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RESEARCH MEMORANDUM

PRELIMINARY INVESTIGATION OF HYDRAZINE AS A ROCKET FUEL

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NATIONAL ADVISORY COMMITTEE
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SUMMARY

The properties of hydrazine, stability and corrosiveness with a number of construction materials, sensitivity to detonation and temperature, and spontaneous reaction with the oxidants, concentrated hydrogen peroxide, sodium permanganate solution, fuming nitric acid, and tetranitromethane, were experimentally investigated. In addition, the theoretical performance of hydrazine with liquid ozone, liquid oxygen, 100-percent hydrogen peroxide, and 100-percent nitric acid was calculated. A brief review of the manufacture, physical, chemical, and physiological properties of hydrazine is given. The results of this investigation indicated that ten metals and three nonmetallic materials were found to be suitable for use with hydrazine at ambient temperatures. Hydrazine decomposed in a closed stainless-steel bomb at constant elevated temperatures or upon gradual heating to elevated temperatures, did not propagate a detonation wave when contained in a 1/2-by-12-inch stainless-steel tube, and produced a violent spontaneous reaction with concentrated hydrogen peroxide, sodium permanganate solution, fuming nitric acid, and tetranitromethane. Theoretical calculations of the maximum specific impulse indicated values of 277.1, 265.7, 247.5, and 241.6 pound-seconds per pound with liquid ozone, liquid oxygen, 100-percent hydrogen peroxide, and 100-percent nitric acid, respectively, at a reaction-chamber pressure of 300 pounds per square inch and an expansion ratio of 20.4.

INTRODUCTION

Considerable interest exists in the use of hydrazine N_2H_4 as a rocket fuel because of the large energy per unit weight available from its decomposition. Although most of the physical, chemical, and physiological properties of hydrazine have been previously determined (references 1 to 10), data on the stability of hydrazine with various construction materials, the sensitivity to temperature and detonation, and the reactivity with various oxidants are scarce.

The results of an investigation conducted at the NACA Cleveland laboratory to determine (1) the stability and corrosiveness of 95.6-percent hydrazine at 68° F with 12 metallic and 7 nonmetallic materials, (2) the sensitivity of 95.6-percent hydrazine to gradual increases in temperature, sudden increases in temperature, prolonged heating at 400° and 446° F, and detonation, and (3) reactivity of 95.6-percent hydrazine with 87-percent hydrogen peroxide, sodium permanganate solution, red fuming nitric acid, tetranitromethane, and liquid oxygen are presented. Theoretical calculations of the specific impulses, reaction temperature, exhaust temperature, reaction-chamber gas composition, and mean molecular weight of exhaust products for a range of fuel-oxidant ratios for hydrazine and each of the oxidants, liquid ozone O_3, liquid oxygen O_2, hydrogen peroxide H_2O_2, and 100-percent nitric acid HNO_3 are also included. A brief review of the manufacture and physical, chemical, and physiological properties of hydrazine is given. The hydrazine for the investigation was supplied by the Western Cartridge Company.

MANUFACTURE AND PROPERTIES OF HYDRAZINE

Manufacture

The present methods of manufacture of hydrazine are based on the synthesis from urea (reference 1) and from ammonia (reference 2).

Synthesis based on urea is as follows:

$$(NH_2)_2\ C{=}O + 2\ NaOH + NaClO \rightarrow N_2H_5OH + NaCl + Na_2CO_3$$

The hydrazine hydrate that forms is concentrated and dehydrated to obtain the hydrazine. This synthesis is expensive because of the high price of urea.

The Raschig method (reference 2) is based on the partial oxidation of ammonia into hydrazine by sodium hypochlorite.

$$2NH_3 + NaClO \rightarrow N_2H_4 + NaCl + H_2O$$

This reaction will take place in the presence of a large excess of ammonia and at high temperatures. The side reactions in the preparation of hydrazine are many and are avoided by keeping an accurate control on all conditions. Salts, certain metals, and purity of water exert a large influence on the percentage yield and purity of hydrazine.

Physical and Chemical Properties

In the investigation of hydrazine a literature survey was made to determine the physical and chemical properties. The data obtained are compiled in the following table:

Property	Description	Reference
Appearance	Viscous, colorless; fuming liquid at room temperature; white crystals at lower temperature.	1, 3
Melting point	1.4 - 1.8° C (34.5 - 35.2° F)	1, 3
Freezing point	0.0° C (32.0° F)	1
Specific gravity 15°/15° C (59°/59° F)	1.01	1, 3
Critical pressure	145 atm (2131 lb/sq in.)	1
Dielectric constant, 22° C (71.6° F)	53	1
Refractive index, n^{22}	1.470	1
Boiling point at 761.5 mm Hg	113.5° C (236.3° F)	4
Heat of hydration	1.700 ± 0.045 kg cal/mole (95.46 ± 2.53 Btu/lb)	4
Heat of formation (liquid)	-12.05 kg cal/mole (-676.7 Btu/lb)	4
Heat of formation (gas) at 298.1° K (77.0° F)	-22.25 kg cal/mole (-1249.5 Btu/lb)	4
Heat of combustion at 25° C (77° F)	148.635 ± 0.030 kg cal/mole (8346.78 ± 1.68 Btu/lb)	4
Vapor pressure	0.093 atm at 56° C (1.366 lb/sq in. at 132.8° F) 1.0 atm at 113.5° C (14.7 lb/sq in. at 236.2° F) 5 atm at 170° C (734.5 lb/sq in. at 338.0° F) 56 atm at 300° C (823 lb/sq in. at 572.0° F) 145 atm at 380° C (2131 lb/sq in. at 716° F)	5
Heat of solution at 25° C (77° F)	-3.895 kg cal/mole (218.72 Btu/lb)	6
Heat of vaporization at 23.1° C (73.6° F)	10.2 kg cal/mole (572.8 Btu/lb)	7
Heat of fusion (measured)	1.02 kg cal/mole (57.3 Btu/lb)	7

Measurements of the vapor density show that hydrazine is not associated in the vapor phase (reference 11).

Physiological Properties

Hydrazine and its salts have a toxic effect on the formed elements of the blood, probably exerting a direct hemolytic effect on the red corpuscles. In this connection, it is of interest to note that the compound phenylhydrazine manifests a similar hemolytic action, which is of value in the treatment of the disease polycythemia vera (excess of red corpuscles, reference 12). In this disease, the red-corpuscle count may rise to from 8 to 14 million per cubic centimeter and the hemolytic action of phenylhydrazine is utilized to reduce the count to normal levels. The mechanism of action would appear to be a function of the hydrazine group, although the role of the phenyl group in the hemolytic process is apparently not considered in the literature. That the toxic effect of hydrazine on the blood is hemolytic in nature is substantiated by the fact that hydrazine (and phenylhydrazine) does not destroy the bone marrow (reference 13); in fact, the rapid destruction of red corpuscles will tend to stimulate the marrow and a sudden increase in the white-corpuscle count may herald the onset of acute toxicity with phenylhydrazine. In addition, hydrazine produces severe liver damage with fatty degeneration, death of live tissue, and lack of growth.

The inhalation of small quantities of hydrazine vapor causes a slight transitory dizziness and nausea. The effect of hydrazine vapor on the eyes is extremely disagreeable, becoming noticeable a few hours after exposure. The eyes begin to itch and finally become completely swollen, showing the symptoms of conjunctivitis. The conjunctiva show small blisters and the patient suffers acute pain. The treatment of this condition consists in boric-acid rinses and the application of boric-acid salve. In order to prevent the effect of hydrazine vapor on the eyes, goggles should be used; gas masks with a filter designed for an ammonia atmosphere should be used in dealing with large quantities of hydrazine.

APPARATUS AND PROCEDURE

Corrosion and Stability Experiments

Corrosion experiments were made to determine the effect of 95.6-percent hydrazine on 19 construction materials; the effect of these materials on the decomposition of hydrazine was observed. Because only a small quantity of 95.6-percent hydrazine was available, the examinations were conducted on a small scale and duplicate runs could not be made.

The procedure and the apparatus were modeled after those described in reference 14. The apparatus consisted of a constant-temperature bath, test tubes containing the samples, and glass closed-end manometers secured to the test tubes by means of gum-rubber couplings, which were wire-sealed to prevent leakage (fig. 1).

In each of 20 test tubes, 1 milliliter of 95.6-percent hydrazine was placed. The metal samples, by necessity small, measured 6 by 16 millimeters. The metal samples were cleaned and polished with No. 1 emery cloth, immersed 10 to 20 seconds in 10-percent sulfuric acid H_2SO_4 at 180° F, washed in distilled water, and dried in acetone before being placed in the hydrazine. The samples were maintained at 68° F for 24 days in the constant-temperature bath. The amount of decomposition was indicated by the rise of the mercury column in the closed-end manometer. The corrosion due to the hydrazine was determined by weighing the sample before and after being subjected to the hydrazine and by visual inspection.

Sensitivity

Temperature. - Temperature-sensitivity experiments were made to determine the stability of 95.6- and 98.15-percent hydrazine to a gradual increase in temperature. The apparatus is shown in figure 2 and consisted of a stainless-steel bomb immersed in an oil bath. The bomb had a volume of 2.5 milliliters and was equipped with either an aluminum or stainless-steel blow-out disk (fig. 2(b)). The disks were designed to rupture at a pressure of 3000 pounds per square inch; under hydraulic pressure, samples ruptured at 2600 and 3300 pounds per square inch.

Experiments to determine the sensitivity of hydrazine to gradual increases in temperature were made by placing 0.5 or 1.0 milliliter of either 95.6- or 98.15-percent hydrazine in the bomb, tightly sealing the apparatus, and gradually heating the assembly in the oil bath until the disk ruptured. In addition, experiments to determine the effect of prolonged heating were made in which the bomb containing 1.0 milliliter of 98.15-percent hydrazine was heated to temperatures of 400° and 446° F and kept at these temperatures until the disk ruptured. Aluminum blow-out disks were used in most of the experiments; in several cases, however, duplicate runs were made using stainless-steel disks because of the possibility of aluminum reacting with hydrazine to form aluminum nitride and hydrogen.

