.41969		
O	.02768	.02566	.01733	.00804	.00169	.00005	-------		
O_2	.04615	.04466	.03643	.02161	.00545	.00014	-------		
OH	.07623	.07289	.05487	.03235	.01181	.00134	.00003		
r = 1.3; o/f = 2.618; percent fuel = 27.64									
T, °K	3600	[b]3511	3200	2800	2400	2000	1600	1200	
CO	0.31832	0.31559	0.30401	0.28536	0.26968	0.25844	0.23869	0.19676	
CO_2	.13587	.14233	.16759	.20428	.23298	.24829	.26862	.31059	
H	.04114	.03872	.03012	.01879	.00806	.00169	.00012	-------	
H_2	.08570	.08436	.07974	.07530	.07733	.08852	.10908	.15109	
H_2O	.30117	.30962	.34012	.37869	.40334	.40236	.38347	.34157	
O	.02157	.01943	.01228	.00457	.00059	.00001	-------	-------	
O_2	.02901	.02789	.02008	.00885	.00120	.00002	-------	-------	
OH	.06721	.06265	.04606	.02417	.00682	.00065	.00001	-------	
r = 1.4; o/f = 2.431; percent fuel = 29.15									
T, °K	3600	[b]3482	3200	2800	2400	2000	1600	1200	
CO	0.34652	0.34425	0.33787	0.32782	0.31953	0.30836	0.28625	0.24044	
CO_2	.11836	.12532	.14302	.16778	.18474	.19854	.22107	.26690	
H	.04383	.04019	.03132	.01834	.00707	.00139	.00010	-------	
H_2	.10516	.10383	.10126	.10090	.10781	.12144	.14435	.19023	
H_2O	.29570	.30638	.33166	.36276	.37632	.36991	.34823	.30243	
O	.01597	.01348	.00803	.00232	.00022	-------	-------	-------	
O_2	.01718	.01521	.01008	.00382	.00030	-------	-------	-------	
OH	.05729	.05134	.03677	.01687	.00401	.00036	.00001	-------	
r = 1.5; o/f = 2.269; percent fuel = 30.59									
T, °K	3600	[b]3433	3200	2800	2400	2000	1600	1200	900
CO	0.37224	0.37083	0.36848	0.36410	0.35847	0.34705	0.32420	0.27730	0.20618
CO_2	.10099	.10840	.11887	.13481	.14659	.15994	.18312	.23005	.30117
H	.04550	.03973	.03143	.01722	.00616	.00115	.00008	-------	-------
H_2	.12777	.12700	.12684	.13055	.14014	.15459	.17819	.22515	.29627
H_2O	.28539	.29886	.31662	.33957	.34599	.33705	.31440	.26751	.19639
O	.01125	.00838	.00492	.00114	.00009	-------	-------	-------	-------
O_2	.00961	.00754	.00471	.00115	.00009	-------	-------	-------	-------
OH	.04724	.03926	.02813	.01146	.00247	.00021	-------	-------	-------
r = 1.6; o/f = 2.127; percent fuel = 31.98									
T, °K	3600	[b]3363	3200	2800	2400	2000	1600	1200	900
CO	0.39489	0.39483	0.39460	0.39314	0.38851	0.37730	0.35487	0.30879	0.23894
CO_2	.08470	.09214	.09711	.10769	.11703	.12976	.15246	.19856	.26841
H	.04608	.03701	.03064	.01585	.00539	.00097	.00006	-------	-------
H_2	.15320	.15414	.15553	.16227	.17293	.18722	.21034	.25647	.32631
H_2O	.27055	.28642	.29617	.31224	.31448	.30461	.28227	.23619	.16634
O	.00761	.00457	.00291	.00058	.00004	-------	-------	-------	-------
O_2	.00514	.00326	.00212	.00043	.00003	-------	-------	-------	-------
OH	.03782	.02764	.02092	.00780	.00159	.00013	-------	-------	-------
r = 1.8; o/f = 1.891; percent fuel = 34.59									
T, °K	3200	[b]3160	2800	2400	2000	1600	1200	900	
CH_4	-------	-------	-------	-------	-------	-------	-------	0.00004	
CO	0.43311	0.43328	0.43364	0.43006	0.42038	0.40078	0.35968	.29702	
CO_2	.06367	.06424	.06930	.07604	.08677	.10656	.14766	.21033	
H	.02752	.02595	.01311	.00417	.00072	.00004			
H_2	.21661	.21747	.22611	.23652	.24896	.26912	.31025	.37281	
H_2O	.24642	.24753	.25383	.25248	.24311	.22350	.18241	.11980	
O	.00101	.00087	.00017	.00001	-------	-------	-------	-------	
O_2	.00044	.00038	.00007	-------	-------	-------	-------	-------	
OH	.01122	.01029	.00377	.00072	.00006	-------	-------	-------	
r = 2.0; o/f = 1.702; percent fuel = 37.01									
T, °K	3200	[b]2900	2800	2400	2000	1600	1200	900	
CH_4	-------	-------	-------	-------	-------	-------	-------	0.00055	
CO	0.45790	.45896	0.45891	0.45629	0.44872	0.43299	0.39898	.34609	
CO_2	.04168	.04423	.04519	.05013	.05848	.07434	.10836	.16126	
H	.02373	.01351	.01073	.00327	.00054	.00003	-------	-------	
H_2	.27592	.28325	.28561	.29456	.30448	.32065	.35469	.40620	
H_2O	.19433	.19729	.19758	.19539	.18775	.17198	.13797	.08589	
O	.00036	.00009	.00005	-------	-------	-------	-------	-------	
O_2	.00010	.00003	.00001	-------	-------	-------	-------	-------	
OH	.00599	.00264	.00190	.00035	.00003	-------	-------	-------	

[a] Mole fractions were computed for all 11 substances considered in this report but are omitted if less than 5×10^{-6}.
[b] Combustion temperature.

