NACA

RESEARCH MEMORANDUM

THEORETICAL PERFORMANCE OF LIQUID AMMONIA, HYDRAZINE AND MIXTURE OF LIQUID AMMONIA AND HYDRAZINE AS FUELS WITH LIQUID OXYGEN BIFLUORIDE AS OXIDANT FOR ROCKET ENGINES

I - MIXTURE OF LIQUID AMMONIA AND HYDRAZINE

By Vearl N. Huff and Sanford Gordon

Lewis Flight Propulsion Laboratory
Cleveland, Ohio

NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

WASHINGTON
February 20, 1952

NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

RESEARCH MEMORANDUM

THEORETICAL PERFORMANCE OF LIQUID AMMONIA, HYDRAZINE, AND MIXTURE OF LIQUID AMMONIA AND HYDRAZINE AS FUELS WITH LIQUID OXYGEN BIFLUORIDE AS OXIDANT FOR ROCKET ENGINES

I - MIXTURE OF LIQUID AMMONIA AND HYDRAZINE

By Vearl N. Huff and Sanford Gordon

SUMMARY

Theoretical values of performance parameters for a mixture of 36.3 percent liquid ammonia and 63.7 percent hydrazine by weight with liquid oxygen bifluoride were calculated on the assumption of equilibrium composition during the expansion process for a wide range of fuel-oxidant and expansion ratios. The parameters included were specific impulse, combustion-chamber temperature, nozzle-exit temperature, equilibrium composition, mean molecular weight, characteristic velocity, coefficient of thrust, and ratio of nozzle-exit area to throat area.

The maximum value of specific impulse was 295.8 pound-seconds per pound for a chamber pressure of 300 pounds per square inch absolute (20.41 atm) and an exit pressure of 1 atmosphere. Additional calculations were made to determine the effects on performance of a small amount of water in the hydrazine.

INTRODUCTION

Both ammonia and hydrazine have been of interest for a number of years as possible rocket fuels because of their high theoretical specific impulse with several oxidants. Extensive data exist in the literature on the availability, cost, and physical, chemical, and handling properties (references 1 and 2).

Interest has also been shown in mixtures of ammonia and hydrazine, inasmuch as some of the properties of the mixtures are more desirable than those of the separate fuels (reference 3). Ammonia, for example, depresses the relatively high freezing point of hydrazine, whereas the hydrazine slightly lowers the vapor pressure of the ammonia.

Oxygen bifluoride is of interest as a rocket oxidant because its performance is better than that of oxygen and its handling and material problems may be simpler than those of fluorine. At the temperature of liquid nitrogen (-195.8° C), the density of liquid oxygen bifluoride is about 1.77 grams per cubic centimeter (reference 4), whereas the density of liquid fluorine at the same temperature is about 1.56 grams per cubic centimeter (according to recent research at Aerojet Engineering Corp.). Additional information concerning oxygen bifluoride may be found in reference 5.

Calculations were made at the NACA Lewis laboratory to determine the theoretical performance of a mixture of liquid ammonia and hydrazine with liquid oxygen bifluoride, over a wide range of fuel-oxidant and expansion ratios. A fuel mixture containing 36.3 percent ammonia by weight was selected as suggested by the Bureau of Aeronautics, Department of the Navy and is based on data from reference 3. This mixture was selected as a compromise between a fuel having a desirable freezing point and one having high performance. In order to determine the effect on performance of a small amount of water in the hydrazine, additional calculations were made assuming the hydrazine contained 5 percent water by weight. It was assumed that the water would combine with hydrazine to form hydrazine hydrate.

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

SYMBOLS

The following symbols are used in this report:

A	area (sq ft)
a	local velocity of sound (ft/sec)
C_F	coefficient of thrust
c^*	characteristic velocity (ft/sec)
F	thrust (lb)
$f_1, f_2, \ldots f_5$	functions
H	enthalpy (cal/mole)

h enthalpy, including both sensible and chemical energy per unit weight (cal/g)

I specific impulse (lb-sec/lb)

J mechanical equivalent of heat

M mean molecular weight (g/mole)

n number of atoms

P pressure

r equivalence ratio, ratio of number of hydrogen atoms to sum of number of fluorine atoms plus two times number of oxygen atoms in propellant $\left(\frac{n_H}{n_F+2n_O}\right)$

S entropy (cal/(mole)($^{\circ}$K))

T temperature ($^{\circ}$K)

Subscripts:

c combustion chamber

e nozzle exit

o conditions at 0° K, assuming recombination is complete

t throat

METHOD OF CALCULATION

The computations were carried out by means of the method described in reference 6 with modifications to adapt it for use with an IBM Card Programmed Electronic Calculator. The machine was operated with floating decimal point notation and eight significant figures. The successive approximation process used to obtain the desired values of the assigned parameters (mass balance and pressure or entropy balance) was continued until seven-figure accuracy was achieved.

