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RESEARCH MEMORANDUM

THEORETICAL PERFORMANCE OF LIQUID HYDRAZINE AND LIQUID FLUORINE AS A ROCKET PROPELLANT

By Sanford Gordon and Vearl N. Huff

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Cleveland, Ohio

[redacted]

NATIONAL ADVISORY COMMITTEE
FOR AERONAUTICS

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RESEARCH MEMORANDUM

THEORETICAL PERFORMANCE OF LIQUID HYDRAZINE AND LIQUID FLUORINE AS A ROCKET PROPELLANT

By Sanford Gordon and Vearl N. Huff

SUMMARY

Theoretical values of performance parameters for liquid hydrazine and liquid fluorine as a rocket propellant were calculated on the assumption of equilibrium composition during the expansion process for four chamber pressures and a wide range of fuel-oxidant and expansion ratios. The parameters included were specific impulse, combustion-chamber temperature, nozzle-exit temperature, equilibrium composition, mean molecular weight, characteristic velocity, coefficient of thrust, ratio of nozzle-exit area to throat area, specific heat at constant pressure, coefficient of viscosity, and coefficient of thermal conductivity. A correlation is presented for the effect of chamber pressure on several of the parameters.

The maximum value of specific impulse was 315.3 pound-seconds per pound for a chamber pressure of 300 pounds per square inch absolute (20.41 atm) and an exit pressure of 1 atmosphere.

INTRODUCTION

Liquid hydrazine and liquid fluorine are of interest as a rocket propellant because of high performance. Extensive data exist in the literature on their availability, cost, and physical, chemical, and handling properties.

The performance of liquid hydrazine and liquid fluorine has been reported in the literature by a number of organizations such as Jet Propulsion Lab., C.I.T.; Douglas Aircraft Co., Inc., Project Rand; and North American Aviation, Inc. Additional performance calculations for this propellant covering a wide range of conditions were made at the NACA Lewis laboratory as part of a series of calculations on propellants containing the chemical elements hydrogen, fluorine, and nitrogen (refs. 1 and 2) to provide a comparison with the performance of other propellants based on the same thermodynamic data and computed to the same degree of accuracy, and to provide several parameters not previously published.

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Data were calculated on the basis of equilibrium composition during expansion for four chamber pressures and a wide range of fuel-oxidant and expansion ratios. The performance parameters included are specific impulse, combustion-chamber temperature, nozzle-exit temperature, equilibrium composition, mean molecular weight, characteristic velocity, coefficient of thrust, ratio of nozzle-exit area to throat area, specific heat at constant pressure, coefficient of viscosity, and coefficient of thermal conductivity.

A correlation was made which permits the determination of specific impulse, characteristic velocity, and ratio of nozzle-exit area to throat area for a wide range of chamber pressures. Equations are given that permit the calculation of specific impulse for nonisentropic expansion or for change in heat content of the combustion gases using the originally calculated data. 2928

Several additional calculations were made assuming frozen composition so that data based on the assumptions of equilibrium and frozen composition during the expansion process could be compared.

SYMBOLS

The following symbols are used in this report:

A	number of equivalent formulas (function of pressure and molecular weight; see ref. 3)
a	local velocity of sound, ft/sec
C_F	coefficient of thrust
C_p^o	molar specific heat at constant pressure, cal/(mole)(^{o}K)
c_p	specific heat at constant pressure, cal/(g)(^{o}K)
c_v	specific heat at constant volume, cal/(g)(^{o}K)
c^*	characteristic velocity, ft/sec
D_A	$\left(\frac{\partial \log A}{\partial \log T}\right)_s$
D_i	$\left(\frac{\partial \log p_i}{\partial \log T}\right)_s$

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g	acceleration due to gravity, 32.174 ft/sec^2
H_T^O	sum of sensible enthalpy and chemical energy, cal/mole
h	sum of sensible enthalpy and chemical energy per unit weight, $\dfrac{\sum_i n_i (H_T^O)_i}{nM}$, cal/g
I	specific impulse, lb-sec/lb
k	coefficient of thermal conductivity, cal/(sec)(cm)($^\circ$K)
M	molecular weight, g/mole
n	number of moles; exponent
P	pressure
p	partial pressure
q	heat, cal/g
R	universal gas constant (consistent units)
r	equivalence ratio, ratio of number of fluorine atoms to hydrogen atoms
S	nozzle area, sq ft
s	entropy, cal/(g)($^\circ$K)
T	temperature, $^\circ$K
w	rate of flow, lb/sec
γ_A	$\left(\dfrac{\partial \log A}{\partial \log T}\right)_P$
γ_i	$\left(\dfrac{\partial \log n_i}{\partial \log T}\right)_P$
γ_s	$\left(\dfrac{\partial \log P}{\partial \log \rho}\right)_s$

μ	coefficient of viscosity, g/(cm)(sec) = poise
ρ	density, g/cu cm

Subscripts:

c	combustion chamber
e	nozzle exit
frozen	composition assumed frozen
i	product of combustion
max	maximum
o	initial value
P	constant pressure
s	constant entropy
t	nozzle throat
x	any point in nozzle

CALCULATION OF PERFORMANCE DATA

Calculations of the performance data were made with a Bell computer and an IBM Card-Programmed Electronic Calculator as described in reference 1. The assumptions, thermodynamic data, and transport properties used for the calculations are the same as those of reference 1.

The products of combustion were assumed to be ideal gases and included the following substances: hydrogen fluoride HF, hydrogen H_2, nitrogen N_2, fluorine F_2, atomic fluorine F, atomic hydrogen H, and atomic nitrogen N. The dissociation energy of F_2 was taken to be 35.6 kilocalories per mole (ref. 4). Physical and thermochemical properties of the propellants were taken from references 3 to 6 and are given in table I.

Procedure for combustion conditions. - The following parameters were computed for ten equivalence ratios for a chamber pressure of 300 pounds per square inch absolute and for five equivalence ratios for chamber pressures of 150, 600, and 1200 pounds per square inch absolute: combustion temperature, equilibrium composition, enthalpy, mean molecular weight, derivative of the logarithm of pressure with respect to the logarithm of density at constant entropy γ_s, specific heat at constant pressure, coefficient of viscosity, coefficient of thermal conductivity, and entropy of the combustion products.

Procedure for exit conditions. - Equilibrium composition, mean molecular weight, pressure, derivative of the logarithm of pressure with respect to the logarithm of density at constant entropy γ_s, enthalpy of the products of combustion, specific heat at constant pressure, coefficient of viscosity, and coefficient of thermal conductivity were computed for each equivalence ratio by assuming isentropic expansion for four assigned exit temperatures selected to cover the exit pressure range from the nozzle-throat pressure to about 0.1 to 0.3 atmosphere.

Interpolation. - Parameters for pressures at and near the nozzle throat, for pressures of 2, 1, 0.5, 0.25, 0.125 atmosphere, and for pressures corresponding to altitudes of 10,000, 20,000, 30,000, 40,000, and 50,000 feet were interpolated by means of cubic equations between each pair of the assigned exit temperatures. The functions and their first derivatives used in the interpolations are described in reference 1.

The errors due to interpolation were checked for several cases. The values presented for all performance parameters appear to be correctly interpolated or in error at most by two or three units in the last place tabulated.

Formulas. - The formulas used in computing the various parameters are given in reference 1 and are summarized as follows:

Specific impulse, lb-sec/lb

$$I = 294.98\sqrt{\frac{h_c - h_e}{1000}} \tag{1}$$

Throat area per unit flow rate, (sq ft)(sec)/lb (pressure in atm)

$$S_t/w = \frac{1.3144\ T_t}{P_t M_t\ a} \tag{2}$$

Characteristic velocity, ft/sec

$$c^* = g\ P_c\ S_t/w = 32.174\ P_c\ S_t/w \tag{3}$$

Coefficient of thrust

$$C_F = Ig/c^* = 32.174\ I/c^* \tag{4}$$

Nozzle-exit area per unit flow rate, (sq ft)(sec)/lb (pressure in atm)

$$S_e/w = \frac{0.040853\ T_e}{P_e\ M_e\ I} \tag{5}$$

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Ratio of nozzle-exit area to throat area

$$S_e/S_t = \frac{S_e/w}{S_t/w} \tag{6}$$

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

$$c_p = \frac{1}{nMT}\left[T\sum_i n_i(C_p^o)_i + \sum_i n_i(H_T^o)_i\ Y_i - \sum_i n_i(H_T^o)_i\ Y_A\right] \tag{7}$$

Derivative of the logarithm of pressure with respect to the logarithm of density at constant entropy

$$\gamma_s = \frac{\sum_i p_i\ D_i}{P(D_A-1)} \tag{8}$$

Coefficient of viscosity, poise

$$\mu = \frac{PM}{\sum_i \frac{p_i}{(\mu_i/M_i)}} \tag{9}$$

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

$$k = \mu\left(c_p + \frac{5}{4}\frac{R}{M}\right) \tag{10}$$

When composition is assumed to be frozen, the partial derivatives Y_i and Y_A in equation (7) are equal to zero and the partial derivatives D_i and D_A in equation (8) are equal to $\frac{(c_p)_{frozen}}{R/M}$. Therefore, equations (7) and (8) become:

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

$$(c_p)_{frozen} = \frac{\sum_i n_i(C_p^o)_i}{nM} \tag{11}$$

Derivative of the logarithm of pressure with respect to the logarithm of density at constant entropy assuming frozen composition

$$(\gamma_s)_{frozen} = \frac{(c_p)_{frozen}}{(c_p)_{frozen} - R/M} = \left(\frac{c_p}{c_v}\right)_{frozen} \qquad (12)$$

The values of viscosity and thermal conductivity for mixtures of combustion gases calculated by means of equations (9) and (10) 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.

THEORETICAL PERFORMANCE DATA

The calculated values of the performance parameters specific impulse, temperature, mean molecular weight, characteristic velocity, coefficient of thrust, and ratio of nozzle-exit area to throat area are given in tables II to IV. For convenience, the parameters are tabulated as functions of altitude in table II and as functions of expansion ratio in table III. As an aid to engine design, the values of the parameters within the rocket nozzle for 80, 90, 100, 110, and 120 percent of the throat pressure are tabulated in table IV. Equilibrium composition, γ_s, specific heat at constant pressure, coefficient of viscosity, coefficient of thermal conductivity, and mean molecular weight in the combustion chamber and at assigned exit temperatures are given in table V. The mole fraction of F_2 was not tabulated in table V, since it was always less than 0.00003 except at 1600° K for the equivalence ratio $r = 1.2$, where it was 0.00007, 0.00015, and 0.00030 for the chamber pressures of 300, 600, and 1200 pounds per square inch absolute, respectively.

Parameters. - The parameters are plotted in figures 1 to 13. Curves of specific impulse for various altitudes are shown in figure 1 plotted against weight percent fuel. The maximum value of specific impulse for the sea-level curve in figure 1(b) is 315.3 pound-seconds per pound at 31.9 percent fuel by weight.

The maximum values of specific impulse and the weight percentages at which they occur were obtained by numerical differentiation of the calculated values and are shown in figure 2 as a function of altitude. The maximum specific impulse in figure 2(b) increases 22 percent for a change in altitude from sea level to 50,000 feet.

Combustion-chamber temperature and nozzle-exit temperature for various altitudes are presented in figure 3 as functions of weight percent fuel. The maximum combustion temperature in figure 3(b) is 4411° K at 27.7 percent fuel by weight. The maximums of the exit temperature curves occur near the stoichiometric ratio.

Characteristic velocity and coefficient of thrust are plotted in figure 4 and the ratio of the area at the nozzle exit to the area at the throat is plotted in figure 5 against weight percent fuel. 2928

Curves of mean molecular weight in the combustion chamber and nozzle exit are plotted against weight percent fuel in figure 6.

Curves of specific heat at constant pressure, coefficient of viscosity, and coefficient of thermal conductivity for six pressures are plotted in figures 7 to 9 as functions of weight percent fuel.

Chamber pressure effect. - The values of the parameters I, c^*, and S_e/S_t (or the logarithms of these parameters) are very nearly linear with the logarithm of chamber pressure for a fixed equivalence ratio and expansion ratio (for example, see fig. 10). It was therefore possible to correlate these data for chamber pressure effects according to the following equations to the accuracies indicated:

$$I = I_{300}\left(\frac{P_c}{300}\right)^n \quad (\pm 0.06 \text{ percent}) \tag{13}$$

$$c^* = c^*_{300}\left(\frac{P_c}{300}\right)^n \quad (\pm 0.07 \text{ percent}) \tag{14}$$

$$S_e/S_t = (S_e/S_t)_{300}\left(\frac{P_c}{300}\right)^n \quad (\pm 0.3 \text{ percent}) \tag{15}$$

where I_{300}, c^*_{300}, and $(S_e/S_t)_{300}$ are the values of these parameters at 300 pounds per square inch absolute, P_c is in pounds per square inch absolute, and n is an exponent given as a function of fuel-oxidant and expansion ratios for each parameter. The values of n shown in figures 11 to 13 were computed from the values of the parameters for the various chamber pressures. However, values of n for specific impulse can also be calculated from data for a single chamber pressure by means of equation (58) derived in the appendix. All the data given in this report for I, c^*, and S_e/S_t are correlated in figures 11 to 13.

As an illustration of the use of these curves, suppose it is desired to obtain the values of I, c^*, and S_e/S_t for a combustion pressure of 800 pounds per square inch absolute and an expansion ratio of 150 at 30 percent fuel by weight. The values read from figures 11 to 13 are:

$I_{300} = 380$ $n = 0.0072$

$c^*_{300} = 7090$ $n = 0.0141$

$S_e/S_t = 17.3$ $n = -0.042$

Using these values in equations (13) to (15) gives $I_{800} = 383$, $c^*_{800} = 7189$, and $(S_e/S_t)_{800} = 16.6$

Change in heat content of propellant gases. - The results presented in this report are computed for adiabatic combustion with propellants at the initial temperature indicated. For a change in heat content of the combustion gases in the combustion chamber (which would result, for example, from heat loss in the combustion-chamber or introduction of the propellants at a temperature other than the one indicated), the corresponding specific impulse assuming isentropic expansion and the same combustion and exit pressures as in the initial calculations may be obtained from the following equation:

$$I^2 = I_o^2 + B\,\Delta h_c + C\,(\Delta h_c)^2 \tag{16}$$

where Δh_c is the change in heat content of the combustion gases in the combustion chamber,

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

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

and the subscript o indicates the values of the parameters before the change is made. The derivation of this equation is given in the appendix.

For example, assume that the enthalpy of the propellant gases following combustion is 100 calories per gram less than the initial value of h_c used in these calculations for the stoichiometric mixture ratio at a chamber pressure of 300 pounds per square inch absolute ($\Delta h_c = -100$). For an expansion ratio of 20.41 ($P_e = 1$ atm), the values of I and T obtained from either table III (b) or figures 1(b) and 3(b) and the values of c_p obtained from figure 7(b) are as follows:

$$I_o = 314.3 \text{ lb-sec/lb}$$

$$T_{c,o} = 4394^\circ \text{ K}$$

$$T_{e,o} = 3239^\circ \text{ K}$$

$$(c_p)_{c,o} = 1.958 \text{ cal/(g)}(^\circ\text{K})$$

$$(c_p)_{e,o} = 1.122 \text{ cal/(g)}(^\circ\text{K})$$

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These values yield the following:

$$I_o^2 = 98,784$$

$$B = 22.87$$

$$C = -0.00278$$

By equation 16,

$$I^2 = 98,784 + 22.87\ (-100) + (-0.00278)\ (10,000)$$

$$= 98,784 - 2,287 - 28 = 96,469$$

$$I = 310.6 \text{ lb-sec/lb}$$

Equation (16) was applied to a specific case having a Δh_c of 250 calories per gram and resulted in an error of less than 0.1 pound-second per pound in specific impulse. For other cases, the relative magnitudes of the successive terms in the series may be used to estimate the approximate magnitude of the error.

Nonisentropic expansion. - For design of rocket engines and for correction of experimental results for heat loss from the nozzle of experimental engines, a need exists for performance data assuming nonisentropic expansion. In general, the performance assuming nonisentropic expansion through the nozzle cannot be computed until sufficient information is available to determine the heat rejection from the nozzle q and the entropy change during expansion Δs. When suitable information is available the computation of performance is possible with the aid of an enthalpy-entropy diagram or by use of an equation such as the following one using data calculated for isentropic expansion:

$$I^2 = I_o^2 - 87.0132 \left\{ q + T_{e,o}(\Delta s) + \left[\frac{T_e}{(c_p)_e}\right]_o \frac{(\Delta s)^2}{2} \right\} \tag{17}$$

This equation is derived in the appendix.

The use of equation (17) is illustrated by imposing an arbitrary relation between q and Δs by assuming that all the heat q is removed from the nozzle throat at constant pressure. For the stoichiometric mixture ratio at a chamber pressure of 300 pounds per square inch absolute and an expansion ratio of 20.41, the values of T_t obtained from table IV(b) and of $(c_p)_t$ obtained from figure 7(b) are as follows:

$$T_t = 4163^{\circ}\ K$$

$$(c_p)_t = 1.860\ cal/(g)(^{\circ}K)$$

If $q = 100$ calories per gram, then by equation (44) of the appendix,

$$\Delta s = -0.02402 - 0.00016 = -0.02418\ cal/(g)(^{\circ}K)$$

This value of Δs, the value assumed for q, and the values of I_o, $T_{e,o}$, and $(c_p)_{e,o}$ given in the previous example are used in equation (17) to give the following result:

$$I^2 = 98,784 - 87.0132 \left[100 + 3239\ (-0.02418) + 2887 \left(\frac{0.00058}{2}\right)\right]$$

$$= 98,784 - 87.0132\ (100 - 78.32 + 0.84) = 96,824$$

$$I = 311.2\ lb\text{-}sec/lb$$

Frozen composition. - In order to compare data based on the assumptions of equilibrium and frozen composition during the expansion process, several additional calculations were made assuming frozen composition. These are presented in table VI together with corresponding equilibrium data for the stoichiometric equivalence ratio and for two expansion ratios. The percentage differences in these parameters for frozen and equilibrium composition are considerably higher for the expansion ratio of 163.3 than for the expansion ratio of 20.41.

For a combustion pressure of 300 pounds per square inch absolute and an exit pressure of 1 atmosphere, the values of maximum specific impulse are 315.3 pound-seconds per pound at 31.9 percent fuel by weight for equilibrium composition during expansion and 292.2 pound-seconds per pound at 32.5 percent fuel by weight for frozen composition during expansion.

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SUMMARY OF RESULTS

Theoretical calculations of the performance parameters of liquid hydrazine with liquid fluorine were made for a wide range of chamber pressures, expansion ratios, and fuel-oxidant ratios and yielded the following results:

1. For a combustion-chamber pressure of 300 pounds per square inch absolute (20.41 atm) and an exit pressure of 1 atmosphere, the maximum specific impulse was 315.3 pound-seconds per pound at 31.9 percent fuel by weight for equilibrium composition during expansion and 292.2 pound-seconds per pound at 32.5 percent fuel by weight for frozen composition during expansion.

2. The maximum combustion temperatures calculated for chamber pressures of 150, 300, 600, and 1200 pounds per square inch absolute were 4260°, 4411°, 4539°, and 4687° K, respectively.

3. The percentage differences in the parameters specific impulse, coefficient of thrust, ratio of nozzle-exit area to throat area, exit temperature, and exit mean molecular weight due to the assumption of frozen or equilibrium composition during expansion are considerably higher for the expansion ratio of 163.3 than for the expansion ratio of 20.41.

4. All the data presented in this report for specific impulse, characteristic velocity, and ratio of nozzle-exit area to throat area have been correlated for chamber-pressure effect in figures 11, 12, and 13, respectively.

5. An equation is given for computing the change in specific impulse resulting from a change in the heat content of the combustion gases.

6. An equation is given for computing the value of specific impulse for a nonisentropic expansion from data for isentropic expansion.

Lewis Flight Propulsion Laboratory
National Advisory Committee for Aeronautics
Cleveland, Ohio, April 9, 1953

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APPENDIX - DERIVATIONS OF EQUATIONS FOR NONIDEAL PERFORMANCE AND FOR EXPONENT IN PRESSURE CORRELATION

All the data presented in this report were computed on the assumptions of adiabatic combustion and isentropic expansion with propellants at the initial temperature indicated. Figure 14 illustrates these assumptions on an enthalpy-entropy diagram. In practice, however, these ideal assumptions are not realized. Equations are derived, therefore, which permit using the data in this report to compute specific impulse for a change in the enthalpy of the propellant gases (eq. (29), see fig. 15), or for nonisentropic expansion (eq. (37), see fig. 16); or to compute the change in entropy for a change in enthalpy along a constant pressure line (eq. (44), see fig. 17).

<u>Correction of specific impulse for a change in enthalpy of propellant gases</u>. - As may be seen from figure 15, h_e is a function of h_c for isentropic expansion from a fixed chamber pressure to a fixed exit pressure,

$$h_e = f(h_c) \tag{19}$$

Expanding this function in a Taylor's series and neglecting all derivatives higher than the second yield

$$h_e = f(h_{c,o}) + f'(h_{c,o})\,\Delta h_c + f''(h_{c,o})\,\frac{(\Delta h_c)^2}{2} \tag{20}$$

For constant pressure,

$$dh = T\,ds \tag{21}$$

$$\frac{dT}{dh} = \frac{1}{c_p} \tag{22}$$

For isentropic expansion,

$$s_e = s_c \quad \text{or} \quad \frac{ds_e}{ds_c} = 1 \tag{23}$$

The relations in equations (21), (22), and (23) are used to obtain

$$f'(h_c) = \frac{dh_e}{dh_c} = \frac{T_e ds_e}{T_c ds_c} = \frac{T_e}{T_c} \tag{24}$$

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$$f''(h_c) = \frac{d\left(\frac{T_e}{T_c}\right)}{dh_c} = \frac{1}{T_c}\left(\frac{dT_e}{dh_c}\right) + T_e \frac{d\left(\frac{1}{T_c}\right)}{dh_c}$$

$$= \frac{1}{T_c}\frac{dT_e}{dh_e}\frac{dh_e}{dh_c} + T_e\left(\frac{-1}{T_c{}^2}\right)\frac{dT_c}{dh_c} = \frac{1}{T_c}\frac{1}{(c_p)_e}\left(\frac{T_e}{T_c}\right) - \frac{T_e}{T_c{}^2}\frac{1}{(c_p)_c}$$

$$= \frac{T_e}{T_c{}^2}\left[\frac{1}{(c_p)_e} - \frac{1}{(c_p)_c}\right] \tag{25}$$

Substituting equations (19), (24), and (25) into equation (20) gives

$$h_e = h_{e,o} + \left(\frac{T_e}{T_c}\right)_o \Delta h_c + \left(\frac{T_e}{T_c{}^2}\right)_o \left[\frac{1}{(c_p)_e} - \frac{1}{(c_p)_c}\right]_o \frac{(\Delta h_c)^2}{2} \tag{26}$$

From equation (1),

$$I^2 = 87.0132\ (h_c - h_e) \tag{27}$$

By definition,

$$\Delta h_c = h_c - h_{c,o} \tag{28}$$

Substituting equations (26) and (28) into equation (27) results in

$$I^2 = 87.0132 \left\{\Delta h_c + h_{c,o} - h_{e,o} - \left(\frac{T_e}{T_c}\right)_o \Delta h_c - \left(\frac{T_e}{T_c{}^2}\right)_o \left[\frac{1}{(c_p)_e} - \frac{1}{(c_p)_c}\right]_o \frac{(\Delta h_c)^2}{2}\right\}$$

By use of equation (27) this may be expressed

$$I^2 = I_o^2 + 87.0132\left(1 - \frac{T_e}{T_c}\right)_o \Delta h_c + \frac{87.0132}{2}\left(\frac{T_c}{T_c^2}\right)_o \left[\frac{1}{(c_p)_c} - \frac{1}{(c_p)_e}\right]_o (\Delta h_c)^2 \tag{29}$$

Equation (29) is identical to equation (16) in the text.

Correction of specific impulse for nonisentropic expansion. - As may be seen from figure 16, h_e is a function of s_e for nonisentropic expansion, since h_e and s_e must lie on the line P_e.

$$h_e = f(s_e) \tag{30}$$

Expanding this function in a Taylor's series and neglecting all derivatives higher than the second give

$$h_e = f(s_{e,o}) + f'(s_{e,o})\,\Delta s + f''(s_{e,o})\,\frac{(\Delta s)^2}{2} \tag{31}$$

For constant pressure,

$$f'(s) = \frac{dh}{ds} = T \tag{32}$$

$$f''(s) = \frac{d^2h}{ds^2} = \frac{dT}{ds} = \frac{T}{c_p} \tag{33}$$

Substituting equations (32) and (33) into equation (31) yields

$$h_e = h_{e,o} + (T_{e,o})\,\Delta s + \left[\frac{T_e}{(c_p)_e}\right]_o \frac{(\Delta s)^2}{2} \tag{34}$$

When equation (27) is modified to account for heat q lost during expansion, the result is

$$I^2 = 87.0132\,(h_c - h_e - q) \tag{35}$$

Taking $h_{c,o} = h_c$ and substituting equation (34) into equation (35)

$$I^2 = 87.0132\left\{h_{c,o} - h_{e,o} - (T_{e,o})\,\Delta s - \left[\frac{T_e}{(c_p)_e}\right]_o \frac{(\Delta s)^2}{2} - q\right\} \tag{36}$$

Equation (27) is used to express this as

$$I^2 = I_o^2 - 87.0132\left\{q + (T_{e,o})\,\Delta s + \left[\frac{T_e}{(c_p)_e}\right]_o \frac{(\Delta s)^2}{2}\right\} \tag{37}$$

Equation (37) is identical to equation (17) in the text.

Change of entropy for change of heat along a constant pressure line. - As may be seen from figure 17, for a change in enthalpy along any line of constant pressure P_x,

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$$s_x = f(h_x) \tag{38}$$

Expanding this function in a Taylor's series and neglecting all derivations higher than the second result in

$$s_x = f(h_{x,o}) + f'(h_{x,o})\,\Delta h + f''(h_{x,o})\,\frac{(\Delta h)^2}{2} \tag{39}$$

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For constant pressure,

$$f'(h) = \frac{ds}{dh} = \frac{1}{T} \tag{40}$$

$$f''(h) = \frac{d^2s}{dh^2} = \frac{d\left(\frac{1}{T}\right)}{dh} = \frac{-1}{T^2}\,\frac{dT}{dh} = \frac{-1}{T^2 c_p} \tag{41}$$

Equations (38), (40), and (41) are substituted into equation (39) to give

$$s_x = s_{x,o} + \left(\frac{1}{T_{x,o}}\right)\Delta h - \left[\frac{1}{T_x^2 (c_p)_x}\right]_o \frac{(\Delta h)^2}{2} \tag{42}$$

When the change in enthalpy at constant pressure P_x is due to removal of heat q from the system,

$$q = -\Delta h \tag{43}$$

(Addition of heat would correspond to negative q.)

With the aid of equation (43), equation (42) becomes

$$\Delta s = -\left(\frac{1}{T_x}\right)_o q - \left[\frac{1}{T_x^2 (c_p)_x}\right]_o \frac{q^2}{2} \tag{44}$$

An example is given in the text of the use of this equation when a nonisentropic expansion is approximated by assuming that the heat is removed at an average pressure.

Equation (44) may also be used to obtain additional points on the constant-pressure lines of an enthalpy-entropy diagram.

Calculation of chamber pressure correlation exponents. - In the general notation, equation (13) may be written

$$I = I_o \left(\frac{P_c}{P_{c,o}}\right)^n \tag{45}$$

Values of n to be used in equation (45) for obtaining specific impulse at any chamber pressure P_c from the value of specific impulse at an initial chamber pressure $P_{c,o}$ for the same expansion ratio and equivalence ratio may be obtained as follows: From equations (27) and (45),

$$I^2 = 87.0132\ (h_c - h_e) = I_o^2 \left(\frac{P_c}{P_{c,o}}\right)^{2n} \tag{46}$$

Differentiating equation (46) with respect to P_c gives

$$87.0132 \left(\frac{dh_c}{dP_c} - \frac{dh_e}{dP_c}\right) = 2n \left(I_o^2\right)\left(\frac{P_c{}^{2n-1}}{P_{c,o}{}^{2n}}\right) \tag{47}$$

Since h_c is constant,

$$dh_c = 0 \tag{48}$$

Substituting equations (46) and (48) into equation (47) yields

$$-\ 87.0132 \left(\frac{dh_e}{dP_c}\right) = 2n\ \frac{I^2}{P_c}$$

or

$$n = -\ \frac{87.0132}{2} \left(\frac{P_c}{I^2}\right)\left(\frac{dh_e}{dP_c}\right) \tag{49}$$

Since entropy s may be expressed as a function of P and h,

$$ds_c = \left(\frac{\partial s_c}{\partial P_c}\right)_{h_c} dP_c + \left(\frac{\partial s_c}{\partial h_c}\right)_{P_c} dh_c \tag{50}$$

and

$$ds_e = \left(\frac{\partial s_e}{\partial P_e}\right)_{h_e} dP_e + \left(\frac{\partial s_e}{\partial h_e}\right)_{P_e} dh_e \tag{51}$$

Substituting equation (48) into equation (50) results in

$$ds_c = \left(\frac{\partial s_c}{\partial P_c}\right)_{h_c} dP_c \tag{52}$$

For isentropic expansion $ds_e = ds_c$; therefore from equations (51) and (52),

$$dh_e \left(\frac{\partial s_e}{\partial h_e}\right)_{P_e} = \left(\frac{\partial s_c}{\partial P_c}\right)_{h_c} dP_c - \left(\frac{\partial s_e}{\partial P_e}\right)_{h_e} dP_e \tag{53}$$

For constant expansion ratio,

$$\frac{P_c}{P_e} = \frac{dP_c}{dP_e} \tag{54}$$

Substituting equation (54) into equation (53) gives

$$dh_e = \left(\frac{\partial h_e}{\partial s_e}\right)_{P_e} \left[\left(\frac{\partial s_c}{\partial P_c}\right)_{h_c} - \frac{P_e}{P_c}\left(\frac{\partial s_e}{\partial P_e}\right)_{h_e}\right] dP_c$$

or

$$\frac{dh_e}{dP_c} = \left(\frac{\partial h_e}{\partial s_e}\right)_{P_e} \left[\left(\frac{\partial s_c}{\partial P_c}\right)_{h_c} - \frac{P_e}{P_c}\left(\frac{\partial s_e}{\partial P_e}\right)_{h_e}\right] \tag{55}$$

Substituting into equation (55) the thermodynamic identity of equation (40) and the following identity

$$\left(\frac{\partial s}{\partial P}\right)_h = -\frac{R}{PM} \tag{56}$$

give

$$\frac{dh_e}{dP_c} = T_e \left[-\frac{R}{P_c M_c} - \frac{P_e}{P_c}\left(-\frac{R}{P_e M_e}\right)\right]$$

or

$$\frac{dh_e}{dP_c} = -\frac{RT_e}{P_c}\left(\frac{1}{M_c} - \frac{1}{M_e}\right) \tag{57}$$

Equation (57) is substituted into equation (49) to yield

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$$n = \frac{87.0132}{2} \frac{P_c}{I^2} \left[\frac{1.98718\ T_e}{P_c} \left(\frac{1}{M_c} - \frac{1}{M_e}\right)\right]$$

or

$$n = 86.4554 \frac{T_e}{I^2} \left(\frac{1}{M_c} - \frac{1}{M_e}\right) \tag{58}$$

The following table presents values of n computed by means of equation (58) for the stoichiometric mixture ratio for a chamber pressure $P_{c,o}$ of 300 pounds per square inch absolute. Also presented is a comparison of the values of specific impulse at other chamber pressures computed directly and computed by means of equation (45) from these values of n and I_{300}.

