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RESEARCH MEMORANDUM

THEORETICAL PERFORMANCE OF SOME ROCKET PROPELLANTS CONTAINING HYDROGEN, NITROGEN, AND OXYGEN

By Riley O. Miller and Paul M. Ordin

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RESEARCH MEMORANDUM

THEORETICAL PERFORMANCE OF SOME ROCKET PROPELLANTS CONTAINING HYDROGEN, NITROGEN, AND OXYGEN

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SUMMARY

Theoretical performance data based on frozen equilibrium and isentropic expansion are presented for ranges of mixtures for a number of propellant combinations at a reaction pressure of 300 pounds per square inch absolute and an expansion ratio of 20.4. The fuels considered are liquid hydrogen, hydrazine, liquid ammonia, hydrazine hydrate, and hydroxylamine; the oxidants are liquid ozone, liquid oxygen, and 100-percent hydrogen peroxide. The theoretical data include nozzle-exit temperature, specific impulse, volume specific impulse, and composition, temperature, and mean molecular weight of the reaction products.

The maximum specific impulse for most of the propellants occurred in the fuel-rich region at a reaction-chamber temperature less than the maximum. Maximum volume specific impulse did or did not occur at the point of maximum specific impulse, depending on the relative density of the fuel and oxidant. On the basis of maximum specific impulse alone, the five fuels assumed the following order for any given oxidant: liquid hydrogen, hydrazine, liquid ammonia, and either hydrazine hydrate or hydroxylamine; and the three oxidants with a given fuel had the following order: liquid ozone, liquid oxygen, and 100-percent hydrogen peroxide. On the basis of maximum volume specific impulse alone, the order of the fuels with a given oxidant was hydrazine, hydroxylamine, hydrazine hydrate, liquid ammonia, and liquid hydrogen. With a given fuel, except for ammonia, the oxidant order was: liquid ozone, 100-percent hydrogen peroxide, and liquid oxygen; with ammonia the order, however, was 100-percent hydrogen peroxide, liquid ozone, and liquid oxygen.

INTRODUCTION

Rocket-propellant performance is evaluated by a number of factors and the relative importance of each factor is governed by the particular application of the craft powered by the rocket engine. A large amount of thrust is desired for a given mass consumption rate of the working fluid (specific impulse). If aerodynamic drag is an important consideration, the rocket propellants should have high densities to give high thrust per unit volume (volume specific impulse). Because of the cooling problem, a low reaction temperature is also desirable. Inasmuch as specific impulse is approximately proportional to the square root of the quotient of gas temperature by mean molecular weight of the reaction products, an increase in specific impulse is more desirably obtained by decreasing the mean molecular weight than by increasing the gas temperature. An appreciable reduction in the mean molecular weight of the reaction products is possible by the use of propellants that do not contain carbon and thereby eliminate the heavy carbon dioxide molecule.

Some calculated rocket performance data for hydrogen-nitrogen-oxygen systems obtained at a selected reaction-chamber pressure of 300 pounds per square inch absolute, an expansion ratio of 20.4, and with assumed frozen equilibrium and isentropic expansion in the nozzle are presented herein. The following fuel-oxidant combinations are considered:

(1) Liquid hydrogen with liquid ozone and with liquid oxygen: H_2-O_3 and H_2-O_2

(2) Hydrazine with liquid ozone, with liquid oxygen, and with 100-percent hydrogen peroxide: N_2H_4-O_3, N_2H_4-O_2, and N_2H_4-H_2O_2

(3) Liquid ammonia with liquid ozone, with liquid oxygen, and with 100-percent hydrogen peroxide: NH_3-O_3, NH_3-O_2, and NH_3-H_2O_2

(4) Hydrazine hydrate with liquid ozone, with liquid oxygen, and with 100-percent hydrogen peroxide: $N_2H_4 \cdot H_2O$-O_3, $N_2H_4 \cdot H_2O$-O_2, and $N_2H_4 \cdot H_2O$-H_2O_2

(5) Hydroxylamine with liquid ozone, with liquid oxygen, and as a monofuel: NH_2OH-O_3, NH_2OH-O_2, and NH_2OH

Performance data for the following combinations have been calculated at California Institute of Technology: liquid hydrogen-liquid

oxygen, hydrazine-liquid oxygen, hydrazine-hydrogen peroxide, and ammonia-liquid oxygen. For sake of completeness and uniformity, however, the performance of these combinations was recalculated.

905 The method used for the calculations is briefly described and is illustrated in the appendix. The physical-chemical and thermodynamic data used in the calculations are presented in tables. The theoretical performance of the propellant combinations in terms of reaction-chamber gas composition, reaction temperature, nozzle-exit temperature, specific impulse, volume specific impulse, and mean molecular weight of reaction-chamber gases is presented as functions of percent by weight of fuel in the fuel-oxidant mixture. The comparative performance of the propellants is discussed and illustrated by tabulated and plotted data.

Method of Calculation

The theoretical performance calculations require the determination of reaction-chamber gas composition, reaction temperature, and nozzle-exit temperature in order to obtain the specific impulse. The method is a modification of that used at the Turbo Laboratory of Massachusetts Institute of Technology. An illustrative calculation of specific impulse is presented in the appendix.

In the calculations, a reaction pressure of 300 pounds per square inch absolute was selected and a reaction temperature assumed. From the selected pressure and assumed temperature, the composition of the gases was determined by a trial solution of the simultaneous equilibrium and material balance equations. The equations were solved by a graphical method developed at the NACA Cleveland laboratory utilizing the temperature-equilibrium data of reference 1. The assumed reaction temperature is the correct temperature when the enthalpy of the reaction equals the enthalpy change of the reaction products from the starting temperature to the assumed temperature. The calculations are repeated until such a balance is obtained. From the reaction temperature and the reaction-chamber gas composition, the nozzle-exit temperature is determined by assuming frozen equilibrium, isentropic expansion, and selection of an expansion ratio of 20.4. The enthalpy change from the reaction temperature to the nozzle-exit temperature is determined and is assumed to be the available energy. The specific impulse is calculated from the available energy and the weight of a given quantity of propellants. Volume specific impulse is obtained by multiplying the specific impulse by the specific gravity of the propellant mixture.

The physical-chemical data for the propellants used in the calculations are presented in table I. In the calculations, the temperature of the propellants is taken to be either 18° or 25° C (it makes an inappreciable difference which temperature is selected) except for liquid ozone, liquid oxygen, and liquid hydrogen, in which cases the boiling temperatures at atmospheric pressure were used. Temperature-enthalpy data and temperature-entropy data for the reaction products were calculated from free-energy data in reference 1 and are presented in table II and table III, respectively. 905

RESULTS AND DISCUSSION

The composition of the reaction-chamber gas for each of the 13 fuel-oxidant combinations is presented by figures 1 to 5. For each combination, the mole fraction of each reaction product is shown plotted against percent by weight of fuel in the fuel-oxidant mixture.

The performance parameters for each fuel-oxidant combination are shown in figures 6 to 10. For each combination, reaction-chamber temperature T_c, nozzle-exit temperature T_e, mean molecular weight of the reaction products $\overline{M}$, specific impulse I, and volume specific impulse I_d are plotted against percent by weight of fuel in the fuel-oxidant mixture.

The performances of the fuel-oxidant combinations are compared in figure 11. Reaction-chamber temperature, nozzle-exit temperature, mean molecular weight, specific impulse, and volume specific impulse for all the combinations are shown plotted against the ratio of fuel to fuel plus fuel equivalent of oxygen r. Using this parameter, the oxidant-rich region occurs from 0 to 0.5 and the fuel-rich region from 0.5 to 1.0 with the stoichiometric ratio at 0.5.

The curves of reaction-chamber gas composition for all propellant combinations (figs. 1 to 5) follow the same general pattern. Concentrations of all oxygen-bearing products and monoatomic nitrogen tend to reach a maximum in the stoichiometric or oxidant-rich region. Maximum concentrations of monoatomic hydrogen occur in the fuel-rich region near the stoichiometric region. Inasmuch as the theoretical performance calculations presented herein are based on frozen equilibrium, the gas-composition data (figs. 1 to 5) provide, if desired, starting points for recalculating the performance of the propellants by assuming that the propellant gas composition shifts during the expansion through the nozzle.

The curves of reaction-chamber and nozzle-exit temperatures for the 13 propellant combinations (figs. 6 to 11(b)) follow a similar trend, increasing to a maximum in the stoichiometric or slightly oxidant-rich region and decreasing in the fuel-rich region.

The mean molecular weights of the reaction-chamber gases in all cases decrease as the percent by weight of fuel is increased (figs. 6 to 10 and 11(c)). The presence of excess hydrogen is the principal cause for the low mean molecular weights occurring in the fuel-rich region.

The maximum specific impulse for most of the propellants occurs in the fuel-rich region at a reaction-chamber temperature less than maximum (figs. 6 to 10 and 11(d)), as a result of the low mean molecular weight values in this region. Maximum volume specific impulse may or may not occur at the point of maximum specific impulse, depending on the relative density of the fuel and the oxidant (figs. 6 to 10, 11(d), and 11(e)). For most of the combinations, maximum specific impulse and volume specific impulse occur at approximately the same mixture. In the case of hydrogen, however, maximum specific impulse is in the extreme fuel-rich region, whereas maximum volume specific impulse is beyond the data on the oxidant-rich side of stoichiometric.

In the calculations, the initial temperatures of the propellants were set at values regarded most convenient in rocket practice. These temperatures, however, may not be optimum for the highest densities. For example, if liquid oxygen were cooled from near the atmospheric boiling point of -183.0° to the melting point of -210.4° C, an 11.4-percent increase in density is gained. (See table I.) If liquid ozone is cooled from its boiling point, -112° C, to the boiling point of liquid oxygen, -183° C, a density gain of 17.1 percent is obtained. Inasmuch as ozone would probably be mixed with liquid oxygen, curves are included in figures 6(a) and 7(a) to show volume specific impulse for ozone at -183° C. These curves, in which the density of ozone was taken at -183° C, are inexact because the enthalpy change for the ozone from -183° to -112° C was neglected. Ammonia, if cooled from 18° to the freezing point at -77.7° C, will increase in density 19.4 percent. If enthalpy changes are neglected, the volume specific impulse may be increased nearly 20 percent by cooling both ozone and ammonia, as shown in figure 8(a).

The performance of the propellants at the stoichiometric region, at the region of maximum specific impulse, and, for some cases, at the region of maximum volume specific impulse is summarized in table IV. On the basis of maximum specific impulse alone, the five

fuels assume the following order for any given oxidant: liquid hydrogen, hydrazine, liquid ammonia, and either hydrazine hydrate or hydroxylamine; and the three oxidants with a given fuel have the following order: liquid ozone, liquid oxygen, and 100-percent hydrogen peroxide. On the basis of maximum volume specific impulse alone, the order of the fuels with a given oxidant is hydrazine, hydroxylamine, hydrazine hydrate, followed by liquid ammonia, and liquid hydrogen; and with a given fuel except for ammonia the oxidant order is liquid ozone, 100-percent hydrogen peroxide, and liquid oxygen; with ammonia the order, however, was 100-percent hydrogen peroxide, liquid ozone, and liquid oxygen.

The advantage of eliminating carbon from the propellant system is illustrated by some typical data shown in table V. Here the reaction temperatures of some carbon-bearing propellants are compared with reaction temperatures of noncarbon-bearing propellants that have similar values of specific impulse. The specific-impulse values are all for constant gas composition during expansion. As shown in table V, hydrazine-hydrogen peroxide yields a slightly higher maximum specific impulse than either ethyl alcohol-oxygen or octane-oxygen at a reaction temperature of 430° or 545° K lower, respectively. With oxygen, liquid ammonia is shown to have temperature advantage over methylamine. Hydroxylamine as a monofuel has a higher specific impulse than the best mixture of aniline-red fuming nitric acid at nearly one-third less absolute reaction temperature.

SUMMARY OF RESULTS

The theoretical performance data, which were based on frozen equilibrium and isentropic expansion over ranges of mixtures for 13 rocket propellant combinations involving oxygen, hydrogen, and nitrogen at a reaction pressure of 300 pounds per square inch absolute and an expansion ratio of 20.4 may be summarized as follows:

1. The maximum specific impulse in pound-seconds per pound for each propellant combination was:

Fuel	Oxidant		
	Liquid ozone	Liquid oxygen	100-percent hydrogen peroxide
	Maximum specific impulse, lb-sec/lb		
Liquid hydrogen	372.7	344.0	----------
Hydrazine	277.1	265.7	247.5
Liquid ammonia	265.0	251.0	235.8
Hydrazine hydrate	249.0	235.5	227.0
Hydroxylamine	248.0	241.0	----------

2. Maximum specific impulse for most of the propellant combinations occurred in the fuel-rich region at a reaction-chamber temperature less than maximum.

3. The reaction-chamber and nozzle-exit temperatures for each combination were at a maximum in the stoichiometric or slightly oxidant-rich region.

4. The mean molecular weight of the reaction-chamber gas in each case was substantially less in the fuel-rich region.

5. The use of propellant combinations not containing carbon resulted in a lower reaction temperature for a given specific impulse than propellant combinations containing carbon.

6. Maximum volume specific impulse for a given propellant combination did or did not occur at the fuel-oxidant mixture yielding maximum specific impulse, depending upon the relative density of the fuel and the oxidant.

7. Volume specific impulse was, in some cases, appreciably affected by varying the initial temperature of the propellants.

8. On the basis of maximum volume specific impulse alone, the order of the fuels with a given oxidant was hydrazine, hydroxylamine, hydrazine hydrate, liquid ammonia, and liquid hydrogen. With a given fuel, except for ammonia, the oxidant order was liquid ozone, 100-percent hydrogen peroxide, and liquid oxygen; with ammonia, however, the order was 100-percent hydrogen peroxide, liquid ozone, and liquid oxygen.

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APPENDIX - TYPICAL CALCULATION OF SPECIFIC IMPULSE

Symbols

The following symbols are used in the report:

c nozzle-exit velocity, ft/sec

g gravitational constant, lb mass-ft/lb force-sec^2

ΔH enthalpy change

ΔH_a energy available for acceleration from w grams of propellant, kg cal

ΔH_f enthalpy of formation, kg cal/gram mole

$\Delta H_{T_1}^{T_2}$ enthalpy change between given temperatures T_1 and T_2, kg cal; temperatures, $^{\circ}K$

I specific impulse, lb-sec/lb

I_d volume specific impulse ($I \times$ specific gravity of fuel-oxidant mixture) lb-sec(62.4)/cu ft

K conversion factor, $I/\sqrt{\Delta H_a/w}$

M molecular weight of given propellant

$\overline{M}$ mean molecular weight of reaction-chamber products

n number of moles of reaction-chamber products

P_c reaction-chamber pressure, atmospheres

P_e nozzle-exit pressure, atmospheres

R universal gas constant, 1.986 kg cal/gram mole-$^{\circ}K$

S^T entropy at given temperature T, cal/gram mole-$^{\circ}K$

T_c reaction-chamber temperature, $^{\circ}K$

T_e nozzle-exit temperature, $^{\circ}K$

w weight of propellant mixture, grams

Calculation of Reaction-Chamber Temperature

For a given propellant combination, the first step in the calculation of specific impulse is to determine the reaction-chamber temperature. A reaction temperature is assumed and the reaction-chamber gas composition is computed at a given pressure by a graphical method developed at the NACA Cleveland laboratory. If the assumed temperature is correct, the enthalpy of the reaction will equal the enthalpy change of the reaction products from the selected inlet temperatures to the assumed reaction temperature. If this equality is not achieved, a new composition is determined for another assumed reaction temperature and the procedure is repeated.

For illustration, the case of hydrazine and ozone at a reaction-chamber pressure of 300 pounds per square inch (20.4 atmospheres) and at approximately the stoichiometric mixture will be used. After two trials, the correct reaction-chamber temperature is interpolated to be approximately 3480° K. A third trial, outlined herein, is made to check this value.

Composition of gas in chamber. - By means of the graphical solution the reaction may be represented by the following chemical equation:

$$N_2H_4 + 0.6740\ O_3 \xrightarrow[20.4\ \text{atm}]{3480^\circ\ \text{K}} 0.0912\ O_2 + 0.0600\ O + 0.3474\ H_2$$

$$+ 0.9688\ N_2 + 0.2640\ OH + 0.0590\ NO + 0.1280\ H + 0.0041\ N$$

$$+ 1.4566\ H_2O$$

Calculation of heat content of gases. - The following enthalpies were interpolated from the values of temperature and enthalpy given in table II:

Gas	Moles of reaction-chamber products n	Enthalpy from 298.1° to 3480° K (kg cal/mole)	Enthalpy from 298.1° to 3480° K for each component (kg cal)
O_2	0.0912	28.062	2.559
O	.0600	15.804	.948
H_2	.3474	25.445	8.840
N_2	.9688	26.458	25.633
OH	.2640	25.753	6.799
NO	.0590	27.062	1.597
H	.1280	15.804	2.023
N	.0041	15.804	.065
H_2O	1.4566	36.833	53.651

$$\Sigma n\Delta H_{298.1}^{3480}, \text{ products} = 102.115 \text{ kg cal}$$

Calculation of total enthalpy of formation of reaction products. - The total enthalpy of formation is calculated as follows:

Gas	Moles of reaction-chamber products n	Enthalpy of formation, ΔH_f (kg cal/mole)	Enthalpy of formation, ΔH_f for each component (kg cal)
O_2	0.0912	0	0
O	.0600	59.10[a]	3.546
H_2	.3474	0	0
N_2	.9688	0	0
OH	.2640	9.31[a]	2.458
NO	.0590	22.55[a]	1.330
H	.1280	51.90[a]	6.643
N	.0041	85.10[a]	.349
H_2O	1.4566	-57.80[a]	-84.191

[a]Reference 3.

$$\Sigma n\Delta H_f, \text{ products} = -69.865 \text{ kg cal}$$

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Enthalpy of formation of reactants. - The literature reports data at both 18° and 25° C. The differences in enthalpies for the two base temperatures are neglected.

Enthalpy of formation ΔH_f of hydrazine is

N_2H_4(liquid, 25° C) $\Delta H_f = -Q_f = 12.05$ kg cal (reference 6)

Enthalpy of formation of liquid ozone at -112.5° C is

O_3(gas, -112.5° C) $\longrightarrow$ O_3(liquid, -112.5° C), $\Delta H = -2.96$ kg cal (reference 3)

O_3(gas, 18° C) $\longrightarrow$ O_3(gas, -112.5° C), $\Delta H = -1.10$ kg cal (reference 4)

1.5 O_2(gas, 18° C) $\longrightarrow$ O_3(gas, 18° C), $\Delta H = 34.5$ kg cal (reference 3)

Therefore

1.5 O_2(gas, 18° C) $\longrightarrow$ O_3(liquid, -112.5° C), $\Delta H_f = 30.44$ kg cal

Enthalpy of formation of the propellant mixture N_2H_4 + .6740 O_3 is $\Sigma\Delta H_f$ of reactants = 12.05 + (.6740)(30.44) = 32.57 kg cal

Enthalpy balance. - If 3480° K is the correct reaction-chamber temperature, the enthalpy of formation of the reactants minus the enthalpy of formation of the products should be equal to the heat content of the gases.

$$\Sigma\Delta H_f \text{ of reactants} - \Sigma\Delta H_f \text{ of products} = \Delta H_{298.1}^{3480} \text{ of products}$$

By substituting values

$$32.57 - (-69.87) = 102.44$$

The heat content of the products is 102.12 kilogram calorie; the true reaction temperature therefore is not more than two or three degrees higher than the value, 3480° K, which is accepted here.

Calculation of Nozzle-Exit Temperature

For isentropic expansion and constant gas composition, the following relation can be shown:

$$\Sigma n\ S^{T_e} = \Sigma n\ S^{T_c} - nR\log_e \frac{P_c}{P_e}$$

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where S^{T_e} and S^{T_c} are the entropies of the reaction-chamber gases at the nozzle-exit temperature T_e and reaction-chamber temperature T_c, respectively. The reaction-chamber and nozzle-exit pressures are P_c and P_e, respectively.

Inasmuch as T_c is known to equal 3480° K, the value of $\Sigma n\ S^{T_c}$ for 1 mole of gas is calculated from entropy values interpolated from table III.