An attempt to determine the effect on hydrazine of a sudden increase in temperature was made by placing approximately 0.5 milliliter of hydrazine in a 10-by-70-millimeter pyrex test tube and melting and vaporizing a $1\frac{1}{2}$-inch length of No. 24 brass wire in the liquid. The wire was twisted into a small coil, connected to a pair of copper lead wires contained in a porcelain insulating rod and melted and vaporized through the application of 110 volts across the leads. Similar experiments were made with water in place of the hydrazine to distinguish between the effects caused by mere melting and vaporization of the wire and those caused by the presence of hydrazine.

Detonation. - Experiments to determine the sensitivity of 95.6- and 98.15-percent hydrazine to detonation were performed in a rising-weight apparatus shown in figure 3. A steel block 4 by 4 by 8 inches was fitted with a cylindrical stainless-steel insert, 4 inches long and $1\frac{1}{2}$ inches in diameter. A 1/2-inch chamber was drilled 3 inches deep in the insert and two 2-by-2-inch upright angle-iron guides, $6\frac{1}{2}$ feet high were welded to the block. The sample and a No. 6 electric detonator cap were placed in the chamber and a 1697-gram weight placed over the chamber. The cap was detonated with a battery and the average height to which the weight traveled upward between the angle-iron guides was measured.

Experiments were made using the No. 6 detonator cap alone and in conjunction with water, alcohol, nitromethane, and hydrazine.

Other experiments to determine the sensitivity of 98.5-percent hydrazine to detonation were conducted using a 12-inch length of 1/2-inch-diameter stainless-steel tubing filled with hydrazine and capped with a tube containing 6 milliliters of an extremely brisant mixture of 80-percent tetranitromethane and 20-percent nitrobenzene. The tetranitromethane-nitrobenzene mixture was detonated by a No. 6 detonator cap. Reference experiments were made using water, tetranitromethane, and nitromethane.

Spontaneous-ignition experiments. - Experiments were made to determine the reactivity of 95.6-percent hydrazine with several oxidants. A medicine dropper was supported 9 inches above a test tube containing approximately 0.5 milliliter of 95.6-percent hydrazine. The oxidant, contained in the medicine dropper, was added dropwise by squeezing the dropper bulb with a pair of long bent tongs that reached around a glass shield to protect the operator. The oxidants investigated were concentrated hydrogen peroxide, sodium permanganate solution, red fuming nitric acid, tetranitromethane, and liquid oxygen.

Theoretical Performance Calculations

Calculations were made to determine the theoretical performance of 100-percent hydrazine as a rocket fuel at a reaction-chamber pressure of 300 pounds per square inch absolute and an expansion pressure ratio of 20.4. Values of reaction-chamber temperature T_c, exit temperature T_e, specific impulse I, "volume" specific impulse I_d (product of specific impulse and propellant density), and average molecular weight of combustion gases M were calculated for a range of fuel-oxidant ratios for each propellant combination. The propellant combinations considered in this report are hydrazine with liquid ozone, liquid oxygen, hydrogen peroxide, and fuming nitric acid.

The method of computing the theoretical performance was similar to that used at the M.I.T. Turbo Laboratory. The computations involved satisfying two simultaneous conditions: a material balance of the reactants and the products and a conservation of energy balance equating the enthalpy of the reactants to the enthalpy of the products.

In the calculation, a flame temperature was first assumed making it possible to determine the composition of the gases at the assumed temperature by means of an unpublished graphical solution of the simultaneous equilibrium and material balance equations developed at the NACA Cleveland laboratory. After the composition of the products at the assumed flame temperature was computed, the enthalpy of the products of the reaction was determined from reference 15. The assumed flame temperature is the correct reaction-chamber temperature when a balance is obtained between the enthalpy of the reactants and the enthalpy of the products.

With the gas composition and the temperature known, the entropy of the gases in the chamber was determined from data presented in reference 15. The exit temperature was determined by assuming that the chemical equilibrium of the gases at the exit of the nozzle was the same as that of the gases entering the nozzle. By assumption of an isentropic expansion through the nozzle, a trial and error solution was used to solve for the exit temperature and the enthalpy of the gases at this temperature was determined. With the enthalpy of the combustion gases at the reaction chamber and at the exit temperature determined, the enthalpy change during the isentropic expansion was obtained and considered as the energy available from the gases. The specific impulse was calculated from the available energy and the weight flow of the propellants.

RESULTS AND DISCUSSION

Corrosion and Stability

The results of the corrosion and stability experiments conducted at 68° F are summarized in the following table:

Sample	Pressure increase, (atm per day per ml N_2H_4)	Condition after experiment
Blank	0.009	--------------------
Cold rolled steel	(leaked)	No change
302 stainless steel	.015	No change
321 stainless steel	.011	No change
430 stainless steel	.010	No change
Monel	.009	No change
Inconel	.012	No change
2SO aluminum	.011	No change
24ST duralumin	.012	No change
Nickel	(leaked)	No change
Copper	.010	No change
Brass	.010	No change
Lead	.010	No change
Natural gum rubber	.016	Absorbed hydrazine but strong and pliable
Neoprene	.009	Same as natural gum rubber
Saran	.009	Dark and brittle
Tygon	(leaked)	Same as natural gum rubber shrunk after drying
Teflon	(leaked)	No change - strong, pliable, absorbed no hydrazine
Graphite valve packing	.009	No change
Asbestos	.008 (leaked)	No change

The results of these experiments indicate that all the metals investigated, Teflon, graphite valve packing, and asbestos are suitable for use with hydrazine at room temperatures. The suitability of rubber, Saran, and Tygon is questionable. The change in pressure per day was approximately the same for both the hydrazine blank and the test samples, thus indicating that no marked decomposition of hydrazine was denoted by the materials investigated. In several of the experimental assemblies, as indicated in the preceding table, leaks developed around the rubber seal.

Sensitivity to Temperature and Detonation

Temperature. - The results of the investigation to determine the stability of hydrazine to a gradual increase in temperature are presented in the following table:

Temperature at which disk ruptured (°F)	Hydrazine (ml)	Rate of heating at time of rupture (°F/min)
Aluminum disks		
478	0.5	1.12
481	.5	1.00
483.5	.5	1.00
479	.5	1.00
481	.5	1.10
Stainless-steel disks		
483	0.5	1.13
485	1.0	1.10

The results indicate that the heating of hydrazine at a rate of approximately 1.10° F per minute to roughly 478° F per minute apparently causes decomposition of the hydrazine to a point sufficient to rupture the disks.

The results of experiments to determine the effect of constant elevated temperature on hydrazine are:

Temperature of oil bath (°F)	Hydrazine (ml)	Length of time before rupture (min)
400	1.0	164
446	1.0	56

The results indicate that the thermal decomposition of hydrazine is accelerated by increasing the temperature. Similar results of thermal decomposition of hydrazine were obtained by other investigators and values of the rates of thermal decomposition of anhydrous hydrazine at various temperatures are presented in reference 16.

The sudden application of heat to hydrazine by means of the melting and vaporization of the brass wire resulted in an intense blue flash, accompanied by a yellow tongue of flame followed by an explosion. In three experiments conducted with water alone, a bright flash was observed with part of the water blown from the test tube. The explosions obtained in each of the four experiments with hydrazine probably resulted from the ignition of hydrazine vapor because it has been reported that pure anhydrous hydrazine vapor when sparked at 212° F explodes and a yellow flame accompanies the decomposition. (See reference 17.)

Detonation. - The results of the detonation tests of 95.6- and 98.15-percent hydrazine performed on the rising-weight detonation apparatus are presented in the following table:

Number of experiments	Material	Height of rise (in.)
5	Cap only	14 - 20
4	Cap + 1 ml H_2O	12 - 20
4	Cap + 0.5 ml C_2H_5OH	20
3	Cap + 0.5 ml CH_3NO_2	[a]108
5	Cap + 0.7 ml 95.6-percent N_2H_4	[a]114 - 132

[a] Estimated beyond 78 in.

The difference in average height of weight rise obtained with hydrazine and with water, alcohol, and the cap alone indicates that in the rising-weight apparatus hydrazine explodes upon detonation of a No. 6 detonator cap. This explosion is further supported by the similarity between the values obtained for hydrazine and for nitromethane, which is sensitive to detonation by a No. 6 cap. The possibility exists, however, that hydrazine vapor generated by the exploding cap may have been the cause of the explosion.

The results of the detonation experiments made on 98.15-percent hydrazine contained in a 1/2-by-12-inch stainless-steel tube are illustrated in figure 4 and indicate that a detonation wave will not propagate in hydrazine. In the experiments performed both with hydrazine and with water, only the upper tube, which contained 6 cubic centimeters of 80-percent tetranitromethane, 20-percent nitrobenzene mixture, was destroyed; whereas, with tetranitromethane and nitromethane, which have been found to be sensitive to detonation, the entire assembly exploded.

Spontaneous-ignition experiments. - The results of spontaneous-ignition experiments with hydrazine and several oxidants are:

Compound	Reaction
Hydrogen peroxide, H_2O_2 (88.8 percent)	Explosion, flame
Sodium permanganate, $NaMnO_4$ (40 percent)	Explosion
Fuming nitric acid, HNO_3NO_2 (6 percent NO_2)	Foaming
Tetranitromethane, $C(NO_2)_4$	Explosion, flame
Liquid oxygen, O_2	No reaction

Theoretical Calculations

The results of the theoretical calculations of reaction-chamber temperature, exit temperature, specific impulse, volume specific impulse, and average molecular weight of exhaust gases for hydrazine with liquid ozone, liquid oxygen, 100-percent hydrogen peroxide, and 100-percent nitric acid are plotted against the percent by weight of hydrazine in figure 5. In figure 6, the variation of specific impulse and volume specific impulse for the four propellants are compared by using the ratio of fuel to fuel plus fuel equivalent of oxygen as the abscissa. The fuel equivalent of oxygen is the amount of fuel that can be completely burned by the oxygen present; by use of this parameter the stoichiometric fuel-oxidant ratio occurs when the ratio of fuel to fuel plus fuel equivalent of oxygen is 0.5.

The curves of reaction-chamber and exit temperature for the four propellants (fig. 5) show a similar trend in decrease with increasing percentages of hydrazine. The curves of exhaust-gas molecular weight follow the same pattern. This decrease in molecular weight is to be expected because hydrazine is rich in low molecular-weight hydrogen. The difference between the values of reaction-chamber and exit temperature also decreases as the percentage of hydrazine increases.

