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THEORETICAL CHARACTERISTICS OF SEVERAL LIQUID PROPELLANT SYSTEMS

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PROJECT RAND

(AAF PROJECT MX-791)

THEORETICAL CHARACTERISTICS OF SEVERAL LIQUID PROPELLANT SYSTEMS

F. J. KRIEGER

RA-15024

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DOUGLAS AIRCRAFT COMPANY, INC.

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SYMBOLS

α = mole ratio, fuel/oxidant

C_p = heat capacity at constant pressure

C_v = heat capacity at constant volume

γ = C_p/C_v

g = acceleration of gravity = 980.665 cm/sec^2

ΔH_i = heat of formation at 298.16°K

$\Delta H^T_{298.16}$ = enthalpy above 298.16°K

I = specific impulse

J = mechanical equivalent of heat = 4.1833×10^7 ergs/cal

K_i = equilibrium constant for reaction i

λ_i = equilibrium constant modified by pressure term

M = average molecular weight of propellant gas

M_i = molecular weight of component i

N_i = mole fraction of component i

N_f = number of moles of fuel required to produce one mole of propellant gas

N_o = number of moles of oxidizer required to produce one mole of propellant gas

P_c = chamber pressure (total pressure of chamber gas)

P_e = exhaust pressure = 1 atmosphere = 14.696 psia

P_i = partial pressure of component i

Q_{av} = available heat in calories per mole

R = gas constant = 1.9869 cal/deg mole

T_c = chamber temperature, °K

T_e = exhaust temperature, °K

V_e = exhaust gas velocity

THEORETICAL CHARACTERISTICS OF SEVERAL LIQUID PROPELLANT SYSTEMS

SUMMARY

The various propellant characteristics, viz, chamber temperature, composition, molecular weight, gamma (ratio of isobaric to isocharic heat capacity), exit temperature and specific impulse, have been calculated at several fuel-oxidant mole ratios and at chamber pressures of 150, 300, 450 and 600 psia for the propellant systems (1) hydrazine-liquid oxygen, (2) hydrazine-liquid fluorine, (3) liquid hydrogen-liquid oxygen, and (4) liquid hydrogen-liquid fluorine, and at chamber pressures of 300, 450 and 600 psia for the systems (5) hydrazine-hydrogen peroxide (anhydrous) and (6) hydrazine-chlorine trifluoride. These calculations were made on the assumption of perfect gas behavior with adiabatic gas expansion from mixing chamber to exhaust and maintenance of chamber composition.

Maximum specific impulse values at each chamber pressure were obtained from specific impulse - mole ratio curves and the corresponding associated characteristics were determined by suitable interpolation. The data summarized in Table XX afford a basis for comparing the fuels hydrogen and hydrazine and the oxidants oxygen, anhydrous hydrogen peroxide, fluorine, and chlorine trifluoride.

The method of calculation is described in detail for the system hydrazine-oxygen at a chamber pressure of 450 psia and a mole ratio of 1.5. Pertinent equations are given for each of the other systems together with tables of basic thermo-chemical data such as heat of formation and heat content of various substances and equilibrium constants for the necessary dissociation reactions.

INTRODUCTION

Although considerable work has been done on the calculation of the specific impulse of various propellant systems both here and abroad, no exhaustive treatment has yet been offered which quantitatively demonstrates the effect of chamber pressure on the maximum specific impulse developed by any rocket liquid propellant system.

Flight mechanical studies of rocket vehicles show that the relationship between specific impulse I and the propellant weight - gross weight ratio ν is given by the equation

$$I \log (1-\nu) \doteq \text{constant.}$$

An immediate consequence of this relationship is the fact that the propellant system having the highest specific impulse, other conditions being equal, will yield a rocket vehicle with the least gross weight. In view of this consequence and the fact that the specific impulse of a system increases with chamber pressure, the desirability for a study of the specific impulse-chamber pressure relationship is evident.

This report describes the progress made in the first stage of a systematic study of the principal characteristics of rocket liquid propellant systems which comprise high energy fuels and powerful oxidants capable of developing high specific impulse.

The six systems studied herein employ the fuels liquid hydrogen and hydrazine and the oxidants liquid oxygen, liquid fluorine, anhydrous hydrogen peroxide and chlorine trifluoride. Values for the specific impulse of these systems were calculated, in most cases, at the four pressures, 150, 300, 450 and 600 psia. Such a spread of data affords the designer of rocket propelled vehicles the opportunity of selecting not only a suitable propellant system but also the operating pressure which will assure the optimum performance of his product.

Since the computations required for determining the various propellant characteristics involve considerable labor, the methods used in this report were developed with an eye to operational simplicity. For instance, the notoriously onerous iteration process necessary for obtaining the equilibrium composition of the chamber gas has been simplified somewhat, without sacrificing mathematical rigor, by a judicious arrangement of the equations to be solved.

In the calculations several fundamental assumptions have been made:

1. Perfect gas behaviour is assumed not only in the sense that the expression $PV = RT$ is the equation of state of a gas but also that heat contents (and, therefore, heat capacities) and equilibrium constants are independent of pressure.

2. Chemical equilibrium is attained in the chamber by the gases which result from the reaction between the fuel and the oxidant.

3. There is no heat transfer through the walls of the chamber.

4. The velocity of the chamber gases is zero.

5. The expansion process from chamber pressure to atmospheric pressure is isentropic.

6. The original equilibrium chamber composition is maintained during the expansion process.

7. The enthalpy (or heat content) decrease of the combustion gases in cooling from chamber temperature to exit temperature is converted into jet velocity. This follows from assumption 5.

The assumption of frozen equilibrium (i.e., constant composition during the expansion process) is preferred to the assumption of shifting equilibrium because it is improbable that the transit time of the propellant gas in the nozzle is long enough for the latter condition to be fully realized. Spot calculations, however, indicate that values of specific impulse based on the assumption of shifting equilibrium are slightly higher than those obtained by assuming frozen equilibrium; at the same time, exit temperatures are higher and gammas are lower. Moreover, the differences increase with rise in chamber temperature (i.e., with increase in dissociation).

BASIC DATA

The fundamental data required for calculating such propellant system characteristics as chamber temperature and specific impulse include the heat of formation and the heat content of both reactants and products and the equilibrium constants for the various gaseous reactions involved. The data used in this report were obtained from several sources. A large part was either taken directly from, or derived from, the tables of Hirschfelder and coworkers [2]. Other data, particularly those pertaining to the halogen compounds, were computed from spectroscopic constants found in the literature.

Table I, p. 25, presents the heat of formation at 25°C in calories per mole of the various species considered in this report. The values taken from Bichowsky and Rossini [3] were corrected from 18° to 25°C.

Table II, p. 26, presents the heat content above 25°C in calories per mole of the various gaseous species appearing in the reaction products. The data for H_2O, H_2, O_2, OH, N_2, and NO were derived from the corresponding internal energy tables appearing in reference [2]. The data for F_2 and HF and for Cl_2 and HCl were obtained from the spectroscopic constants given for those compounds by Murphy and Vance [4] and by Giauque and Overstreet [5], respectively.

The equilibrium constants together with their pressure modified derivatives for the reactions

$$H_2 = 2H$$
$$N_2 = 2N$$
$$\tfrac{1}{2}N_2 + H_2O = NO + H_2$$
$$2H_2O = 2H_2 + O_2$$
$$H_2O = H_2 + O$$
$$H_2O = \tfrac{1}{2}H_2 + OH$$

are presented in Tables VI to XI inclusive. These data were derived from the pertinent free energy tables found in the Hirschfelder report. The equilibrium constants for the reactions

$$\tfrac{1}{2}H_2 + \tfrac{1}{2}F_2 = HF$$
$$F_2 = 2F$$
$$\tfrac{1}{2}H_2 + \tfrac{1}{2}Cl_2 = HCl$$
$$Cl_2 = 2Cl$$

are presented in Tables III to V inclusive and were obtained from free energy data derived from spectroscopic constants. The thermodynamic data of Murphy and Vance on HF and F_2 were reworked and extended to 5000°K, while the corresponding data of Giauque and Overstreet on HCl and Cl_2 were reworked and extended to 4000°K. The method of Giauque and Overstreet was used to calculate the rotational contribution to the sums over states required in deriving the free energy and heat content data for HF, F_2, HCl and Cl_2.

For references see page 24

The heat content data for liquid oxygen below 298.16°K (i.e., the heat required to vaporize one mole of liquid oxygen at the temperature corresponding to the chamber pressure plus the heat required to raise the temperature of the vapor to 298.16°K) were taken from Millar and Sullivan [6]. The corresponding data for liquid fluorine were computed from the critical constants given by Claussen [7] and by Cady and Hildebrand [8], using the vapor pressure relationship between pairs of liquids due to Ramsay and Young [9] and the method of calculating heats of vaporization developed by Meissner [10]. A single value for the heat content of liquid hydrogen below 298.16°K at each of the chamber pressures considered was taken from the temperature-entropy diagram of Keesom and Houthoff [11]. The above data are presented in Table XII, p. 36 .

GENERAL PROCEDURE

The temperature 298.16°K (25°C) is chosen as a reference level. Both fuel and oxidant are assumed to enter the motor in the liquid state. Of the fuels, hydrazine enters the motor at 298.16°K while hydrogen enters at 20.4°K. Of the oxidants, oxygen and fluorine enter the motor at temperatures at which their vapor pressures are equal to the chamber pressure, while anhydrous hydrogen peroxide and chlorine trifluoride enter at 298.16°K.

The first step in the procedure is the calculation of the composition of the chamber gas at equilibrium at an assumed temperature and a given pressure, and the determination of the isobaric flame or chamber temperature, T_c. The general approach is described in many places but the procedure used in this report is similar in certain respects to that described by Lemmon [1].

The next step is the calculation of the exhaust temperature, T_e, which is obtained from the isentropic expansion law for a perfect gas when the chamber temperature, the chamber pressure, and the exhaust pressure are known. This step assumes the average value of the heat capacity of the propellant gas over the temperature interval T_c to T_e. This assumption, although not strictly correct, affords a convenient and quite accurate procedure.

The last step involves the calculation of the specific impulse which follows from the exhaust velocity which in turn is derived from the equivalence relationship between the kinetic energy of the exhaust gas and the heat content decrease of the propellant gas in cooling from the chamber temperature to the exhaust temperature.

The steps outlined above are worked out in detail in the following section for the system $\alpha N_2H_4(\ell) + O_2(\ell)$ at $P_c = 450$ psi and $\alpha = 1.5$. Pertinent equations are given for each of the other five propellant systems investigated.

THE SYSTEM : HYDRAZINE-OXYGEN

Determination of Propellant Gas Composition

If α represents the mole ratio of fuel to oxidant, then inspection of the system $\alpha N_2H_4(\ell) + O_2(\ell)$ indicates the following proportion

$$\frac{n(\mathrm{N})}{2\alpha} = \frac{n(\mathrm{H})}{4\alpha} = \frac{n(\mathrm{O})}{2} , \qquad (1)$$

where n represents the number of atoms of each element. The components of the combustion products which will be present in significant amounts are: H_2O, H_2, H, O_2, O, OH, N_2, N and NO. We may therefore, write

$$N_f(\mathrm{N_2H_4}) + N_o(\mathrm{O_2}) = N_1(\mathrm{H_2O}) + N_2(\mathrm{H_2}) + N_3(\mathrm{H}) + N_4(\mathrm{O_2}) + N_5(\mathrm{O}) + N_6(\mathrm{OH}) + N_7(\mathrm{N_2}) + N_8(\mathrm{N}) + N_9(\mathrm{NO}) , \qquad (2)$$

where N_f and N_o are the number of moles of N_2H_4 and O_2, respectively, required to form one mole of propellant gas, and where N_i represents the mole fraction of component i. The following relations are evident:

$$N_f = \alpha N_o \qquad (3)$$

and

$$\sum_{i=1}^{9} N_i = 1 . \qquad (4)$$

On substituting terms from the right hand side of eq. (2) in eq. (1) and simplifying we obtain

$$2N_7 + N_8 + N_9 = N_1 + N_2 + 0.5N_3 + 0.5N_6 = \alpha(N_1 + 2N_4 + N_5 + N_6 + N_9). \qquad (5)$$

Further inspection of eq. (2) gives

$$N_f = N_7 + 0.5N_8 + 0.5N_9 \qquad (6)$$

and

$$N_o = 0.5N_1 + N_4 + 0.5N_5 + 0.5N_6 + 0.5N_9 . \qquad (7)$$

Eqs. (4) and (5) give us three relationships involving nine unknown quantities. Six additional relationships can be obtained from the definitions of the equilibrium constants in terms of partial pressures for the following reactions:

$$\mathrm{H_2} = 2\mathrm{H} \; ; \; K_2 = P_{\mathrm{H}}{}^2/P_{\mathrm{H_2}}$$

$$\mathrm{N_2} = 2\mathrm{N} \; ; \; K_4 = P_{\mathrm{N}}{}^2/P_{\mathrm{N_2}}$$

$$\tfrac{1}{2}\mathrm{N_2} + \mathrm{H_2O} = \mathrm{NO} + \mathrm{H_2} \; ; \; K_5 = P_{\mathrm{NO}}P_{\mathrm{H_2}}/P_{\mathrm{N_2}}{}^{\frac{1}{2}}P_{\mathrm{H_2O}}$$

$$2H_2O = 2H_2 + O_2 \; ; \; K_6 = P_{H_2}^{\,2}P_{O_2}/P_{H_2O}^{\,2}$$

$$H_2O = H_2 + O \; ; \; K_7 = P_{H_2}P_O/P_{H_2O}$$

$$H_2O = \tfrac{1}{2}H_2 + OH \; ; \; K_8 = P_{H_2}^{\,1/2}P_{OH}/P_{H_2O}$$

In view of the fact that the partial pressure of a component in a gaseous mixture is equal to the product of the mole fraction of the component and the total pressure, the above equations involving equilibrium constants may be rewritten as follows:

$$\lambda_2 = K_2/P_c = N_3^{\,2}/N_2 \tag{8}$$

$$\lambda_4 = K_4/P_c = N_8^{\,2}/N_7 \tag{9}$$

$$\lambda_5 = K_5/P_c^{\,1/2} = N_2N_9/N_1N_7^{\,1/2} \tag{10}$$

$$\lambda_6 = K_6/P_c = N_2^{\,2}N_4/N_1^{\,2} \tag{11}$$

$$\lambda_7 = K_7/P_c = N_2N_4/N_1 \tag{12}$$

$$\lambda_8 = K_8/P_c^{\,1/2} = N_2^{\,1/2}N_6/N_1 \tag{13}$$

In the above equations P_c is the total or chamber pressure and is expressed in atmospheres. The λ's are dimensionless numbers and assume different values at various pressures and temperatures. They are tabulated in Tables III to XII.

Now eqs. (4), (5) and (8) through (13) may be rearranged for computational purposes as follows:

$$N_1 = \frac{1}{3\alpha}\left[2 - N_3 - (2 + 6\alpha)N_4 - (2 + 3\alpha)N_5 - (1 + 3\alpha)N_6 - N_8 - (1 + 3\alpha)N_9\right] \tag{14}$$

$$N_2 = \frac{1}{3}\,(2 - 3N_1 - 2.5N_3 - 2N_4 - 2N_5 - 2.5N_6 - N_8 - N_9) \tag{15}$$

$$N_7 = 0.5N_1 + 0.5N_2 + 0.25N_3 + 0.25N_6 - 0.5N_8 - 0.5N_9 \tag{16}$$

$$N_3 = (\lambda_2N_2)^{1/2} \tag{17}$$

$$N_4 = \lambda_6N_1^{\,2}/N_2^{\,2} \tag{18}$$

$$N_5 = \lambda_7N_1/N_2 \tag{19}$$

$$N_6 = \lambda_8N_1/N_2^{\,1/2} \tag{20}$$

$$N_8 = (\lambda_4N_7)^{1/2} \tag{21}$$

$$N_9 = \lambda_6 N_1 N_7^{1/2}/N_2 \qquad (22)$$

This particular arrangement is chosen on the basis of dominant terms. Inspection of eq. (2) shows that for values of $\alpha > 1$ (the stoichiometric ratio of fuel to oxidant) the dominant components on the right hand side of the equation are H_2O, H_2 and N_2.

In order to determine the composition of the propellant gas at the adiabatic chamber temperature T_c, a pressure P, a mole ratio α and an approximate temperature T are assumed. Then the constants λ are chosen from the appropriate tables. An approximate value for N_1 is found from eq. (14) by assuming N_3, N_4, N_5, N_6, N_8 and N_9 negligible. This crude value for N_1 is substituted in eq. (15) and an approximate value of N_2 obtained. These values of N_1 and N_2 are substituted in eq. (16) and a value for N_7 obtained. In this manner rough values are obtained for the mole fractions N_1 through N_9. By a process of iteration refined values are obtained which satisfy the condition in eq. (4).

Table XIII gives the composition of the propellant gas at several temperatures for the system $\alpha N_2H_4(\ell) + O_2(\ell)$ at a chamber pressure of 450 psia and a mole ratio of 1.5.

Determination of Chamber Temperature

The adiabatic flame temperature, T_c, is attained when

$$-Q_{av} = \Delta H_{298.16}^{T_c}, \qquad (23)$$

where Q_{av} is the heat available from the reaction (2) and is equal to the sum of the initial enthalpy of the reactants plus the heat of combustion, while $\Delta H_{298.16}^{T_c}$ is the change in heat content of the propellant gas from 298.16°K to the flame temperature T_c. Specifically,

$$-Q_{av} = N_f\, \Delta H_{T_f}^{298.16} + N_o\, \Delta H_{T_o}^{298.16} + \sum_{i=1}^{9} N_i\, \Delta H_i - N_f\, \Delta H_f - N_o \Delta H_o, \qquad (24)$$

where T_f and T_o are the temperatures of the incoming fuel and oxidant respectively, and

$$\Delta H_{298.16}^{T_c} = \sum_{i=1}^{9} N_i\, \Delta H_{i,298.16}^{T_c}. \qquad (25)$$

Calculations are generally made for three values of the temperature in the vicinity of T_c. The corresponding values of Q_{av} and $\Delta H_{298.16}^{T_c}$ are plotted graphically against T. The point of intersection of the two curves determines T_c. For greater accuracy a three point Lagrangean interpolation may be made instead of a plot.

Table XIII gives the composition of the propellant gas, the available heat and the enthalpy change above 298.16°K for the three assumed temperatures 3000, 3100 and 3200°K. The chamber temperature, T_c, was found by interpolation to be 3118°K. The composition of the propellant gas at T_c was also found by interpolation.

Determination of Molecular Weight

The molecular weight, M, of the propellant gas in the chamber at temperature T_c is given by the relation

$$M = \sum_{i=1}^{9} N_i M_i, \tag{26}$$

where M_i is the molecular weight of the component i. For the present case $M = 17.461$.

Determination of Exit Temperature

The exit temperature, T_e, is determined under the following conditions:

(1) The composition of the gas remains unchanged from T_c to T_e;

(2) The expansion process from P_c to P_e (1 atm) is adiabatic.

Condition (1) permits us to write

$$\Delta H_{T_e}^{T_c} = \Delta H_{298.16}^{T_c} - \Delta H_{298.16}^{T_e}, \tag{27}$$

where $\Delta H_{T_e}^{T_c}$ is the change in enthalpy of the propellant gas between T_c and T_e, and $\Delta H_{298.16}^{T}$ is the enthalpy change between 298.16 and T°K.

Condition (2) is simply the adiabatic expansion formula

$$\frac{T_e}{T_c} = \left(\frac{P_e}{P_c}\right)^{\frac{\gamma-1}{\gamma}}, \tag{28}$$

where γ is the ratio of the isobaric (C_p) and isochoric (C_v) heat capacities. For our purposes, since $C_p = \Delta H_{T_e}^{T_c}/(T_c - T_e)$ we may write

$$\frac{\gamma - 1}{\gamma} = \frac{R(T_c - T_e)}{\Delta H_{T_e}^{T_c}}, \tag{29}$$

where R is the gas constant.

To illustrate the manner of determining T_e for the present system we assume a temperature slightly greater than $0.5T_c$, namely 1600°K. Then we compute in turn:

$$\Delta H_{1600}^{3118} = \Delta H_{298.16}^{3118} - \Delta H_{298.16}^{1600}$$

$$= 26{,}459 - 10{,}932$$

$$= 15{,}527 \text{ cal};$$

$$\Delta T_{1600}^{3118} = 1518°\text{K};$$

$$\frac{\gamma - 1}{\gamma} = \frac{1.9869(1518)}{15,527} = 0.19420 \; ;$$

and

$$T_e = T_c \left(\frac{P_e}{P_c}\right)^{\frac{\gamma - 1}{\gamma}}$$

$$= 3118(.032658)^{0.19420}$$

$$= 1604°\text{K}.$$

Then repeating the above computations with $T = 1604°$K;

$$\Delta H_{1604}^{3118} = 15,489 \text{ cal};$$

$$\Delta T_{1604}^{3118} = 1514°\text{K};$$

$$\frac{\gamma - 1}{\gamma} = .194164 \; ;$$

$$T_e = 3118(.032658)^{.19416} = 1604°\text{K}.$$

Thus the exit temperature T_e is found to be 1604°K.

Determination of Specific Impulse

Specific impulse is defined by the relation

$$I = \frac{V_e}{g} \, , \tag{30}$$

where V_e is the exit velocity of the propellant gas and g is the acceleration of gravity. By equating the enthalpy decrease of the propellant gas in cooling from T_c to T_e to the kinetic energy of one mole of exhaust gas we obtain

$$J \Delta H_{T_e}^{T_c} = \tfrac{1}{2} M V_e^2 \, , \tag{31}$$

where M is the mass, i.e., molecular weight, of one mole of gas, and J is the mechanical equivalent of heat. Solving eq. (31) for V_e and substituting in eq. (30) we obtain for the specific impulse

$$I = \frac{1}{g} \left(\frac{2 \Delta H_{T_e}^{T_c} \, J}{M} \right)^{\frac{1}{2}} . \tag{32}$$

Substituting the values $g = 980.665$ cm/sec^2 and $J = 4.1833 \times 10^7$ erg/cal we obtain the expression

$$I = 9.327 \left(\frac{\Delta H_{T_e}^{T_c}}{M} \right)^{\frac{1}{2}} . \tag{33}$$

For the present example the specific impulse becomes

$$I = 9.327 \left(\frac{15,489}{17.461}\right)^{½} = 277.9 \text{ sec.}$$

In order to prevent cumulative errors in calculation the computations for this and subsequent systems were carried out to six figures even though the basic data are given to four and/or five figures. The results are presented, generally, to four figures as a matter of form and in a few cases (e.g., molecular weight and gamma) to five figures in order to indicate trends rather than accuracy. In view of the broad working assumptions and the coarseness of the basic data four place accuracy for the calculated results is somewhat optimistic.