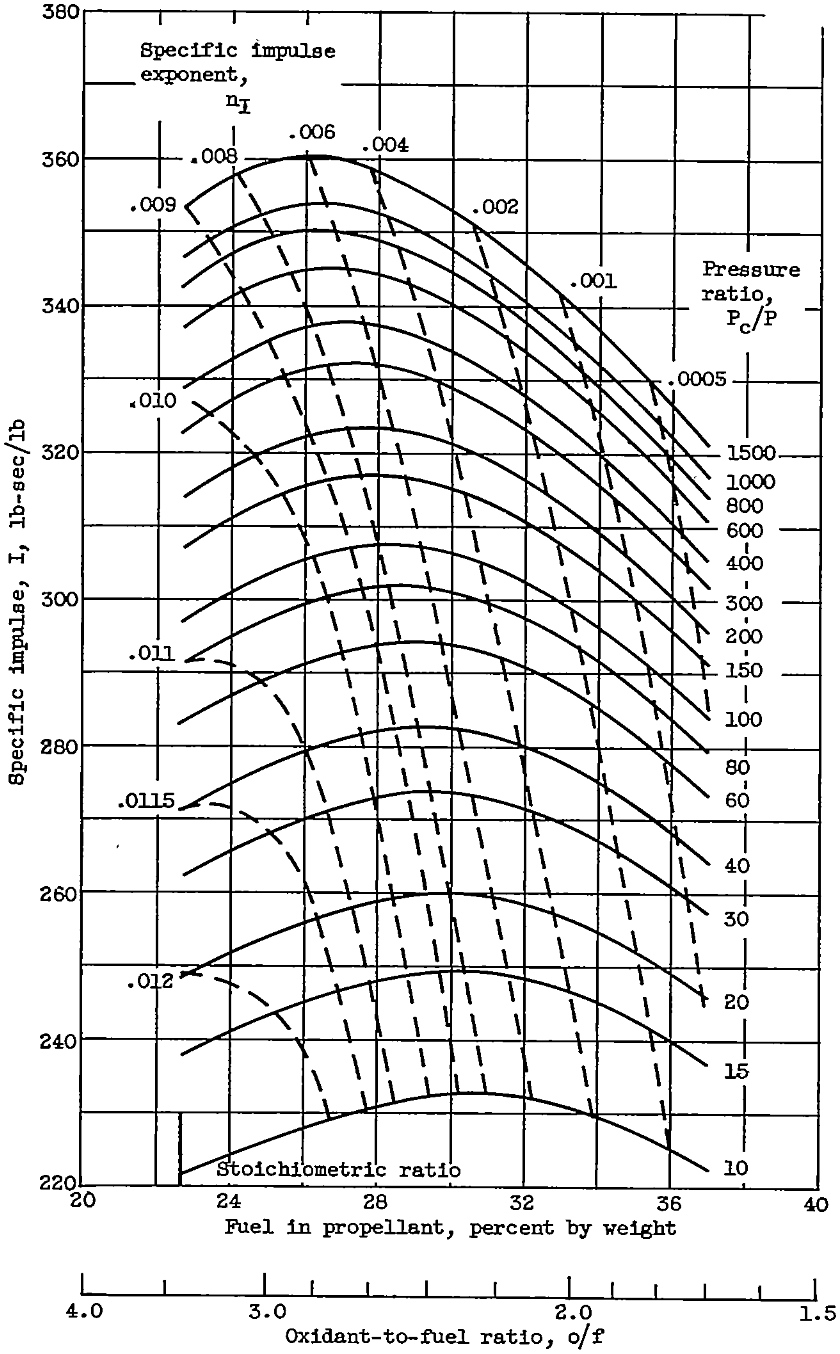


(a) Chamber pressure, 600 pounds per square inch absolute.

Exponent n_I for use in equation $I = I_{600}\left(\frac{P_c}{600}\right)^{n_I}$.

Figure 1. - Theoretical specific impulse of JP-4 fuel with liquid oxygen. Equilibrium composition during isentropic expansion to pressure ratio indicated.

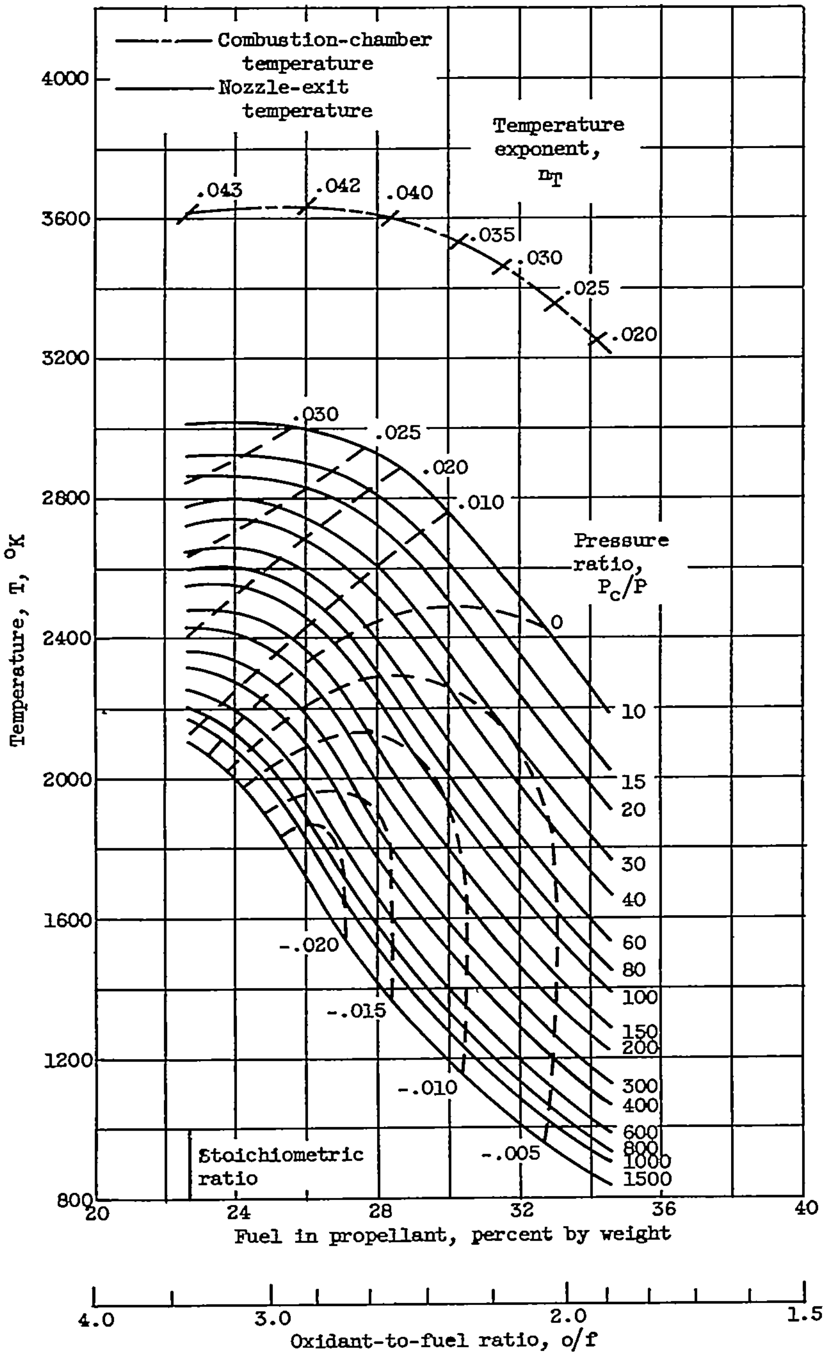
CW-5 back 4045



(b) Chamber pressure, 300 pounds per square inch absolute.

Exponent n_I for use in equation $I = I_{300}\left(\frac{P_c}{300}\right)^{n_I}$.

Figure 1. - Concluded. Theoretical specific impulse of JP-4 fuel with liquid oxygen. Equilibrium composition during isentropic expansion to pressure ratio indicated.



(a) Chamber pressure, 600 pounds per square inch absolute.

Exponent n_T for use in equation $T = T_{600}\left(\frac{P_c}{600}\right)^{n_T}$.

Figure 2. - Theoretical combustion-chamber temperature and nozzle-exit temperature of JP-4 fuel with liquid oxygen. Equilibrium composition during isentropic expansion to pressure ratio indicated.