The maximum specific impulse and the maximum temperature do not occur at the same propellant ratio, as shown in figure 5. The maximum specific impulse occurs on the fuel rich side of the propellant ratio, whereas the maximum temperature is obtained in the stoichiometric region. This difference indicates the importance of the effect of dissociation and of the change in average molecular weight of combustion products that is used in determining the specific impulse.

The curves of specific impulse for the four propellants increase to a maximum on the fuel rich side of the stoichiometric ratio and finally decrease with increasing percentages of fuel. The curves of volume specific impulse also increase to a maximum; however, the position of maximum volume specific impulse with respect to the stoichiometric fuel-oxidant ratio varies, being dependent for the most part on the oxidant used.

On the basis of maximum specific impulse, the curves indicate the following order of performance for the four oxidants (fig. 6); liquid ozone, liquid oxygen, 100-percent hydrogen peroxide, and 100-percent nitric acid; whereas on the basis of the maximum volume specific impulse, the rating of the performance of the four oxidants is: liquid ozone, 100-percent hydrogen peroxide, 100-percent nitric acid, and liquid oxygen. The volume specific impulse is important inasmuch as the weight and size of propellant tanks and the drag produced by the tanks in flight is affected to a large extent by the density of the propellant.

A summary of the theoretical performance of hydrazine with the four oxidants is shown in the following table:

Oxidant	Maximum specific impulse, I (lb-sec/lb)	Maximum volume specific impulse, $I_d/62.4$ (lb-sec/cu ft)	Average molecular weight of gases at maximum specific impulse, M	Hydrazine at maximum specific impulse (percent by weight)
Liquid ozone	277.1	321.7	16.80	61.0
Liquid oxygen	265.7	282.0	17.75	58.0
100-percent hydrogen peroxide	247.5	310.0	18.00	40.0
100-percent nitric acid	241.6	298.5	19.00	46.0

The combustion-gas composition for the four propellants is shown plotted against percentage by weight of hydrazine in figure 7. The constituents considered include water H_2O, nitrogen N_2, hydrogen H_2, hydroxyl radical OH, nascent hydrogen H, oxygen O_2, nascent oxygen O, nitric oxide NO, and nascent nitrogen N. These curves would facilitate recalculating the performance of the propellants if it were desired to assume shifting equilibrium of the products of combustion throughout the expansion process.

SUMMARY OF RESULTS

The results of a preliminary investigation to determine the characteristics of hydrazine, stability and corrosiveness, sensitivity to detonation and temperature, and spontaneous reaction with the oxidants, concentrated hydrogen peroxide, sodium permanganate solution, fuming nitric acid, and tetranitromethane, and the calculation of the theoretical performance of hydrazine indicate that:

1. At ambient temperatures, steel, stainless steel, monel, Inconel, 2SO aluminum, 24ST duralumin, nickel, copper, brass, lead, Teflon, graphite valve packing, and asbestos did not appear to accelerate the decomposition of hydrazine and appeared to be unaffected by the hydrazine. Natural gum rubber, neoprene, Saran, and Tygon were affected by hydrazine and their suitability is questionable.

2. Hydrazine was sensitive to temperature, showing a tendency to decompose in a closed stainless-steel bomb either at constant elevated temperatures or upon gradual heating.

3. Hydrazine was sensitive to the detonation produced by the discharge of a No. 6 electric detonator cap when contained in a rising-weight apparatus. Hydrazine, however, would not propagate a detonation wave produced in a 1/2-by-12-inch stainless-steel tube by a charge of 6 cubic centimeters of a mixture of 80-percent tetranitromethane and 20-percent nitrobenzene.

4. Hydrazine reacted spontaneously and violently with concentrated hydrogen peroxide, sodium permanganate, fuming nitric acid, and tetranitromethane solutions but not with liquid oxygen.

5. Values of the theoretical maximum specific impulse I, for 100-percent hydrazine with each of four oxidants at a reaction-chamber pressure of 300 pounds per square inch and an expansion ratio of 20.4 were as follows:

Oxidant	I (lb-sec/lb)
Liquid ozone	277.1
Liquid oxygen	265.7
100-percent hydrogen peroxide	247.5
100-percent nitric acid	241.6

6. Maximum values of volume specific impulse I_d, for 100-percent hydrazine with each of the four oxidants at a reaction-chamber pressure of 300 pounds per square inch and an expansion ratio of 20.4 indicated that the order of performance was not the same as that obtained on the basis of specific impulse and were:

Oxidant	$I_d/62.4$ (lb-sec/cu ft)
Liquid ozone	321.7
100-percent hydrogen peroxide	310.0
100-percent nitric acid	298.5
Liquid oxygen	282.0