THE SYSTEM : HYDRAZINE - FLUORINE

For the system $\alpha N_2H_4(\ell) + F_2(\ell)$ we may write

$$N_f(N_2H_4) + N_o(F_2) = N_1(HF) + N_2(H_2) + N_3(H) + N_4(F_2) + N_5(F) + N_6(N_2) + N_7(N), \quad (34)$$

where

$$\sum_{i=1}^{7} N_i = 1. \quad (35)$$

Material balance considerations of (34) give

$$N_f = N_6 + .5N_7 \quad (36)$$

$$N_o = 0.5N_1 + N_4 + 0.5N_5 \quad (37)$$

and

$$N_1 + 2N_2 + N_3 = 4N_6 + 2N_7 = 2\alpha(N_1 + 2N_4 + N_5), \quad (38)$$

while equilibrium considerations give

$$\lambda_1 = K_1 = N_1(N_2N_4)^{½} \quad (39)$$

$$\lambda_2 = K_2/P_c = N_3{}^2/N_2 \quad (40)$$

$$\lambda_3 = K_3/P_c = N_5{}^2/N_4 \quad (41)$$

$$\lambda_4 = K_4/P_c = N_7{}^2/N_6 \quad (42)$$

For the sake of ease in computation eqs. (35) and (38) through (42) may be rearranged as follows:

$$N_1 = \frac{1 - 0.5(N_3 + N_7) - (1 + 1.5\alpha)N_5}{0.5 + 1.5\alpha} \tag{43}$$

$$N_2 = (\alpha - 0.5)N_1 - 0.5N_3 + \alpha N_5 \tag{44}$$

$$N_6 = 0.25N_1 + 0.5N_2 + 0.25N_3 - 0.5N_7 \tag{45}$$

$$N_3 = (\lambda_2 N_2)^{½} \tag{46}$$

$$N_5 = \lambda_3^{½} N_1/\lambda_1 N_2^{½} \tag{47}$$

$$N_7 = (\lambda_4 N_6)^{½} \tag{48}$$

Since trial shows that $N_4 < 0.00001$ in every case considered it may be neglected.

THE SYSTEM : HYDROGEN - OXYGEN

For the system $\alpha H_2(\ell) + O_2(\ell)$ we may write

$$N_f(H_2) + N_o(O_2) = N_1(H_2O) + N_2(H_2) + N_3(H) + N_4(O_2) + N_5(O) + N_6(OH), \tag{49}$$

where

$$\sum_{i=1}^{6} N_i = 1. \tag{50}$$

Material balance considerations of (49) give

$$N_f = N_1 + N_2 + 0.5N_3 + 0.5N_6 \tag{51}$$

$$N_o = 0.5N_1 + N_4 + 0.5N_5 + 0.5N_6 \tag{52}$$

and

$$N_1 + 2N_2 + N_3 + N_6 = \alpha(N_1 + 2N_4 + N_5 + N_6), \tag{53}$$

while equilibrium considerations give

$$\lambda_2 = K_2/P_c = N_3^2/N_2 \tag{54}$$

$$\lambda_6 = K_6/P_c = N_2^2\, N_4/N_1^2 \tag{55}$$

$$\lambda_7 = K_7/P_c = N_2N_5/N_1 \tag{56}$$

$$\lambda_8 = K_8/P_c^{\frac{1}{2}} = N_2^{\frac{1}{2}}N_6/N_1 \ . \tag{57}$$

For the sake of ease in computation eqs. (50) and (53) through (57) may be rewritten as follows:

$$N_1 = \frac{2 - N_3 - (2 + 2a)N_4 - (2 + a)N_5 - (1 + a)N_6}{a}$$

$$N_2 = \frac{a - 2 - (a - 1)N_3 + (2 + a)N_4 + 2N_5 + N_6}{a}$$

$$N_3 = (\lambda_2N_2)^{\frac{1}{2}}$$

$$N_4 = \lambda_6N_1^{\,2}/N_2^{\,2}$$

$$N_5 = \lambda_7N_1/N_2$$

$$N_6 = \lambda_8N_1/N_2^{\frac{1}{2}}$$

THE SYSTEM : HYDROGEN - FLUORINE

For the system $aH_2(\ell) + F_2(\ell)$ we may write

$$N_f(H_2) + N_o(F_2) = N_1(HF) + N_2(H_2) + N_3(H) + N_4(F_2) + N_5(F) \tag{58}$$

where

$$\sum_{i=1}^{5} N_i = 1. \tag{59}$$

Material balance considerations of (58) give

$$N_f = 0.5N_1 + N_2 + 0.5N_3 \ , \tag{60}$$

$$N_o = 0.5N_1 + N_4 + 0.5N_5 \ , \tag{61}$$

and

$$2N_1 + 2N_2 + N_3 = a(N_1 + 2N_4 + N_5) \ , \tag{62}$$

while equilibrium considerations give

$$\lambda_1 = K_1 = N_1/N_2^{\frac{1}{2}}N_4^{\frac{1}{2}} \tag{63}$$

$$\lambda_2 = K_2/P_c = N_3^2/N_2 \tag{64}$$

$$\lambda_3 = K_3/P_c = N_5^2/N_4 \tag{65}$$

Eqs. (59) and (62) through (65) may be rearranged as follows:

$$N_1 = \frac{2 - N_3 - (2 + \alpha)N_5}{1 + \alpha}$$

$$N_2 = \frac{(\alpha - 1)N_1 - N_3 + \alpha N_5}{2}$$

$$N_3 = (\lambda_2 N_2)^{1/2}$$

$$N_5 = \lambda_3^{1/2} N_1/\lambda_1 N_2^{1/2}$$

In this system N_4 is found to be negligible.

THE SYSTEM : HYDRAZINE - HYDROGEN PEROXIDE (ANHYDROUS)

For the system $\alpha N_2H_4(\ell) + H_2O_2(\ell)$ we may write

$$N_f(N_2H_4) + N_o(H_2O_2) = N_1(H_2O) + N_2(H_2) + N_3(H) + N_4(O_2) + N_5(O) + N_6(OH) +$$
$$N_7(N_2) + N_8(N) + N_9(NO) \,, \tag{66}$$

where

$$\sum_{i=1}^{9} N_i = 1 \,. \tag{67}$$

Material balance considerations of (66) give

$$N_f = N_7 + 0.5N_8 + 0.5N_9 \tag{68}$$

$$N_o = 0.5N_1 + N_4 + 0.5N_5 + 0.5N_6 + 0.5N_9 \tag{69}$$

and

$$\frac{2N_1 + 2N_2 + N_3 + N_6}{2\alpha + 1} = N_1 + 2N_4 + N_5 + N_6 + N_9 = \frac{2N_7 + N_8 + N_9}{2\alpha} \,, \tag{70}$$

while equilibrium considerations give

$$\lambda_2 = K_2/P_c = N_3{}^2/N_2 \tag{71}$$

$$\lambda_4 = K_4/P_c = N_8{}^2/N_7 \tag{72}$$

$$\lambda_5 = K_5/P_c{}^{1/2} = N_2N_9/N_1N_7^{1/2} \tag{73}$$

$$\lambda_6 = K_6/P_c = N_2{}^2N_4/N_1{}^2 \tag{74}$$

$$\lambda_7 = K_7/P_c = N_2N_5/N_1 \tag{75}$$

$$\lambda_8 = K_8/P_c{}^{1/2} = N_2^{1/2}N_6/N_1 \ . \tag{76}$$

For the sake of ease in computation eqs. (67) and (70) through (76) may be rearranged as follows:

$$N_1 = \frac{2 - N_3 - (4 + 6a)N_4 - (3 + 3a)N_5 - (2 + 3a)N_6 - N_8 - (2 + 3a)H_9}{1 + 3a}$$

$$N_2 = \frac{4a - 2 - 5aN_3 + (6 + 8a)N_4 + (4 + 2a)N_5 + (2 + a)N_6 - (2a - 1)N_8 + (3 + 4a)N_9}{2 + 6a}$$

$$N_7 = \frac{2a - aN_3 - 2aN_4 - 2aN_5 - aN_6 - (1 + 4a)N_8 - (1 + 4a)N_9}{2 + 6a}$$

$$N_3 = (\lambda_2N_2)^{1/2}$$

$$N_4 = \lambda_6N_1{}^2/N_2{}^2$$

$$N_5 = \lambda_7N_1/N_2$$

$$N_6 = \lambda_8N_1/N_2{}^{1/2}$$

$$N_8 = (\lambda_4\ N_7)^{1/2}$$

$$N_9 = \lambda_5N_1N_7{}^{1/2}/N_2\ .$$

THE SYSTEM : HYDRAZINE - CHLORINE TRIFLUORIDE

For the system $aN_2H_4(\ell) + ClF_3(\ell)$ we may write

$$N_f(N_2H_4) + N_o(ClF_3) = N_1(HF) + N_2(H_2) + N_3(N_2) + N_4(HCl) + N_5(H) + N_6(E) + N_7(Cl) + N_8(N) + N_9(F_2) + N_{10}(Cl_2) \ , \qquad (77)$$

where

$$\sum_{i=1}^{10} N_i = 1 \ . \qquad (78)$$

Material balance considerations of (77) give

$$N_f = N_3 + 0.5N_8 \ , \qquad (79)$$

$$N_o = N_4 + N_7 + 2N_{10} \ , \qquad (80)$$

and

$$\frac{2N_3 + N_8}{2a} = \frac{N_1 + 2N_2 + N_4 + N_5}{4a} = \frac{N_4 + N_7 + 2N_{10}}{1} = \frac{N_1 + N_6 + 2N_9}{3} \ , \qquad (81)$$

while equilibrium considerations give

$$\lambda_1 = K_1 = N_1/N_2^{1/2}N_9^{1/2} \qquad (82)$$

$$\lambda_2 = K_2/P_c = N_5^2/N_2 \qquad (83)$$

$$\lambda_3 = K_3/P_c = N_6^2/N_9 \qquad (84)$$

$$\lambda_4 = K_4/P_c = N_8^2/N_3 \qquad (85)$$

$$\lambda_9 = K_9 = N_4/N_2^{1/2}N_{10}^{1/2} \qquad (86)$$

$$\lambda_{10} = K_{10}/P_c = N_7^2/N_{10} \qquad (87)$$

To facilitate computation somewhat eqs. (78) and (81) through (87) may be rearranged as follows:

$$N_1 = \frac{6 - 3N_5 - (6a + 7)\,N_6 - 3N_7 - 3N_6 - (12a + 8)N_9}{6a + 4}$$

$$N_2 = \frac{2a - 2 - 2.5aN_5 + (2 + 0.5a)(N_6 + N_7) - (a - 1)N_8}{3a + 2} + N_9 + N_{10}$$

$$N_4 = \frac{1}{3}\left(N_1 + N_6 - 3N_7 + 2N_9 - 6N_{10}\right)$$

$$N_3 = \frac{1}{4}\left(N_1 + 2N_2 + N_4 + N_5 - 2N_8\right)$$

$$N_5 = (\lambda_2 N_2)^{1/2}$$

$$N_6 = \lambda_3^{1/2} N_1 / \lambda_1 N_2^{1/2}$$

$$N_7 = \lambda_{10}^{1/2} N_4 / \lambda_9 N_2^{1/2}$$

$$N_8 = (\lambda_4 N_3)^{1/2}$$

$$N_9 = N_1^2 / \lambda_1^2 N_2$$

$$N_{10} = N_4^2 / \lambda_9^2 N_2 \ .$$

RESULTS AND DISCUSSION

The System Hydrazine-Oxygen

The data calculated for the system hydrazine-oxygen at the pressures 150, 300, 450 and 600 psia and the mole ratios 1, 1.2, 1.5, 2, 2.5 and 3 are presented in Table XIV. Fig. 1 shows a plot of specific impulse versus mole ratio for each of the chamber pressures together with cross plots of constant chamber temperature, constant molecular weight and constant γ. The curves indicate the following optimum values for the specific impulse and associated characteristics:

Chamber Pressure P_c, psia	Mole Ratio a	Chamber Temp. T_c°K	Molecular Weight M	$\gamma = \dfrac{C_p}{C_v}$	Exit Temp. T_e, °K	Specific Impulse I, sec
150	1.54	3013	17.205	1.2404	1922	238.1
300	1.46	3115	17.570	1.2391	1741	264.7
450	1.41	3180	17.815	1.2378	1647	278.2
600	1.38	3224	17.975	1.2374	1580	286.6

Figs. 2 through 5 indicate plots on semi-logarithmic paper of propellant gas composition versus mole ratio for the system hydrazine-oxygen at the chamber pressures 150, 300, 450 and 600 psia, respectively. The effect of pressure on composition is quite pronounced.

As a matter of interest the following table affords a comparison at a pressure of 300 psia and several values of mole ratio between the data of this report and those listed by Lemmon [1] for the system hydrazine-oxygen.

α	T_c, °K		T_e, °K		I, sec	
	Lemmon	This report	Lemmon	This report	Lemmon	This report
1	3278	3286	1878	1878	257.0	257.9
1.5	3083	3089	1717	1721	264.0	264.6
2.5	2506	2489	1378	1303	252.5	253.0
3	2272	2272	1167	1160	246.0	246.2

As a matter of further interest calculations show that when hydrazine is reacted with gaseous oxygen at 298.16°K instead of liquid oxygen the absolute chamber temperature is increased by approximately 0.1%, while the specific impulse is increased by approximately 0.5%. The following table gives specific data for the conditions P_c = 300 psia and α = 1.5.

System	T_c, °K	M	γ	T_e, °K	I, sec
N_2H_4 + O_2(liquid)	3089	17.421	1.2404	1721	264.6
N_2H_4 + O_2(gas)	3116	17.386	1.2405	1736	266.0

The System Hydrazine-Fluorine

The data calculated for the system hydrazine-fluorine at the pressures 150, 300, 450, and 600 psia and the mole ratios 0.55, 0.65, 0.8, 1, 2, and 3 together with data at 600 psia and a mole ratio of 0.6 are presented in Table XV. These data are plotted in Figs. 6 and 7, the latter giving a better view of the specific impulse-mole ratio curves in the region of maximum specific impulse. The curves indicate the following optimum values for the specific impulse and associated characteristics:

Chamber Pressure P_c, psia	Mole Ratio α	Chamber Temp. T_c, °K	Molecular Weight M	$\gamma = \frac{C_p}{C_v}$	Exit Temp. T_e, °K	Specific Impulse I, sec
150	0.615	4374	18.430	1.3221	2480	269.9
300	0.605	4518	18.650	1.3212	2170	299.4
450	0.600	4610	18.780	1.3205	2010	314.1
600	0.595	4680	18.870	1.3201	1904	324.0

Figs. 8 through 11 indicate plots on semi-logarithmic paper of propellant gas composition versus mole ratio for the system hydrazine-fluorine at the chamber pressures 150, 300, 450 and 600 psia, respectively.

If hydrazine is reacted with gaseous fluorine at 298.16°K instead of liquid fluorine then the absolute chamber temperature is increased by approximately 0.1%, while the specific impulse is increased by approximately 0.5%. For the case $P_c = 300$ psia and $\alpha = 1$ the following comparative data obtain:

System	T_c, °K	M	γ	T_e, °K	I, sec
$N_2H_4 + F_2$(liquid)	3781	16.584	1.3166	1831	290.7
$N_2H_4 + F_2$(gas)	3808	16.542	1.3171	1842	292.1

For the system hydrazine-liquid fluorine at $P_c = 300$ psia and $\alpha = 1$ Lemmon 1 lists the following: $T_c = 3806$°K, $I = 292$ sec.

A comparison of results between the systems hydrazine-oxygen and hydrazine-fluorine shows that while the latter system exhibits values of specific impulse approximately 13% higher than those of the hydrazine-oxygen system at the pressures considered, the corresponding absolute chamber temperatures are approximately 45% higher.

P_c	I (max), sec		ΔI	Per Cent Increase	T_c, °K		ΔT_c	Per Cent Increase
	$N_2H_4 + O_2$	$N_2H_4 + F_2$			$N_2H_4 + O_2$	$N_2H_4 + F_2$		
150	238.1	269.9	31.8	13.4	3013	4374	1361	45.2
300	264.7	299.4	34.7	13.1	3115	4518	1403	45.0
450	278.2	314.1	35.9	12.9	3180	4610	1430	45.0
600	286.6	324.0	37.4	13.0	3224	4680	1456	45.2
Average				13.1				45.1

The System Hydrogen-Oxygen

The data calculated for this system at the pressures 150, 300, 450 and 600 psia and the mole ratios 4, 4.5, 5, 5.5, 6 and 7 are presented in Table XVI. Fig. 12 shows a plot of specific impulse versus mole ratio for each of the chamber pressures together with cross plots of constant chamber temperature, constant molecular weight and constant γ. The curves indicate the following values for maximum specific impulse and associated characteristics:

Chamber Pressure P_c, psia	Mole Ratio α	Chamber Temp. T_c, °K	Molecular Weight M	$\gamma = \frac{C_p}{C_v}$	Exit Temp. T_e, °K	Specific Impulse I, sec
150	5.42	2427	7.899	1.2610	1501	313.1
300	5.14	2528	8.216	1.2600	1357	345.6
450	4.98	2588	8.415	1.2588	1282	361.5
600	4.88	2630	8.550	1.2582	1230	371.6

Figs. 13 through 16 indicate plots on semi-logarithmic paper of propellant gas composition versus mole ratio for the system hydrogen-oxygen at the chamber pressures 150, 300, 450 and 600 psia, respectively.

The following comparative data are presented for the case P_c = 300 psia and $\alpha = 5$:

	T_c °K	M	γ	I, sec
This report	2572	8.388	1.2573	345.4
Lemmon 1	2561	8.4	1.23	343

If gaseous hydrogen is reacted with gaseous oxygen at 298.16°K instead of liquid hydrogen with liquid oxygen then the following comparative data obtain at P_c = 300 psia and α = 5:

System	T_c,°K	M	γ	T_e,°K	I, sec
H_2(liq) + O_2(liq)	2572	8.388	1.2573	1387	345.4
H_2(gas) + O_2(gas)	2760	8.356	1.2527	1502	359.1

The System Hydrogen-Fluorine

The data calculated for this system at the pressures 150, 300, 450 and 600 psia and the mole ratios 4, 4.5, 5, 6 and 7 are presented in Table XVII. Fig. 17 shows a plot of specific impulse versus mole ratio for each of the chamber pressures together with cross plots of constant chamber temperature, constant molecular weight and constant γ. The curves indicate the following values for maximum specific impulse and the associated characteristics:

Chamber Pressure P_c, psia	Mole Ratio α	Chamber Temp. T_c,°K	Molecular Weight M	$\gamma = \frac{C_p}{C_v}$	Exit Temp. T_e,°K	Specific Impulse I, sec
150	4.95	2730	8.000	1.3199	1552	323.7
300	4.68	2848	8.283	1.3222	1363	356.3
450	4.50	2927	8.482	1.3232	1269	371.9
600	4.42	2975	8.580	1.3240	1199	382.4

Figs. 18 through 21 indicate plots on semi-logarithmic paper of propellant gas composition versus mole ratio for the system hydrogen-fluorine at the chamber pressures 150, 300, 450 and 600 psia, respectively.

If gaseous hydrogen is reacted with gaseous fluorine at 298.16°K instead of liquid hydrogen with liquid fluorine then the following comparative data obtain at P_c = 300 psia and α = 5:

System	T_c, °K	M	γ	T_e, °K	I, sec
H_2(liq) + F_2(liq)	2738	7.966	1.3244	1308	355.9
H_2(gas) + F_2(gas)	2906	7.929	1.3208	1397	368.0

A comparison of results between the systems hydrogen-oxygen and hydrogen-fluorine shows that while the latter system exhibits values of specific impulse approximately 3% higher than those of the hydrogen-oxygen system at the pressures considered, the corresponding absolute chamber temperatures are approximately 12.5% higher.

P_c	I (max), sec		ΔI	Per Cent Increase	T_c, °K		ΔT_c	Per Cent Increase
	$H_2 + O_2$	$H_2 + F_2$			$H_2 + O_2$	$H_2 + F_2$		
150	313.1	323.7	10.6	3.4	2427	2730	303	12.5
300	345.6	356.3	10.7	3.1	2528	2848	320	12.7
450	361.5	371.9	10.4	2.9	2588	2927	339	13.1
600	371.6	382.4	10.8	2.9	2630	2975	345	13.1
Average				3.1				12.8

A similar comparison of results between the analogous systems hydrogen-oxygen and hydrazine-oxygen shows that while the specific impulse values of the latter system are approximately 23% lower than the corresponding values of the hydrogen-oxygen system at the pressures considered, the corresponding absolute chamber temperatures are approximately 23% higher

P_c	I (max), sec		ΔI	Per Cent Decrease	T_c, °K		ΔT_c	Per Cent Increase
	$H_2 + O_2$	$N_2H_4 + O_2$			$H_2 + O_2$	$N_2H_4 + O_2$		
150	313.1	238.1	-75.0	23.95	2427	3013	586	24.15
300	345.6	264.7	-80.9	23.41	2528	3145	617	24.41
450	361.5	278.2	-83.3	23.04	2588	3180	592	22.87
600	371.6	286.6	-85.0	22.87	2630	3224	594	22.59
Average				23.32				23.51

A comparison of results between the analogous systems hydrogen-fluorine and hydrazine-fluorine, however, shows that while the specific impulse values of the latter system are approximately 15.5% lower than the corresponding values of the hydrogen-fluorine system at the pressures considered, the corresponding absolute chamber temperatures are approximately 58% higher.

P_c	I (max), sec		ΔI	Per Cent Decrease	T_c, °K		ΔT_c	Per Cent Increase
	$H_2 + F_2$	$N_2H_4 + F_2$			$H_2 + F_2$	$N_2H_4 + F_2$		
150	323.7	269.9	-53.8	16.62	2730	4374	1644	60.22
300	356.3	299.4	-56.9	15.97	2848	4518	1670	58.64
450	371.9	314.1	-57.8	15.54	2927	4610	1683	57.50
600	382.4	324.0	-58.4	15.27	2975	4680	1705	57.31
Average				15.85				58.42

The System Hydrazine-Hydrogen Peroxide (Anhydrous)

The data calculated for this system at the pressures 300, 450 and 600 psia and the mole ratios 0.6, 0.65, 0.7, 0.75 and 1.0 are presented in Table XVIII. Figure 22 shows a plot of specific impulse versus mole ratio for each of the chamber pressures together with cross plots of constant chamber temperature, constant molecular weight and constant γ. The curves indicate the following values for maximum specific impulse and associated characteristics:

Chamber Pressure P_c, psia	Mole Ratio a	Chamber Temp. T_c, °K	Molecular Weight M	$\gamma = \frac{C_p}{C_v}$	Exit Temp. T_e, °K	Specific Impulse I, sec
300	0.675	2780	18.238	1.2189	1617	247.7
450	0.66	2806	18.363	1.2190	1518	259.8
600	0.65	2825	18.449	1.2191	1450	267.7

Figs. 23 through 25 indicate plots on semi-logarithmic paper of propellant gas composition versus mole ratio for the system hydrazine-hydrogen peroxide at the chamber pressures 300, 450 and 600 psia, respectively.

The following table affords a comparison at a pressure of 300 psia and two values of mole ratio between the data of this report and those calculated by Stosick [18] for the system hydrazine-hydrogen peroxide (anhydrous):

a	T_c, °K		γ		T_e, °K		I, sec	
	Stosick	This Report	Stosick	This Report	Stosick	This Report	Stosick	This Report
0.75	2716	2712	1.209	1.2244	1610	1561	249.0	247.3
1.00	2509	2488	1.240	1.2421	1400	1382	244.0	243.9

The System Hydrazine-Chlorine Trifluoride

The data calculated for this system at the pressures 300, 450 and 600 psia and the mole ratios 1.125, 1.25, 1.5 and 2 are presented in Table XIX. Fig. 26 shows a plot of specific impulse versus mole ratio for each of the chamber pressures together with cross plots of constant chamber temperature, constant molecular weight and constant γ. The curves indicate the following values for maximum specific impulse and associated characteristics:

Chamber Pressure P_c, psia	Mole Ratio a	Chamber Temp. T_c, °K	Molecular Weight M	$\gamma = \frac{C_p}{C_v}$	Exit Temp. T_e, °K	Specific Impulse I, sec
300	1.41	3353	21.465	1.3125	1634	241.0
450	1.36	3427	21.750	1.3133	1514	252.2
600	1.32	3483	21.990	1.3137	1435	259.6

Figs. 27 through 29 indicate plots on semi-logarithmic paper of propellant gas composition versus mole ratio for the system hydrazine-chlorine trifluoride at the chamber pressures 300, 450 and 600 psia, respectively.