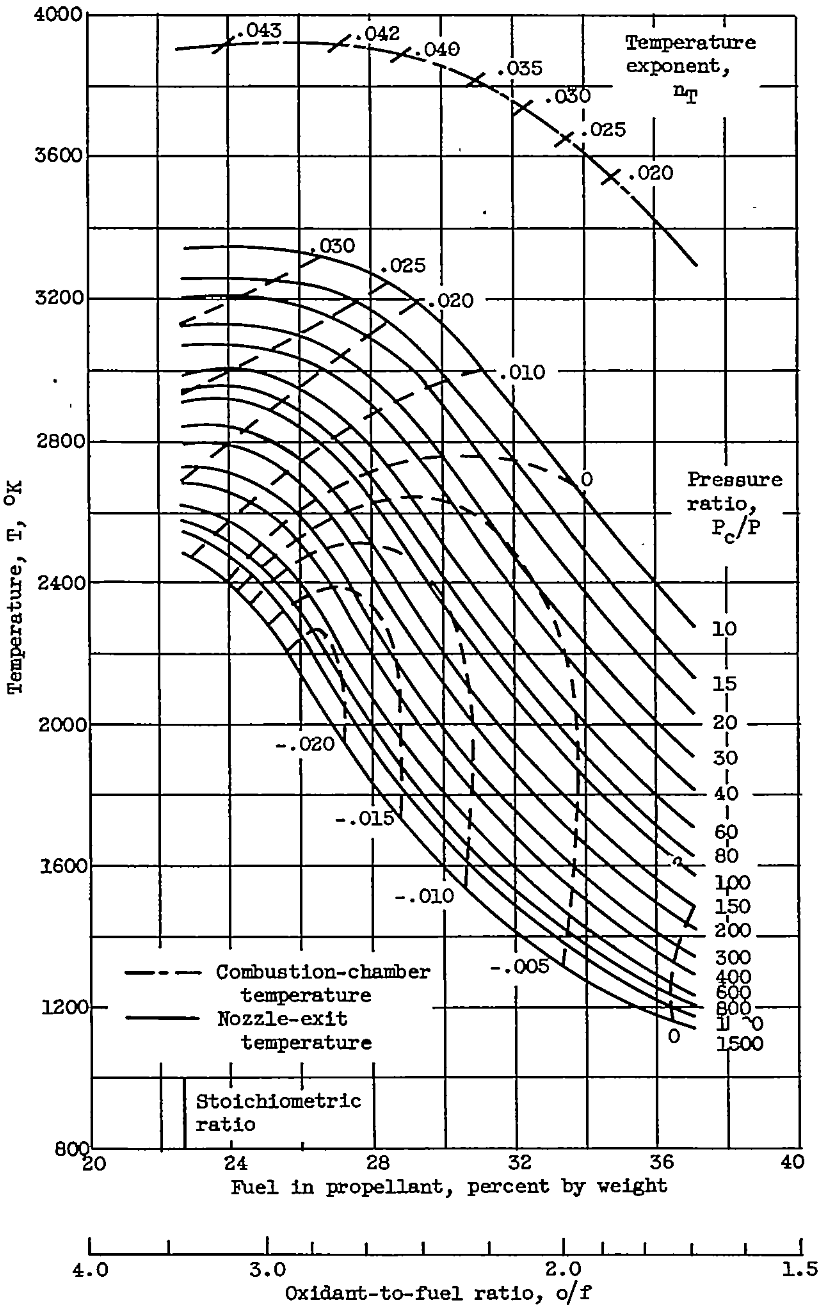
ERRATA

NACA Research Memorandum E56D23

By Vearl N. Huff, Anthony Fortini, and Sanford Gordon
September 7, 1956

Figure 2, page 37: The ordinate should be 400, 800, 1200, 1600, 2000, 2400, 2800, 3200, and 3600 instead of 800, 1200, 1600, 2000, 2400, 2800, 3200, 3600, and 4000.

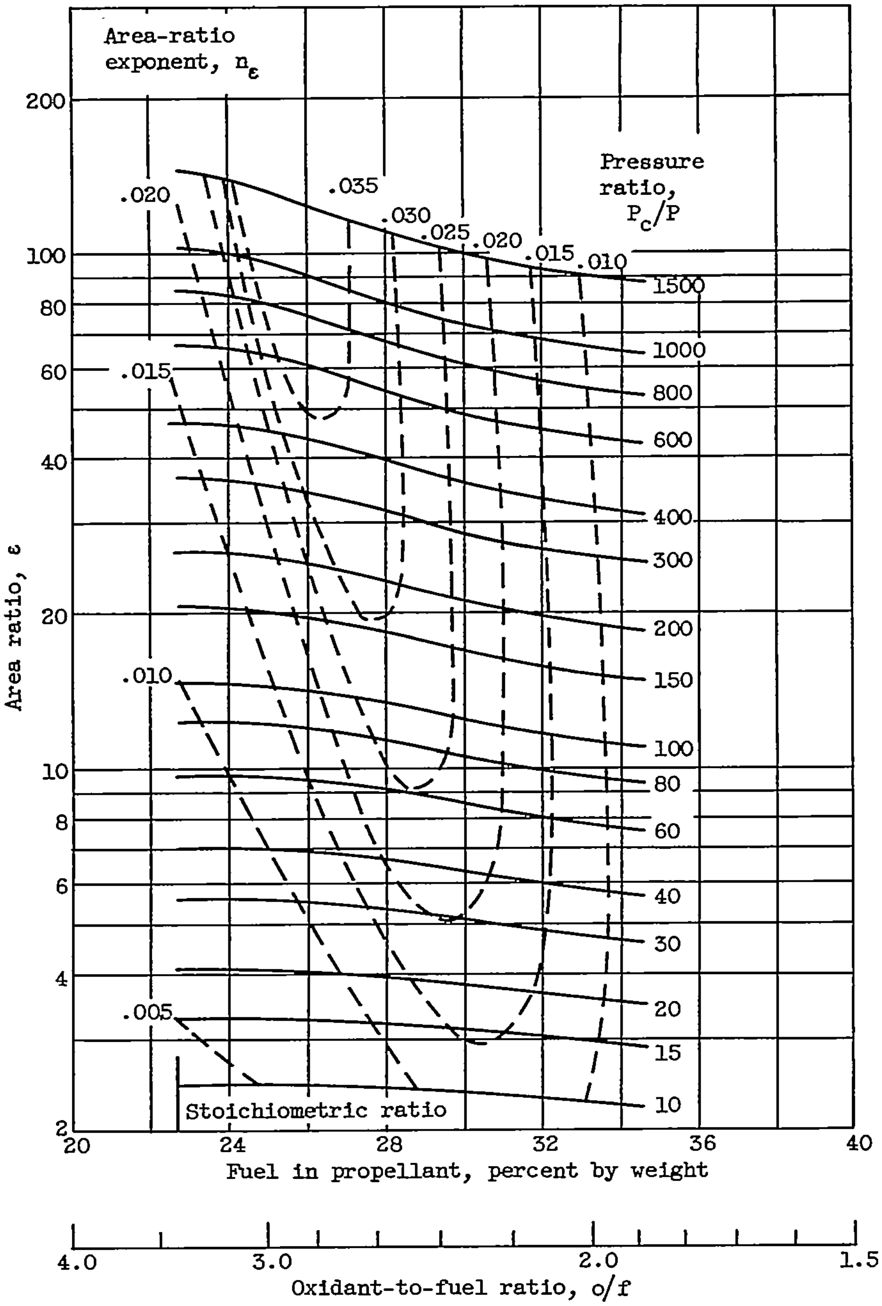
Issued 1-18-57.



(b) Chamber pressure, 300 pounds per square inch absolute.

Exponent n_T for use in equation $T = T_{300}\left(\frac{P_c}{300}\right)^{n_T}$.

