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RESEARCH MEMORANDUM

THEORETICAL PERFORMANCE OF DIBORANE AS A ROCKET FUEL

By Vearl N. Huff, Clyde S. Calvert
and Virginia C. Erdmann

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Cleveland, Ohio

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THEORETICAL PERFORMANCE OF DIBORANE AS A ROCKET FUEL

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SUMMARY

Theoretical performance data based on equilibrium isentropic expansion and constant-composition (frozen) isentropic expansion from a combustion-chamber pressure of 20.4 atmospheres (300 lb/sq in. absolute) to an ambient pressure of 1 atmosphere are presented for a range of mixtures for four rocket-propellant combinations of diborane with liquid fluorine, liquid fluorine oxide, liquid oxygen, and 100-percent hydrogen peroxide. The theoretical data include combustion-chamber and nozzle-exit temperatures, specific impulse, and volume specific impulse. Composition and mean molecular weight of the reaction products are given for both the combustion chamber and the nozzle exit.

The maximum specific impulse for all the combinations occurred in the fuel-rich region. On the basis of maximum specific impulse, the four oxidants reacting with diborane assumed the following order: liquid fluorine, liquid fluorine oxide, liquid oxygen, and 100-percent hydrogen peroxide. On the basis of calculated maximum volume specific impulse, the order of the four oxidants reacting with diborane was: liquid fluorine oxide, liquid fluorine, 100-percent hydrogen peroxide, and liquid oxygen.

INTRODUCTION

Considerable interest has been shown in some of the boron compounds as rocket propellants because their high heat of combustion per unit weight indicates a high specific impulse.

Pentaborane and diborane are two of the more significant of the boron hydrides under consideration because chemically they are sufficiently stable to permit synthesis and use. Pentaborane has several advantages over diborane including higher density and boiling point, but diborane is more readily available and more data on its heat of combustion exist.

Computed performance of diborane and liquid oxygen for three mixture ratios under equilibrium-expansion conditions and for a range of mixture ratios under frozen-expansion conditions is presented in reference 1. A theoretical and experimental investigation of boron compounds as rocket fuels is being conducted at the NACA Lewis laboratory and calculations are reported herein that were made from December 1947 to May 1948. These computations extend the mixture range of reference 1 for diborane and liquid oxygen and, in addition, give performance over a considerable mixture range of diborane with liquid fluorine, liquid fluorine oxide, and hydrogen peroxide. The results include combustion-chamber temperature, nozzle-exit temperature, specific impulse, volume specific impulse, composition, and mean molecular weight as functions of mixture ratio.

METHOD OF CALCULATION

The calculation of specific impulse involves the determination of the gas composition and the temperature in the combustion chamber and at the nozzle exit. The products of reaction were assumed to expand from a combustion-chamber pressure of 20.4 atmospheres (300 lb/sq in. absolute) to an ambient pressure of 1 atmosphere. The ideal gas laws were used.

The molecules considered to be present in the gas phase for the appropriate reactions were: atomic hydrogen H, hydrogen H_2, water vapor H_2O, hydroxyl radical OH, hydrogen fluoride HF, boron hydride BH, atomic oxygen O, oxygen O_2, boron trioxide B_2O_3, boron oxide BO, atomic fluorine F, fluorine F_2, boron trifluoride BF_3, boron fluoride BF, atomic boron B, and diatomic boron B_2. At nozzle-exit temperatures below 2000° K, liquid boron trioxide B_2O_3 was also included but boron B in the liquid and solid states, which could also be present, was neglected. The boiling point of boron is given as 2823° K in reference 2 (p. 1750). For many of the calculations, the liquid and solid states of boron would not be present and, for the remaining calculations, the effect on specific impulse is probably small.

The theoretical performance was calculated on the basis of constant enthalpy from the fuel and the oxidant at the assumed initial state of the propellants (tank conditions) to the state of the reaction products in the combustion chamber. The term enthalpy H_T^0 is defined by

$$H_T^o = \int_0^T c_p dT + H_0^o$$

where

H_0^o heat of formation at 0° K, calories per mole

T temperature, °K

c_p specific heat at constant pressure, calories per mole per °K

The superscript o denotes the thermodynamic standard reference state of unit activity; the subscript T denotes the absolute temperature in degrees Kelvin. After the enthalpy of the fuel plus the oxidant at initial states was calculated, the combustion temperature was obtained by simultaneously solving the equations for equilibrium, mass balance, and enthalpy by a method of successive approximations. The equation for enthalpy of the reaction is

$$H_T^o \text{ (reactants)} = \sum_i n_i \, (H_T^o)_i \text{ (products of reaction)}$$

where

H_T^o (reactants) enthalpy of reactants at initial states, calories

n_i moles of product i

$(H_T^o)_i$ enthalpy of product i, calories per mole

The nozzle-exit temperature was calculated on the assumption that chemical equilibrium prevailed throughout expansion (equilibrium expansion) and on the assumption that no chemical recombination took place (frozen expansion). In each case, isentropic expansion was assured by comparing the entropy of the fluid at the exit S_e to the entropy of the fluid in the combustion chamber S_c.

$$S_c = S_e = \frac{1}{\sum_i n_i M_i} \left[\sum_i n_i \, (S_T^o)_i - R \sum_i n_i \log_e p_i \right]$$

where

M_i molecular weight of product i

$(S_T^o)_i$ absolute entropy of product i, calories per mole per °K

R gas constant, 1.98714 calories per mole per °K

p_i partial pressure of product i, atmospheres

Specific impulse I (lb-sec/lb) was calculated from the difference in enthalpy between the combustion chamber and the nozzle exit by the equation

$$I = 9.328 \sqrt{\left(\frac{H_T^o}{\sum_i n_i M_i}\right)_c - \left(\frac{H_T^o}{\sum_i n_i M_i}\right)_e}$$

Volume specific impulse I_d (lb-sec/(cu ft)(62.43) or gram-sec/cc) is also included.

THERMOCHEMICAL DATA

The heats of formation of diborane B_2H_6, boron trioxide B_2O_3, and boron trifluoride BF_3 were taken from reference 3. Some uncertainty exists concerning the thermochemical data for the various states of boron and its compounds. The heat of combustion of diborane with oxygen, however, is not subject to so much question and is given by reference 3 as 510 kilocalories per mole. The value of the heat of formation of B_2H_6 has been given as -44 kilocalories per mole in reference 3, -29.5 kilocalories per mole in reference 4, and recently a value of 26 kilocalories per mole in reference 5. (Heat liberated is considered to be negative.) All the data presented herein are based on a heat of formation of -44 kilocalories per mole for diborane. One calculation, however, was made for the stoichiometric mixture of diborane and liquid oxygen using the value of 26 kilocalories per mole and the specific impulse was 2.5 percent lower than by using the value of -44 kilocalories. The heat of transition of B_2O_3 (amorphous) to B_2O_3 (crystalline) was neglected. The effect of this assumption is small and will change the specific-impulse values on the order of 0.7 percent.

The heats of formation of hydrogen fluoride HF and atomic fluorine F were taken from reference 6. The lower value ((1/2)(63.5 k-cal)) given for F was used because it is the basis of the thermodynamic properties of F and F_2 (reference 6). The heats of formation of H_2O, O, OH, and H were obtained from reference 7. The sensible enthalpies and entropies of HF, F, and F_2 were taken from reference 6 and those of H_2O, O, O_2, OH, H, and H_2 from reference 7.

The heats of fusion and vaporization of B and B_2O_3, the heats of formation of BO and B, and the sensible enthalpies and free energies of B_2O_3, B, B_2, and BO to 5000° K were taken from reference 8. The functions for B were extended to 6000° K in the same manner in which the calculations were made in reference 8. Free energy, sensible enthalpy, and entropy of BF_3 in the ideal gas state from 298.16° to 1000° K were taken from reference 9 and extended to 6000° K from spectroscopic data of reference 10, by assuming that the BF_3 molecule is a rigid rotator and a harmonic oscillator.

Similar calculations were also made for BH and BF from the spectroscopic data of reference 11. The $^3\pi$ state was considered the ground state for BF because no other information was found in the literature. The values of enthalpy, entropy, and free energy for BF_3, BF, BH, and B are listed in tables I, II, and III, respectively.

The propellants were taken as liquids at the following initial temperatures:

Propellant (100 percent)	Initial temperature (°K)
Diborane	298.16
Fluorine	85.16
Fluorine oxide	128.30
Oxygen	90.10
Hydrogen peroxide	298.16

Liquid B_2H_6 was used at 298.16 °K because no specific-heat data were available to adjust the initial temperature to or below the boiling point. The effect on specific impulse of using this initial temperature for B_2H_6 is small and an error in the opposite direction and of the same order of magnitude was introduced when the heat of transition of B_2O_3 (amorphous) to B_2O_3 (crystalline) was neglected.

The density of diborane increases as the temperature is lowered and therefore the highest density reported in reference 12 (0.4818 gram/cc at -129° C) was used for the computation of volume specific impulse. Additional physical and thermochemical properties of diborane and the oxidants considered were taken from references 13 to 16 and are given in table IV.

RESULTS AND DISCUSSION

The performance parameters of diborane reacting with liquid fluorine, liquid fluorine oxide, liquid oxygen, and 100-percent hydrogen peroxide are plotted against the percent by weight of fuel in the mixture in figure 1. The quantities plotted for each combination for both frozen and equilibrium expansions are combustion-chamber temperature T_c, nozzle-exit temperature T_e, specific impulse I, volume specific impulse I_d, and mean molecular weight in combustion chamber M_c. The mean molecular weight at the nozzle exit M_e was also included for equilibrium expansion.

The curves of combustion-chamber temperature for the combinations considered reached a maximum near the stoichiometric mixture for all of the cases except fluorine oxide, which did not reach a maximum in the range considered. The highest combustion-chamber temperature obtained was 5380° K for the fluorine-diborane reaction (figs. 1(a) and (b)). The hydrogen peroxide (figs. 1(g) and (h)) and oxygen (figs. 1(e) and (f)) combinations gave temperatures substantially lower than the fluorine. The combustion-chamber temperatures reached maximum computed values of 4750°, 4022°, and 3230° K for fluorine oxide, oxygen, and hydrogen peroxide, respectively. The nozzle-exit-temperature curves for both the frozen and the equilibrium expansions follow a trend similar to those of the combustion-chamber temperature and reach a maximum in the region of the stoichiometric mixture.

The specific-impulse curves for all the combinations considered reached maximum values in the fuel-rich region as a result of the liberation of free hydrogen, which reduces the average molecular weight of the products of combustion. The trends of the specific-impulse curves based on both frozen and equilibrium expansions are similar. The maximum deviation between the equilibrium-expansion and the frozen-expansion specific-impulse values was 8.08 percent of the equilibrium values.

The maximum specific-impulse values that were calculated for equilibrium expansion are listed in the following table, together with the corresponding volume specific impulse.

Oxidant	Fuel (percent by wt)	Maximum specific impulse, I (lb-sec/lb)	Volume specific impulse, I_d $\left[\frac{\text{lb-sec}}{(\text{cu ft})(62.43)}\right]$	Combustion-chamber temperature, T_c (°K)
Fluorine	13.63	322.4	309.8	5240
Fluorine oxide	20.41	316.2	375.3	4460
Oxygen	36.58	311.4	236.7	3740
Hydrogen peroxide	35.18	289.0	245.3	2850

Because the densities of liquids F_2, F_2O, O_2, and H_2O_2 are greater than that of liquid B_2H_6, the maximum volume specific impulse occurred at a mixture ratio less fuel rich than that required for maximum specific impulse. The general trend of the volume-specific-impulse curves is similar for both the equilibrium and frozen expansions for all the fuel-oxidant combinations. For the fluorine compounds, the maximum volume specific impulse occurs at a lower percentage of fuel than was considered. The maximum volume-specific-impulse values that were calculated for equilibrium expansion are listed in the following table, together with the corresponding specific impulse values.