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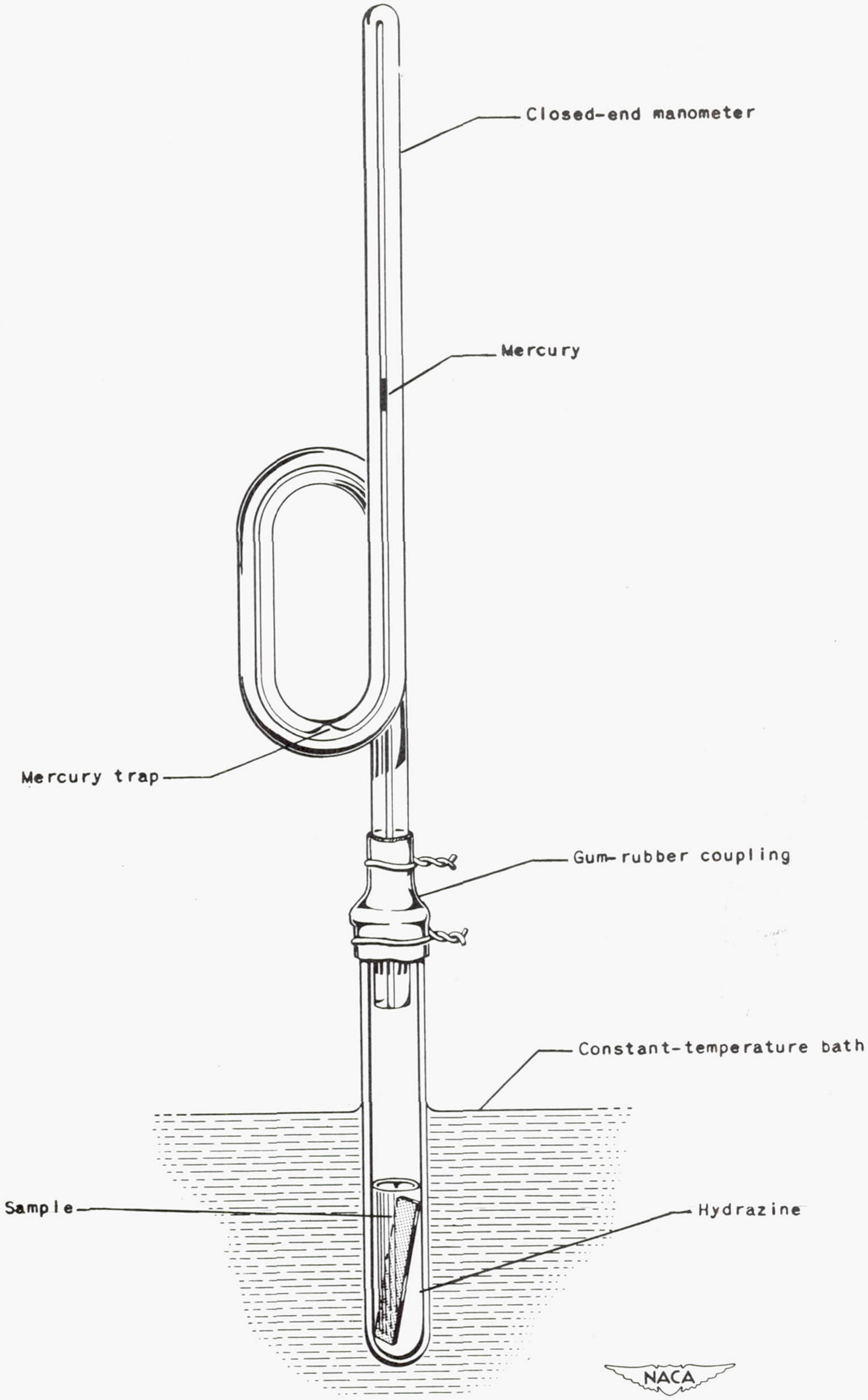
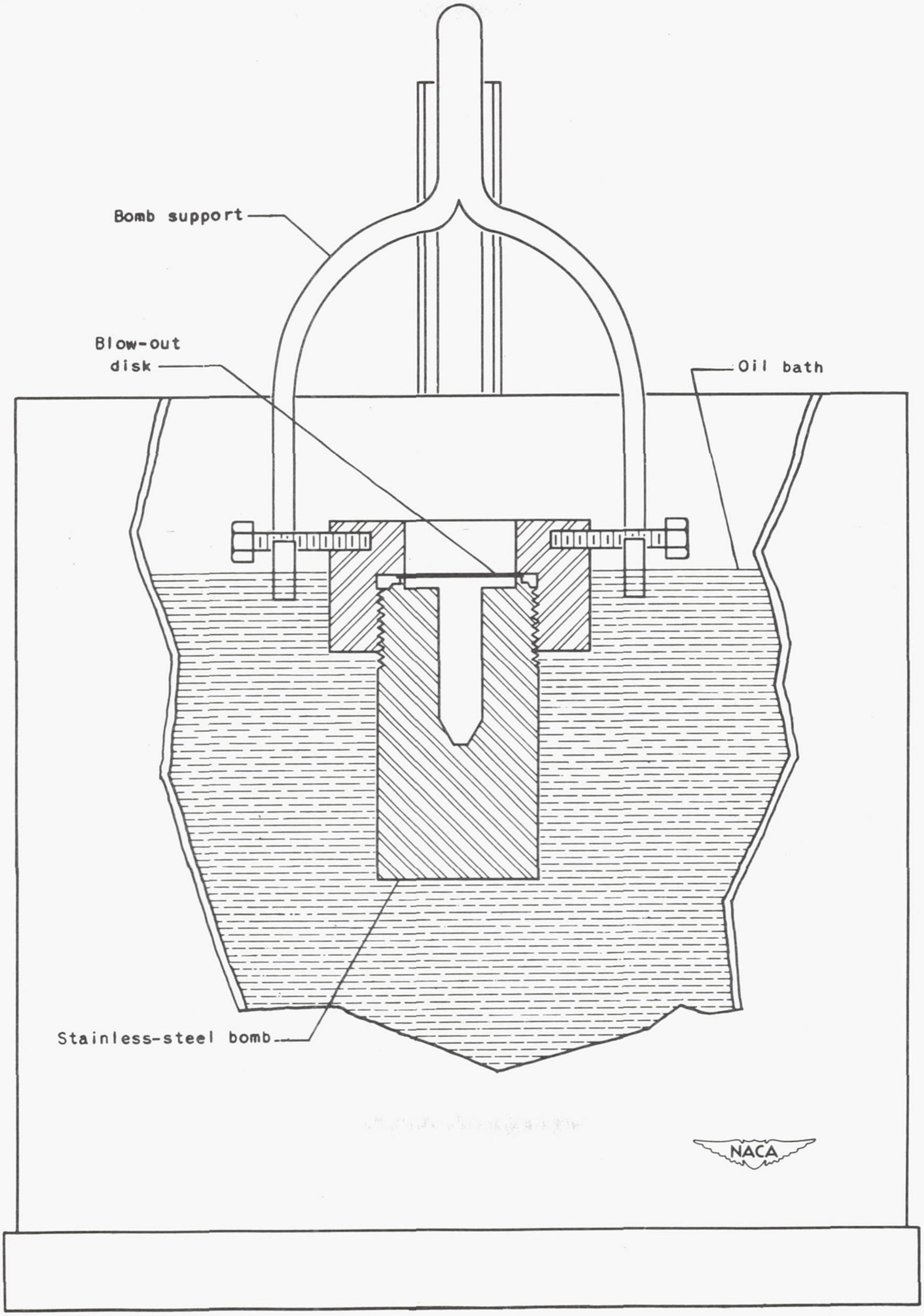
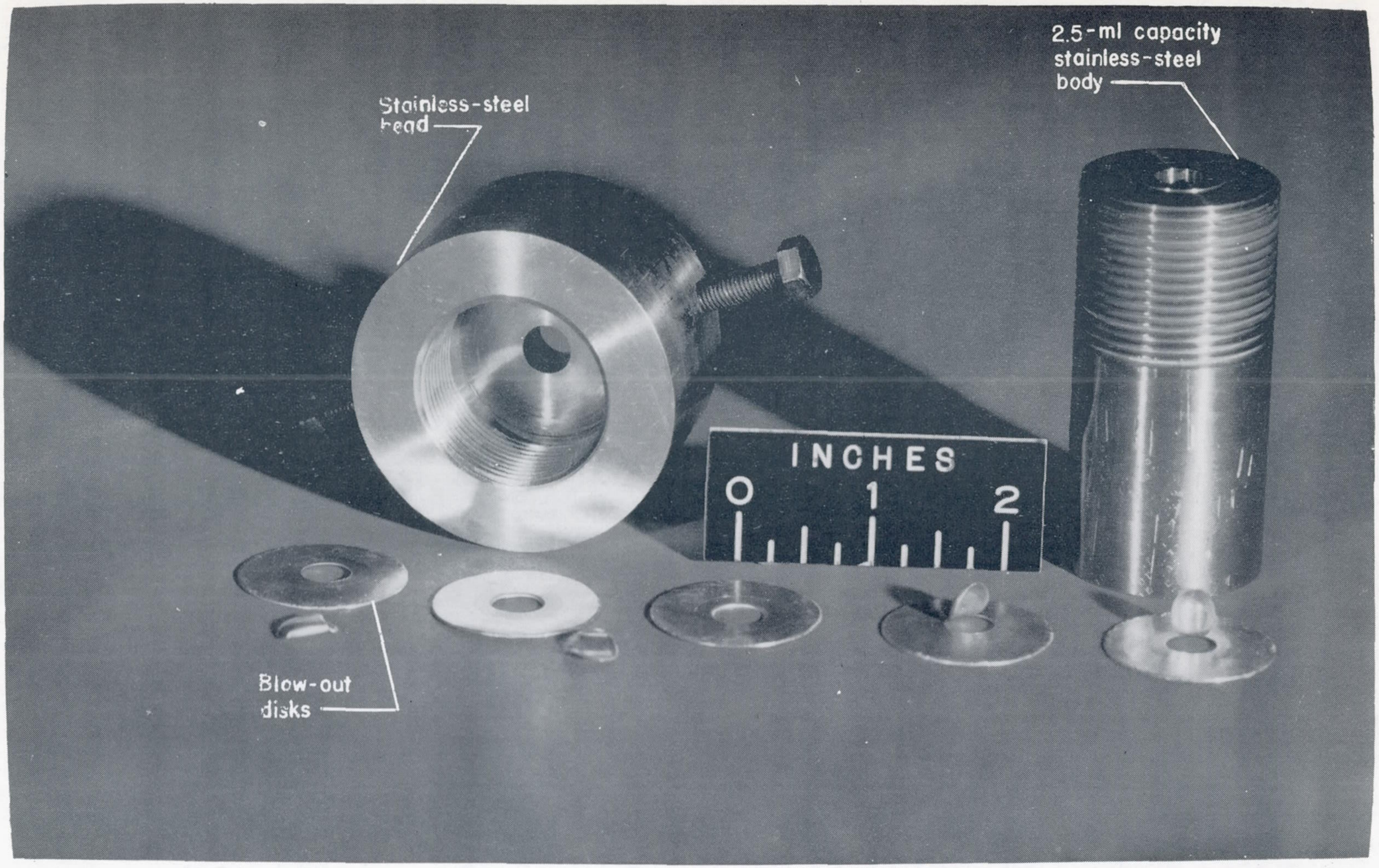


Figure 1. - Corrosion and stability experimental apparatus.



(a) Temperature-sensitivity-bomb assembly.

Figure 2. - Temperature-sensitivity experimental apparatus.



(b) Temperature-sensitivity bomb and blow-out disks.

Figure 2. - Concluded. Temperature-sensitivity experimental apparatus.

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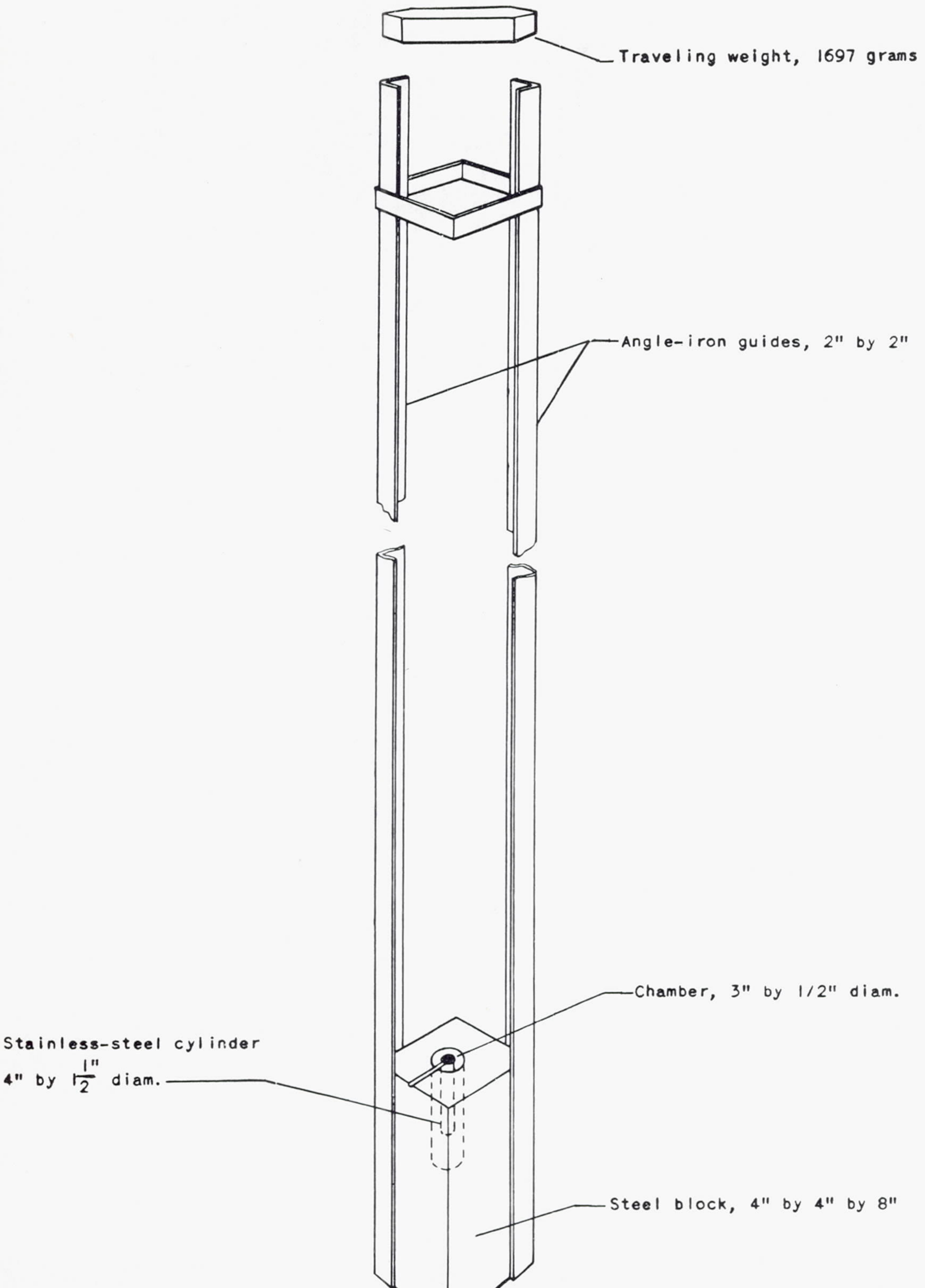

Figure 3. - Rising-weight detonation experimental apparatus.