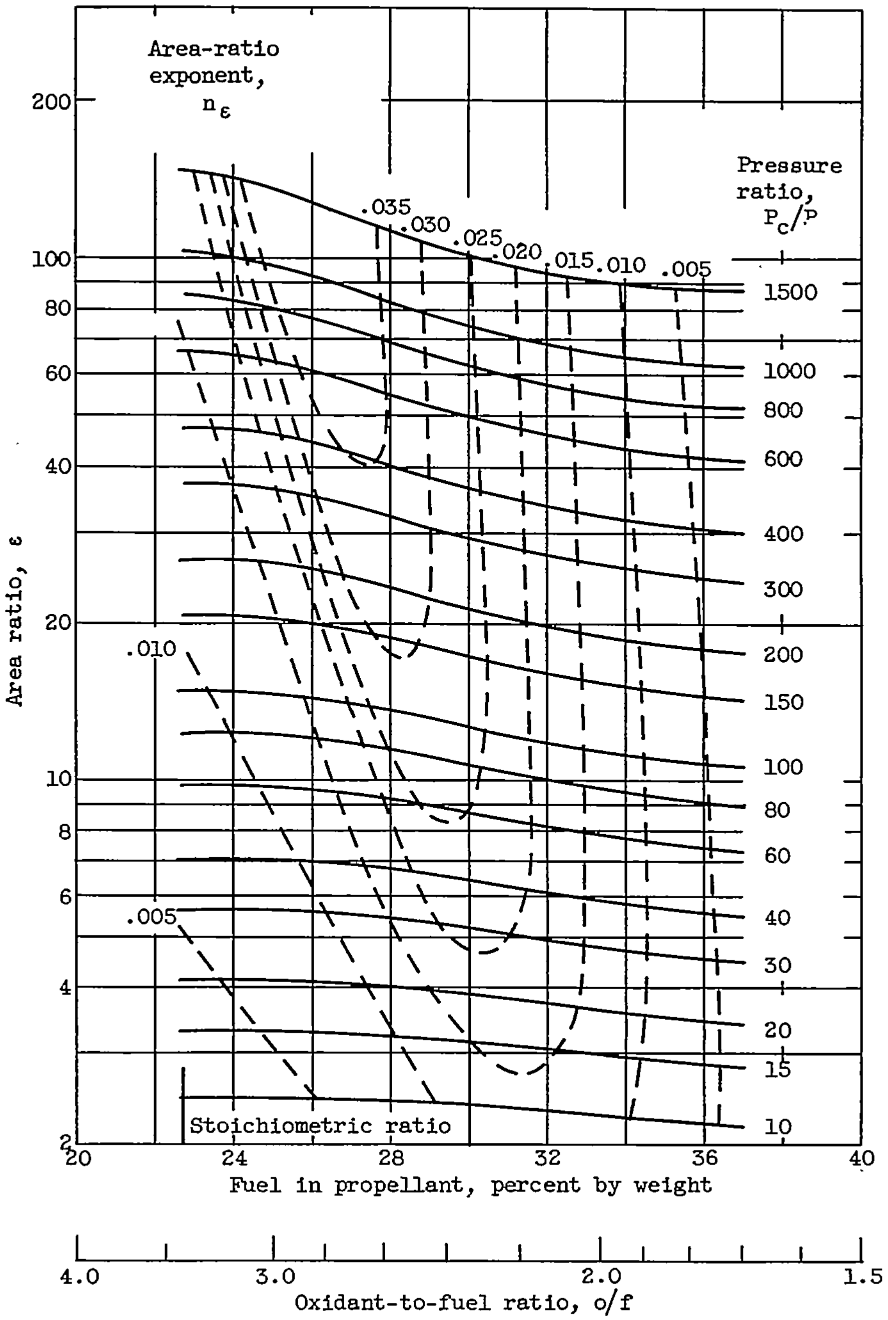
Figure 2. - Concluded. Theoretical combustion-chamber temperature and nozzle-exit temperature of JP-4 fuel with oxygen. Equilibrium composition during isentropic expansion to pressure ratio indicated.



(a) Chamber pressure, 600 pounds per square inch absolute.

Exponent n_ε for use on equation $\varepsilon = \varepsilon_{600}\left(\frac{P_c}{600}\right)^{n_\varepsilon}$.

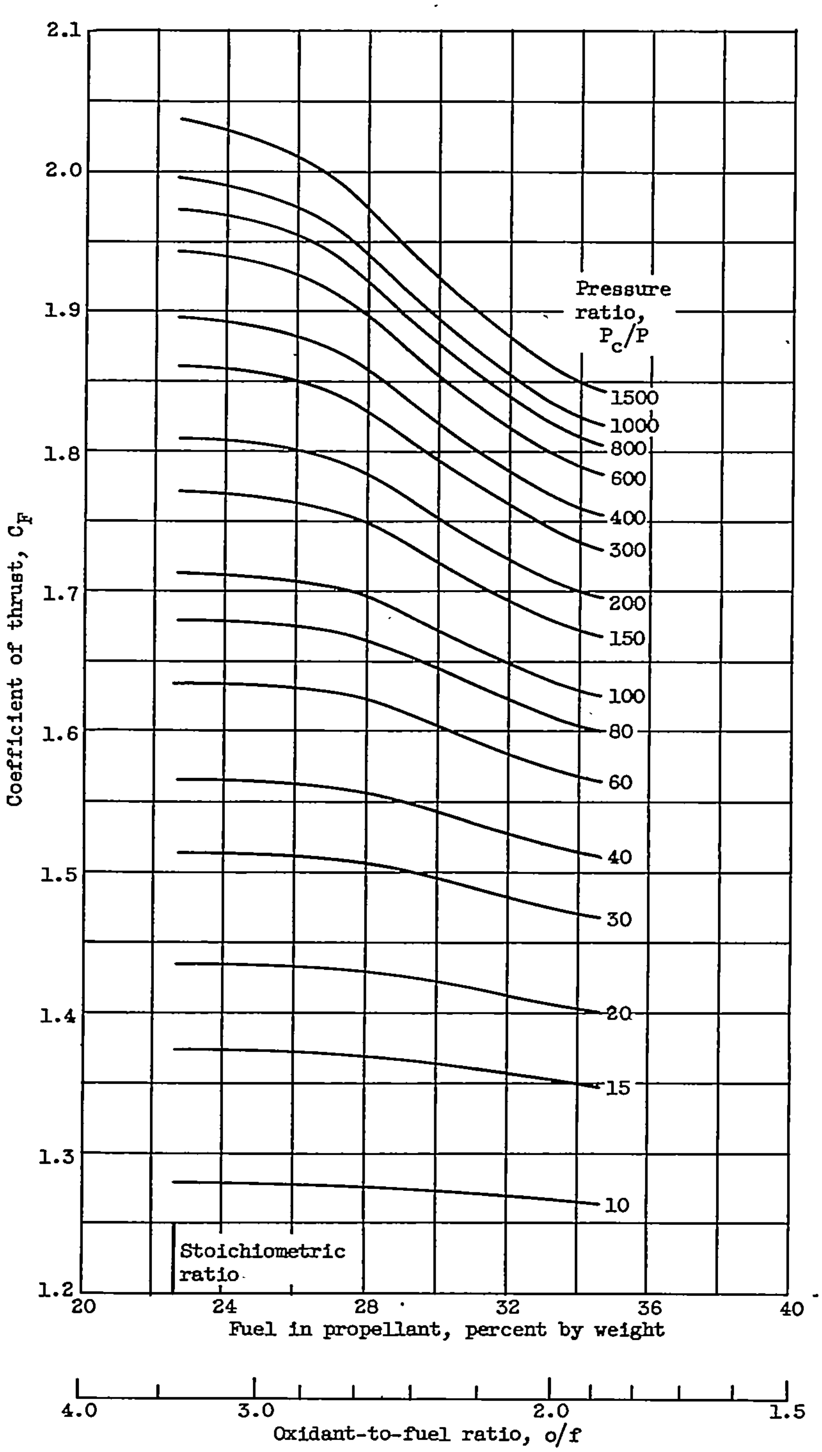
Figure 3. - Theoretical ratio of nozzle area to throat area for JP-4 fuel with liquid oxygen. Equilibrium composition during isentropic expansion to pressure ratio indicated.