Oxidant	Fuel (percent by wt)	Maximum volume specific impulse, I_d $\left[\frac{\text{lb-sec}}{(\text{cu ft})(62.43)}\right]$	Specific impulse, I (lb-sec/lb)	Combustion-chamber temperature, T_c (°K)
Fluorine oxide	12.030	424.2	302.3	4750
Fluorine	9.853	317.0	315.5	5380
Hydrogen peroxide	11.950	300.9	259.0	3218
Oxygen	25.710	243.2	288.2	4022

The mean molecular weight at both the combustion chamber and the exit decreased as the percent by weight of fuel increased. In the case of the H_2O_2 reaction with greater than 35 percent fuel, liquid B_2O_3 appeared at the exit condition and caused the molecular weight to increase. For all propellant combinations considered, the mean molecular weight was from 12.0 to 1.7 percent higher at the exit than in the combustion chamber.

The calculated values of the various performance parameters for each of the propellant combinations and for several mixture ratios are listed in table V.

The compositions of the products of combustion in the combustion chamber and at the nozzle exit are shown in figure 2. The mole fraction of each product present in the gas mixture for each of the combinations is plotted against the percent by weight of fuel.

The curves of composition are similar for the combustion-chamber and nozzle-exit conditions for any one propellant combination (fig. 2). The general trend of a given molecule is the same for all propellant combinations. As the mixture becomes more fuel rich, B_2, B, and H_2 increase and F_2, F, O_2, and O decrease. The molecules H_2O and HF are principal constituents throughout most of the mixture range considered, but are reduced by boron at the extreme fuel-rich region. The molecules BF_3 and B_2O_3 are comparatively constant throughout the range of mixture ratios considered. Certain molecules reach a maximum (for example, H) or a minimum (for example, BF_3) because of the opposing effects of the variation of temperature and mixture ratio.

SUMMARY OF RESULTS

Theoretical performance data, which were based on both frozen and equilibrium expansions, obtained over a range of mixtures for the four rocket propellant combinations of diborane with liquid fluorine, liquid fluorine oxide, liquid oxygen, and 100-percent hydrogen peroxide at a reaction pressure of 20.4 atmospheres (300 lb/sq in. absolute) and a nozzle-exit pressure of 1 atmosphere, are summarized as follows:

1. The maximum calculated specific-impulse values in pound-seconds per pound for diborane reacting with liquid fluorine, liquid fluorine oxide, liquid oxygen, and 100-percent hydrogen peroxide, were 322.4, 316.2, 311.4, and 289.0, respectively, for equilibrium expansion.

2. The maximum specific impulse for all the propellant combinations occurred in the fuel-rich region at a combustion-chamber temperature less than maximum.

3. The specific impulse for equilibrium expansion was a maximum of 8.08 percent greater than that for frozen expansion.

4. The maximum calculated volume-specific-impulse values (lb-sec/(cu ft)(62.43)) for the mixture range considered were 424.2, 317.0, 300.9, and 243.2 for liquid fluorine oxide, liquid fluorine, 100-percent hydrogen peroxide, and liquid oxygen, respectively, for equilibrium expansion.

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TABLE I - ENTHALPY OF GASES

Temperature (°K)	Enthalpy, $H_T^o - H_0^o$, cal/mole			
	BF_3	BF	BH	B
1000	14,007	7,617	7,188	4,997
1100	15,833	8,465	7,972	5,494
1200	17,683	9,319	8,767	5,991
1300	19,551	10,179	9,574	6,487
1400	21,435	11,043	10,387	6,984
1500	23,332	11,911	11,213	7,481
1600	25,239	12,782	12,043	7,978
1700	27,154	13,656	12,880	8,475
1800	29,077	14,532	13,721	8,971
1900	31,007	15,409	14,568	9,468
2000	32,942	16,288	15,419	9,965
2100	34,882	17,169	16,273	10,462
2200	36,825	18,050	17,130	10,959
2300	38,773	18,933	17,990	11,455
2400	40,723	19,817	18,853	11,952
2500	42,677	20,701	19,718	12,449
2600	44,632	21,587	20,586	12,946
2700	46,591	22,473	21,455	13,443
2800	48,551	23,359	22,325	13,939
2900	50,512	24,246	23,197	14,436
3000	52,476	25,133	24,071	14,933
3100	54,440	26,021	24,946	15,430
3200	56,407	26,910	25,822	15,927
3300	58,374	27,798	26,699	16,423
3400	60,342	28,687	27,577	16,920
3500	62,312	29,576	28,456	17,417
3600	64,283	30,466	29,335	17,914
3700	66,254	31,356	30,216	18,411
3800	68,226	32,246	31,097	18,907
3900	70,198	33,136	31,979	19,404
4000	72,172	34,026	32,861	19,901
4100	74,146	34,917	33,744	20,398
4200	76,121	35,808	34,627	20,895
4300	78,097	36,699	35,511	21,391
4400	80,072	37,590	36,396	21,888
4500	82,045	38,481	37,280	22,385
4600	84,025	39,372	38,166	22,882
4700	86,001	40,264	39,051	23,379
4800	87,977	41,155	39,937	23,875
4900	89,957	42,047	40,823	24,372
5000	91,935	42,939	41,710	24,869
5100	93,913	43,831	42,597	25,366
5200	95,893	44,723	43,484	25,863
5300	97,872	45,615	44,371	26,360
5400	99,851	46,507	45,259	26,857
5500	101,831	47,399	46,147	27,354
5600	103,810	48,291	47,035	27,851
5700	105,792	49,184	47,923	28,349
5800	107,771	50,076	48,812	28,845
5900	109,751	50,968	49,700	29,343
6000	111,736	51,861	50,589	29,840

TABLE II - ENTROPY OF GASES AT 1 ATMOSPHERE

Temperature (°K)	Entropy, S_T^o, cal/mole - °K			
	BF_3	BF	BH	B
1000	79.293	61.764	49.703	42.662
1100	81.033	62.572	50.450	43.112
1200	82.642	63.315	51.143	43.538
1300	84.138	64.003	51.792	43.941
1400	85.534	64.644	52.392	44.320
1500	86.842	65.243	52.960	44.676
1600	88.073	65.805	53.496	45.009
1700	89.234	66.334	54.003	45.318
1800	90.333	66.835	54.484	45.604
1900	91.377	67.309	54.942	45.866
2000	92.369	67.760	55.378	46.105
2100	93.316	68.190	55.795	46.342
2200	94.220	68.600	56.194	46.573
2300	95.085	68.993	56.577	46.795
2400	95.915	69.369	56.944	47.008
2500	96.713	69.730	57.297	47.214
2600	97.480	70.077	57.637	47.411
2700	98.219	70.411	57.965	47.600
2800	98.939	70.734	58.287	47.781
2900	99.620	71.045	58.588	47.955
3000	100.286	71.346	58.884	48.119
3100	100.930	71.637	59.171	48.276
3200	101.554	71.919	59.449	48.431
3300	102.160	72.192	59.719	48.582
3400	102.747	72.458	59.981	48.729
3500	103.318	72.715	60.236	48.875
3600	103.873	72.966	60.483	49.015
3700	104.413	73.210	60.725	49.154
3800	104.940	73.447	60.959	49.288
3900	105.452	73.678	61.189	49.421
4000	105.951	73.904	61.412	49.549
4100	106.439	74.124	61.630	49.675
4200	106.915	74.338	61.843	49.796
4300	107.380	74.548	62.051	49.916
4400	107.834	74.753	62.254	50.031
4500	108.278	74.953	62.450	50.143
4600	108.712	75.149	62.648	50.252
4700	109.137	75.341	62.838	50.359
4800	109.553	75.529	63.025	50.461
4900	109.962	75.712	63.207	50.561
5000	110.361	75.893	63.386	50.657
5100	110.753	76.069	63.562	50.756
5200	111.138	76.243	63.734	50.852
5300	111.514	76.412	63.903	50.947
5400	111.884	76.579	64.069	51.040
5500	112.248	76.743	64.232	51.131
5600	112.604	76.903	64.392	51.221
5700	112.955	77.062	64.549	51.309
5800	113.299	77.217	64.704	51.395
5900	113.637	77.369	64.856	51.480
6000	113.972	77.519	65.005	51.564

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TABLE III - FREE-ENERGY FUNCTION OF GASES

Temperature (°K)	Free-energy function of gases, $-\frac{F_T^o - H_0^o}{T}$ cal/mole - °K			
	BF_3	BF	BH	B
1000	65.286	54.147	42.515	37.665
1100	66.639	54.876	43.203	38.115
1200	67.907	55.549	43.836	38.544
1300	69.098	56.173	44.428	38.949
1400	70.223	56.756	44.971	39.329
1500	71.288	57.302	45.485	39.689
1600	72.299	57.816	45.969	40.021
1700	73.261	58.302	46.427	40.331
1800	74.179	58.762	46.861	40.619
1900	75.057	59.199	47.275	40.881
2000	75.898	59.616	47.669	41.123
2100	76.705	60.014	48.046	41.358
2200	77.481	60.395	48.408	41.592
2300	78.228	60.761	48.755	41.814
2400	78.947	61.111	49.088	42.026
2500	79.642	61.449	49.409	42.234
2600	80.314	61.774	49.719	42.431
2700	80.963	62.088	50.019	42.621
2800	81.600	62.391	50.313	42.802
2900	82.202	62.684	50.589	42.977
3000	82.794	62.968	50.860	43.142
3100	83.369	63.243	51.134	43.297
3200	83.927	63.510	51.379	43.454
3300	84.470	63.768	51.628	43.606
3400	84.999	64.020	51.870	43.753
3500	85.515	64.265	52.105	43.899
3600	86.017	64.503	52.335	44.038
3700	86.507	64.735	52.558	44.178
3800	86.985	64.961	52.776	44.314
3900	87.452	65.182	52.989	44.446
4000	87.908	65.397	53.197	44.574
4100	88.354	65.607	53.400	44.700
4200	88.791	65.813	53.598	44.820
4300	89.218	66.013	53.792	44.941
4400	89.636	66.210	53.982	45.056
4500	90.046	66.402	54.166	45.169
4600	90.446	66.590	54.350	45.278
4700	90.839	66.774	54.529	45.384
4800	91.224	66.954	54.704	45.487
4900	91.603	67.131	54.876	45.587
5000	91.974	67.305	55.044	45.683
5100	92.339	67.475	55.210	45.782
5200	92.697	67.642	55.372	45.879
5300	93.048	67.806	55.531	45.973
5400	93.393	67.967	55.688	46.066
5500	93.733	68.125	55.842	46.158
5600	94.067	68.280	55.993	46.247
5700	94.395	68.433	56.142	46.335
5800	94.718	68.583	56.288	46.422
5900	95.036	68.730	56.432	46.507
6000	95.349	68.876	56.574	46.590