Assumptions. - The calculations were based on the following usual assumptions: perfect gas law, adiabatic combustion at constant pressure, isentropic expansion, no friction, homogeneous mixing, and one-dimensional flow. The products of combustion were assumed to be ideal gases and included the following substances: fluorine F_2, hydrogen H_2, oxygen O_2, nitrogen N_2, water H_2O, hydroxyl radical OH, hydrogen fluoride HF, nitric oxide NO, atomic fluorine F, atomic hydrogen H, atomic oxygen O, and atomic nitrogen N.

Thermodynamic data. - The thermodynamic data used in the calculations were taken from reference 7, which selected the lower value of 35.6 kilocalories per mole for the dissociation energy of F_2. Physical and thermochemical properties of the propellants were taken from references 4 and 7 to 10 and are given in table I. The heat of solution was neglected in estimating the heat of formation of each mixture.

Composition of fuel mixtures. - Performance calculations were made for two fuel mixtures with oxygen bifluoride as the oxidant. One fuel mixture was ammonia and hydrazine containing no water, which will be designated pure fuel, and the other was ammonia and commercial hydrazine in which the hydrazine contained 5 percent water by weight, which will be designated commercial fuel.

The compositions of the two fuels are summarized in the following table:

Component	Fuel composition			
	Pure		Commercial	
	Weight percent	Moles	Weight percent	Moles
Ammonia	36.3	1	36.3	1
Hydrazine	63.7	0.9326	54.85	0.8030
Hydrazine hydrate	0	0	8.85	0.08295

Procedure for combustion conditions. - For each of eight equivalence ratios, equilibrium composition, enthalpy, and entropy of the combustion products were computed at a combustion pressure of 300 pounds per square inch absolute (20.41 atm) for three temperatures 100° K apart which were selected to be near the combustion temperature. These data and the value of enthalpy of the propellant were then used to interpolate the values of temperature, entropy, equilibrium composition, and mean molecular weight of the products of combustion corresponding to an adiabatic combustion process.

Procedure for exit conditions. - Equilibrium composition, mean molecular weight, pressure, local velocity of sound, and enthalpy of the products of combustion were computed for each equivalence ratio by assuming isentropic expansion for four exit temperatures selected to cover the exit pressure range from the nozzle-throat pressure to about 0.02 atmosphere.

The data computed for combustion and exit conditions were used to interpolate for throat conditions and exit conditions corresponding to altitudes of 0, 20,000, 40,000, 60,000, and 80,000 feet. The interpolated data were used to compute specific impulse, characteristic velocity, coefficient of thrust, and area ratios.

Interpolation formulas. - Temperature and equilibrium composition for combustion conditions were obtained by means of a three-point Lagrange interpolation formula (see reference 11 for interpolation formulas). The combustion entropy was obtained by means of Neville's interpolation formula using three points and three slopes. The slopes were known from the thermodynamic relation $\left(\frac{\partial H}{\partial S}\right)_P = T$. A five-point Lagrange interpolation formula was used for all exit interpolations.

The errors due to interpolation were checked for several cases. For combustion conditions, the errors were negligible, but for exit conditions it was necessary to use special functions to obtain acceptable accuracy. The values tabulated for all performance parameters except exit temperature and area ratio appear to be correctly interpolated to one or two units in the last place tabulated. Interpolated exit temperatures may be in error by as much as six units and area ratios by 0.4 percent.

The functions used in the exit interpolations are: $f_1 = \log\left(h_e + \frac{a}{2J} - h_o\right)$, $f_2 = \log\,(h_e - h_o)$, $f_3 = \log T$, $f_4 = \log\,(M_o - M_e)$, and $f_5 = \log P$. The pressure at the throat was found by interpolating f_5 as a function of f_1 for the point $f_1 = \log\,(h_c - h_o)$, at which the velocity of flow equals the velocity of sound. The values of the remaining functions were interpolated as functions of f_5 for the desired pressures.