Gas	Mole fraction	Entropy S^{3480} per mole	Entropy S^{3480} of each component
O_2	0.0270	69.424	1.874
O	.0178	50.776	.904
H_2	.1028	49.789	5.118
N_2	.2867	65.111	18.667
OH	.0781	62.723	4.899
NO	.0175	70.220	1.229
H	.0379	39.613	1.501
N	.0012	48.830	.059
H_2O	.4311	70.538	30.409

$$\Sigma n\ S^{3480} = 64.660$$

The entropy of 1 mole of expanded gas is computed as follows:

$$\Sigma n\ S^{T_e} = \Sigma n\ S^{T_c} - nR\log_e \frac{P_c}{P_e} = 64.660 - 1.986\ (\log_e 20.4) = 64.660 - 5.990 = 58.670$$

The nozzle-exit temperature is the temperature at which the gas mixture will have an entropy of 58.670 and is solved for by trial. By using the method shown, the following values are found for 1 mole reaction-chamber gas:

[redacted]

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$$\Sigma n\ S^{1950} = 58.649$$

$$\Sigma n\ S^{1958} = 58.690$$

By linear intropolation $T_e = 1954$.

Calculation of Specific Impulse

Calculation of available energy. - The available energy ΔH_a is assumed to be the difference between the heat content at T_c and the heat content at T_e. At the reaction temperature $T_c = 3480^\circ$ K, the heat content of the products from the reaction $N_2H_4 + 0.6740\ O_3$ was shown to be 102.44 kilogram calories. By use of the method previously described, the heat content at $T_e = 1954^\circ$ K is found to be 48.40 kilogram calories. The available energy ΔH_a is computed.

$$\Sigma n\Delta H_a = \Sigma n\Delta H^{3480}_{298.1} - \Sigma n\Delta H^{1954}_{298.1} = 102.44 - 48.40 = 53.71 \text{ kg cal}$$

Calculation of weight of products. - Inasmuch as the available energy was computed for the reaction of 1 mole of N_2H_4 with 0.6740 mole of O_3, the weight of the products is

$$w = M_{N_2H_4} + .6740\ M_{O_3}$$

$$= 32.05 + .6740\ (48.00) = 64.40 \text{ grams}$$

Specific impulse. - By assuming that the available energy is all translated to kinetic energy, the following relation holds:

$$I = \frac{c}{g} = \frac{1}{g}\sqrt{2\frac{\Delta H_a}{w}}$$

where c is the nozzle-exit velocity of the gases, ΔH_a is the available energy from the expansion of the reaction-chamber gases, and w is the weight of the reaction-chamber gases.

Inasmuch as I is usually expressed as pound-seconds per pound and ΔH_a and w are computed in metric units, a factor K including the constants and the conversion factors is computed as follows:

$$I = K\sqrt{\frac{\Delta H_a,\ \text{kg cal}}{w,\ \text{grams}}}$$

$$I = \frac{1}{32.17}\ \frac{\text{lb-sec}^2}{\text{lb-ft}}\sqrt{\frac{2\left(3087\frac{\text{ft-lb}}{\text{kg cal}}\right)\left(32.17\frac{\text{lb-ft}}{\text{lb-sec}^2}\right)\Delta H_a,\ \text{kg cal}}{\left(0.002205\ \frac{\text{lb}}{\text{gram}}\right)w,\ \text{grams}}}$$

$$I,\ \frac{\text{lb-sec}}{\text{lb}} = 295.0\sqrt{\frac{\Delta H_a,\ \text{kg cal}}{w,\ \text{grams}}}$$

Substituting values,

$$I = 295.0\sqrt{\frac{53.71}{64.40}}$$

$$I = 269.4$$

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TABLE I - PHYSICAL-CHEMICAL PROPERTIES OF PROPELLANTS

[Temperatures in superscripts, °C. References in parentheses.]

Propellant	Specific gravity	Enthalpy of formation (kg cal/mole)	Enthalpy of vaporization (kg cal/mole)	Vapor pressure (atm)	Boiling point (°C)	Freezing point (°C)	Viscosity (centipoises)	Refractive index (n_D)	Molecular weight M
Liquid hydrogen	0.070 (2)	$-2.01^{-252.8}$ [a](3,4)	0.216^{-255} (3)	$12.8^{-239.91}$ (crit.) (2)	-252.8 (2)	-259.18 (2)	$0.0130^{-252.6}$ (4)	$1.097^{-252.8}$ (5790A) (4)	2.0162 (2)
Hydrazine	1.0024^{25} (5)	12.05^{25} (6)	$10.2^{23.1}$ (6)	0.093^{56} (6)	113.5 (6)	0.0 (6)	0.903^{25} (5)	1.470^{22} (6)	32.05 (6)
Liquid ammonia	0.6131^{18} $.7323^{-77.7}$ (2)	-16.07^{18} (3)	5.56^{-33} (3)	10.2^{26} (2)	-33.35 (2)	-77.7 (2)	$0.266^{-33.5}$ (2)	$1.325^{16.5}$ (2)	17.03 (2)
Hydrazine hydrate	1.032^{25} (5)	-58.0^{25} (7)	----------	0.0342^{46} (8)	118.5 @ 740 mm (2)	-46.8 (5)	1.703^{25} (5)	----------	50.06 (2)
Hydroxylamine	$1.204^{23.5}$ (2,8)	-25.5^{18} (3)	----------	----------	56.5 @ 22 mm (2)	33.05 (2)	----------	$1.44^{23.5}$ (2)	33.03 (2)
Liquid ozone	1.43^{-112} 1.71^{-183} [a](4)	30.4^{-112} [a](3,4)	$2.96^{-112.5}$ (3)	67^{-5} (crit.) (2)	-112 (4)	-251 (2)	----------	----------	48.00
Liquid oxygen	1.14^{-182} $1.27^{-210.4}$ (4)	-2.87^{-183} [a](3,4)	1.629^{-183} (3)	$49.7^{-118.8}$ (crit.) (2)	-183 (2)	-218.4 (2)	$0.189^{-252.07}$ (96%) (4)	1.221^{-181} (4)	32.00
Hydrogen peroxide, 100-percent	1.4631^{0} (2)	-45.20^{18} (3)	11.61^{18} (3)	$0.025^{24.5}$ (9)	152.1 (2)	-1.7 (2)	$1.272^{19.6}$ (9)	1.414^{22} (2)	34.02 (2)

[a]Calculated from data in references cited.

TABLE II - ENTHALPIES OF GASES ABOVE 298.1° K

[No gas imperfections. Calculated from free-energy data of reference 1.]

Temperature, T (°K)	Enthalpy, $\Delta H^{T}_{298.1}$, kg cal/gram mole						
	H_2O	H_2	OH	H,N,O	N_2	NO	O_2
300	0.015	0.013	0.013	0.010	0.014	0.013	0.009
400	.826	.708	.723	.507	.712	.728	.730
500	1.656	1.406	1.428	1.003	1.413	1.451	1.456
600	2.511	2.106	2.134	1.500	2.126	2.189	2.212
700	3.394	2.808	2.840	1.996	2.853	2.947	2.989
800	4.308	3.515	3.552	2.494	3.597	3.722	3.787
900	5.249	4.225	4.270	2.991	4.358	4.515	4.603
1000	6.224	4.944	4.998	3.487	5.133	5.321	5.430
1100	7.226	5.670	5.737	3.984	5.922	6.140	6.267
1200	8.262	6.406	6.478	4.481	6.724	6.971	7.115
1300	9.327	7.151	7.248	4.977	7.535	7.809	7.972
1400	10.414	7.908	8.015	5.474	8.357	8.656	8.839
1500	11.534	8.677	8.802	5.971	9.188	9.509	9.713
1600	12.675	9.452	9.597	6.467	10.024	10.368	10.589
1700	13.836	10.239	10.396	6.964	10.869	11.232	11.472
1800	15.021	11.036	11.210	7.461	11.718	12.101	12.361
1900	16.221	11.841	12.026	7.957	12.573	12.972	13.255
2000	17.439	12.657	12.847	8.454	13.432	13.840	14.155
2100	18.673	13.478	13.686	8.950	14.293	14.725	15.058
2200	19.924	14.308	14.519	9.448	15.158	15.606	15.967
2300	21.186	15.145	15.374	9.945	16.028	16.489	16.882
2400	22.461	15.988	16.226	10.440	16.898	17.374	17.801
2500	23.748	16.840	17.093	10.938	17.773	18.262	18.726
2600	25.046	17.696	17.949	11.435	18.651	19.152	19.658
2700	26.353	18.555	18.817	11.931	19.531	20.044	20.595
2800	27.671	19.423	19.691	12.428	20.414	20.937	21.537
2900	28.995	20.295	20.569	12.925	21.299	21.832	22.485
3000	30.330	21.173	21.460	13.421	22.185	22.729	23.436
3100	31.673	22.054	22.348	13.918	23.073	23.630	24.393
3200	33.021	22.939	23.239	14.414	23.961	24.531	25.352
3300	34.377	23.831	24.134	14.911	24.852	25.434	26.317
3400	35.738	24.725	25.034	15.408	25.744	26.338	27.285
3500	37.107	25.624	25.933	15.904	26.637	27.242	28.256
3600	38.481	26.525	26.835	16.402	27.531	28.148	29.228
3700	39.860	27.429	27.743	16.899	28.427	29.054	30.207
3800	41.246	28.339	28.653	17.395	29.322	29.961	31.187
3900	42.634	29.249	29.565	17.892	30.220	30.869	32.173
4000	44.025	30.166	30.480	18.389	31.119	31.779	33.162

TABLE III - ENTROPIES OF GASES

[Calculated from the free-energy data of reference 1]

Temperature, T (°K)	Entropy, S^T, cal/gram mole - °K								
	H_2	H_2O	N_2	N	NO	O_2	OH	H	O
300	31.269	45.179	45.828	36.654	50.407	49.049	43.941	27.439	38.092
400	33.267	47.510	47.833	38.083	52.457	51.122	45.994	28.868	39.634
500	34.826	49.361	49.401	39.191	54.084	52.740	47.569	29.976	40.819
600	36.102	50.920	50.701	40.096	55.414	54.118	48.856	30.881	41.779
700	37.184	52.280	51.822	40.862	56.592	55.315	49.948	31.647	42.587
800	38.129	53.500	52.815	41.526	57.616	56.382	50.894	32.311	43.283
900	38.964	54.609	53.710	42.111	58.556	57.342	51.745	32.896	43.893
1000	39.721	55.634	54.527	42.605	59.399	58.214	52.507	33.420	44.438
1100	40.412	56.591	55.278	43.108	60.185	59.009	53.212	33.893	44.928
1200	41.052	57.491	55.976	43.540	60.901	59.748	53.856	34.325	45.375
1300	41.648	58.344	56.625	43.938	61.573	60.436	54.471	34.723	45.785
1400	42.208	59.149	57.234	44.306	62.196	61.077	55.042	35.091	46.164
1500	42.739	59.921	57.807	44.649	62.787	61.680	55.587	35.434	46.517
1600	43.243	60.661	58.347	44.969	63.338	62.246	56.098	35.754	46.845
1700	43.723	61.351	58.859	45.271	63.863	62.781	56.636	36.055	47.154
1800	44.179	62.039	59.345	45.554	64.358	63.289	57.048	36.339	47.444
1900	44.612	62.693	59.808	45.823	64.828	63.771	57.491	36.608	47.719
2000	45.026	63.313	60.249	46.078	65.275	64.234	57.909	36.863	47.980
2100	45.428	63.919	60.668	46.319	65.707	64.675	58.383	37.104	48.226
2200	45.813	64.472	61.071	46.551	66.119	65.097	58.711	37.336	48.462
2300	46.185	65.070	61.457	46.772	66.512	65.506	59.087	37.557	48.687
2400	46.544	65.605	61.827	46.982	66.888	65.817	59.451	37.767	48.901
2500	46.891	66.136	62.184	47.187	67.248	66.273	59.803	37.971	49.109
2600	47.226	66.633	62.528	47.382	67.599	66.358	60.140	38.166	49.306
2700	47.552	67.137	62.860	47.569	67.936	66.719	60.470	38.353	49.497
2800	47.867	67.618	63.181	47.750	68.260	67.071	60.786	38.534	49.681
2900	48.174	68.074	63.491	47.925	68.573	67.411	61.096	38.708	49.858
3000	48.471	68.529	63.792	48.093	68.877	67.991	61.396	38.877	50.030
3100	48.759	68.971	64.082	48.255	69.173	68.305	61.688	39.039	50.194
3200	49.039	69.399	64.364	48.413	69.461	68.613	61.971	39.197	50.354
3300	49.314	69.815	64.638	48.567	69.739	68.909	62.249	39.350	50.509
3400	49.580	70.217	64.904	48.715	70.010	69.198	62.515	39.498	50.659
3500	49.841	70.618	65.163	48.859	70.272	69.480	62.775	39.642	50.805
3600	50.095	71.007	65.414	49.000	70.527	69.753	63.029	39.782	50.947
3700	50.342	71.381	65.660	49.136	70.775	70.018	63.277	39.918	51.085
3800	50.585	71.757	65.899	49.270	71.017	70.281	63.520	40.051	51.220
3900	50.821	72.109	66.132	49.400	71.252	70.537	63.759	40.180	51.351
4000	51.054	72.458	66.360	49.527	71.481	70.787	63.989	40.306	51.479

TABLE IV - SUMMARY OF THEORETICAL

Propellants	Formula	At stoichiometric			
		Fuel (percent by weight)	Reaction-chamber temperature, T_c (°K)	Specific impulse I, (lb-sec/lb)	Volume specific impulse, $I_d/62.4$ (lb-sec/cu ft)
Liquid hydrogen and liquid ozone	H_2-O_3	11.19	3640	314.0	[a]143.0
Liquid hydrogen and liquid oxygen	H_2-O_2	11.19	3440	296.0	[c]124.8
Hydrazine and liquid ozone	N_2H_4-O_3	50.04	3480	269.4	[a]321.5
Hydrazine and liquid oxygen	N_2H_4-O_2	50.04	3280	258.0	[c]277.0
Hydrazine and hydrogen peroxide	N_2H_4-H_2O_2	32.03	2840	242.0	309.0
Liquid ammonia and liquid ozone	NH_3-O_3	41.52	3290	263.0	[b]244.0
Liquid ammonia and liquid oxygen	NH_3-O_2	41.52	3038	249.0	[d]210.0
Liquid ammonia and hydrogen peroxide	NH_3-H_2O_2	25.03	2585	234.4	255.0
Hydrazine hydrate and liquid ozone	$N_2H_4 \cdot H_2O$-O_3	61.04	3000	248.5	[a]289.2
Hydrazine hydrate and liquid oxygen	$N_2H_4 \cdot H_2O$-O_2	61.04	2750	235.4	[c]252.0
Hydrazine hydrate and hydrogen peroxide	$N_2H_4 \cdot H_2O$-H_2O_2	42.38	2455	226.7	281.8
Hydroxylamine and liquid ozone	NH_2OH-O_3	80.53	2980	246.5	[a]307.0
Hydroxylamine and liquid oxygen	NH_2OH-O_2	80.53	2850	240.0	[c]285.5

[a]Inlet temperature of liquid ozone, -112° C.

[b]Inlet temperature of liquid ozone, -112° C: liquid ammonia, 18° C.

[c]Inlet temperature of liquid oxygen, -182° C.

[d]Inlet temperature of liquid oxygen, -182° C: liquid ammonia, 18° C.

PERFORMANCE OF ROCKET FUELS

At maximum specific impulse				At maximum volume specific impulse			
Fuel (percent by weight)	Reaction-chamber temperature, T_c (°K)	Specific impulse I, (lb-sec/lb)	Volume specific impulse I_d/62.4 (lb-sec/cu ft)	Fuel (percent by weight)	Reaction-chamber temperature, T_c (°K)	Specific impulse, I (lb-sec/lb)	Volume specific impulse, I_d/62.4 (lb-sec/cu ft)
27.0	2665	372.7	[a] 85.0	--------	----------	----------	----------
24.5	2505	344.0	[c] 82.3	--------	----------	----------	----------
61.0	3275	277.1	[a] 318.0	54.0	3450	274.0	[a] 321.7
58.0	3160	265.7	[c] 282.0	57.0	3190	265.5	[c] 282.0
40.0	2750	247.5	307.0	35.0	2815	245.0	310.0
48.0	3158	265.0	[b] 233.2	--------	----------	----------	----------
46.5	2870	251.0	[d] 204.5	--------	----------	----------	----------
26.0	2588	235.8	253.0	21.0	2490	227.0	257.5
63.0	2950	249.0	[a] 288.0	60.0	3010	248.0	[a] 289.8
61.4	2748	235.5	[c] 251.8	61.0	2750	235.4	[c] 252.3
42.0	2460	227.0	282.0	41.5	2461	226.0	282.2
83.5	2920	248.0	[a] 307.0	82.0	2950	247.5	[a] 307.5
83.4	2820	241.0	[c] 287.0	85.0	2770	240.7	[c] 287.3

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TABLE V - COMPARISON OF PERFORMANCE OF CARBON-BEARING PROPELLANTS

WITH NONCARBON-BEARING PROPELLANTS

Propellant combination at maximum specific impulse (percent by weight)	Mean molecular weight of reaction-chamber gases, $\bar{M}$	Maximum specific impulse, I (lb-sec/lb)	Reaction-chamber temperature at maximum I, T_c, (°K)	Source of data
40-percent C_2H_5OH, 60-percent O_2	———	243.0	3180	Reference 10
27.6-percent C_8H_{18}, 72.4-percent O_2	22.66	242.0	3295	Reference 10
40.0-percent N_2H_4, 60.0-percent H_2O_2	18.00	247.5	2750	Figure 7(c)
32.6-percent CH_3NH_2, 67.4-percent O_2	———	251.5	3390	Reference 10
46.5-percent NH_3, 53.5-percent O_2	18.10	251.0	2870	Figure 8(b)
25-percent $C_6H_5 \cdot NH_2$, 75-percent HNO_3+6%NO_2 (red fuming nitric acid)	25.41	220.5	3070	Reference 10
NH_2OH (monofuel)	16.50	223.0	2085	Figure 10