TABLE IV - PHYSICAL-CHEMICAL PROPERTIES OF PROPELLANTS

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

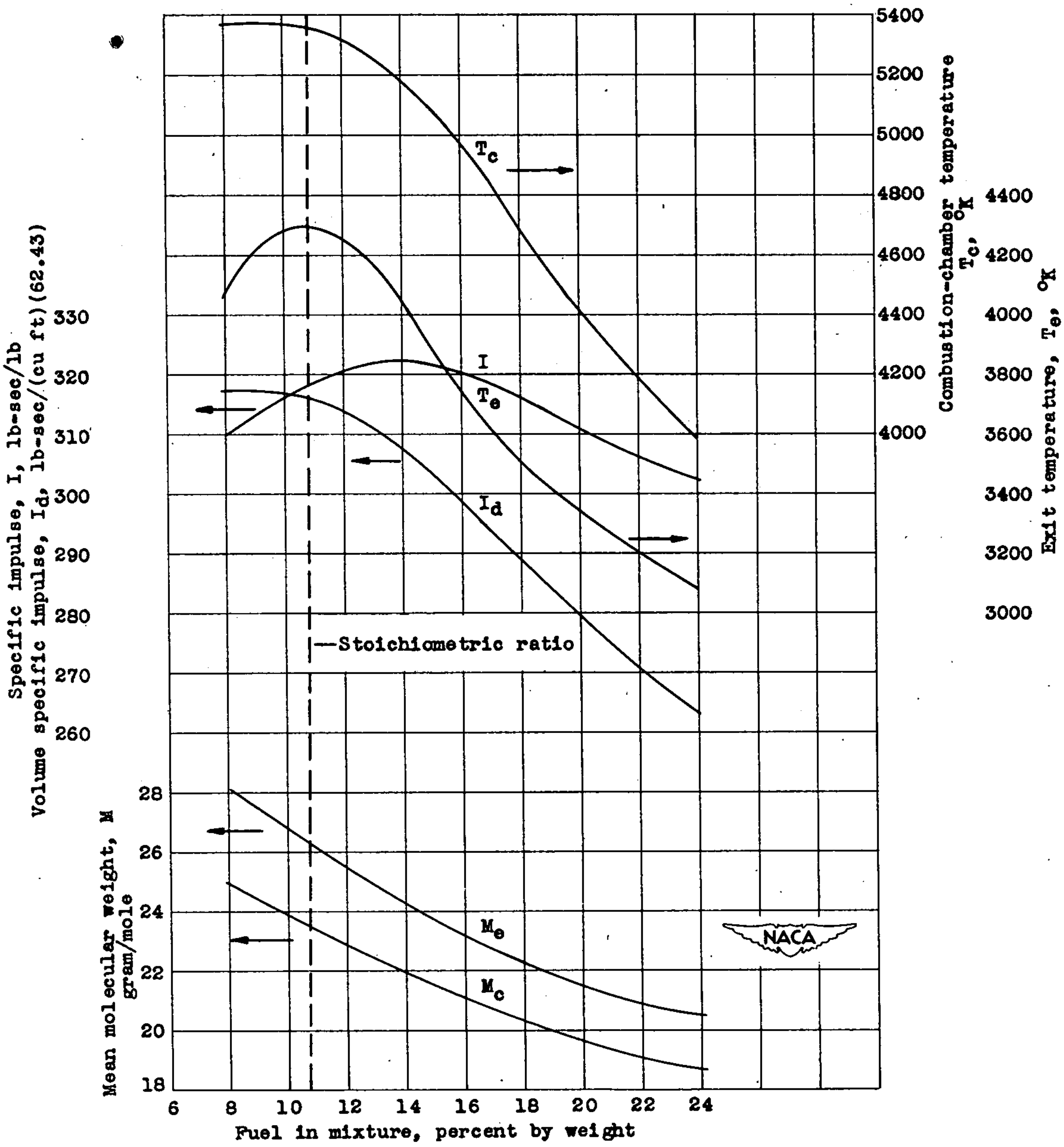
Propellants	Molecular weight M	Density (gram/cc)	Enthalpy of formation, ΔH_f (k-cal/mole)	Enthalpy of vaporization, ΔH (k-cal/mole)	Boiling point (°C)	Freezing point (°C)	Vapor pressure (mm)	Refractive index n_D	Viscosity (centipoises)
Diborane	27.688	(liquid) $0.4818^{-129.5}$ (12)	(gas) -44^{25} (3)	3.1^{18} (15)	-92.5 (2)	-165.5 (2)	212.23^{-112} (16)	----------	------------
Fluorine	38.000	(liquid) 1.14^{-200} (16)	(gas) 0^{25}	1.60^{-188} (15)	-188 (15)	-223.0 (2)	$760^{-187.92}$ (14)	(gas) 1.000195^{20} (2)	------------
Fluorine oxide	54.000	(liquid) $1.90^{-223.8}$ (2)	(gas) 5.5^{25} (14)	$2.65^{-144.9}$ (14)	-144.9 (14)	-223.8 (2)	$760^{-144.9}$ (14)	----------	------------
Oxygen	32.000	(liquid) 1.14^{-183} (2)	(gas) 0^{25}	1.629^{-183} (15)	-183.0 (2)	-218.4 (2)	$760^{-182.97}$ (14)	(liquid) 1.221^{-181} (16)	(liquid) $0.189^{-252.07}$ (96%) (16)
Hydrogen peroxide	34.016	(liquid) 1.436^{25} [a](13)	(liquid) -45.2^{18} (15)	11.61^{18} (15)	152.1 (2)	-0.89 (2)	2.1^{25} (14)	(liquid) 1.4139^{22} (13)	(liquid) 1.307^{18} (13)

[a] Extrapolated.

TABLE V - CALCULATED PERFORMANCE OF DIBORANE

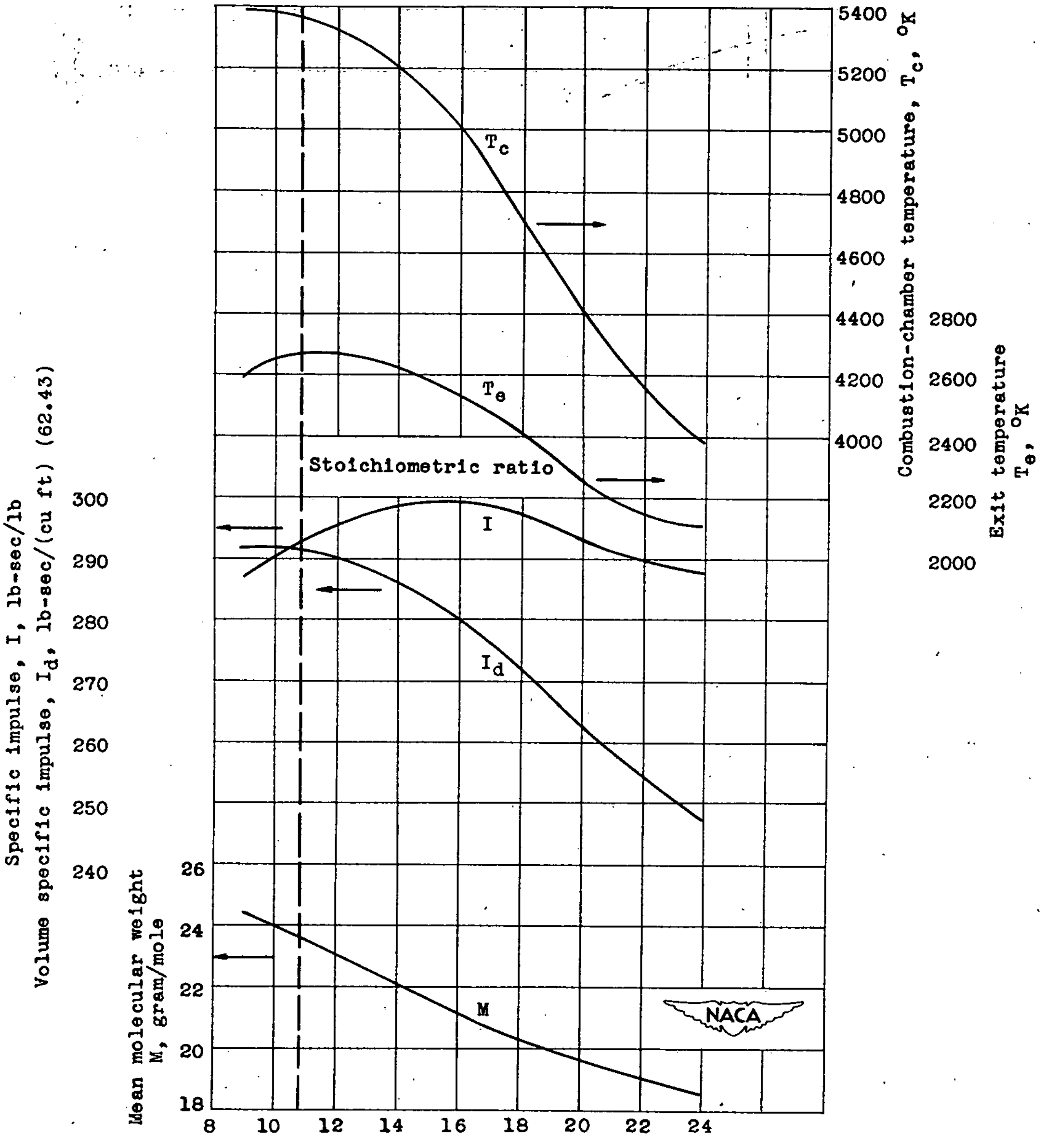
Fuel (percent by weight)	Propellant density (gram/cc)	Combustion-chamber temperature T_c (°K)	Mean molecular weight in combustion chamber, M_c (gram/mole)	Frozen expansion			Equilibrium expansion			
				Specific impulse, I (lb-sec/lb)	Volume specific impulse, I_d $\left[\frac{\text{lb-sec}}{\text{cu ft (62.43)}}\right]$	Temperature at nozzle exit, T_e (°K)	Specific impulse, I (lb-sec/lb)	Volume specific impulse, I_d $\left[\frac{\text{lb-sec}}{\text{cu ft (62.43)}}\right]$	Temperature at nozzle exit, T_e (°K)	Mean molecular weight at nozzle exit, M_e (gram/mole)
$B_2H_6 + F_2$										
9.85	1.005	5380	24.00	289.8	291.2	2655	315.5	317.0	4270	26.87
[a]10.83	.993	5374	23.53	292.8	290.8	2667	317.4	315.2	4298	26.30
13.63	.961	5240	22.23	298.0	286.3	2640	322.4	309.8	4113	24.59
16.69	.928	4900	20.80	298.7	277.3	2481	318.4	295.6	3650	22.73
17.11	.924	4835	20.62	298.1	275.5	2451	317.9	293.7	3600	22.56
19.54	.900	4467	19.72	293.7	264.3	2287	312.9	281.6	3389	21.68
23.29	.865	4040	18.76	288.5	249.5	2110	307.1	265.6	3122	20.55
$B_2H_6 + F_2O$										
12.03	1.403	4750	23.03	280.0	392.8	2432	302.3	424.2	3737	25.18
[a]14.60	1.329	4701	21.97	286.0	380.1	2440	309.2	410.9	3749	23.95
20.41	1.187	4460	19.83	295.0	350.2	2373	316.2	375.3	3493	21.53
22.51	1.143	4309	19.22	295.3	337.4	2315	314.7	359.6	3357	20.93
25.48	1.086	4007	18.49	293.5	318.7	2216	311.3	338.0	3172	20.14
$B_2H_6 + O_2$										
20.61	0.890	3953	23.98	261.3	232.4	2438	270.9	241.0	3139	26.08
[a]22.38	.873	3990	23.10	267.5	233.6	2462	278.2	242.8	3170	25.16
25.71	.844	4022	21.50	278.3	234.8	2475	288.2	243.2	3176	23.38
32.90	.786	3915	18.42	295.4	232.3	2380	305.3	240.1	2980	19.78
36.58	.760	3740	17.11	299.9	227.9	2240	311.4	236.7	2830	18.21
38.82	.745	3500	16.47	294.7	219.5	2086	303.5	226.1	2481	17.27
$B_2H_6 + H_2O_2$										
7.53	1.250	2858	22.48	230.6	288.2	1780	234.9	293.5	1968	22.95
[a]11.95	1.161	3218	21.41	251.2	291.7	2042	259.1	300.9	2467	22.56
21.34	1.009	3204	17.99	271.7	274.2	1980	277.4	280.0	2197	18.50
28.93	.913	3020	15.69	281.2	256.7	1814	284.3	259.6	1931	15.95
35.18	.846	2846	14.16	285.8	241.9	1672	289.9	245.4	1899	14.69
37.38	.825	2473	13.60	270.2	223.0	1422	279.2	230.4	1845	14.80