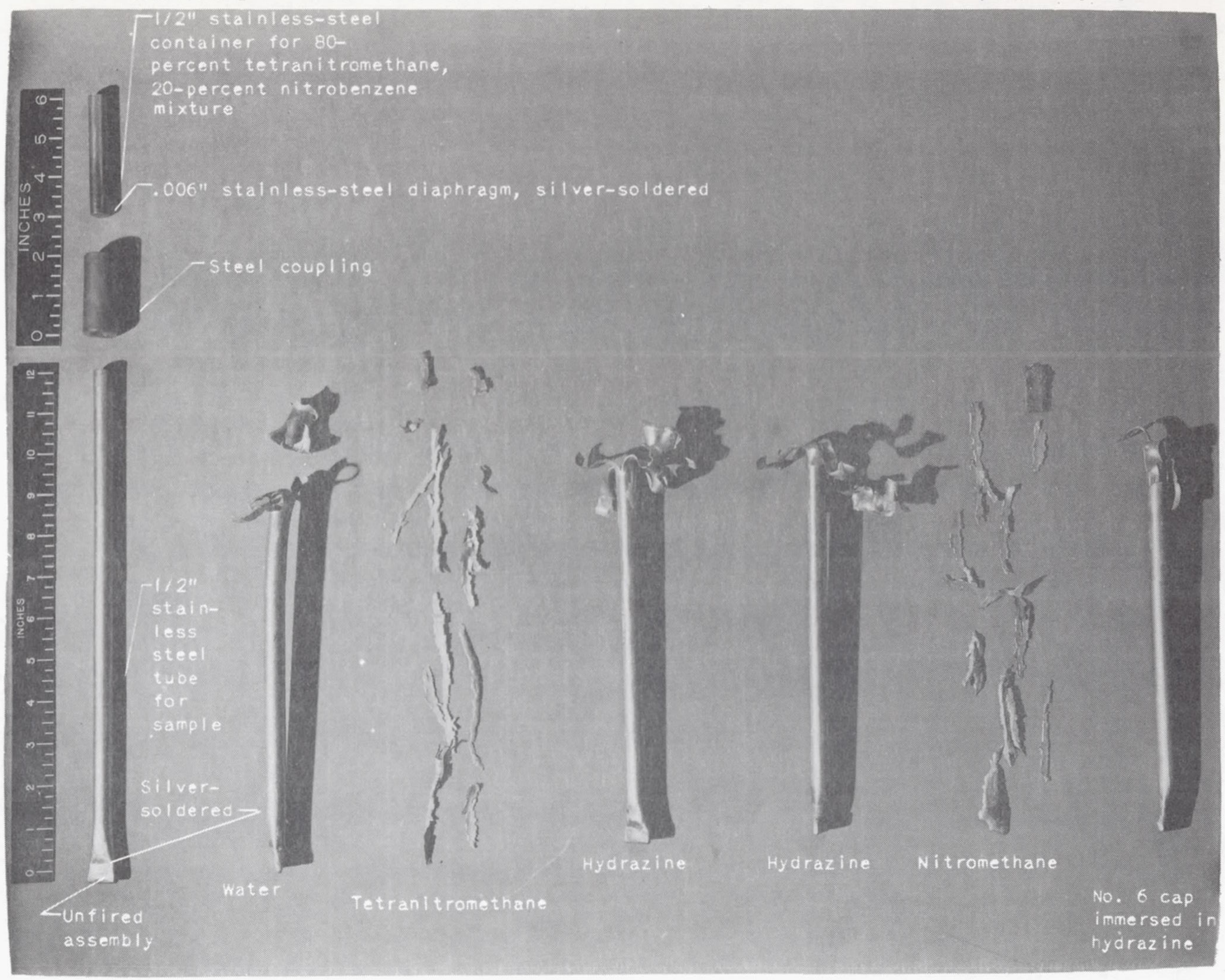

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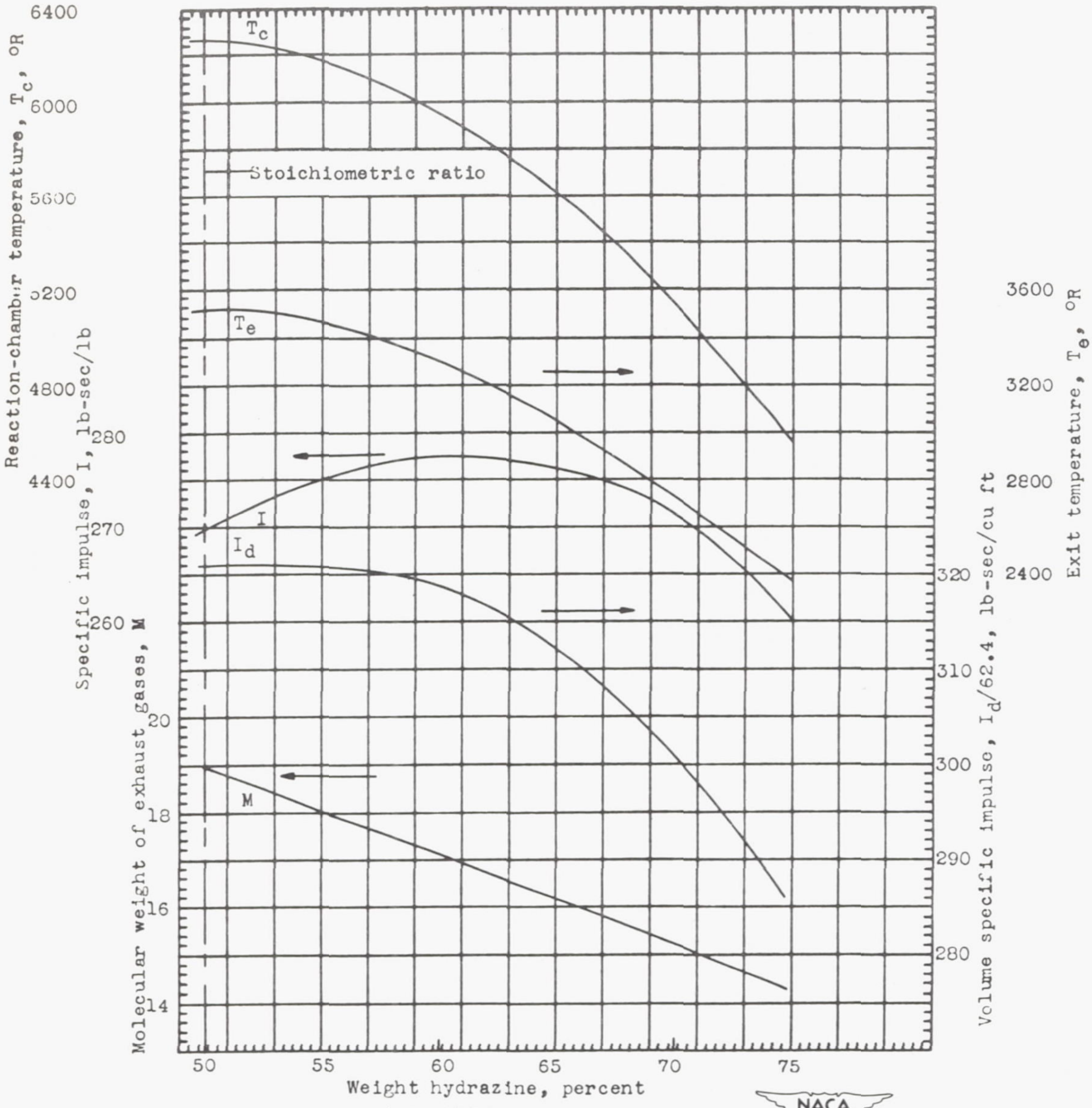
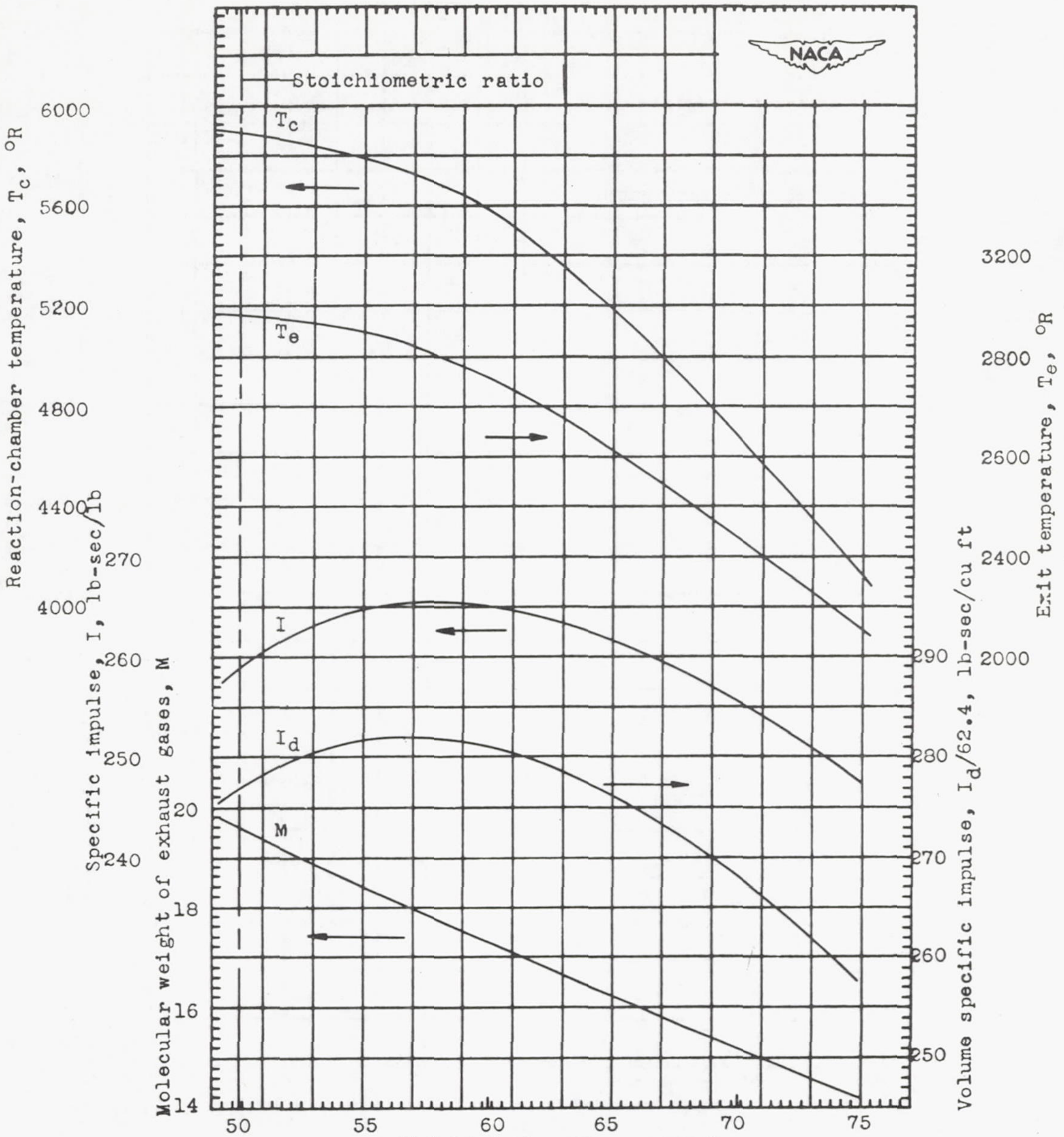
Figure 4. - Results of tube-detonation experiments with 98.15-percent hydrazine.