P_c/P_e	n (from eq. (58))	P_c, lb/sq in. abs	I (direct computation), lb-sec/lb	I (from eq. (45)), lb-sec/lb	Error in I, lb-sec/lb
20.41	0.01240	150	311.53	311.58	0.05
		300	314.27	------	----
		600	316.92	316.98	.06
		1200	319.45	319.72	.27
81.65	0.00966	150	361.27	361.37	0.10
		300	363.80	------	----
		600	366.16	366.24	.08
		1200	368.33	368.70	.37
163.3	0.00804	150	380.48	380.59	0.11
		300	382.72	------	----
		600	384.76	384.86	.10
		1200	386.62	387.01	.39

Equations similar to equation (58) may be derived for evaluating the exponent n for c^* and S_e/S_t; however, these equations are omitted inasmuch as they involve partial derivatives which have not been tabulated in this report.

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TABLE I. - PROPERTIES OF LIQUID PROPELLANTS

Propellant → Properties ↓	Hydrazine	Fluorine
Molecular weight, M	32.048	38.00
Density, g/cc	$^{a}1.011$ (at 15° C)	$^{b}1.54$ (at -196° C)
Freezing point, °C	$^{c}1.5$	$^{c}-217.96$
Boiling point, °C	$^{c}113.5$	$^{c}-187.92$
Enthalpy of formation from elements at 25° C, ΔH_f, kcal/mole	$^{d}12.05$ (at 25° C)	$^{d}-3.030$ (at -187.92° C)
Enthalpy of vaporization, ΔH, kcal/mole	$^{c}10$ (at 113.5° C)	$^{c}1.51$ (at -187.92° C)
Enthalpy of fusion, ΔH, kcal/mole	--------	$^{c}0.372$ (at -217.96° C)

[a] Reference 5.
[b] Reference 6.
[c] Reference 4.
[d] Reference 3.

TABLE II. - CALCULATED PERFORMANCE OF LIQUID HYDRAZINE WITH LIQUID FLUORINE AS FUNCTIONS OF ALTITUDE

(a) Combustion-chamber pressure, 150 lb/sq in. absolute

Propellant			Combustion chamber		Characteristic velocity, c*, ft/sec	[b]Nozzle exit						
Equivalence ratio, r	Weight-percent fuel	[a]Density, g/cc	Temperature, T_c, °K	Mean molecular weight, M_c		Altitude, ft	Pressure, P_e, atm	Temperature, T_e, °K	Mean molecular weight, M_e	Ratio of nozzle-exit area to throat area, S_e/S_t	Coefficient of thrust, C_F	Specific impulse, I, lb-sec/lb
1.2	26.00	1.356	4260	19.68	6888	0	1.0	3318	21.04	2.578	1.277	273.4
						10,000	.6876	3124	21.16	3.043	1.359	290.9
						20,000	.4594	2887	21.25	3.969	1.436	307.5
						30,000	.2968	2611	21.25	5.284	1.509	323.0
						40,000	.1852	2327	21.25	7.224	1.576	337.5
						50,000	.1149	2064	21.25	9.961	1.634	349.7
1.0	29.66	1.333	4257	19.04	7014	0	1.0	3425	20.47	2.427	1.280	279.0
						10,000	.6876	3299	20.67	3.160	1.364	297.4
						20,000	.4594	3163	20.87	4.258	1.445	315.1
						30,000	.2968	3014	21.08	5.869	1.524	332.3
						40,000	.1852	2846	21.26	8.385	1.600	348.8
						50,000	.1149	2663	21.42	12.04	1.669	363.8
0.8	34.52	1.304	4142	18.17	7061	0	1.0	3211	19.40	2.374	1.277	280.3
						10,000	.6876	3060	19.56	3.067	1.359	298.3
						20,000	.4594	2897	19.72	4.075	1.438	315.5
						30,000	.2968	2717	19.87	5.577	1.513	332.1
						40,000	.1852	2516	20.00	7.853	1.585	347.8
						50,000	.1149	2307	20.09	11.10	1.649	361.8
0.6	41.27	1.266	3855	17.09	6979	0	1.0	2858	18.11	2.324	1.274	276.4
						10,000	.6876	2699	18.22	2.984	1.354	293.7
						20,000	.4594	2526	18.32	3.934	1.430	310.3
						30,000	.2968	2333	18.40	5.332	1.503	326.0
						40,000	.1852	2120	18.45	7.407	1.571	340.7
						50,000	.1149	1906	18.48	10.32	1.631	353.7
0.4	51.32	1.214	3402	15.79	6783	0	1.0	2339	16.38	2.234	1.269	267.5
						10,000	.6876	2163	16.41	2.828	1.345	283.7
						20,000	.4594	1976	16.42	3.669	1.417	298.8
						30,000	.2968	1782	16.43	4.889	1.484	312.9
						40,000	.1852	1588	16.43	6.699	1.546	326.0
						50,000	.1149	1408	16.43	9.251	1.600	337.3

[a] Based on F_2 density of 1.54 at -196° C and N_2H_4 density of 1.011 at 15° C.

[b] Nozzle designed for exit pressure equal to ambient pressure corresponding to altitude indicated.

TABLE II. - CALCULATED PERFORMANCE OF LIQUID HYDRAZINE WITH LIQUID FLUORINE AS FUNCTIONS OF ALTITUDE - Continued

(b) Combustion-chamber pressure, 300 lb/sq in. absolute

Propellant			Combustion chamber		Characteristic velocity, c*, ft/sec	[b]Nozzle exit						
Equivalence ratio, r	Weight-percent fuel	[a]Density, g/cc	Temperature, T_c, °K	Mean molecular weight, M_c		Altitude, ft	Pressure, P_e, atm	Temperature, T_e, °K	Mean molecular weight, M_e	Ratio of nozzle-exit area to throat area, S_e/S_t	Coefficient of thrust, C_F	Specific impulse, I, lb-sec/lb
1.2	26.00	1.356	4393	19.83	6954	0	1.0	2918	21.25	3.664	1.417	306.2
						10,000	.6876	2673	21.25	4.671	1.480	319.8
						20,000	.4594	2422	21.25	6.091	1.539	332.6
						30,000	.2968	2172	21.25	8.158	1.595	344.7
						40,000	.1852	1926	21.25	11.23	1.646	355.9
						50,000	.1149	1702	21.25	15.57	1.692	365.6
1.1	27.71	1.345	4411	19.54	7029	0	1.0	3175	21.25	3.878	1.424	311.2
						10,000	.6876	2985	21.35	5.039	1.492	325.9
						20,000	.4594	2754	21.41	6.653	1.556	340.0
						30,000	.2968	2494	21.42	8.966	1.617	353.4
						40,000	.1852	2225	21.42	12.37	1.675	365.9
						50,000	.1149	1974	21.42	17.20	1.724	376.7
1.0	29.66	1.333	4394	19.19	7085	0	1.0	3239	20.95	3.942	1.427	314.3
						10,000	.6876	3099	21.12	5.192	1.496	329.4
						20,000	.4594	2945	21.28	7.014	1.563	34[illegible].2
						30,000	.2968	2765	21.41	9.725	1.628	353.6
						40,000	.1852	2558	21.52	13.81	1.691	372.4
						50,000	.1149	2333	21.58	19.60	1.747	384.8
0.9	31.91	1.320	4352	18.79	7121	0	1.0	3133	20.41	3.882	1.424	315.3
						10,000	.6876	2973	20.55	5.080	1.492	330.2
						20,000	.4594	2794	20.67	6.805	1.557	344.7
						30,000	.2968	2592	20.78	9.344	1.620	358.7
						40,000	.1852	2369	20.86	13.15	1.681	372.0
						50,000	.1149	2142	20.90	18.53	1.734	383.8
0.8	34.52	1.304	4272	18.32	7128	0	1.0	2960	19.79	3.791	1.419	314.4
						10,000	.6876	2794	19.91	4.943	1.485	329.0
						20,000	.4594	2611	20.01	6.596	1.549	343.0
						30,000	.2968	2408	20.09	9.022	1.610	356.6
						40,000	.1852	2187	20.15	12.64	1.668	369.4
						50,000	.1149	1967	20.17	17.76	1.719	380.8

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[a] Based on F_2 density of 1.54 at -196° C and N_2H_4 density of 1.011 at 15° C.

[b] Nozzle designed for exit pressure equal to ambient pressure corresponding to altitude indicated.

TABLE II. - CALCULATED PERFORMANCE OF LIQUID HYDRAZINE WITH LIQUID FLUORINE AS FUNCTIONS OF ALTITUDE - Continued

(b) Combustion-chamber pressure, 300 lb/sq in. absolute - Concluded

Propellant			Combustion chamber		Characteristic velocity, c^*, ft/sec	[b]Nozzle exit						
Equivalence ratio, r	Weight-percent fuel	[a]Density, g/cc	Temperature, T_c, °K	Mean molecular weight, M_c		Altitude, ft	Pressure, P_e, atm	Temperature, T_e, °K	Mean molecular weight, M_e	Ratio of nozzle-exit area to throat area, S_e/S_t	Coefficient of thrust, C_F	Specific impulse, I, lb-sec/lb
0.7	37.59	1.287	4140	17.80	7095	0	1.0	2777	19.11	3.724	1.416	312.2
						10,000	.6876	2607	19.21	4.840	1.480	326.4
						20,000	.4594	2421	19.28	6.432	1.542	340.1
						30,000	.2968	2217	19.33	8.753	1.602	353.2
						40,000	.1852	1998	19.36	12.20	1.658	365.6
						50,000	.1149	1786	19.37	17.06	1.707	376.4
0.6	41.27	1.266	3963	17.23	7035	0	1.0	2569	18.35	3.658	1.412	308.8
						10,000	.6876	2394	18.41	4.730	1.476	322.7
						20,000	.4594	2204	18.45	6.247	1.536	335.9
						30,000	.2968	2001	18.48	8.451	1.594	348.4
						40,000	.1852	1790	18.49	11.72	1.648	360.2
						50,000	.1149	1592	18.49	16.33	1.695	370.6
0.5	45.75	1.243	3745	16.60	6947	0	1.0	2315	17.47	3.564	1.408	304.0
						10,000	.6876	2137	17.49	4.576	1.469	317.3
						20,000	.4594	1949	17.51	6.007	1.528	329.8
						30,000	.2968	1757	17.51	8.085	1.583	341.7
						40,000	.1852	1564	17.51	11.17	1.634	352.9
						50,000	.1149	1386	17.51	15.52	1.679	362.6
0.4	51.32	1.214	3477	15.88	6818	0	1.0	2005	16.43	3.427	1.400	296.7
						10,000	.6876	1836	16.43	4.577	1.459	309.2
						20,000	.4594	1664	16.43	5.720	1.515	320.9
						30,000	.2968	1492	16.43	7.674	1.567	332.0
						40,000	.1852	1323	16.43	10.57	1.616	342.4
						50,000	.1149	1168	16.43	14.66	1.658	351.4
0.3	58.43	1.179	3122	15.00	6595	0	1.0	1652	15.24	3.277	1.390	284.9
						10,000	.6876	1505	15.24	4.172	1.446	296.5
						20,000	.4594	1359	15.24	5.438	1.499	307.3
						30,000	.2968	1213	15.24	7.275	1.549	317.5
						40,000	.1852	1071	15.24	9.996	1.595	327.0
						50,000	.1149	942.3	15.24	13.83	1.635	335.2

[a]Based on F_2 density of 1.54 at -196° C and N_2H_4 density of 1.011 at 15° C.

[b]Nozzle designed for exit pressure equal to ambient pressure corresponding to altitude indicated.

TABLE II. - CALCULATED PERFORMANCE OF LIQUID HYDRAZINE WITH LIQUID FLUORINE AS FUNCTIONS OF ALTITUDE - Continued

(c) Combustion-chamber pressure, 600 lb/sq in. absolute

Propellant			Combustion chamber		Characteristic velocity, c*, ft/sec	[b]Nozzle exit						
Equivalence ratio, r	Weight-percent fuel	[a]Density, g/cc	Temperature, T_c, °K	Mean molecular weight, M_c		Altitude, ft	Pressure, P_e, atm	Temperature, T_e, °K	Mean molecular weight, M_e	Ratio of nozzle-exit area to throat area, S_e/S_t	Coefficient of thrust, C_F	Specific impulse, I, lb-sec/lb
1.2	26.00	1.356	4533	19.99	7018	0	1.0	2445	21.25	5.616	1.520	331.5
						10,000	.6876	2227	21.25	7.210	1.568	342.0
						20,000	.4594	2011	21.25	9.468	1.614	352.0
						30,000	.2968	1797	21.25	12.76	1.657	361.5
						40,000	.1852	1589	21.25	17.64	1.698	370.4
						50,000	.1149	1401	21.26	24.53	1.733	378.1
1.0	29.66	1.333	4539	19.36	7155	0	1.0	2994	21.33	6.481	1.546	343.8
						10,000	.6876	2828	21.44	8.545	1.602	356.4
						20,000	.4594	2639	21.52	11.49	1.658	368.6
						30,000	.2968	2426	21.57	15.80	1.711	380.5
						40,000	.1852	2190	21.60	22.18	1.762	391.8
						50,000	.1149	1960	21.61	31.18	1.807	401.7
0.8	34.52	1.304	4405	18.49	7189	0	1.0	2649	20.05	6.098	1.532	342.3
						10,000	.6876	2465	20.11	7.953	1.585	354.1
						20,000	.4594	2267	20.15	10.59	1.636	365.5
						30,000	.2968	2058	20.17	14.42	1.685	376.4
						40,000	.1852	1842	20.18	20.13	1.731	386.7
						50,000	.1149	1639	20.18	28.20	1.772	395.8
0.6	41.27	1.266	4074	17.37	7087	0	1.0	2229	18.46	5.782	1.519	334.7
						10,000	.6876	2050	18.48	7.479	1.570	345.7
						20,000	.4594	1865	18.49	9.879	1.617	356.2
						30,000	.2968	1677	18.49	13.37	1.663	366.2
						40,000	.1852	1490	18.49	18.57	1.705	375.6
						50,000	.1149	1319	18.49	25.92	1.743	383.9
0.4	51.32	1.214	3547	15.97	6848	0	1.0	1690	16.43	5.343	1.500	319.2
						10,000	.6876	1540	16.43	6.869	1.546	329.0
						20,000	.4594	1390	16.43	9.027	1.590	338.3
						30,000	.2968	1242	16.43	12.16	1.631	347.2
						40,000	.1852	1097	16.43	16.82	1.670	355.4
						50,000	.1149	965.2	16.43	23.38	1.704	362.6

[a] Based on F_2 density of 1.54 at -196° C and N_2H_4 density of 1.011 at 15° C.

[b] Nozzle designed for exit pressure equal to ambient pressure corresponding to altitude indicated.

TABLE II. - CALCULATED PERFORMANCE OF LIQUID HYDRAZINE WITH LIQUID FLUORINE AS FUNCTIONS OF ALTITUDE - Concluded

(d) Combustion-chamber pressure, 1200 lb/sq in. absolute

Propellant			Combustion chamber		Characteristic velocity, c^*, ft/sec	[b]Nozzle exit						
Equivalence ratio, r	Weight-percent fuel	[a]Density, g/cc	Temperature, T_c, ^{o}K	Mean molecular weight, M_c		Altitude, ft	Pressure, P_e, atm	Temperature, T_e, ^{o}K	Mean molecular weight, M_e	Ratio of nozzle-exit area to throat area, S_e/S_t	Coefficient of thrust, C_F	Specific impulse, I, lb-sec/lb
1.2	26.00	1.356	4673	20.15	7078	0	1.0	2034	21.25	8.748	1.596	351.0
						10,000	.6876	1848	21.25	11.29	1.633	359.3
						20,000	.4594	1664	21.25	14.89	1.669	367.3
						30,000	.2968	1484	21.26	20.14	1.704	374.8
1.0	29.66	1.333	4687	19.53	7224	0	1.0	2661	21.54	10.54	1.640	368.3
						10,000	.6876	2469	21.58	13.82	1.686	378.7
						20,000	.4594	2262	21.60	18.45	1.731	388.6
						30,000	.2968	2045	21.61	25.18	1.773	398.2
0.8	34.52	1.304	4536	18.65	7250	0	1.0	2287	20.16	9.743	1.619	364.8
						10,000	.6876	2102	20.17	12.68	1.661	374.4
						20,000	.4594	1913	20.18	16.85	1.702	383.5
						30,000	.2968	1720	20.18	22.93	1.741	392.3
0.6	41.27	1.266	4182	17.51	7135	0	1.0	1885	18.49	9.140	1.602	355.2
						10,000	.6876	1721	18.49	11.84	1.641	363.9
						20,000	.4594	1557	18.49	15.67	1.679	372.3
						30,000	.2968	1394	18.49	21.26	1.715	380.3
0.4	51.32	1.214	3612	16.05	6873	0	1.0	1414	16.43	8.440	1.577	336.9
						10,000	.6876	1284	16.43	10.90	1.614	344.7
						20,000	.4594	1156	16.43	14.37	1.648	352.1
						30,000	.2968	1029	16.43	19.41	1.681	359.2

[a] Based on F_2 density of 1.54 at -196° C and N_2H_4 density of 1.011 at 15° C.

[b] Nozzle designed for exit pressure equal to ambient pressure corresponding to altitude indicated.

TABLE III. - CALCULATED PERFORMANCE OF LIQUID HYDRAZINE WITH LIQUID FLUORINE AS FUNCTIONS OF EXPANSION RATIO

(a) Combustion-chamber pressure, 150 lb/sq in. absolute

Propellant			Combustion chamber		Characteristic velocity, c^*, ft/sec	[b]Nozzle exit						
Equivalence ratio, r	Weight-percent fuel	[a]Density, g/cc	Temperature, T_c, °K	Mean molecular weight, M_c		Expansion ratio, P_c/P_e	Pressure, P_e, atm	Temperature, T_e, °K	Mean molecular weight, M_e	Ratio of nozzle-exit area to throat area, S_e/S_t	Coefficient of thrust, C_F	Specific impulse I, lb-sec/lb
1.2	26.00	1.356	4260	19.68	6888	10.21 20.41 40.83 81.65	1.0 .5 .25 .125	3318 2939 2505 2108	21.04 21.22 21.25 21.25	2.378 3.755 5.917 9.410	1.277 1.421 1.534 1.624	273.4 304.2 328.5 347.7
1.0	29.66	1.333	4257	19.04	7014	10.21 20.41 40.83 81.65	1.0 .5 .25 .125	3425 3132 2954 2696	20.47 20.83 21.15 21.33	2.427 3.982 6.680 11.30	1.280 1.429 1.553 1.657	279.0 311.5 338.5 361.3
0.8	34.52	1.304	4142	18.17	7061	10.21 20.41 40.83 81.65	1.0 .5 .25 .125	3211 2931 2645 2344	19.40 19.69 19.92 20.08	2.374 3.837 6.316 10.45	1.277 1.422 1.540 1.638	280.3 312.1 338.0 359.5
0.6	41.27	1.266	3655	17.09	6979	10.21 20.41 40.83 81.65	1.0 .5 .25 .125	2858 2562 2256 1943	18.11 18.30 18.43 18.48	2.324 3.711 6.010 9.737	1.274 1.415 1.529 1.621	276.4 307.0 331.6 351.6
0.4	51.32	1.214	3402	15.79	6783	10.21 20.41 40.83 81.65	1.0 .5 .25 .125	2339 2015 1709 1438	16.38 16.42 16.43 16.43	2.234 3.472 5.479 8.736	1.269 1.403 1.508 1.591	267.5 295.8 317.9 335.4

[a] Based on F_2 density of 1.54 at -196° C and N_2H_4 density of 1.011 at 15° C.

[b] Nozzle designed for exit pressure equal to ambient pressure.

TABLE III. - CALCULATED PERFORMANCE OF LIQUID HYDRAZINE WITH LIQUID FLUORINE AS FUNCTIONS OF EXPANSION RATIO - Continued

(b) Combustion-chamber pressure, 300 lb/sq in. absolute

Propellant			Combustion chamber		Characteristic velocity, c^*, ft/sec	[b]Nozzle exit						
Equivalence ratio, r	Weight-percent fuel	[a]Density, g/cc	Temperature, T_c, °K	Mean molecular weight, M_c		Expansion ratio, P_c/P_e	Pressure, P_e, atm	Temperature, T_e, °K	Mean molecular weight, M_e	Ratio of nozzle-exit area to throat area, S_e/S_t	Coefficient of thrust, C_F	Specific impulse, I, lb-sec/lb
1.2	26.00	1.356	4393	19.83	6954	10.21	2.0	3339	21.11	2.343	1.275	275.5
						20.41	1.0	2918	21.23	3.664	1.417	306.2
						40.83	.5	2473	21.25	5.758	1.527	330.1
						81.65	.25	2080	21.25	9.160	1.614	348.9
						163.3	.125	1740	21.25	14.69	1.684	364.0
1.1	27.71	1.345	4411	19.54	7029	10.21	2.0	3482	20.96	2.403	1.278	279.2
						20.41	1.0	3175	21.25	3.878	1.424	311.2
						40.83	.5	2804	21.40	6.278	1.543	337.2
						81.65	.25	2394	21.42	10.08	1.639	358.1
						163.3	.125	2016	21.42	16.22	1.716	374.9
1.0	29.66	1.333	4394	19.19	7085	10.21	2.0	3493	20.60	2.411	1.279	281.7
						20.41	1.0	3239	20.95	3.942	1.427	314.3
						40.83	.5	2978	21.25	6.584	1.549	341.2
						81.65	.25	2692	21.46	11.05	1.652	363.8
						163.3	.125	2374	21.57	18.43	1.738	382.7
0.9	31.91	1.320	4352	18.79	7121	10.21	2.0	3415	20.11	2.394	1.278	282.9
						20.41	1.0	3133	20.41	3.882	1.424	315.3
						40.83	.5	2832	20.65	6.399	1.544	341.8
						81.65	.25	2511	20.81	10.58	1.643	363.7
						163.3	.125	2182	20.90	17.45	1.725	381.8
0.8	34.52	1.304	4272	18.32	7128	10.21	2.0	3262	19.52	2.356	1.276	282.6
						20.41	1.0	2960	19.79	3.791	1.419	314.4
						40.83	.5	2650	19.99	6.208	1.536	340.2
						81.65	.25	2328	20.11	10.20	1.632	361.4
						163.3	.125	2006	20.17	16.73	1.710	378.9

[a]Based on F_2 density of 1.54 at -196° C and N_2H_4 density of 1.011 at 15° C.

[b]Nozzle designed for exit pressure equal to ambient pressure.

TABLE III. - CALCULATED PERFORMANCE OF LIQUID HYDRAZINE WITH LIQUID FLUORINE AS FUNCTIONS OF EXPANSION RATIO - Continued

(b) Combustion-chamber pressure, 300 lb/sq in. absolute - Concluded

Propellant			Combustion chamber		Characteristic velocity, c^*, ft/sec	[b]Nozzle exit						
Equivalence ratio, r	Weight-percent fuel	[a]Density, g/cc	Temperature, T_c, ^oK	Mean molecular weight, M_c		Expansion ratio, P_c/P_e	Pressure, P_e, atm	Temperature, T_e, ^oK	Mean molecular weight, M_e	Ratio of nozzle-exit area to throat area, S_e/S_t	Coefficient of thrust, C_F	Specific impulse, I, lb-sec/lb
0.7	37.59	1.287	4140	17.80	7095	10.21	2.0	3087	18.89	2.327	1.274	281.0
						20.41	1.0	2777	19.11	3.724	1.416	312.2
						40.83	.5	2461	19.27	6.059	1.530	337.4
						81.65	.25	2136	19.35	9.878	1.623	357.9
						163.3	.125	1822	19.37	16.08	1.699	374.6
0.6	41.27	1.266	3963	17.23	7035	10.21	2.0	2887	18.18	2.302	1.273	278.3
						20.41	1.0	2569	18.35	3.658	1.412	308.8
						40.83	.5	2244	18.45	5.893	1.524	333.2
						81.65	.25	1923	18.48	9.517	1.614	352.9
						163.3	.125	1626	18.49	15.40	1.687	368.8
0.5	45.75	1.243	3745	16.60	6947	10.21	2.0	2645	17.37	2.267	1.271	274.5
						20.41	1.0	2315	17.47	3.564	1.408	304.0
						40.83	.5	1988	17.50	5.672	1.516	327.3
						81.65	.25	1685	17.51	9.092	1.602	346.0
						163.3	.125	1416	17.51	14.64	1.672	361.0
0.4	51.32	1.214	3477	15.88	6818	10.21	2.0	2336	16.39	2.209	1.268	268.6
						20.41	1.0	2005	16.43	3.427	1.400	296.7
						40.83	.5	1699	16.43	5.405	1.504	318.6
						81.65	.25	1429	16.43	8.620	1.586	336.0
						163.3	.125	1194	16.43	13.84	1.651	349.9
0.3	58.43	1.179	3122	15.00	6595	10.21	2.0	1953	15.23	2.132	1.263	258.9
						20.41	1.0	1652	15.24	3.277	1.390	284.9
						40.83	.5	1388	15.24	5.142	1.489	305.2
						81.65	.25	1160	15.24	8.164	1.567	321.1
						163.3	.125	964	15.24	13.05	1.629	333.9

[a]Based on F_2 density of 1.54 at -196° C and N_2H_4 density of 1.011 at 15° C.

[b]Nozzle designed for exit pressure equal to ambient pressure.

TABLE III. - CALCULATED PERFORMANCE OF LIQUID HYDRAZINE WITH LIQUID FLUORINE AS FUNCTIONS OF EXPANSION RATIO - Continued

(c) Combustion-chamber pressure, 600 lb/sq in. absolute

Propellant			Combustion chamber		Characteristic velocity, c^*, ft/sec	^{b}Nozzle exit						
Equivalence ratio, r	Weight-percent fuel	^{a}Density, g/cc	Temperature, T_c, °K	Mean molecular weight, M_c		Expansion ratio, P_c/P_e	Pressure, P_e, atm	Temperature, T_e, °K	Mean molecular weight, M_e	Ratio of nozzle-exit area to throat area, S_e/S_t	Coefficient of thrust, C_F	Specific impulse, I, lb-sec/lb
1.2	26.00	1.356	4533	19.99	7018	20.41	2.0	2893	21.24	3.577	1.412	308.0
						40.83	1.0	2445	21.25	5.616	1.520	331.5
						81.65	.5	2055	21.25	8.939	1.605	350.1
						163.3	.25	1719	21.25	14.35	1.673	364.9
						326.6	.125	1432	21.26	23.14	1.728	376.9
1.0	29.66	1.333	4539	19.36	7155	20.41	2.0	3282	21.07	3.901	1.425	316.9
						40.83	1.0	2994	21.33	6.481	1.546	343.8
						81.65	.5	2680	21.50	10.80	1.646	366.2
						163.3	.25	2340	21.59	17.89	1.730	384.8
						326.6	.125	1999	21.61	29.37	1.799	400.1
0.8	34.52	1.304	4405	18.49	7189	20.41	2.0	2982	19.87	3.744	1.417	316.6
						40.83	1.0	2649	20.05	6.098	1.532	342.3
						81.65	.5	2308	20.14	9.969	1.626	363.2
						163.3	.25	1978	20.18	16.28	1.702	380.4
						326.6	.125	1673	20.18	26.56	1.765	394.4
0.6	41.27	1.266	4074	17.37	7087	20.41	2.0	2570	18.39	3.606	1.409	310.4
						40.83	1.0	2229	18.46	5.782	1.519	334.7
						81.65	.5	1903	18.49	9.317	1.608	354.1
						163.3	.25	1607	18.49	15.06	1.679	369.8
						326.6	.125	1349	18.49	24.45	1.736	382.5
0.4	51.32	1.214	3547	15.97	6848	20.41	2.0	1997	16.43	3.388	1.398	297.5
						40.83	1.0	1690	16.43	5.343	1.500	319.2
						81.65	.5	1421	16.43	8.522	1.581	336.5
						163.3	.25	1187	16.43	13.68	1.646	350.3
						326.6	.125	987	16.43	22.06	1.698	361.4

NACA

[a] Based on F_2 density of 1.54 at -196° C and N_2H_4 density of 1.011 at 15° C.
[b] Nozzle designed for exit pressure equal to ambient pressure.