[a]Stoichiometric mixture



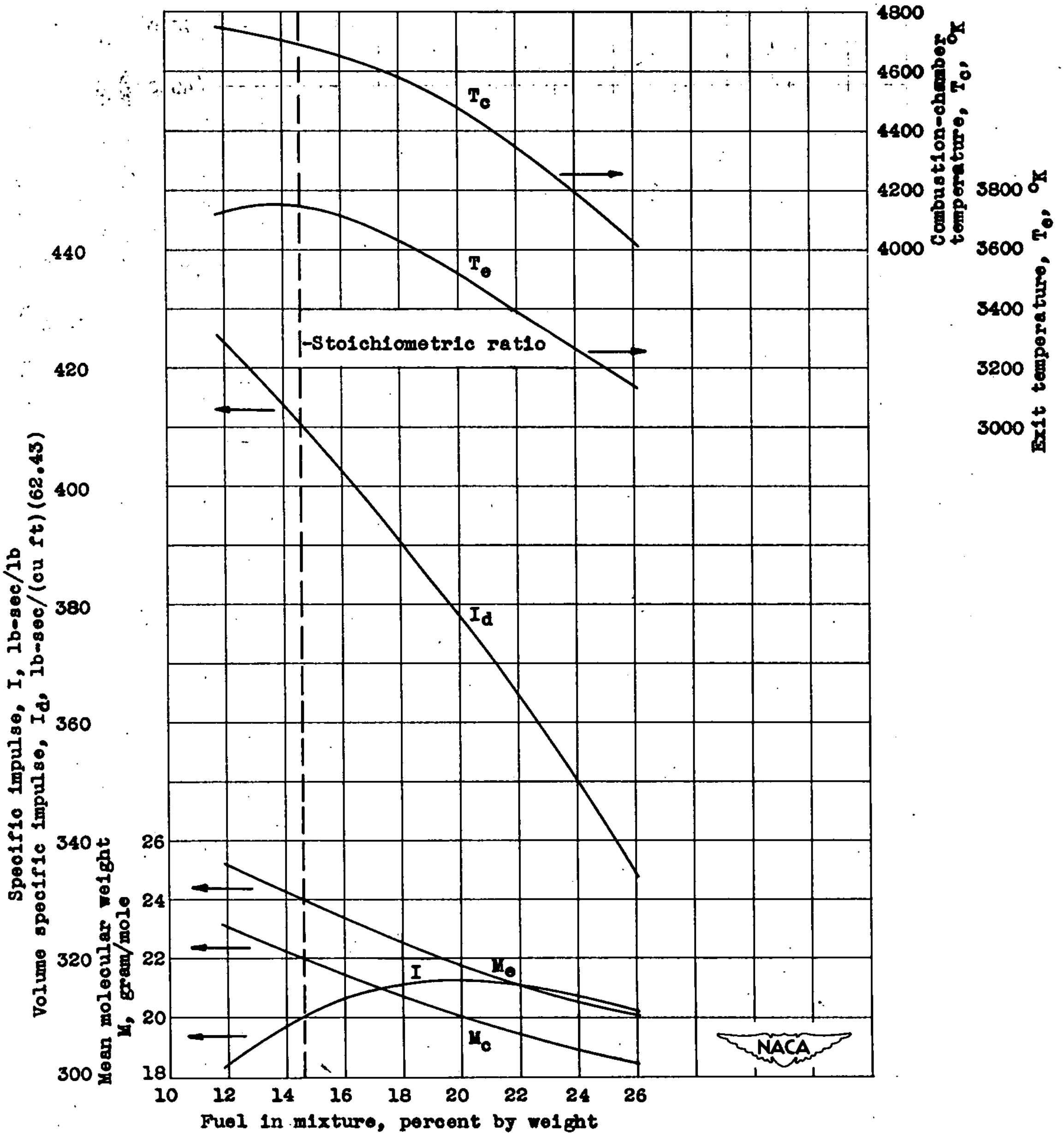
(a) Liquid fluorine F_2; equilibrium expansion.

Figure 1. - Theoretical performance of diborane with liquid fluorine, liquid fluorine oxide, liquid oxygen, and 100-percent hydrogen peroxide. Isentropic expansion from 20.4 to 1 atmosphere.



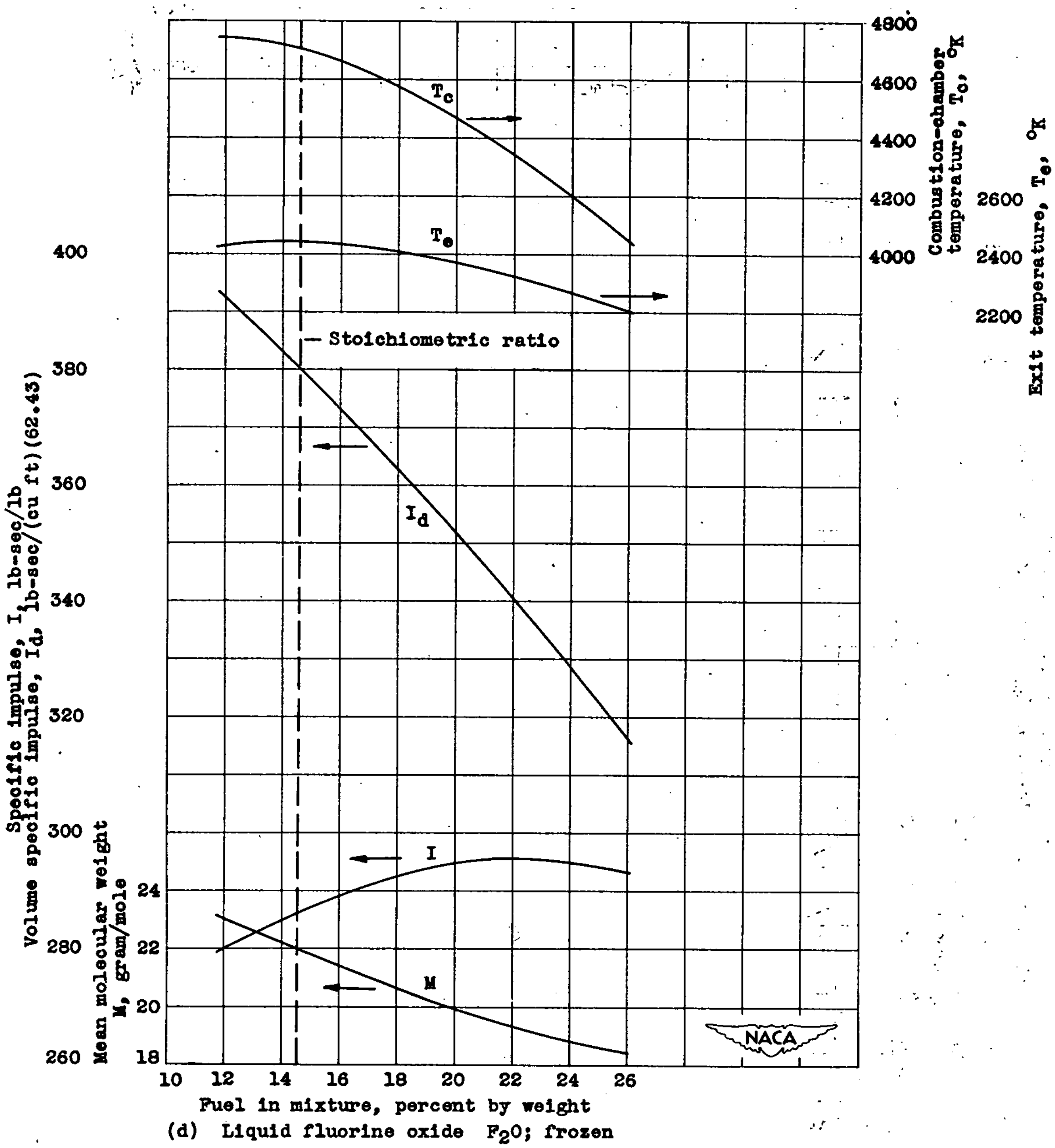
(b) Liquid fluorine F_2; frozen expansion.

Figure 1. - Continued. Theoretical performance of diborane with liquid fluorine, liquid fluorine oxide, liquid oxygen, and 100-percent hydrogen peroxide. Isentropic expansion from 20.4 to 1 atmosphere.



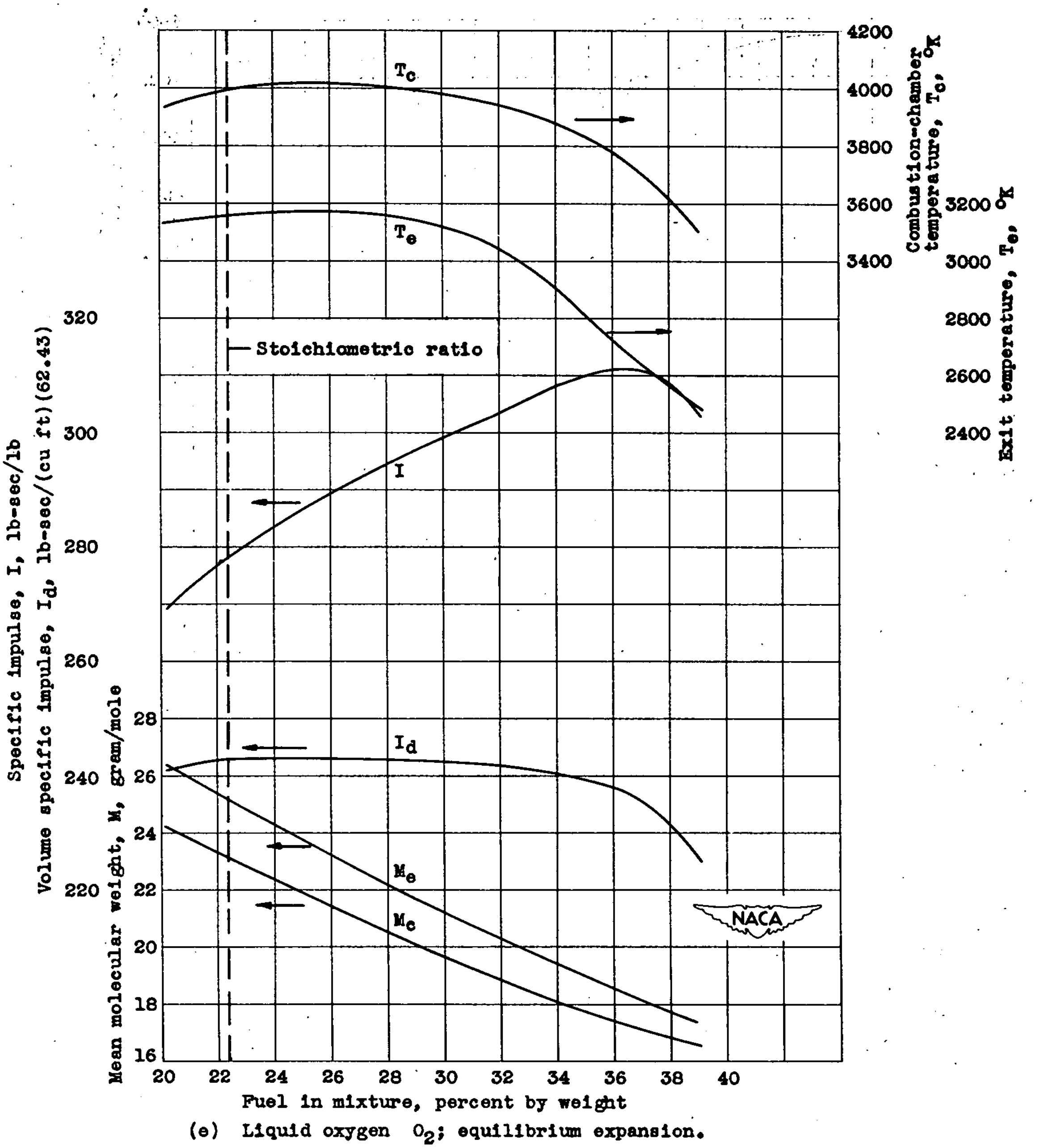
(c) Liquid fluorine oxide F_2O; equilibrium expansion.