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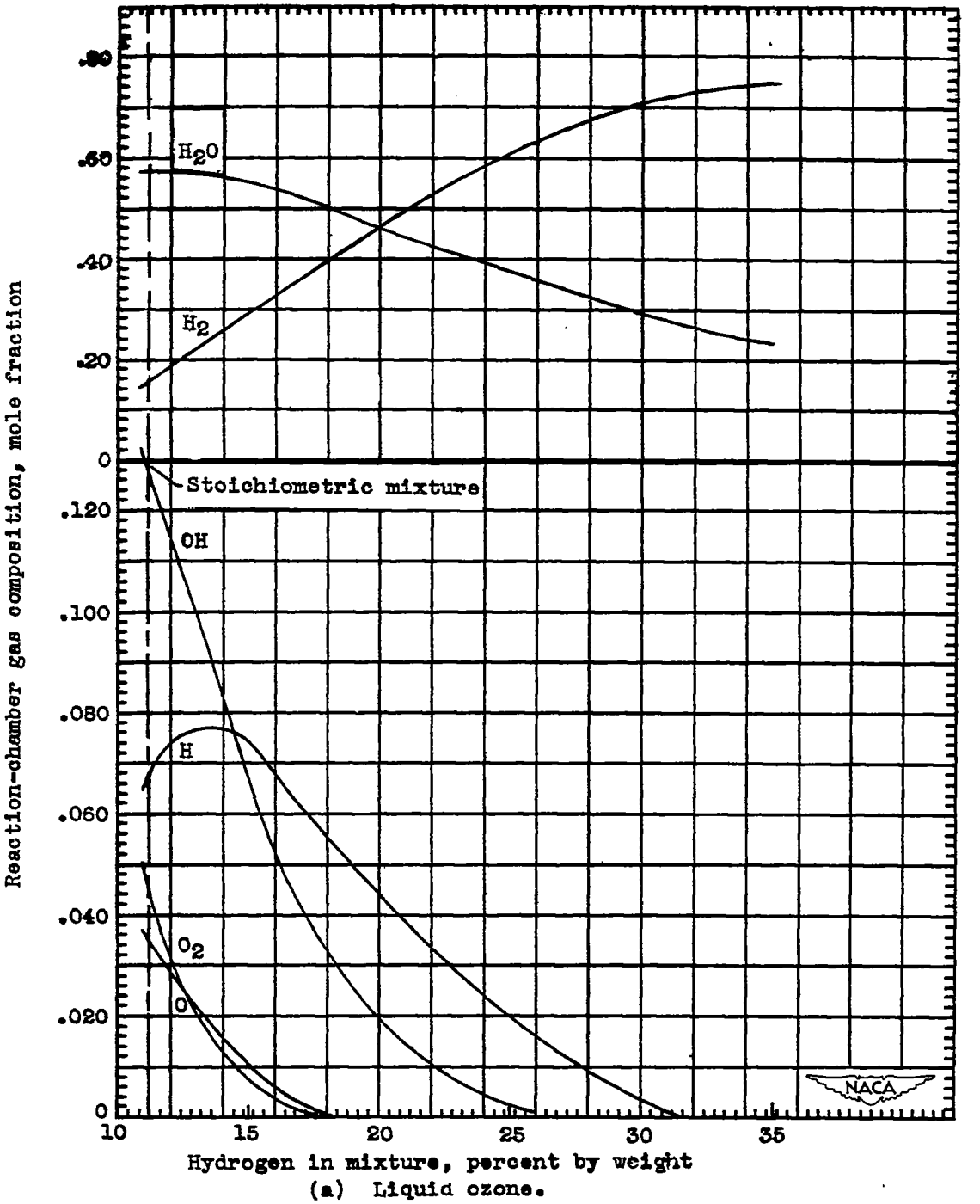
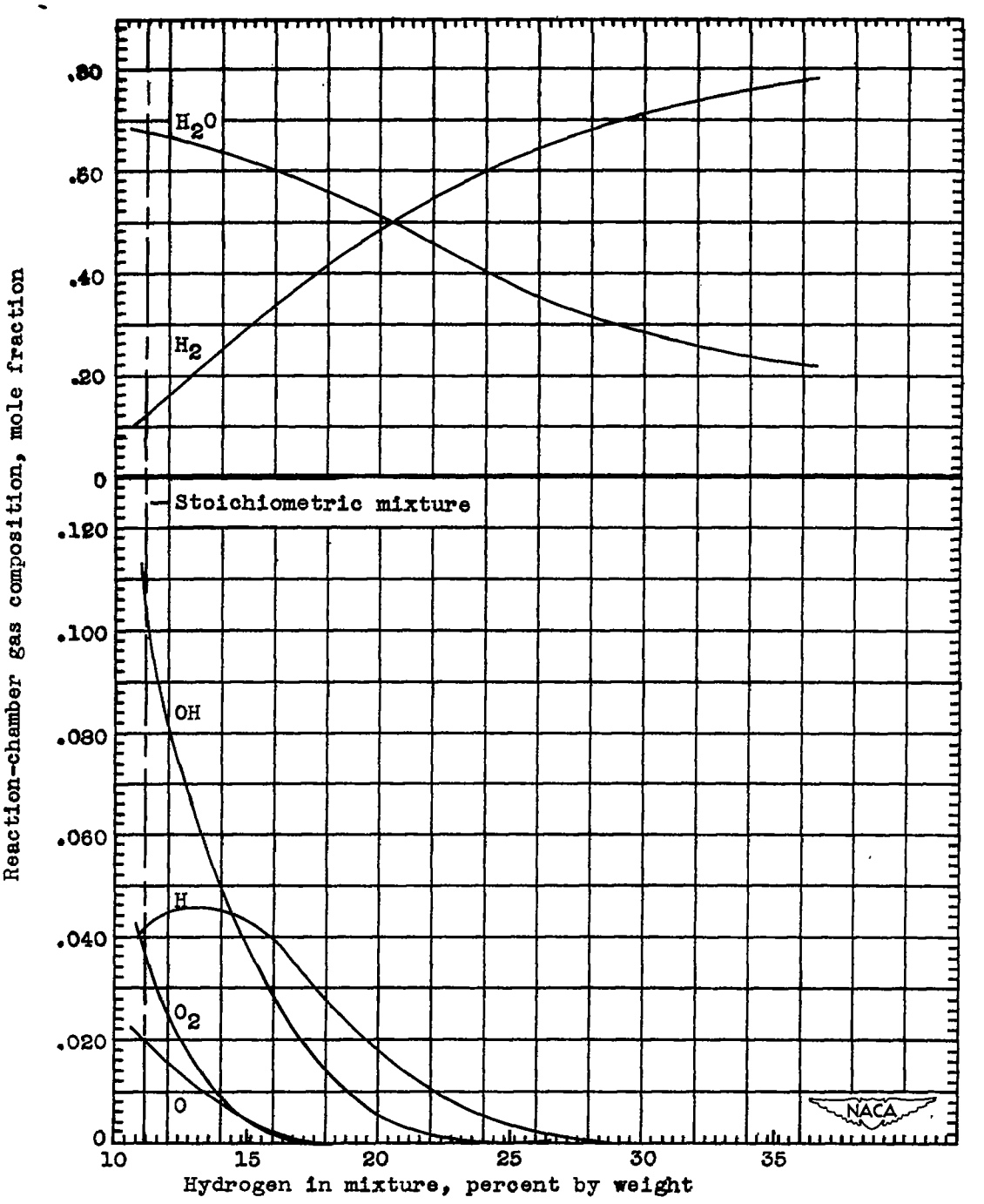


(a) Liquid ozone.

Figure 1. - Composition of reaction-chamber gas from hydrogen with liquid ozone and with liquid oxygen. Reaction-chamber pressure, 300 pounds per square inch absolute.



(b) Liquid oxygen.

Figure 1. - Concluded. Composition of reaction-chamber gas from hydrogen with liquid ozone and with liquid oxygen. Reaction-chamber pressure, 300 pounds per square inch absolute.

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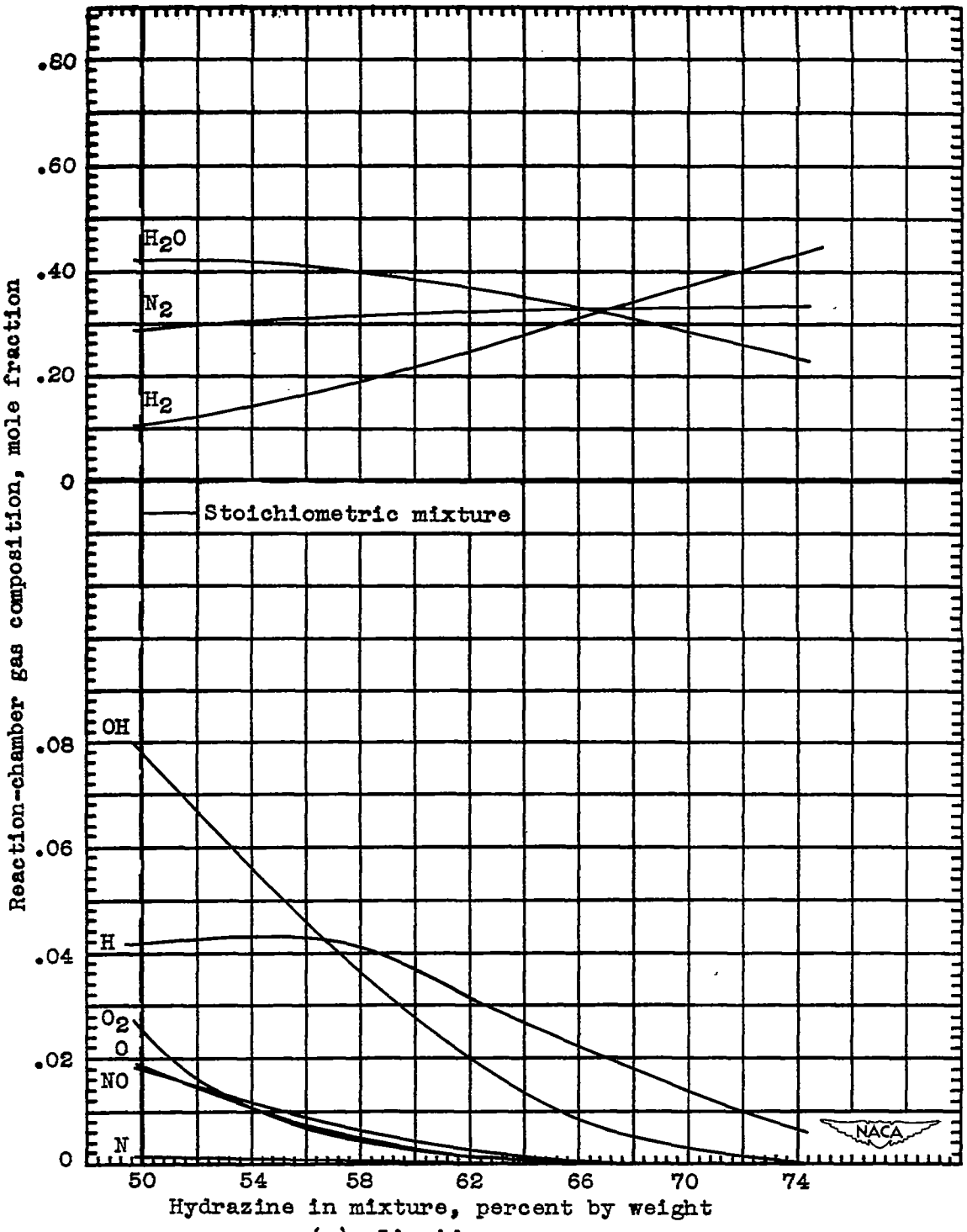
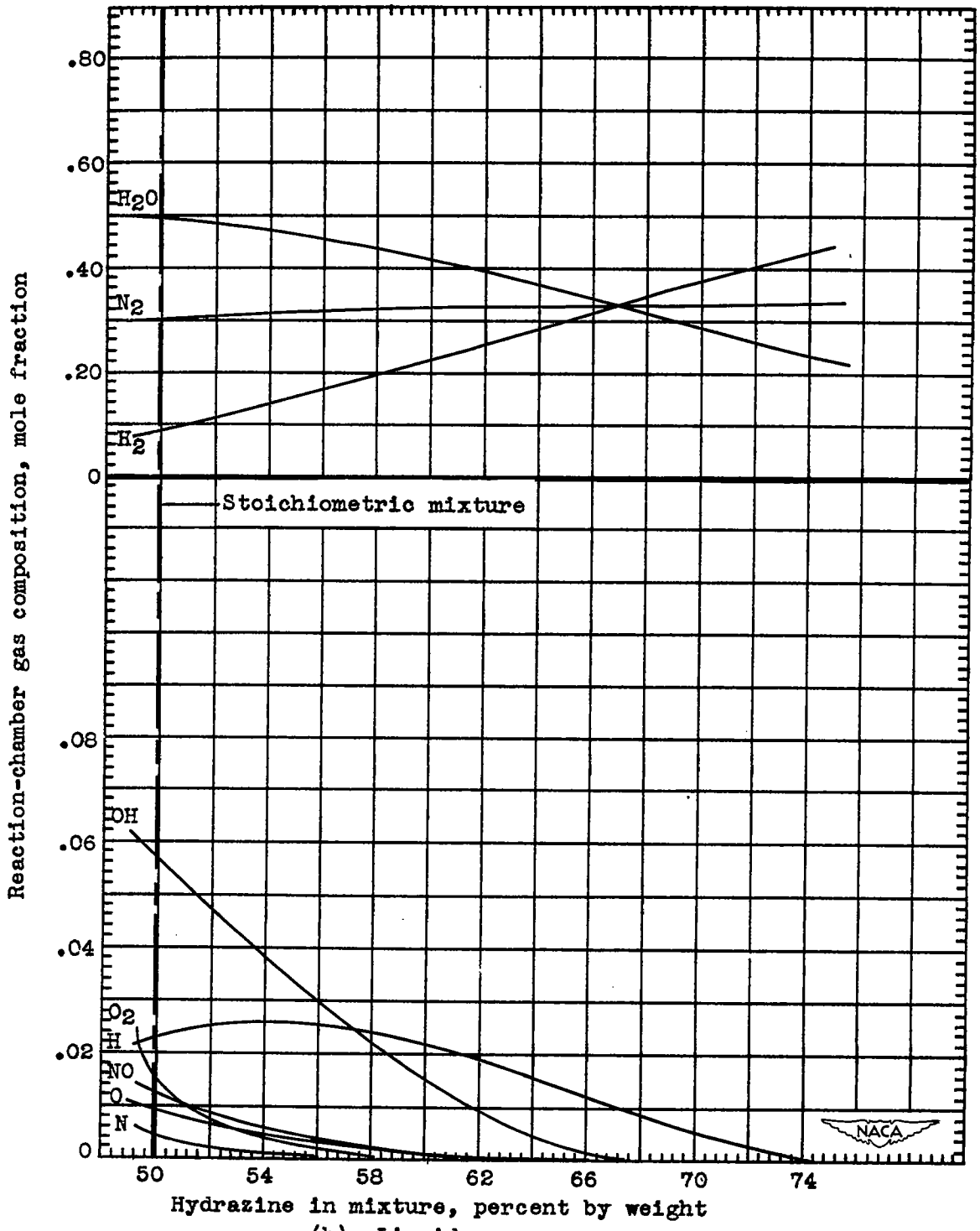


(a) Liquid ozone.

Figure 2. - Composition of reaction-chamber gas from hydrazine with liquid ozone, with liquid oxygen, and with 100-percent hydrogen peroxide. Reaction-chamber pressure, 300 pounds per square inch absolute. (Curves from reference 6)



(b) Liquid oxygen.

Figure 2. - Continued. Composition of reaction-chamber gas from hydrazine with liquid ozone, with liquid oxygen, and with 100-percent hydrogen peroxide. Reaction-chamber pressure, 300 pounds per square inch absolute. (Curves from reference 6)

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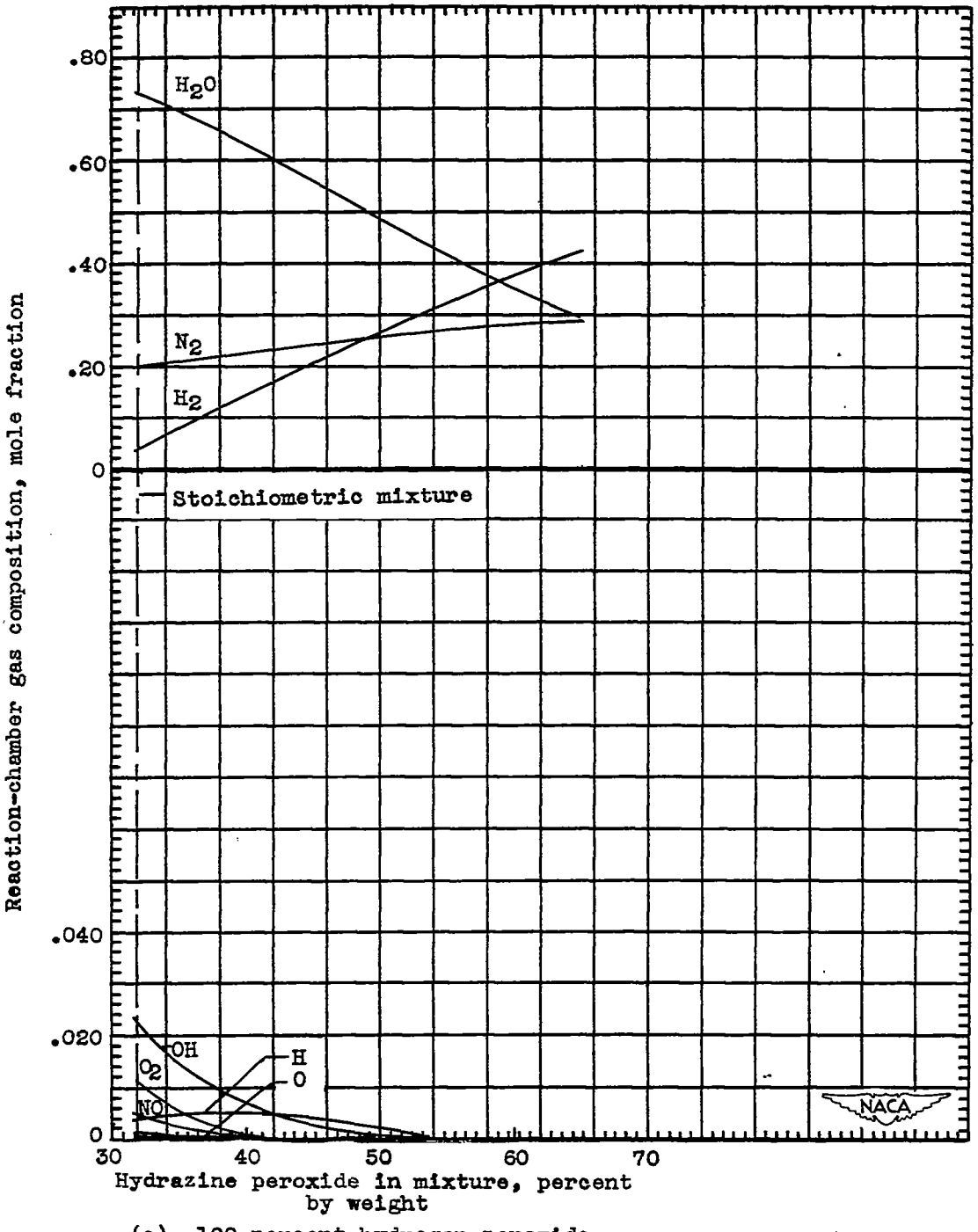
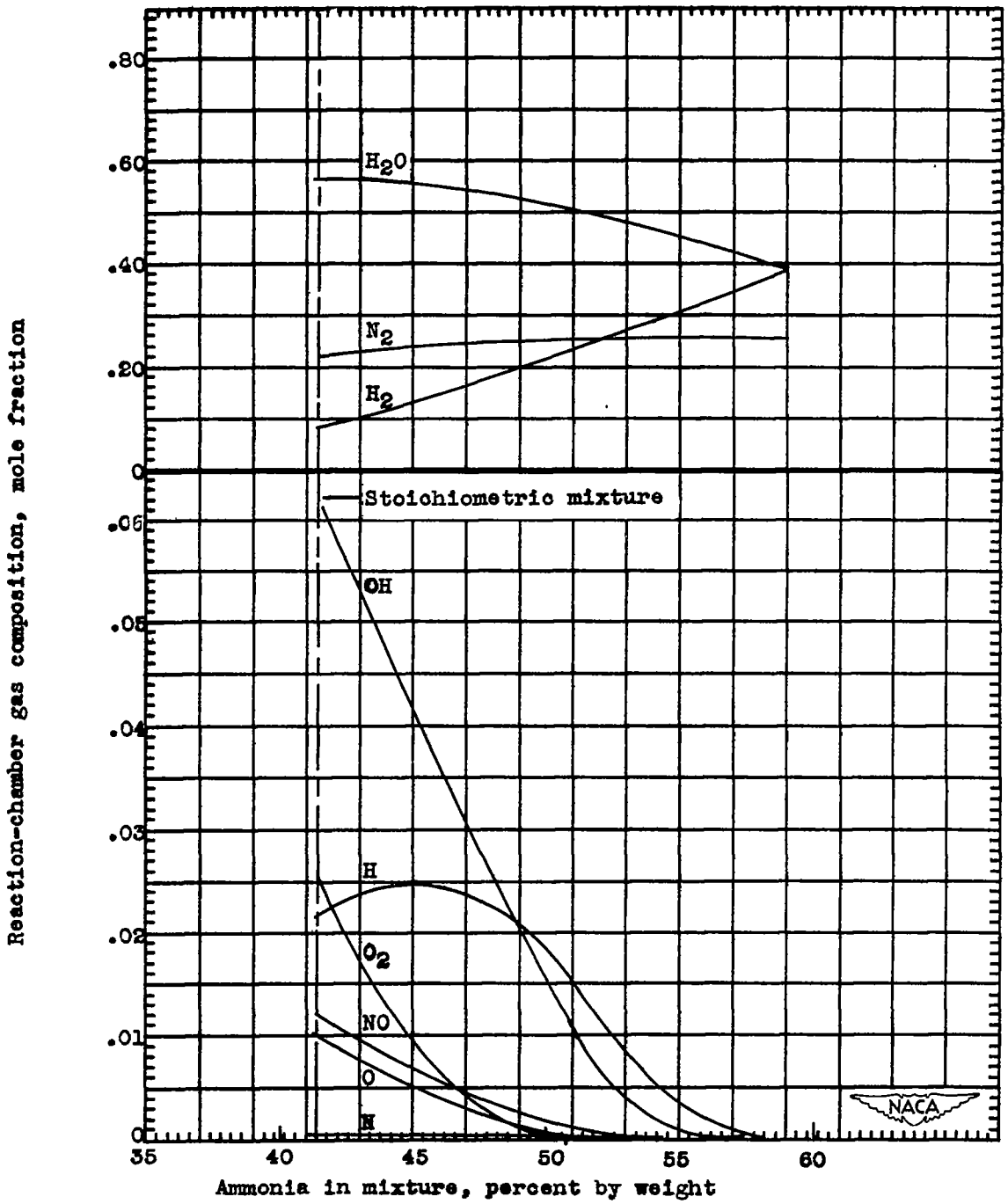