THEORETICAL PERFORMANCE

The calculated values of the various performance parameters for both propellants (pure fuel and commercial fuel) for a combustion pressure of 300 pounds per square inch absolute and at exit pressures corresponding to altitudes of 0, 20,000, 40,000, 60,000, and 80,000 feet are given in tables II and III for eight equivalence ratios. The values of pressure corresponding to the assigned altitudes were taken from references 12 and 13. Equilibrium compositions in the combustion chamber and at assigned exit temperatures are given in tables IV and V.

The parameters for both propellants are plotted in figures 1 to 6. Curves of specific impulse for the five altitudes are shown in figure 1 plotted against weight-percent fuel. The difference between the curves for pure and commercial fuels for any altitude is about one to three impulse units over the entire range of weight-percent fuel presented. For pure fuel the maximum value of specific impulse for the sea-level curve is about 295.8 pound-seconds per pound at about 38.3 percent of fuel by weight, whereas for commercial fuel the maximum is about 293.7 pound-seconds per pound at about 38.5 percent of fuel by weight.

The maximum values of specific impulse and the values of weight-percent fuel at which they occur are shown plotted in figure 2 as functions of altitude. The maximum specific impulse increases 32.0 percent for both fuels for a change in altitude from sea level to 80,000 feet.

Curves of combustion-chamber temperature and nozzle-exit temperature for the five altitudes are presented in figure 3 as functions of weight-percent fuel. The maximum combustion temperature occurs at the extreme oxidant-rich end of the curves, being 3906° K at about 20.5 percent fuel by weight for pure fuel and 3885° K at about 20.8 percent fuel by weight for commercial fuel. The maximums of the exit-temperature curves occur near the stoichiometric mixture.

Characteristic velocity and coefficient of thrust are plotted in figure 4 and ratios of the area at the nozzle exit to area at the throat are shown in figure 5 as functions of weight-percent fuel. The coefficient-of-thrust and area-ratio functions may be used to determine the values of A_t and A_e for a combustion-chamber pressure of 300 pounds per square inch absolute for any specified thrust and expansion ratio by means of the conventional equations

$$A_t = \frac{F}{P_c C_F} \tag{1}$$

and

$$A_e = \left(\frac{A_e}{A_t}\right)\left(\frac{F}{P_c C_F}\right) \tag{2}$$

where the values of C_F and A_e/A_t correspond to the specified expansion ratio.

According to the calculations for several propellant combinations at this laboratory, the variation in the coefficient-of-thrust function is less than 1 percent over the range of combustion-chamber pressures from 300 to 2000 pounds per square inch absolute for constant expansion ratio, and the variation in A_e/A_t is about 6 percent for the same conditions. Equations (1) and (2) may therefore be used to obtain throat and exit areas for specified thrusts and expansion ratios to about these same percentages of accuracy for a range of combustion-chamber pressures from 300 to 2000 pounds per square inch absolute when the values of C_F and A_e/A_t are taken to correspond to the specified expansion ratio.

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

SUMMARY OF RESULTS

Theoretical calculations of the performance parameters of liquid oxygen bifluoride with two sets of fuels, one containing 36.3 percent liquid ammonia and 63.7 percent liquid hydrazine by weight (pure fuel) and the other containing 36.3 percent liquid ammonia, 54.85 percent liquid hydrazine, and 8.85 percent liquid hydrazine hydrate by weight (commercial fuel), were made for a wide range of fuel-oxidant and expansion ratios and yielded the following results:

1. For a combustion-chamber pressure of 300 pounds per square inch absolute (20.41 atm) and an exit pressure of 1 atmosphere, the maximum specific impulse was 295.8 pound-seconds per pound at 38.3 percent fuel by weight for pure fuel and 293.7 pound-seconds per pound at 38.5 percent fuel by weight for commercial fuel.

2. The maximum combustion temperature for a chamber pressure of 300 pounds per square inch absolute was 3906° K at about 20.5 percent fuel by weight for pure fuel and 3885° K at about 20.8 percent fuel by weight for commercial fuel.