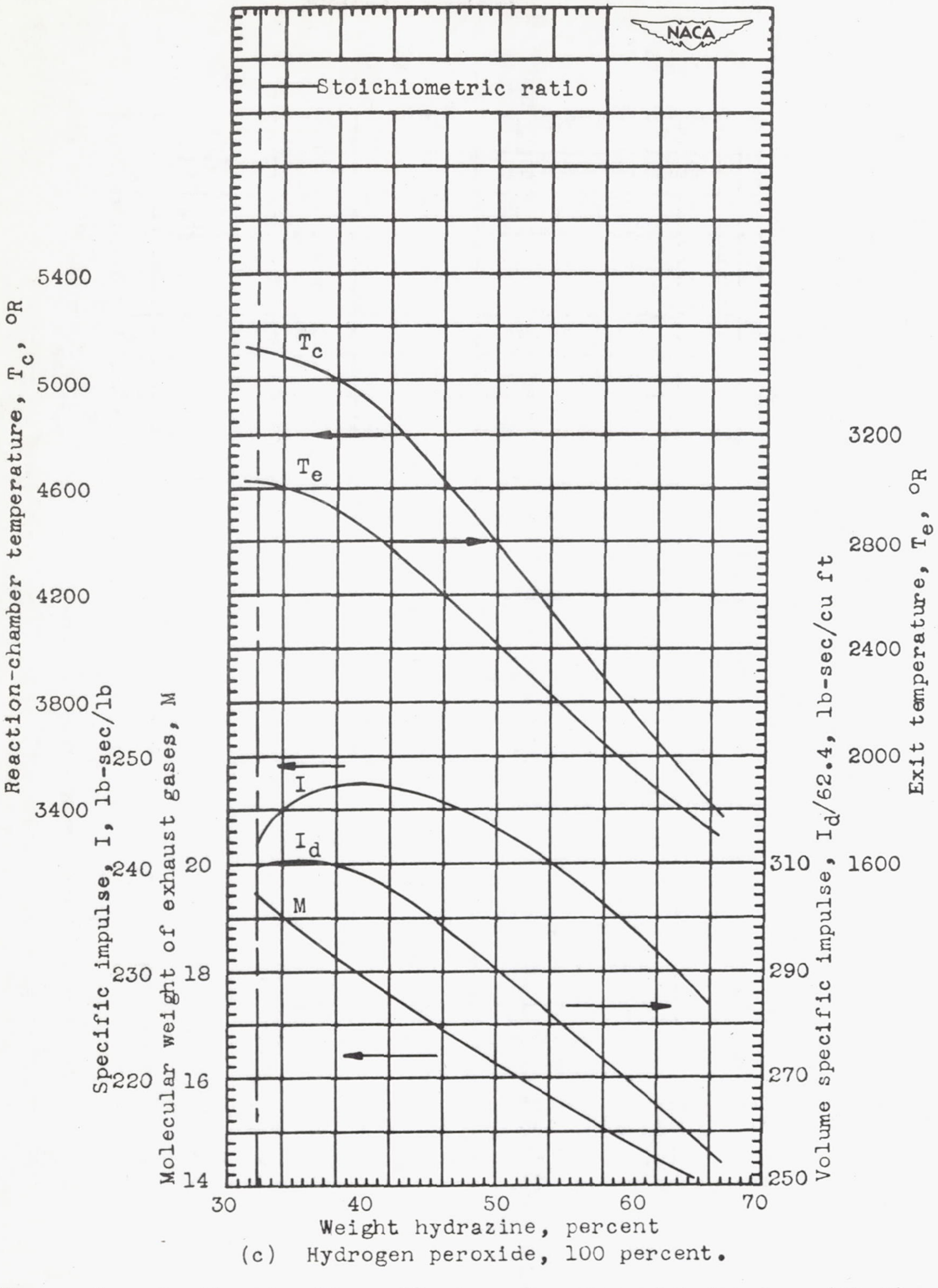
(a) Liquid ozone.

Figure 5. - Theoretical performance of hydrazine with liquid ozone, liquid oxygen, 100-percent hydrogen peroxide, and 100-percent nitric acid. Chamber pressure, 300 pounds per square inch absolute; expansion ratio, 20.4; frozen equilibrium during expansion.



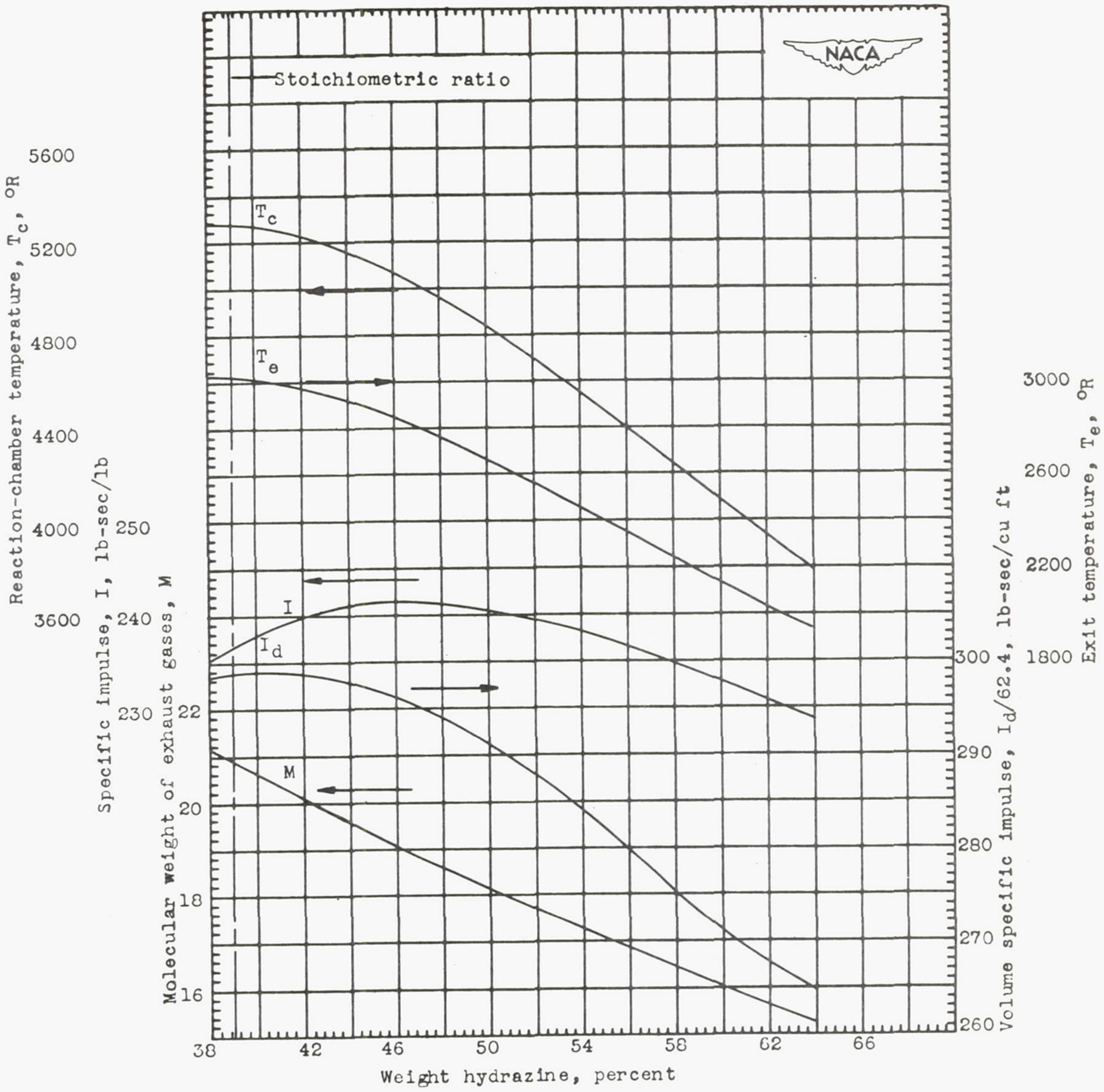
(b) Liquid oxygen.

Figure 5. - Continued. Theoretical performance of hydrazine with liquid ozone, liquid oxygen, 100-percent hydrogen peroxide, and 100-percent nitric acid. Chamber pressure, 300 pounds per square inch absolute; expansion ratio, 20.4; frozen equilibrium during expansion.



(c) Hydrogen peroxide, 100 percent.

Figure 5. - Continued. Theoretical performance of hydrazine with liquid ozone, liquid oxygen, 100-percent hydrogen peroxide, and 100-percent nitric acid. Chamber pressure, 300 pounds per square inch absolute; expansion ratio, 20.4; frozen equilibrium during expansion.



(d) Nitric acid, 100 percent.