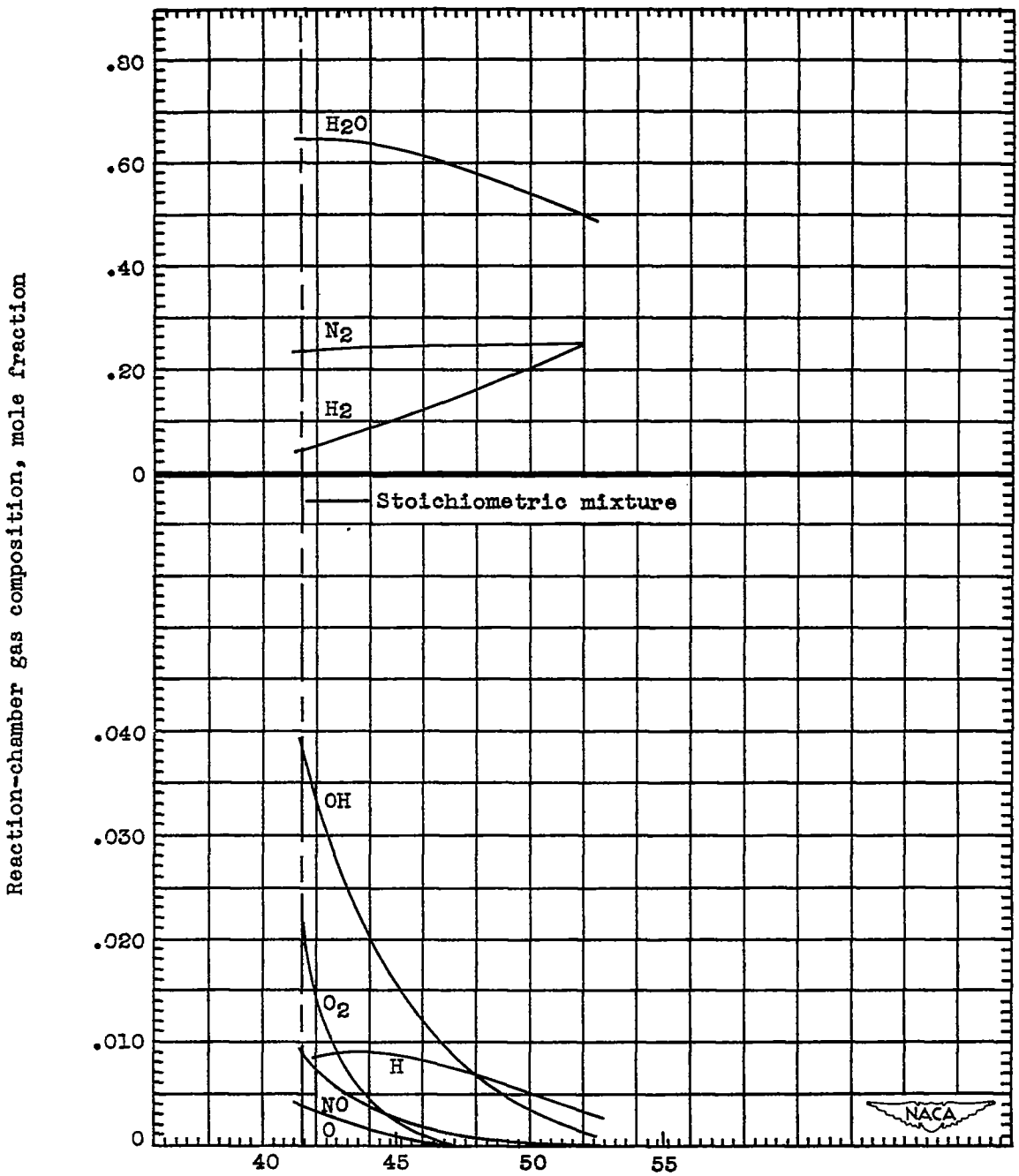
(c) 100-percent hydrogen peroxide.

Figure 2. - Concluded. Composition of reaction-chamber gas from hydrazine with liquid ozone, with liquid oxygen, and with 100-percent hydrogen peroxide. Reaction-chamber pressure, 300 pounds per square inch absolute. (Curves from reference 6)



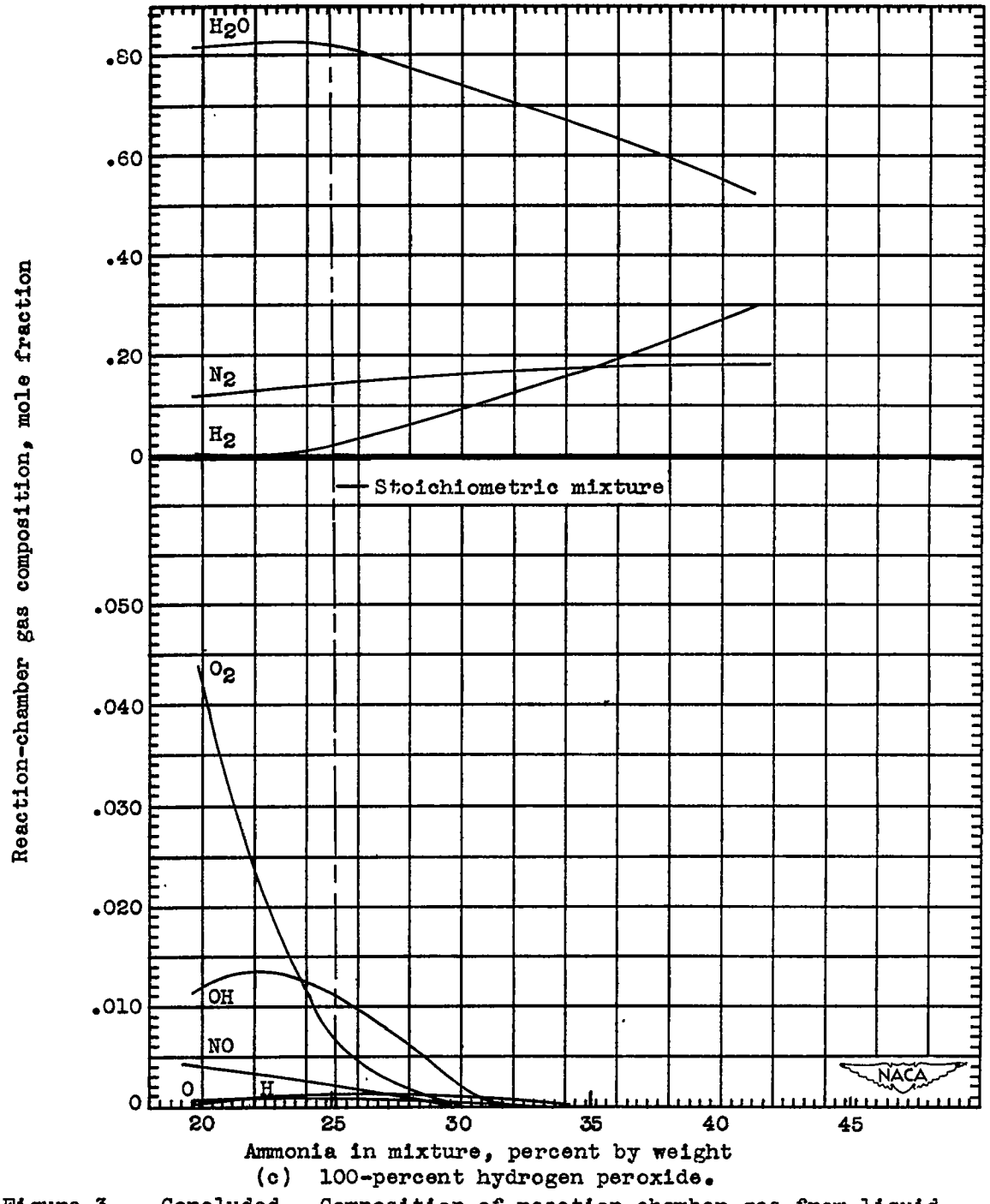
(a) Liquid ozone.

Figure 3. - Composition of reaction-chamber gas from liquid ammonia with liquid ozone, with liquid oxygen, and with 100-percent hydrogen peroxide. Reaction-chamber pressure, 300 pounds per square inch absolute.



(b) Liquid oxygen.

Figure 3. - Continued. Composition of reaction-chamber gas from liquid ammonia with liquid ozone, with liquid oxygen, and with 100-percent hydrogen peroxide. Reaction-chamber pressure, 300 pounds per square inch absolute.



(c) 100-percent hydrogen peroxide.

Figure 3. - Concluded. Composition of reaction-chamber gas from liquid ammonia with liquid ozone, with liquid oxygen, and with 100-percent hydrogen peroxide. Reaction-chamber pressure, 300 pounds per square inch absolute.

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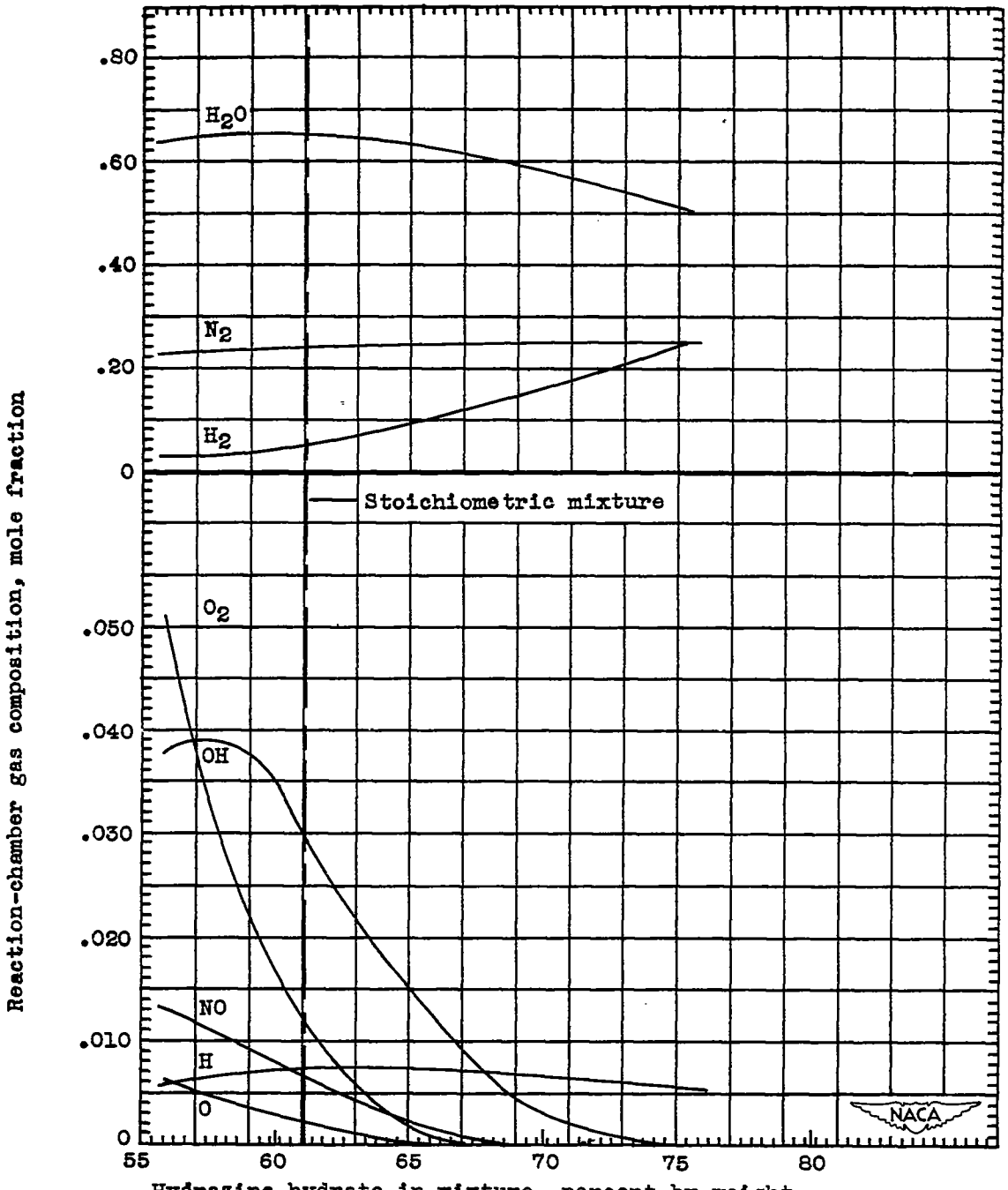
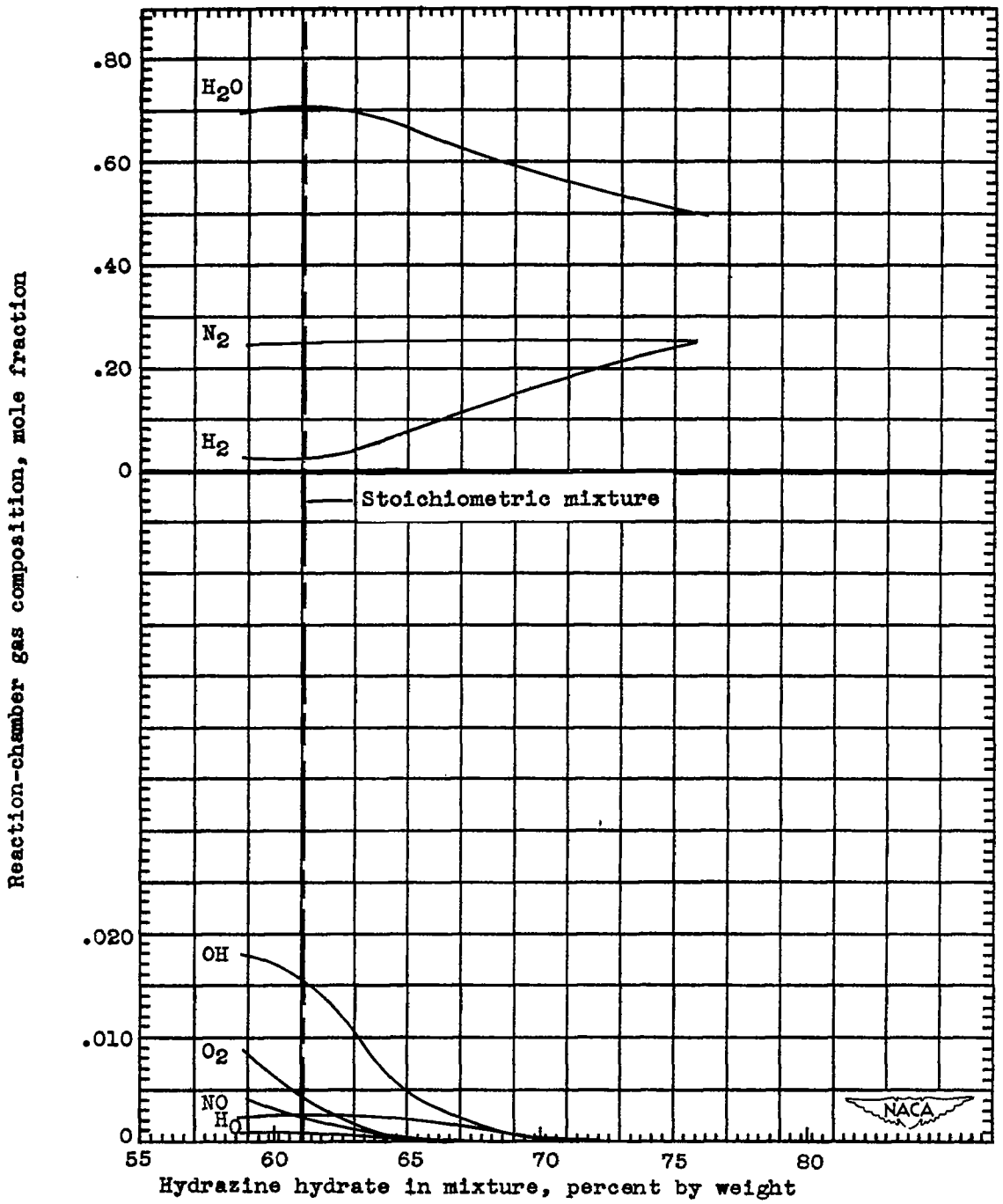


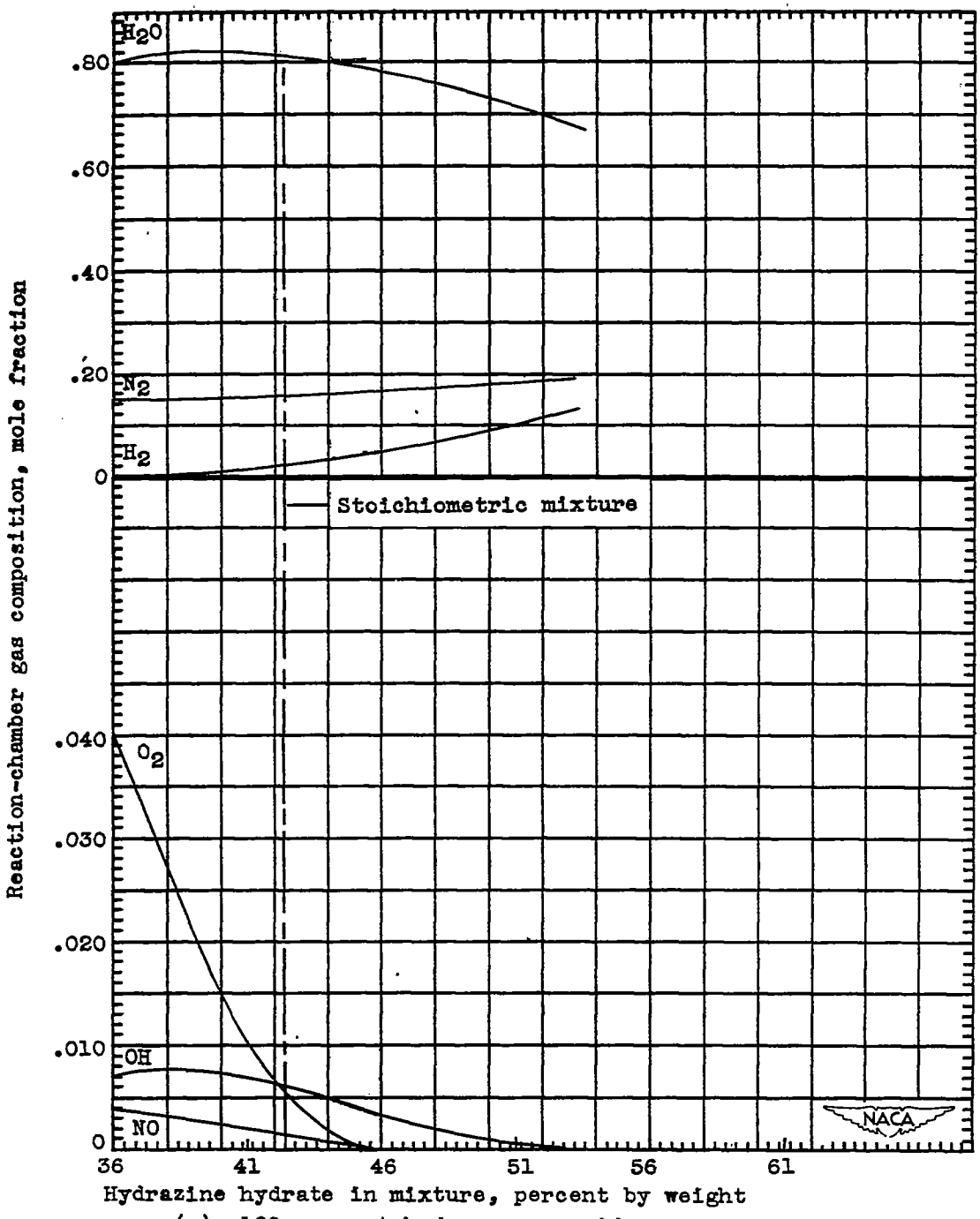
(a) Liquid ozone.

Figure 4. - Composition of reaction-chamber gas from hydrazine hydrate with liquid ozone, with liquid oxygen, and with 100-percent hydrogen peroxide. Reaction-chamber pressure, 300 pounds per square inch absolute.