Figure 1. - Continued. Theoretical performance of diborane with liquid fluorine, liquid fluorine oxide, liquid oxygen, and 100-percent hydrogen peroxide. Isentropic expansion from 20.4 to 1 atmosphere.



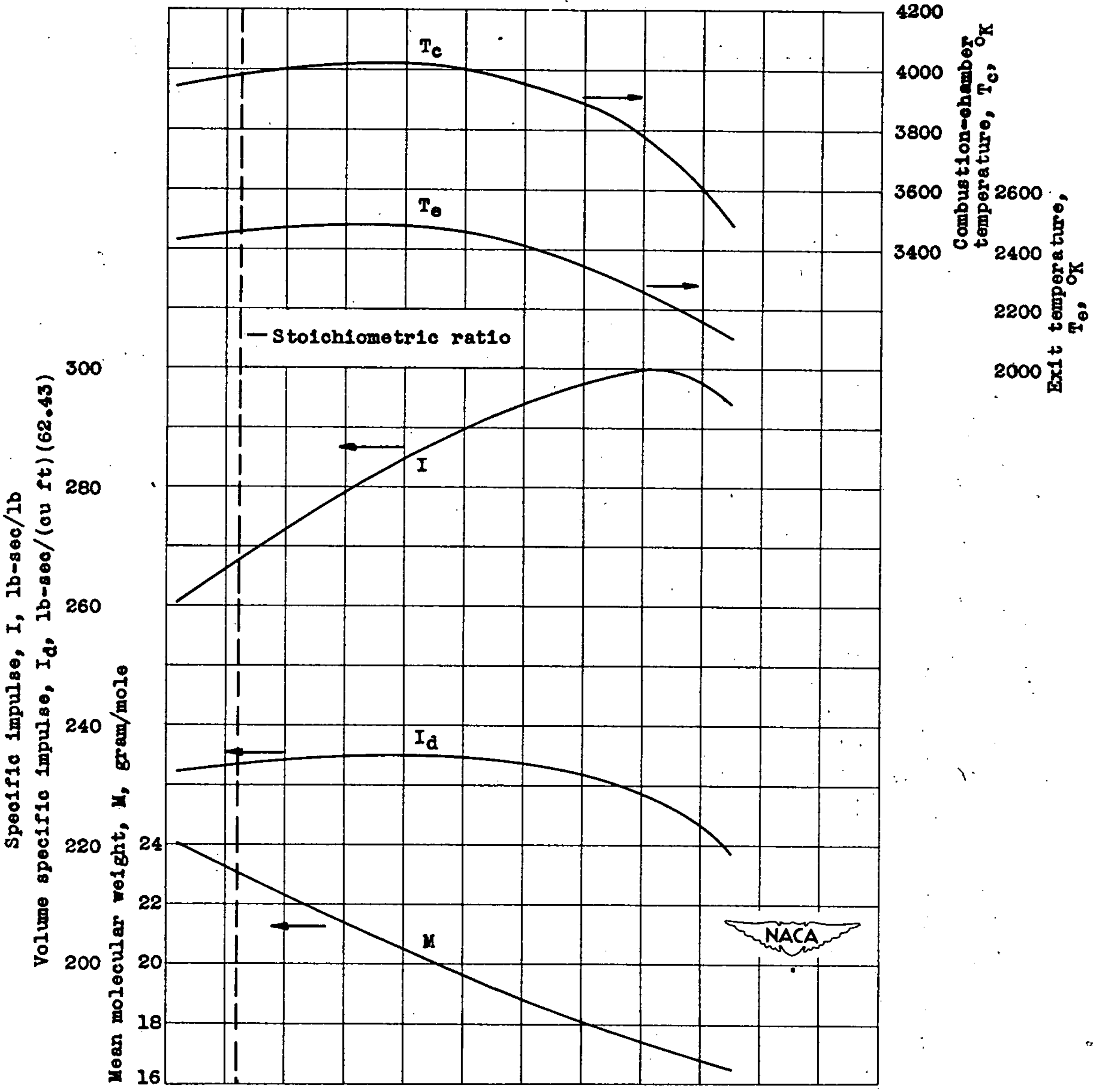
(d) Liquid fluorine oxide F_2O; frozen expansion.

Figure 1. - Continued. Theoretical performance of diborane with liquid fluorine, liquid fluorine oxide, liquid oxygen, and 100-percent hydrogen peroxide. Isentropic expansion from 20.4 to 1 atmosphere.



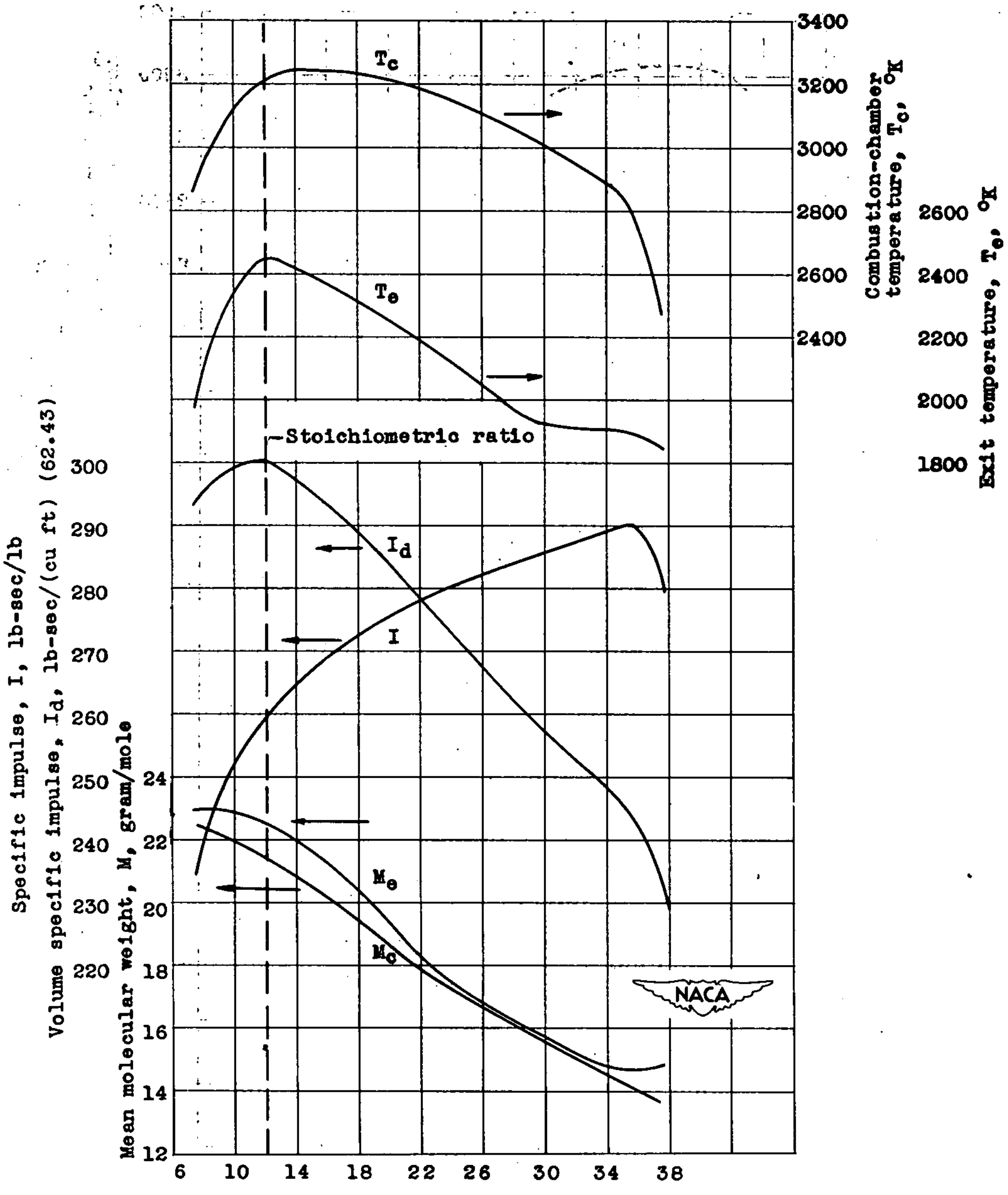
(e) Liquid oxygen O_2; equilibrium expansion.

Figure 1. - Continued. Theoretical performance of diborane with liquid fluorine, liquid fluorine oxide, liquid oxygen, and 100-percent hydrogen peroxide. Isentropic expansion from 20.4 to 1 atmosphere.



(f) Liquid oxygen O_2; frozen expansion.