(b) Chamber pressure, 300 pounds per square inch absolute.

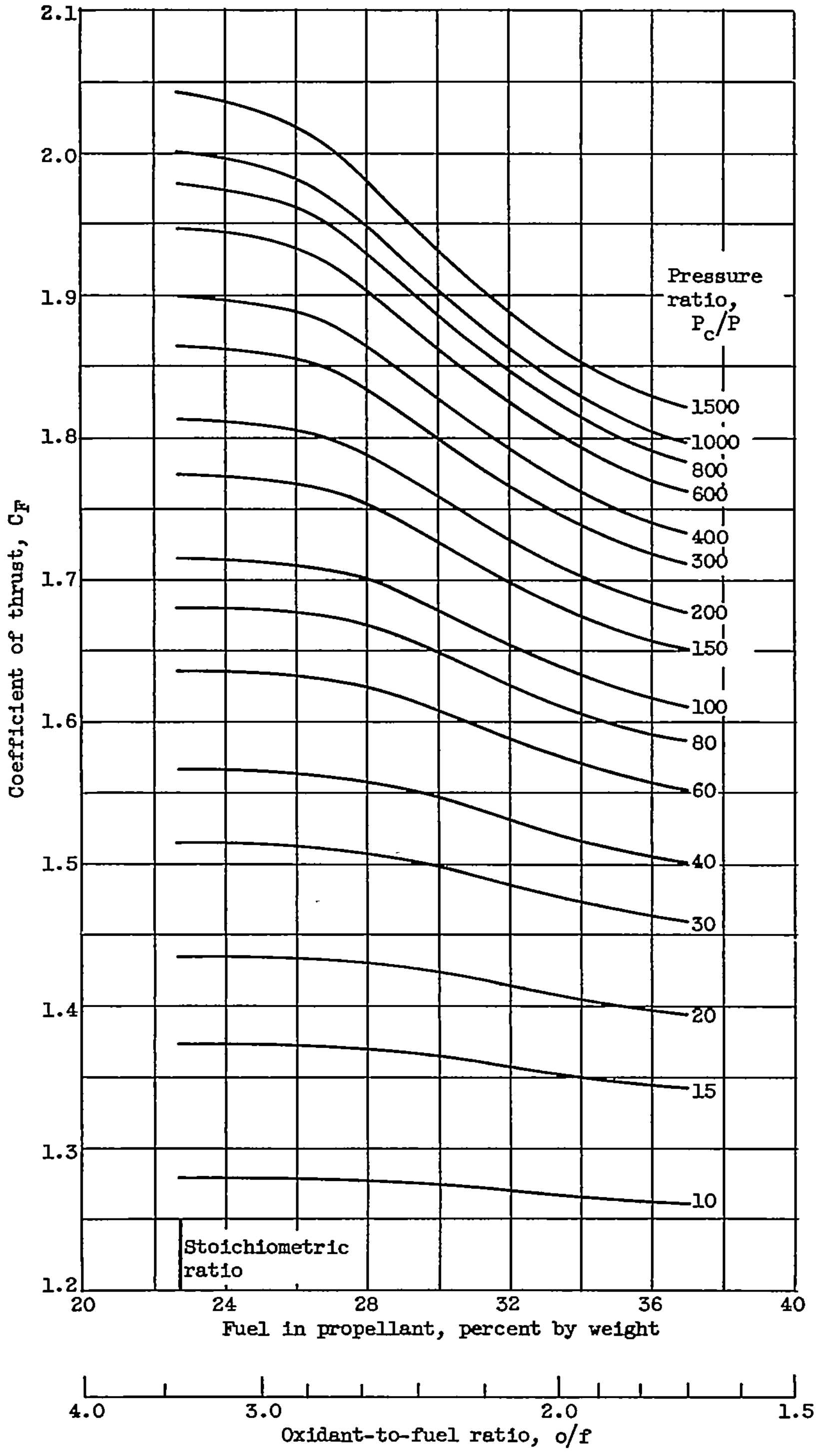
Exponent n_ε for use in equation $\varepsilon = \varepsilon_{300}\left(\frac{P_c}{300}\right)^{n_\varepsilon}$.

Figure 3. - Concluded. Theoretical ratio of nozzle area to throat area for JP-4 fuel with liquid oxygen. Equilibrium composition during isentropic expansion to pressure ratio indicated.



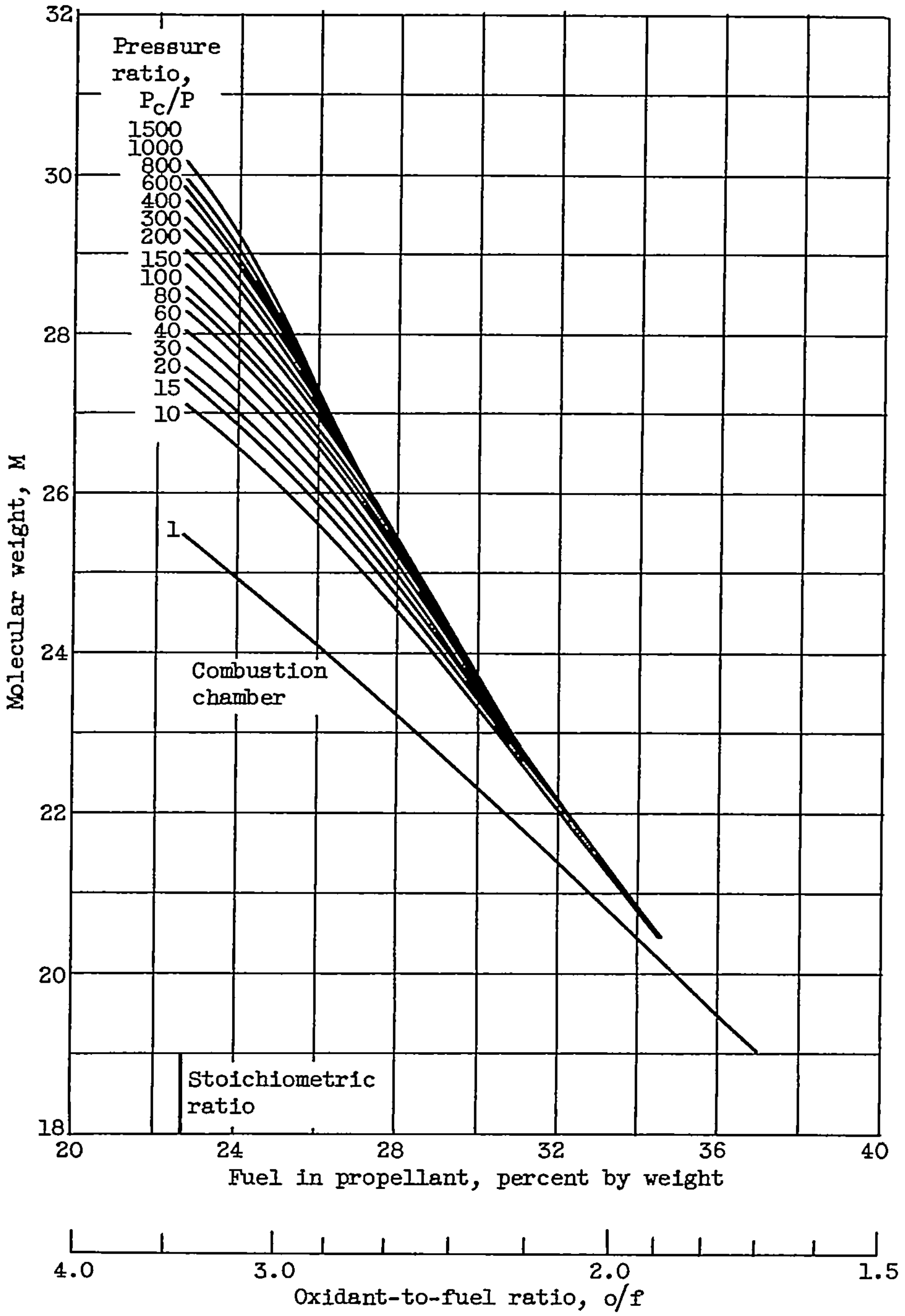
(a) Chamber pressure, 600 pounds per square inch absolute.