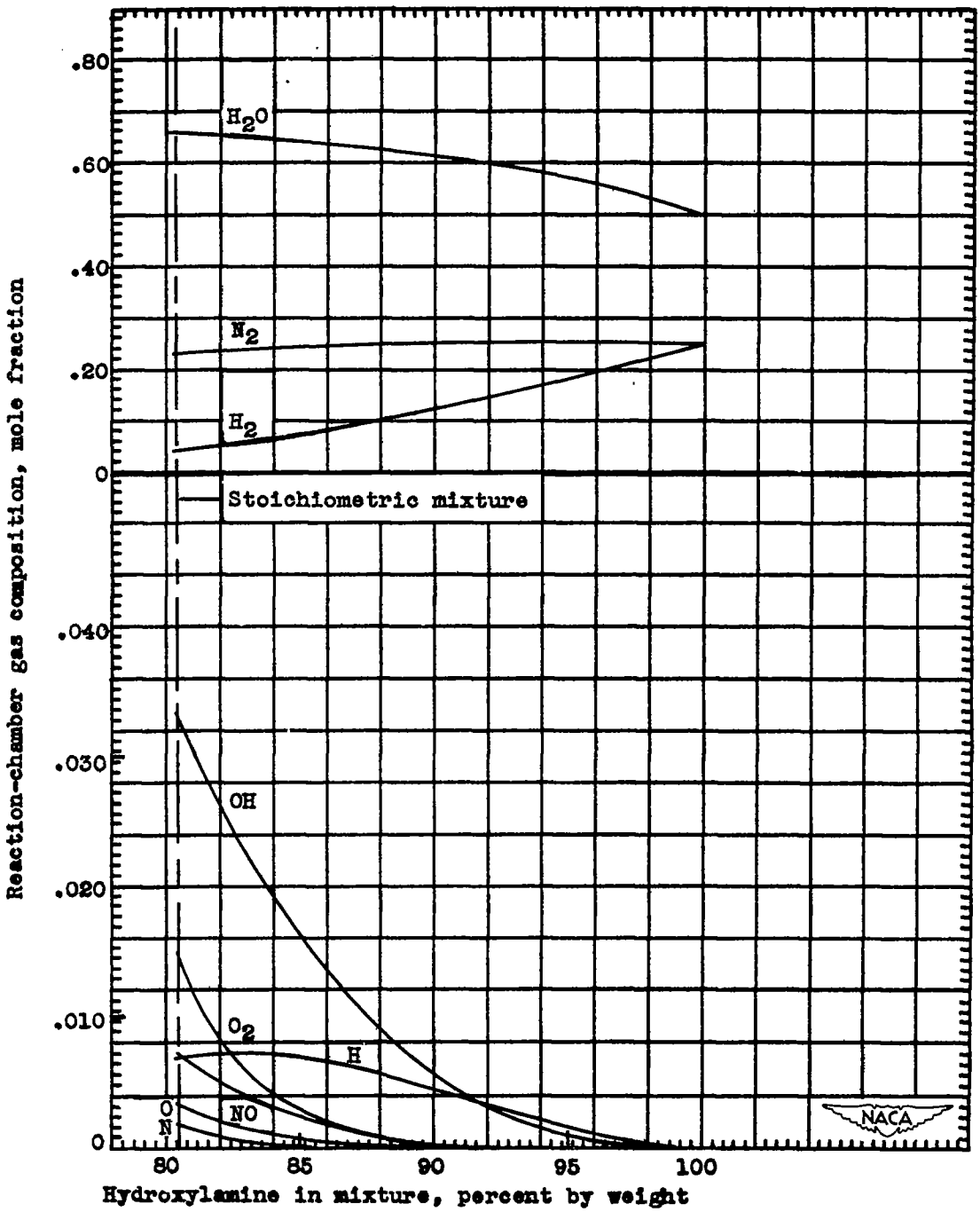
(b) Liquid oxygen.

Figure 4. - Continued. Composition of reaction-chamber gas from hydrazine hydrate with liquid ozone, with liquid oxygen, and with 100-percent hydrogen peroxide. Reaction-chamber pressure, 300 pounds per square inch absolute.



(c) 100-percent hydrogen peroxide.

Figure 4. - Concluded. Composition of reaction-chamber gas from hydrazine hydrate with liquid ozone, with liquid oxygen, and with 100-percent hydrogen peroxide. Reaction-chamber pressure, 300 pounds per square inch absolute.



(a) Liquid ozone.

Figure 5. - Composition of reaction-chamber gas from hydroxylamine as monofuel, with liquid ozone, and with liquid oxygen. Reaction-chamber pressure, 300 pounds per square inch absolute.

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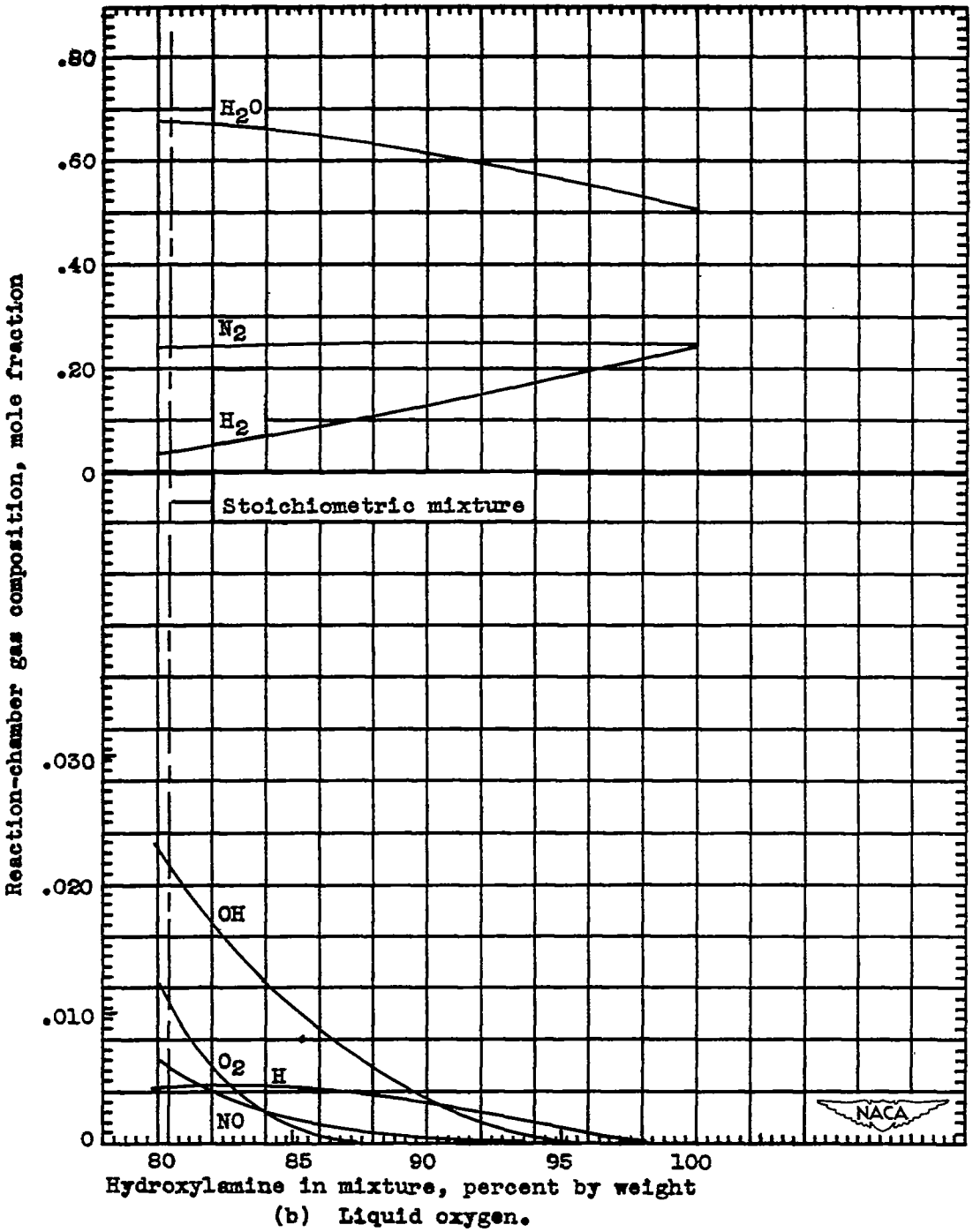
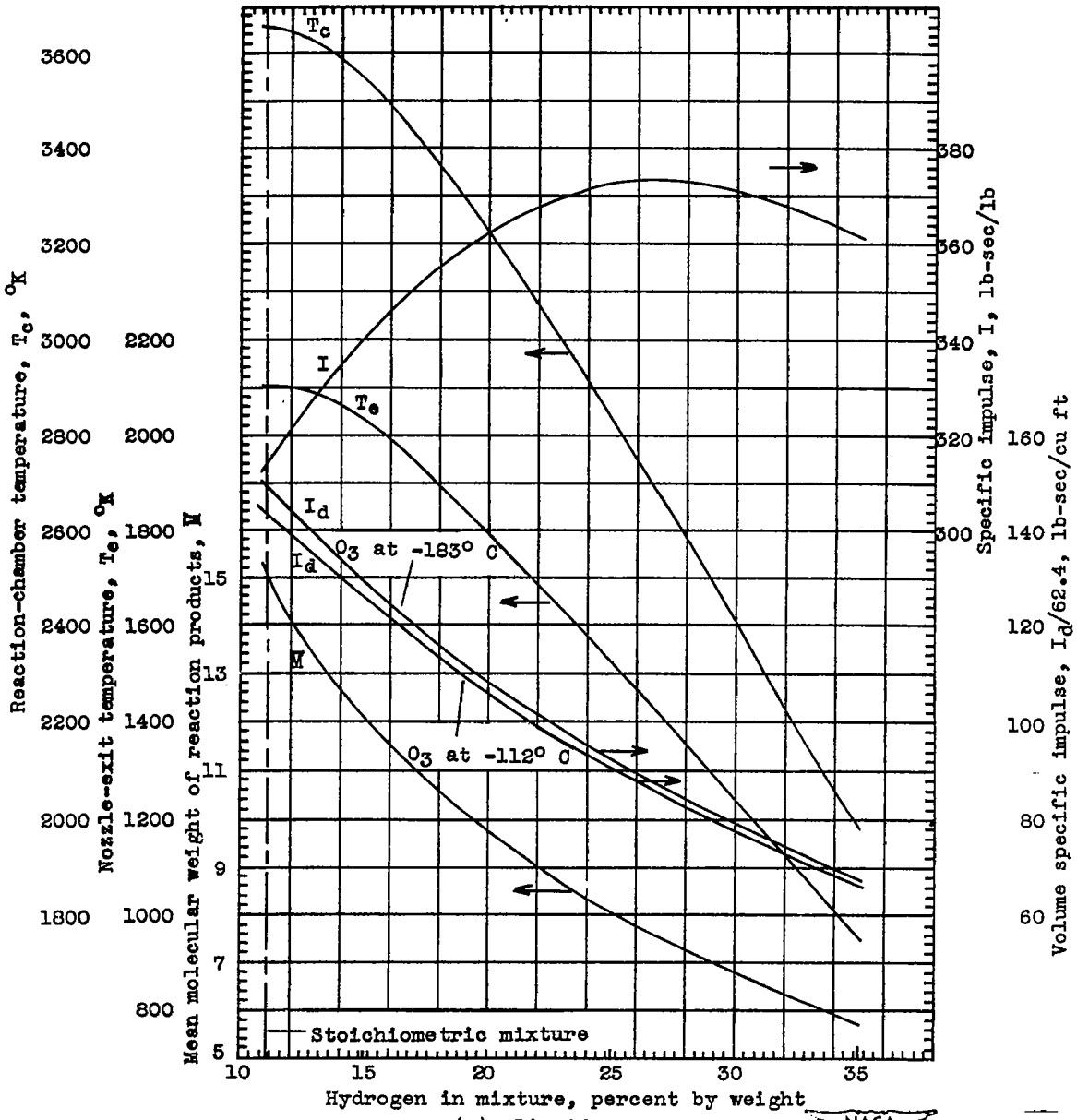


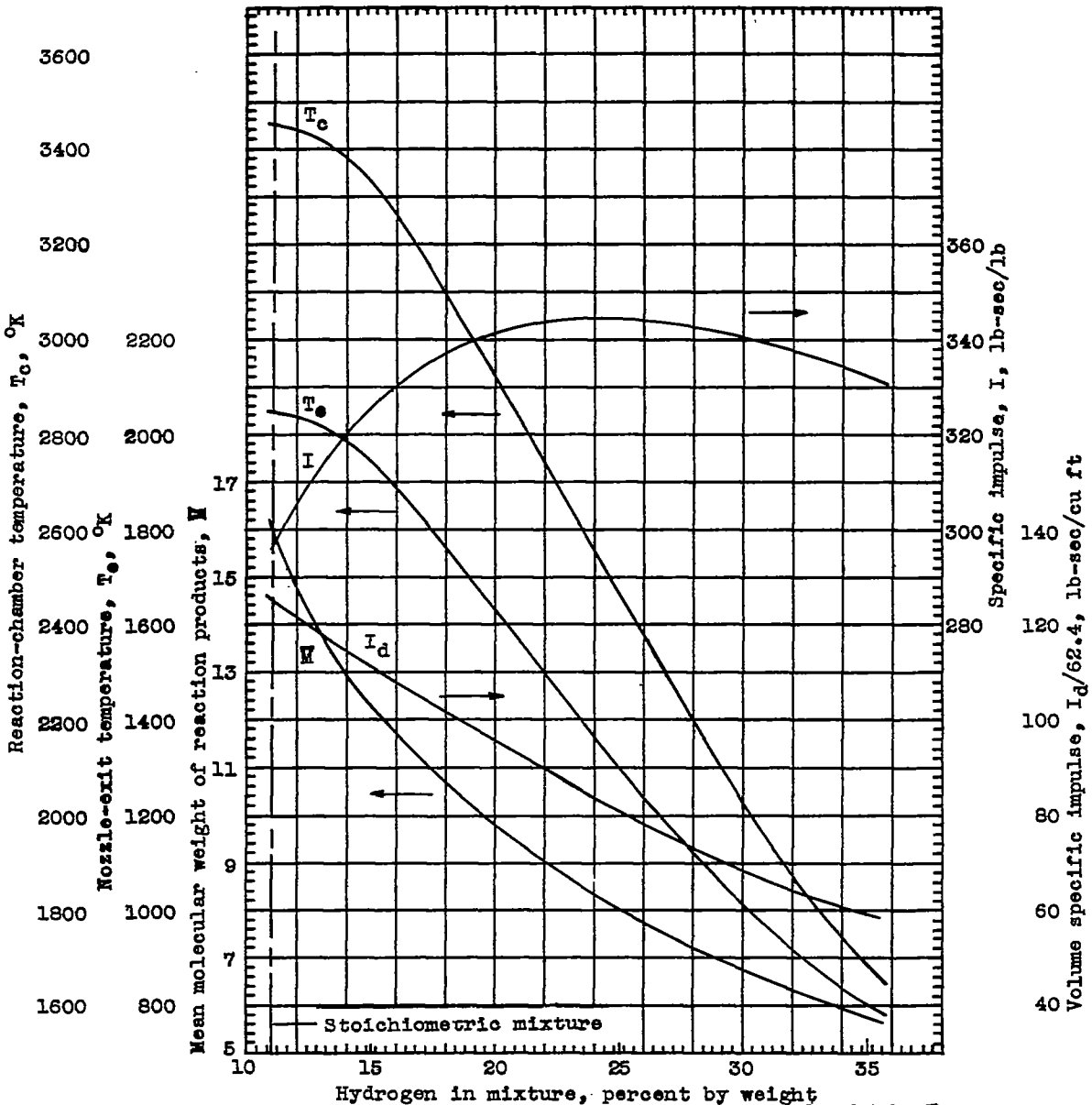
(b) Liquid oxygen.

Figure 5. - Concluded. Composition of reaction-chamber gas from hydroxylamine as monofuel, and with liquid ozone, and with liquid oxygen. Reaction-chamber pressure, 300 pounds per square inch absolute.



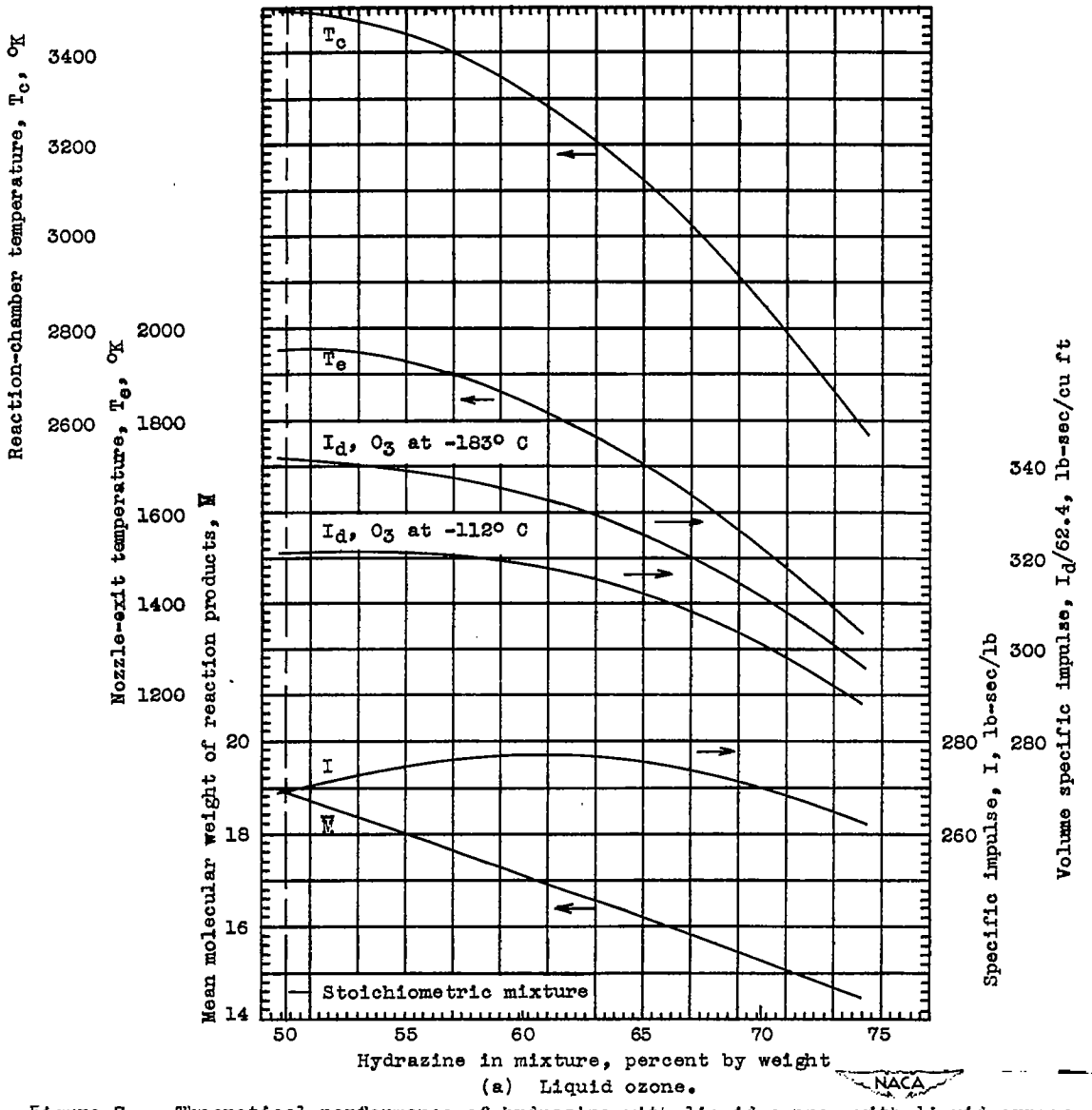
(a) Liquid ozone.

Figure 6. - Theoretical performance of liquid hydrogen with liquid ozone and with liquid oxygen. Reaction-chamber pressure, 300 pounds per square inch absolute; expansion ratio, 20.4; frozen equilibrium during expansion.



(b) Liquid oxygen.

Figure 6. - Concluded. Theoretical performance of liquid hydrogen with liquid ozone and with liquid oxygen. Reaction-chamber pressure, 300 pounds per square inch absolute; expansion ratio, 20.4; frozen equilibrium during expansion.