3. The maximum specific impulse increased 32.0 percent for both fuels for a change in altitude from sea level to 80,000 feet.

4. For a combustion-chamber pressure of 300 pounds per square inch absolute and for the range of exit pressures corresponding to altitudes of 0 to 80,000 feet, the reduction in specific impulse due to the addition of 5 percent water by weight in the hydrazine (commercial fuel) was from about one to three units for a wide range of percent fuel by weight.

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

REFERENCES

1. Swager, W. L., and Lund, R. J.: Economic Survey: The Potential Availability of Ammonia, Nitric Acid, and Nitrogen Tetroxide, Propellants for Supersonic Vehicles. R-121, Battelle Mem. Inst., The Rand Corp. (Santa Monica), Dec. 20, 1948. (USAF Proj. MX-791, Proj. RAND.)

2. Winternitz, Paul F.: Summary Report on Theoretical, Laboratory, and Experimental Investigations of High Energy Propellants. Ammonia, vol. I, Rep. RM1-293-S1, RMI Proj. 293, Reaction Motors Inc., July 5, 1950. (Navy Contract NOa(s)9469.)

3. Winternitz, Paul F.: Summary Report on Theoretical, Laboratory and Experimental Investigations of High Energy Propellants. Vol. I. Hydrazine as a Rocket Fuel. Rep. No. RMI-293-S6, Jan. 14, 1948 to May 5, 1949. Reaction Motors, Inc., Aug. 3, 1950. (Bur. Aero., Navy Contract NOa(s)9469.)

4. Ruff, Otto, and Menzel, Walter: Die Möglichkeit der Bildung höherer Sauerstofffluoride und die Eigenschaften des Sauerstoff-2-fluorids. Zeitschr. f. anorg. u. allg. Chem., Bd. 198, 1931, S. 39-52.

5. Doescher, Russell N.: The Properties of Fluorine, Oxygen Bifluoride, and Chlorine Trifluoride. Memo. 9-16, Jet Prop. Lab., C.I.T., Sept. 6, 1949. (Proj. TU2-1, Contract W-04-200-ORD-1482.)

6. Huff, Vearl N., and Morrell, Virginia E.: General Method for Computation of Equilibrium Composition and Temperature of Chemical Reactions. NACA TN 2113, 1950.

7. Huff, Vearl N., and Gordon, Sanford: Tables of Thermodynamic Functions for Analysis of Aircraft-Propulsion Systems. NACA TN 2161, 1950.

8. Anon.: Handbook of Chemistry and Physics, Charles D. Hodgman, ed. Chem. Rubber Pub. Co. (Cleveland), 29th ed., 1945.

9. Anon.: Tables of Selected Values of Chemical Thermodynamic Properties, table 18-2, ser. II. Nat. Bur. Standards, Dec. 31, 1947.

10. Anon.: Tables of Selected Values of Chemical Thermodynamic Properties, table 9, ser. II. Nat. Bur. Standards, June 30, 1947.

11. Milne-Thompson, L. M.: The Calculus of Finite Differences. Macmillan and Co., Ltd. (London), 1933.

12. Diehl, Walter S.: Standard Atmosphere - Tables and Data. NACA Rep. No. 218, 1925.

13. Warfield, Calvin N.: Tentative Tables for the Properties of the Upper Atmosphere. NACA TN 1200, 1947.

TABLE I - PROPERTIES OF LIQUID PROPELLANTS

[Temperatures in superscripts, °C.]

Propellant	Molecular weight M	Density (g/cc)	Freezing point (°C)	Boiling point (°C)	Viscosity (centipoises)	Enthalpy of formation at boiling point from elements at 25 °C ΔH_f (kcal/mole)	Enthalpy of vaporization ΔH (kcal/mole)	Enthalpy of fusion ΔH (kcal/mole)
Ammonia	17.032	(liquid) [a]$0.68^{-33.4}$	[b]-77.74	[b]-33.40	[a]$0.255^{-33.5}$	[c]-17.14	[b]5.581	[b]1.351
Hydrazine	32.048	(liquid) [a]1.011^{15}	[b]1.5	[b]113.5	----------	[c]12.05	[b]10	-----
Hydrazine hydrate	50.064	(liquid) [a]1.03^{21}	[b]-40	[b]118.5	----------	[c]-57.95	-------	-----
Oxygen bifluoride	54.00	(liquid) [d]$1.53^{-144.8}$ $1.77^{-195.8}$	[d]-223.8	[d]-144.8	----------	[c]1.3	[e]2.65	-----

[a]Reference 8.
[b]Reference 9.
[c]Reference 7.
[d]Reference 4.
[e]Reference 10.