TABLE III. - CALCULATED PERFORMANCE OF LIQUID HYDRAZINE WITH LIQUID FLUORINE AS FUNCTIONS OF EXPANSION RATIO - Concluded

(d) Combustion-chamber pressure, 1200 lb/sq in. absolute

Propellant			Combustion chamber		Characteristic velocity, c^*, ft/sec	[b]Nozzle exit						
Equivalence ratio, r	Weight-percent fuel	[a]Density, g/cc	Temperature, T_c, °K	Mean molecular weight, M_c		Expansion ratio, P_c/P_e	Pressure, P_e, atm	Temperature, T_e, °K	Mean molecular weight, M_e	Ratio of nozzle-exit area to throat area, S_e/S_t	Coefficient of thrust, C_F	Specific impulse, I, lb-sec/lb
1.2	26.00	1.356	4673	20.15	7078	40.83	2.0	2420	21.25	5.493	1.512	332.7
						81.65	1.0	2034	21.25	8.748	1.596	351.0
						163.3	.5	1701	2125	14.05	1.662	365.7
						326.6	.25	1419	21.27	22.69	1.716	377.5
1.0	29.66	1.333	4687	19.53	7224	40.83	2.0	3002	21.40	6.371	1.542	346.2
						81.65	1.0	2661	21.54	10.54	1.640	368.3
						163.3	.5	2306	21.60	17.36	1.722	386.6
						326.6	.25	1963	21.61	28.45	1.789	401.6
0.8	34.52	1.304	4536	18.65	7250	40.83	2.0	2642	20.09	5.986	1.527	344.1
						81.65	1.0	2287	20.16	9.743	1.619	364.8
						163.3	.5	1952	20.18	15.88	1.694	381.7
						326.6	.25	1649	20.18	25.89	1.755	395.4
0.6	41.27	1.266	4182	17.51	7135	40.83	2.0	2214	18.47	5.680	1.515	335.9
						81.65	1.0	1885	18.49	9.140	1.602	355.2
						163.3	.5	1590	18.49	14.78	1.671	370.6
						326.6	.25	1333	18.49	23.97	1.728	383.2
0.4	51.32	1.214	3612	16.05	6873	40.83	2.0	1683	16.43	5.291	1.497	319.7
						81.65	1.0	1414	16.43	8.440	1.577	336.9
						163.3	.5	1182	16.43	13.55	1.641	350.6
						326.6	.25	982	16.43	21.85	1.693	361.7

NACA

[a]Based on F_2 density of 1.54 at -196° C and N_2H_4 density of 1.011 at 15° C.
[b]Nozzle designed for exit pressure equal to ambient pressure.

TABLE IV. - CALCULATED PARAMETERS AT PRESSURES NEAR NOZZLE THROAT FOR LIQUID HYDRAZINE WITH LIQUID FLUORINE

[Throat conditions correspond to $P_x/P_t = 1.0$. I = (velocity of flow)/g]

(a) Combustion-chamber pressure, 150 lb/sq in. absolute

Equivalence ratio, r	Weight-percent fuel	$\frac{P_x}{P_t}$	Pressure, P_x, atm	Temperature, T_x, °K	Mean molecular weight, M_x	Ratio of nozzle area to throat area, S_x/S_t	Coefficient of thrust, C_F	Specific impulse, I, lb-sec/lb
1.2	26.00	1.2	7.031	4110	19.93	1.0362	0.5448	116.6
		1.1	6.445	4073	19.99	1.0086	.6034	129.2
		1.0	5.859	4033	20.05	1.0000	.6610	141.5
		.9	5.273	3991	20.12	1.0080	.7185	153.8
		.8	4.688	3945	20.19	1.0326	.7770	166.3
1.0	29.66	1.2	7.048	4112	19.28	1.0360	0.5423	118.2
		1.1	6.461	4078	19.33	1.0085	.6010	131.0
		1.0	5.874	4042	19.40	1.0000	.6587	143.6
		.9	5.286	4002	19.46	1.0081	.7164	156.2
		.8	4.699	3959	19.54	1.0329	.7751	169.0
0.8	34.52	1.2	7.024	3987	18.39	1.0353	0.5462	119.9
		1.1	6.438	3951	18.44	1.0083	.6047	132.7
		1.0	5.853	3912	18.49	1.0000	.6622	145.3
		.9	5.268	3870	18.55	1.0080	.7197	158.0
		.8	4.682	3823	18.62	1.0324	.7781	170.8
0.6	41.27	1.2	6.970	3682	17.28	1.0342	0.5544	120.3
		1.1	6.389	3644	17.32	1.0081	.6124	132.8
		1.0	5.809	3601	17.37	1.0000	.6695	145.2
		.9	5.228	3555	17.42	1.0078	.7265	157.6
		.8	4.647	3504	17.47	1.0316	.7845	170.2
0.4	51.32	1.2	6.918	3223	15.93	1.0329	0.5621	118.5
		1.1	6.341	3183	15.96	1.0076	.6197	130.6
		1.0	5.765	3140	15.99	1.0000	.6762	142.6
		.9	5.188	3092	16.03	1.0075	.7329	154.5
		.8	4.612	3039	16.06	1.0306	.7904	166.6

TABLE IV. - CALCULATED PARAMETERS AT PRESSURES NEAR NOZZLE THROAT FOR LIQUID HYDRAZINE WITH LIQUID FLUORINE - Continued

[Throat conditions correspond to $P_x/P_t = 1.0$. I = (velocity of flow)/g]

(b) Combustion-chamber pressure, 300 lb/sq in. absolute

Equivalence ratio, r	Weight-percent fuel	$\frac{P_x}{P_t}$	Pressure, P_x, atm	Temperature, T_x, °K	Mean molecular weight, M_x	Ratio of nozzle area to throat area, S_x/S_t	Coefficient of thrust, C_F	Specific impulse, I, lb-sec/lb
1.2	26.00	1.2	14.04	4230	20.08	1.0359	0.5472	118.3
		1.1	12.87	4190	20.14	1.0086	.6056	130.9
		1.0	11.70	4147	20.20	1.0000	.6631	143.3
		.9	10.53	4101	20.26	1.0078	.7205	155.7
		.8	9.358	4050	20.34	1.0320	.7789	168.3
1.1	27.71	1.2	14.07	4252	19.79	1.0364	0.5449	119.0
		1.1	12.90	4213	19.85	1.0088	.6034	131.8
		1.0	11.72	4172	19.91	1.0000	.6609	144.4
		.9	10.55	4128	19.98	1.0078	.7185	157.0
		.8	9.379	4079	20.05	1.0322	.7770	169.8
1.0	29.66	1.2	14.07	4239	19.44	1.0358	0.5445	119.9
		1.1	12.90	4202	19.49	1.0085	.6031	132.8
		1.0	11.72	4163	19.55	1.0000	.6607	145.5
		.9	10.55	4120	19.62	1.0080	.7183	158.2
		.8	9.380	4072	19.69	1.0326	.7768	171.1
0.9	31.91	1.2	14.06	4193	19.02	1.0355	0.5456	120.8
		1.1	12.88	4156	19.07	1.0084	.6041	133.7
		1.0	11.71	4115	19.13	1.0000	.6617	146.4
		.9	10.54	4072	19.19	1.0080	.7192	159.2
		.8	9.370	4024	19.26	1.0326	.7777	172.1
0.8	34.52	1.2	14.01	4102	18.54	1.0349	0.5486	121.5
		1.1	12.84	4063	18.59	1.0083	.6069	134.5
		1.0	11.68	4021	18.64	1.0000	.6643	147.2
		.9	10.51	3975	18.70	1.0079	.7216	159.9
		.8	9.341	3924	18.76	1.0321	.7799	172.8

TABLE IV. - CALCULATED PARAMETERS AT PRESSURES NEAR NOZZLE THROAT FOR LIQUID HYDRAZINE WITH LIQUID FLUORINE - Continued

[Throat conditions correspond to $P_x/P_t = 1.0$. I = (velocity of flow)/g]

(b) Combustion-chamber pressure, 300 lb/sq in. absolute - Concluded

Equivalence ratio, r	Weight-percent fuel	$\frac{P_x}{P_t}$	Pressure, P_x, atm	Temperature, T_x, ^{o}K	Mean molecular weight, M_x	Ratio of nozzle area to throat area, S_x/S_t	Coefficient of thrust, C_F	Specific impulse, I, lb-sec/lb
0.7	37.59	1.2	13.96	3961	18.00	1.0343	0.5532	122.0
		1.1	12.79	3921	18.05	1.0081	.6112	134.8
		1.0	11.63	3876	18.10	1.0000	.6684	147.4
		.9	10.47	3828	18.15	1.0078	.7255	160.0
		.8	9.305	3774	18.21	1.0317	.7835	172.8
0.6	41.27	1.2	13.91	3777	17.41	1.0338	0.5570	121.8
		1.1	12.75	3736	17.45	1.0080	.6149	134.4
		1.0	11.59	3690	17.50	1.0000	.6718	146.9
		.9	10.43	3640	17.55	1.0077	.7287	159.3
		.8	9.270	3585	17.60	1.0314	.7865	172.0
0.5	45.75	1.2	13.86	3555	16.76	1.0333	0.5605	121.0
		1.1	12.71	3513	16.80	1.0079	.6181	133.5
		1.0	11.55	3468	16.84	1.0000	.6749	145.7
		.9	10.40	3417	16.88	1.0076	.7316	158.0
		.8	9.241	3361	16.92	1.0310	.7892	170.4
0.4	51.32	1.2	13.79	3281	16.01	1.0325	0.5658	119.9
		1.1	12.64	3239	16.04	1.0077	.6231	132.0
		1.0	11.49	3192	16.07	1.0000	.6796	144.0
		.9	10.34	3141	16.10	1.0074	.7360	156.0
		.8	9.192	3083	16.13	1.0301	.7933	168.1
0.3	58.43	1.2	13.63	2913	15.08	1.0309	0.5772	118.3
		1.1	12.50	2868	15.10	1.0074	.6338	129.9
		1.0	11.36	2819	15.11	1.0000	.6896	141.4
		.9	10.22	2765	15.13	1.0070	.7454	152.8
		.8	9.089	2704	15.14	1.0287	.8020	164.4

TABLE IV. - CALCULATED PARAMETERS AT PRESSURES NEAR NOZZLE THROAT FOR LIQUID HYDRAZINE WITH LIQUID FLUORINE - Continued

[Throat conditions correspond to $P_x/P_t = 1.0$. I = (velocity of flow)/g]

(c) Combustion-chamber pressure, 600 lb/sq in. absolute

Equivalence ratio, r	Weight-percent fuel	$\frac{P_x}{P_t}$	Pressure, P_x, atm	Temperature, T_x, ^{o}K	Mean molecular weight, M_x	Ratio of nozzle area to throat area, S_x/S_t	Coefficient of thrust, C_F	Specific impulse, I, lb-sec/lb
1.2	26.00	1.2	28.00	4350	20.23	1.0354	0.5501	120.0
		1.1	25.67	4307	20.29	1.0085	.6084	132.7
		1.0	23.33	4261	20.35	1.0000	.6657	145.2
		.9	21.00	4210	20.41	1.0077	.7230	157.7
		.8	18.67	4154	20.48	1.0316	.7812	170.4
1.0	29.66	1.2	28.08	4367	19.60	1.0353	0.5469	121.6
		1.1	25.74	4328	19.66	1.0083	.6054	134.6
		1.0	23.40	4285	19.72	1.0000	.6629	147.4
		.9	21.06	4239	19.78	1.0080	.7203	160.2
		.8	18.72	4188	19.85	1.0326	.7787	173.2
0.8	34.52	1.2	27.96	4218	18.70	1.0346	0.5513	123.2
		1.1	25.63	4176	18.74	1.0082	.6095	136.2
		1.0	23.30	4131	18.80	1.0000	.6668	149.0
		.9	20.97	4081	18.85	1.0079	.7240	161.8
		.8	18.64	4025	18.92	1.0319	.7821	174.8
0.6	41.27	1.2	27.74	3871	17.55	1.0334	0.5599	123.3
		1.1	25.43	3826	17.59	1.0079	.6176	136.0
		1.0	23.12	3777	17.63	1.0000	.6743	148.5
		.9	20.80	3723	17.67	1.0076	.7311	161.0
		.8	18.49	3663	17.72	1.0310	.7887	173.7
0.4	51.32	1.2	27.48	3335	16.09	1.0321	0.5696	121.2
		1.1	25.19	3289	16.11	1.0076	.6267	133.4
		1.0	22.90	3239	16.14	1.0000	.6829	145.4
		.9	20.61	3183	16.16	1.0073	.7391	157.3
		.8	18.32	3121	16.19	1.0297	.7962	169.5

TABLE IV. - CALCULATED PARAMETERS AT PRESSURES NEAR NOZZLE THROAT FOR LIQUID HYDRAZINE WITH LIQUID FLUORINE - Concluded

[Throat conditions correspond to P_x/P_t = 1.0. I = (velocity of flow)/g]

(d) Combustion-chamber pressure, 1200 lb/sq in. absolute

Equivalence ratio, r	Weight-percent fuel	$\frac{P_x}{P_t}$	Pressure, P_x, atm	Temperature, T_x, ^{o}K	Mean molecular weight, M_x	Ratio of nozzle area to throat area, S_x/S_t	Coefficient of thrust, C_F	Specific impulse, I, lb-sec/lb
1.2	26.00	1.2	55.84	4467	20.38	1.0345	0.5535	121.8
		1.1	51.19	4422	20.44	1.0080	.6116	134.5
		1.0	46.53	4371	20.49	1.0000	.6687	147.1
		.9	41.88	4316	20.56	1.0076	.7258	159.7
		.8	37.23	4254	20.62	1.0312	.7838	172.4
1.0	29.66	1.2	56.04	4498	19.77	1.0350	0.5493	123.3
		1.1	51.37	4455	19.82	1.0083	.6076	136.4
		1.0	46.70	4409	19.88	1.0000	.6650	149.3
		.9	42.03	4359	19.95	1.0080	.7223	162.2
		.8	37.36	4303	20.02	1.0323	.7806	175.3
0.8	34.52	1.2	55.77	4334	18.86	1.0342	0.5540	124.8
		1.1	51.12	4289	18.90	1.0081	.6121	137.9
		1.0	46.48	4239	18.95	1.0000	.6691	150.8
		.9	41.83	4185	19.01	1.0078	.7262	163.6
		.8	37.18	4125	19.07	1.0316	.7842	176.7
0.6	41.27	1.2	55.32	3961	17.68	1.0330	0.5628	124.8
		1.1	50.71	3912	17.71	1.0078	.6204	137.6
		1.0	46.10	3859	17.75	1.0000	.6770	150.1
		.9	41.49	3801	17.79	1.0076	.7336	162.7
		.8	36.88	3737	17.84	1.0307	.7910	175.4
0.4	51.32	1.2	54.76	3382	16.15	1.0315	0.5733	122.5
		1.1	50.20	3333	16.18	1.0075	.6302	134.6
		1.0	45.63	3279	16.20	1.0000	.6863	146.6
		.9	41.07	3220	16.22	1.0072	.7423	158.6
		.8	36.51	3153	16.24	1.0294	.7991	170.7

TABLE V. - PROPERTIES AND COMPOSITION IN COMBUSTION CHAMBER AND FOLLOWING AN ISENTROPIC EXPANSION TO ASSIGNED EXIT TEMPERATURES FOR LIQUID HYDRAZINE WITH LIQUID FLUORINE

(a) Combustion-chamber pressure, 150 lb/sq in. absolute

Temperature, T, ^{o}K	Pressure, P, atm	γ_s, $\left(\frac{\partial \log P}{\partial \log \rho}\right)_s$	Specific heat at constant pressure, c_p, cal/(g)(^{o}K)	Coefficient of viscosity, μ, micropoise	Coefficient of thermal conductivity, k, microcal/(sec)(cm)(^{o}K)	Mean molecular weight, M	Equilibrium composition, mole fraction					
							HF	H_2	N_2	F	H	N
r = 1.2 (26.00 percent fuel by weight)												
4260	10.21	1.1530	1.9087	1710	3479	19.623	0.56538	0.00638	0.15301	0.20117	0.06067	0.01338
4000	5.393	1.1515	1.6988	1635	2979	20.105	.59907	.00430	.15838	.18393	.04463	.00948
3000	.5531	1.2574	.4989	1307	805	21.202	.68620	.00007	.17165	.13954	.00178	.00076
2600	.2917	1.3188	.3894	1161	588	21.247	.65946	.00000	.17233	.13600	.00009	.00011
1600	.01309	1.3587	.3545	772	364	21.250	.68968	.00000	.17242	.13787	.00000	.00000
r = 1.0 (29.66 percent fuel by weight)												
4257	10.21	1.1483	2.1742	1670	3850	19.056	0.57649	0.01611	0.16919	0.12822	0.09601	0.01397
4000	5.252	1.1442	2.0377	1599	3462	19.438	.61311	.01355	.17512	.10759	.08054	.01011
3200	.5145	1.1473	1.2827	1354	1899	20.816	.72914	.00564	.19161	.04150	.02982	.00210
3000	.2852	1.1575	1.0427	1287	1494	21.093	.75330	.00422	.19465	.02757	.01913	.00113
2300	.04989	1.2620	.4645	1033	598	21.573	.79631	.00062	.19964	.00232	.00108	.00003
r = 0.8 (34.52 percent fuel by weight)												
4142	10.21	1.1549	1.9074	1574	3218	16.171	0.56777	0.04252	0.19017	0.05648	0.13000	0.01106
3900	5.677	1.1548	1.7165	1507	2789	18.508	.59530	.04315	.19548	.04259	.11576	.00772
2900	.4631	1.1903	.6654	1194	1184	19.715	.67647	.06499	.21206	.00301	.04291	.00056
2700	.2852	1.2053	.7408	1127	975	19.882	.68402	.07204	.21402	.00123	.02846	.00023
2000	.05784	1.2934	.4453	878	499	20.164	.69495	.08589	.21717	.00001	.00196	.00000
r = 0.6 (41.27 percent fuel by weight)												
3855	10.21	1.1741	1.4913	1396	2284	17.052	0.51373	0.11779	0.21746	0.01455	0.13115	0.00531
3600	5.792	1.1764	1.3490	1324	1976	17.369	.52829	.12862	.22212	.00858	.10924	.00315
2500	.4330	1.2279	.6781	993	806	18.336	.56660	.18089	.23612	.00015	.01620	.00005
2300	.2754	1.2535	.5798	929	664	18.414	.56911	.18577	.23714	.00004	.00793	.00001
1600	.05561	1.3308	.4331	693	393	18.487	.57140	.19042	.23608	.00000	.00010	.00000
r = 0.4 (51.32 percent fuel by weight)												
3402	10.21	1.1910	1.2119	1150	1575	15.789	0.40264	0.26647	0.25222	0.00170	0.07555	0.00123
3200	6.578	1.1954	1.0984	1099	1378	15.947	.40765	.27813	.25503	.00094	.05757	.00068
2000	.4844	1.2997	.5334	768	526	16.423	.42078	.31493	.26299	.00000	.00131	.00000
1700	.2443	1.3242	.4951	678	438	16.432	.42102	.31568	.26314	.00000	.00017	.00000
1100	.04458	1.3621	.4549	482	292	16.434	.42105	.31579	.26316	.00000	.00000	.00000

TABLE V. - PROPERTIES AND COMPOSITION IN COMBUSTION CHAMBER AND FOLLOWING AN ISENTROPIC EXPANSION TO ASSIGNED EXIT TEMPERATURES FOR LIQUID HYDRAZINE WITH LIQUID FLUORINE - Continued

(b) Combustion-chamber pressure, 500 lb/sq in. absolute

Temperature, T, °K	Pressure, P, atm	γ_s, $\left(\frac{\partial \log P}{\partial \log \rho}\right)_s$	Specific heat at constant pressure, c_p, cal/(g)(°K)	Coefficient of viscosity, μ, micropoise	Coefficient of thermal conductivity, k, microcal/(sec)(cm)(°K)	Mean molecular weight, M	Equilibrium composition, mole fraction					
							HF	H_2	N_2	F	H	N
r = 1.2 (26.00 percent fuel by weight)												
4393	20.41	1.1593	1.6987	1757	3204	19.833	0.57741	0.00658	0.15394	0.19499	0.05312	0.01395
4100	10.50	1.1590	1.4832	1672	2692	20.266	.61171	.00420	.15995	.17755	.03762	.00896
3000	1.135	1.2820	.4454	1307	735	21.225	.68790	.00003	.17194	.13871	.00087	.00053
2600	.6135	1.3222	.3851	1161	583	21.248	.68956	.00000	.17236	.13796	.00004	.00008
1600	.09078	1.3583	.3550	772	364	21.251	.68970	.00000	.17243	.13780	.00000	.00000
r = 1.1 (27.71 percent fuel by weight)												
4411	20.41	1.1557	1.8910	1745	3521	19.541	0.58400	0.01089	0.16242	0.15947	0.07011	0.01311
4100	9.667	1.1519	1.7189	1656	3053	20.019	.62413	.00776	.16836	.13751	.05275	.00949
3100	.8580	1.2097	.6513	1336	1026	21.298	.73123	.00041	.18365	.07908	.00461	.00102
2900	.5902	1.2564	.4899	1265	766	21.378	.73776	.00010	.18462	.07560	.00146	.00046
2000	.1211	1.3307	.3734	925	452	21.416	.74074	.00000	.18518	.07407	.00000	.00000
r = 1.0 (29.66 percent fuel by weight)												
4394	20.41	1.1536	1.9580	1718	3585	19.193	0.58855	0.01755	0.17028	0.12199	0.08690	0.01473
4100	10.05	1.1497	1.8239	1635	3189	19.651	.62720	.01447	.17705	.10029	.07135	.00964
3100	.6886	1.1642	.9756	1323	1447	21.118	.75498	.00466	.19487	.02683	.01747	.00117
3000	.5294	1.1718	.6784	1289	1283	21.224	.76440	.00391	.19601	.02133	.01352	.00083
2300	.1074	1.2738	.4423	1033	576	21.583	.79731	.00052	.19975	.00172	.00067	.00002
r = 0.9 (31.91 percent fuel by weight)												
4352	20.41	1.1554	1.8997	1677	3406	18.789	0.58676	0.02857	0.18039	0.08663	0.10431	0.01333
4100	11.29	1.1530	1.7605	1606	3036	19.154	.61783	.02670	.18602	.06862	.09149	.00933
3000	.7321	1.1917	.7949	1262	1156	20.527	.72928	.02854	.20399	.00640	.03106	.00072
2900	.5822	1.2015	.7264	1227	1039	20.604	.73415	.03014	.20488	.00429	.02606	.00049
2100	.1051	1.2932	.4292	936	513	20.906	.74923	.04067	.20613	.00003	.00193	.00000
r = 0.8 (34.52 percent fuel by weight)												
4273	20.41	1.1611	1.7271	1616	3010	18.325	0.57664	0.04708	0.19203	0.05492	0.11866	0.01067
4000	11.13	1.1614	1.5435	1540	2582	18.669	.60464	.04780	.19738	.03878	.10402	.00737
2900	.8730	1.2038	.7621	1195	1060	19.831	.68134	.07025	.21338	.00213	.03249	.00041
2700	.5582	1.2202	.6597	1127	884	19.963	.68717	.07598	.21493	.00086	.02090	.00017
1900	.09894	1.3101	.4203	842	457	20.177	.69539	.08656	.21731	.00000	.00074	.00000

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TABLE V. - PROPERTIES AND COMPOSITION IN COMBUSTION CHAMBER AND FOLLOWING AN ISENTROPIC EXPANSION TO ASSIGNED EXIT TEMPERATURES FOR LIQUID HYDRAZINE WITH LIQUID FLUORINE - Continued

(b) Combustion-chamber pressure, 300 lb/sq in. absolute - Concluded

Temperature, T, ^{o}K	Pressure, P, atm	γ_s, $\left(\frac{\partial \log P}{\partial \log \rho}\right)_s$	Specific heat at constant pressure, c_p, cal/(g)(^{o}K)	Coefficient of viscosity, μ, micropoise	Coefficient of thermal conductivity, k, microcal/(sec)(cm)(^{o}K)	Mean molecular weight, M	Equilibrium composition, mole fraction					
							HF	H_2	N_2	F	H	N
r = 0.7 (37.59 percent fuel by weight)												
4140	20.41	1.1703	1.5182	1532	2540	17.802	0.55501	0.07805	0.20465	0.02972	0.12422	0.00835
3900	12.24	1.1727	1.3738	1465	2213	18.069	.57331	.08270	.20924	.02018	.10913	.00544
2700	.8437	1.2202	.6902	1094	897	19.158	.62875	.12422	.22466	.00050	.02173	.00014
2500	.5442	1.2420	.5977	1027	746	19.254	.63223	.12949	.22584	.00017	.01223	.00005
1800	.1187	1.3161	.4275	785	436	19.371	.63624	.13615	.22723	.00000	.00038	.00000
r = 0.6 (41.27 percent fuel by weight)												
3963	20.41	1.1803	1.3602	1427	2147	17.230	0.51868	0.12593	0.21917	0.01369	0.11686	0.00547
3700	11.83	1.1833	1.2325	1354	1861	17.469	.53242	.13587	.22369	.00815	.09678	.00309
2600	1.070	1.2325	.6610	1025	816	18.340	.56668	.18117	.23616	.00018	.01575	.00007
2300	.5634	1.2666	.5432	929	630	18.436	.56980	.18718	.23742	.00003	.00556	.00001
1500	.09065	1.3377	.4260	658	369	18.467	.57142	.19040	.23809	.00000	.00003	.00000
r = 0.5 (45.75 percent fuel by weight)												
3745	20.41	1.1890	1.2390	1306	1814	16.602	0.46871	0.19176	0.23555	0.00529	0.09578	0.00291
3500	12.36	1.1922	1.1275	1240	1581	16.811	.47700	.20373	.23920	.00299	.07551	.00157
2400	1.194	1.2593	.5946	925	682	17.449	.49816	.24552	.24909	.00003	.00719	.00002
2100	.6364	1.2924	.5137	833	546	17.495	.49951	.24679	.24976	.00000	.00194	.00000
1300	.08975	1.3495	.4382	569	330	17.512	.50000	.25000	.25000	.00000	.00000	.00000
r = 0.4 (51.32 percent fuel by weight)												
3477	20.41	1.1996	1.0978	1170	1467	15.881	0.40533	0.27367	0.25374	0.00157	0.06456	0.00113
3200	11.67	1.2070	.9656	1099	1231	16.063	.41086	.28707	.25697	.00070	.04390	.00051
2100	1.223	1.2956	.5404	797	552	16.421	.42072	.31475	.26295	.00000	.00158	.00000
1800	.6339	1.3189	.5019	708	462	16.432	.42100	.31562	.26312	.00000	.00025	.00000
1200	.1273	1.3554	.4611	517	316	16.434	.42105	.31579	.26316	.00000	.00000	.00000
r = 0.3 (58.43 percent fuel by weight)												
3122	20.41	1.2208	.9073	1014	1086	15.001	0.32793	0.36792	0.27336	0.00027	0.03024	0.00029
2900	13.29	1.2331	.8112	960	937	15.087	.32997	.37553	.27501	.00011	.01926	.00012
1800	1.419	1.3195	.5401	674	474	15.234	.33330	.38876	.27775	.00000	.00019	.00000
1400	.5166	1.3423	.5115	558	376	15.236	.33333	.38889	.27778	.00000	.00000	.00000
1200	.2846	1.3548	.4961	497	328	15.236	.33333	.38889	.27778	.00000	.00000	.00000

TABLE V. - PROPERTIES AND COMPOSITION IN COMBUSTION CHAMBER AND FOLLOWING AN ISENTROPIC EXPANSION TO ASSIGNED EXIT TEMPERATURES FOR LIQUID HYDRAZINE WITH LIQUID FLUORINE - Continued

(c) Combustion-chamber pressure, 600 lb/sq in. absolute

Temperature, T, °K	Pressure, P, atm	γ_s, $\left(\frac{\partial \log P}{\partial \log \rho}\right)_s$	Specific heat at constant pressure, c_p, cal/(g)(°K)	Coefficient of viscosity, μ, micropoise	Coefficient of thermal conductivity, k, microcal/(sec)(cm)(°K)	Mean molecular weight, M	Equilibrium composition, mole fraction					
							HF	H_2	N_2	F	H	N
r = 1.2 (26.00 percent fuel by weight)												
4533	40.83	1.1666	1.5124	1806	2955	19.990	0.58922	0.00671	0.15570	0.18925	0.04613	0.01298
4200	20.57	1.1675	1.2948	1708	2420	20.423	.62414	.00398	.16154	.17125	.03075	.00334
3100	2.716	1.2853	.4393	1343	747	21.226	.68805	.00004	.17195	.13363	.00078	.00056
2500	1.094	1.3273	.3796	1123	558	21.249	.68964	.00000	.17240	.13792	.00001	.00003
1600	.1901	1.3576	.3560	772	365	21.253	.68976	.00000	.17244	.13766	.00000	.00000
r = 1.0 (29.66 percent fuel by weight)												
4539	40.83	1.1598	1.7653	1767	3346	19.359	0.60049	0.01897	0.17222	0.11618	0.07324	0.01389
4300	24.20	1.1567	1.6744	1701	3062	19.694	.62923	.01637	.17712	.09985	.06711	.01031
3100	1.285	1.1787	.8288	1325	1253	21.243	.76562	.00429	.19618	.02081	.01224	.00086
3000	1.014	1.1876	.7521	1290	1121	21.326	.77311	.00354	.19707	.01638	.00930	.00060
2300	.2307	1.2827	.4271	1033	560	21.591	.79802	.00044	.19982	.00129	.00042	.00001
r = 0.8 (34.52 percent fuel by weight)												
4405	40.83	1.1678	1.5595	1659	2809	18.485	0.58583	0.05170	0.19411	0.05126	0.10714	0.00996
4100	21.85	1.1685	1.3839	1573	2384	18.831	.61405	.05251	.19935	.03496	.09220	.00694
3000	2.076	1.2106	.7232	1229	1042	19.862	.68229	.07203	.21369	.00224	.02931	.00044
2700	1.111	1.2349	.5965	1127	812	20.025	.68955	.07908	.21561	.00060	.01510	.00012
1900	.2109	1.3134	.4155	841	453	20.179	.69547	.08668	.21734	.00000	.00051	.00000
r = 0.6 (41.27 percent fuel by weight)												
4074	40.83	1.1875	1.2390	1459	2016	17.371	0.52412	0.13379	0.22127	0.01279	0.10315	0.00489
3800	24.19	1.1906	1.1231	1383	1748	17.608	.53661	.14293	.22528	.00762	.08459	.00297
2400	1.417	1.2668	.5427	961	651	18.434	.56973	.18706	.23740	.00004	.00576	.00001
2300	1.156	1.2772	.5174	929	606	18.451	.57029	.18817	.23763	.00002	.00389	.00001
1500	.1901	1.3379	.4257	658	368	18.487	.57142	.19047	.23809	.00000	.00003	.00000
r = 0.4 (51.32 percent fuel by weight)												
3547	40.83	1.2083	.9959	1187	1367	15.969	0.40772	0.28050	0.25515	0.00141	0.05411	0.00111
3300	25.72	1.2153	.8991	1125	1185	16.106	.41194	.29051	.25764	.00071	.03867	.00052
2100	2.485	1.3004	.5307	797	544	16.425	.42088	.31506	.26301	.00000	.00111	.00000
1800	1.295	1.3202	.4998	708	461	16.432	.42102	.31567	.26313	.00000	.00018	.00000
1200	.2602	1.3554	.4611	517	316	16.434	.42105	.31579	.26316	.00000	.00000	.00000