A comparison of the results of the systems hydrazine-hydrogen peroxide and hydrazine-chlorine trifluoride shows that while the maximum specific impulse values of the latter system are only approximately 3% lower than those of the former system at the pressures considered, the corresponding absolute chamber temperatures are approximately 22% higher.

P_c	I (max), sec		ΔI	Per Cent Decrease	T_c, °K		ΔT_c	Per Cent Increase
	$N_2H_4 + H_2O_2$	$N_2H_4 + ClF_3$			$N_2H_4 + H_2O_2$	$N_2H_4 + ClF_3$		
300	247.7	241.0	-6.7	2.70	2780	3353	573	20.6
450	259.8	252.2	-7.6	2.93	2806	3427	621	22.1
600	267.7	259.6	-8.1	3.03	2825	3483	658	23.3
Average				2.89				22.0

Similar comparisons can be made with respect to molecular weight, γ, and exit temperature between any pair or group of systems by reference to Table XX which presents a summary of maximum specific impulse data and associated characteristics for the six liquid propellant systems considered in this report.

Further inspection of Table XX shows that for each system and at each chamber pressure the maximum specific impulse occurs at a fuel-oxidant mole ratio somewhat greater than the stoichiometric value and that the mole ratio for each system decreases toward the stoichiometric value with increase in pressure.

CONCLUSIONS

Mindful of the working assumptions of perfect gas law adherence, frozen equilibrium and adiabatic expansion of propellant gases the following general conclusions obtain.

With increase in chamber pressure each liquid propellant system investigated experiences an increase in maximum specific impulse, in the corresponding chamber temperature and molecular weight of the exhaust gas, and a decrease in the corresponding fuel-oxidant mole ratio and exit temperature. The ratio of isobaric to isocharic heat capacity ($\gamma = C_p/C_v$) remains essentially constant.

The fact that fluorine is a more powerful oxidant than oxygen is evidenced by the higher maximum specific impulse obtained with various fuels. For example, in the pressure range from 150 to 600 psia the maximum specific impulse is 3 per cent higher with hydrogen as a fuel and 13 per cent higher with hydrazine as a fuel. Furthermore, in the same pressure range at maximum specific impulse, fluorine develops a higher chamber temperature than does oxygen; e.g., 12.5 per cent higher with hydrogen as a fuel and 45 per cent higher with hydrazine as a fuel.

Hydrazine, a liquid at room temperature, is an excellent fuel. In the chamber pressure range from 150 to 600 psia, when oxidized by liquid oxygen, it develops a maximum specific impulse only 23 per cent less than that developed by liquid hydrogen; but it also develops a chamber temperature 23.5 per cent higher than does hydrogen. Similarly, when oxidized by liquid fluorine it develops a maximum specific impulse only 16 per cent less than that developed by hydrogen, but a chamber temperature 58 per cent higher.

Of the two systems hydrazine-hydrogen peroxide and hydrazine-chlorine trifluoride, all components of which are liquids at normal temperature and pressure, the former appears to be superior to the latter since it develops a maximum specific impulse 3 per cent higher and a chamber temperature 22 per cent lower in the pressure range from 300 to 600 psia.

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Table I

MOLECULAR WEIGHT AND HEAT OF FORMATION AT 298.16°K IN CALORIES PER MOLE OF VARIOUS SUBSTANCES

Substance	Molecular Weight	$\Delta H_{298.16}$	Reference
H_2O (*g*)	18.016	-57,798	(12)
H_2 (*g*)	2.016	0	
H (*g*)	1.008	51,911	(3)
O_2 (*g*)	32.000	0	
O (*g*)	16.000	59,112	(3)
OH (*g*)	17.008	9,310	(2)
N_2 (*g*)	28.016	0	
N (*g*)	14.008	85,110	(3)
NO (*g*)	30.008	21,532	(3)
F_2 (*g*)	38.000	0	
F (*g*)	19.000	31,750	(3)
HF (*g*)	20.008	-64,440	(4)
Cl_2 (*g*)	70.914	0	
Cl (*g*)	35.457	28,900	(3)
HCl (*g*)	36.465	-22,063	(3)
ClF_3 (*l*)	92.457	-59,300	(13)
N_2H_4 (*l*)	32.032	12,050	(14)
H_2O_2 (*l*)	34.016	-45,160	(3)

Table II

HEAT CONTENT $\Delta H^{T}_{298.16}$ IN CALORIES PER MOLE FOR VARIOUS GASES

T°K	H_2O	H_2	O_2	OH	N_2	NO	F_2	HF	Cl_2	HCl	Cl	H, F, N, O
600	2508	2106	2211	2134	2126	2189	2421	2121	2515	2532	1626	1499
700	3392	2809	2989	2855	2853	2947	3265	2812	3365	3110	2169	1996
800	4305	3516	3787	3552	3597	3722	4120	3511	4224	3724	2709	2493
900	5246	4225	4602	4292	4357	4515	4983	4218	5089	4374	3246	2989
1000	6221	4945	5430	4999	5133	5322	5852	4934	5963	5058	3779	3486
1100	7223	5670	6257	5739	5921	6141	5625	5659	6843	5774	4308	3983
1200	8259	6406	7095	6478	6723	6971	7601	6393	7731	6520	4835	4480
1300	9325	7151	7954	7236	7535	7810	8480	7136	8625	7291	5358	4976
1400	10411	7908	8822	8015	8356	8656	9361	7890	9526	8083	5878	5473
1500	11531	8677	9712	8774	9187	9510	10244	8654	10432	8895	6397	5970
1600	12672	9452	10560	9597	10023	10369	11128	9431	11345	9724	6918	6467
1700	13833	10239	11448	10351	10868	11232	12013	10217	12263	10567	7427	6963
1800	15018	11036	12337	11210	11717	12101	12899	11012	13185	11422	7940	7460
1900	16218	11841	13246	12018	12572	12973	13786	11816	14113	12285	8452	7957
2000	17436	12657	14154	12847	13431	13849	14674	12627	15045	13153	8962	8453
2100	18671	13479	15063	13686	14393	14728	15562	13445	15980	14025	9472	8950
2200	19921	14308	15962	14519	15157	15608	16451	14270	16920	14899	9980	9447
2300	21183	15145	16870	15393	16027	16490	17340	15102	17862	15772	10488	9944
2400	22459	15989	17779	16226	16898	17374	18230	15939	18808	16644	10994	10440
2500	23745	16840	18725	17093	17772	18260	19120	16782	19756	17514	11500	10937
2600	25043	17696	19626	17949	18650	19149	20010	17631	20705	18383	12006	11434
2700	26350	18556	20565	18827	19531	20041	20900	18485	21657	19253	12511	11931
2800	27668	19423	21513	19691	20413	20934	21791	19344	22610	20125	13015	12427
2900	28992	20295	22472	20575	21298	21831	22682	20208	23564	20999	13519	12924
3000	30327	21173	23436	21460	22184	22730	23574	21077	24518	21875	14022	13421
3100	31670	22054	24392	22348	23072	23630	24465	21951	25473	22753	14525	13917
3200	33018	22940	25352	23240	23961	24532	25357	22829	26427	23633	15028	14414
3300	34374	23831	26317	24134	24851	25434	26249	23711	27380	24519	15531	14911
3400	35735	24725	27284	25034	25743	26338	27141	24596	28332	25418	16033	15408
3500	37105	25625	28256	25934	26637	27243	28033	25486	29283	26332	16534	15904
3600	38478	26525	29228	26835	27530	28148	28925	26379	30232	27266	17036	16401
3700	39857	27429	30206	27743	28426	29055	29817	27275	31178	28223	17537	16898
3800	41244	28339	31187	28653	29322	29962	30709	28174	32122	29210	18038	17395
3900	42631	29249	32172	29565	30219	30869	31601	29076	33063	30229	18539	17891
4000	44022	30166	33161	30480	31118	31779	32494	29981	34000	31284	19040	18388
4100		31085			32019		33387	30889				18885
4200		32006			32922		34280	31801				19381
4300		32929			33827		35173	32716				19878
4400		33854			34734		36065	33635				20375
4500		34781			35642		36957	34558				20872
4600		35709			36551		37850	35484				21368
4700		36638			37461		38743	36415				21865
4800		37568			38372		39636	37349				22362
4900		38499			39284		40529	38287				22858
5000		39431			40196		41423	39229				23355

Table III

EQUILIBRIUM CONSTANTS FOR THE REACTIONS
$\frac{1}{2}H_2 + \frac{1}{2}F_2 = HF$ AND $\frac{1}{2}H_2 + \frac{1}{2}Cl_2 = HCl$

$T°K$	$K_1 = P_{HF}/P_{H_2}^{1/2}P_{F_2}^{1/2}$	$K_9 = P_{HCl}/P_{H_2}^{1/2}P_{Cl_2}^{1/2}$
1000	$2.401(10^{14})$	$1.850(10^{5})$
1100	$1.229(10^{13})$	$6.574(10^{4})$
1200	$1.030(10^{12})$	$2.769(10^{4})$
1300	$1.263(10^{11})$	$1.333(10^{4})$
1400	$2.087(10^{10})$	$7.109(10^{3})$
1500	$4.374(10^{9})$	$4.121(10^{3})$
1600	$1.112(10^{9})$	$2.554(10^{3})$
1700	$3.321(10^{8})$	$1.674(10^{3})$
1800	$1.133(10^{8})$	$1.150(10^{3})$
1900	$4.330(10^{7})$	$8.224(10^{2})$
2000	$1.822(10^{7})$	$6.081(10^{2})$
2100	$8.310(10^{6})$	$4.621(10^{2})$
2200	$4.070(10^{6})$	$3.599(10^{2})$
2300	$2.120(10^{6})$	$2.865(10^{2})$
2400	$1.166(10^{6})$	$2.324(10^{2})$
2500	$6.728(10^{5})$	$1.919(10^{2})$
2600	$4.050(10^{5})$	$1.607(10^{2})$
2700	$2.528(10^{5})$	$1.362(10^{2})$
2800	$1.633(10^{5})$	$1.168(10^{2})$
2900	$1.087(10^{5})$	$1.011(10^{2})$
3000	$7.434(10^{4})$	$8.843(10)$
3100	$5.211(10^{4})$	$7.805(10)$
3200	$3.734(10^{4})$	$6.944(10)$
3300	$2.729(10^{4})$	$6.214(10)$
3400	$2.032(10^{4})$	$5.604(10)$
3500	$1.539(10^{4})$	$5.080(10)$
3600	$1.183(10^{4})$	$4.629(10)$
3700	$9.230(10^{3})$	$4.240(10)$
3800	$7.295(10^{3})$	$3.900(10)$
3900	$5.833(10^{3})$	$3.605(10)$
4000	$4.718(10^{3})$	$3,344(10)$
4100	$3.857(10^{3})$	
4200	$3.183(10^{3})$	
4300	$2.650(10^{3})$	
4400	$2.224(10^{3})$	
4500	$1.882(10^{3})$	
4600	$1.604(10^{3})$	
4700	$1.377(10^{3})$	
4800	$1.190(10^{3})$	
4900	$1.033(10^{3})$	
5000	$9.028(10^{2})$	

Table IV

EQUILIBRIUM CONSTANTS FOR THE REACTION $F_2 = 2F$

T°K	$K_3 = \frac{P_F^{\,2}}{P_{F_2}}$	$\lambda_3 = K_3/P_c$ (P_c, atm)			
		P_c (psia)			
		150	300	450	600
1000	$1.550(10^{-8})$	$1.519(10^{-9})$	$7.593(10^{-10})$	$5.062(10^{-10})$	$3.796(10^{-10})$
1100	$3.148(10^{-7})$	$3.084(10^{-8})$	$1.542(10^{-8})$	$1.028(10^{-8})$	$7.710(10^{-9})$
1200	$3.900(10^{-6})$	$3.821(10^{-7})$	$1.910(10^{-7})$	$1.274(10^{-7})$	$9.552(10^{-8})$
1300	$3.289(10^{-5})$	$3.222(10^{-6})$	$1.611(10^{-6})$	$1.074(10^{-6})$	$8.056(10^{-7})$
1400	$2.056(10^{-4})$	$2.014(10^{-5})$	$1.007(10^{-5})$	$6.714(10^{-6})$	$5.036(10^{-6})$
1500	$1.009(10^{-3})$	$9.886(10^{-5})$	$4.943(10^{-5})$	$3.295(10^{-5})$	$2.471(10^{-5})$
1600	$4.067(10^{-3})$	$3.985(10^{-4})$	$1.992(10^{-4})$	$1.328(10^{-4})$	$9.961(10^{-5})$
1700	$1.396(10^{-2})$	$1.368(10^{-3})$	$6.839(10^{-4})$	$4.559(10^{-4})$	$3.419(10^{-4})$
1800	$4.183(10^{-2})$	$4.098(10^{-3})$	$2.049(10^{-3})$	$1.366(10^{-3})$	$1.025(10^{-3})$
1900	$1.118(10^{-1})$	$1.095(10^{-2})$	$5.477(10^{-3})$	$3.651(10^{-3})$	$2.738(10^{-3})$
2000	$2.713(10^{-1})$	$2.658(10^{-2})$	$1.329(10^{-2})$	$8.860(10^{-3})$	$6.645(10^{-3})$
2100	$6.062(10^{-1})$	$5.939(10^{-2})$	$2.970(10^{-2})$	$1.980(10^{-2})$	$1.485(10^{-2})$
2200	1.260	$1.234(10^{-1})$	$6.172(10^{-2})$	$4.115(10^{-2})$	$3.086(10^{-2})$
2300	2.460	$2.410(10^{-1})$	$1.205(10^{-1})$	$8.034(10^{-2})$	$6.025(10^{-2})$
2400	4.552	$4.460(10^{-1})$	$2.230(10^{-1})$	$1.487(10^{-1})$	$1.115(10^{-1})$
2500	8.019	$7.856(10^{-1})$	$3.928(10^{-1})$	$2.619(10^{-1})$	$1.964(10^{-1})$
2600	1.354(10)	1.327	$6.633(10^{-1})$	$4.422(10^{-1})$	$3.316(10^{-1})$
2700	2.199(10)	2.154	1.077	$7.181(10^{-1})$	$5.386(10^{-1})$
2800	3.454(10)	3.384	1.692	1.128	$8.460(10^{-1})$
2900	5.260(10)	5.153	2.577	1.718	1.288
3000	7.804(10)	7.646	3.823	2.549	1.911
3100	$1.128(10^{2})$	1.105(10)	5.526	3.684	2.763
3200	$1.594(10^{2})$	1.562(10)	7.808	5.206	3.904
3300	$2.208(10^{2})$	2.163(10)	1.082(10)	7.211	5.408
3400	$3.004(10^{2})$	2.943(10)	1.472(10)	9.810	7.358
3500	$4.014(10^{2})$	3.933(10)	1.966(10)	1.311(10)	9.832
3600	$5.276(10^{2})$	5.169(10)	2.585(10)	1.723(10)	1.292(10)
3700	$6.845(10^{2})$	6.706(10)	3.353(10)	2.235(10)	1.677(10)
3800	$8.760(10^{2})$	8.582(10)	4.291(10)	2.861(10)	2.146(10)
3900	$1.107(10^{3})$	$1.085(10^{2})$	5.423(10)	3.615(10)	2.711(10)
4000	$1.383(10^{3})$	$1.355(10^{2})$	6.775(10)	4.517(10)	3.387(10)
4100	$1.710(10^{3})$	$1.675(10^{2})$	8.377(10)	5.584(10)	4.188(10)
4200	$2.095(10^{3})$	$2.053(10^{2})$	$1.026(10^{2})$	6.842(10)	5.131(10)
4300	$2.543(10^{3})$	$2.491(10^{2})$	$1.246(10^{2})$	8.305(10)	6.229(10)
4400	$3.058(10^{3})$	$2.996(10^{2})$	$1.498(10^{2})$	9.987(10)	7.490(10)
4500	$3.648(10^{3})$	$3.574(10^{2})$	$1.787(10^{2})$	$1.191(10^{2})$	8.935(10)
4600	$4.324(10^{3})$	$4.236(10^{2})$	$2.118(10^{2}))$	$1.412(10^{2})$	$1.059(10^{2})$
4700	$5.090(10^{3})$	$4.987(10^{2})$	$2.493(10^{2})$	$1.662(10^{2})$	$1.247(10^{2})$
4800	$5.947(10^{3})$	$5.826(10^{2})$	$2.913(10^{2})$	$1.942(10^{2})$	$1.457(10^{2})$
4900	$6.907(10^{3})$	$6.767(10^{2})$	$3.384(10^{2})$	$2.256(10^{2})$	$1.692(10^{2})$
5000	$7.969(10^{3})$	$7.807(10^{2})$	$3.904(10^{2})$	$2.603(10^{2})$	$1.952(10^{2})$

Table V

EQUILIBRIUM CONSTANTS FOR THE REACTION $Cl_2 = 2Cl$

T°K	$K_{10} = \frac{P_{Cl}^2}{P_{Cl_2}}$	$\lambda_{10} = K_{10}/P_e$ (P_e, atm)			
		P_e (psia)			
		150	300	450	600
1000	$1.718(10^{-7})$	$1.683(10^{-8})$	$8.416(10^{-9})$	$5.611(10^{-9})$	$4.208(10^{-9})$
1100	$2.576(10^{-6})$	$2.524(10^{-7})$	$1.262(10^{-7})$	$8.413(10^{-8})$	$6.309(10^{-8})$
1200	$2.476(10^{-5})$	$2.426(10^{-6})$	$1.213(10^{-6})$	$8.086(10^{-7})$	$6.065(10^{-7})$
1300	$1.688(10^{-4})$	$1.654(10^{-5})$	$8.269(10^{-6})$	$5.513(10^{-6})$	$4.134(10^{-6})$
1400	$8.780(10^{-4})$	$8.602(10^{-5})$	$4.301(10^{-5})$	$2.867(10^{-5})$	$2.151(10^{-5})$
1500	$3.680(10^{-3})$	$3.605(10^{-4})$	$1.803(10^{-4})$	$1.202(10^{-4})$	$9.014(10^{-5})$
1600	$1.293(10^{-2})$	$1.267(10^{-3})$	$6.334(10^{-4})$	$4.223(10^{-4})$	$3.167(10^{-4})$
1700	$3.925(10^{-2})$	$3.845(10^{-3})$	$1.923(10^{-3})$	$1.282(10^{-3})$	$9.614(10^{-4})$
1800	$1.055(10^{-1})$	$1.034(10^{-2})$	$5.168(10^{-3})$	$3.445(10^{-3})$	$2.584(10^{-3})$
1900	$2.561(10^{-1})$	$2.509(10^{-2})$	$1.255(10^{-2})$	$8.364(10^{-3})$	$6.273(10^{-3})$
2000	$5.694(10^{-1})$	$5.580(10^{-2})$	$2.789(10^{-2})$	$1.860(10^{-2})$	$1.395(10^{-2})$
2100	1.174	$1.150(10^{-1})$	$5.751(10^{-2})$	$3.834(10^{-2})$	$2.876(10^{-2})$
2200	2.269	$2.223(10^{-1})$	$1.112(10^{-1})$	$7.410(10^{-2})$	$5.558(10^{-2})$
2300	4.145	$4.061(10^{-1})$	$2.030(10^{-1})$	$1.354(10^{-1})$	$1.015(10^{-1})$
2400	7.204	$7.058(10^{-1})$	$3.529(10^{-1})$	$2.353(10^{-1})$	$1.764(10^{-1})$
2500	1.199(10)	1.175	$5.874(10^{-1})$	$3.916(10^{-1})$	$2.937(10^{-1})$
2600	1.920(10)	1.881	$9.405(10^{-1})$	$6.270(10^{-1})$	$4.703(10^{-1})$
2700	2.969(10)	2.909	1.454	$9.696(10^{-1})$	$7.272(10^{-1})$
2800	4.451(10)	4.361	2.180	1.454	1.090
2900	6.494(10)	6.362	3.181	2.121	1.591
3000	9.241(10)	9.054	4.527	3.018	2.263
3100	$1.286(10^{2})$	1.260(10)	6.300	4.200	3.150
3200	$1.754(10^{2})$	1.718(10)	8.592	5.728	4.296
3300	$2.346(10^{2})$	2.298(10)	1.149(10)	7.662	5.746
3400	$3.087(10^{2})$	3.024(10)	1.512(10)	1.008(10)	7.561
3500	$4.000(10^{2})$	3.919(10)	1.959(10)	1.306(10)	9.797
3600	$5.111(10^{2})$	5.007(10)	2.504(10)	1.669(10)	1.252(10)
3700	$6.443(10^{2})$	6.312(10)	3.156(10)	2.104(10)	1.578(10)
3800	$8.028(10^{2})$	7.865(10)	3.933(10)	2.622(10)	1.966(10)
3900	$9.892(10^{2})$	9.692(10)	4.846(10)	3.231(10)	2.423(10)
4000	$1.207(10^{3})$	$1.183(10^{2})$	5.913(10)	3.942(10)	2.956(10)