(a) Liquid ozone.

Figure 7. - Theoretical performance of hydrazine with liquid ozone, with liquid oxygen, and with 100-percent hydrogen peroxide. Reaction-chamber pressure, 300 pounds per square inch absolute; expansion ratio, 20.4; frozen equilibrium during expansion. (Reference 6).

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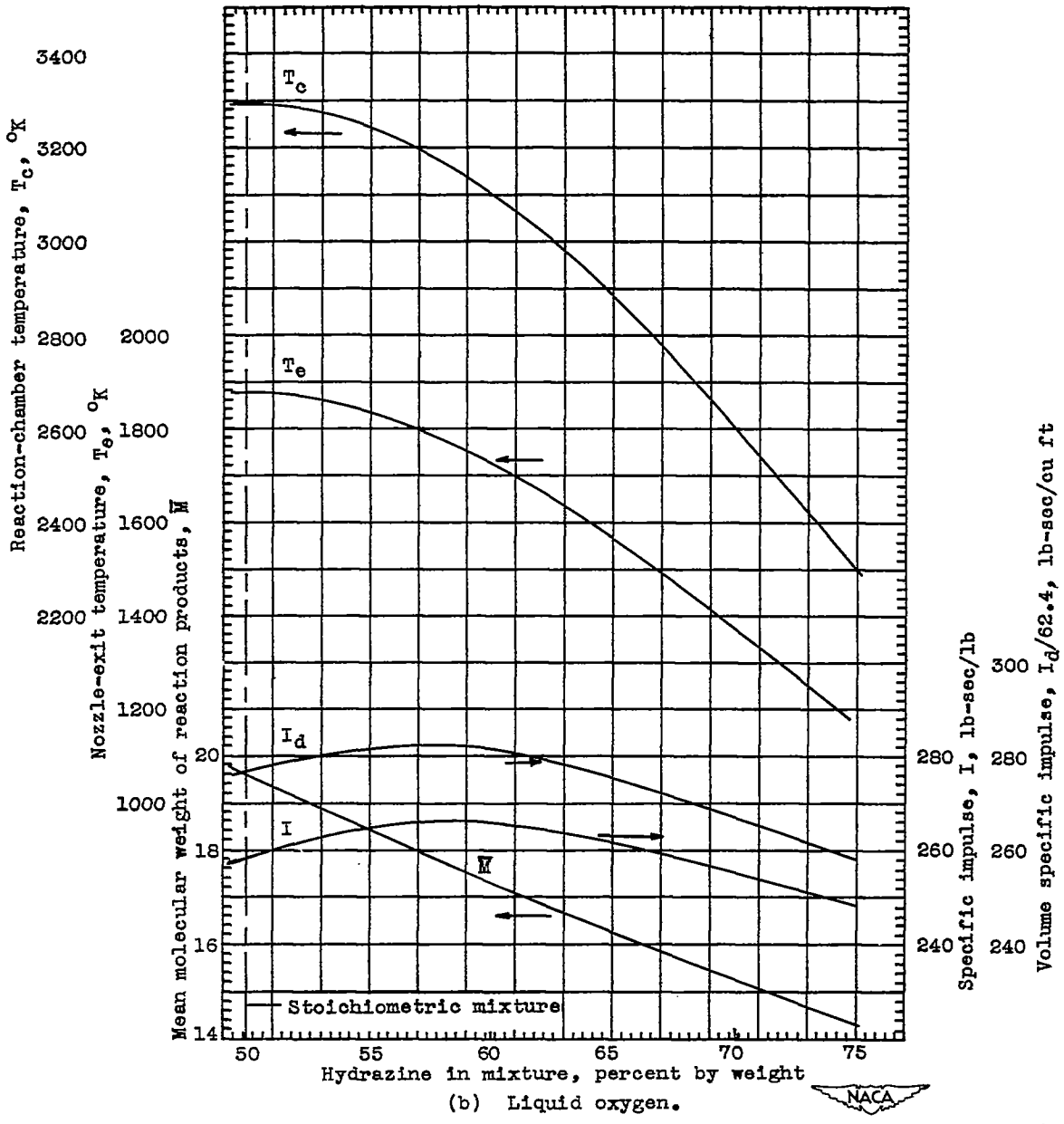
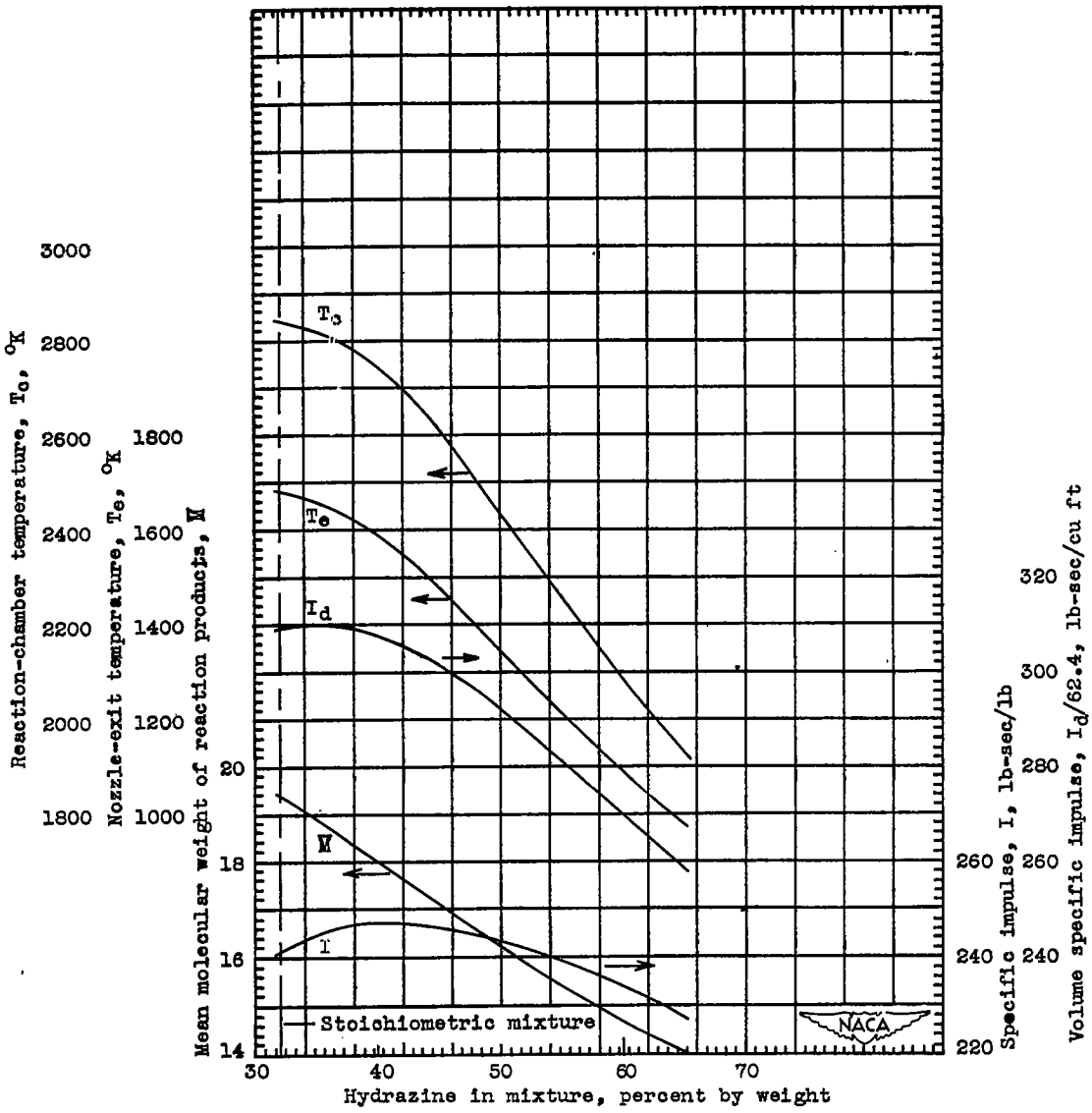


(b) Liquid oxygen.

Figure 7. - Continued. Theoretical performance of hydrazine with liquid ozone, with liquid oxygen, and with 100-percent hydrogen peroxide. Reaction-chamber pressure, 300 pounds per square inch absolute; expansion ratio, 20.4; frozen equilibrium during expansion. (Reference 6).



(c) 100-percent hydrogen peroxide.

Figure 7. - Concluded. Theoretical performance of hydrazine with liquid ozone, with liquid oxygen, and with 100-percent hydrogen peroxide. Reaction-chamber pressure, 300 pounds per square inch absolute; expansion ratio, 20.4; frozen equilibrium during expansion. (Reference 6).

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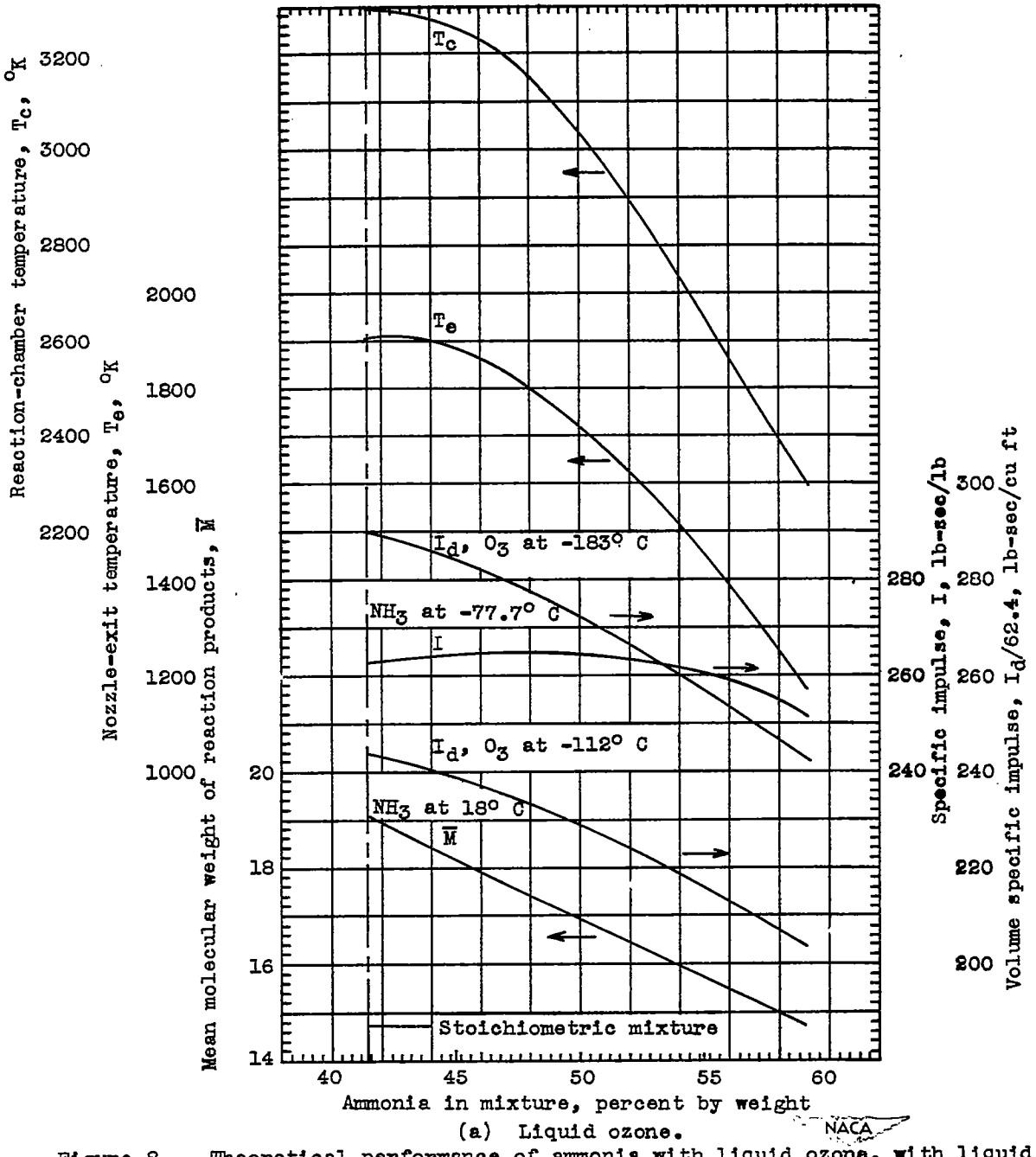
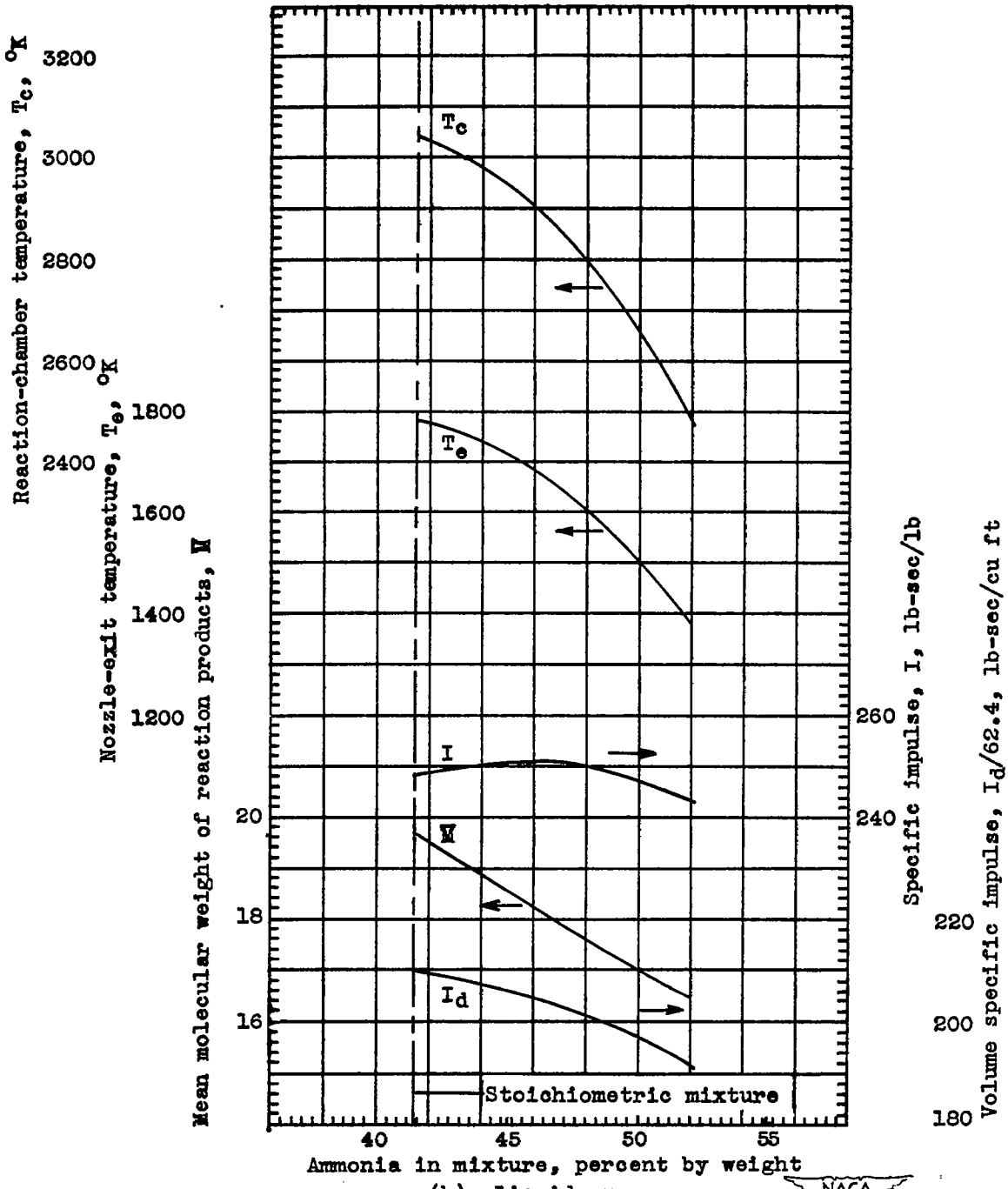


(a) Liquid ozone.

Figure 8. - Theoretical performance of ammonia with liquid ozone, with liquid oxygen, and with 100-percent hydrogen peroxide. Reaction-chamber pressure, 300 pounds per square inch absolute; expansion ratio, 20.4; frozen equilibrium during expansion.



(b) Liquid oxygen.

Figure 8. - Continued. Theoretical performance of ammonia with liquid ozone, with liquid oxygen, and with 100-percent hydrogen peroxide. Reaction-chamber pressure, 300 pounds per square inch absolute; expansion ratio, 20.4; frozen equilibrium during expansion.