TABLE II - CALCULATED PERFORMANCE OF A MIXTURE CONTAINING 36.3 PERCENT AMMONIA AND 63.7 PERCENT HYDRAZINE BY WEIGHT WITH OXYGEN BIFLUORIDE

[Pure fuel; combustion-chamber pressure, 300 lb/sq in. absolute.]

Propellant			Combustion chamber		Characteristic velocity	Nozzle exit						
Equivalence ratio r	Weight-percent fuel	[a] Density (g/cc)	Temperature T_c (°K)	Mean molecular weight M_c	c^* (ft/sec)	Altitude (ft)	Pressure P (atm)	Temperature T_e (°K)	Mean molecular weight M_e	Ratio of nozzle-exit area to throat area A_e/A_t	Coefficient of thrust C_F	Specific impulse I (lb-sec/lb)
0.5	20.52	1.454	3906	21.29	6332	0	1	2786	22.82	3.899	1.427	280.8
						20,000	0.4594	2490	23.05	6.866	1.561	307.1
						40,000	.1852	2129	23.18	13.41	1.685	331.6
						60,000	.07125	1729	23.22	26.67	1.786	351.5
						80,000	.02780	1363	23.22	51.62	1.863	366.7
0.75	27.92	1.366	3873	19.91	6519	0	1	2810	21.52	3.930	1.428	289.3
						20,000	0.4594	2547	21.81	6.988	1.563	316.8
						40,000	.1852	2224	22.02	13.86	1.691	342.7
						60,000	.07125	1849	22.10	28.09	1.797	364.1
						80,000	.02780	1492	22.11	55.55	1.879	380.7
1.0	34.05	1.301	3781	18.86	6629	0	1	2787	20.44	3.967	1.429	294.3
						20,000	0.4594	2555	20.76	7.111	1.566	322.6
						40,000	.1852	2273	21.04	14.29	1.697	349.6
						60,000	.07125	1939	21.21	29.52	1.807	372.4
						80,000	.02780	1611	21.25	59.85	1.894	390.3
1.25	39.23	1.250	3667	18.00	6674	0	1	2590	19.28	3.865	1.425	295.7
						20,000	0.4594	2277	19.41	6.724	1.557	323.1
						40,000	.1852	1904	19.46	12.91	1.679	348.3
						60,000	.07125	1554	19.47	25.87	1.776	368.4
						80,000	.02780	1235	19.47	50.57	1.851	383.9
1.50	43.65	1.210	3526	17.26	6666	0	1	2293	18.12	3.680	1.414	293.0
						20,000	0.4594	1958	18.15	6.277	1.538	318.7
						40,000	.1852	1591	18.16	11.79	1.650	341.9
						60,000	.07125	1277	18.16	23.33	1.739	360.3
						80,000	.02780	1009	18.16	45.50	1.806	374.3
1.75	47.47	1.177	3363	16.61	6609	0	1	2028	17.15	3.525	1.403	288.2
						20,000	0.4594	1707	17.16	5.955	1.521	312.5
						40,000	.1852	1374	17.16	11.11	1.627	334.3
						60,000	.07125	1091	17.16	21.82	1.711	351.4
						80,000	.02780	857	17.16	42.37	1.774	364.3
2.0	50.81	1.150	3192	16.05	6506	0	1	1813	16.38	3.419	1.398	282.6
						20,000	0.4594	1514	16.38	5.744	1.512	305.8
						40,000	.1852	1214	16.38	10.70	1.614	326.4
						60,000	.07125	954	16.38	20.83	1.694	342.7
						80,000	.02780	745	16.38	40.26	1.754	354.8
2.5	56.35	1.108	2856	15.11	6271	0	1	1499	15.22	3.290	1.390	271.0
						20,000	0.4594	1240	15.22	5.490	1.500	292.4
						40,000	.1852	985	15.22	10.17	1.597	311.4
						60,000	.07125	766	15.22	19.60	1.674	326.2
						80,000	.02780	593	15.22	37.66	1.730	337.1

[a] Based on OF_2 density of 1.77 at -195.8° C.