Figure 5. - Concluded. Theoretical performance of hydrazine with liquid ozone, liquid oxygen, 100-percent hydrogen peroxide, and 100-percent nitric acid. Chamber pressure, 300 pounds per square inch absolute; expansion ratio, 20.4; frozen equilibrium during expansion.

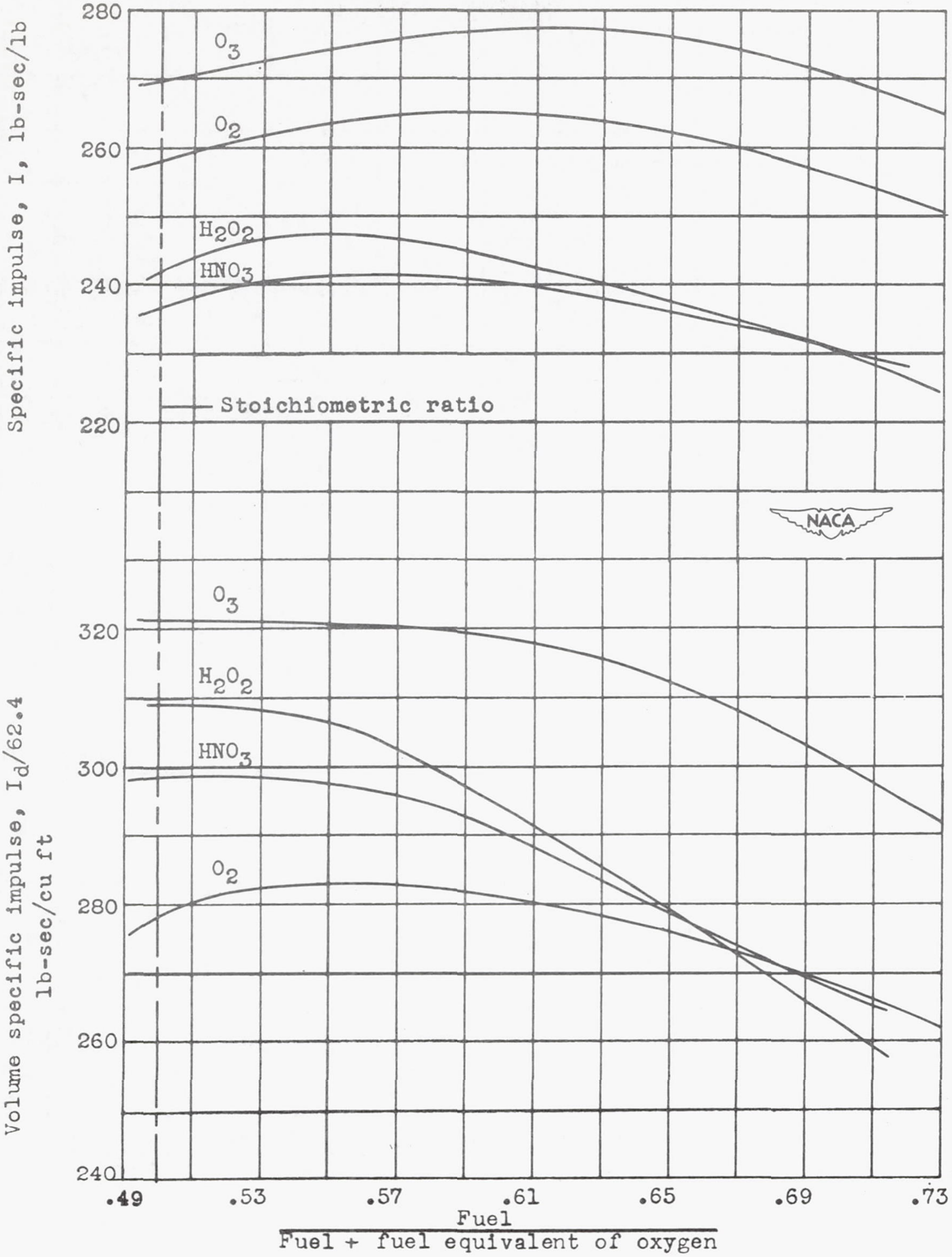
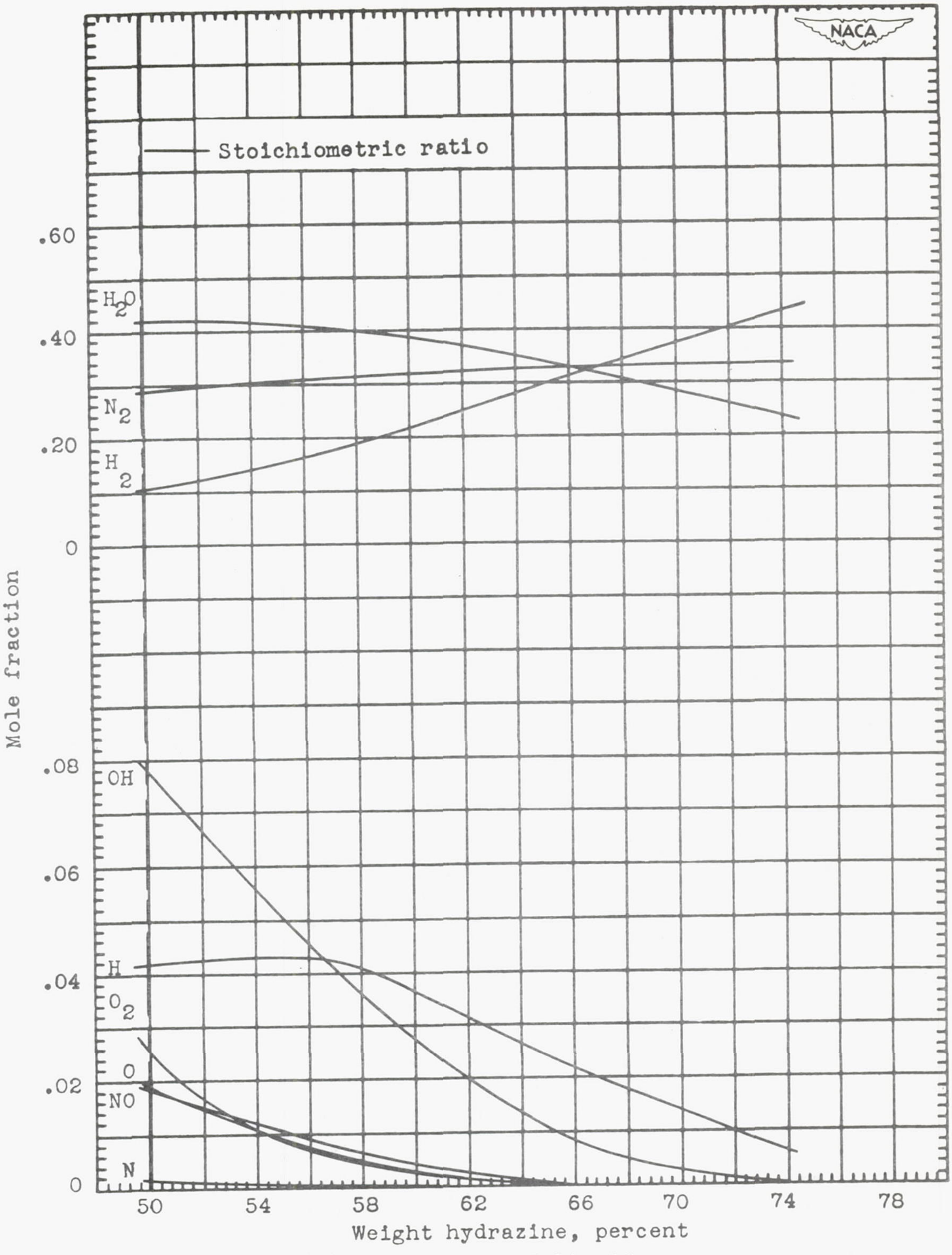
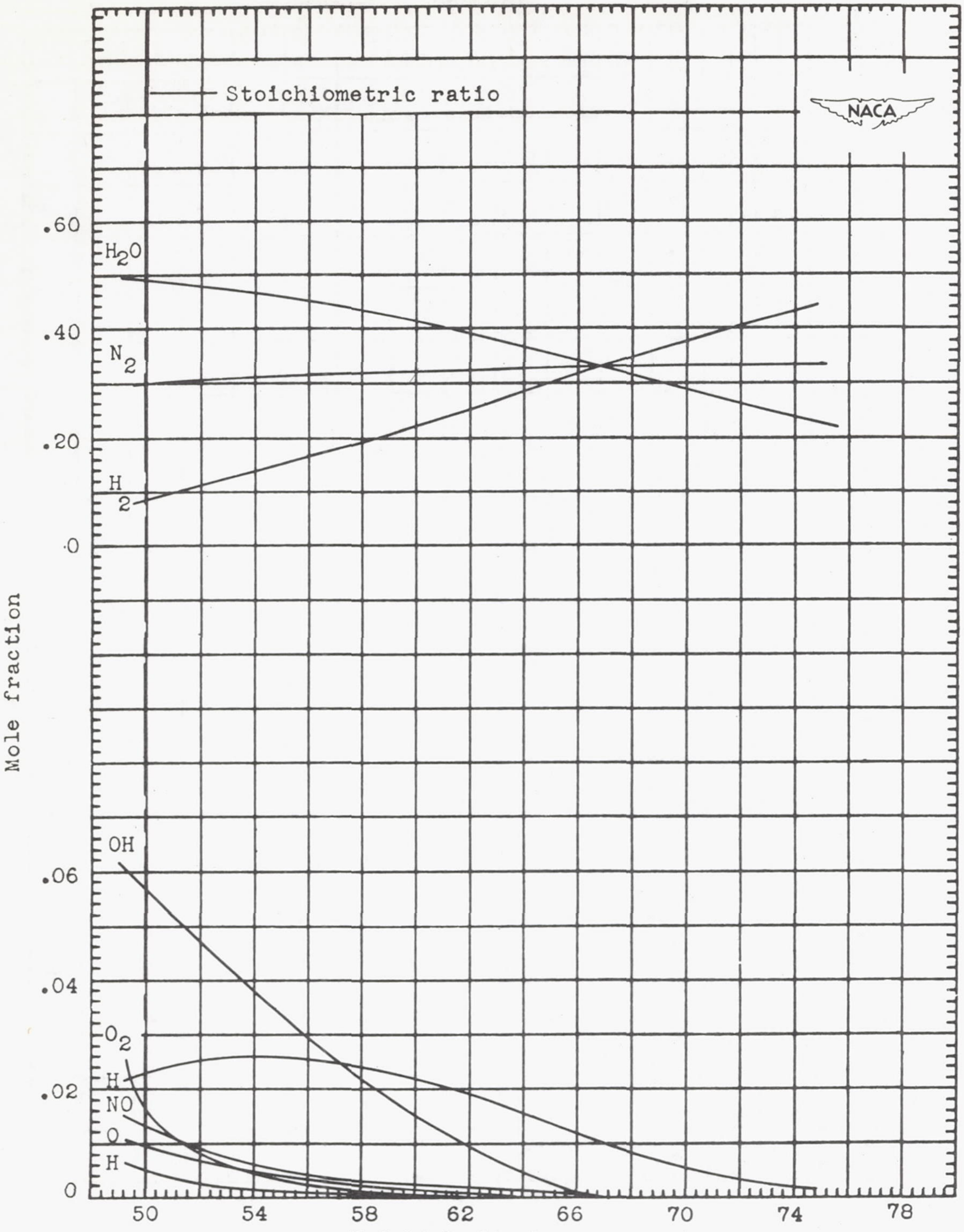