TABLE V. - PROPERTIES AND COMPOSITION IN COMBUSTION CHAMBER AND FOLLOWING AN ISENTROPIC EXPANSION TO ASSIGNED EXIT TEMPERATURES FOR LIQUID HYDRAZINE WITH LIQUID FLUORINE - Concluded

(d) Combustion-chamber pressure, 1200 lb/sq in. absolute

Temperature, T, °K	Pressure, P, atm	γ_s, $\left(\frac{\partial \log P}{\partial \log \rho}\right)_s$	Specific heat at constant pressure, c_p, cal/(g)(°K)	Coefficient of viscosity, μ, micropoise	Coefficient of thermal conductivity, k, microcal/(sec)(cm)(°K)	Mean molecular weight, M	Equilibrium composition, mole fraction					
							HF	H_2	N_2	F	H	N
r = 1.2 (26.00 percent fuel by weight)												
4673	81.65	1.1743	1.3391	1655	2713	20.149	0.60153	0.00665	0.15741	0.16314	0.03910	0.01215
4300	40.63	1.1773	1.1206	1745	2166	20.573	.63598	.00364	.16310	.16520	.02442	.00764
3100	5.587	1.2990	.4154	1343	715	21.237	.68884	.00002	.17212	.13825	.00038	.00039
2500	2.279	1.3278	.3791	1123	557	21.250	.68966	.00000	.17240	.13790	.00000	.00002
1600	.3953	1.3562	.3582	772	367	21.256	.68986	.00000	.17247	.13737	.00000	.00000
r = 1.0 (29.66 percent fuel by weight)												
4687	81.65	1.1661	1.5871	1818	3116	19.530	0.61311	0.02026	0.17419	0.10990	0.06940	0.01713
4400	45.84	1.1627	1.4902	1738	2806	19.892	.64469	.01704	.17933	.09173	.05765	.00255
3200	3.078	1.1859	.7801	1361	1221	21.266	.76721	.00462	.19639	.02008	.01084	.00087
3000	1.990	1.2038	.6575	1291	999	21.402	.77980	.00314	.19786	.01252	.00625	.00043
2200	.4060	1.2987	.4039	994	516	21.602	.79913	.00022	.19993	.00058	.00013	.00000
r = 0.8 (34.52 percent fuel by weight)												
4536	81.65	1.1744	1.3992	1701	2606	18.648	0.59569	0.05635	0.19575	0.04703	0.09501	0.01014
4200	43.06	1.1760	1.2387	1606	2199	18.992	.62336	.05714	.20133	.03119	.08055	.00644
3000	4.016	1.2245	.6478	1229	949	19.947	.68589	.07591	.21468	.01159	.02163	.00032
2700	2.239	1.2485	.5489	1127	758	20.070	.69131	.08128	.21612	.00042	.01079	.00008
1900	.4469	1.3157	.4123	841	450	20.181	.69553	.08677	.21735	.00000	.00035	.00000
r = 0.6 (41.27 percent fuel by weight)												
4182	81.65	1.1948	1.1235	1490	1885	17.510	0.52952	0.14154	0.22315	0.01166	0.08941	0.00470
3900	49.61	1.1984	1.0227	1412	1642	17.723	.54076	.14965	.22684	.00703	.07292	.00281
2600	4.263	1.2591	.5649	1025	717	18.413	.56902	.18575	.23711	.00009	.00799	.00003
2300	2.374	1.2854	.4992	929	589	18.462	.57063	.18886	.23777	.00001	.00272	.00000
1500	.3964	1.3381	.4255	658	368	18.488	.57143	.19047	.23809	.00000	.00001	.00000
r = 0.4 (51.32 percent fuel by weight)												
3612	81.65	1.2175	.9077	1204	1279	16.050	0.40998	0.28675	0.25654	0.00123	0.04455	0.00094
3300	47.36	1.2271	.8078	1125	1081	16.189	.41428	.29695	.25905	.00052	.02881	.00039
2100	5.038	1.3039	.5239	797	538	16.427	.42089	.31528	.26306	.00000	.00078	.00000
1700	2.086	1.3264	.4917	678	436	16.433	.42104	.31575	.26315	.00000	.00006	.00000
1200	.5301	1.3554	.4611	517	316	16.434	.42105	.31579	.26316	.00000	.00000	.00000

TABLE VI. - COMPARISON OF CALCULATED PERFORMANCE OF LIQUID HYDRAZINE WITH LIQUID FLUORINE ASSUMING EQUILIBRIUM AND FROZEN COMPOSITION DURING EXPANSION

[r = 1.00; 29.66 percent fuel by weight]

Expansion ratio, P_c/P_e	Combustion-chamber pressure, P_c, lb/sq in. abs	Composition assumed during expansion	Specific impulse, I, lb-sec/lb	Characteristic velocity, c*, ft/sec	Coefficient of thrust, C_F	Ratio of nozzle-exit area to throat area, S_e/S_t	Temperature at nozzle exit, T_e, °K	Mean molecular weight at nozzle exit, M_e
20.41	150	Equilibrium	311.5	7014	1.429	3.982	3192	20.83
		Frozen	286.1	6656	1.383	3.094	1975	19.04
	300	Equilibrium	314.3	7085	1.427	3.942	3239	20.95
		Frozen	290.0	6742	1.384	3.111	2056	19.19
	600	Equilibrium	316.9	7155	1.425	3.901	3282	21.07
		Frozen	294.0	6832	1.385	3.128	2142	19.36
	1200	Equilibrium	319.5	7224	1.423	3.855	3317	21.17
		Frozen	298.0	6920	1.385	3.146	2231	19.53
163.3	150	Equilibrium	380.5	7014	1.745	18.99	2403	21.55
		Frozen	332.1	6656	1.605	11.97	1109	19.04
	300	Equilibrium	382.7	7085	1.738	18.43	2374	21.57
		Frozen	337.0	6742	1.608	12.11	1162	19.19
	600	Equilibrium	384.8	7155	1.730	17.89	2340	21.59
		Frozen	342.0	6832	1.611	12.25	1219	19.36
	1200	Equilibrium	386.6	7224	1.722	17.36	2306	21.60
		Frozen	347.0	6920	1.613	12.39	1279	19.53

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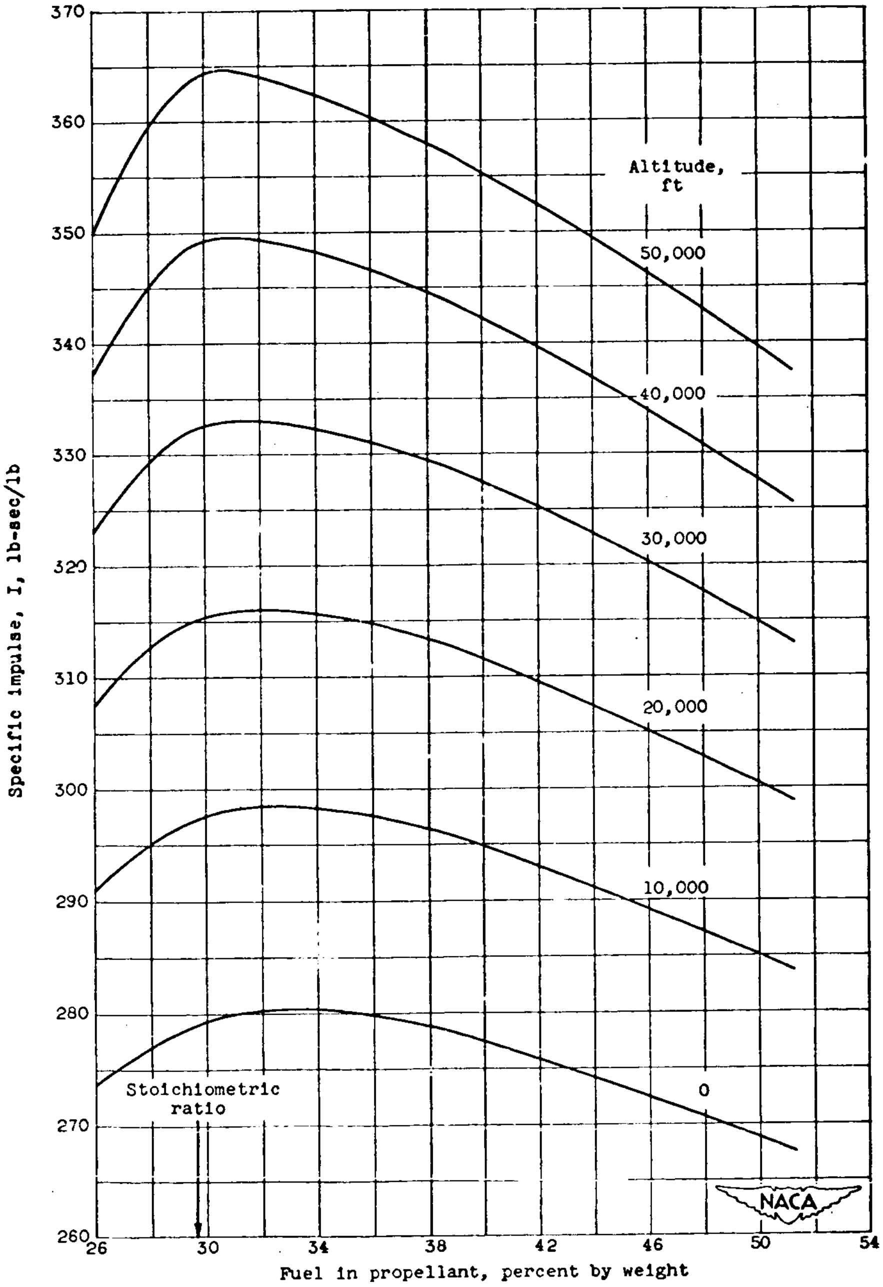

(a) Combustion-chamber pressure, 150 pounds per square inch absolute.

Figure 1. - Theoretical specific impulse of liquid hydrazine with liquid fluorine. Isentropic expansion to altitude indicated assuming equilibrium composition.

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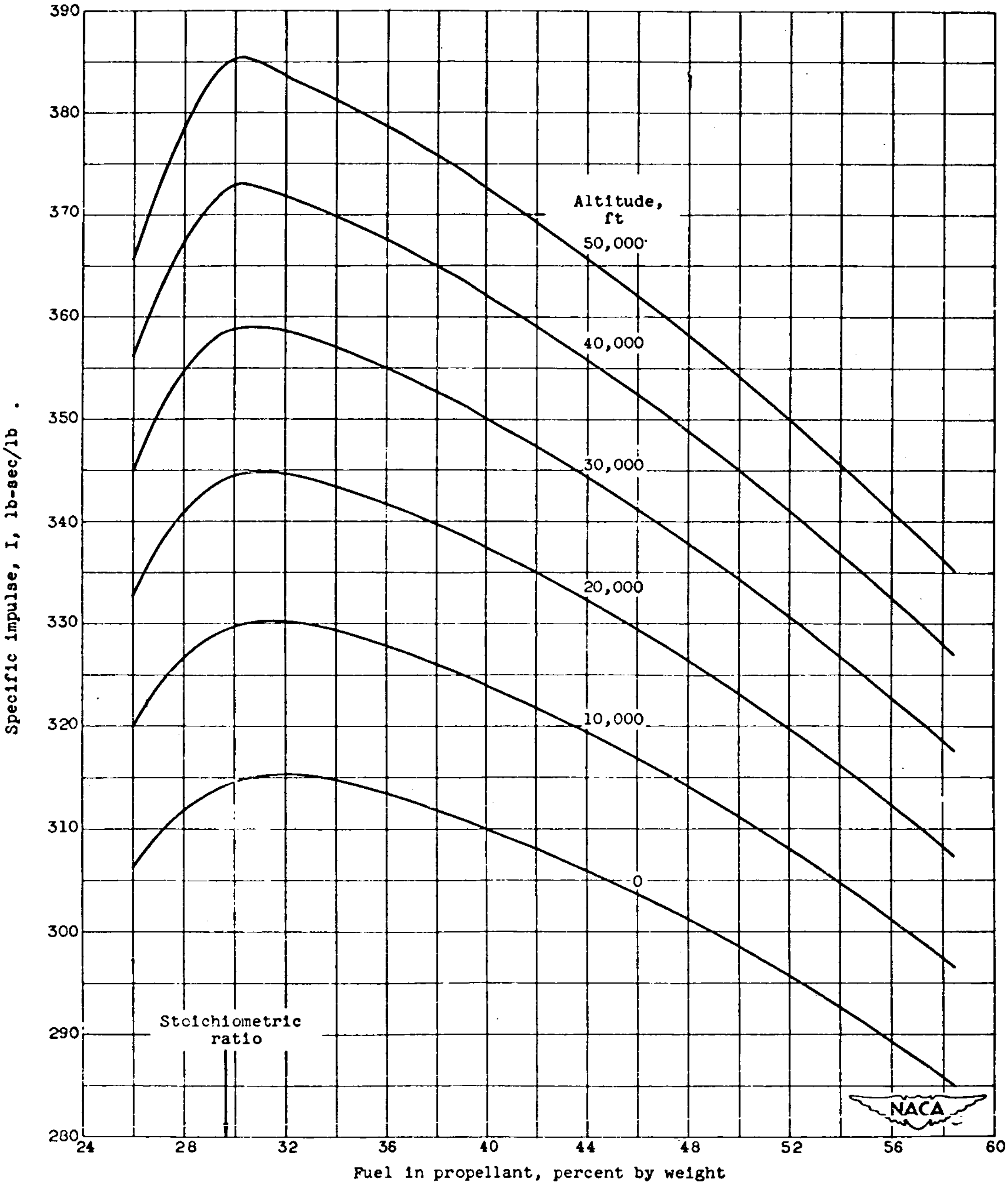

(b) Combustion-chamber pressure, 300 pounds per square inch absolute.

Figure 1. - Continued. Theoretical specific impulse of liquid hydrazine with liquid fluorine. Isentropic expansion to altitude indicated assuming equilibrium composition.

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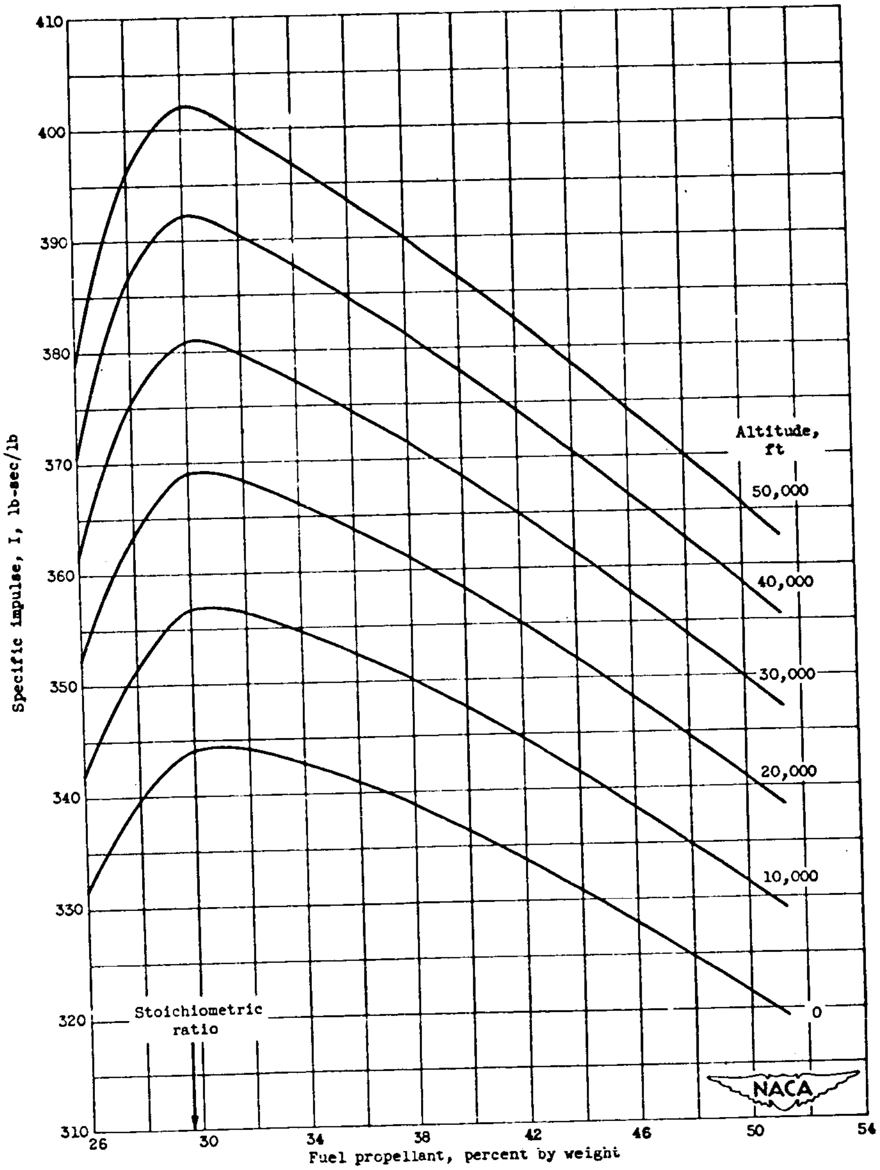
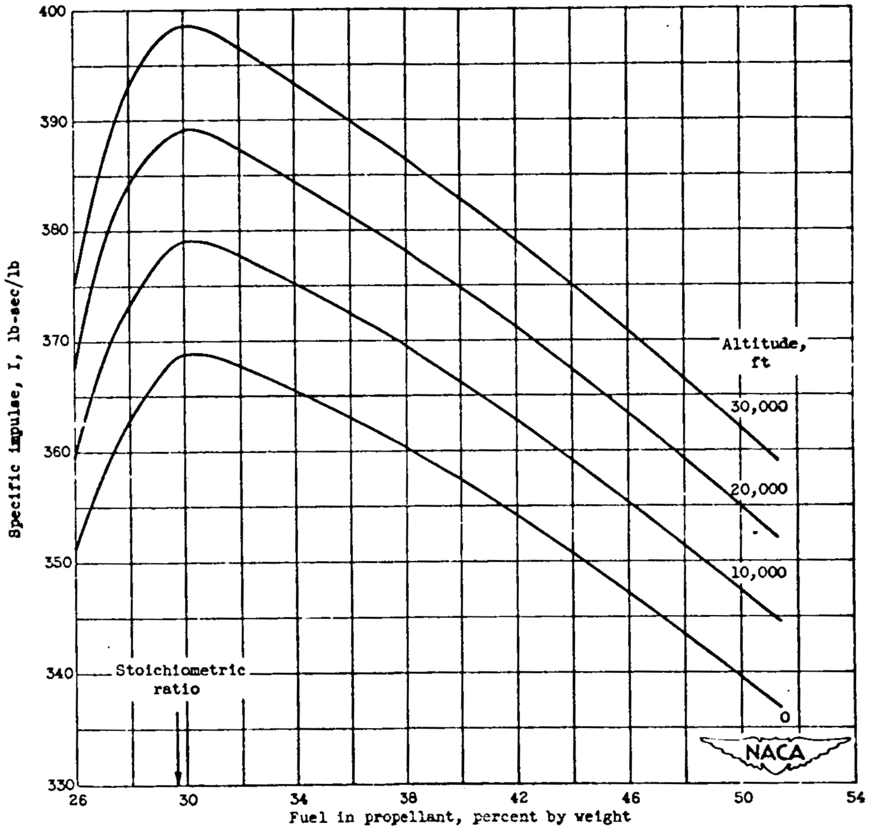


(c) Combustion chamber pressure, 600 pounds per square inch absolute.

Figure 1. - Continued. Theoretical specific impulse of liquid hydrazine with liquid fluorine. Isentropic expansion to altitude indicated assuming equilibrium composition.

2928



(d) Combustion-chamber pressure, 1200 pounds per square inch absolute.

Figure 1. - Concluded. Theoretical specific impulse of liquid hydrazine with liquid fluorine. Isentropic expansion to altitude indicated assuming equilibrium composition.

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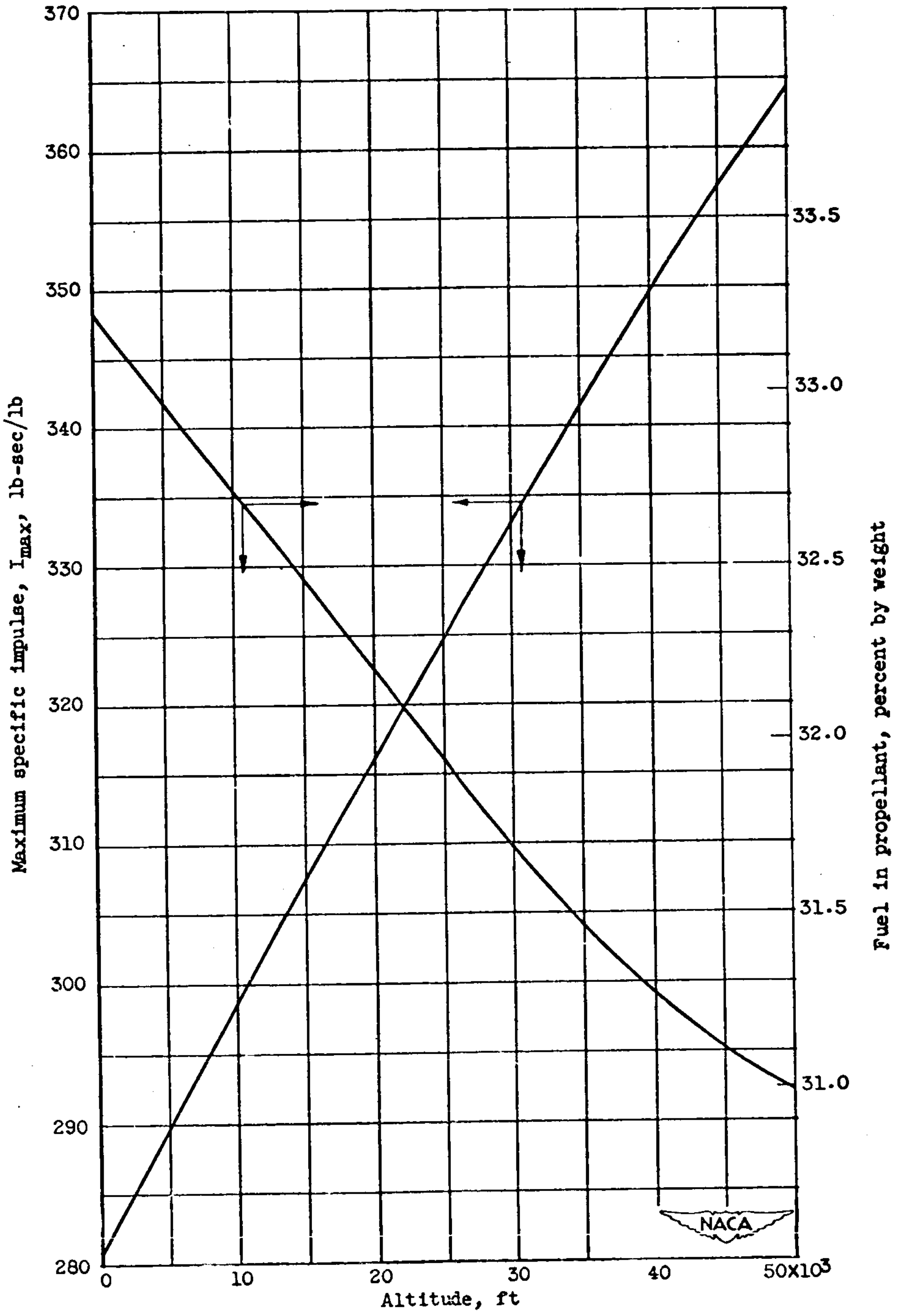

(a) Combustion-chamber pressure, 150 pounds per square inch absolute.

Figure 2. - Maximum theoretical specific impulse and corresponding weight percent fuel in propellant of liquid hydrazine with liquid fluorine. Isentropic expansion to altitude indicated assuming equilibrium composition.

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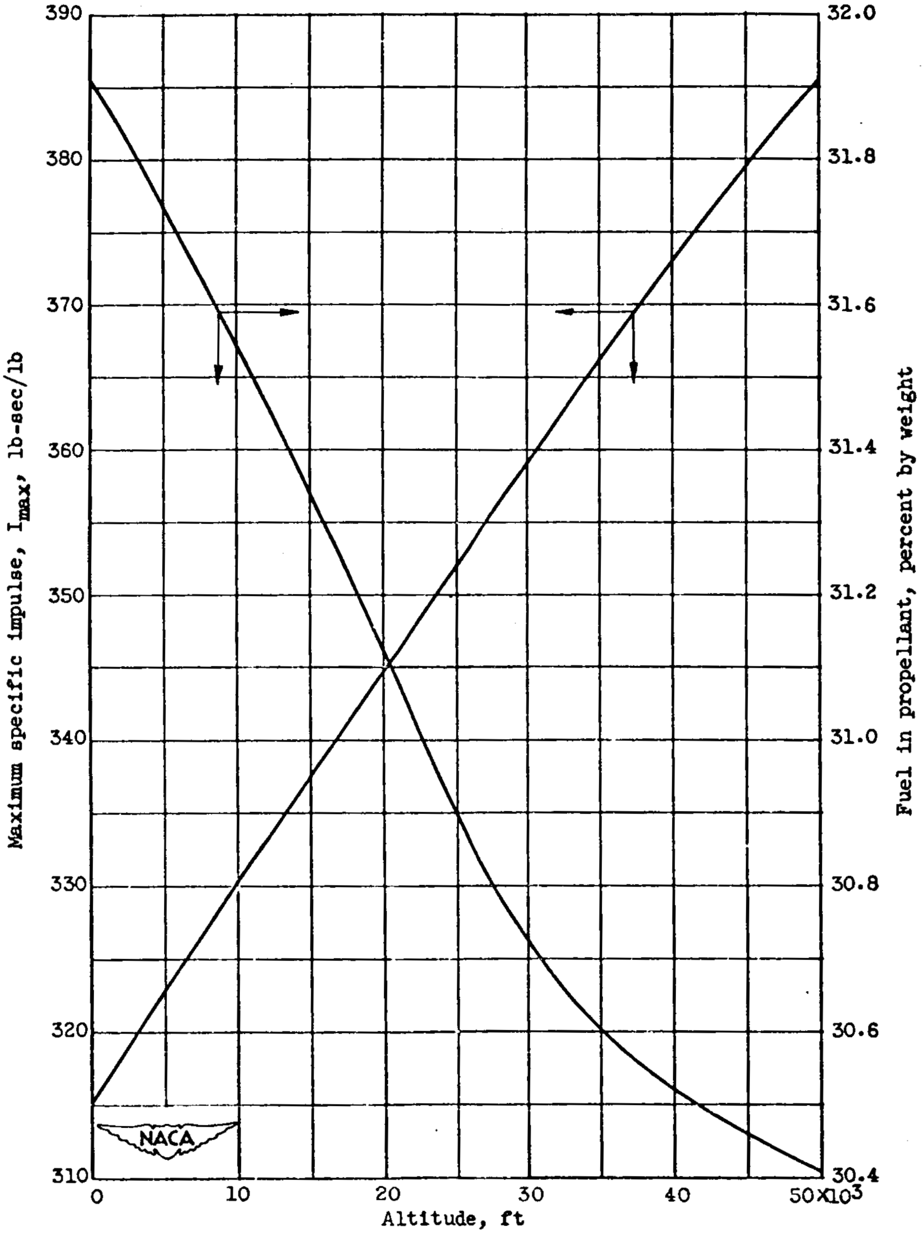

(b) Combustion-chamber pressure, 300 pounds per square inch absolute.

Figure 2. - Continued. Maximum theoretical specific impulse and corresponding weight percent fuel in propellant of liquid hydrazine with liquid fluorine. Isentropic expansion to altitude indicated assuming equilibrium composition.