NACA

TABLE III - CALCULATED PERFORMANCE OF A MIXTURE CONTAINING 36.3 PERCENT AMMONIA, 54.85 PERCENT HYDRAZINE, AND 8.85 PERCENT HYDRAZINE HYDRATE BY WEIGHT WITH OXYGEN BIFLUORIDE

[Commercial fuel; combustion-chamber pressure, 300 lb/sq in. absolute.]

Propellant			Combustion chamber		Characteristic velocity	Nozzle exit						
Equivalence ratio r	Weight-percent fuel	[a]Density (g/cc)	Temperature T_c (°K)	Mean molecular weight M_c	c^* (ft/sec)	Altitude (ft)	Pressure P (atm)	Temperature T_e (°K)	Mean molecular weight M_e	Ratio of nozzle-exit area to throat area A_e/A_t	Coefficient of thrust C_F	Specific impulse I (lb-sec/lb)
0.5	20.78	1.451	3885	21.33	6313	0	1	2764	22.84	3.892	1.426	279.7
						20,000	0.4594	2466	23.06	6.844	1.559	306.0
						40,000	.1852	2101	23.18	13.33	1.683	330.3
						60,000	.07125	1699	23.21	26.41	1.783	349.9
						80,000	.02780	1332	23.21	50.89	1.860	364.9
0.75	28.36	1.362	3842	19.95	6487	0	1	2781	21.54	3.926	1.428	287.9
						20,000	0.4594	2516	21.81	6.972	1.563	315.2
						40,000	.1852	2190	22.00	13.81	1.690	340.8
						60,000	.07125	1814	22.07	27.89	1.795	362.0
						80,000	.02780	1460	22.07	55.02	1.877	378.4
1.0	34.69	1.295	3747	18.89	6593	0	1	2758	20.45	3.966	1.429	292.8
						20,000	0.4594	2524	20.76	7.103	1.566	320.9
						40,000	.1852	2239	21.02	14.25	1.697	347.7
						60,000	.07125	1902	21.17	29.34	1.807	370.2
						80,000	.02780	1576	21.21	59.34	1.893	388.0
1.25	40.05	1.243	3627	18.02	6628	0	1	2539	19.24	3.849	1.426	293.7
						20,000	0.4594	2221	19.35	6.674	1.557	320.7
						40,000	.1852	1846	19.39	12.75	1.678	345.6
						60,000	.07125	1507	19.39	25.57	1.774	365.3
						80,000	.02780	1200	19.39	50.14	1.847	380.5
1.50	44.66	1.202	3474	17.26	6614	0	1	2222	18.03	3.646	1.412	290.2
						20,000	0.4594	1890	18.06	6.202	1.535	315.5
						40,000	.1852	1532	18.06	11.63	1.646	338.2
						60,000	.07125	1229	18.06	23.02	1.733	356.3
						80,000	.02780	971	18.06	44.87	1.800	369.9
1.75	48.65	1.169	3295	16.58	6532	0	1	1950	17.04	3.495	1.402	284.6
						20,000	0.4594	1638	17.04	5.896	1.519	308.4
						40,000	.1852	1317	17.05	11.01	1.624	329.7
						60,000	.07125	1043	17.05	21.56	1.707	346.5
						80,000	.02780	819	17.05	41.83	1.769	359.0
2.0	52.15	1.141	3104	15.99	6413	0	1	1729	16.24	3.387	1.396	278.2
						20,000	0.4594	1442	16.25	5.686	1.509	300.8
						40,000	.1852	1155	16.25	10.59	1.610	320.9
						60,000	.07125	907	16.25	20.59	1.689	336.7
						80,000	.02780	707	16.25	39.78	1.748	348.5
2.5	57.99	1.097	2730	15.00	6134	0	1	1410	15.07	3.270	1.390	264.9
						20,000	0.4594	1165	15.07	5.451	1.499	285.7
						40,000	.1852	924	15.07	10.08	1.595	304.1
						60,000	.07125	717	15.07	19.41	1.671	318.5
						80,000	.02780	555	15.07	37.27	1.726	329.1

[a]Based on OF_2 density of 1.77 at -195.8° C.