Table VI

EQUILIBRIUM CONSTANTS FOR THE REACTION $H_2 = 2H$

T°K	$K_2 = \frac{P_H^2}{P_{H_2}}$	$\lambda_2 = K_2/P_c$ (P_c, atm)			
		P_c (psia)			
		150	300	450	600
1500	$3.104(10^{-10})$	$3.041(10^{-11})$	$1.521(10^{-11})$	$1.014(10^{-11})$	$7.603(10^{-12})$
1600	$2.954(10^{-9})$	$2.894(10^{-10})$	$1.447(10^{-10})$	$9.647(10^{-11})$	$7.235(10^{-11})$
1700	$2.166(10^{-8})$	$2.122(10^{-9})$	$1.061(10^{-9})$	$7.074(10^{-10})$	$5.305(10^{-10})$
1800	$1.279(10^{-7})$	$1.253(10^{-8})$	$6.265(10^{-9})$	$4.177(10^{-9})$	$3.133(10^{-9})$
1900	$6.291(10^{-7})$	$6.164(10^{-8})$	$3.082(10^{-8})$	$2.055(10^{-8})$	$1.541(10^{-8})$
2000	$2.649(10^{-6})$	$2.595(10^{-7})$	$1.298(10^{-7})$	$8.651(10^{-8})$	$6.488(10^{-8})$
2100	$9.712(10^{-6})$	$9.515(10^{-7})$	$4.758(10^{-7})$	$3.172(10^{-7})$	$2.379(10^{-8})$
2200	$3.174(10^{-5})$	$3.110(10^{-6})$	$1.555(10^{-6})$	$1.037(10^{-6})$	$7.774(10^{-7})$
2300	$9.371(10^{-5})$	$9.181(10^{-6})$	$4.591(10^{-6})$	$3.060(10^{-6})$	$2.295(10^{-6})$
2400	$2.532(10^{-4})$	$2.481(10^{-5})$	$1.240(10^{-5})$	$8.269(10^{-6})$	$6.202(10^{-6})$
2500	$6.326(10^{-4})$	$6.198(10^{-5})$	$3.099(10^{-5})$	$2.066(10^{-5})$	$1.549(10^{-5})$
2600	$1.475(10^{-3})$	$1.445(10^{-4})$	$7.226(10^{-5})$	$4.817(10^{-5})$	$3.613(10^{-5})$
2700	$3.229(10^{-3})$	$3.164(10^{-4})$	$1.582(10^{-4})$	$1.055(10^{-4})$	$7.909(10^{-5})$
2800	$6.697(10^{-3})$	$6.561(10^{-4})$	$3.281(10^{-4})$	$2.187(10^{-4})$	$1.640(10^{-4})$
2900	$1.321(10^{-2})$	$1.294(10^{-3})$	$6.471(10^{-4})$	$4.314(10^{-4})$	$3.236(10^{-4})$
3000	$2.495(10^{-2})$	$2.444(10^{-3})$	$1.222(10^{-3})$	$8.148(10^{-4})$	$6.111(10^{-4})$
3100	$4.522(10^{-2})$	$4.430(10^{-3})$	$2.215(10^{-3})$	$1.477(10^{-3})$	$1.108(10^{-3})$
3200	$7.907(10^{-2})$	$7.747(10^{-3})$	$3.873(10^{-3})$	$2.582(10^{-3})$	$1.937(10^{-3})$
3300	$1.336(10^{-1})$	$1.309(10^{-2})$	$6.545(10^{-3})$	$4.363(10^{-3})$	$3.272(10^{-3})$
3400	$2.191(10^{-1})$	$2.147(10^{-2})$	$1.073(10^{-2})$	$7.155(10^{-3})$	$5.366(10^{-3})$
3500	$3.492(10^{-1})$	$3.421(10^{-2})$	$1.711(10^{-2})$	$1.140(10^{-2})$	$8.553(10^{-3})$
3600	$5.429(10^{-1})$	$5.319(10^{-2})$	$2.659(10^{-2})$	$1.773(10^{-2})$	$1.330(10^{-2})$
3700	$8.243(10^{-1})$	$8.076(10^{-2})$	$4.038(10^{-2})$	$2.692(10^{-2})$	$2.019(10^{-2})$
3800	1.225	$1.200(10^{-1})$	$6.001(10^{-2})$	$4.001(10^{-2})$	$3.000(10^{-2})$
3900	1.784	$1.748(10^{-1})$	$8.739(10^{-2})$	$5.826(10^{-2})$	$4.370(10^{-2})$
4000	2.550	$2.498(10^{-1})$	$1.249(10^{-1})$	$8.328(10^{-2})$	$6.246(10^{-2})$
4100	3.583	$3.510(10^{-1})$	$1.755(10^{-1})$	$1.170(10^{-1})$	$8.776(10^{-2})$
4200	4.956	$4.856(10^{-1})$	$2.428(10^{-1})$	$1.619(10^{-1})$	$1.214(10^{-1})$
4300	6.751	$6.614(10^{-1})$	$3.307(10^{-1})$	$2.205(10^{-1})$	$1.654(10^{-1})$
4400	9.072	$8.888(10^{-1})$	$4.444(10^{-1})$	$2.963(10^{-1})$	$2.222(10^{-1})$
4500	$1.203(10)$	1.179	$5.893(10^{-1})$	$3.929(10^{-1})$	$2.947(10^{-1})$
4600	$1.576(10)$	1.544	$7.720(10^{-1})$	$5.147(10^{-1})$	$3.860(10^{-1})$
4700	$2.043(10)$	2.002	1.001	$6.672(10^{-1})$	$5.004(10^{-1})$
4800	$2.617(10)$	2.564	1.282	$8.547(10^{-1})$	$6.410(10^{-1})$
4900	$3.322(10)$	3.255	1.627	1.085	$8.137(10^{-1})$
5000	$4.176(10)$	4.091	2.046	1.364	1.023

Table VII

EQUILIBRIUM CONSTANTS FOR THE REACTION $N_2 = 2N$

$T°K$	$K_4 = \frac{P_N{}^2}{P_{N_2}}$	$\lambda_4 = K_4/P_c$ (P_c, atm)			
		P_c (psia)			
		150	300	450	600
2000	$7.865(10^{-13})$	$7.706(10^{-14})$	$3.853(10^{-14})$	$2.569(10^{-14})$	$1.926(10^{-14})$
2100	$6.378(10^{-12})$	$6.249(10^{-13})$	$2.124(10^{-13})$	$2.083(10^{-13})$	$1.562(10^{-13})$
2200	$4.279(10^{-11})$	$4.192(10^{-12})$	$2.096(10^{-12})$	$1.397(10^{-12})$	$1.048(10^{-12})$
2300	$2.438(10^{-10})$	$2.389(10^{-11})$	$1.194(10^{-11})$	$7.962(10^{-12})$	$5.971(10^{-12})$
2400	$1.203(10^{-9})$	$1.179(10^{-10})$	$5.893(10^{-11})$	$3.929(10^{-11})$	$2.947(10^{-11})$
2500	$5.230(10^{-9})$	$5.124(10^{-10})$	$2.562(10^{-10})$	$1.708(10^{-10})$	$1.281(10^{-10})$
2600	$2.032(10^{-8})$	$1.991(10^{-9})$	$9.954(10^{-10})$	$6.636(10^{-10})$	$4.977(10^{-10})$
2700	$7.142(10^{-8})$	$6.997(10^{-9})$	$3.499(10^{-9})$	$2.332(10^{-9})$	$1.749(10^{-9})$
2800	$2.298(10^{-7})$	$2.251(10^{-8})$	$1.126(10^{-8})$	$7.505(10^{-9})$	$5.629(10^{-9})$
2900	$6.830(10^{-7})$	$6.692(10^{-8})$	$3.346(10^{-8})$	$2.231(10^{-8})$	$1.673(10^{-8})$
3000	$1.886(10^{-6})$	$1.848(10^{-7})$	$9.239(10^{-8})$	$6.159(10^{-8})$	$4.619(10^{-8})$
3100	$4.883(10^{-6})$	$4.784(10^{-7})$	$2.392(10^{-7})$	$1.595(10^{-7})$	$1.196(10^{-7})$
3200	$1.192(10^{-5})$	$1.168(10^{-6})$	$5.839(10^{-7})$	$3.893(10^{-7})$	$2.920(10^{-7})$
3300	$2.761(10^{-5})$	$2.705(10^{-6})$	$1.353(10^{-6})$	$9.017(10^{-7})$	$6.763(10^{-7})$
3400	$6.083(10^{-5})$	$5.960(10^{-6})$	$2.980(10^{-6})$	$1.987(10^{-6})$	$1.490(10^{-6})$
3500	$1.282(10^{-4})$	$1.256(10^{-5})$	$6.280(10^{-6})$	$4.187(10^{-6})$	$3.140(10^{-6})$
3600	$2.596(10^{-4})$	$2.543(10^{-5})$	$1.272(10^{-5})$	$8.478(10^{-6})$	$6.358(10^{-6})$
3700	$5.054(10^{-4})$	$4.952(10^{-5})$	$2.476(10^{-5})$	$1.651(10^{-5})$	$1.238(10^{-5})$
3800	$9.521(10^{-4})$	$9.328(10^{-5})$	$4.664(10^{-5})$	$3.109(10^{-5})$	$2.332(10^{-5})$
3900	$1.736(10^{-3})$	$1.701(10^{-4})$	$8.504(10^{-5})$	$5.669(10^{-5})$	$4.252(10^{-5})$
4000	$3.074(10^{-3})$	$3.012(10^{-4})$	$1.506(10^{-4})$	$1.004(10^{-4})$	$7.529(10^{-5})$
4100	$5.290(10^{-3})$	$5.183(10^{-4})$	$2.591(10^{-4})$	$1.728(10^{-4})$	$1.296(10^{-5})$
4200	$8.882(10^{-3})$	$8.702(10^{-4})$	$4.351(10^{-4})$	$2.901(10^{-4})$	$2.175(10^{-4})$
4300	$1.456(10^{-2})$	$1.426(10^{-3})$	$7.132(10^{-4})$	$4.755(10^{-4})$	$3.566(10^{-4})$
4400	$2.335(10^{-2})$	$2.288(10^{-3})$	$1.144(10^{-3})$	$7.626(10^{-4})$	$5.719(10^{-4})$
4500	$3.671(10^{-2})$	$3.597(10^{-3})$	$1.798(10^{-3})$	$1.199(10^{-3})$	$8.991(10^{-4})$
4600	$5.660(10^{-2})$	$5.545(10^{-3})$	$2.773(10^{-3})$	$1.848(10^{-3})$	$1.386(10^{-3})$
4700	$8.561(10^{-2})$	$8.387(10^{-3})$	$4.194(10^{-3})$	$2.796(10^{-3})$	$2.097(10^{-3})$
4800	$1.274(10^{-1})$	$1.248(10^{-2})$	$6.241(10^{-3})$	$4.161(10^{-3})$	$3.120(10^{-3})$
4900	$1.867(10^{-1})$	$1.829(10^{-2})$	$9.146(10^{-3})$	$6.097(10^{-3})$	$4.573(10^{-3})$
5000	$2.695(10^{-1})$	$2.640(10^{-2})$	$1.320(10^{-2})$	$8.801(10^{-3})$	$6.601(10^{-3})$

Table VIII

EQUILIBRIUM CONSTANTS FOR THE REACTION $\frac{1}{2}N_2 + H_2O = NO + H_2$

T°K	$K_5 = \dfrac{P_{NO}P_{H_2}}{P_{N_2}{}^{1/2}P_{H_2O}}$	$\lambda_5 = K_5/P_c{}^{1/2}$ (P_c, atm)			
		P_c (psia)			
		150	300	450	600
1500	$6.167(10^{-9})$	$1.930(10^{-9})$	$1.365(10^{-9})$	$1.114(10^{-9})$	$9.652(10^{-10})$
1600	$3.401(10^{-8})$	$1.065(10^{-8})$	$7.527(10^{-9})$	$6.146(10^{-9})$	$5.323(10^{-9})$
1700	$1.541(10^{-7})$	$4.823(10^{-8})$	$3.411(10^{-8})$	$2.785(10^{-8})$	$2.412(10^{-8})$
1800	$5.891(10^{-7})$	$1.844(10^{-7})$	$1.304(10^{-7})$	$1.065(10^{-7})$	$9.220(10^{-8})$
1900	$1.951(10^{-6})$	$6.107(10^{-7})$	$4.318(10^{-7})$	$3.526(10^{-7})$	$3.053(10^{-7})$
2000	$5.756(10^{-6})$	$1.802(10^{-6})$	$1.274(10^{-6})$	$1.040(10^{-6})$	$9.008(10^{-7})$
2100	$1.531(10^{-5})$	$4.792(10^{-6})$	$3.389(10^{-6})$	$2.767(10^{-6})$	$2.396(10^{-6})$
2200	$3.782(10^{-5})$	$1.184(10^{-5})$	$8.371(10^{-6})$	$6.835(10^{-6})$	$5.919(10^{-6})$
2300	$8.371(10^{-5})$	$2.620(10^{-5})$	$1.853(10^{-5})$	$1.513(10^{-5})$	$1.310(10^{-5})$
2400	$1.771(10^{-4})$	$5.543(10^{-5})$	$3.920(10^{-5})$	$3.200(10^{-5})$	$2.772(10^{-5})$
2500	$3.505(10^{-4})$	$1.097(10^{-4})$	$7.758(10^{-5})$	$6.334(10^{-5})$	$5.485(10^{-5})$
2600	$6.641(10^{-4})$	$2.079(10^{-4})$	$1.470(10^{-4})$	$1.200(10^{-4})$	$1.039(10^{-4})$
2700	$1.188(10^{-3})$	$3.719(10^{-4})$	$2.629(10^{-4})$	$2.147(10^{-4})$	$1.859(10^{-4})$
2800	$2.047(10^{-3})$	$6.407(10^{-4})$	$4.531(10^{-4})$	$3.699(10^{-4})$	$3.204(10^{-4})$
2900	$3.414(10^{-3})$	$1.068(10^{-3})$	$7.555(10^{-4})$	$6.169(10^{-4})$	$5.342(10^{-4})$
3000	$5.474(10^{-3})$	$1.713(10^{-3})$	$1.212(10^{-3})$	$9.892(10^{-4})$	$8.567(10^{-4})$
3100	$8.521(10^{-3})$	$2.667(10^{-3})$	$1.886(10^{-3})$	$1.540(10^{-3})$	$1.334(10^{-3})$
3200	$1.290(10^{-2})$	$4.038(10^{-3})$	$2.855(10^{-3})$	$2.331(10^{-3})$	$2.019(10^{-3})$
3300	$1.909(10^{-2})$	$5.975(10^{-3})$	$4.225(10^{-3})$	$3.450(10^{-3})$	$2.988(10^{-3})$
3400	$2.758(10^{-2})$	$8.633(10^{-3})$	$6.104(10^{-3})$	$4.984(10^{-3})$	$4.316(10^{-3})$
3500	$3.892(10^{-2})$	$1.218(10^{-2})$	$8.614(10^{-3})$	$7.033(10^{-3})$	$6.091(10^{-3})$
3600	$5.391(10^{-2})$	$1.687(10^{-2})$	$1.193(10^{-2})$	$9.742(10^{-3})$	$8.437(10^{-3})$
3700	$7.345(10^{-2})$	$2.299(10^{-2})$	$1.626(10^{-2})$	$1.327(10^{-2})$	$1.150(10^{-2})$
3800	$9.818(10^{-2})$	$3.073(10^{-2})$	$2.173(10^{-2})$	$1.774(10^{-2})$	$1.536(10^{-2})$
3900	$1.301(10^{-1})$	$4.072(10^{-2})$	$2.879(10^{-2})$	$2.351(10^{-2})$	$2.036(10^{-2})$
4000	$1.696(10^{-1})$	$5.307(10^{-2})$	$3.753(10^{-2})$	$3.064(10^{-2})$	$2.654(10^{-2})$

Table IX

EQUILIBRIUM CONSTANTS FOR THE REACTION $2H_2 = 2H_2 + O_2$

$T°K$	$K_6 = \frac{P_{H_2}^2 P_{O_2}}{P_{H_2O}^2}$	$\lambda_6 = K_6/P_c$ (P_c, atm)			
		P_c (psia)			
		150	300	450	600
1500	$3.488(10^{-12})$	$3.417(10^{-13})$	$1.709(10^{-13})$	$1.139(10^{-13})$	$8.543(10^{-14})$
1600	$4.293(10^{-11})$	$4.206(10^{-12})$	$2.103(10^{-12})$	$1.402(10^{-12})$	$1.051(10^{-12})$
1700	$3.967(10^{-10})$	$3.887(10^{-11})$	$1.943(10^{-11})$	$1.296(10^{-11})$	$9.716(10^{-12})$
1800	$2.850(10^{-9})$	$2.792(10^{-10})$	$1.396(10^{-10})$	$9.307(10^{-11})$	$6.981(10^{-11})$
1900	$1.654(10^{-8})$	$1.620(10^{-9})$	$8.102(10^{-10})$	$5.402(10^{-10})$	$4.051(10^{-10})$
2000	$8.131(10^{-8})$	$7.966(10^{-9})$	$3.983(10^{-9})$	$2.655(10^{-9})$	$1.992(10^{-9})$
2100	$3.424(10^{-7})$	$3.355(10^{-8})$	$1.677(10^{-8})$	$1.118(10^{-8})$	$8.387(10^{-9})$
2200	$1.306(10^{-6})$	$1.280(10^{-7})$	$6.398(10^{-8})$	$4.265(10^{-8})$	$3.199(10^{-8})$
2300	$4.169(10^{-6})$	$4.085(10^{-6})$	$2.042(10^{-7})$	$1.362(10^{-7})$	$1.021(10^{-7})$
2400	$1.259(10^{-5})$	$1.233(10^{-6})$	$6.167(10^{-7})$	$4.112(10^{-7})$	$3.084(10^{-7})$
2500	$3.438(10^{-5})$	$3.368(10^{-6})$	$1.684(10^{-6})$	$1.123(10^{-6})$	$8.421(10^{-7})$
2600	$8.843(10^{-5})$	$8.664(10^{-6})$	$4.332(10^{-6})$	$2.888(10^{-6})$	$2.166(10^{-6})$
2700	$2.079(10^{-4})$	$2.037(10^{-5})$	$1.018(10^{-5})$	$6.790(10^{-6})$	$5.092(10^{-6})$
2800	$4.636(10^{-4})$	$4.542(10^{-5})$	$2.271(10^{-5})$	$1.514(10^{-5})$	$1.136(10^{-5})$
2900	$9.881(10^{-4})$	$9.681(10^{-5})$	$4.840(10^{-5})$	$3.227(10^{-5})$	$2.420(10^{-5})$
3000	$1.981(10^{-3})$	$1.941(10^{-4})$	$9.704(10^{-5})$	$6.470(10^{-5})$	$4.852(10^{-5})$
3100	$3.799(10^{-3})$	$3.722(10^{-4})$	$1.861(10^{-4})$	$1.241(10^{-4})$	$9.305(10^{-5})$
3200	$7.011(10^{-3})$	$6.869(10^{-4})$	$3.434(10^{-4})$	$2.290(10^{-4})$	$1.717(10^{-4})$
3300	$1.250(10^{-2})$	$1.225(10^{-3})$	$6.123(10^{-4})$	$4.082(10^{-4})$	$3.062(10^{-4})$
3400	$2.155(10^{-2})$	$2.111(10^{-3})$	$1.055(10^{-3})$	$7.036(10^{-4})$	$5.277(10^{-4})$
3500	$3.580(10^{-2})$	$3.507(10^{-3})$	$1.754(10^{-3})$	$1.169(10^{-3})$	$8.769(10^{-4})$
3600	$5.793(10^{-2})$	$5.676(10^{-3})$	$2.838(10^{-3})$	$1.892(10^{-3})$	$1.419(10^{-3})$
3700	$9.147(10^{-2})$	$8.962(10^{-3})$	$4.481(10^{-3})$	$2.987(10^{-3})$	$2.240(10^{-3})$
3800	$1.405(10^{-1})$	$1.377(10^{-2})$	$6.883(10^{-3})$	$4.588(10^{-3})$	$3.441(10^{-3})$
3900	$2.138(10^{-1})$	$2.095(10^{-2})$	$1.047(10^{-2})$	$6.982(10^{-3})$	$5.237(10^{-3})$
4000	$3.169(10^{-1})$	$3.105(10^{-2})$	$1.552(10^{-2})$	$1.035(10^{-2})$	$7.762(10^{-3})$

Table X

EQUILIBRIUM CONSTANTS FOR THE REACTION $H_2O = H_2 + O$

$T°K$	$K_7 = \frac{P_{H_2}P_O}{P_{H_2O}}$	$\lambda_7 = K_7/P_c$ (P_c, atm)			
		P_c (psia)			
		150	300	450	600
1500	$8.535(10^{-12})$	$8.362(10^{-13})$	$4.181(10^{-13})$	$2.787(10^{-13})$	$2.091(10^{-13})$
1600	$1.062(10^{-10})$	$1.040(10^{-11})$	$5.202(10^{-12})$	$3.468(10^{-12})$	$2.601(10^{-12})$
1700	$9.883(10^{-10})$	$9.683(10^{-11})$	$4.841(10^{-11})$	$3.228(10^{-11})$	$2.421(10^{-11})$
1800	$7.161(10^{-9})$	$7.016(10^{-10})$	$3.508(10^{-10})$	$2.339(10^{-10})$	$1.754(10^{-10})$
1900	$4.210(10^{-8})$	$4.125(10^{-9})$	$2.062(10^{-9})$	$1.375(10^{-9})$	$1.031(10^{-9})$
2000	$2.083(10^{-7})$	$2.041(10^{-8})$	$1.020(10^{-8})$	$6.803(10^{-9})$	$5.102(10^{-9})$
2100	$8.839(10^{-7})$	$8.660(10^{-8})$	$4.330(10^{-8})$	$2.887(10^{-8})$	$2.165(10^{-8})$
2200	$3.344(10^{-6})$	$3.276(10^{-7})$	$1.638(10^{-7})$	$1.092(10^{-7})$	$8.191(10^{-8})$
2300	$1.093(10^{-5})$	$1.071(10^{-6})$	$5.354(10^{-7})$	$3.569(10^{-7})$	$2.677(10^{-7})$
2400	$3.305(10^{-5})$	$3.238(10^{-6})$	$1.619(10^{-6})$	$1.079(10^{-6})$	$8.095(10^{-7})$
2500	$9.101(10^{-5})$	$8.917(10^{-6})$	$4.458(10^{-6})$	$2.972(10^{-6})$	$2.229(10^{-6})$
2600	$2.336(10^{-4})$	$2.289(10^{-5})$	$1.144(10^{-5})$	$7.629(10^{-6})$	$5.722(10^{-6})$
2700	$5.545(10^{-4})$	$5.433(10^{-5})$	$2.716(10^{-5})$	$1.811(10^{-5})$	$1.358(10^{-5})$
2800	$1.242(10^{-3})$	$1.217(10^{-4})$	$6.084(10^{-5})$	$4.056(10^{-5})$	$3.042(10^{-5})$
2900	$2.645(10^{-3})$	$2.591(10^{-4})$	$1.296(10^{-4})$	$8.638(10^{-5})$	$6.478(10^{-5})$
3000	$5.332(10^{-3})$	$5.224(10^{-4})$	$2.612(10^{-4})$	$1.741(10^{-4})$	$1.306(10^{-4})$
3100	$1.026(10^{-2})$	$1.005(10^{-3})$	$5.026(10^{-4})$	$3.351(10^{-4})$	$2.513(10^{-4})$
3200	$1.899(10^{-2})$	$1.861(10^{-3})$	$9.303(10^{-4})$	$6.202(10^{-4})$	$4.651(10^{-4})$
3300	$3.392(10^{-2})$	$3.323(10^{-3})$	$1.662(10^{-3})$	$1.108(10^{-3})$	$8.308(10^{-4})$
3400	$5.855(10^{-2})$	$5.736(10^{-3})$	$2.868(10^{-3})$	$1.912(10^{-3})$	$1.434(10^{-3})$
3500	$9.770(10^{-2})$	$9.572(10^{-3})$	$4.786(10^{-3})$	$3.191(10^{-3})$	$2.393(10^{-3})$
3600	$1.586(10^{-1})$	$1.554(10^{-2})$	$7.769(10^{-3})$	$5.180(10^{-3})$	$3.885(10^{-3})$
3700	$2.512(10^{-1})$	$2.461(10^{-2})$	$1.231(10^{-2})$	$8.204(10^{-3})$	$6.153(10^{-3})$
3800	$3.875(10^{-1})$	$3.796(10^{-2})$	$1.898(10^{-2})$	$1.265(10^{-2})$	$9.491(10^{-3})$
3900	$5.884(10^{-1})$	$5.765(10^{-2})$	$2.882(10^{-2})$	$1.922(10^{-2})$	$1.441(10^{-2})$
4000	$8.729(10^{-1})$	$8.552(10^{-2})$	$4.276(10^{-2})$	$2.851(10^{-2})$	$2.138(10^{-2})$