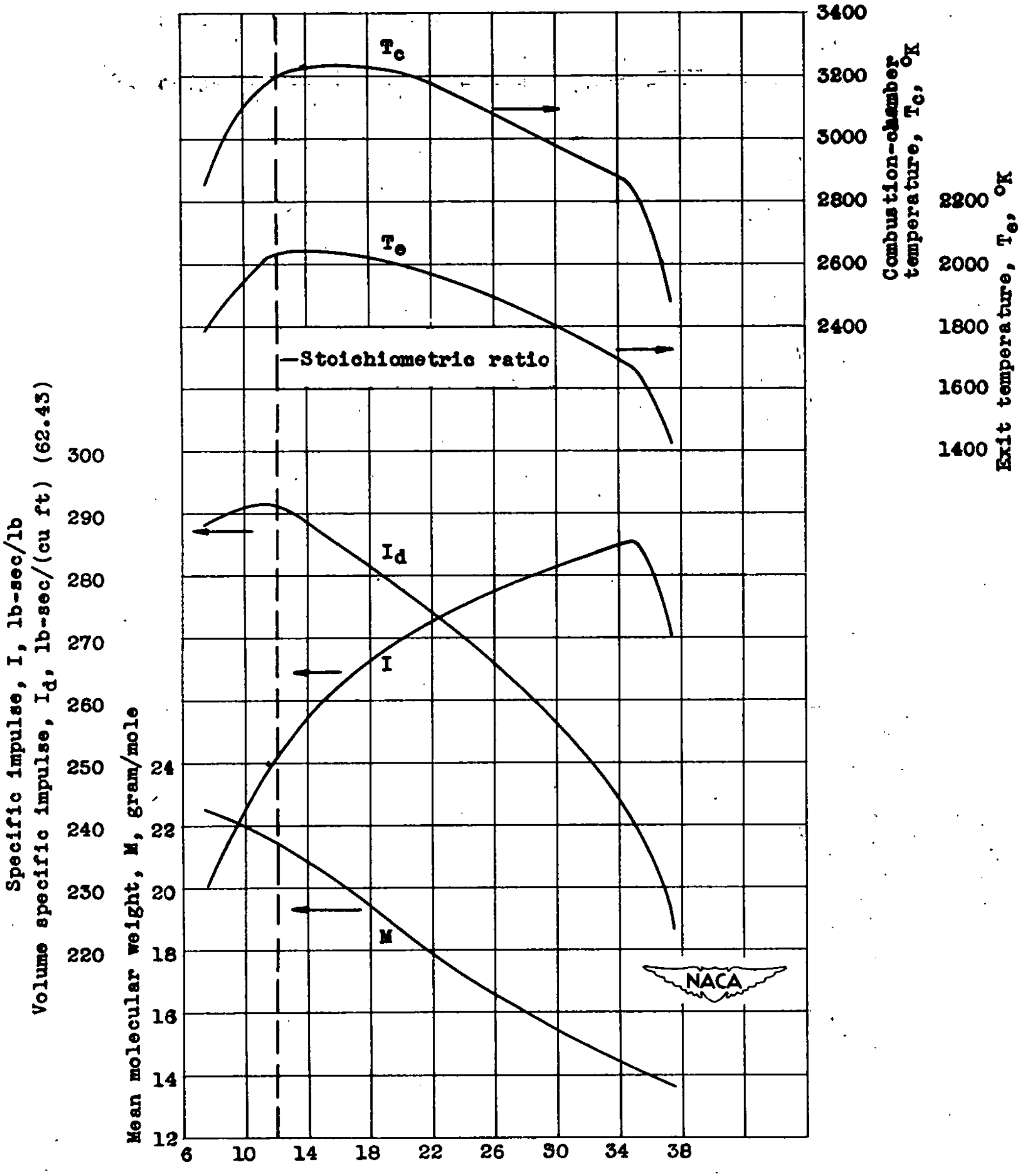
Figure 1. - Continued. Theoretical performance of diborane with liquid fluorine, liquid fluorine oxide, liquid oxygen, and 100-percent hydrogen peroxide. Isentropic expansion from 20.4 to 1 atmosphere.



Fuel in mixture, percent by weight

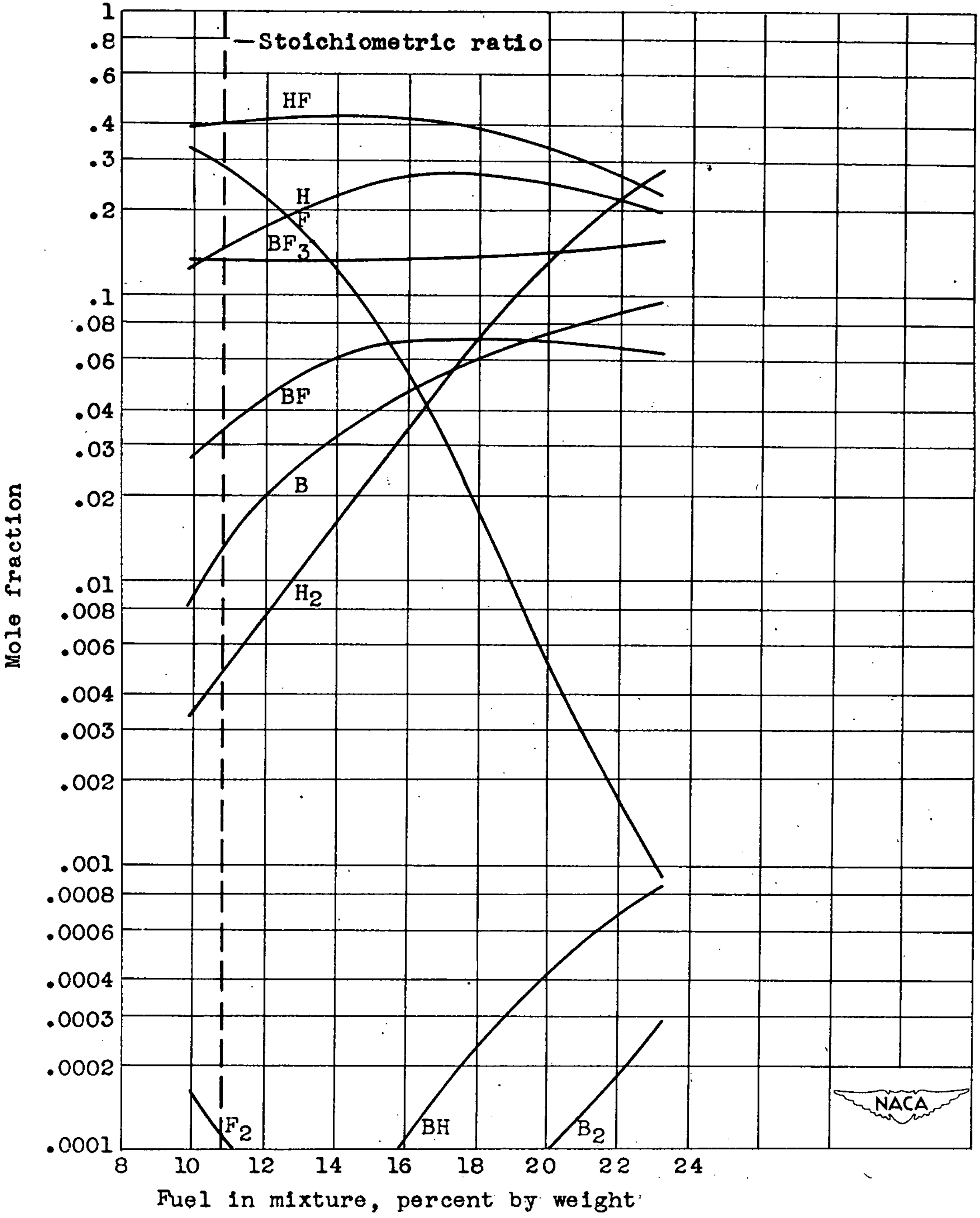
(g) Hydrogen peroxide (100-percent) H_2O_2; equilibrium expansion.

Figure 1. - Continued. Theoretical performance of diborane with liquid fluorine, liquid fluorine oxide, liquid oxygen, and 100-percent hydrogen peroxide. Isentropic expansion from 20.4 to 1 atmosphere.



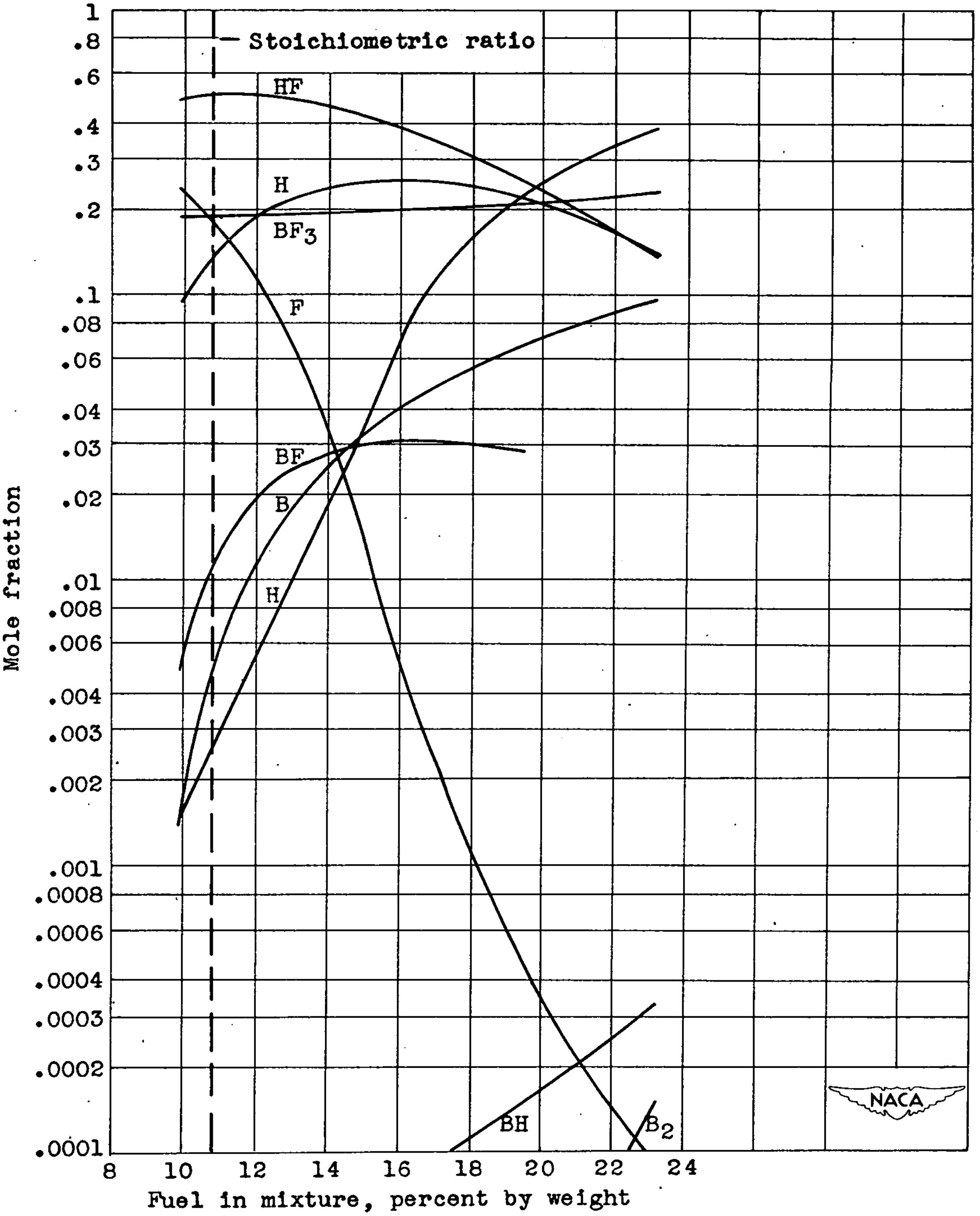
(h) Hydrogen peroxide (100-percent) H_2O_2; frozen expansion.

Figure 1. - Concluded. Theoretical performance of diborane with liquid fluorine, liquid fluorine oxide, liquid oxygen, and 100-percent hydrogen peroxide. Isentropic expansion from 20.4 to 1 atmosphere.