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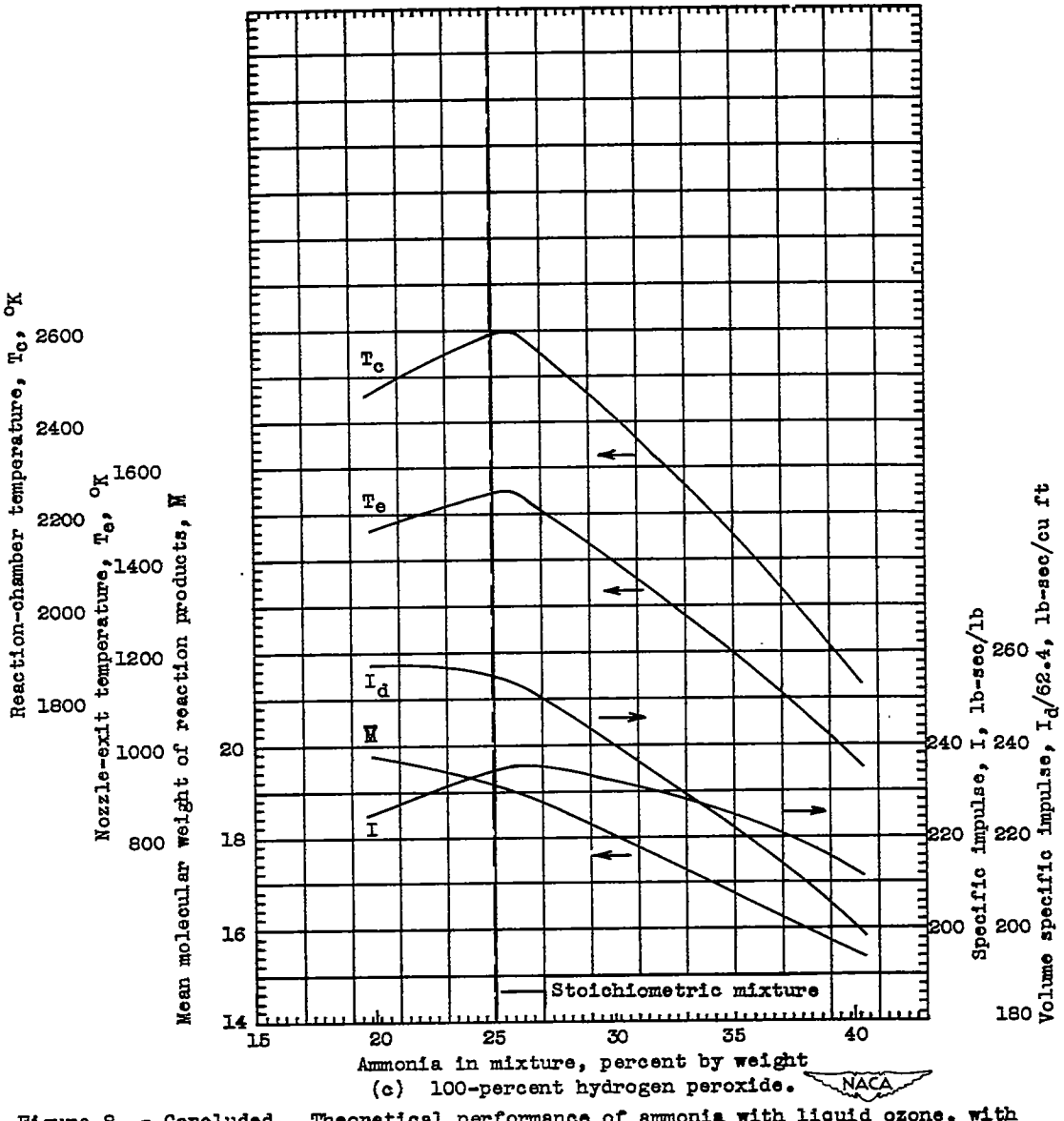
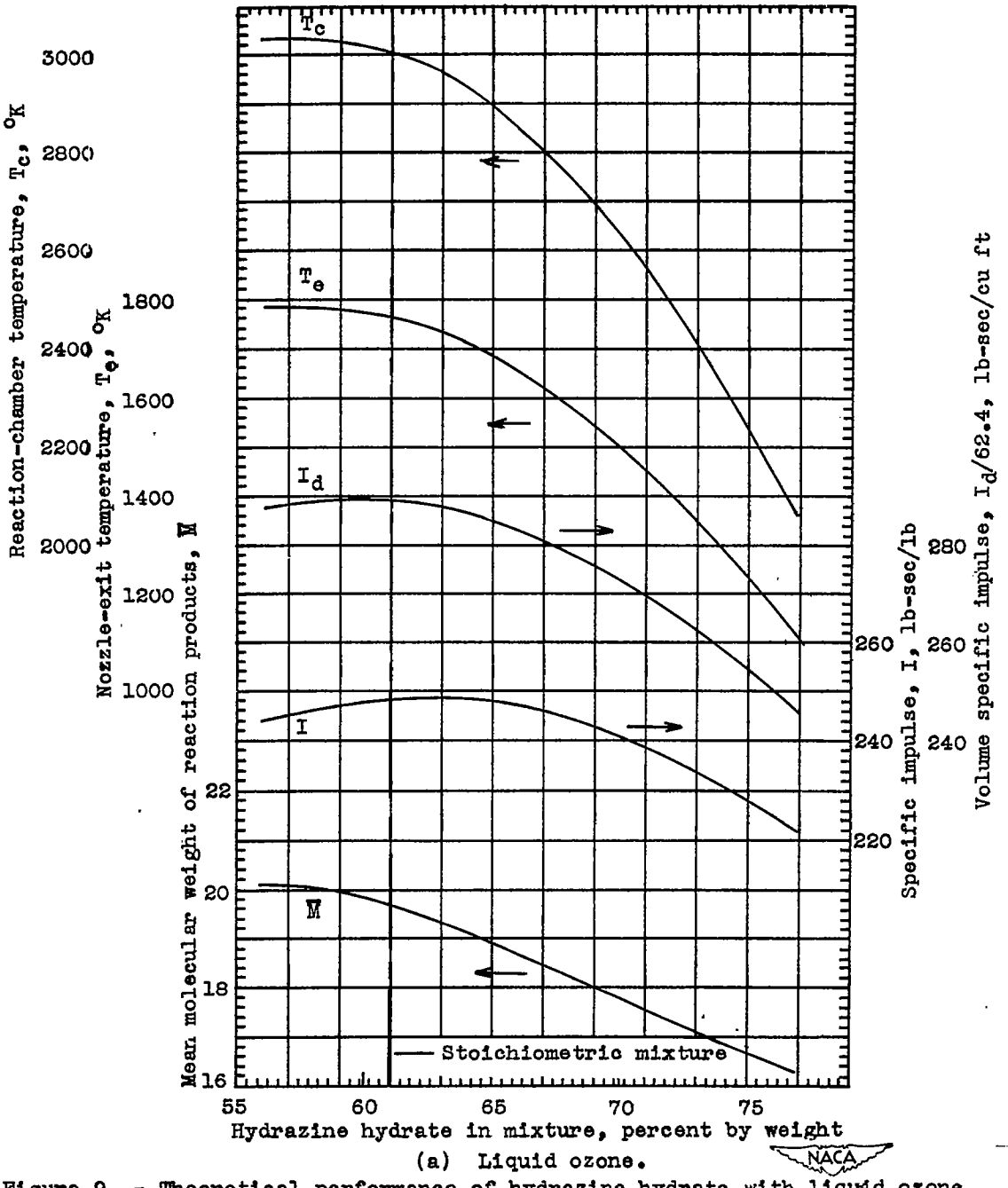


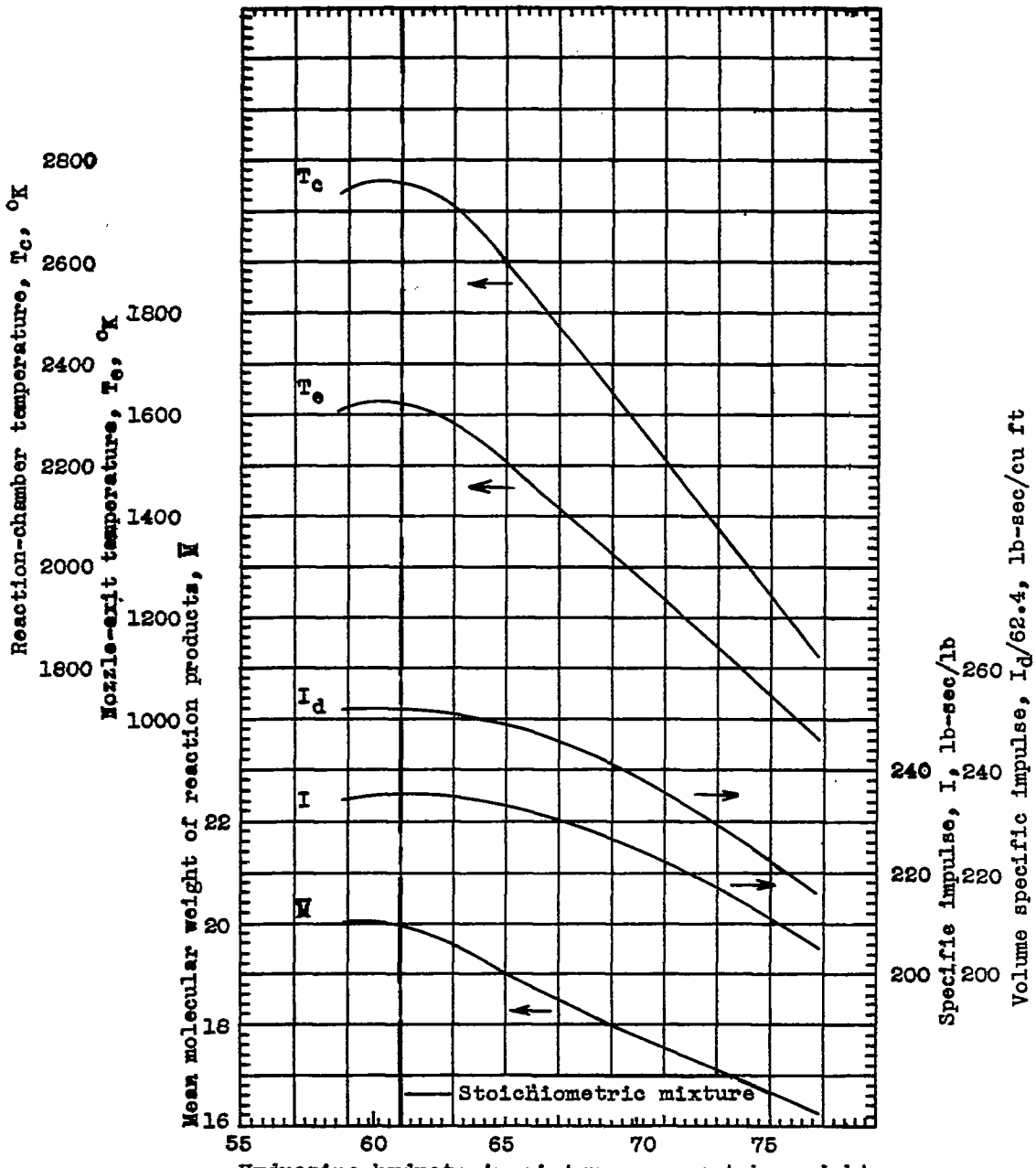
(c) 100-percent hydrogen peroxide.

Figure 8. - Concluded. Theoretical performance of ammonia with liquid ozone, with liquid oxygen, and with 100-percent hydrogen peroxide. Reaction-chamber pressure, 300 pounds per square inch absolute; expansion ratio, 20.4; frozen equilibrium during expansion.



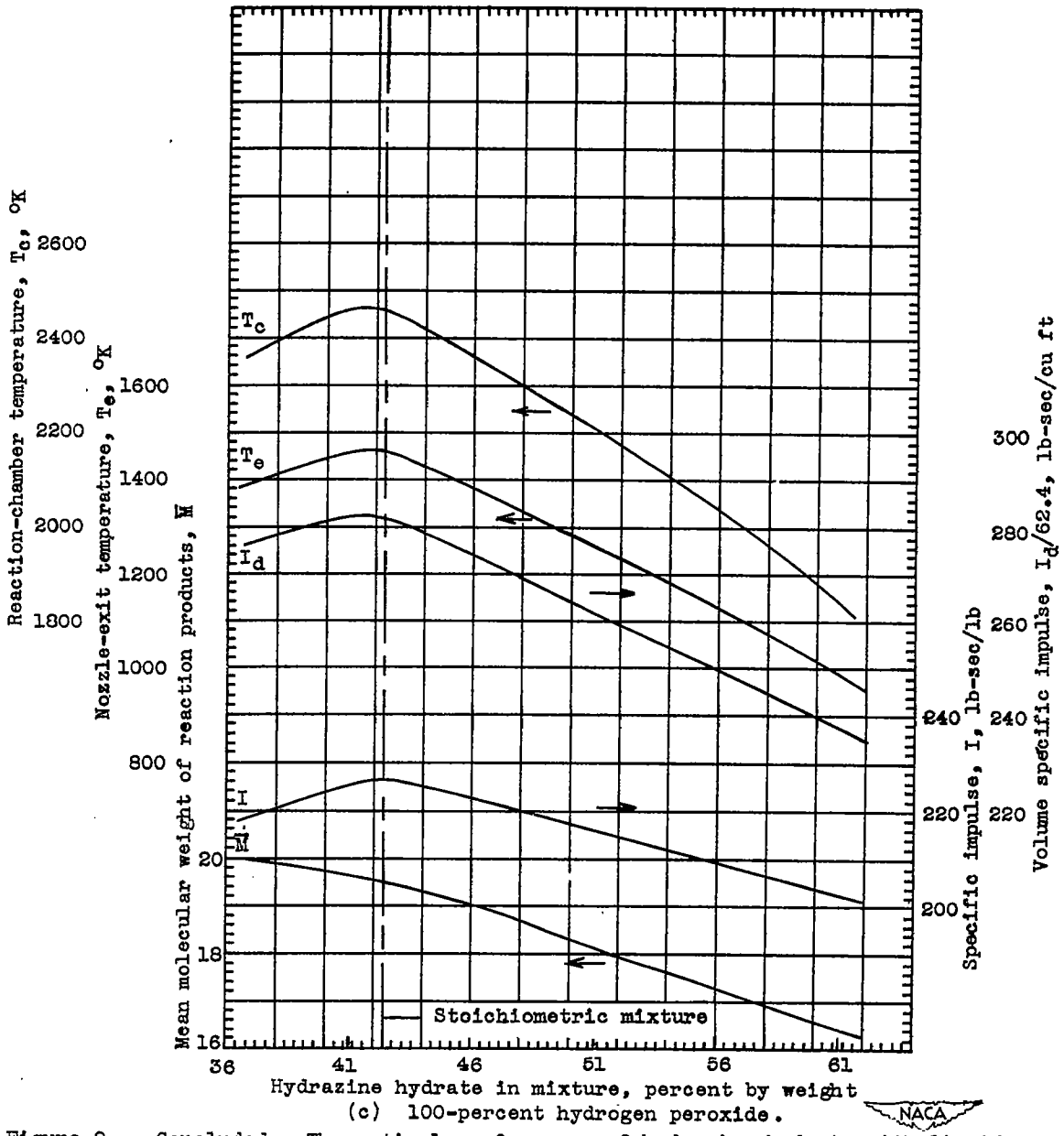
(a) Liquid ozone.

Figure 9. - Theoretical performance of hydrazine hydrate with liquid ozone, with liquid oxygen, and with 100-percent hydrogen peroxide. Reaction-chamber pressure, 300 pounds per square inch absolute; expansion ratio, 20.4; frozen equilibrium during expansion.



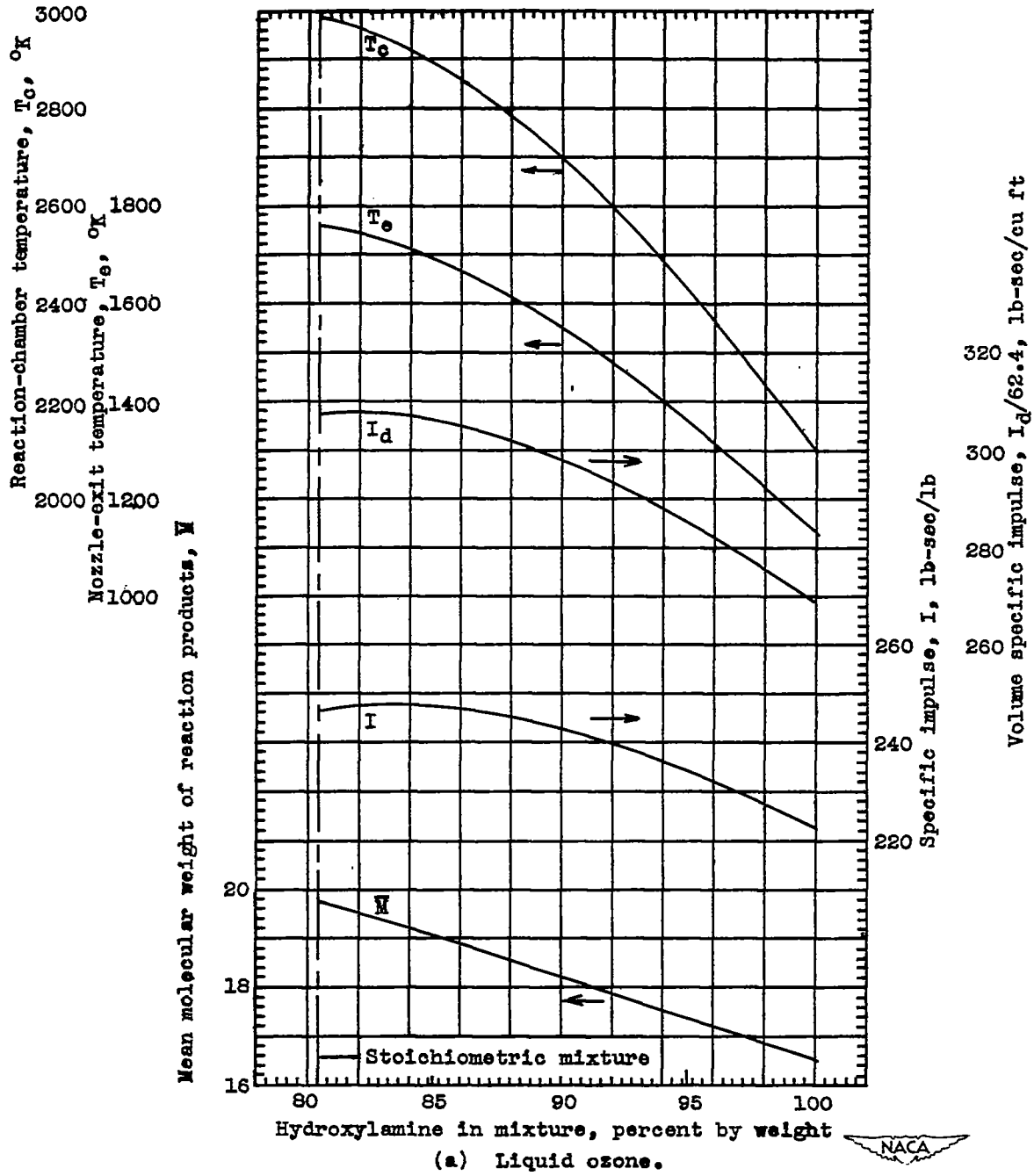
(b) Liquid oxygen.

Figure 9. - Continued. Theoretical performance of hydrazine hydrate with liquid ozone, with liquid oxygen, and with 100-percent hydrogen peroxide. Reaction-chamber pressure, 300 pounds per square inch absolute; expansion ratio, 20.4; frozen equilibrium during expansion.



(c) 100-percent hydrogen peroxide.

Figure 9. - Concluded. Theoretical performance of hydrazine hydrate with liquid ozone, with liquid oxygen, and with 100-percent hydrogen peroxide. Reaction-chamber pressure, 300 pounds per square inch absolute; expansion ratio, 20.4; frozen equilibrium during expansion.



(a) Liquid ozone.

Figure 10. - Theoretical performance of hydroxylamine with liquid ozone and with liquid oxygen. Reaction-chamber pressure, 300 pounds per square inch absolute; expansion ratio, 20.4; frozen equilibrium during expansion.

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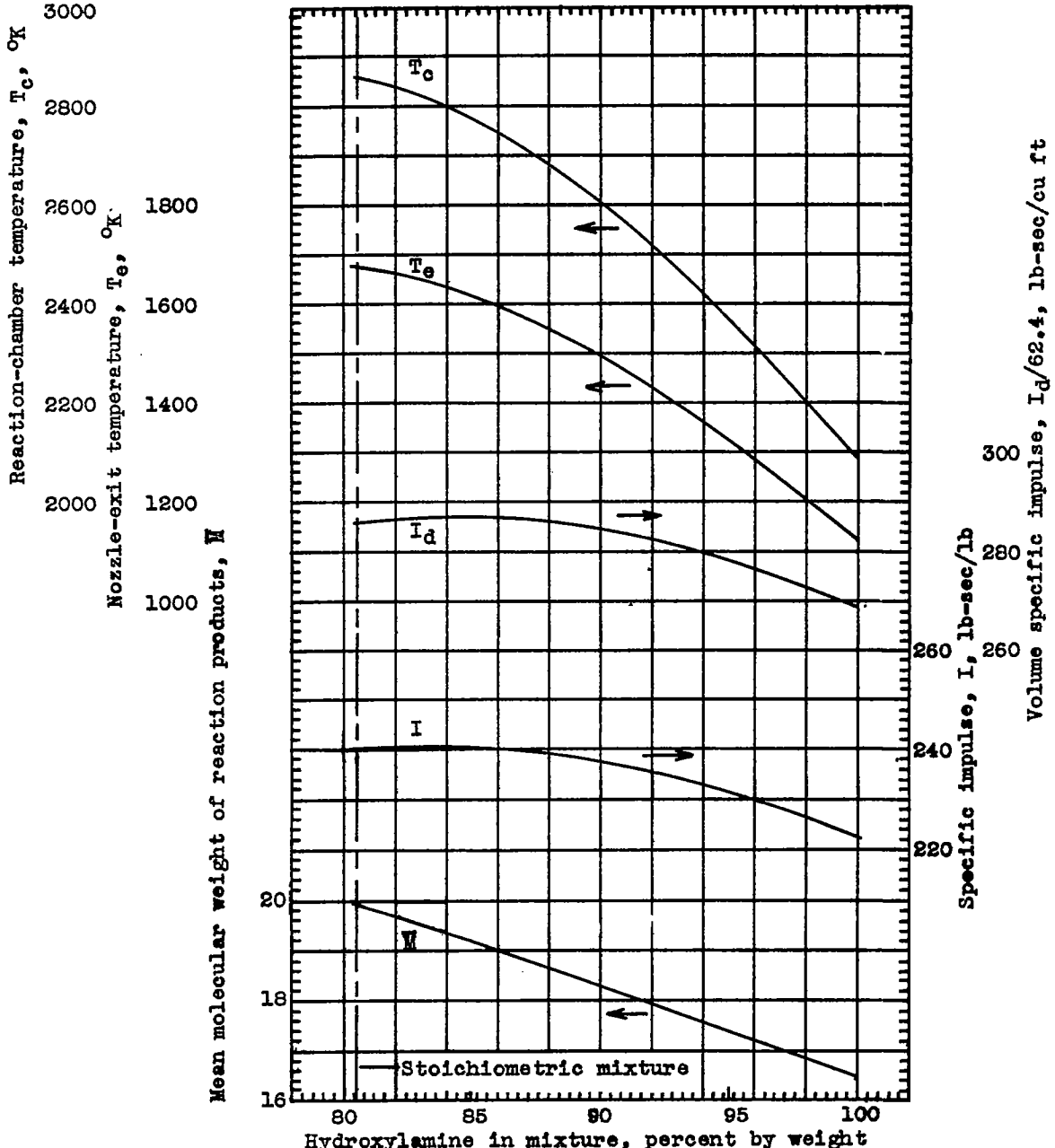

(b) Liquid oxygen.