Figure 4. - Theoretical coefficient of thrust for JP-4 fuel with liquid oxygen. Equilibrium composition during isentropic expansion to pressure ratio indicated.



(b) Chamber pressure, 300 pounds per square inch absolute.

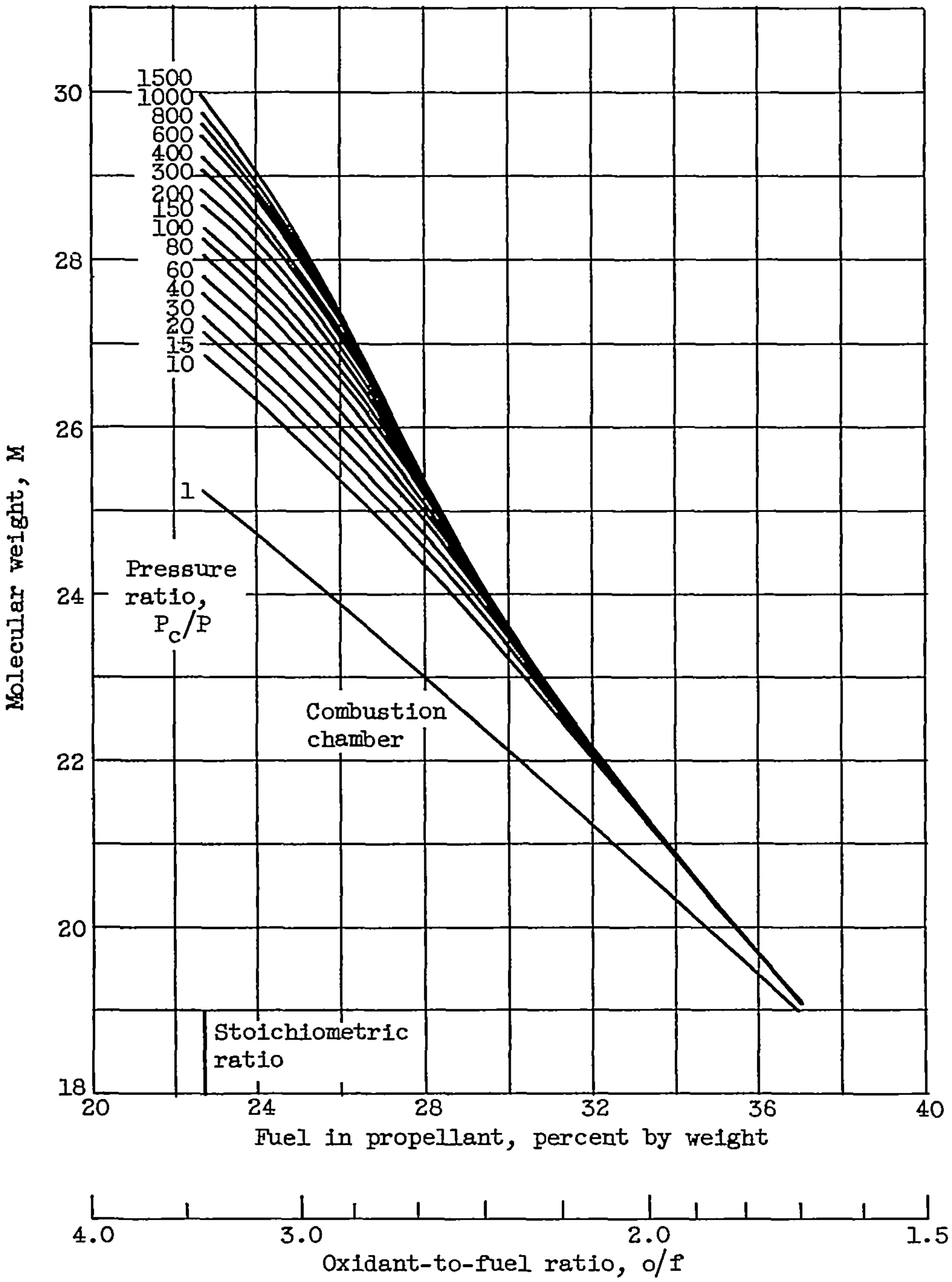
Figure 4. - Concluded. Theoretical coefficient of thrust for JP-4 fuel with liquid oxygen. Equilibrium composition during isentropic expansion to pressure ratio indicated.



(a) Chamber pressure, 600 pounds per square inch absolute.

Figure 5. - Theoretical molecular weight for JP-4 fuel with liquid oxygen. Equilibrium composition during isentropic expansion to pressure ratio indicated.

CW-6 back 4045



(b) Chamber pressure, 300 pounds per square inch absolute.

Figure 5. - Concluded. Theoretical molecular weight for JP-4 fuel with liquid oxygen. Equilibrium composition during isentropic expansion to pressure ratio indicated.