Table XI

EQUILIBRIUM CONSTANTS FOR THE REACTION $H_2O = \frac{1}{2}H_2 + OH$

T°K	$K_8 = \dfrac{P_{H_2}^{1/2} P_{OH}}{P_{H_2O}}$	$\lambda_8 = K_8/P_c^{1/2}$ (P_c, atm)			
		P_c (psia)			
		150	300	450	600
1500	$5.123(10^{-7})$	$1.603(10^{-7})$	$1.134(10^{-7})$	$9.258(10^{-8})$	$8.018(10^{-8})$
1600	$2.165(10^{-6})$	$6.777(10^{-7})$	$4.792(10^{-7})$	$3.912(10^{-7})$	$3.388(10^{-7})$
1700	$7.943(10^{-6})$	$2.486(10^{-6})$	$1.758(10^{-6})$	$1.435(10^{-6})$	$1.243(10^{-6})$
1800	$2.402(10^{-5})$	$7.518(10^{-6})$	$5.316(10^{-6})$	$4.341(10^{-6})$	$3.759(10^{-6})$
1900	$6.595(10^{-5})$	$2.064(10^{-5})$	$1.460(10^{-5})$	$1.192(10^{-5})$	$1.032(10^{-5})$
2000	$1.642(10^{-4})$	$5.140(10^{-5})$	$3.634(10^{-5})$	$2.967(10^{-5})$	$2.570(10^{-5})$
2100	$3.694(10^{-4})$	$1.156(10^{-4})$	$8.176(10^{-5})$	$6.676(10^{-5})$	$5.781(10^{-5})$
2200	$8.058(10^{-4})$	$2.522(10^{-4})$	$1.783(10^{-4})$	$1.456(10^{-4})$	$1.261(10^{-4})$
2300	$1.566(10^{-3})$	$4.902(10^{-4})$	$3.466(10^{-4})$	$2.830(10^{-4})$	$2.451(10^{-4})$
2400	$2.946(10^{-3})$	$9.221(10^{-4})$	$6.520(10^{-4})$	$5.324(10^{-4})$	$4.611(10^{-4})$
2500	$5.230(10^{-3})$	$1.637(10^{-3})$	$1.158(10^{-3})$	$9.451(10^{-4})$	$8.185(10^{-4})$
2600	$8.970(10^{-3})$	$2.808(10^{-3})$	$1.985(10^{-3})$	$1.621(10^{-3})$	$1.404(10^{-3})$
2700	$1.463(10^{-2})$	$4.579(10^{-3})$	$3.238(10^{-3})$	$2.644(10^{-3})$	$2.290(10^{-3})$
2800	$2.312(10^{-2})$	$7.237(10^{-3})$	$5.117(10^{-3})$	$4.178(10^{-3})$	$3.618(10^{-3})$
2900	$3.556(10^{-2})$	$1.113(10^{-2})$	$7.869(10^{-3})$	$6.425(10^{-3})$	$5.564(10^{-3})$
3000	$5.289(10^{-2})$	$1.655(10^{-2})$	$1.171(10^{-2})$	$9.558(10^{-3})$	$8.277(10^{-3})$
3100	$7.674(10^{-2})$	$2.402(10^{-2})$	$1.698(10^{-2})$	$1.387(10^{-2})$	$1.201(10^{-2})$
3200	$1.087(10^{-1})$	$3.402(10^{-2})$	$2.406(10^{-2})$	$1.964(10^{-2})$	$1.701(10^{-2})$
3300	$1.513(10^{-1})$	$4.736(10^{-2})$	$3.349(10^{-2})$	$2.734(10^{-2})$	$2.368(10^{-2})$
3400	$2.060(10^{-1})$	$6.448(10^{-2})$	$4.559(10^{-2})$	$3.723(10^{-2})$	$3.224(10^{-2})$
3500	$2.749(10^{-1})$	$8.605(10^{-2})$	$6.084(10^{-2})$	$4.968(10^{-2})$	$4.302(10^{-2})$
3600	$3.615(10^{-1})$	$1.132(10^{-1})$	$8.001(10^{-2})$	$6.533(10^{-2})$	$5.658(10^{-2})$
3700	$4.688(10^{-1})$	$1.467(10^{-1})$	$1.038(10^{-1})$	$8.472(10^{-2})$	$7.337(10^{-2})$
3800	$5.983(10^{-1})$	$1.873(10^{-1})$	$1.324(10^{-1})$	$1.081(10^{-1})$	$9.364(10^{-2})$
3900	$7.598(10^{-1})$	$2.378(10^{-1})$	$1.682(10^{-1})$	$1.373(10^{-1})$	$1.189(10^{-1})$
4000	$9.489(10^{-1})$	$2.970(10^{-1})$	$2.100(10^{-1})$	$1.715(10^{-1})$	$1.485(10^{-1})$

Table XII

HEAT CONTENT BELOW 298.16°K IN CALORIES PER MOLE OF LIQUID OXYGEN, FLUORINE AND HYDROGEN AT VARIOUS PRESSURES

Pressure, psia	OXYGEN		FLUORINE		HYDROGEN	
	Temp., °K	$\Delta H_T^{298.16}$	Temp., °K	$\Delta H_T^{298.16}$	Temp., °K	$\Delta H_T^{298.16}$
150	120.0	2584	111.6	2660	20.4	1905
300	133.1	2299	123.1	2466	20.4	1905
450	142.2	2159	130.9	2277	20.4	1905
600	149.2	1813	137.0	2100	20.4	1905

Table XIII

COMPOSITION, AVAILABLE HEAT, ENTHALPY CHANGE, AND MOLECULAR WEIGHT OF PROPELLANT GAS AT VARIOUS TEMPERATURES: $\alpha N_2H_4 + O_2$; P_c = 450 psi ; α = 1.5

Component	Temperature, °K			
	3000	3100	3200	3118
N_1 (H_2O)	.42806	.42068	.41080	.41909
N_2 (H_2)	.21937	.21924	.21942	.21925
N_3 (H)	.01337	.01799	.02380	.01895
N_4 (O_2)	.00025	.00046	.00080	.00051
N_5 (O)	.00034	.00064	.00116	.00072
N_6 (OH)	.00874	.01246	.01723	.01324
N_7 (N_2)	.32862	.32661	.32395	.32618
N_8 (N)	.00014	.00023	.00036	.00025
N_9 (NO)	.00111	.00169	.00248	.00182
$-Q_{av}$	27,377	26,621	25,622	26,459
$\Delta H^{T_c}_{298.16}$	25,321	26,286	27,206	26,459
M				17.461

Table XIV

SUMMARY OF CALCULATED DATA FOR THE SYSTEM HYDRAZINE-OXYGEN AT VARIOUS PRESSURES AND MOLE RATIOS

Mole Ratio α	Chamber Pressure P_c, psia	Chamber Temperature T_c, °K	Molecular Weight M	$\gamma = \frac{C_p}{C_v}$	Exit Temperature T_e, °K	Specific Impulse I, sec
1	150	3207	19.585	1.2282	2083	231.0
	300	3286	19.719	1.2279	1878	257.9
	450	3334	19.796	1.2277	1767	271.5
	600	3367	19.849	1.2275	1693	280.4
1.2	150	3175	18.579	1.2315	2051	235.8
	300	3248	18.694	1.2315	1842	262.9
	450	3291	18.758	1.2315	1729	276.6
	600	3321	18.803	1.2316	1653	285.5
1.5	150	3037	17.347	1.2394	1939	238.0
	300	3089	17.421	1.2404	1721	264.6
	450	3118	17.461	1.2409	1604	277.8
	600	3138	17.487	1.2415	1525	286.2
2	150	2743	15.891	1.2548	1712	235.0
	300	2767	15.919	1.2575	1492	260.0
	450	2780	15.933	1.2591	1375	272.1
	600	2789	15.941	1.2603	1297	279.8
2.5	150	2479	14.911	1.2694	1514	229.5
	300	2489	14.921	1.2731	1303	253.0
	450	2495	14.925	1.2754	1192	264.3
	600	2500	14.928	1.2769	1118	271.5
3	150	2266	14.225	1.2821	1360	223.7
	300	2272	14.229	1.2866	1160	246.2
	450	2275	14.230	1.2889	1056	257.0
	600	2278	14.231	1.2909	988	263.6

Table XV

SUMMARY OF CALCULATED DATA FOR THE SYSTEM HYDRAZINE-FLUORINE AT VARIOUS PRESSURES AND MOLE RATIOS

Mole Ratio α	Chamber Pressure P_c, psia	Chamber Temperature T_c, °K	Molecular Weight M	$\gamma = \frac{C_p}{C_v}$	Exit Temperature T_e, °K	Specific Impulse I, sec
.55	150	4484	18.985	1.3226	2545	269.1
	300	4622	19.124	1.3214	2220	298.8
	450	4705	19.210	1.3206	2050	313.7
	600	4767	19.265	1.3202	1939	323.4
.6	600	4670	18.827	1.3198	1901	323.9
.65	150	4299	18.151	1.3219	2442	269.5
	300	4422	18.290	1.3209	2125	298.9
	450	4496	18.375	1.3203	1960	313.6
	600	4551	18.430	1.3199	1852	323.2
.8	150	3978	17.245	1.3207	2263	266.0
	300	4094	17.383	1.3198	1971	295.1
	450	4161	17.465	1.3192	1818	309.6
	600	4212	17.519	1.3188	1718	319.1
1	150	3681	16.466	1.3167	2105	262.3
	300	3781	16.584	1.3166	1831	290.7
	450	3839	16.653	1.3162	1687	304.9
	600	3882	16.697	1.3160	1593	314.1
2	150	2872	14.431	1.3119	1653	247.8
	300	2904	14.462	1.3148	1411	273.0
	450	2921	14.479	1.3166	1283	285.2
	600	2935	14.489	1.3177	1200	293.0
3	150	2379	13.393	1.3210	1353	233.4
	300	2388	13.399	1.3257	1138	256.1
	450	2392	13.401	1.3284	1027	266.9
	600	2397	13.402	1.3299	955	273.8

Table XVI

SUMMARY OF CALCULATED DATA FOR THE SYSTEM HYDROGEN-OXYGEN AT VARIOUS PRESSURES AND MOLE RATIOS

Mole Ratio a	Chamber Pressure P_c, psia	Chamber Temperature T_c, °K	Molecular Weight M	$\gamma = \frac{C_p}{C_v}$	Exit Temperature T_e, °K	Specific Impulse I, sec
4	150	2883	9.858	1.2353	1852	308.1
	300	2922	9.889	1.2373	1638	342.0
	450	2942	9.904	1.2385	1522	358.8
	600	2957	9.915	1.2399	1443	369.4
4.5	150	2718	9.049	1.2441	1723	311.2
	300	2742	9.067	1.2471	1508	344.6
	450	2756	9.074	1.2488	1393	361.0
	600	2766	9.079	1.2503	1316	371.4
5	150	2556	8.379	1.2531	1599	312.6
	300	2572	8.388	1.2573	1387	345.4
	450	2581	8.392	1.2592	1276	361.3
	600	2588	8.395	1.2607	1202	371.4
5.5	150	2404	7.817	1.2625	1483	312.9
	300	2414	7.821	1.2668	1279	345.1
	450	2420	7.823	1.2692	1171	360.7
	600	2425	7.824	1.2708	1100	370.7
6	150	2263	7.341	1.2715	1378	312.5
	300	2270	7.343	1.2764	1182	343.9
	450	2274	7.345	1.2791	1078	359.1
	600	2278	7.345	1.2810	1010	368.9
7	150	2019	6.586	1.2887	1200	309.8
	300	2023	6.586	1.2943	1019	340.4
	450	2026	6.586	1.2971	925	355.2
	600	2029	6.587	1.2991	864	364.4

Table XVII

SUMMARY OF CALCULATED DATA FOR THE SYSTEM HYDROGEN-FLUORINE AT VARIOUS PRESSURES AND MOLE RATIOS

Mole Ratio α	Chamber Pressure P_c, psia	Chamber Temperature T_c, °K	Molecular Weight M	$\gamma = \frac{C_p}{C_v}$	Exit Temperature T_e, °K	Specific Impulse I, sec
4	150	3033	9.023	1.3164	1735	321.7
	300	3086	9.056	1.3190	1488	355.1
	450	3113	9.073	1.3205	1357	371.3
	600	3136	9.083	1.3216	1272	381.8
4.5	150	2869	8.452	1.3176	1639	323.0
	300	2907	8.473	1.3211	1397	356.0
	450	2927	8.482	1.3232	1269	371.9
	600	2943	8.489	1.3245	1186	382.2
5	150	2712	7.953	1.3202	1544	323.5
	300	2738	7.966	1.3244	1308	256.0
	450	2752	7.973	1.3269	1185	371.4
	600	2764	7.977	1.3284	1105	381.4
6	150	2422	7.140	1.3278	1365	321.9
	300	2434	7.144	1.3330	1146	353.2
	450	2440	7.146	1.3359	1032	368.0
	600	2447	7.147	1.3375	960	377.6
7	150	2170	6.510	1.3370	1208	318.4
	300	2177	6.511	1.3426	1008	348.7
	450	2180	6.512	1.3451	906	363.0
	600	2185	6.512	1.3469	841	372.3

Table XVIII

SUMMARY OF CALCULATED DATA FOR THE SYSTEM HYDRAZINE-HYDROGEN PEROXIDE (ANHYDROUS) AT VARIOUS PRESSURES AND MOLE RATIOS

Mole Ratio α	Chamber Pressure P_c, psia	Chamber Temperature T_c, °K	Molecular Weight M	$\gamma = \frac{C_p}{C_v}$	Exit Temperature T_e, °K	Specific Impulse I, sec
.60	300	2833	18.754	1.2137	1665	247.2
	450	2852	18.787	1.2146	1558	259.5
	600	2865	18.810	1.2153	1485	267.5
.65	300	2800	18.405	1.2172	1635	247.6
	450	2815	18.432	1.2182	1525	259.8
	600	2825	18.449	1.2191	1450	267.7
.70	300	2758	18.072	1.2207	1599	247.6
	450	2770	18.093	1.2220	1488	259.7
	600	2778	18.106	1.2230	1413	267.3
.75	300	2712	17.758	1.2244	1561	247.3
	450	2722	17.774	1.2259	1449	259.2
	600	2728	17.784	1.2270	1374	266.7
1.00	300	2488	16.485	1.2421	1382	243.9
	450	2492	16.490	1.2444	1273	255.0
	600	2494	16.493	1.2457	1200	262.2

Table XIX

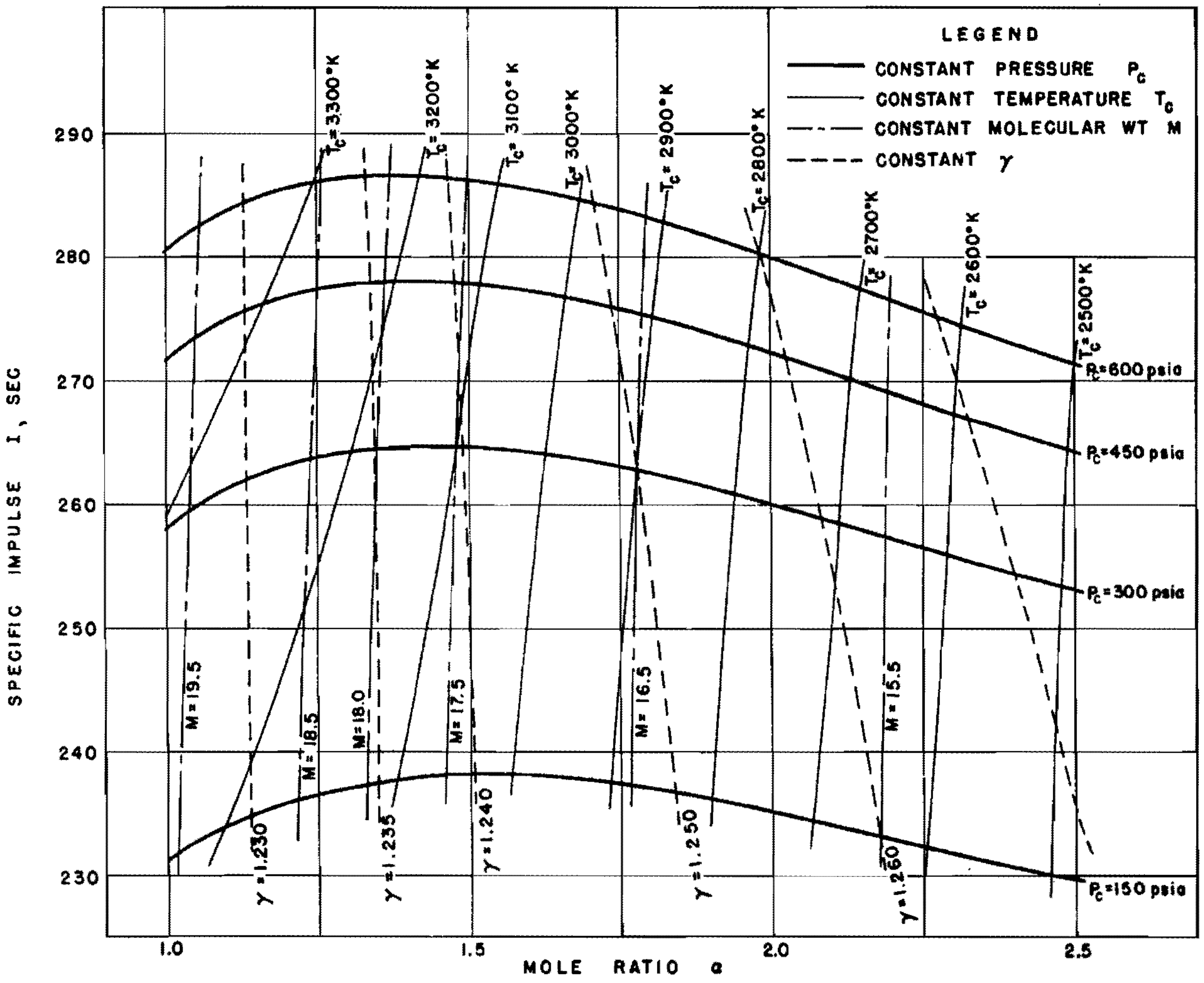
SUMMARY OF CALCULATED DATA FOR THE SYSTEM HYDRAZINE-CHLORINE TRIFLUORIDE AT VARIOUS PRESSURES AND MOLE RATIOS

Mole Ratio α	Chamber Pressure P_c, psia	Chamber Temperature T_c, °K	Molecular Weight M	$\gamma = \frac{C_p}{C_v}$	Exit Temperature T_e, °K	Specific Impulse I, sec
1.125	300	3557	22.841	1.3153	1725	240.5
	450	3601	22.928	1.3154	1585	251.7
	600	3634	22.986	1.3155	1493	259.1
1.25	300	3466	22.206	1.3138	1686	240.8
	450	3507	22.281	1.3140	1548	252.1
	600	3537	22.332	1.3141	1457	259.5
1.5	300	3290	21.090	1.3121	1606	240.9
	450	3323	21.145	1.3128	1471	252.1
	600	3346	21.183	1.3134	1381	259.2
2	300	2981	19.357	1.3128	1453	239.3
	450	3000	19.384	1.3144	1323	250.0
	600	3012	19.402	1.3155	1237	256.7

Table XX

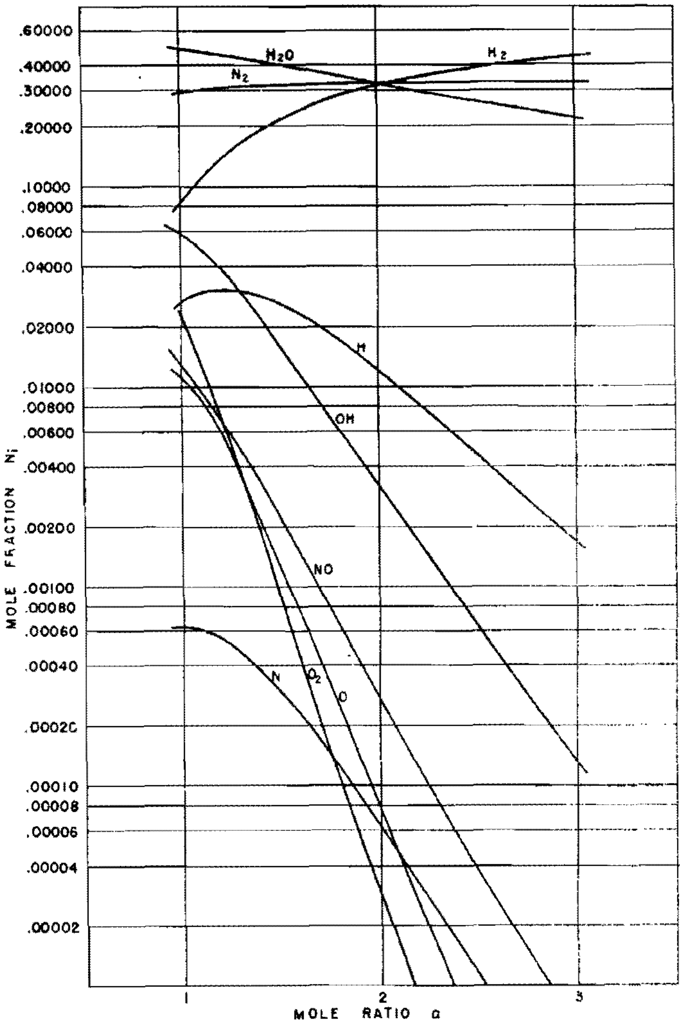
SUMMARY OF MAXIMUM SPECIFIC IMPULSE DATA AND ASSOCIATED CHARACTERISTICS FOR SIX LIQUID PROPELLANT SYSTEMS AT VARIOUS PRESSURES

Mole Ratio a	Chamber Pressure P_c, psia	Chamber Temperature T_c, °K	Molecular Weight M	$\gamma = \frac{C_p}{C_v}$	Exit Temperature T_e, °K	Specific Impulse I, sec
Hydrazine - Oxygen						
1.54	150	3013	17.205	1.2404	1922	238.1
1.46	300	3115	17.570	1.2391	1741	264.7
1.41	450	3180	17.815	1.2378	1647	278.2
1.38	600	3224	17.975	1.2374	1580	286.6
Hydrazine - Fluorine						
0.615	150	4374	18.425	1.3221	2482	269.9
0.605	300	4518	18.645	1.3212	2170	299.4
0.600	450	4610	18.765	1.3205	2010	314.1
0.595	600	4680	18.860	1.3201	1904	324.0
Hydrogen - Oxygen						
5.42	150	2427	7.899	1.2610	1501	313.1
5.14	300	2528	8.216	1.2600	1357	345.6
4.98	450	2588	8.415	1.2588	1282	361.5
4.88	600	2630	8.550	1.2582	1230	371.6
Hydrogen - Fluorine						
4.95	150	2730	8.000	1.3199	1552	323.7
4.68	300	2848	8.283	1.3222	1363	356.3
4.50	450	2927	8.482	1.3232	1269	371.9
4.42	600	2975	8.580	1.3240	1199	382.4
Hydrazine - Hydrogen Peroxide (Anhydrous)						
0.675	300	2780	18.238	1.2189	1617	247.7
0.66	450	2806	18.363	1.2190	1518	259.8
0.65	600	2825	18.449	1.2191	1450	267.7
Hydrazine - Chlorine Trifluoride						
1.41	300	3353	21.465	1.3125	1634	241.0
1.36	450	3427	21.750	1.3133	1514	252.2
1.32	600	3483	21.990	1.3137	1435	259.6