Figure 10. - Concluded. Theoretical performance of hydroxylamine with liquid ozone and with liquid oxygen. Reaction-chamber pressure, 300 pounds per square inch absolute; expansion ratio, 20.4; frozen equilibrium during expansion.

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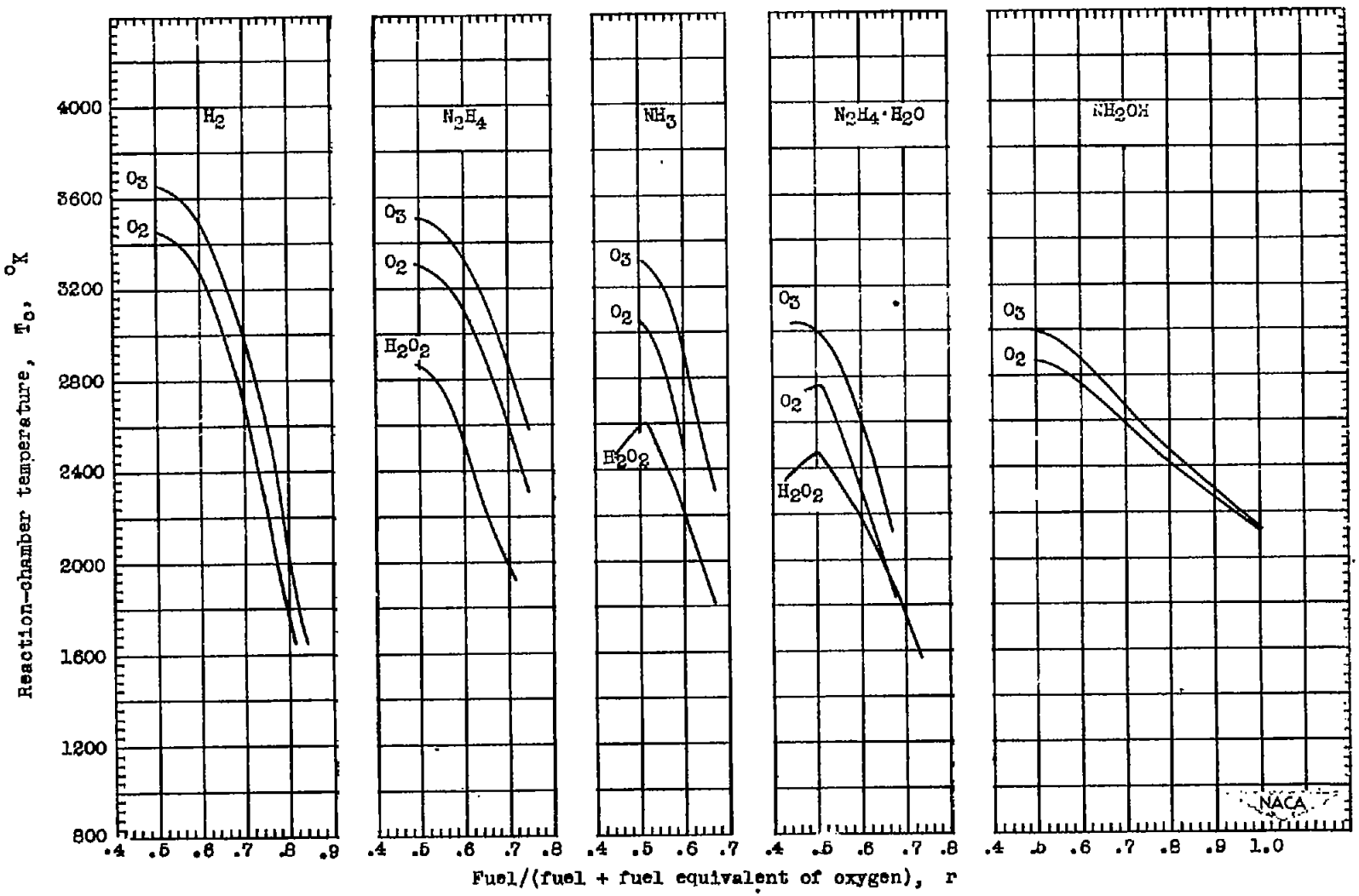
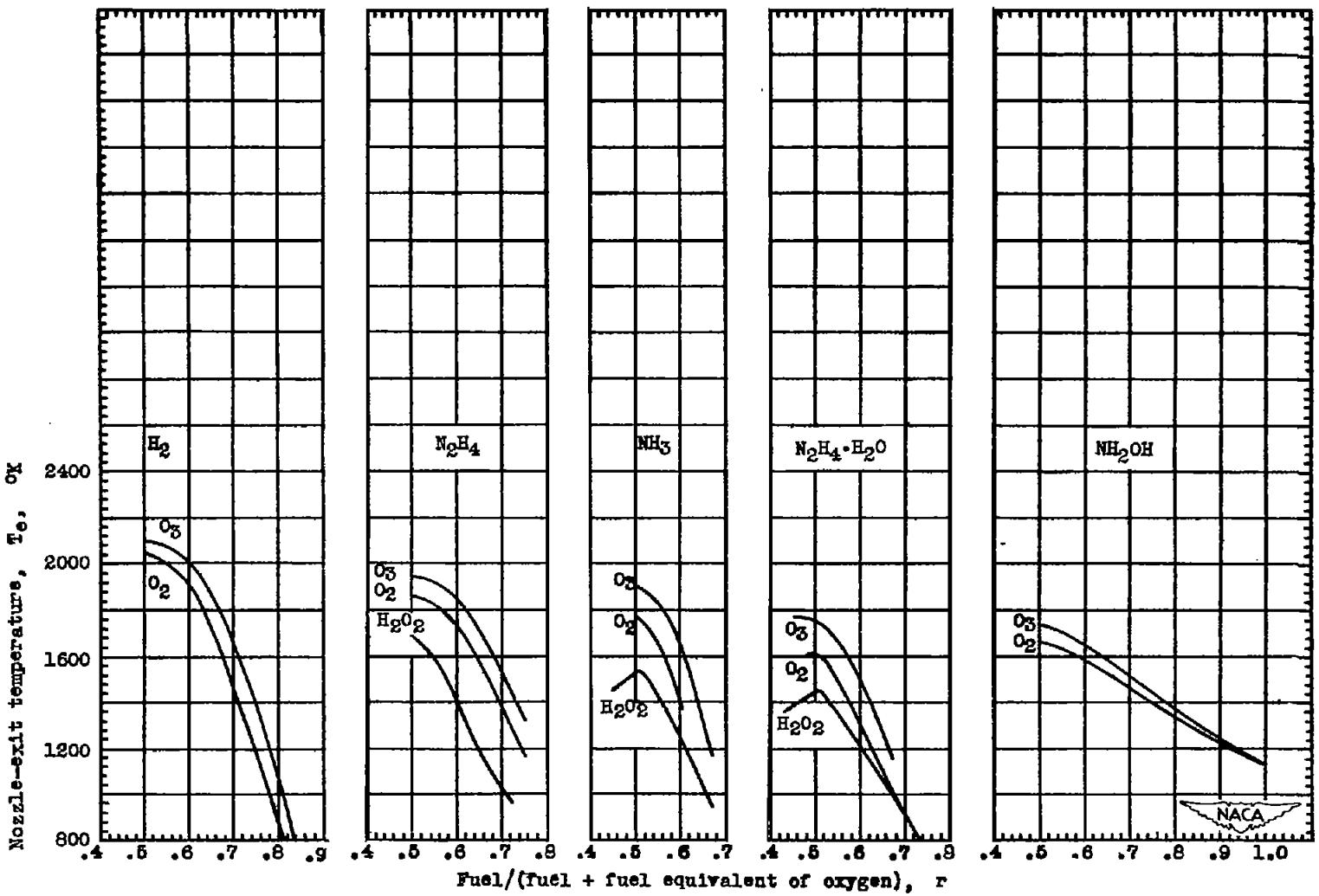


(a) Reaction-chamber temperature.

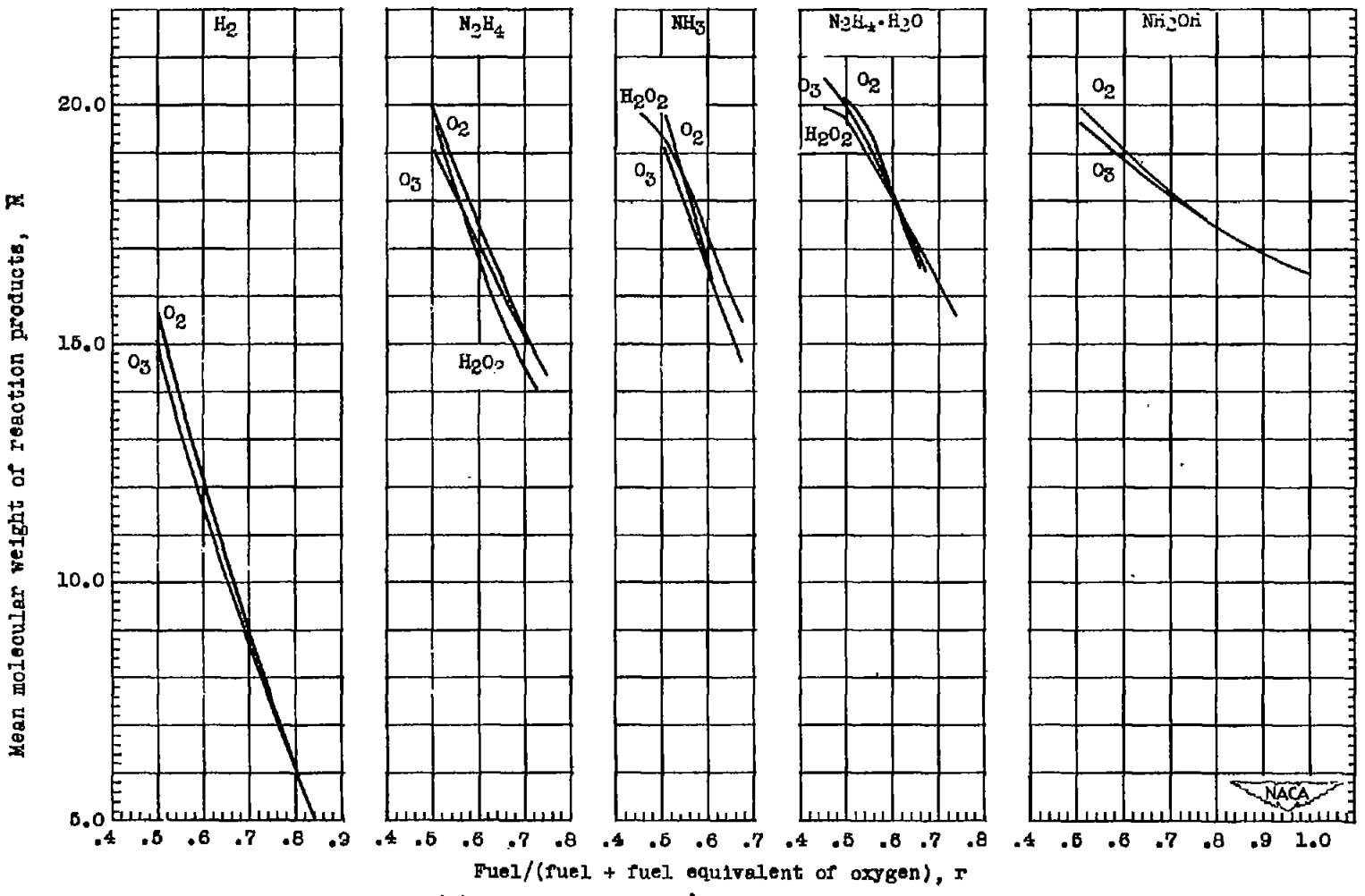
Figure 11. - Comparison of performance parameters of several rocket propellant combinations. Reaction-chamber pressure, 300 pounds per square inch absolute; expansion ratio, 20.4; frozen equilibrium during expansion.

[redacted]



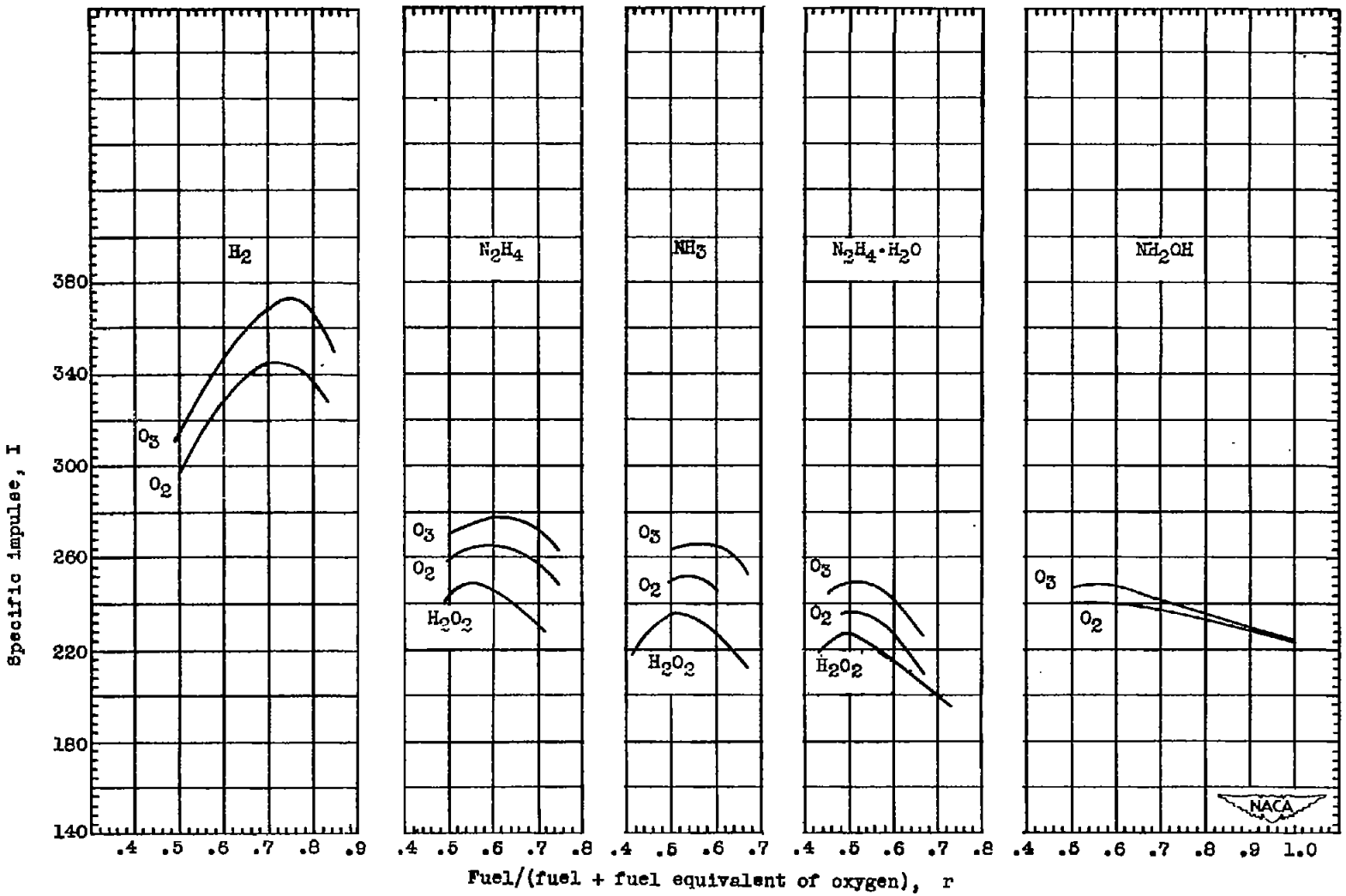
(b) Nozzle-exit temperature.

Figure 11. - Continued. Comparison of performance parameters of several rocket propellant combinations. Reaction-chamber pressure, 300 pounds per square inch absolute; expansion ratio, 20.4; frozen equilibrium during expansion.



(c) Mean molecular weight of reaction products.

Figure 11. - Continued. Comparison of performance parameters of several rocket propellant combinations. Reaction-chamber pressure, 300 pounds per square inch absolute; expansion ratio, 20.4; frozen equilibrium during expansion.



(d) Specific impulse.

Figure 11. - Continued. Comparison of performance parameters of several rocket propellant combinations. Reaction-chamber pressure, 300 pounds per square inch absolute; expansion ratio, 20.4; frozen equilibrium during expansion.

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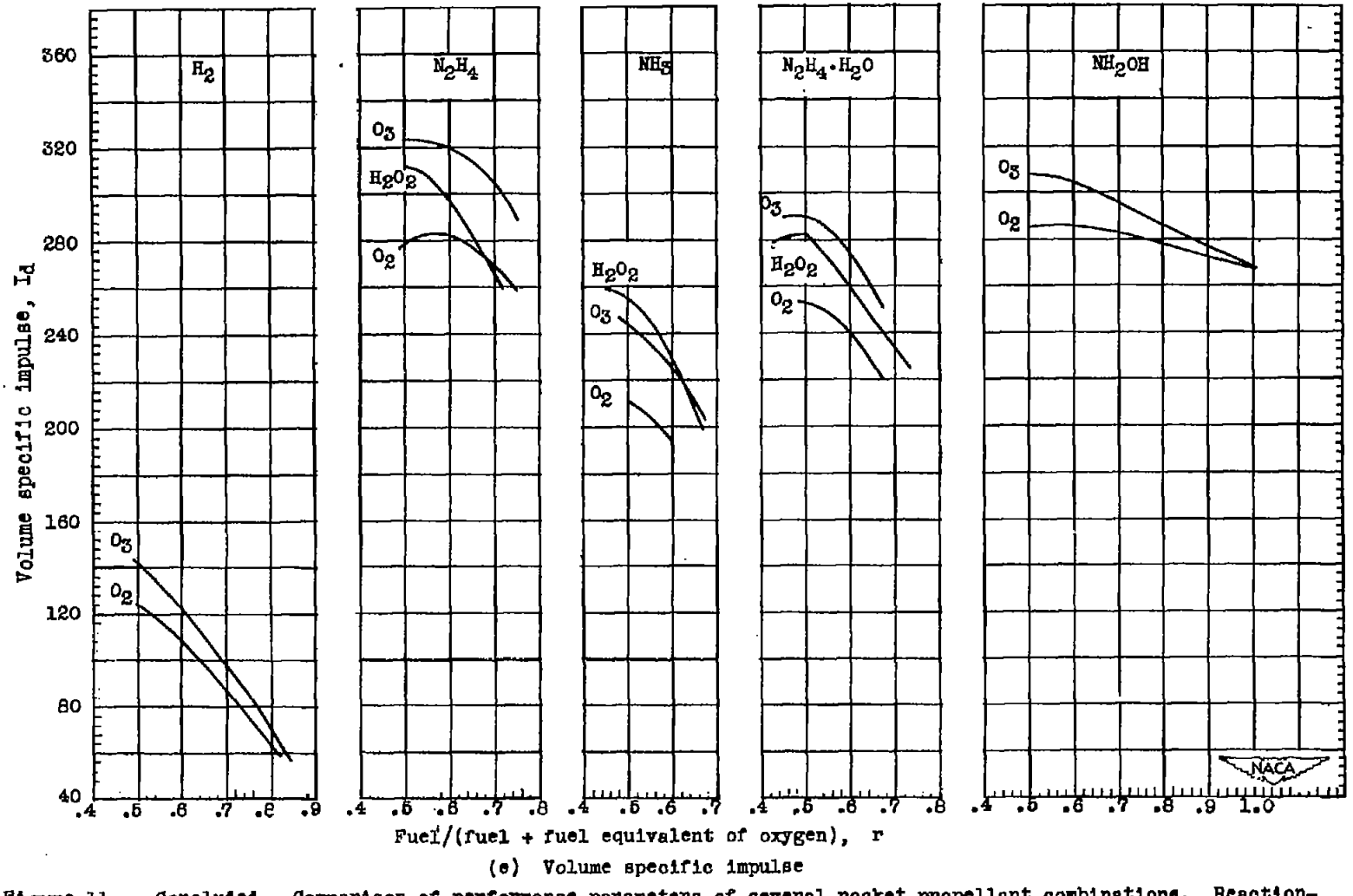

(e) Volume specific impulse

Figure 11. - Concluded. Comparison of performance parameters of several rocket propellant combinations. Reaction-chamber pressure, 300 pounds per square inch absolute; expansion ratio, 20.4; frozen equilibrium during expansion.

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