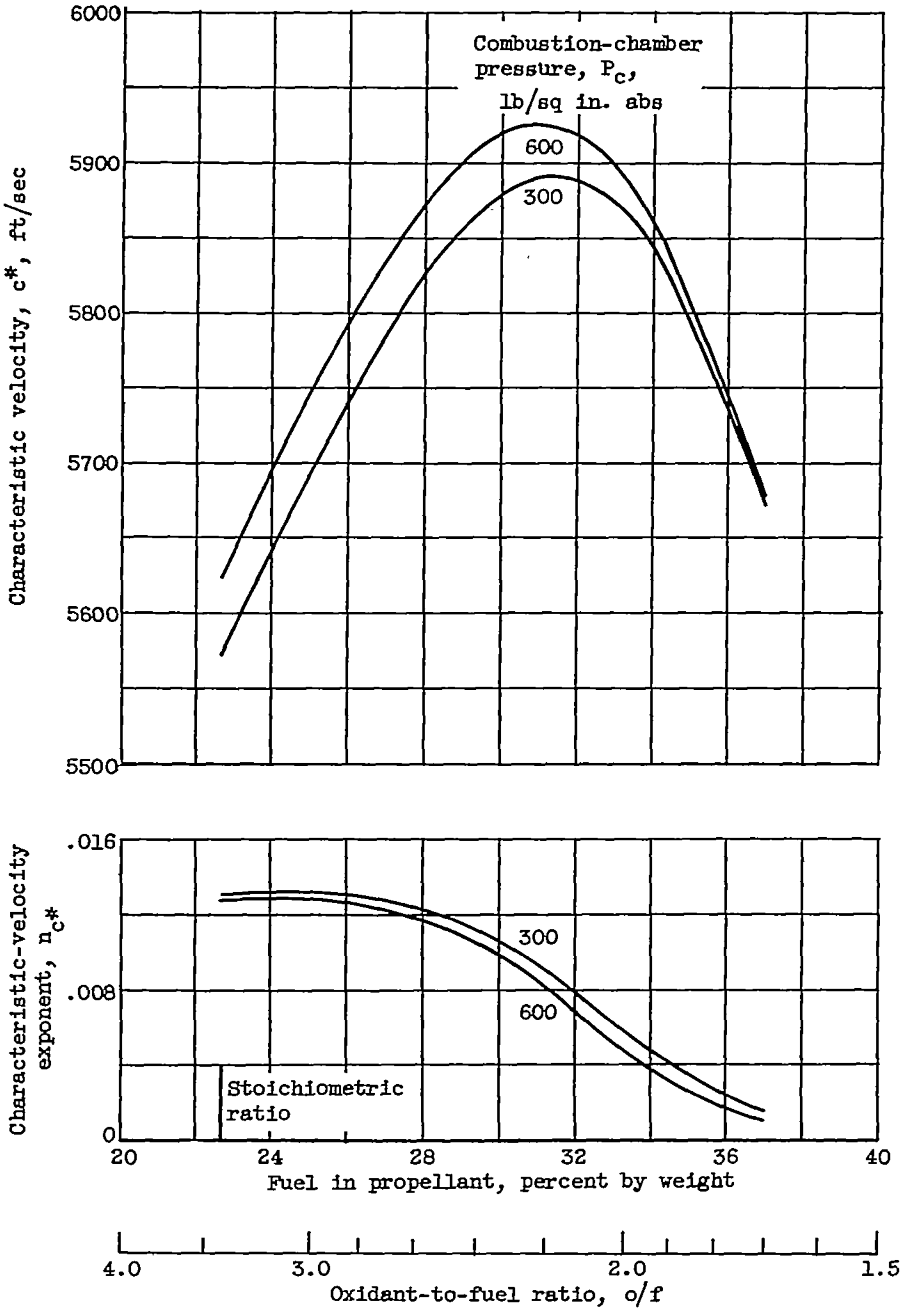


Figure 6. - Theoretical characteristic velocity and characteristic-velocity exponent for JP-4 fuel and liquid oxygen. Exponent n_{c^*} for use in equation $c^* = c_1^* \left(\frac{P_c}{P_{c,1}}\right)^{n_{c_1^*}}$. Equilibrium composition during isentropic expansion from chamber pressure indicated.

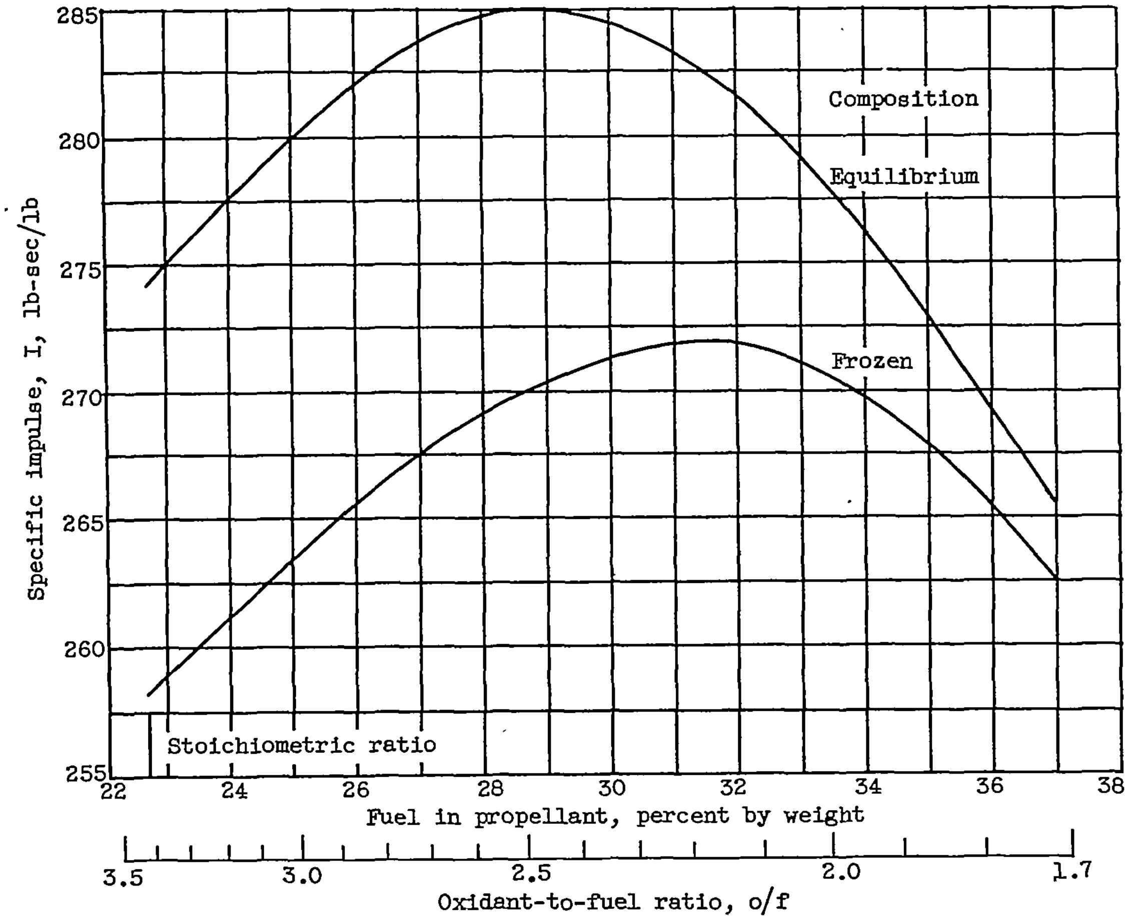
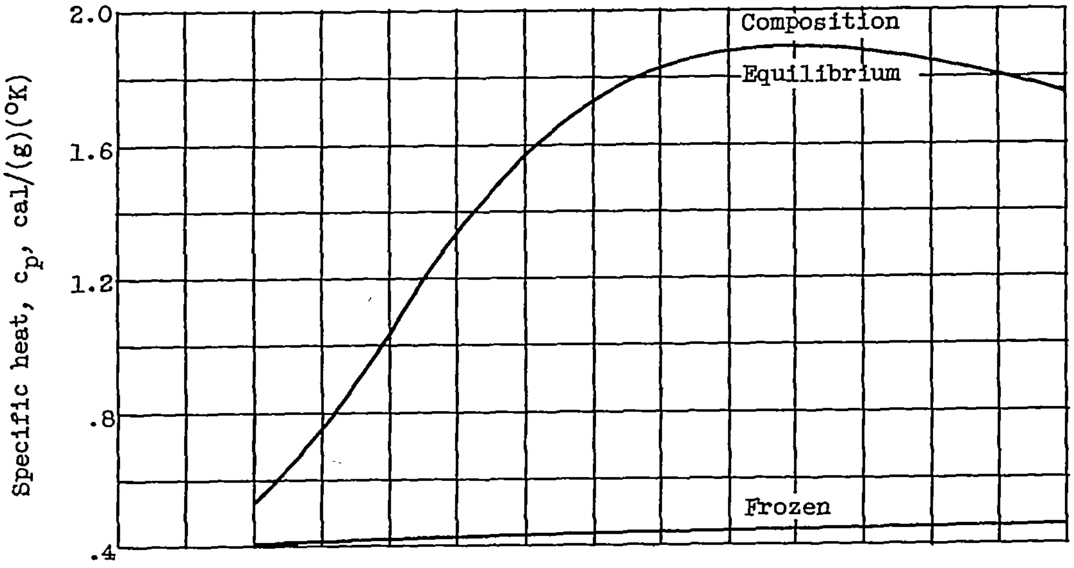
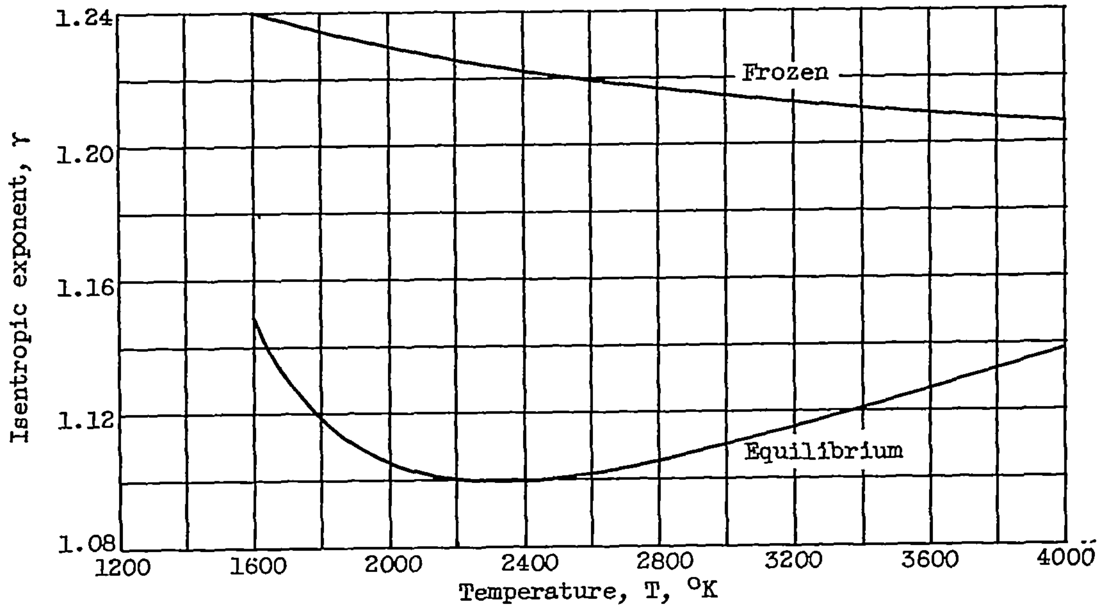