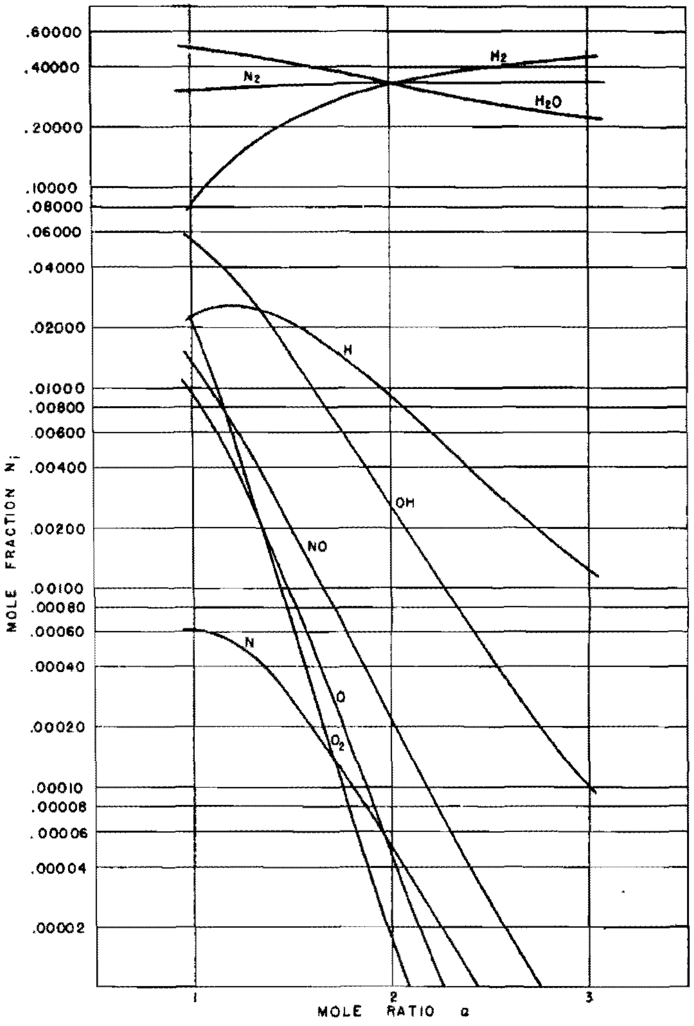
SPECIFIC IMPULSE VERSUS FUEL-OXIDANT MOLE RATIO AND CHAMBER PRESSURE FOR THE SYSTEM HYDRAZINE – OXYGEN

FIG. I



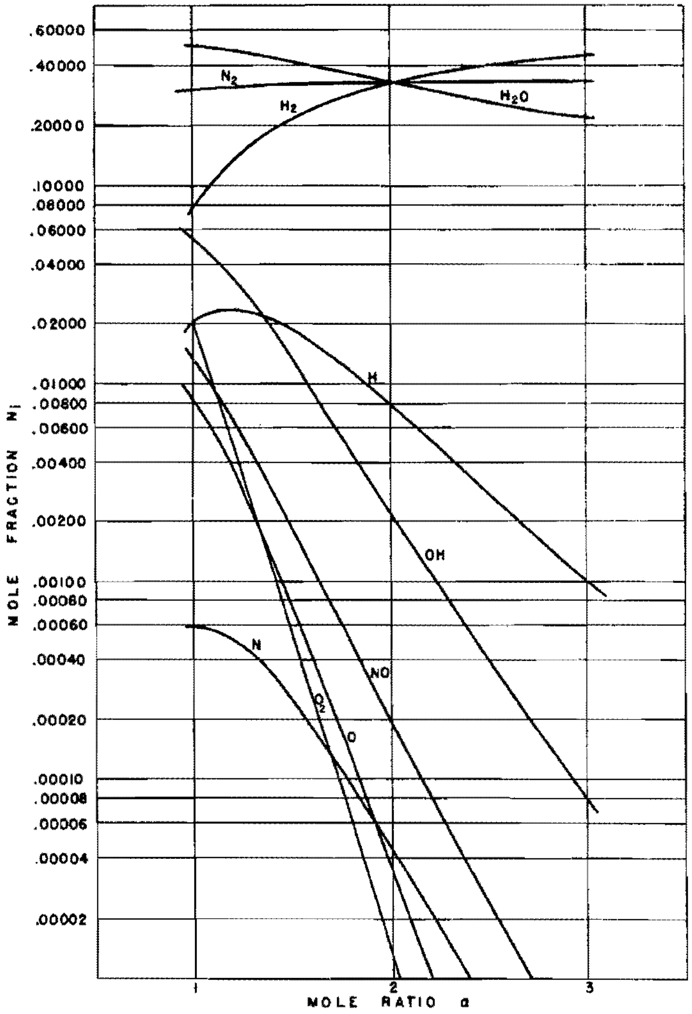
EXHAUST GAS COMPOSITION VERSUS FUEL-OXIDANT MOLE RATIO FOR THE SYSTEM HYDRAZINE-OXYGEN AT 150 PSIA CHAMBER PRESSURE

FIG. 2



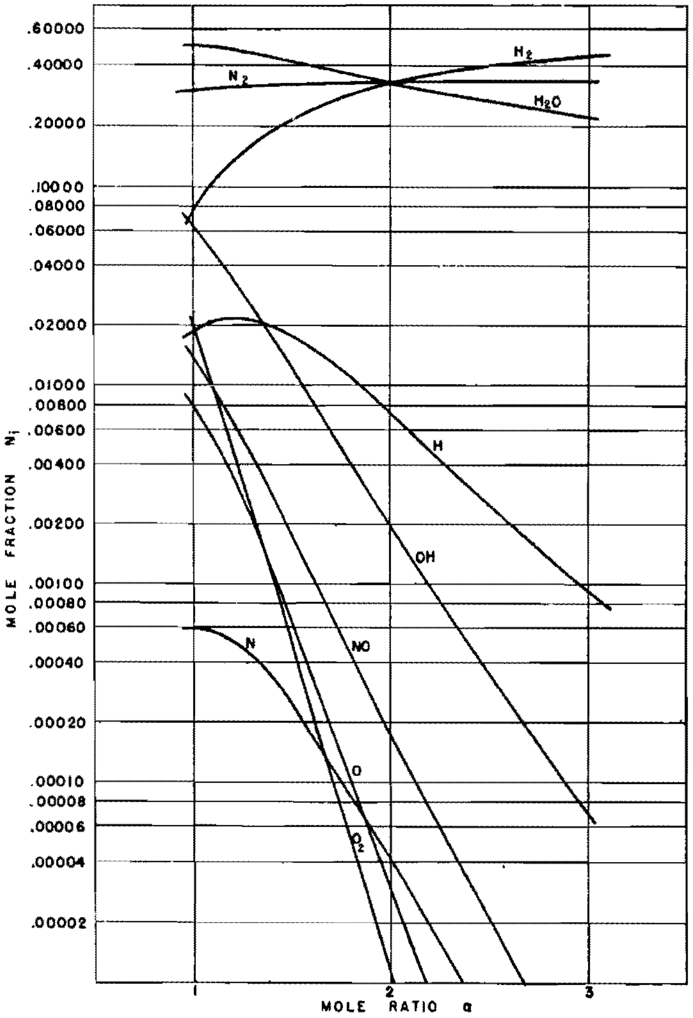
EXHAUST GAS COMPOSITION VERSUS FUEL-OXIDANT MOLE RATIO FOR THE SYSTEM HYDRAZINE-OXYGEN AT 300 PSIA CHAMBER PRESSURE

FIG. 3



EXHAUST GAS COMPOSITION VERSUS FUEL-OXIDANT MOLE RATIO FOR THE SYSTEM HYDRAZINE-OXYGEN AT 450 PSIA CHAMBER PRESSURE

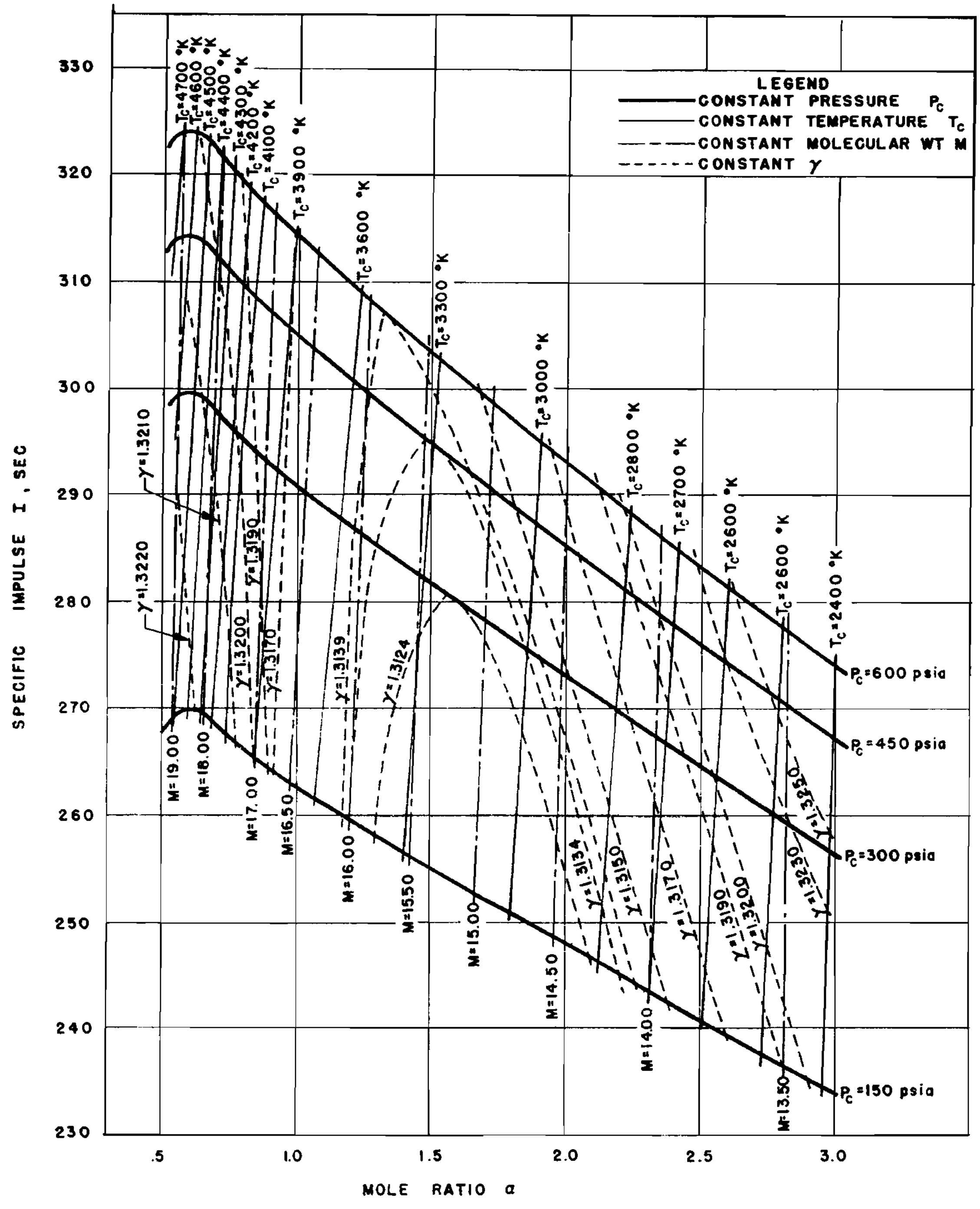
FIG. 4



EXHAUST GAS COMPOSITION VERSUS FUEL-OXIDANT MOLE RATIO FOR THE SYSTEM HYDRAZINE-OXYGEN AT 600 PSIA CHAMBER PRESSURE

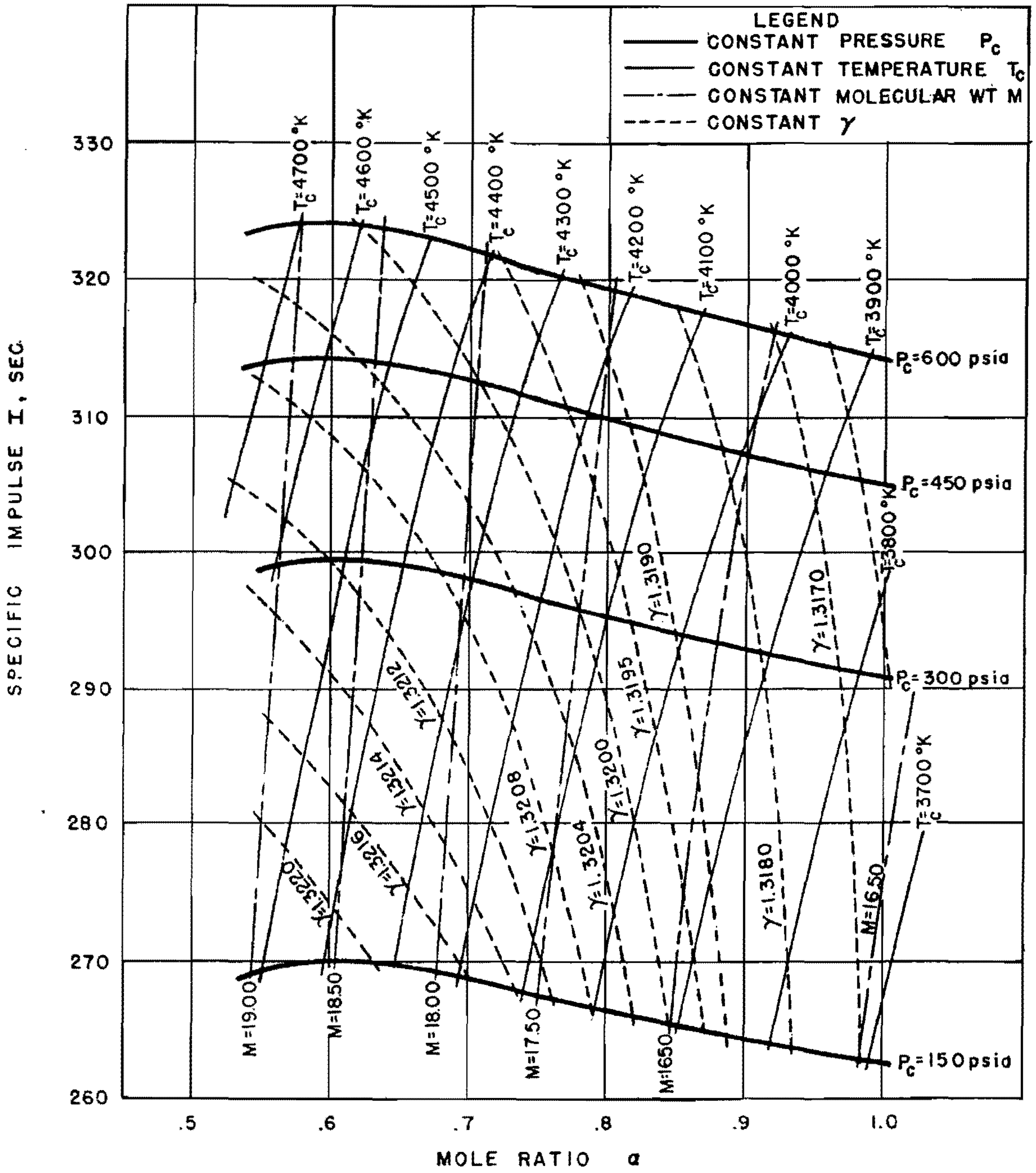
FIG. 5

February 1, 1947



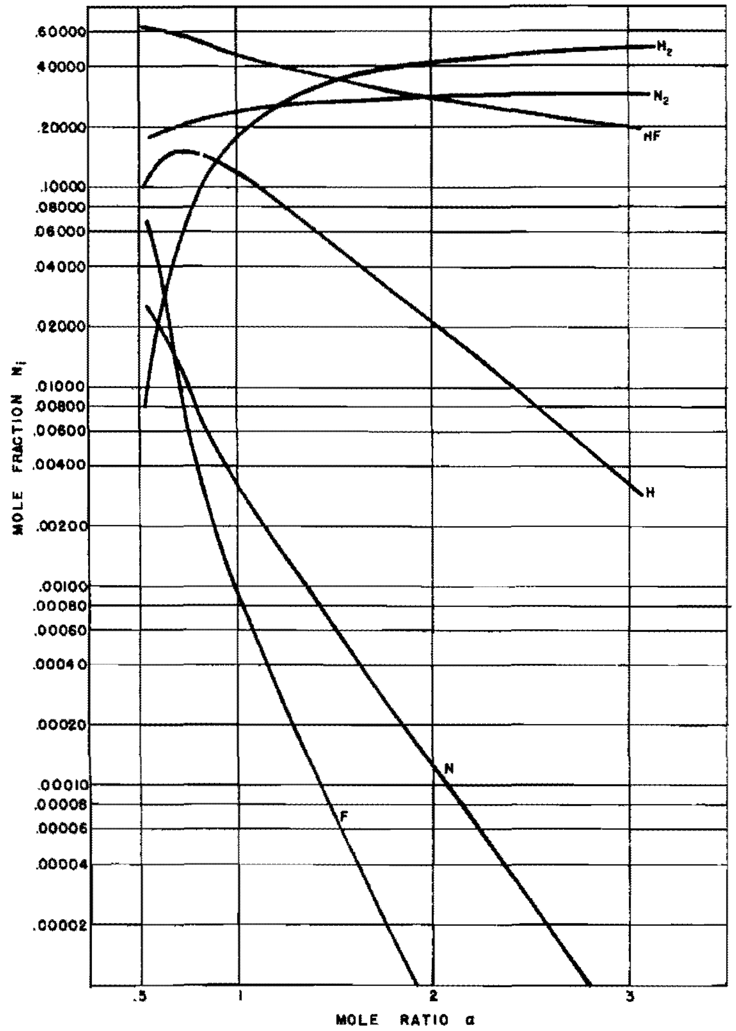
SPECIFIC IMPULSE VERSUS FUEL–OXIDANT MOLE RATIO AND CHAMBER PRESSURE FOR THE SYSTEM HYDRAZINE-FLUORINE

FIG. 6



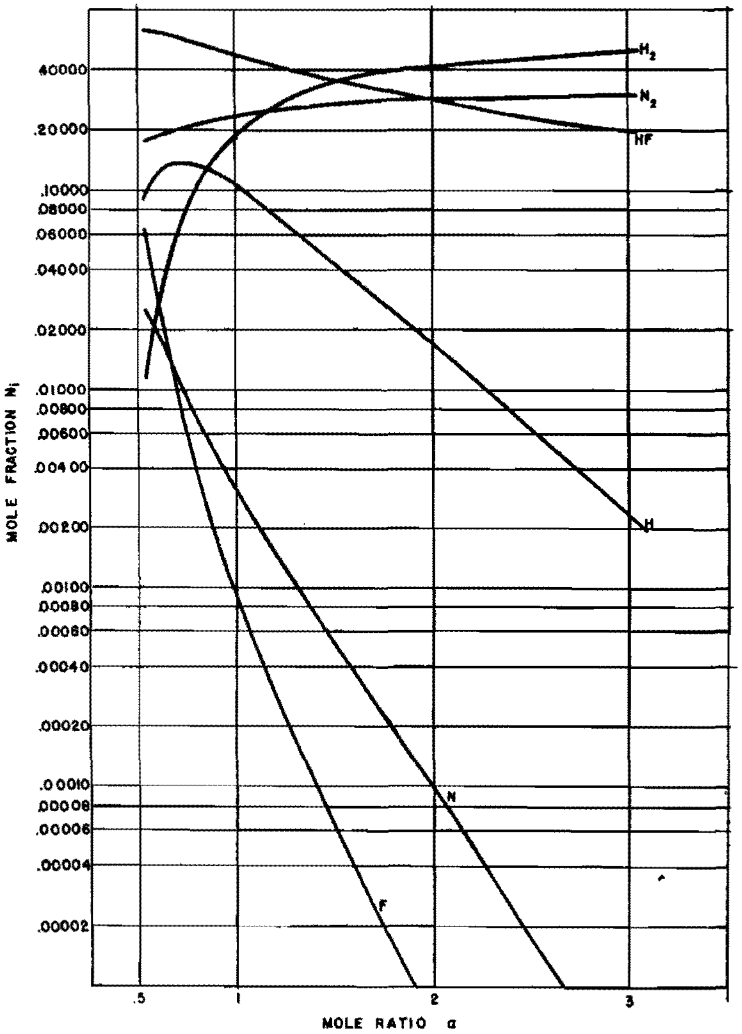
SPECIFIC IMPULSE VERSUS FUEL-OXIDANT MOLE RATIO AND CHAMBER PRESSURE FOR THE SYSTEM HYDRAZINE-FLUORINE (EXPANDED SCALE)

FIG. 7



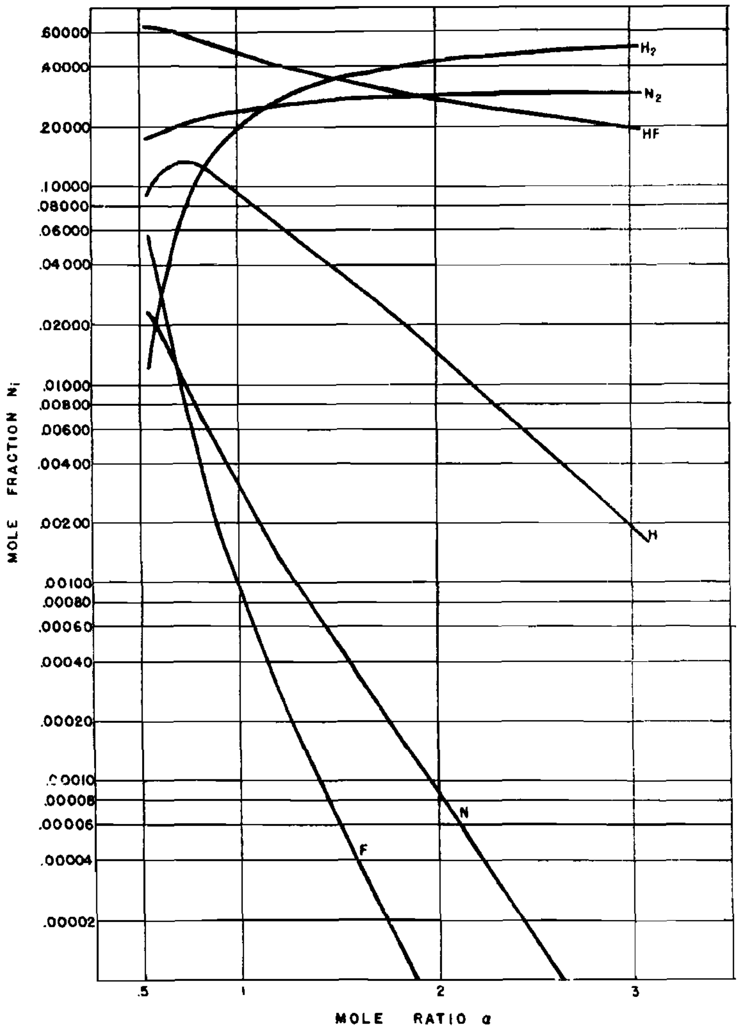
EXHAUST GAS COMPOSITION VERSUS FUEL-OXIDANT MOLE RATIO FOR THE SYSTEM HYDRAZINE-FLUORINE AT 150 PSIA CHAMBER PRESSURE

FIG. 8



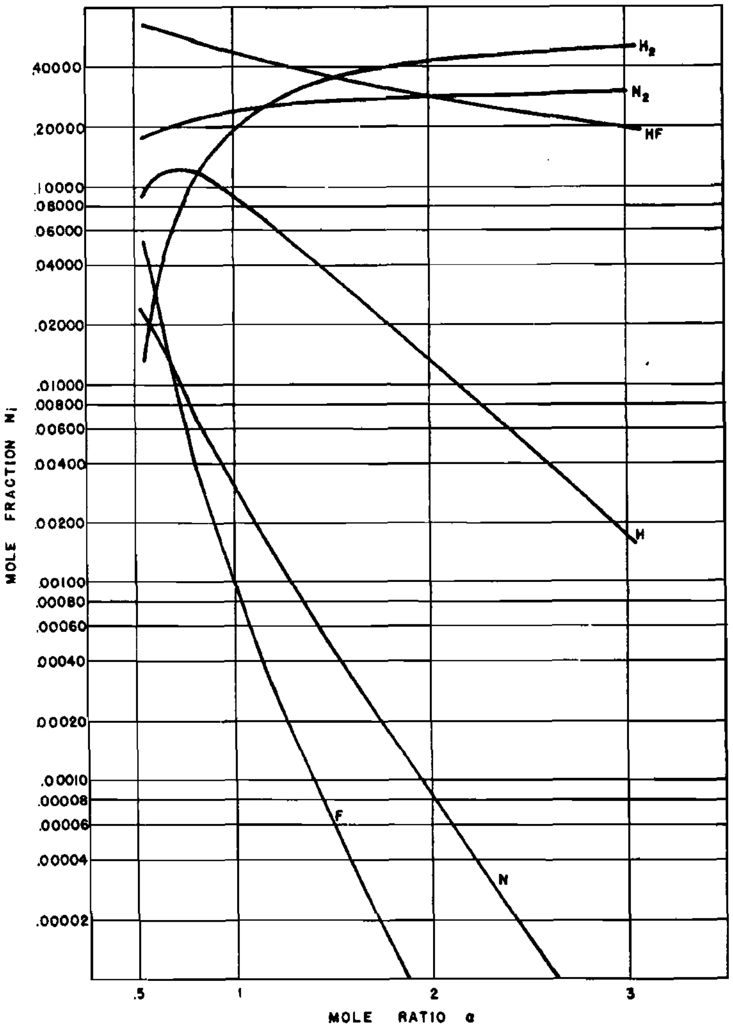
EXHAUST GAS COMPOSITION VERSUS FUEL-OXIDANT MOLE RATIO FOR THE SYSTEM HYDRAZINE-FLUORINE AT 300 PSIA CHAMBER PRESSURE