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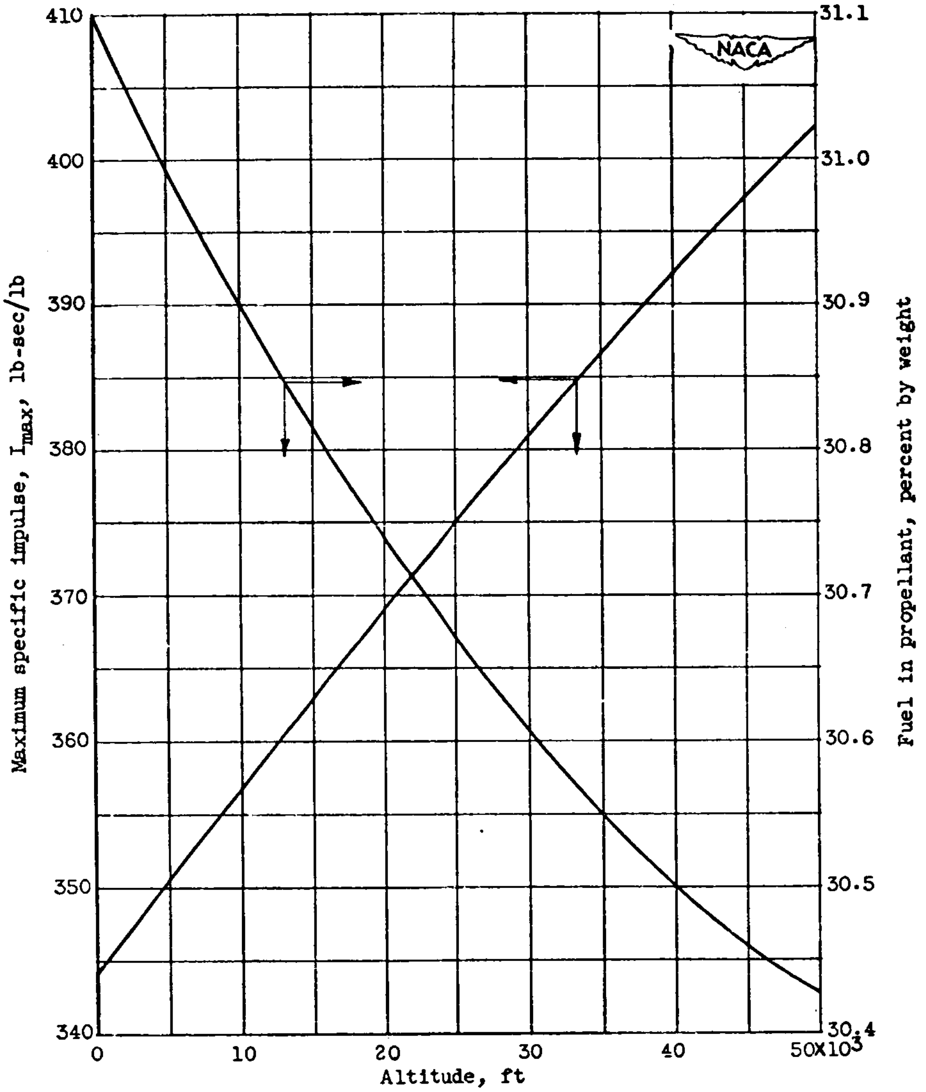
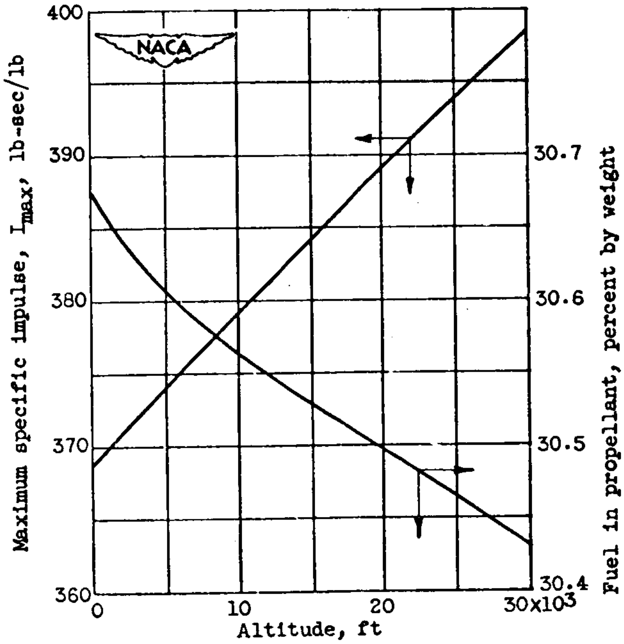


(c) Combustion-chamber pressure, 600 pounds per square inch absolute.

Figure 2. - Continued. Maximum theoretical specific impulse and corresponding weight percent fuel in propellant of liquid hydrazine with liquid fluorine. Isentropic expansion to altitude indicated assuming equilibrium composition.

2928



(d) Combustion-chamber pressure, 1200 pounds per square inch absolute.

Figure 2. - Concluded. Maximum theoretical specific impulse and corresponding weight percent fuel in propellant of liquid hydrazine with liquid fluorine. Isentropic expansion to altitude indicated assuming equilibrium composition.

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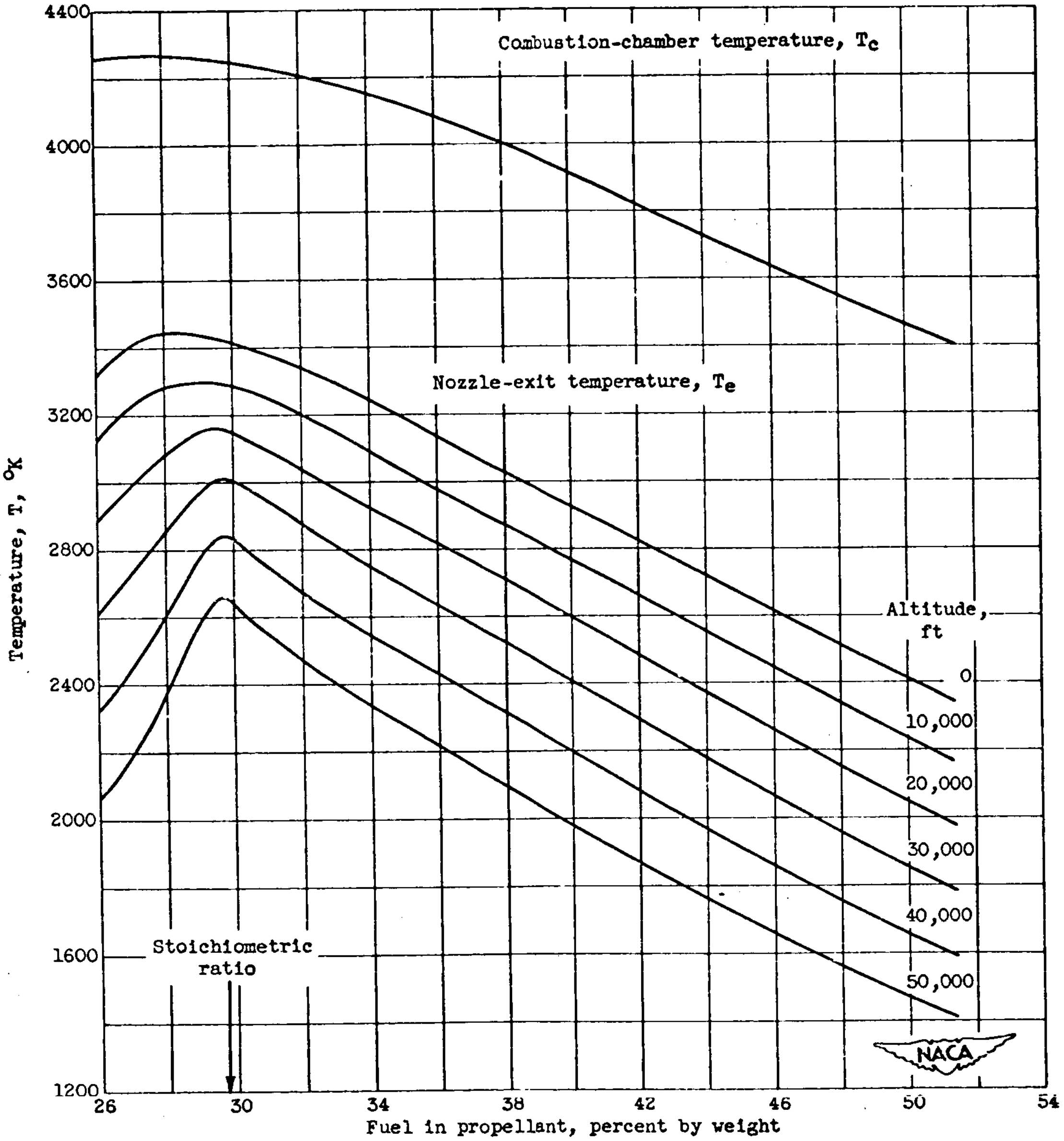

(a) Combustion-chamber pressure, 150 pounds per square inch absolute.

Figure 3. - Theoretical combustion-chamber temperature and nozzle-exit temperature of liquid hydrazine with liquid fluorine. Isentropic expansion to altitude indicated assuming equilibrium composition.

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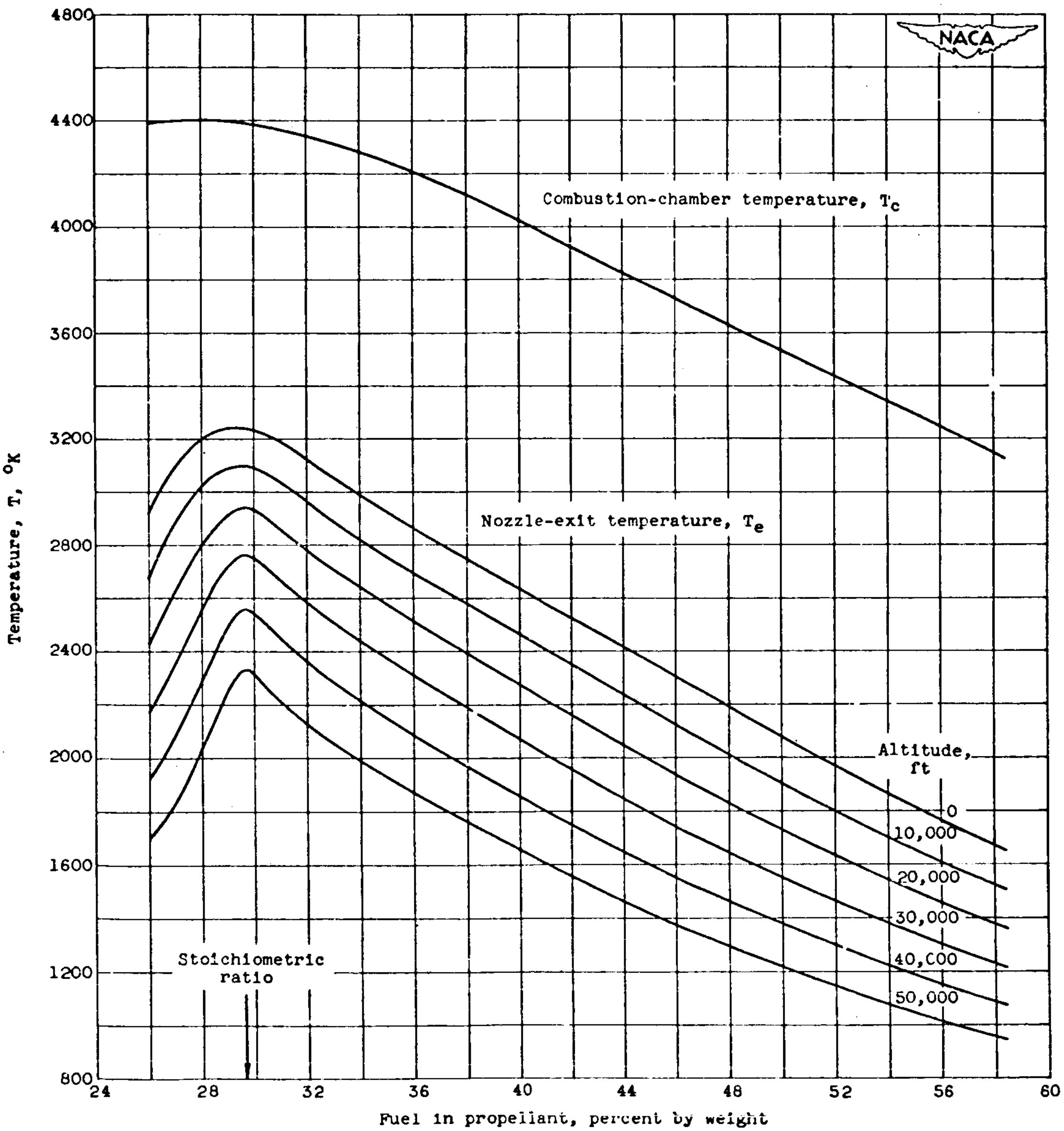
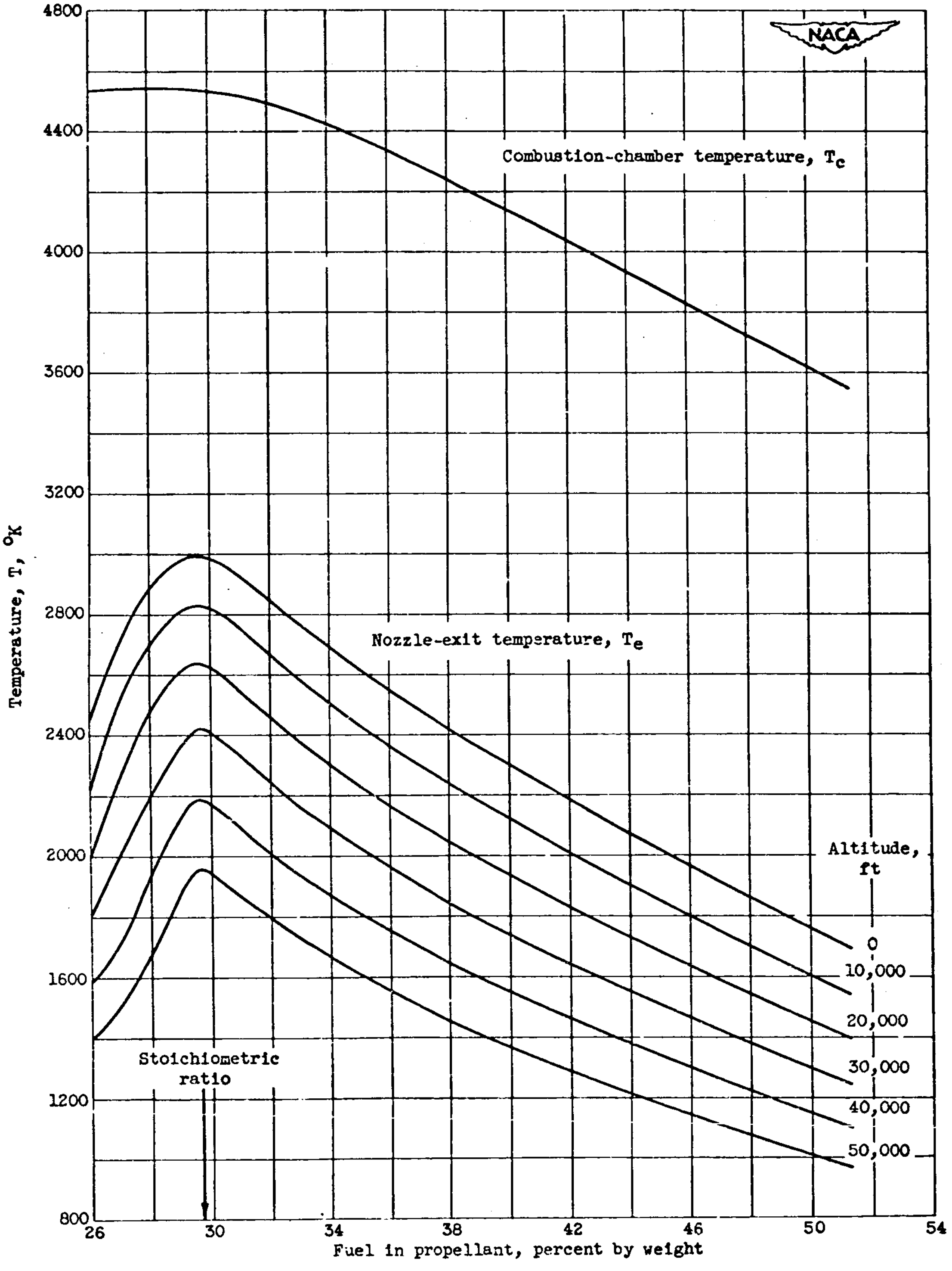


(b) Combustion-chamber pressure, 300 pounds per square inch absolute.

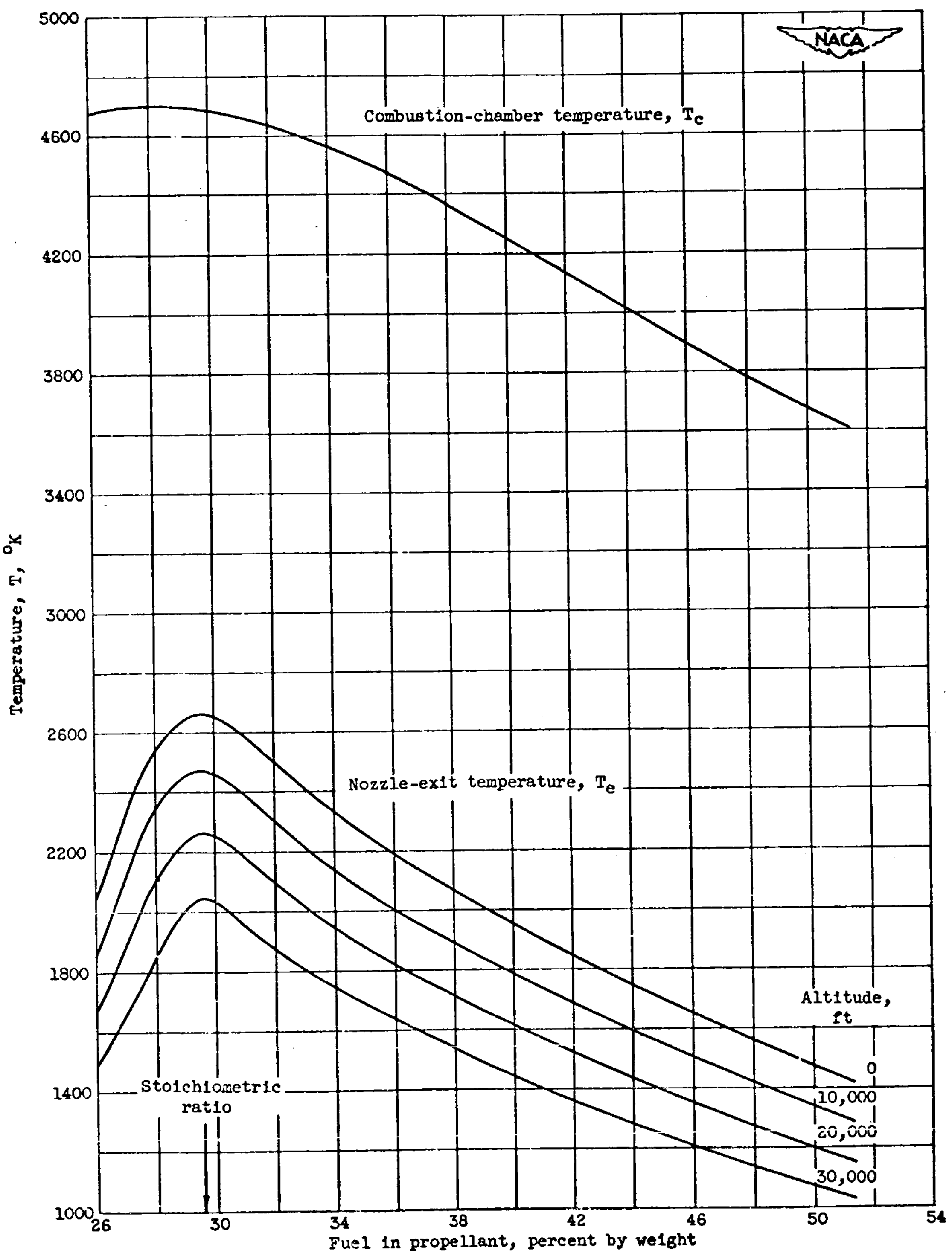
Figure 3. - Continued. Theoretical combustion-chamber temperature and nozzle-exit temperature of liquid hydrazine with liquid fluorine. Isentropic expansion to altitude indicated assuming equilibrium composition.

2928



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

Figure 3. - Continued. Theoretical combustion-chamber temperature and nozzle-exit temperature of liquid hydrazine with liquid fluorine. Isentropic expansion to altitude indicated assuming equilibrium composition.



(d) Combustion-chamber pressure, 1200 pounds per square inch absolute.

Figure 3. - Concluded. Theoretical combustion-chamber temperature and nozzle-exit temperature of liquid hydrazine with liquid fluorine. Isentropic expansion to altitude indicated assuming equilibrium composition.

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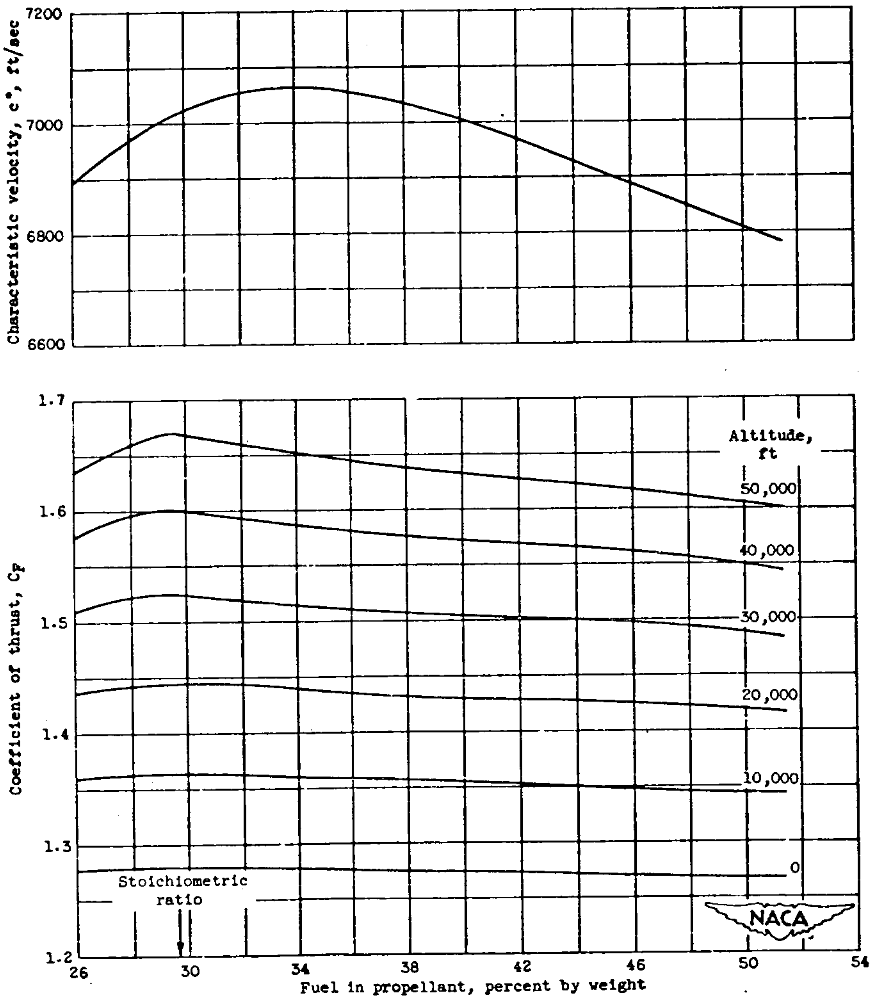
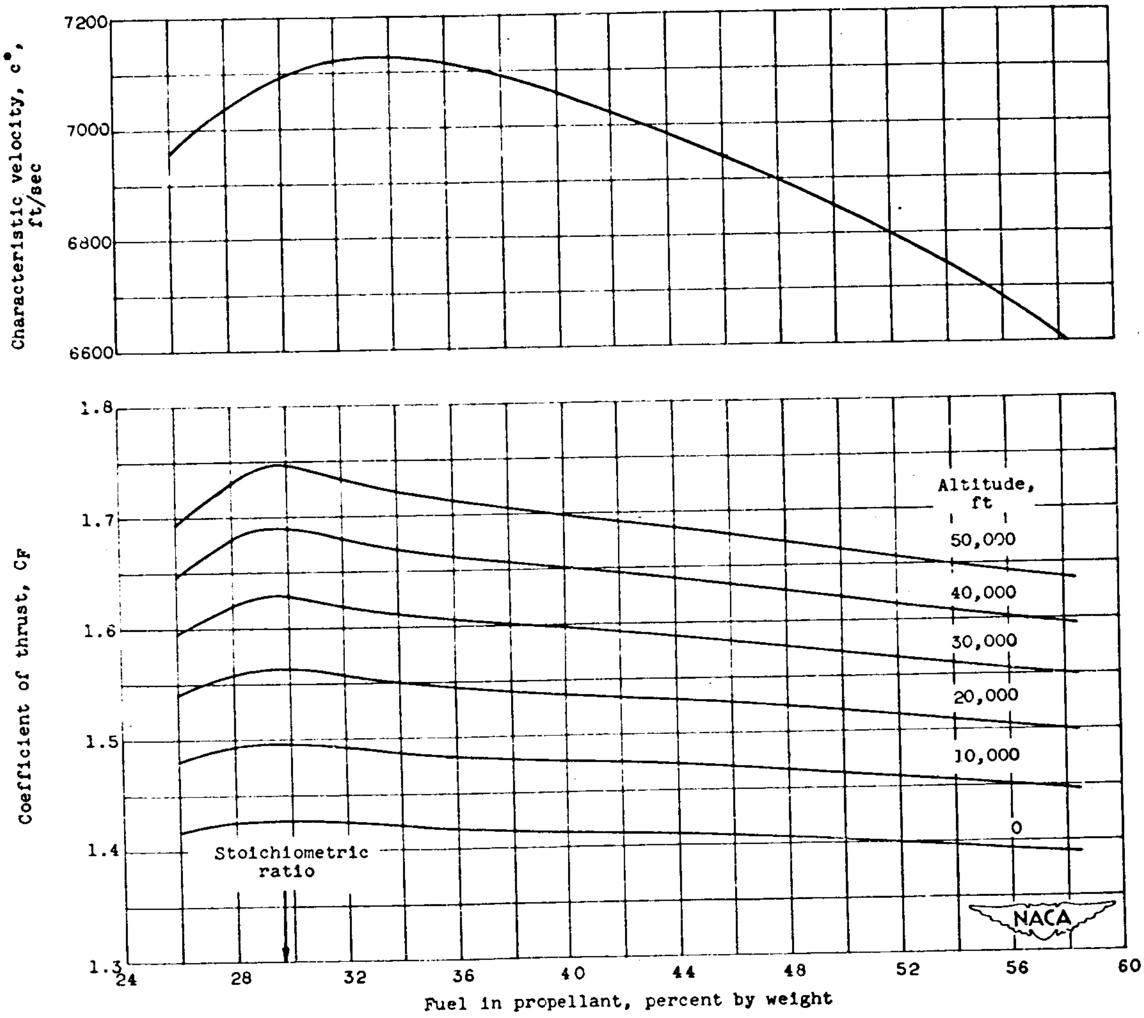


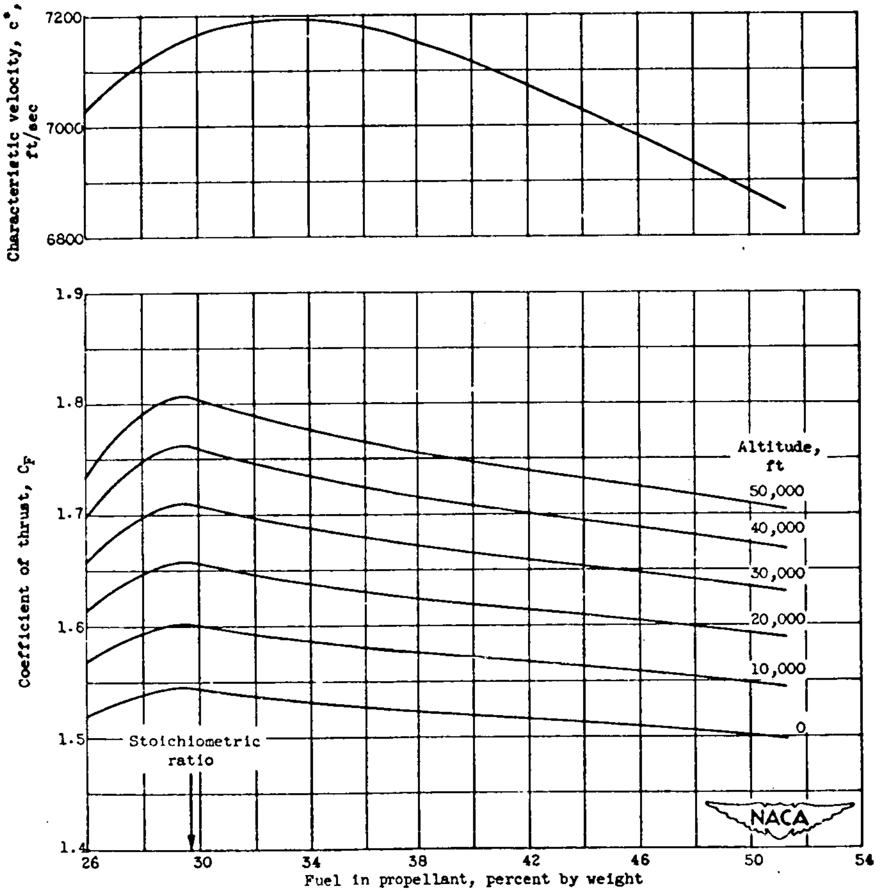
(a) Combustion-chamber pressure, 150 pounds per square inch absolute.