Figure 7. - Comparison of theoretical specific impulse assuming frozen and equilibrium composition for JP-4 fuel with liquid oxygen. Chamber pressure, 600 pounds per square inch absolute; isentropic expansion to 1 atmosphere; pressure ratio, 40.83.

4045



(a) Theoretical specific heat.



(b) Theoretical isentropic exponent.

Figure 8. - Variation of theoretical specific heat and isentropic exponent with temperature for both frozen and equilibrium composition. Isentropic expansion; combustion pressure 600 pounds per square inch absolute; stoichiometric equivalence ratio for JP-4 fuel with liquid oxygen.

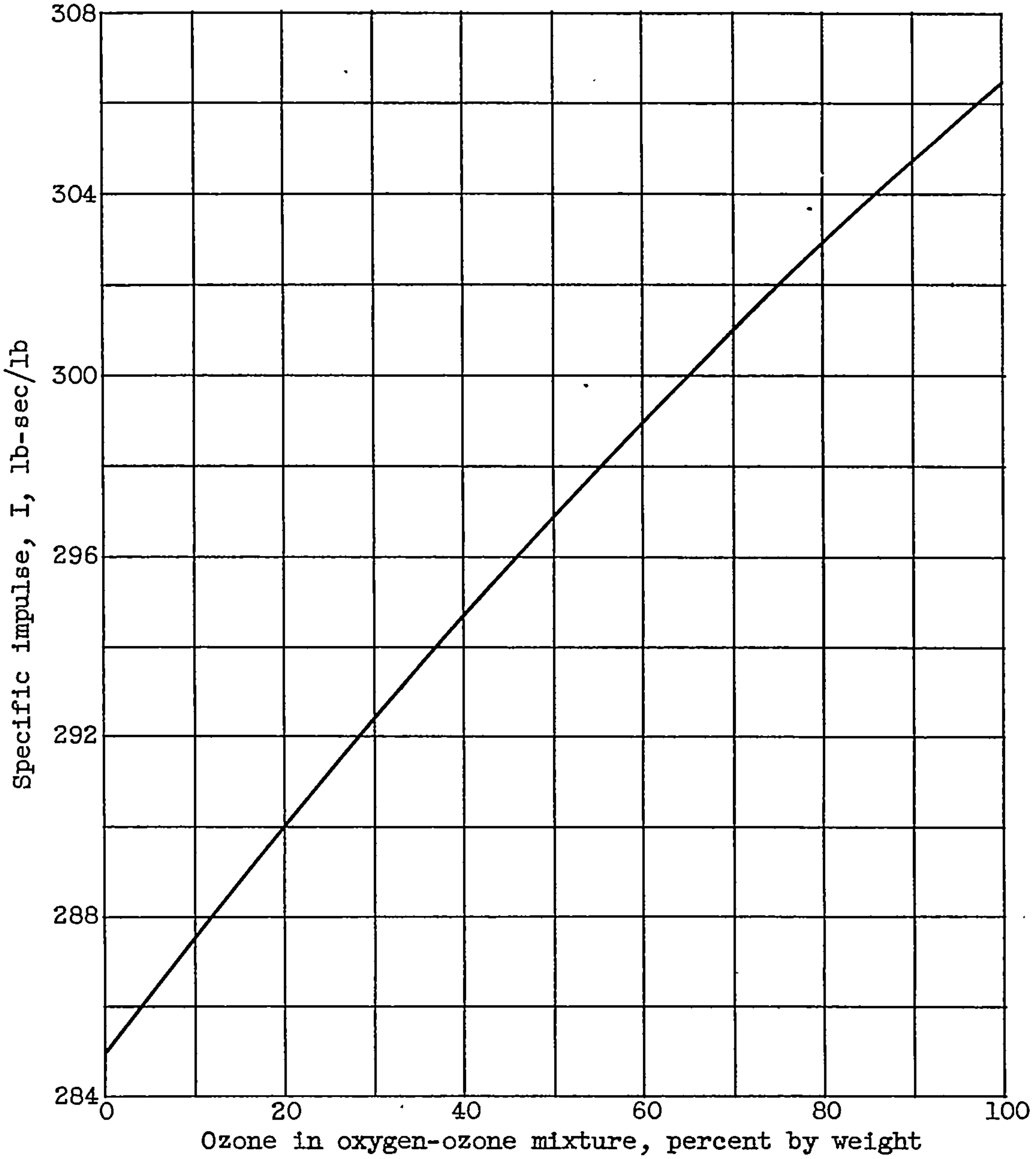


Figure 9. - Estimated equilibrium specific impulse of JP-4 fuel with mixtures of liquid oxygen and ozone as oxidant. Percent fuel by weight, 29.15; chamber pressure, 600 pounds per square inch absolute; exit pressure, 1 atmosphere.