FIG. 9



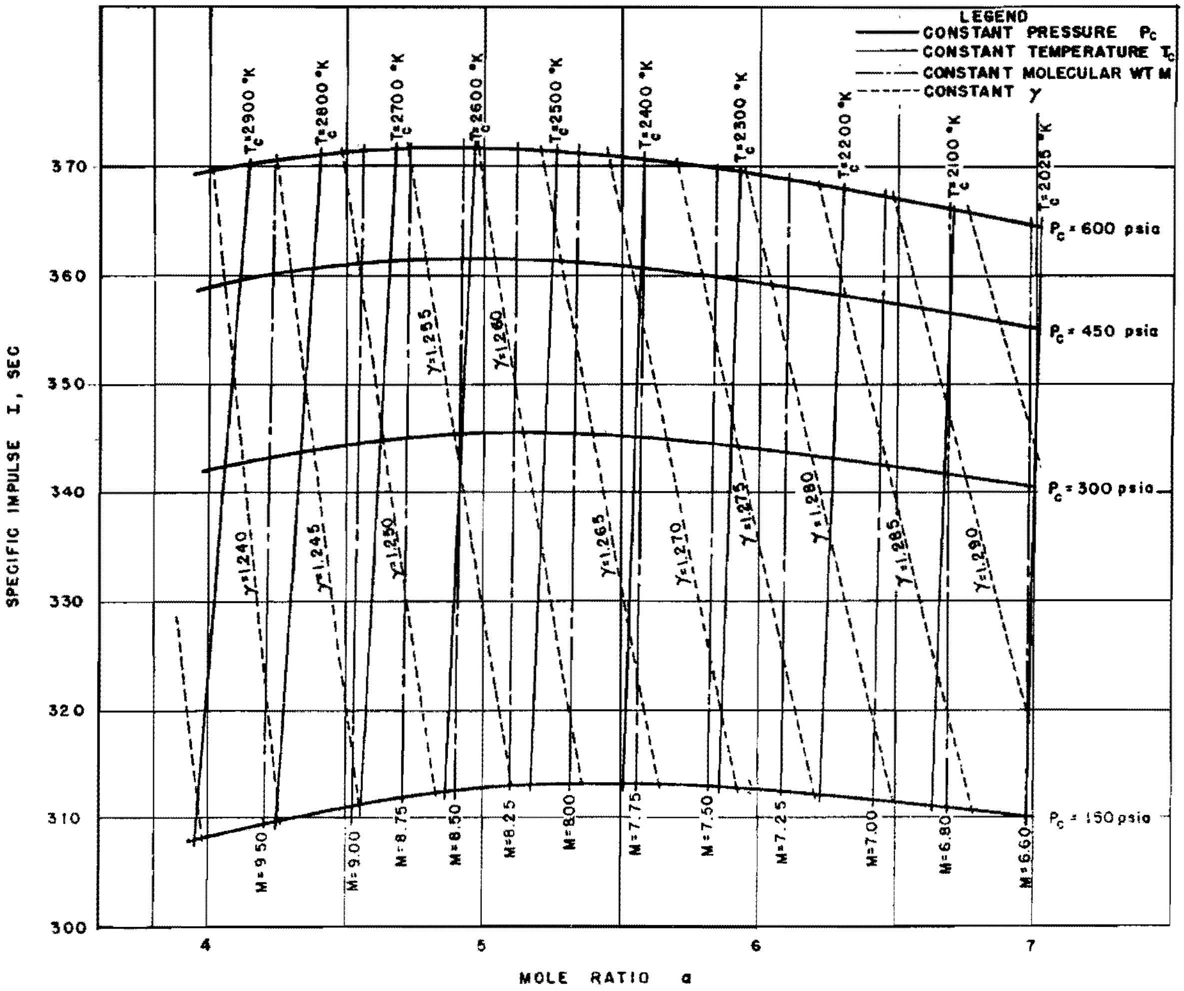
EXHAUST GAS COMPOSITION VERSUS FUEL-OXIDANT MOLE RATIO FOR THE SYSTEM HYDRAZINE-FLUORINE AT 450 PSIA CHAMBER PRESSURE

FIG. 10



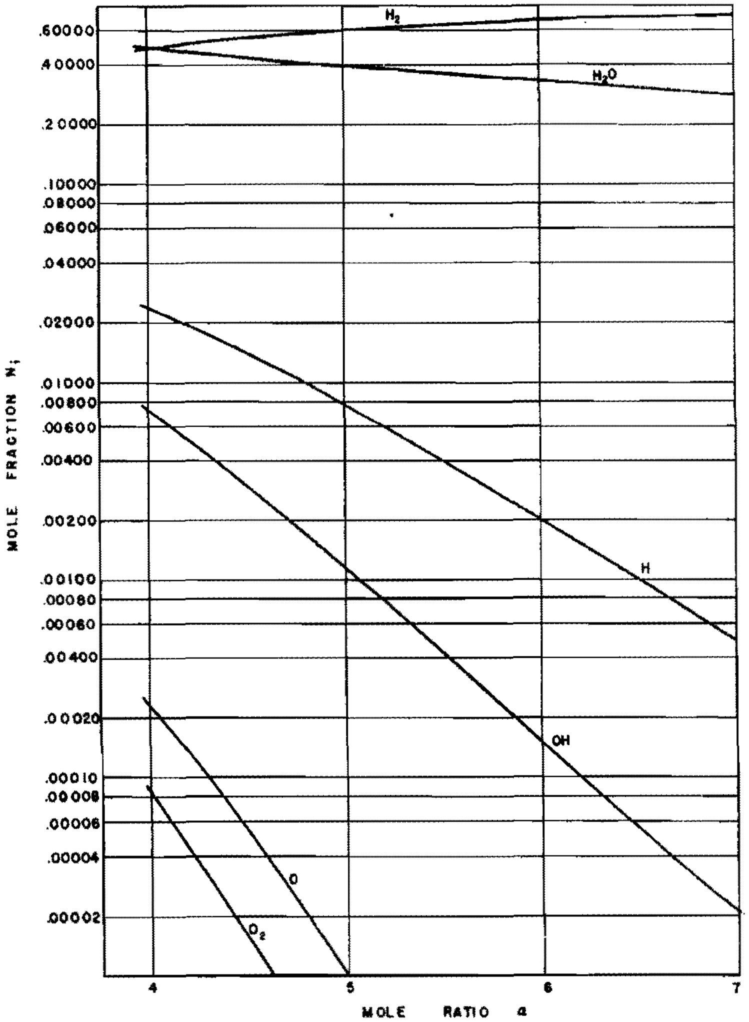
EXHAUST GAS COMPOSITION VERSUS FUEL-OXIDANT MOLE RATIO FOR THE SYSTEM HYDRAZINE-FLUORINE AT 600 PSIA CHAMBER PRESSURE

FIG. 11



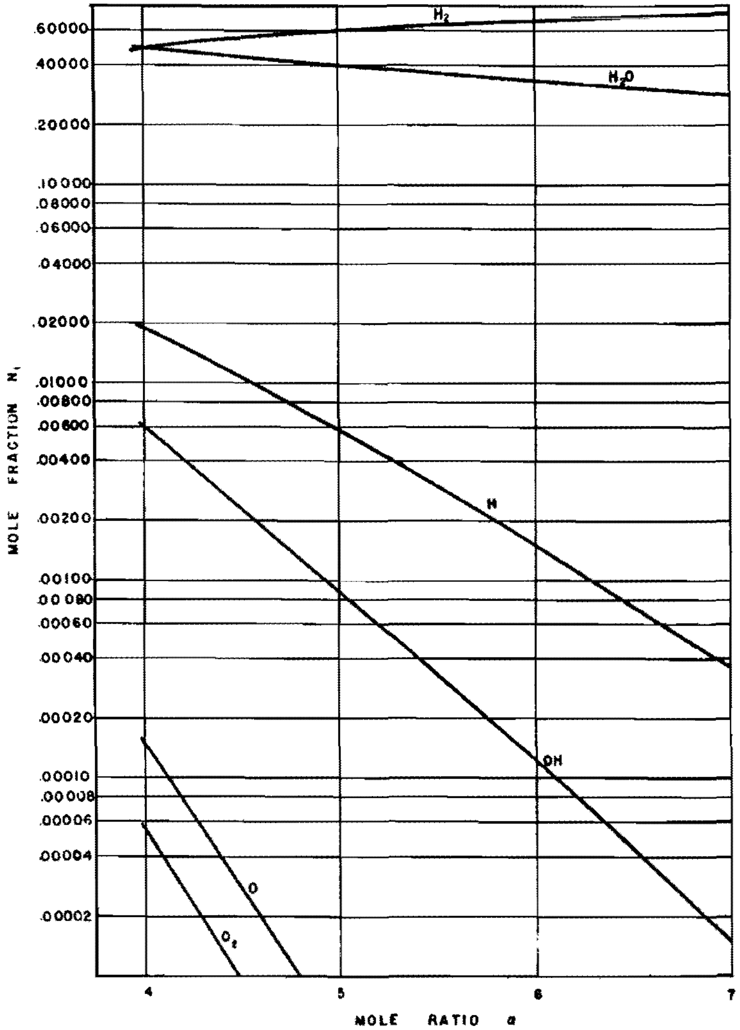
SPECIFIC IMPULSE VERSUS FUEL–OXIDANT MOLE RATIO AND CHAMBER PRESSURE FOR THE SYSTEM HYDROGEN-OXYGEN

FIG. 12



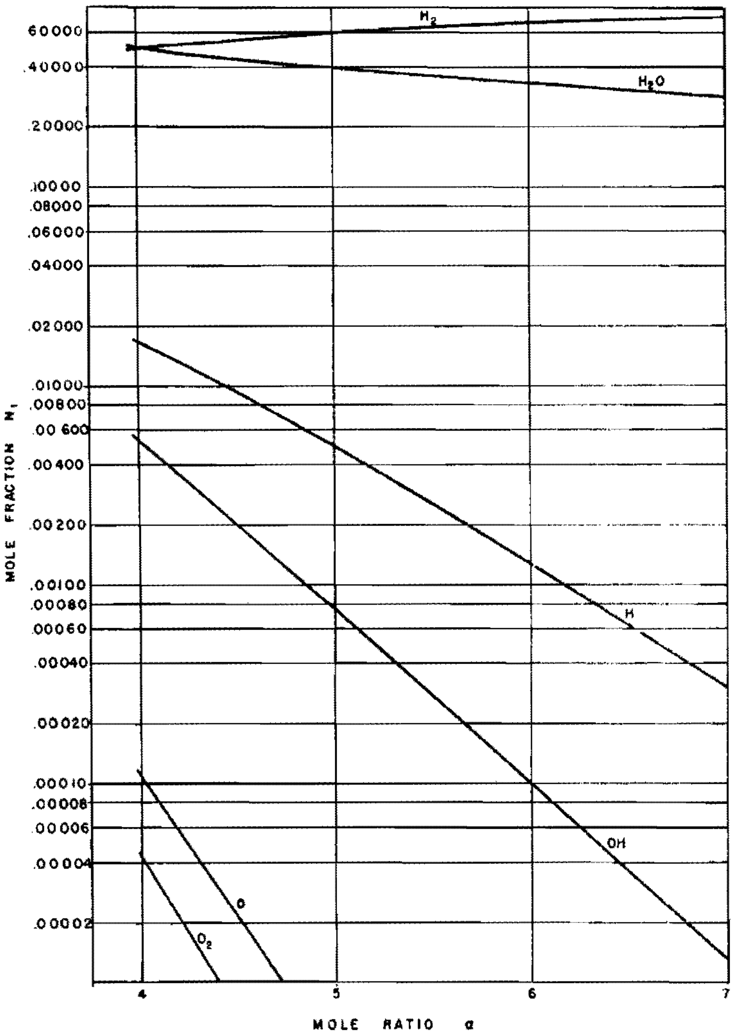
EXHAUST GAS COMPOSITION VERSUS FUEL-OXIDANT MOLE RATIO FOR THE SYSTEM HYDROGEN-OXYGEN AT 150 PSIA CHAMBER PRESSURE

FIG. 13



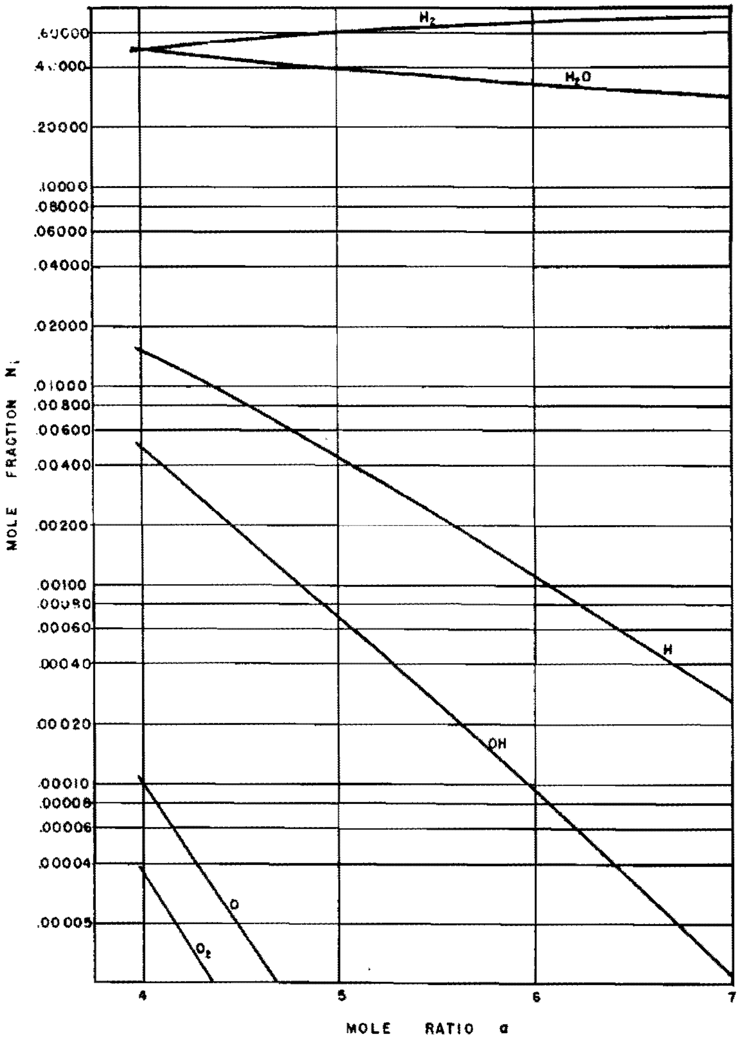
EXHAUST GAS COMPOSITION VERSUS FUEL-OXIDANT MOLE RATIO FOR THE SYSTEM HYDROGEN-OXYGEN AT 300 PSIA CHAMBER PRESSURE

FIG. 14



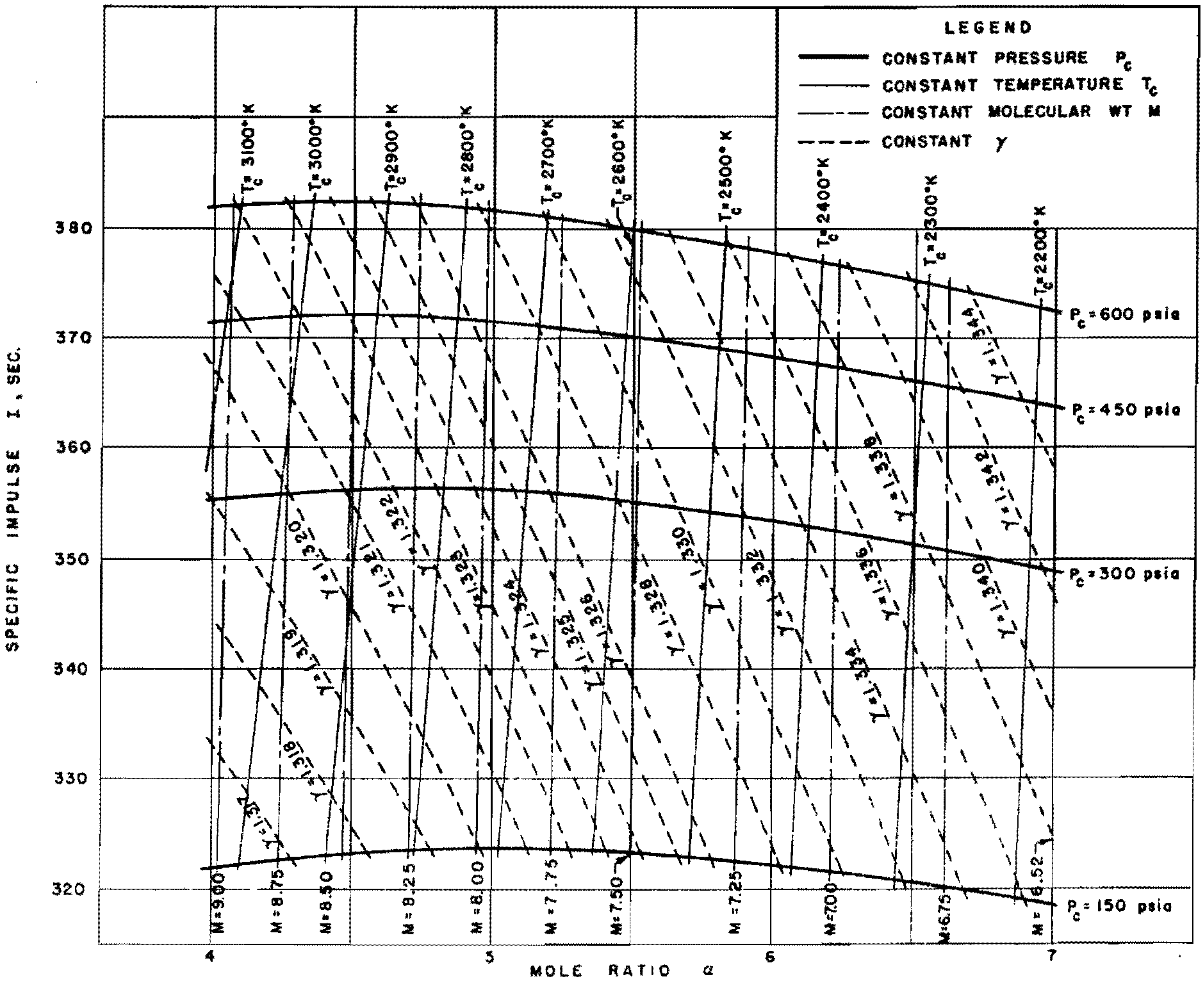
EXHAUST GAS COMPOSITION VERSUS FUEL-OXIDANT MOLE RATIO FOR THE SYSTEM HYDROGEN-OXYGEN AT 450 PSIA CHAMBER PRESSURE

FIG. 15



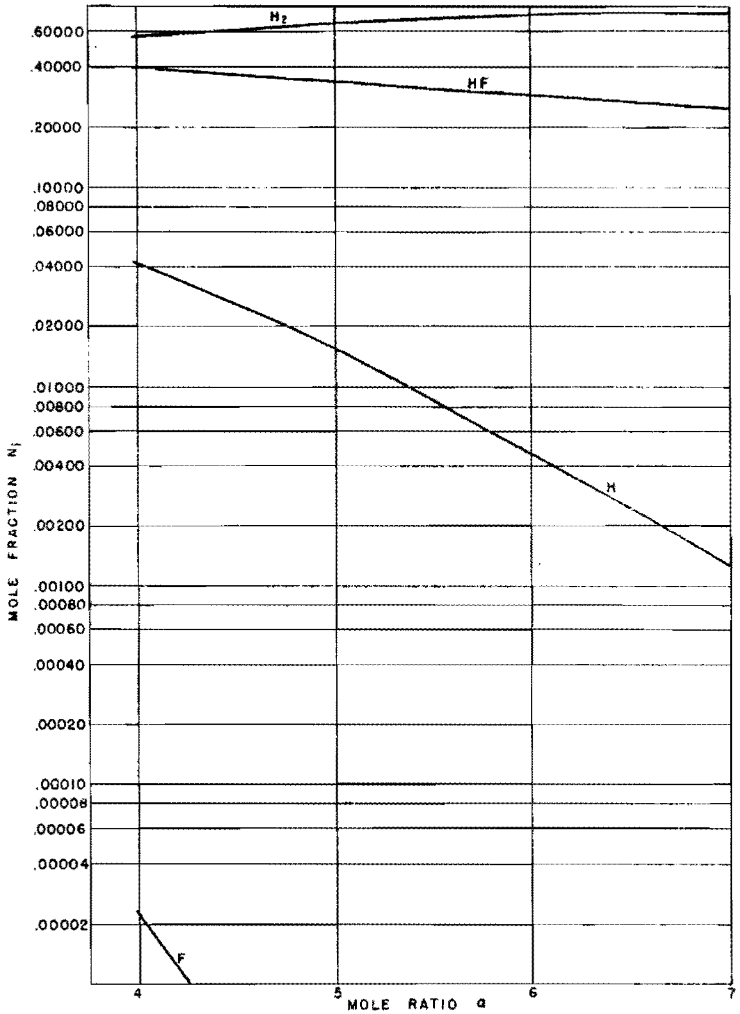
EXHAUST GAS COMPOSITION VERSUS FUEL-OXIDANT MOLE RATIO FOR THE SYSTEM HYDROGEN-OXYGEN AT 600 PSIA CHAMBER PRESSURE