Figure 4. - Theoretical characteristic velocity and coefficient of thrust of liquid hydrazine with liquid fluorine. Isentropic expansion to altitude indicated assuming equilibrium composition.



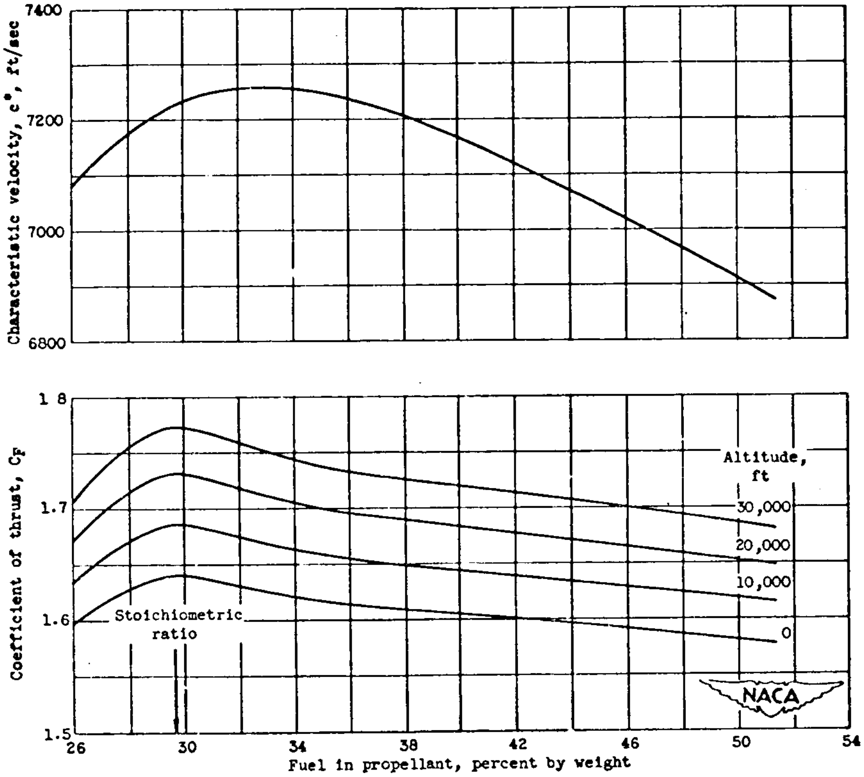
(b) Combustion-chamber pressure, 300 pounds per square inch absolute.

Figure 4. - Continued. Theoretical characteristic velocity and coefficient of thrust of liquid hydrazine with liquid fluorine. Isentropic expansion to altitude indicated assuming equilibrium composition.



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

Figure 4. - Continued. Theoretical characteristic velocity and coefficient of thrust of liquid hydrazine with liquid fluorine. Isentropic expansion to altitude indicated assuming equilibrium composition.



(d) Combustion-chamber pressure, 1200 pounds per square inch absolute.

Figure 4. - Concluded. Theoretical characteristic velocity and coefficient of thrust of liquid hydrazine with liquid fluorine. Isentropic expansion to altitude indicated assuming equilibrium composition.

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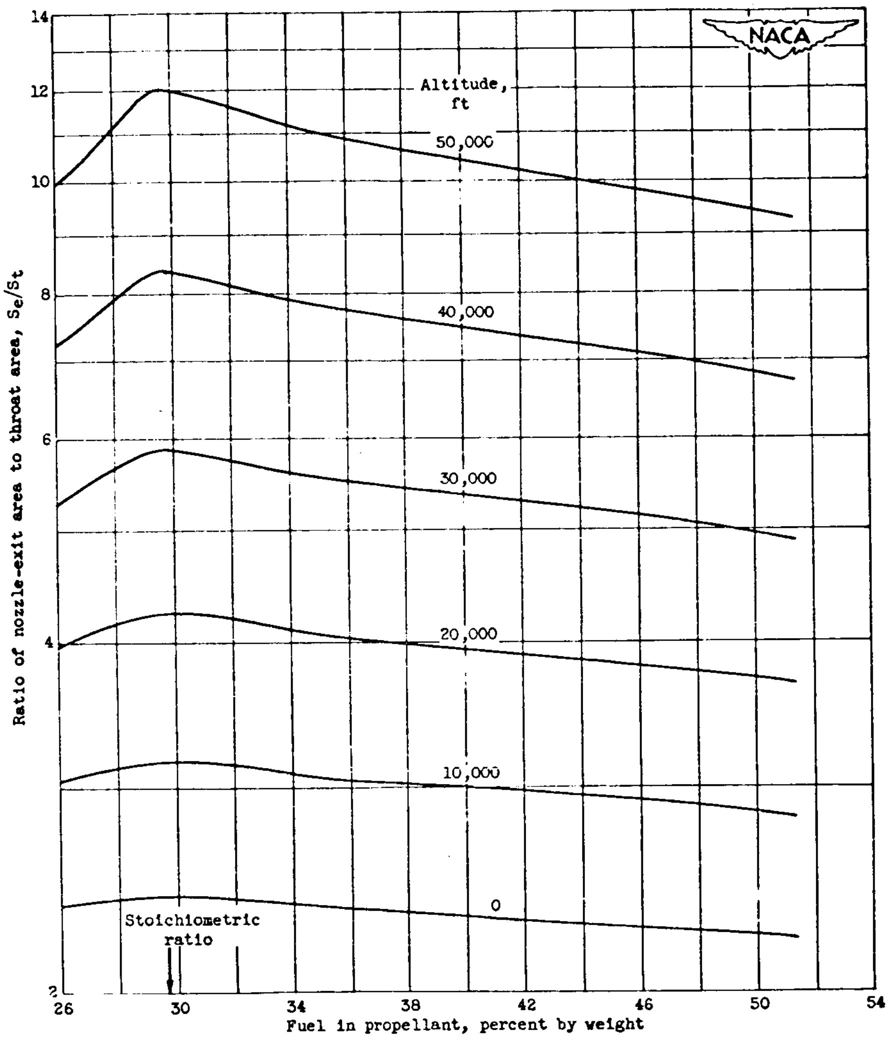

(a) Combustion-chamber pressure, 150 pounds per square inch absolute.

Figure 5. - Theoretical ratios of nozzle-exit area to throat area for liquid hydrazine with liquid fluorine. Isentropic expansion to altitude indicated assuming equilibrium composition.

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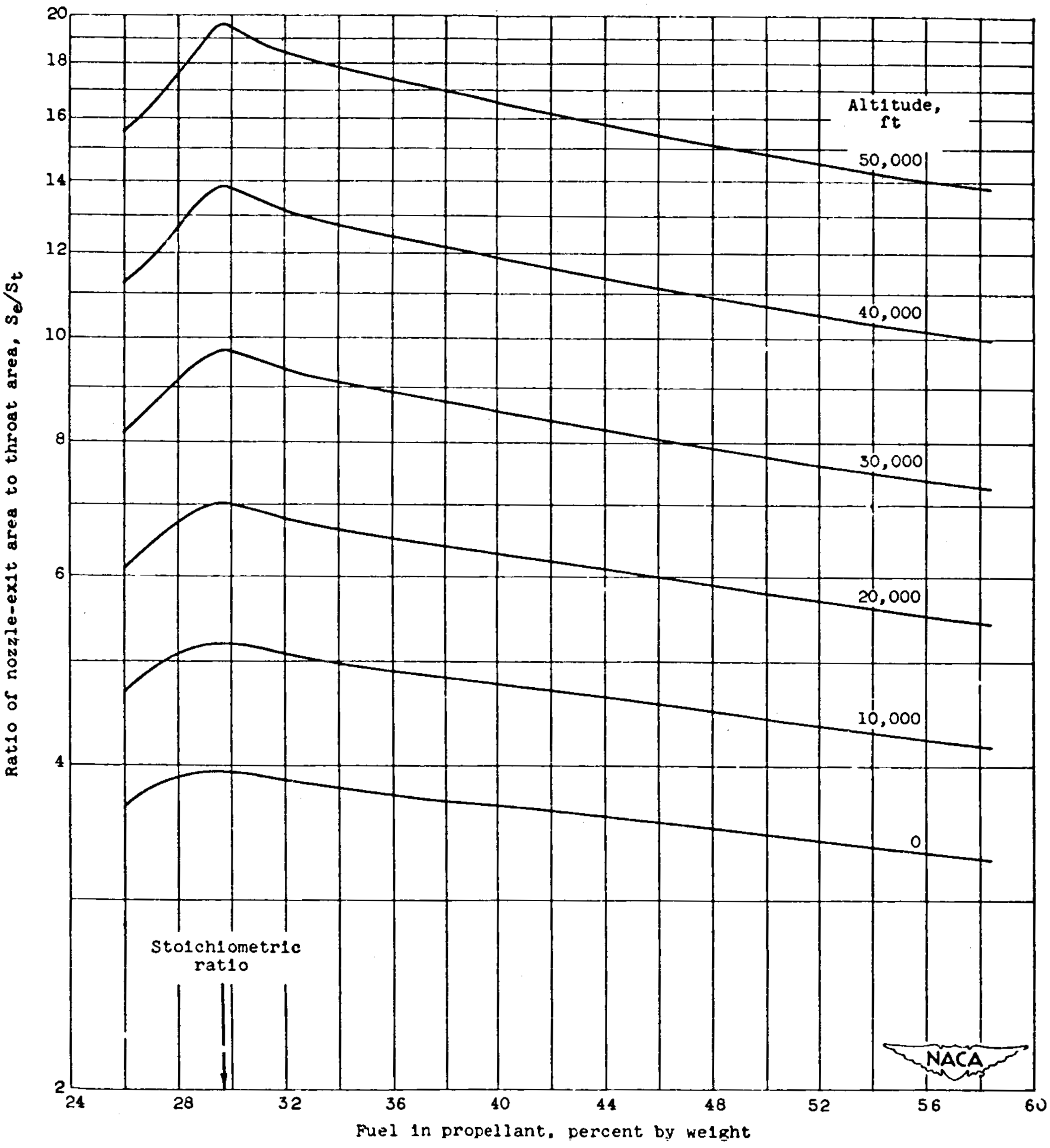

(b) Combustion-chamber pressure, 300 pounds per square inch absolute.

Figure 5. Continued. Theoretical ratios of nozzle-exit area to throat area for liquid hydrazine with liquid fluorine. Isentropic expansion to altitude indicated assuming equilibrium composition.

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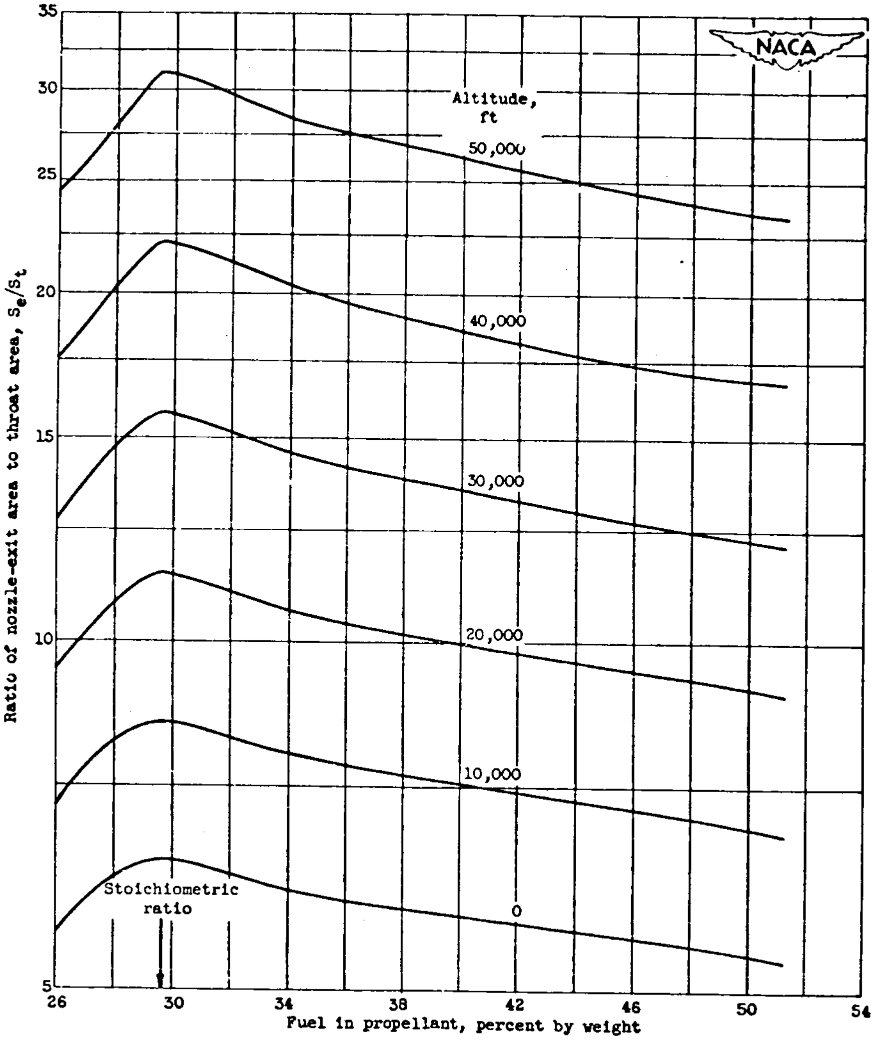
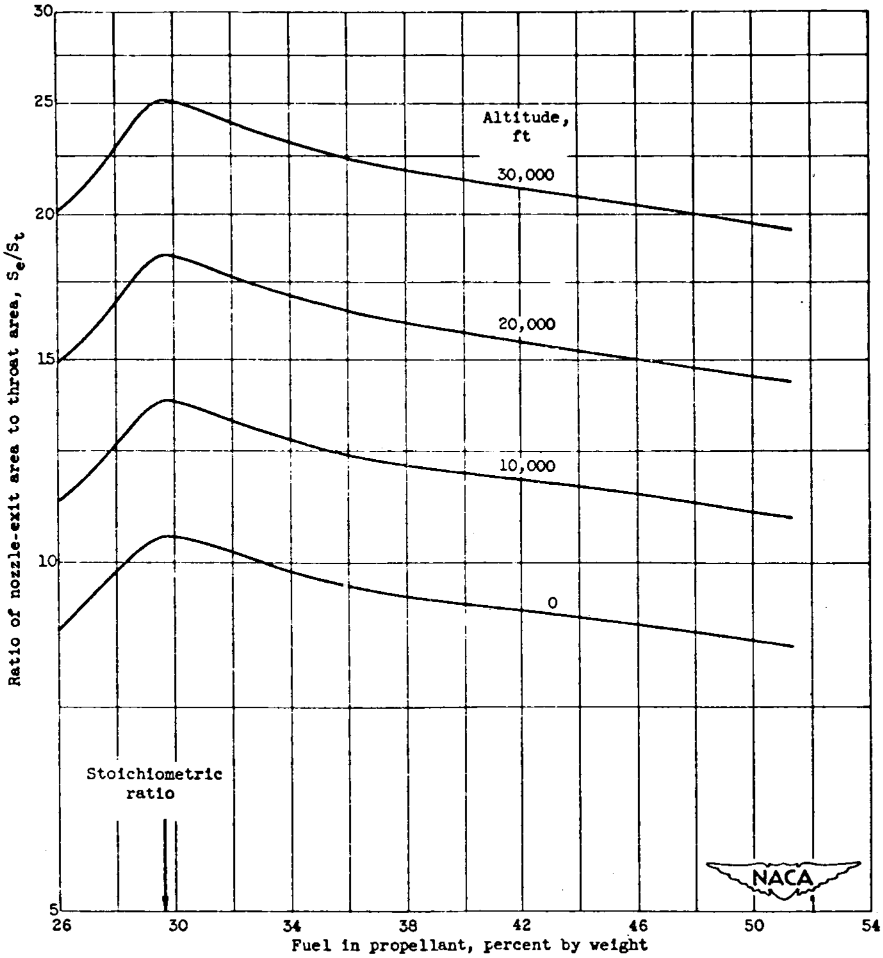


(c) Combustion-chamber pressure, 600 pounds per square inch absolute.

Figure 5. - Continued. Theoretical ratios of nozzle-exit area to throat area for liquid hydrazine with liquid fluorine. Isentropic expansion to altitude indicated assuming equilibrium composition.

[redacted]



(d) Combustion-chamber pressure, 1200 pounds per square inch absolute.

Figure 5. - Concluded. Theoretical ratios of nozzle-exit area to throat area for liquid hydrazine with liquid fluorine. Isentropic expansion to altitude indicated assuming equilibrium composition.

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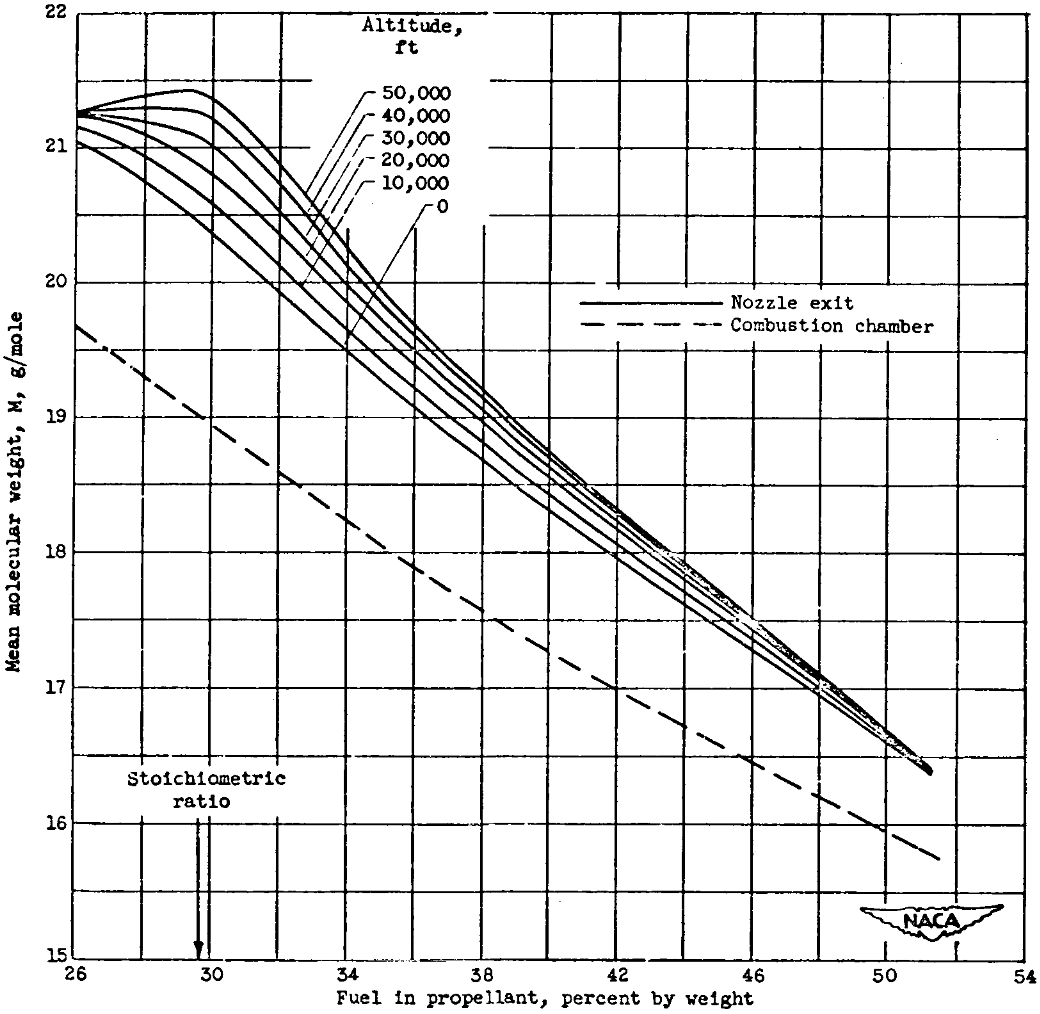
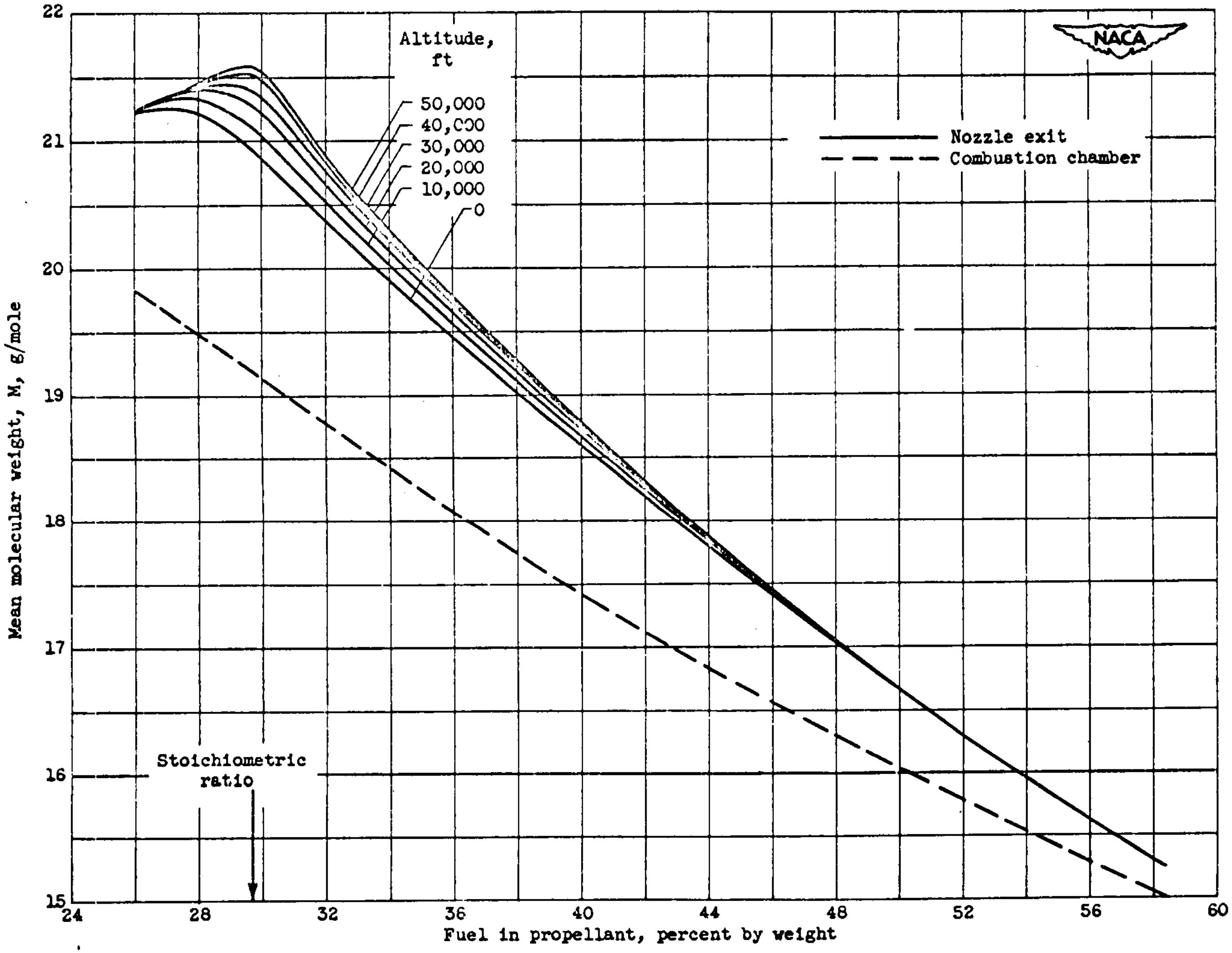


(a) Combustion-chamber pressure, 150 pounds per square inch absolute.

Figure 6. - Theoretical mean molecular weight in combustion chamber and at nozzle exit for liquid hydrazine with liquid fluorine. Isentropic expansion to altitude indicated assuming equilibrium composition.

[redacted]



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

Figure 6. - Continued. Theoretical mean molecular weight in combustion chamber and at nozzle exit for liquid hydrazine with liquid fluorine. Isentropic expansion to altitude indicated assuming equilibrium composition.

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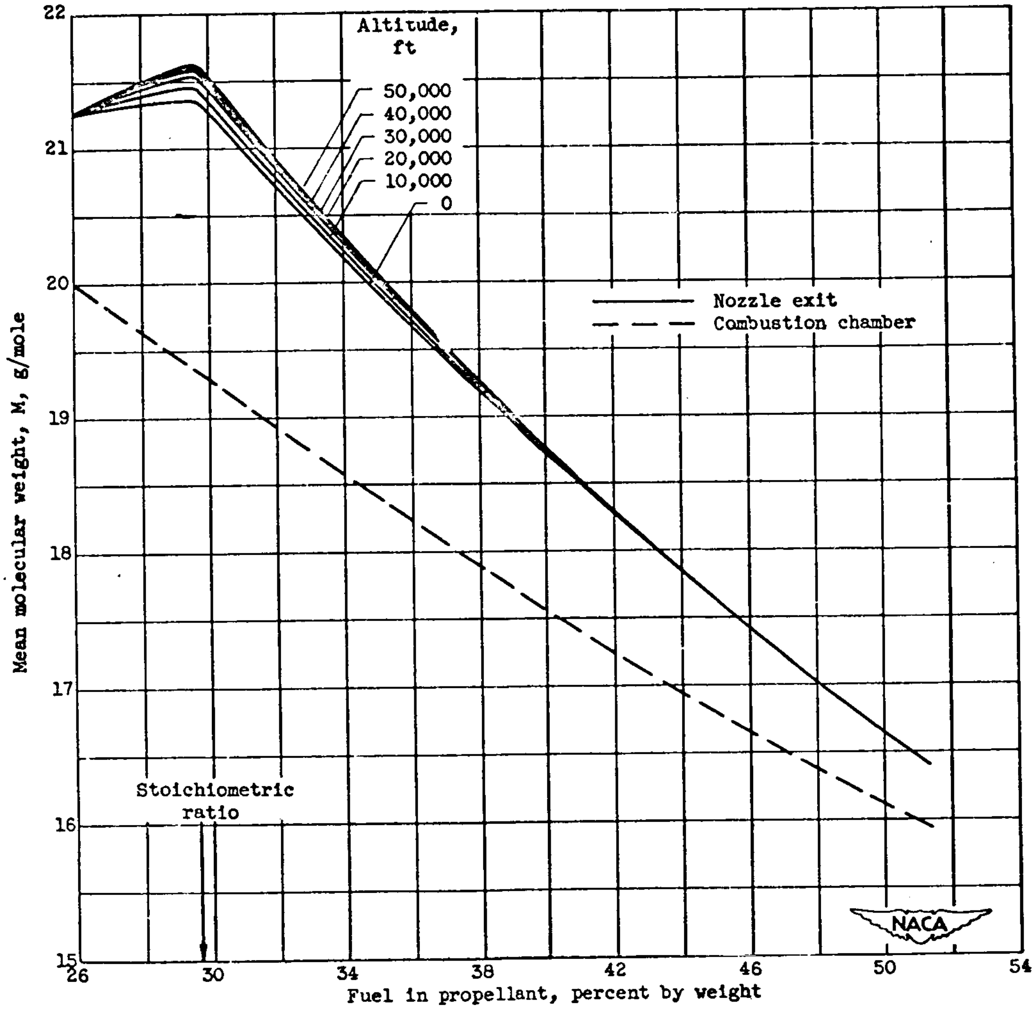

(c) Combustion-chamber pressure, 600 pounds per square inch absolute.

Figure 6. - Continued. Theoretical mean molecular weight in combustion chamber and at nozzle exit for liquid hydrazine with liquid fluorine. Isentropic expansion to altitude indicated assuming equilibrium composition.

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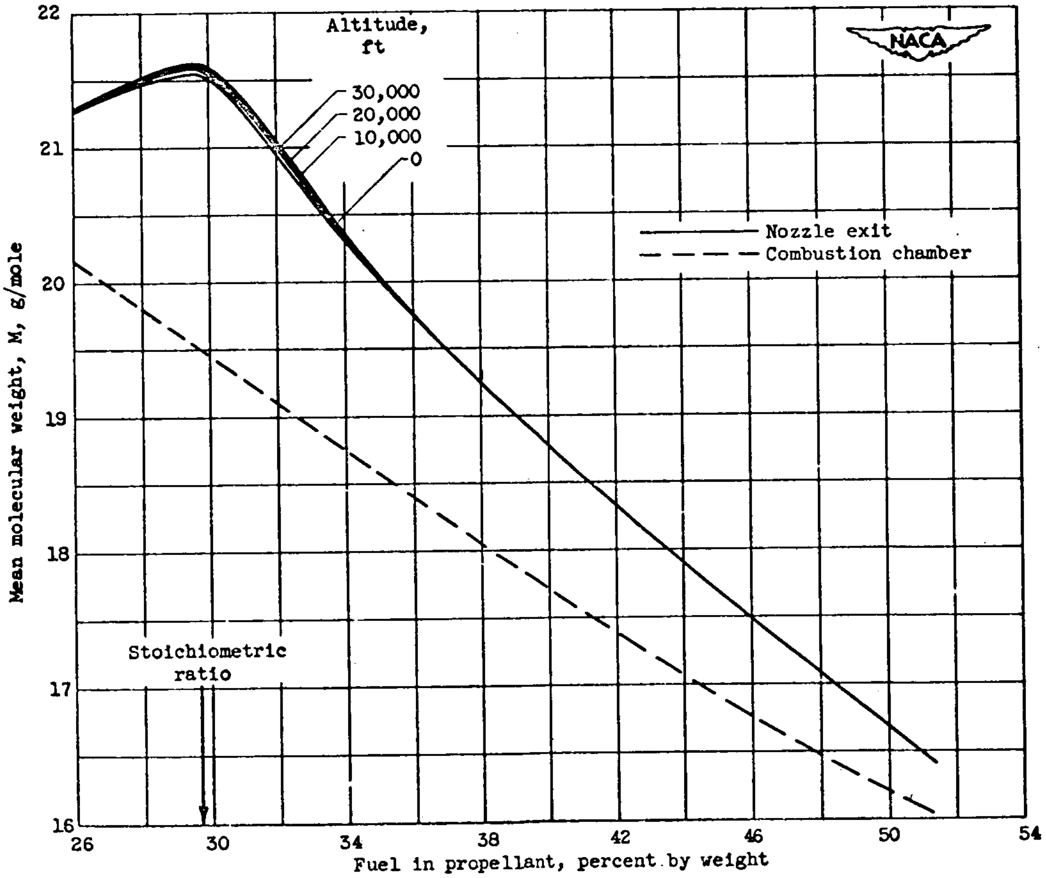

(d) Combustion-chamber pressure, 1200 pounds per square inch absolute.