Figure 6. - Comparison of specific impulse and volume specific impulse for hydrazine and liquid ozone, liquid oxygen, 100-percent hydrogen peroxide, and 100-percent nitric acid. Chamber pressure, 300 pounds per square inch absolute; expansion ratio, 20.4; frozen equilibrium during expansion.



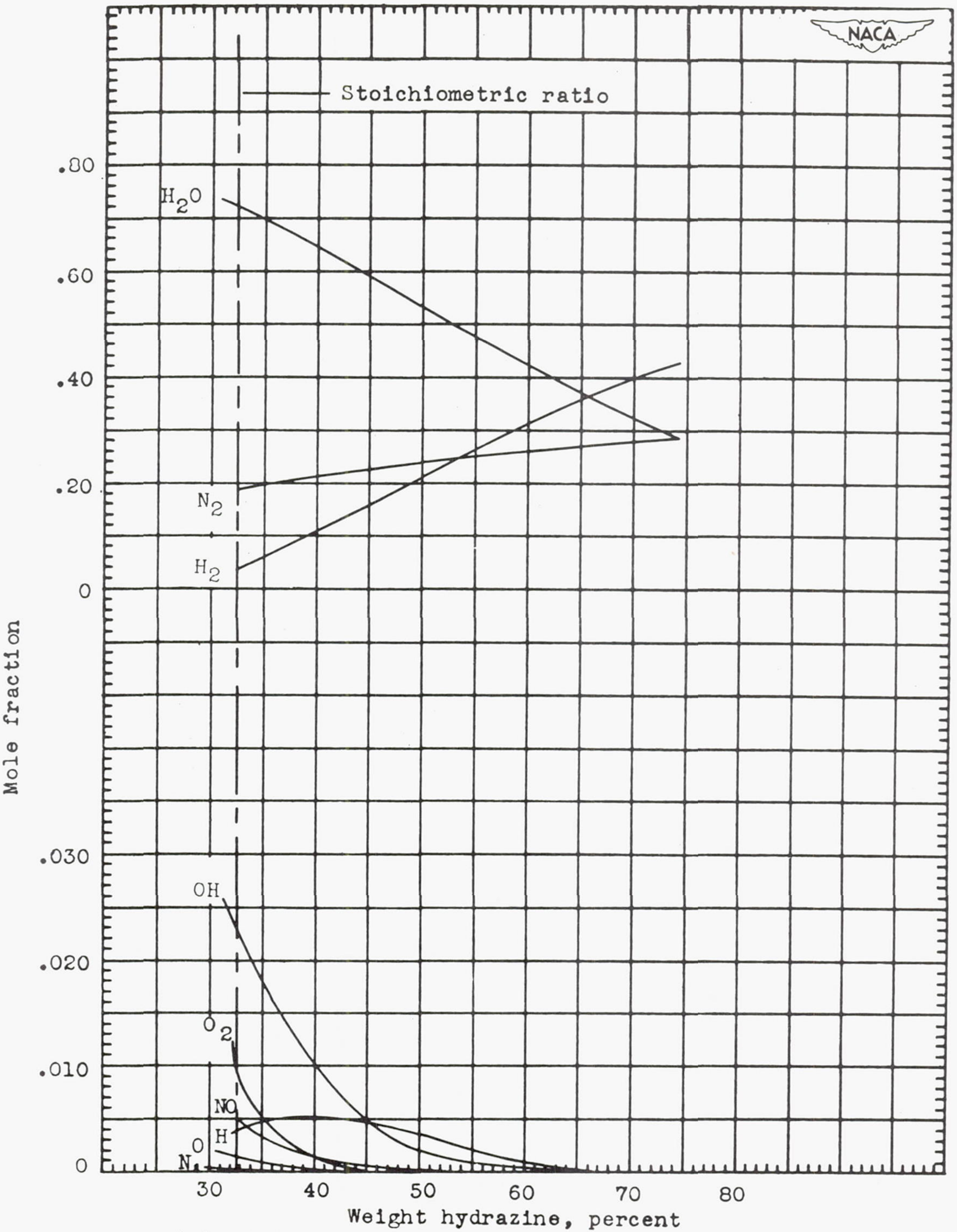
(a) Hydrazine and liquid ozone.

Figure 7. - Combustion-gas composition for hydrazine and liquid ozone, liquid oxygen, 100-percent hydrogen peroxide, and 100-percent nitric acid.



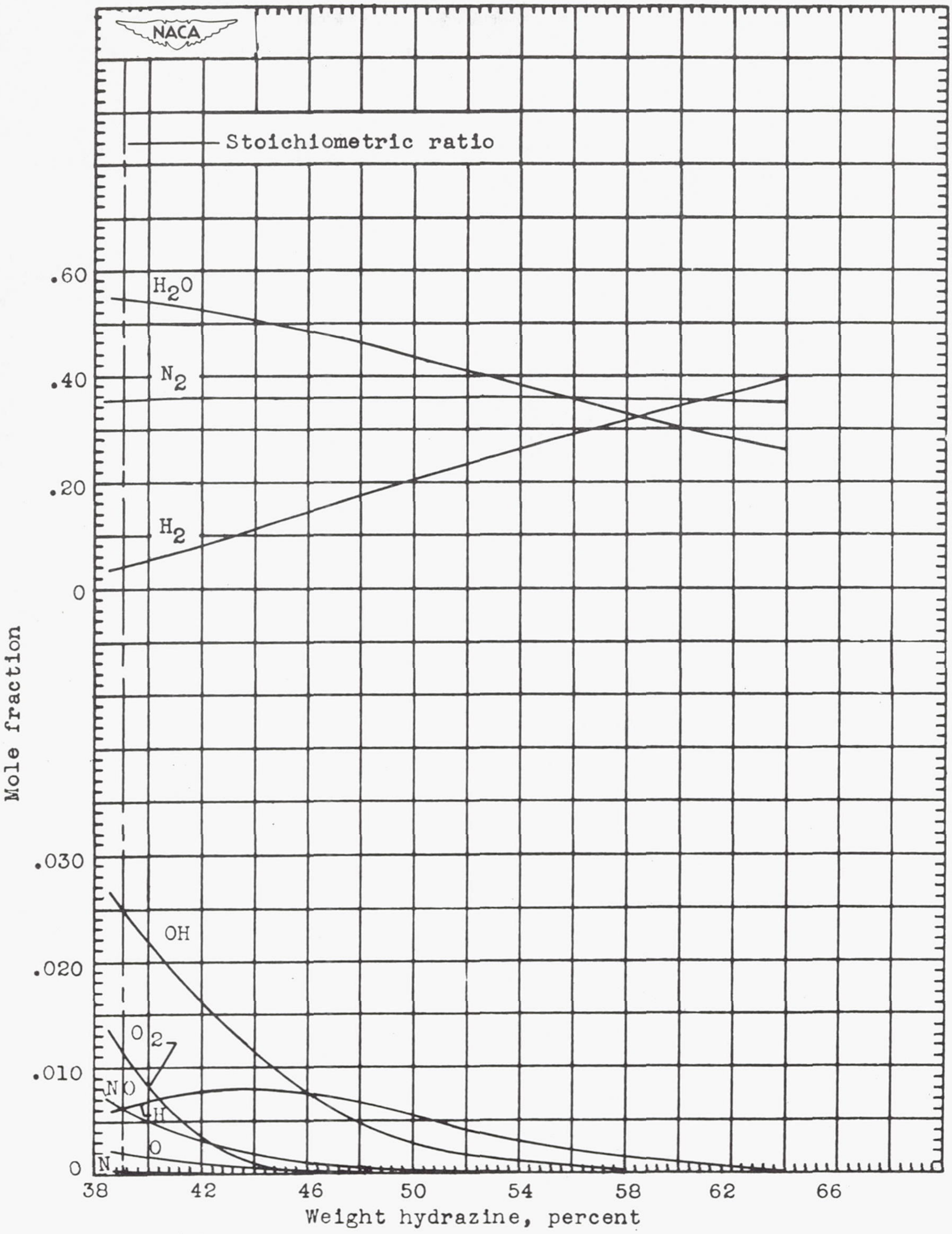
(b) Hydrazine and liquid oxygen.

Figure 7. - Continued. Combustion-gas composition for hydrazine and liquid ozone, liquid oxygen, 100-percent hydrogen peroxide, and 100-percent nitric acid.



(c) Hydrazine and 100-percent hydrogen peroxide.

Figure 7. - Continued. Combustion-gas composition for hydrazine and liquid ozone, liquid oxygen, 100-percent hydrogen peroxide, and 100-percent nitric acid.



(d) Hydrazine and 100-percent nitric acid.

Figure 7. - Concluded. Combustion-gas composition for hydrazine and liquid ozone, liquid oxygen, 100-percent hydrogen peroxide, and 100-percent nitric acid.

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