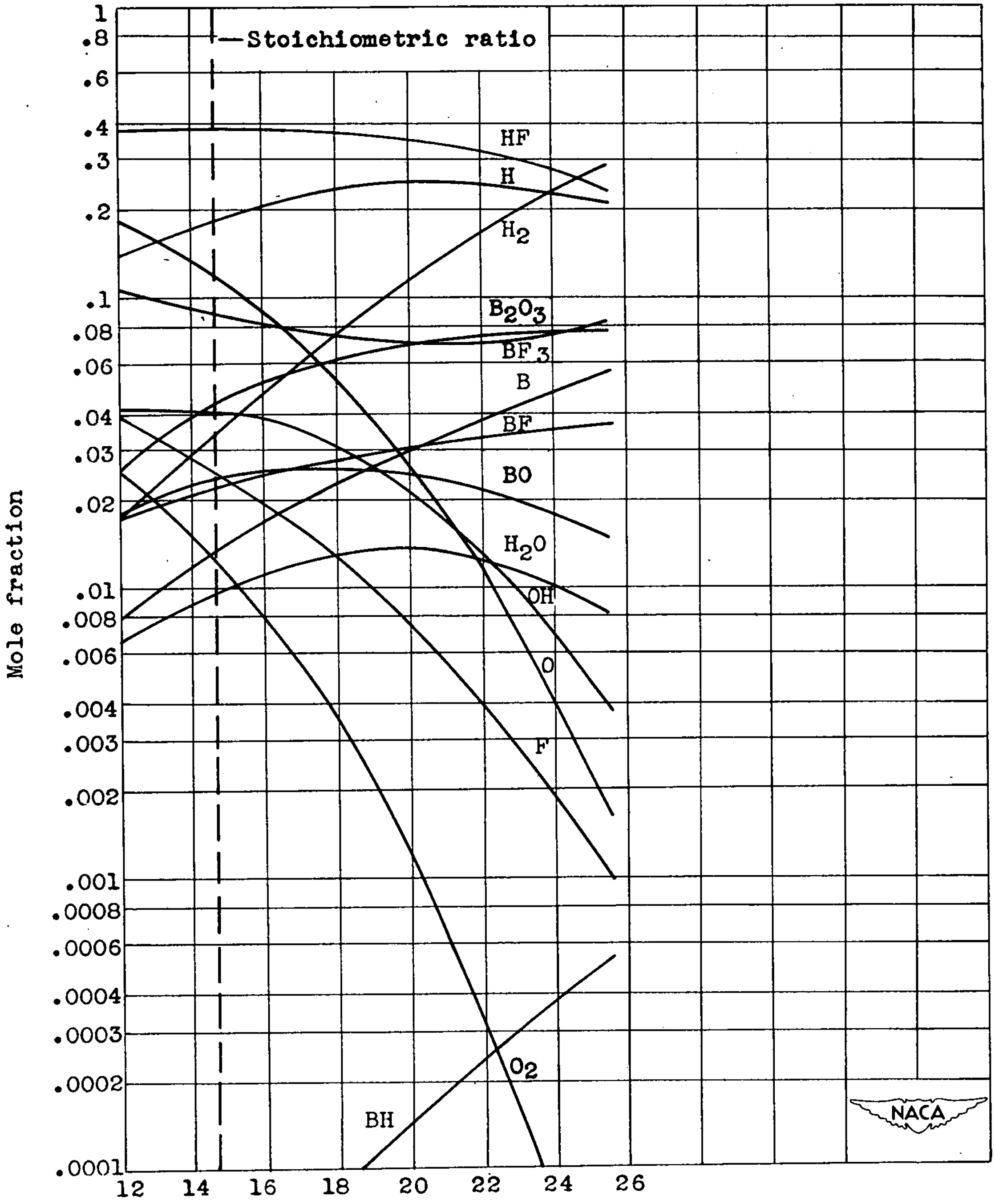
(a) Liquid fluorine F_2; combustion-chamber conditions.

Figure 2. - Composition of products of reaction of diborane with liquid fluorine oxide, liquid oxygen, and 100-percent hydrogen peroxide.



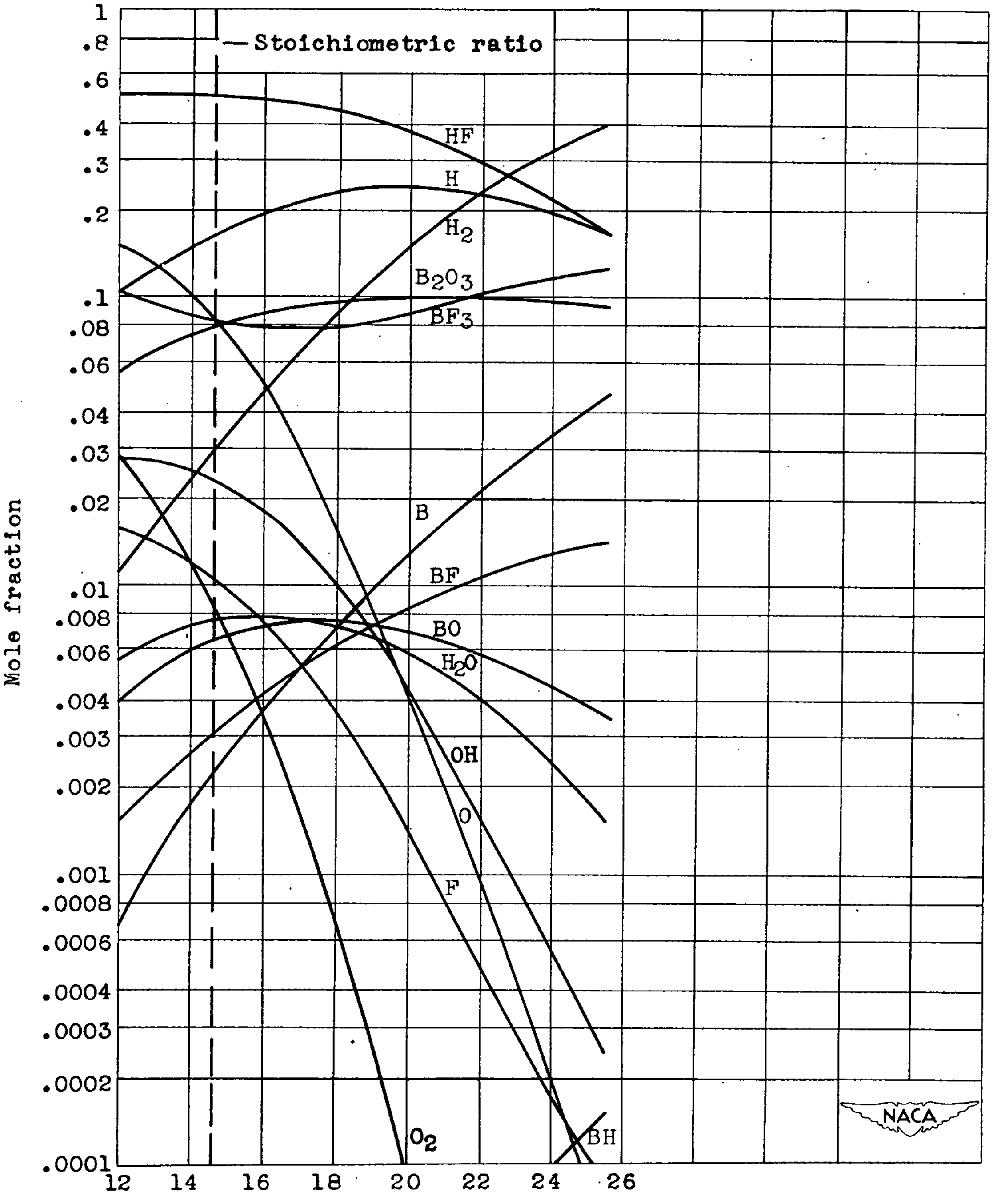
(b) Liquid fluorine F_2; equilibrium nozzle-exit conditions.

Figure 2. - Continued. Composition of products of reaction of diborane with liquid fluorine oxide, liquid oxygen, and 100-percent hydrogen peroxide.



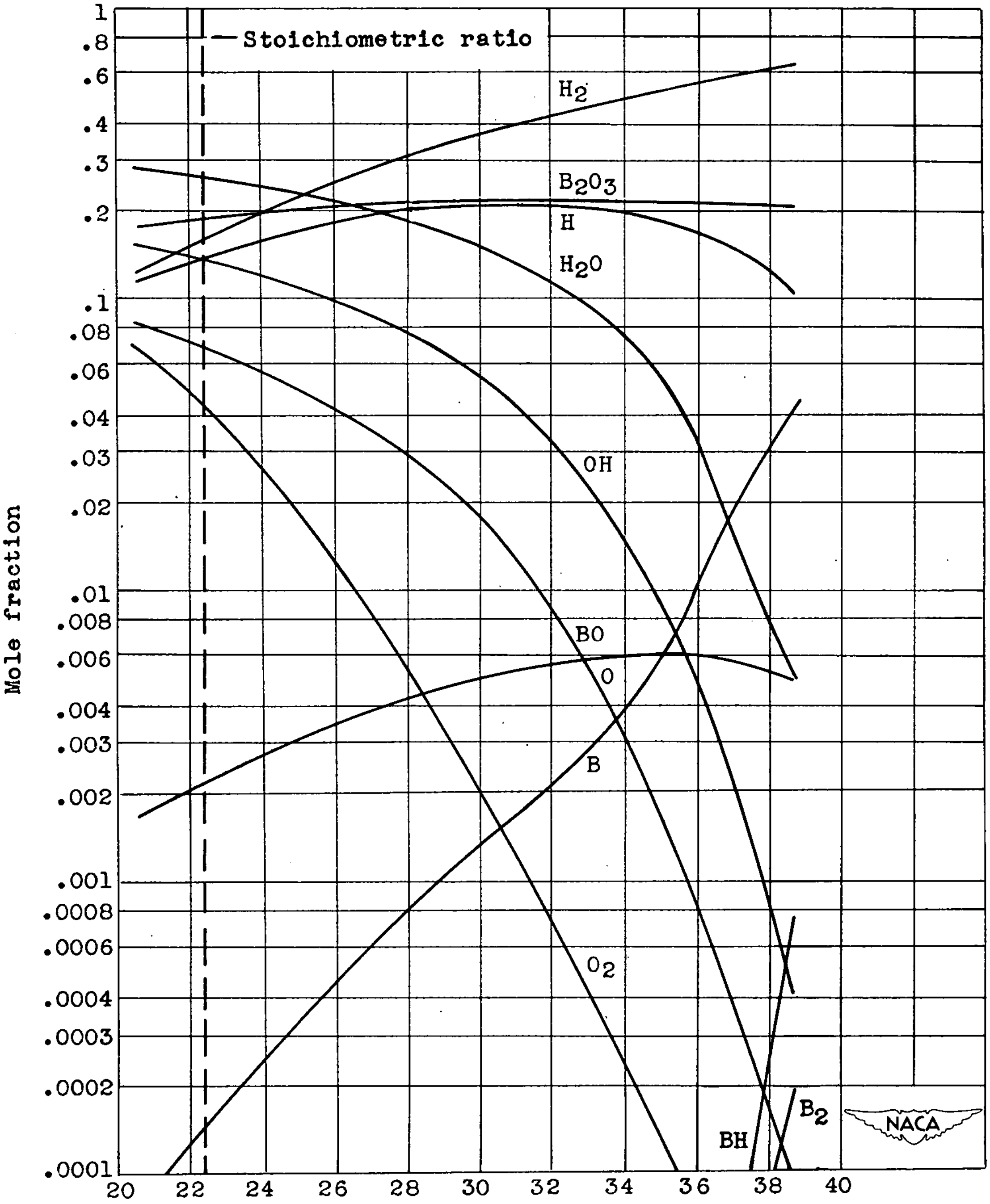
(c) Liquid fluorine oxide F_2O; combustion-chamber conditions.

Figure 2. - Continued. Composition of products of reaction of diborane with liquid fluorine oxide, liquid oxygen, and 100-percent hydrogen peroxide.