Figure 6. - Concluded. Theoretical mean molecular weight in combustion chamber and at nozzle exit for liquid hydrazine with liquid fluorine. Isentropic expansion to altitude indicated assuming equilibrium composition.

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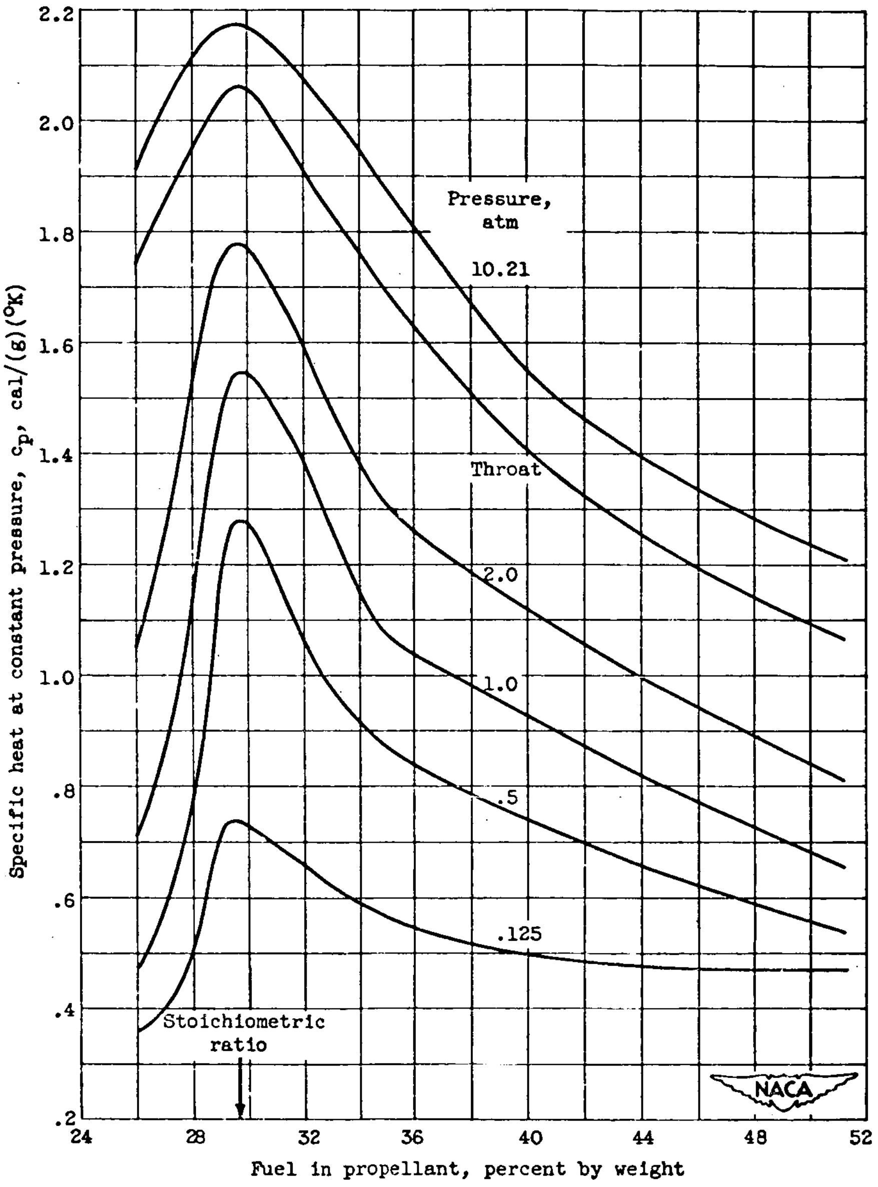
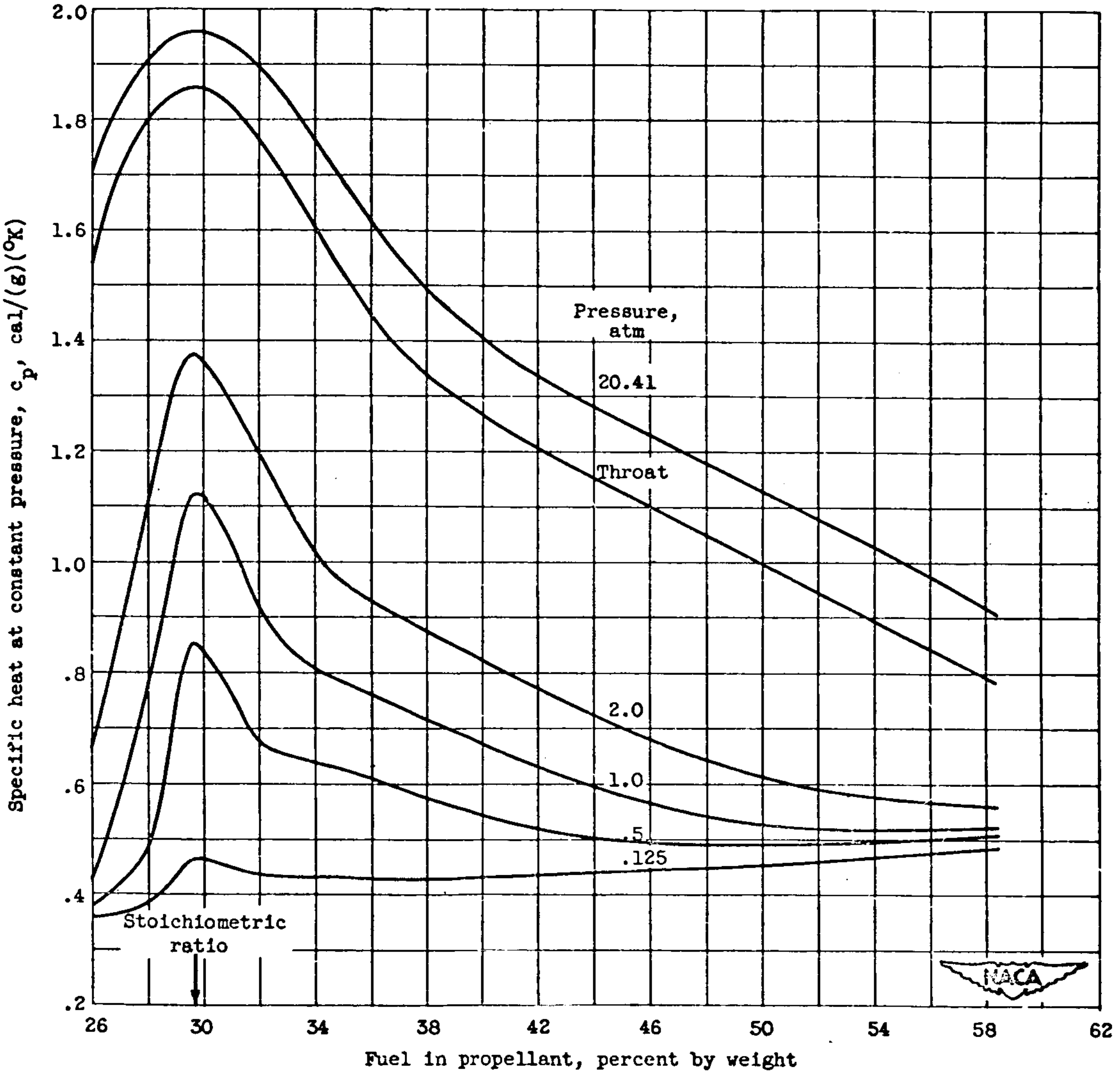


(a) Combustion-chamber pressure, 150 pounds per square inch absolute.

Figure 7. - Theoretical specific heat at constant pressure of combustion products (including energy of dissociation) of liquid hydrazine with liquid fluorine. Isentropic expansion to pressures indicated assuming equilibrium composition.

[redacted]



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

Figure 7. - Continued. Theoretical specific heat at constant pressure of combustion products (including energy of dissociation) of liquid hydrazine with liquid fluorine. Isentropic expansion to pressures indicated assuming equilibrium composition.

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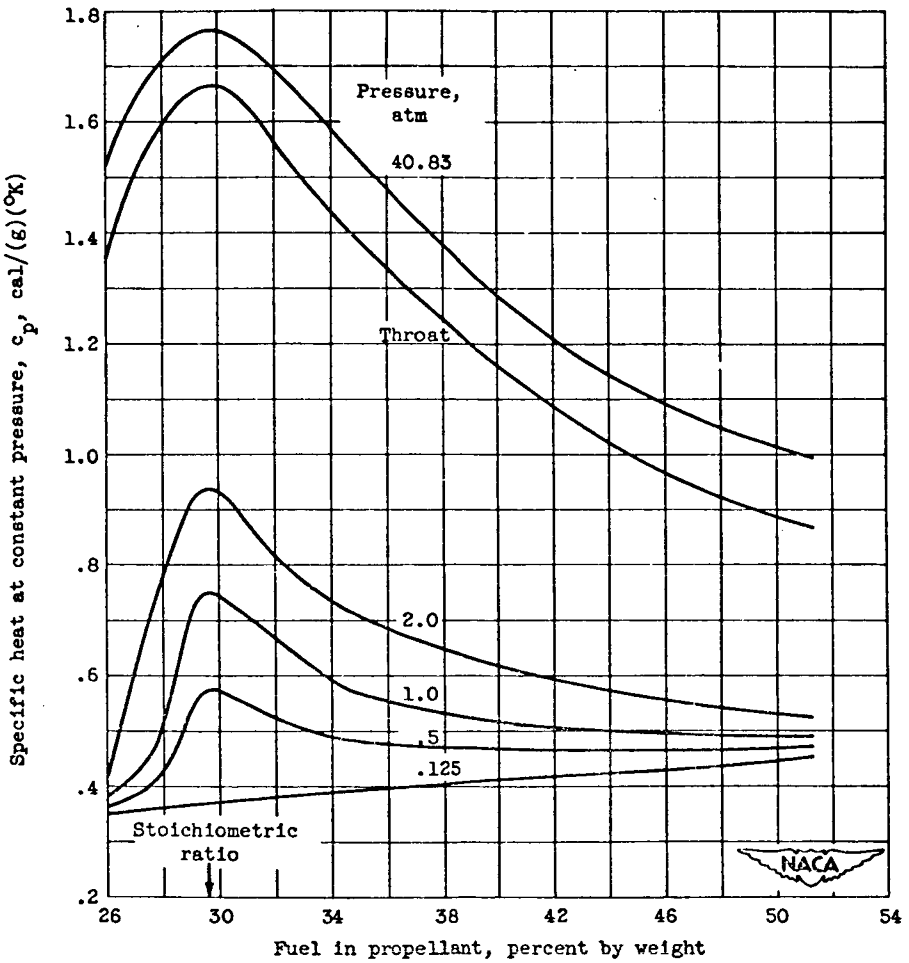
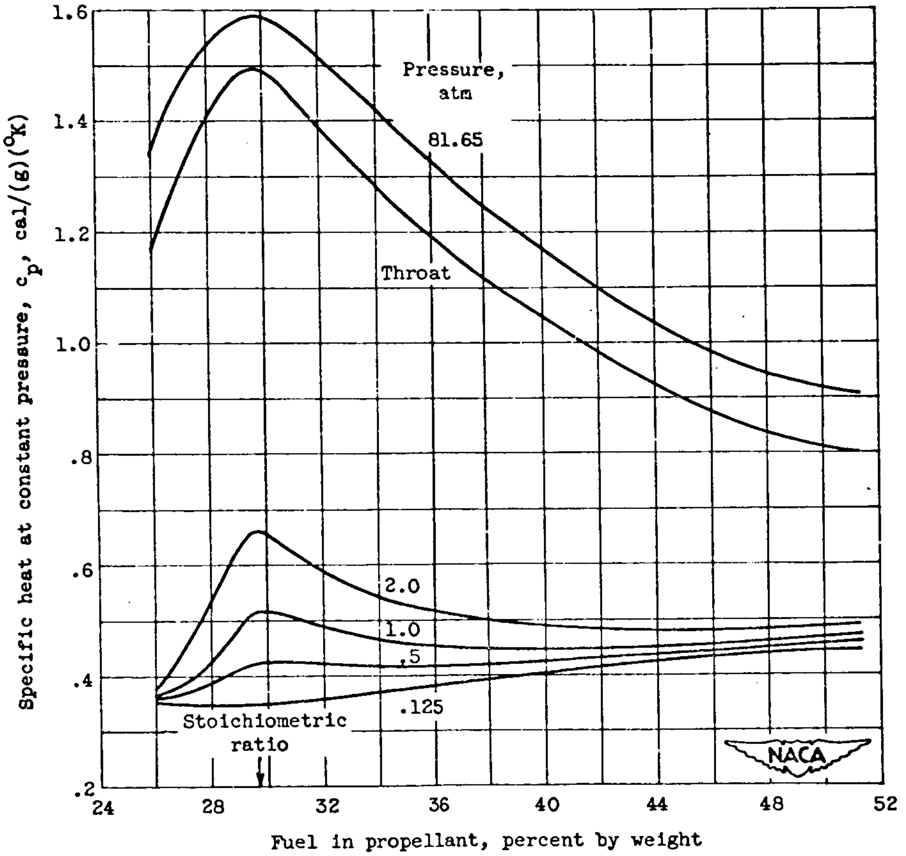


(c) Combustion-chamber pressure, 600 pounds per square inch absolute.

Figure 7. - Continued. Theoretical specific heat at constant pressure of combustion products (including energy of dissociation) of liquid hydrazine with liquid fluorine. Isentropic expansion to pressures indicated assuming equilibrium composition.

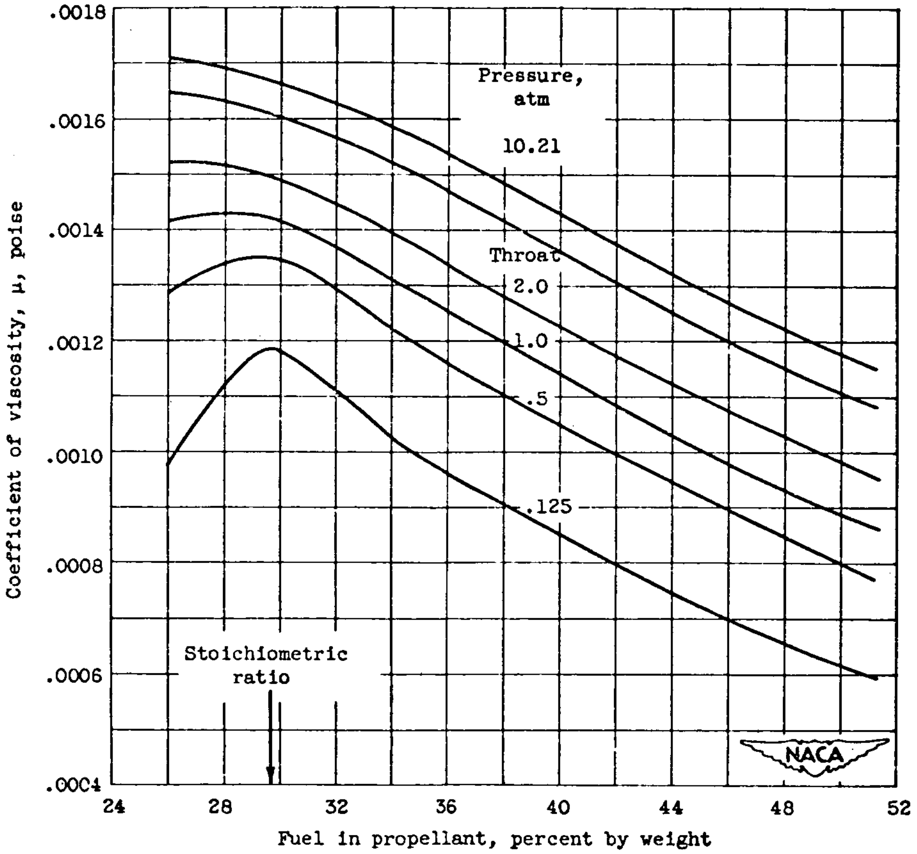
[redacted]



(d) Combustion-chamber pressure, 1200 pounds per square inch absolute.

Figure 7. - Concluded. Theoretical specific heat at constant pressure of combustion products (including energy of dissociation) of liquid hydrazine with liquid fluorine. Isentropic expansion to pressures indicated assuming equilibrium composition.

2928



(a) Combustion-chamber pressure, 150 pounds per square inch absolute.

Figure 8. - Theoretical coefficient of viscosity of combustion products of liquid hydrazine with liquid fluorine. Isentropic expansion to pressures indicated assuming equilibrium composition.

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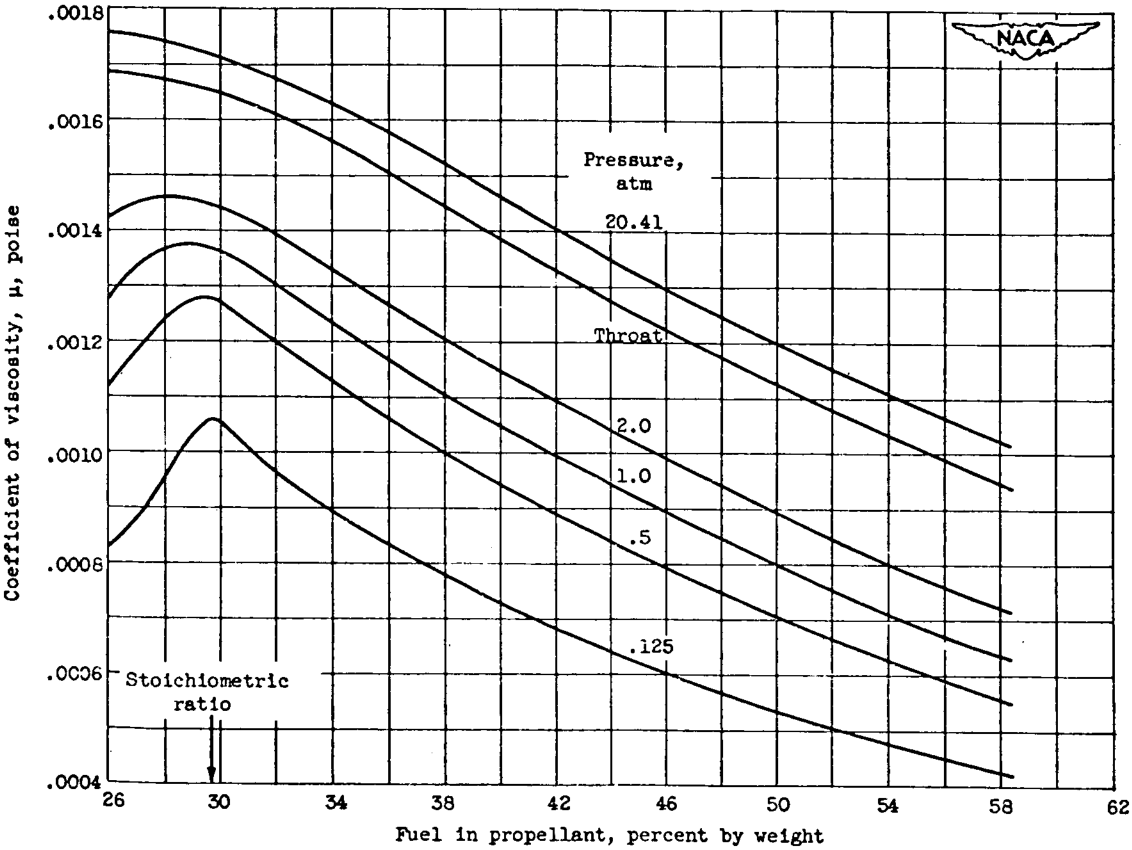

(b) Combustion-chamber pressure, 300 pounds per square inch absolute.

Figure 8. - Continued. Theoretical coefficient of viscosity of combustion products of liquid hydrazine with liquid fluorine. Isentropic expansion to pressures indicated assuming equilibrium composition.

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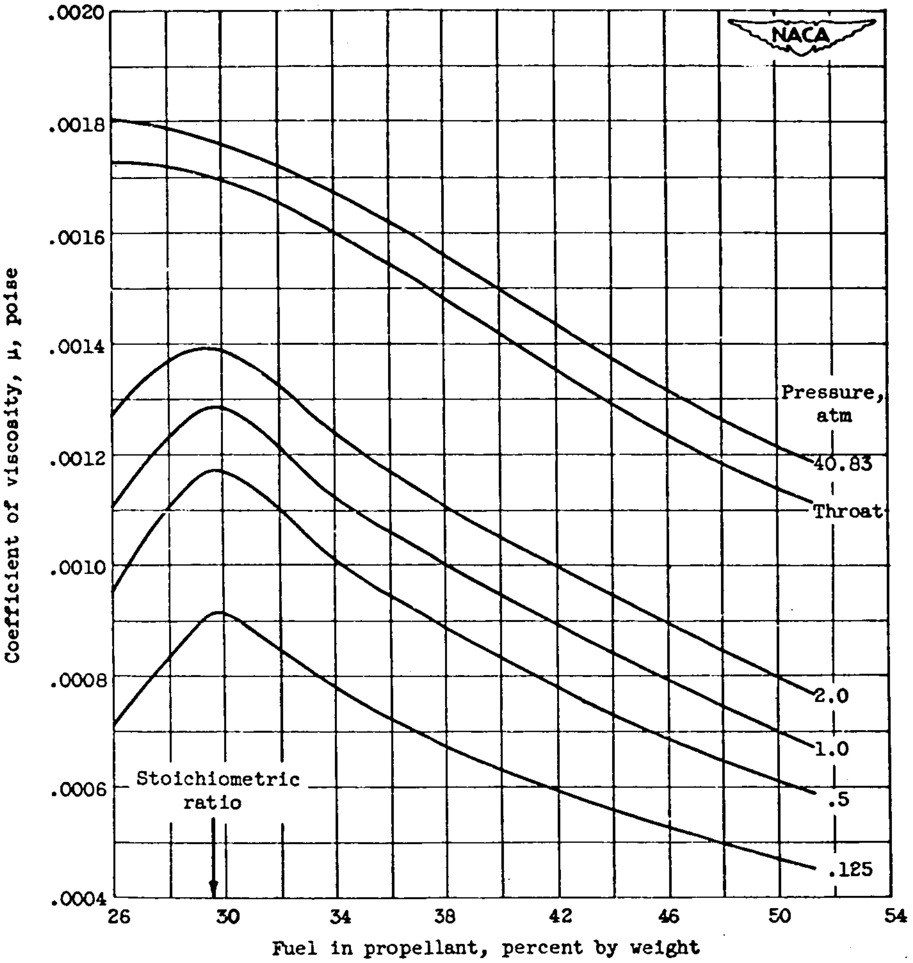

(c) Combustion-chamber pressure, 600 pounds per square inch absolute.

Figure 8. - Continued. Theoretical coefficient of viscosity of combustion products of liquid hydrazine with liquid fluorine. Isentropic expansion to pressures indicated assuming equilibrium composition.

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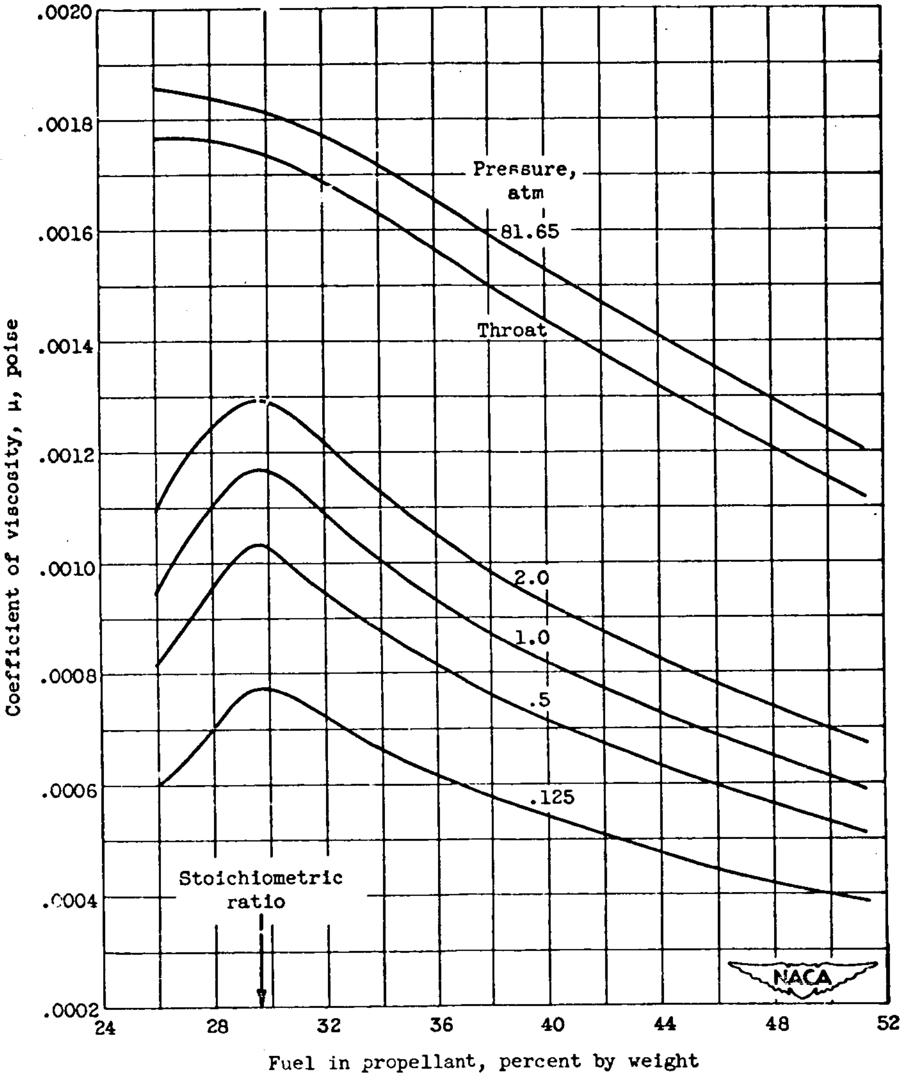
[redacted]



(d) Combustion-chamber pressure, 1200 pounds per square inch absolute.

Figure 8. - Concluded. Theoretical coefficient of viscosity of combustion products of liquid hydrazine with liquid fluorine. Isentropic expansion to pressures indicated assuming equilibrium composition.

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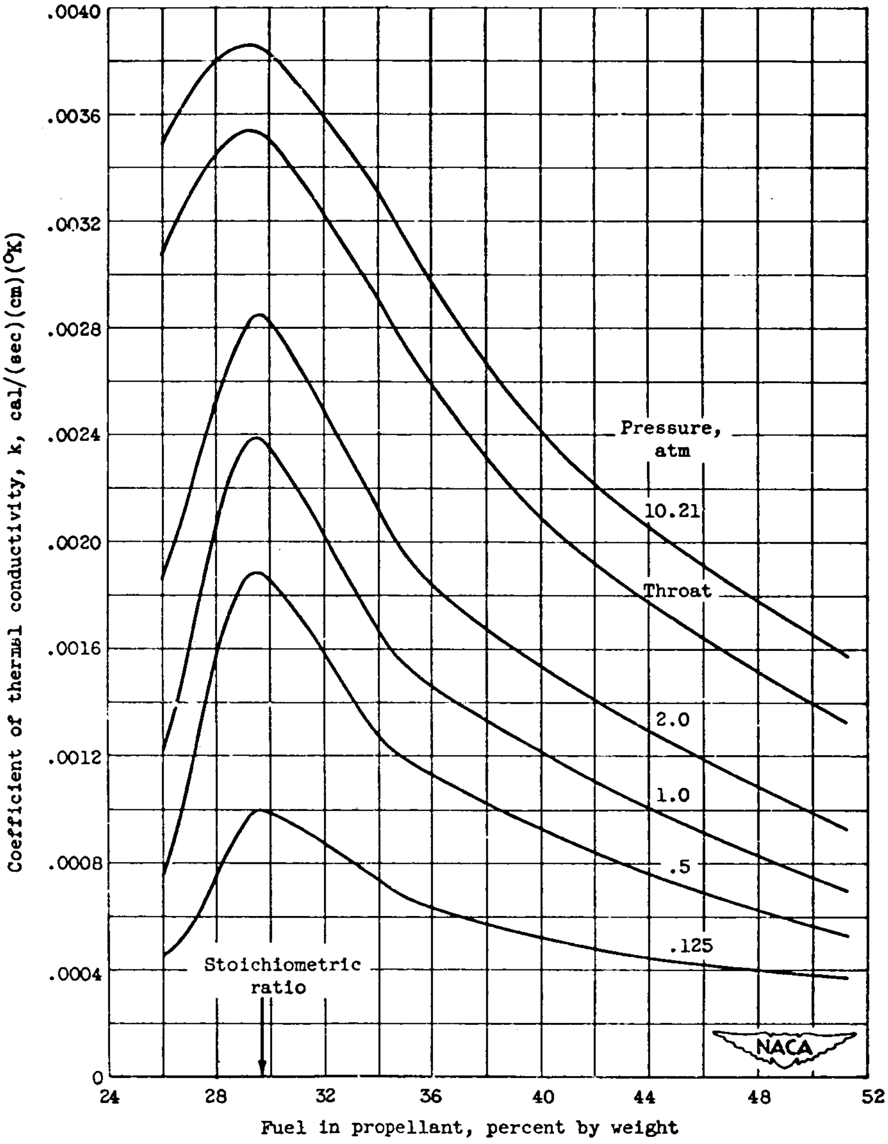

(a) Combustion-chamber pressure, 150 pounds per square inch absolute.