FIG. 16



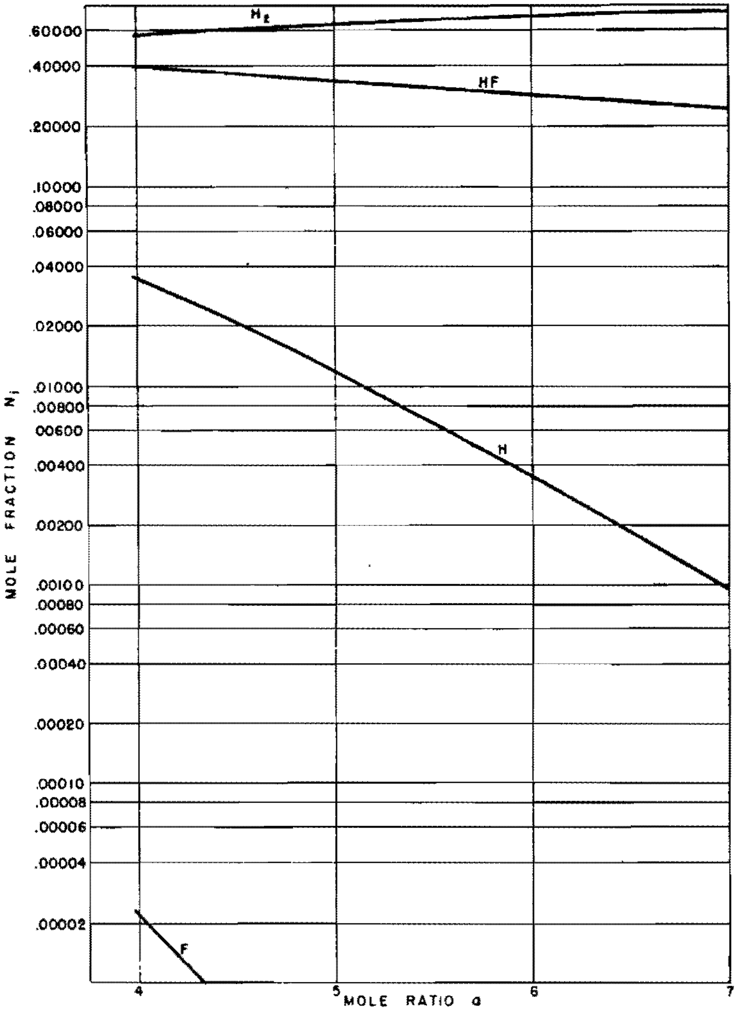
SPECIFIC IMPULSE VERSUS FUEL-OXIDANT MOLE RATIO AND CHAMBER PRESSURE FOR THE SYSTEM HYDROGEN-FLUORINE

FIG. 17



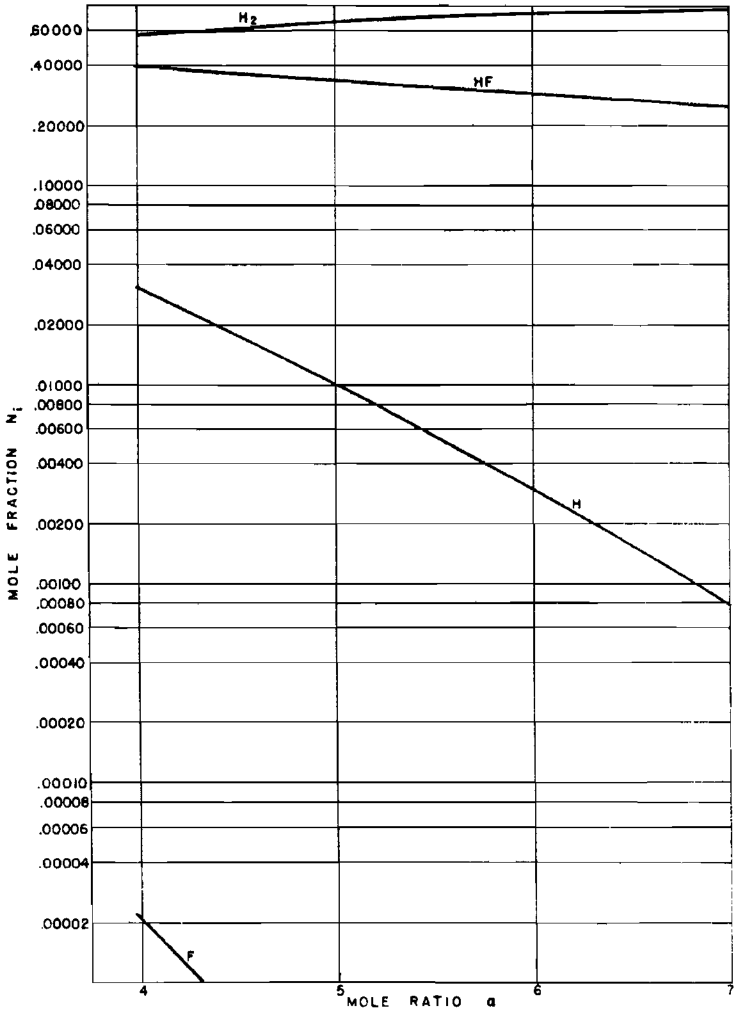
EXHAUST GAS COMPOSITION VERSUS FUEL-OXIDANT MOLE RATIO FOR THE SYSTEM HYDROGEN-FLUORINE AT 150 PSIA CHAMBER PRESSURE

FIG. 18



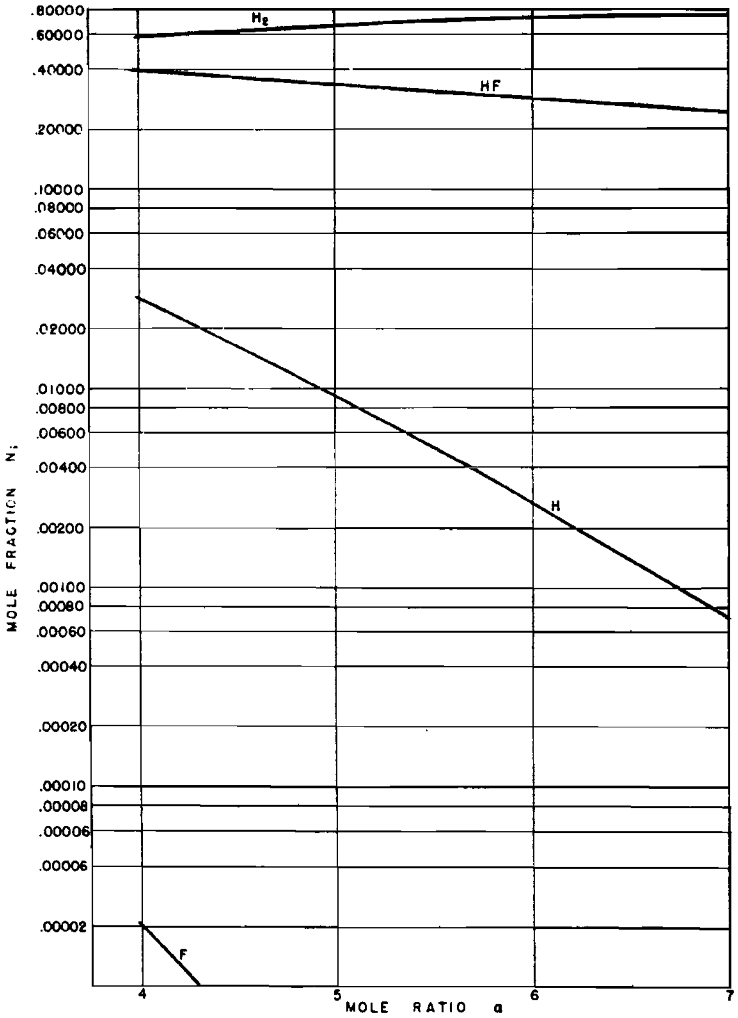
EXHAUST GAS COMPOSITION VERSUS FUEL-OXIDANT MOLE RATIO FOR THE SYSTEM HYDROGEN-FLUORINE AT 300 PSIA CHAMBER PRESSURE

FIG. 19



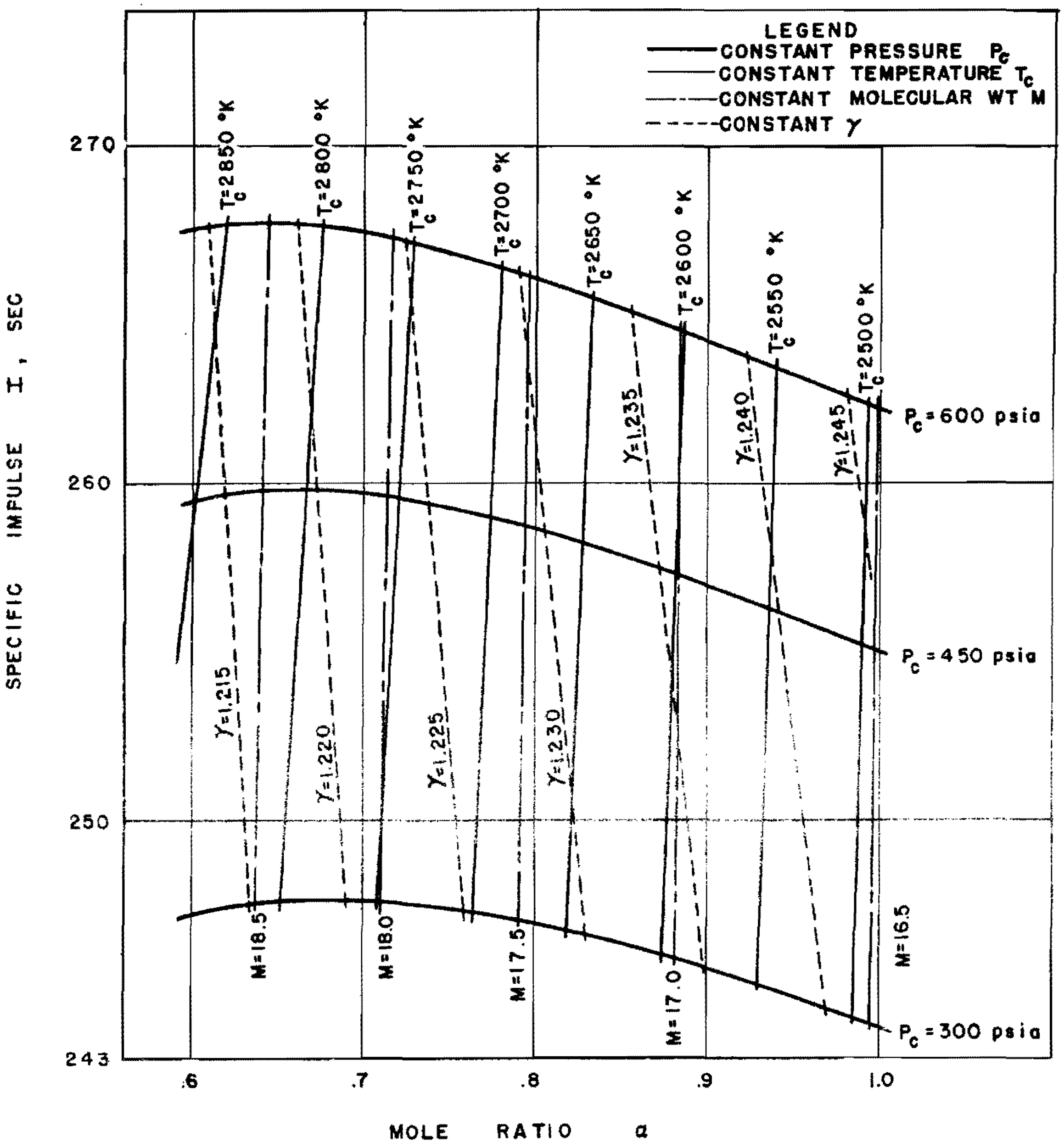
EXHAUST GAS COMPOSITION VERSUS FUEL-OXIDANT MOLE RATIO FOR THE SYSTEM HYDROGEN-FLUORINE AT 450 PSIA CHAMBER PRESSURE

FIG. 20



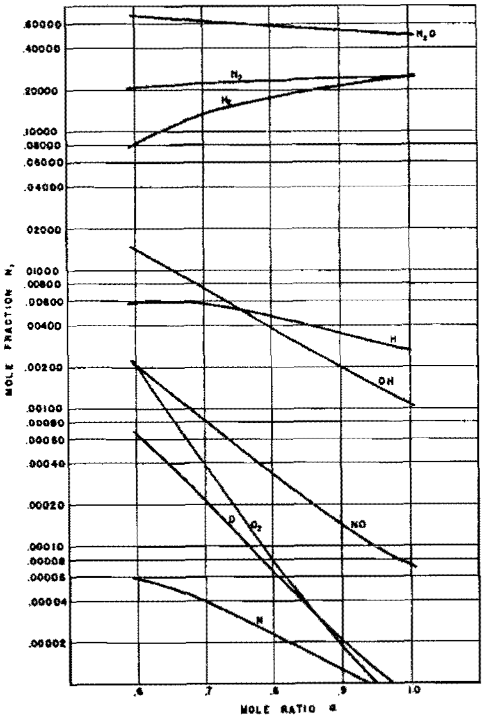
EXHAUST GAS COMPOSITION VERSUS FUEL-OXIDANT MOLE RATIO FOR THE SYSTEM HYDROGEN-FLUORINE AT 600 PSIA CHAMBER PRESSURE

FIG. 21



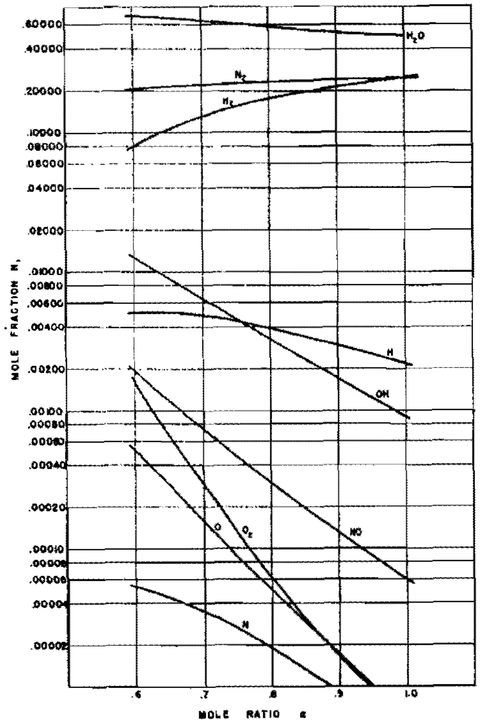
SPECIFIC IMPULSE VERSUS FUEL-OXIDANT MOLE RATIO AND CHAMBER PRESSURE FOR THE SYSTEM HYDRAZINE-HYDROGEN PEROXIDE

FIG. 22



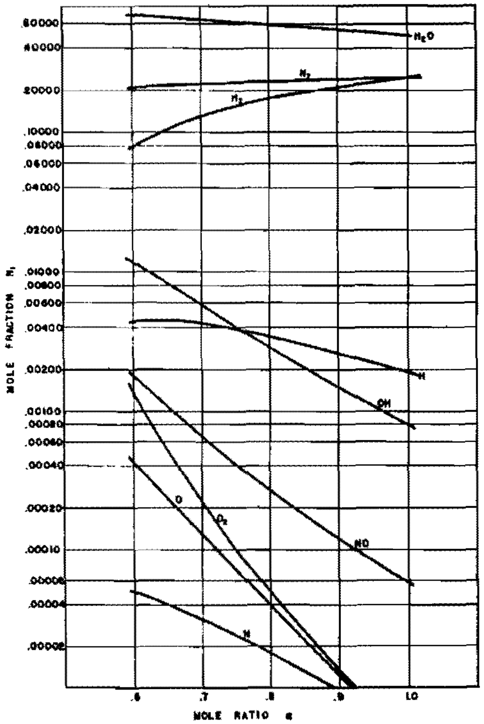
EXHAUST GAS COMPOSITION VERSUS FUEL-OXIDANT MOLE RATIO FOR THE SYSTEM HYDRAZINE-HYDROGEN PEROXIDE AT 300 PSIA CHAMBER PRESSURE

FIG. 23



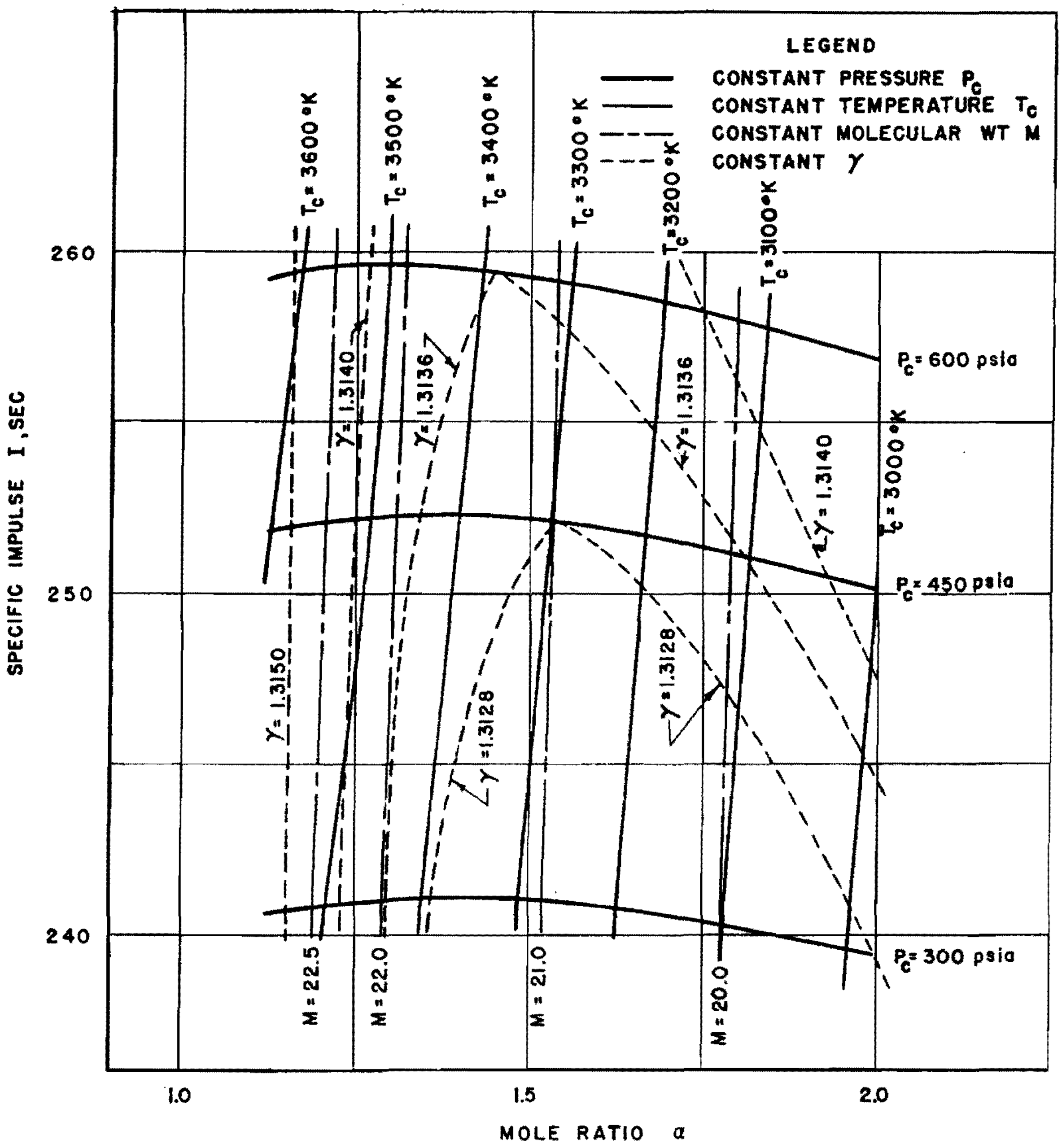
EXHAUST GAS COMPOSITION VERSUS FUEL-OXIDANT MOLE RATIO FOR THE SYSTEM HYDRAZINE-HYDROGEN PEROXIDE AT 450 PSIA CHAMBER PRESSURE

FIG. 24



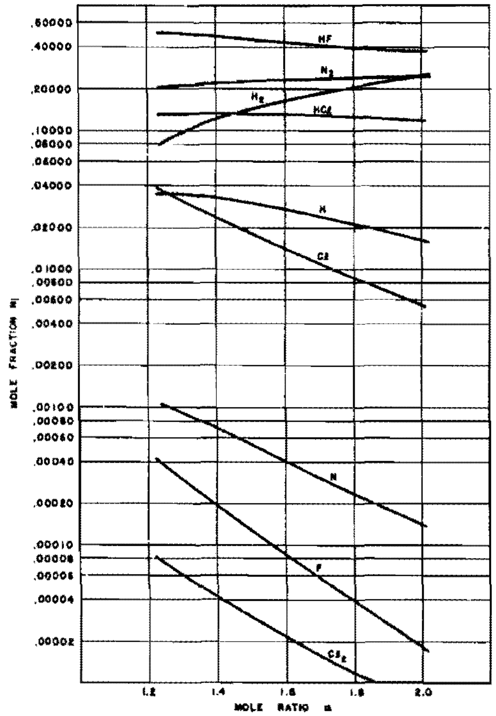
EXHAUST GAS COMPOSITION VERSUS FUEL-OXIDANT MOLE RATIO FOR THE SYSTEM HYDRAZINE-HYDROGEN PEROXIDE AT 600 PSIA CHAMBER PRESSURE

FIG. 25



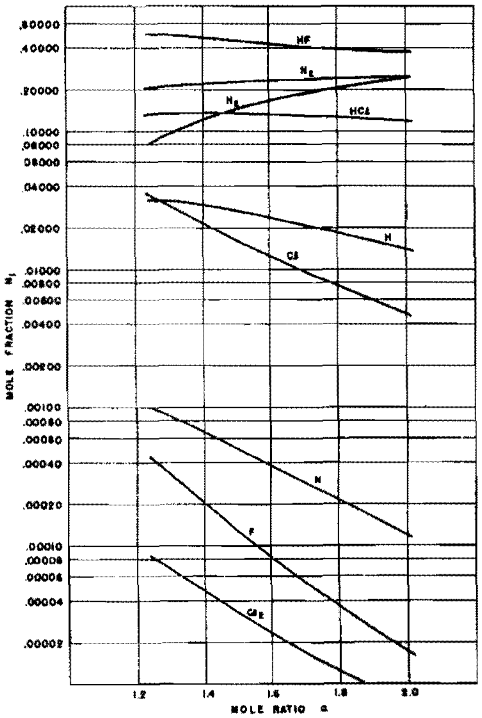
SPECIFIC IMPULSE VERSUS FUEL - OXIDANT MOLE RATIO AND CHAMBER PRESSURE FOR THE SYSTEM HYDRAZINE - CHLORINE TRIFLUORIDE

FIG. 26



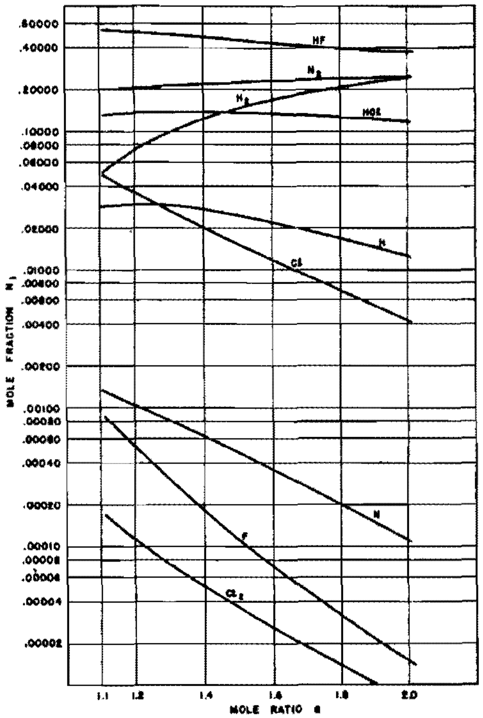
EXHAUST GAS COMPOSITION VERSUS FUEL-OXIDANT MOLE RATIO FOR THE SYSTEM HYDRAZINE-CHLORINE TRIFLUORIDE AT 300 PSIA CHAMBER PRESSURE

FIG. 27



EXHAUST GAS COMPOSITION VERSUS FUEL-OXIDANT MOLE RATIO FOR THE SYSTEM HYDRAZINE-CHLORINE TRIFLUORIDE AT 450 PSIA CHAMBER PRESSURE

FIG. 28



EXHAUST GAS COMPOSITION VERSUS FUEL-OXIDANT MOLE RATIO FOR THE SYSTEM HYDRAZINE-CHLORINE TRIFLUORIDE AT 600 PSIA CHAMBER PRESSURE

FIG. 29

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