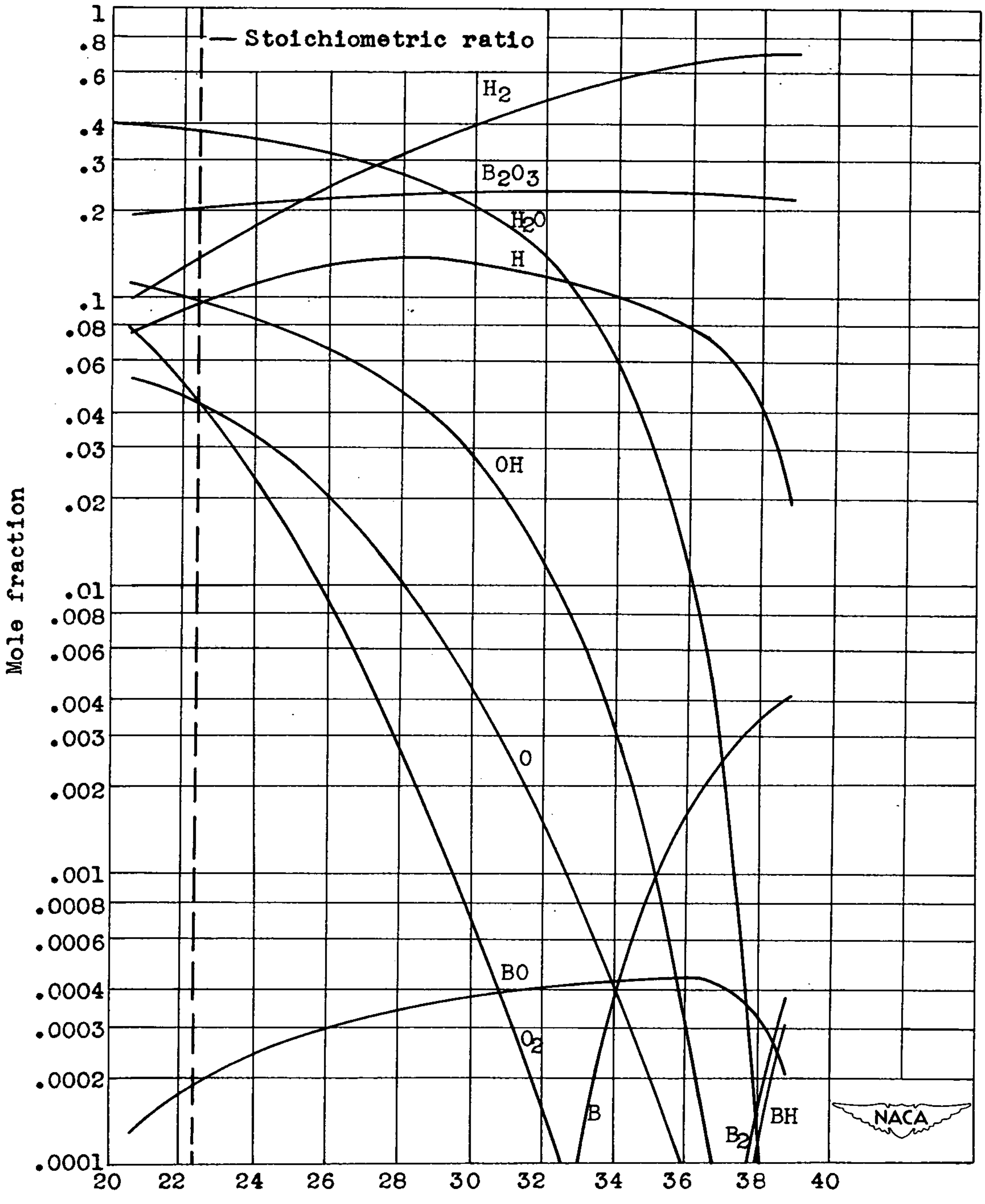
(d) Liquid fluorine oxide F_2O; equilibrium nozzle-exit conditions.

Figure 2. - Continued. Composition of products of reaction of diborane with liquid fluorine oxide, liquid oxygen, and 100-percent hydrogen peroxide.



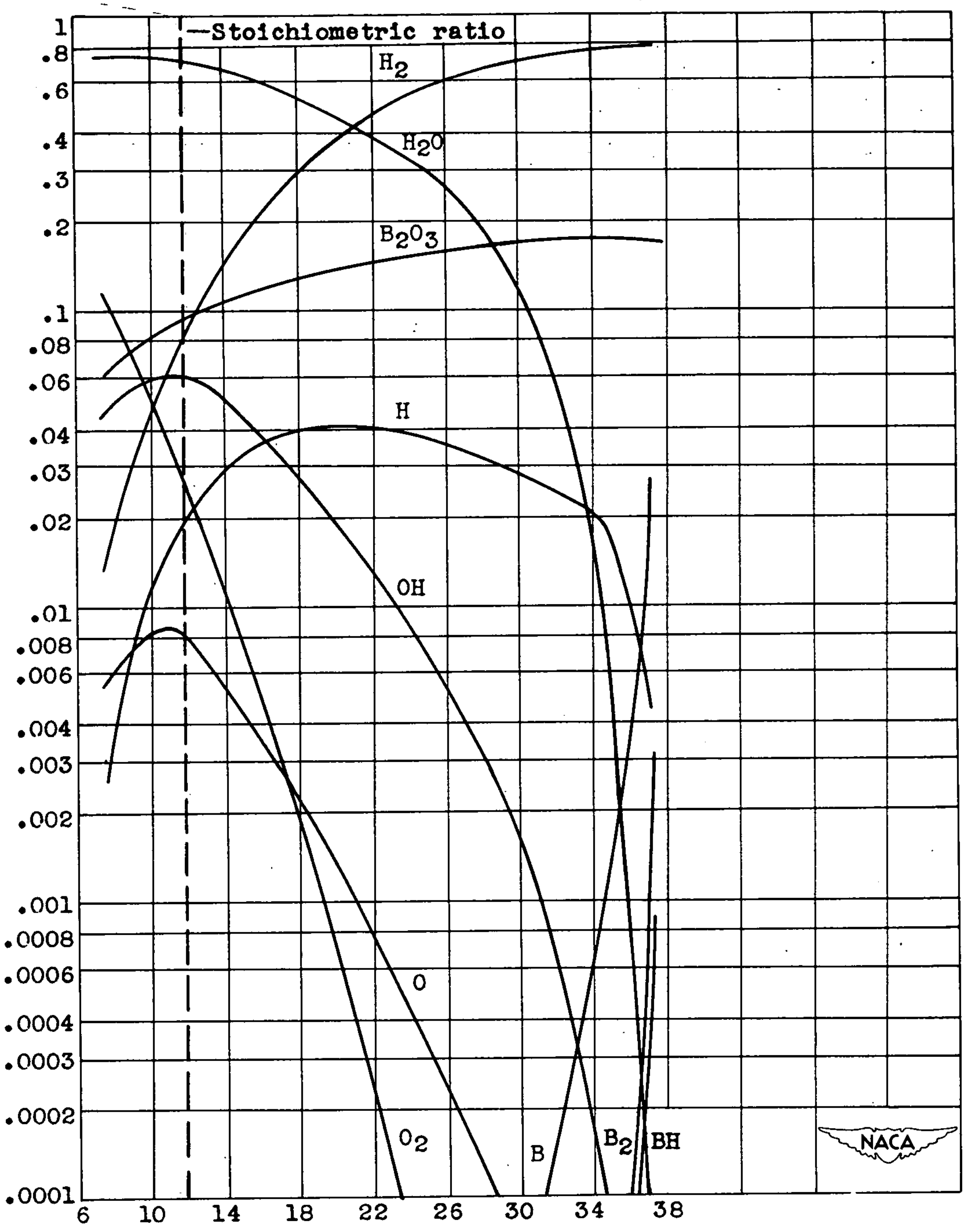
(e) Liquid oxygen O_2; combustion-chamber conditions.

Figure 2. - Continued. Composition of products of reaction of diborane with liquid fluorine oxide, liquid oxygen, and 100-percent hydrogen peroxide.



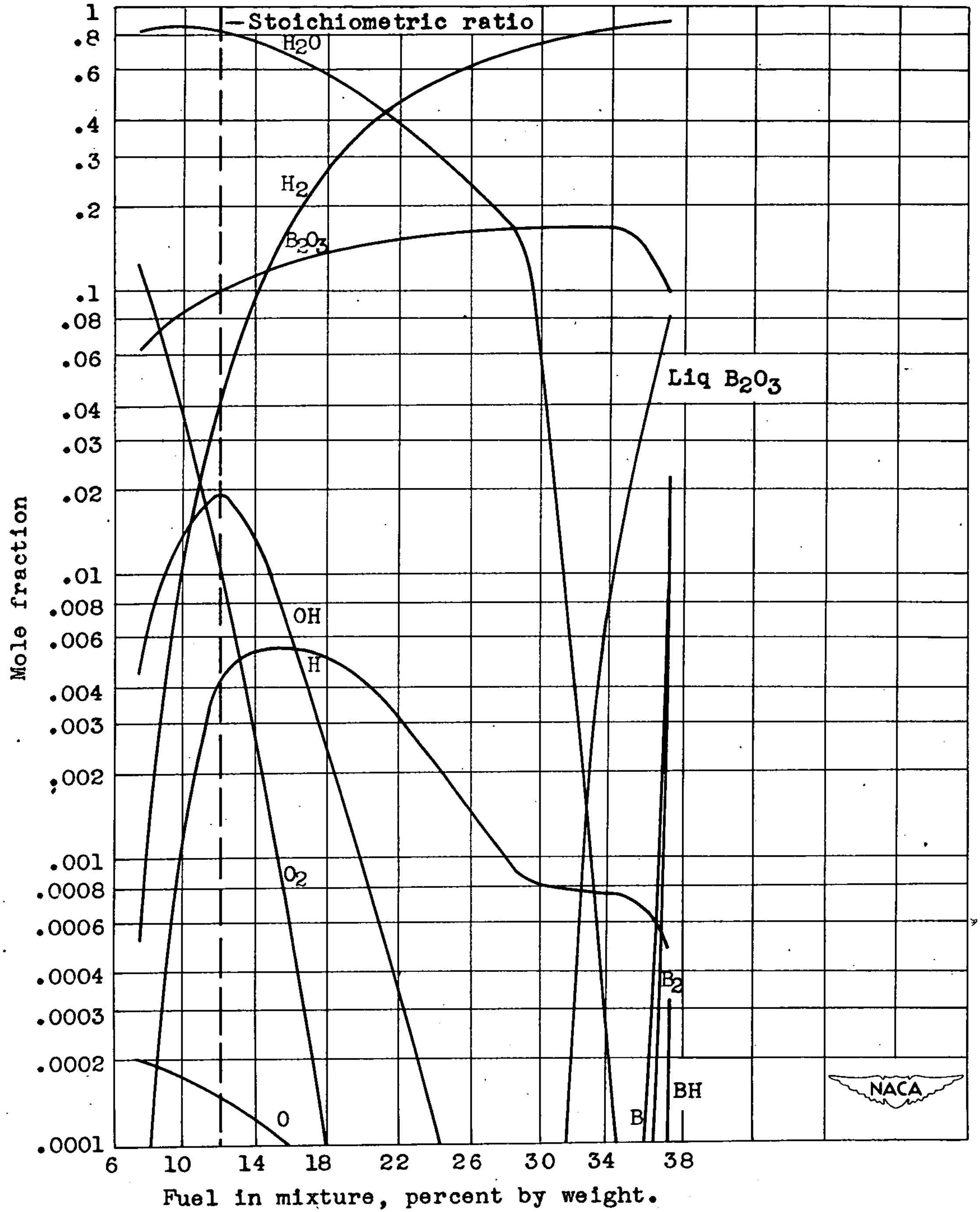
(f) Liquid oxygen O_2; equilibrium nozzle-exit conditions.

Figure 2. - Continued. Composition of products of reaction of diborane with liquid fluorine oxide, liquid oxygen, and 100-percent hydrogen peroxide.



(g) Hydrogen peroxide (100 percent) H_2O_2; combustion-chamber conditions.

Figure 2. - Continued. Composition of products of reaction of diborane with liquid fluorine oxide, liquid oxygen, and 100-percent hydrogen peroxide.



(h) Hydrogen peroxide (100 percent) H_2O_2; equilibrium nozzle-exit conditions.

Figure 2. - Concluded. Composition of products of reaction of diborane with liquid fluorine oxide, liquid oxygen, and 100-percent hydrogen peroxide.