Figure 9. - Theoretical coefficient of thermal conductivity of combustion products of liquid hydrazine with liquid fluorine. Isentropic expansion to pressures indicated assuming equilibrium composition.

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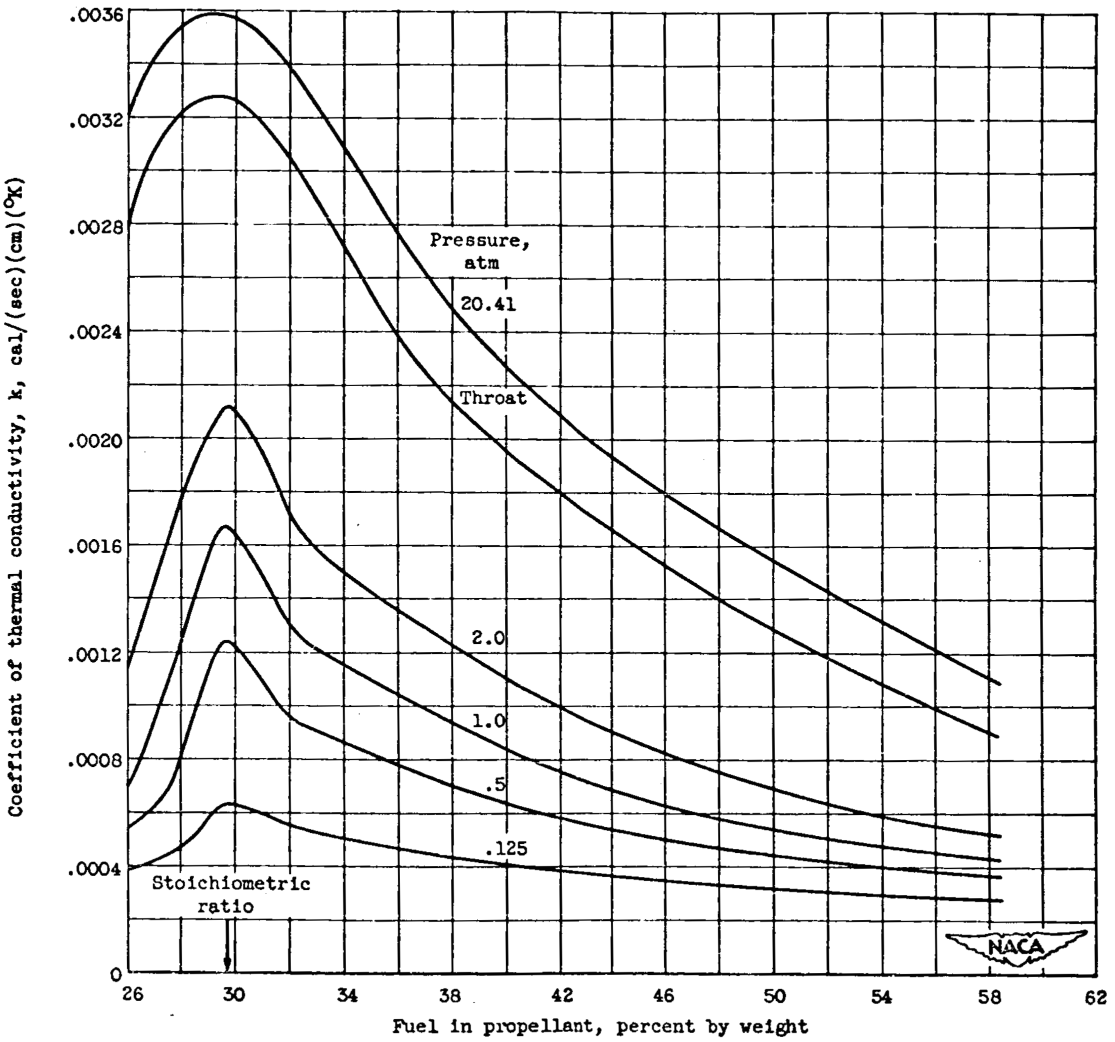

(b) Combustion-chamber pressure, 300 pounds per square inch absolute.

Figure 9. - Continued. Theoretical coefficient of thermal conductivity of combustion products of liquid hydrazine with liquid fluorine. Isentropic expansion to pressures indicated assuming equilibrium composition.

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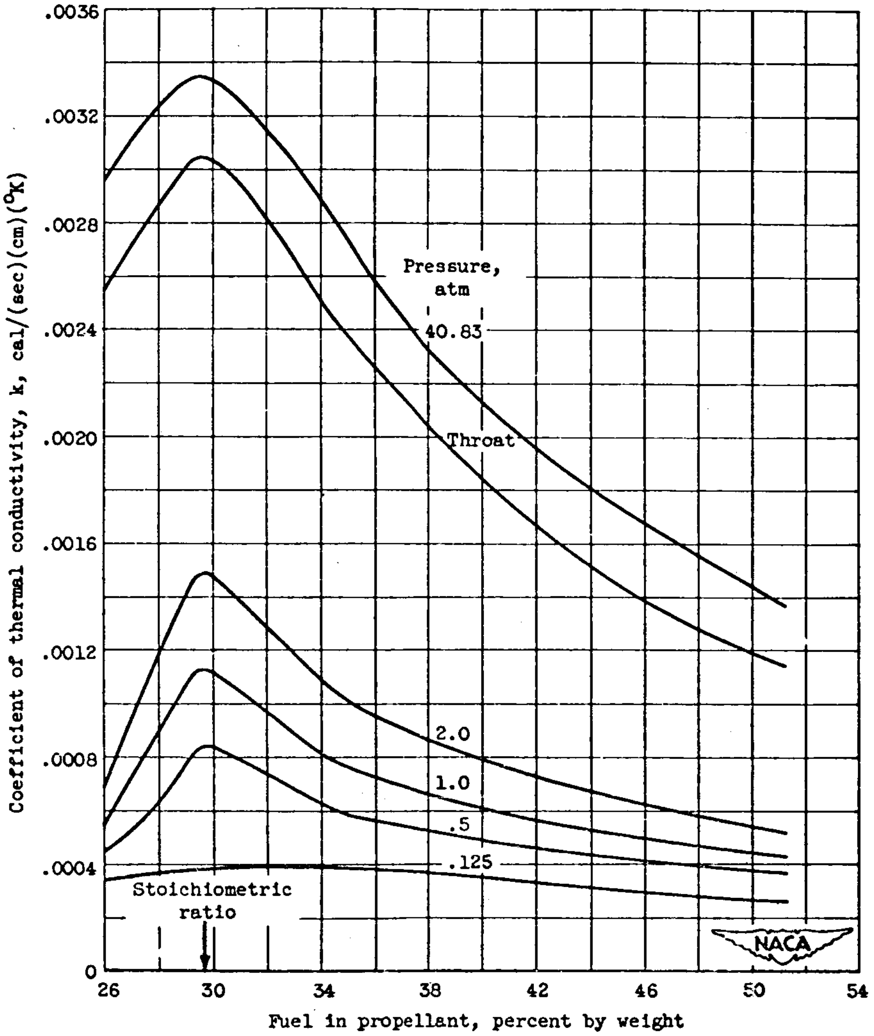

(c) Combustion-chamber pressure, 600 pounds per square inch absolute.

Figure 9. - Continued. Theoretical coefficient of thermal conductivity of combustion products of liquid hydrazine with liquid fluorine. Isentropic expansion to pressures indicated assuming equilibrium composition.

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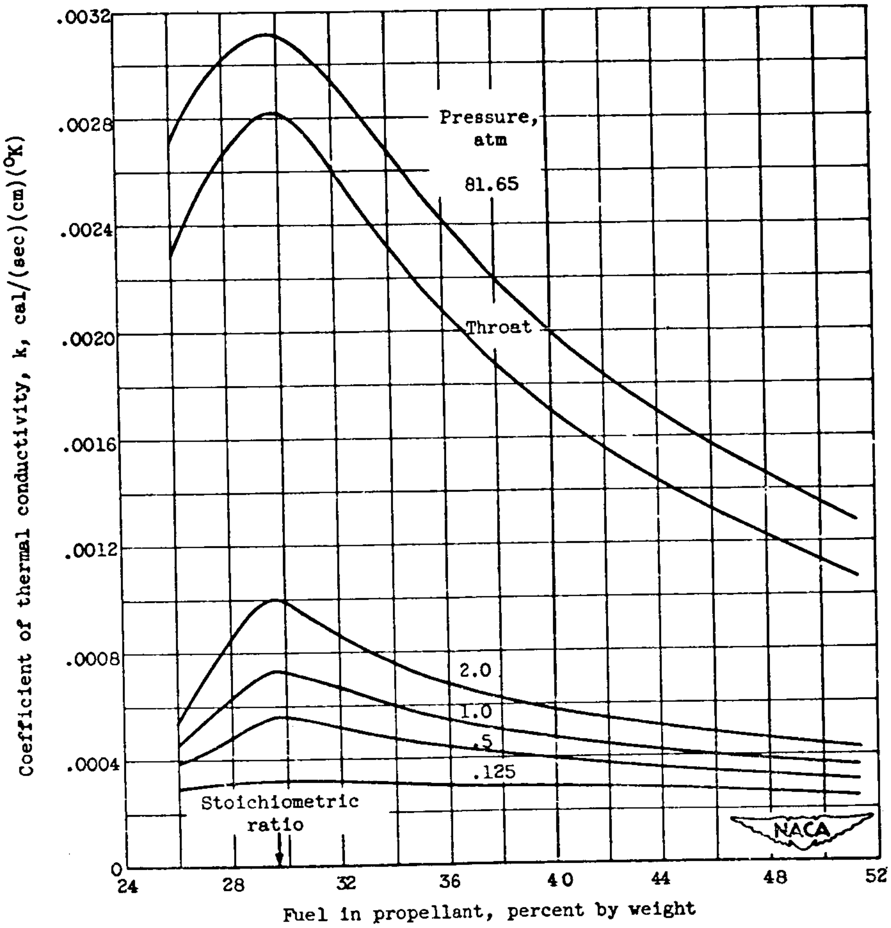

(d) Combustion-chamber pressure, 1200 pounds per square inch absolute.

Figure 9. - Concluded. Theoretical coefficient of thermal conductivity of combustion products of liquid hydrazine with liquid fluorine. Isentropic expansion to pressures indicated assuming equilibrium composition.

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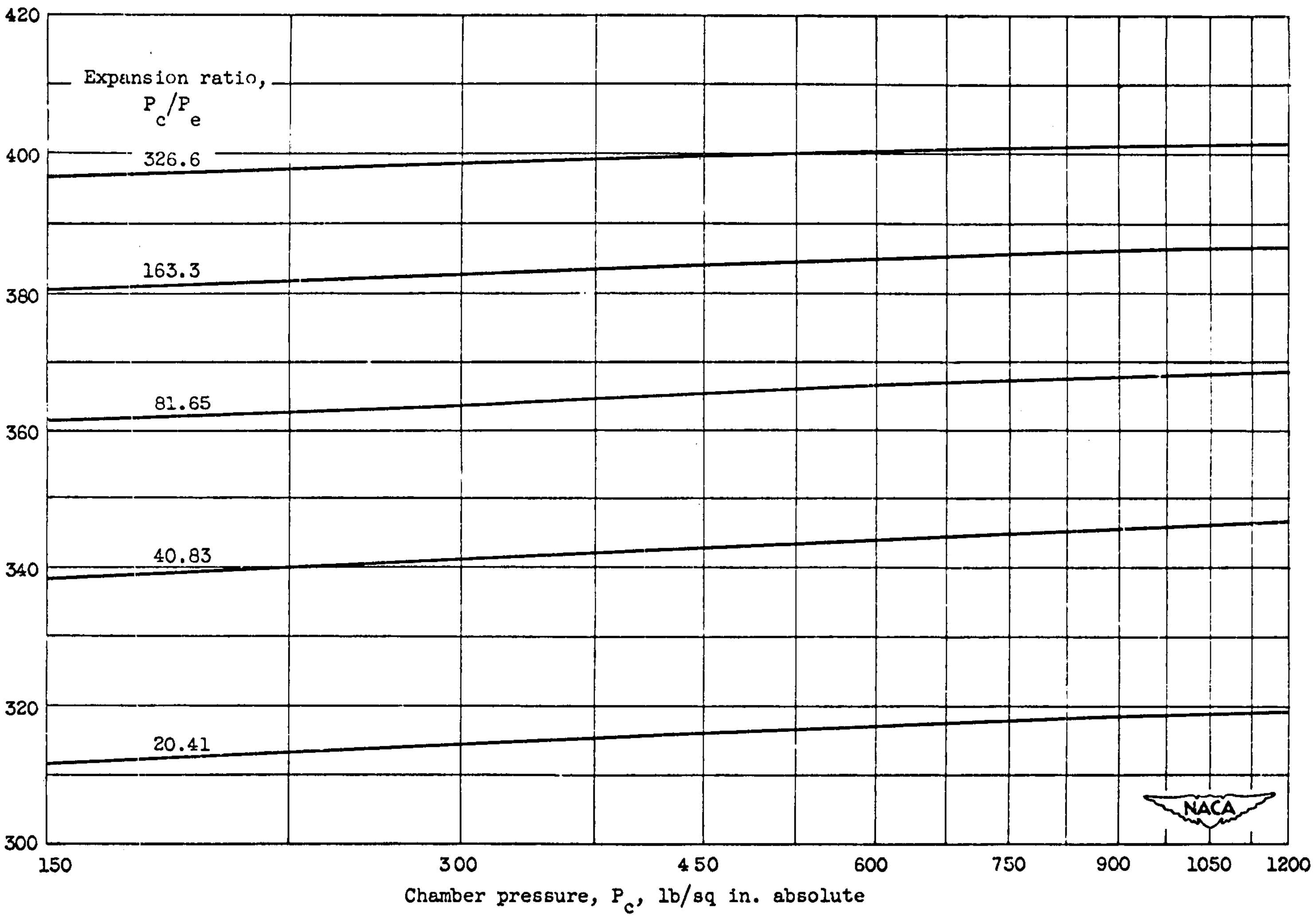

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Figure 10. - Example of linear variation of specific impulse with logarithm of chamber pressure for fixed expansion ratios. Stoichiometric equivalence ratio; isentropic expansion to expansion ratio indicated assuming equilibrium composition.

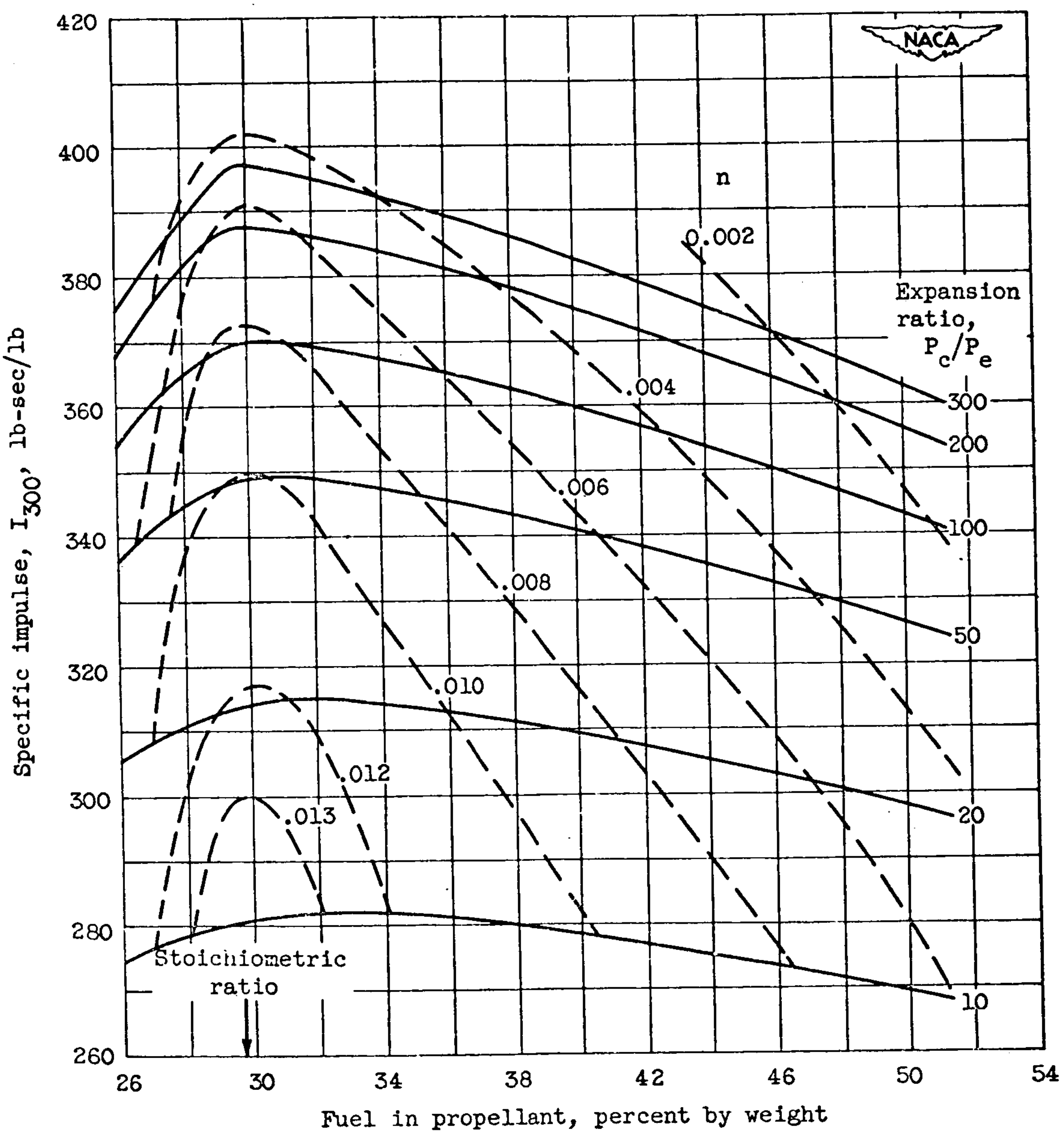

Figure 11. - Theoretical specific impulse for chamber pressure of 300 pounds per square inch absolute and exponent n for equation $I = I_{300} (P_c/300)^n$ for liquid hydrazine with liquid fluorine. Isentropic expansion to expansion ratio indicated assuming equilibrium composition.

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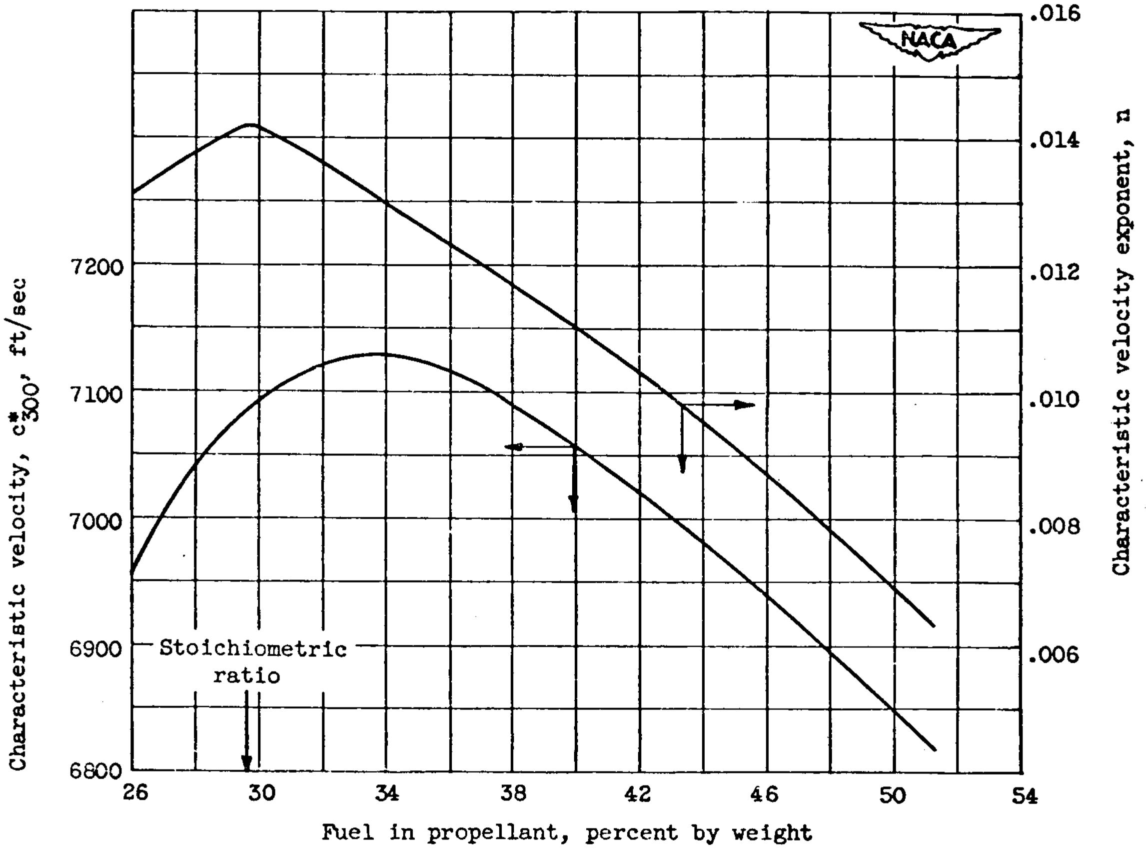

Figure 12. - Theoretical characteristic velocity for chamber pressure of 300 pounds per square inch absolute and exponent n for equation $c^* = c^*_{300}\,(P_c/300)^n$ for liquid hydrazine with liquid fluorine. Isentropic expansion to nozzle throat assuming equilibrium composition.

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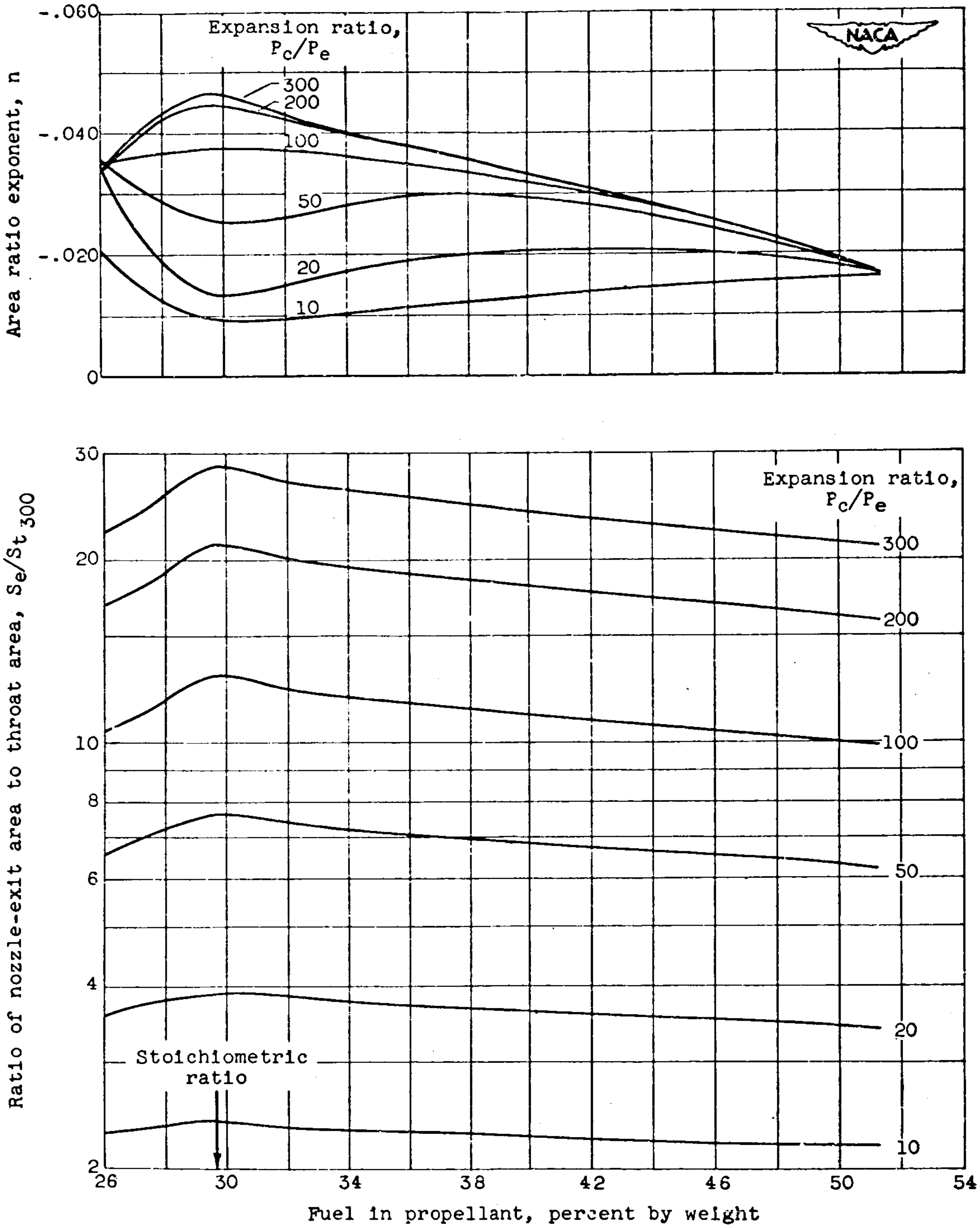

Figure 13. - Theoretical ratio of nozzle-exit area to throat area for chamber pressure of 300 pounds per square inch absolute and exponent n for equation $S_e/S_t = (S_e/S_t)_{300}\,(P_c/300)^n$ for liquid hydrazine with liquid fluorine. Isentropic expansion to expansion ratio indicated assuming equilibrium composition.

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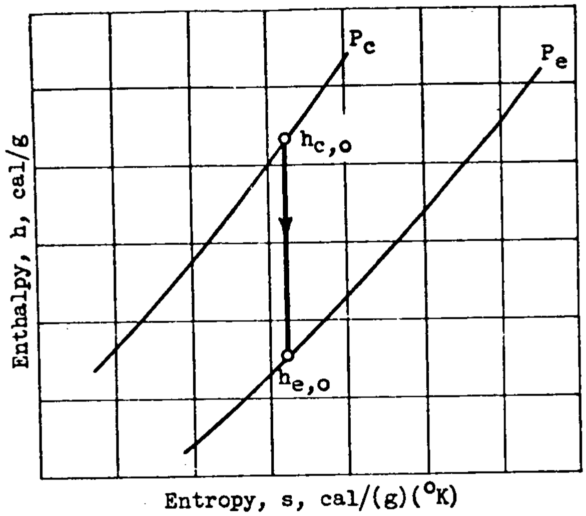

Figure 14. - Adiabatic combustion and isentropic expansion from P_c to P_e.

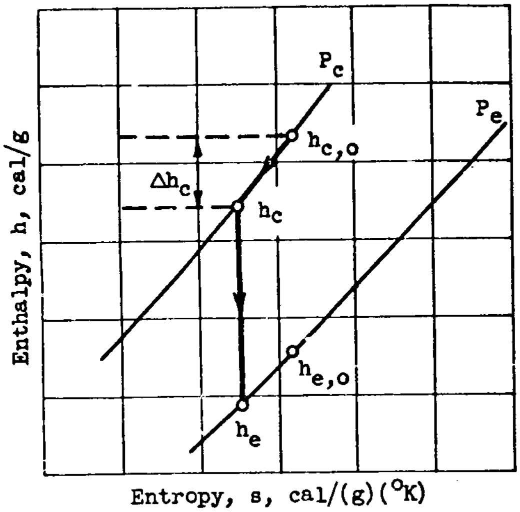

Figure 15. - Loss of heat in combustion chamber followed by isentropic expansion from P_c to P_e.

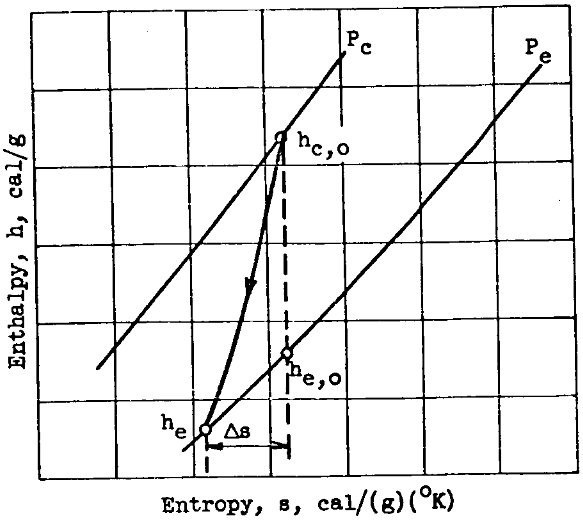

Figure 16. - Nonisentropic expansion from P_c to P_e.

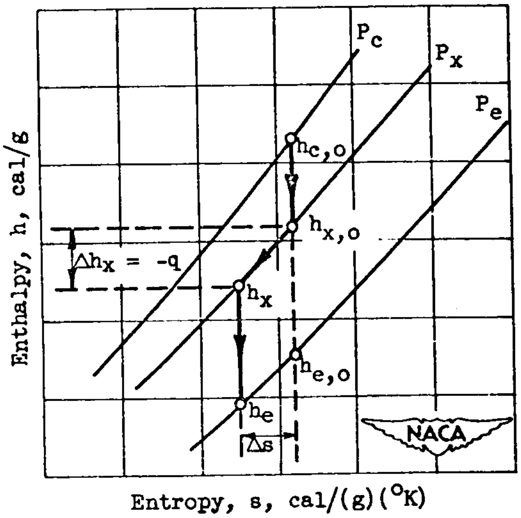

Figure 17. - Adiabatic combustion and isentropic expansion from P_c to P_x; removal of heat q at constant P_x; isentropic expansion from P_x to P_e.