TABLE IV - EQUILIBRIUM COMPOSITION IN COMBUSTION CHAMBER AND FOLLOWING AN ISENTROPIC EXPANSION TO ASSIGNED EXIT TEMPERATURES FOR PURE FUEL

[Pure fuel: 36.3 percent NH_3, 63.7 percent N_2H_4 by weight; oxidant: OF_2.]

Temperature T (°K)	Pressure P (atm)	Equilibrium composition (mole fraction)										
		HF	H_2	H_2O	OH	O_2	NO	N_2	F	H	O	N
r = 0.50 (20.52 percent fuel by weight)												
3906	20.41	0.55488	0.00378	0.00985	0.02640	0.08349	0.02769	0.11797	0.07194	0.01828	0.08250	0.00322
3600	9.428	.58524	.00237	.00895	.02065	.09915	.02441	.12313	.05490	.01161	.06775	.00184
2900	1.363	.64700	.00041	.00547	.00749	.13973	.01470	.13476	.02122	.00198	.02701	.00026
2300	0.2832	.67625	.00002	.00183	.00111	.16370	.00614	.14190	.00488	.00008	.00408	.00001
1400	0.03073	.68355	-------	.00002	-------	.17073	.00030	.14535	.00004	-------	-------	-------
r = 0.75 (27.92 percent fuel by weight)												
3873	20.41	0.51069	0.03171	0.06067	0.05198	0.03935	0.02144	0.15728	0.02078	0.04978	0.05295	0.00337
3500	7.707	.53485	.02581	.07727	.04508	.04652	.01776	.16486	.01191	.03404	.04022	.00165
2900	1.312	.56802	.01312	.11190	.02753	.05874	.01092	.17682	.00335	.01145	.01785	.00030
2300	0.2281	.58653	.00234	.13999	.00825	.06887	.00455	.18512	.00041	.00098	.00295	.00001
1500	0.02840	.59019	.00001	.14747	.00014	.07355	.00038	.18825	-------	-------	.00001	-------
r = 1.00 (stoichiometric, 34.05 percent fuel by weight)												
3781	20.41	0.45129	0.07191	0.10715	0.04879	0.01617	0.01403	0.18766	0.00929	0.06295	0.02798	0.00278
3500	9.514	.46534	.06509	.12797	.04232	.01626	.01139	.19409	.00587	.04865	.02140	.00162
2800	1.046	.49768	.03830	.19375	.02025	.01221	.00474	.20987	.00113	.01561	.00625	.00021
2300	0.2015	.51321	.01496	.23754	.00589	.00549	.00139	.21784	.00015	.00263	.00089	.00002
1600	0.02689	.51911	.00063	.25886	.00011	.00027	.00004	.22097	-------	.00001	-------	-------
r = 1.25 (39.23 percent fuel by weight)												
3667	20.41	0.40059	0.12053	0.13528	0.03557	0.00552	0.00795	0.21054	0.00446	0.06484	0.01269	0.00204
3400	9.915	.41071	.11617	.15591	.02808	.00433	.00567	.21655	.00264	.05043	.00836	.00115
2700	1.330	.43186	.10679	.20587	.00717	.00062	.00097	.22943	.00029	.01605	.00083	.00011
2100	0.2988	.43767	.10872	.21841	.00039	-------	.00003	.23289	.00001	.00187	.00001	-------
1200	0.02490	.43819	.10955	.21909	-------	-------	-------	.23318	-------	-------	-------	-------

NACA

TABLE IV - EQUILIBRIUM COMPOSITION IN COMBUSTION CHAMBER AND FOLLOWING AN ISENTROPIC EXPANSION TO ASSIGNED EXIT TEMPERATURES FOR PURE FUEL - Concluded

[Pure fuel: 36.3 percent NH_3, 63.7 percent N_2H_4 by weight; oxidant: OF_2.]

Temperature T (°K)	Pressure P (atm)	Equilibrium composition (mole fraction)										
		HF	H_2	H_2O	OH	O_2	NO	N_2	F	H	O	N
r = 1.50 (43.65 percent fuel by weight)												
3526	20.41	0.35810	0.17499	0.14650	0.02172	0.00156	0.00391	0.22737	0.00206	0.05767	0.00482	0.00131
3200	8.951	.36640	.17665	.16483	.01323	.00075	.00201	.23327	.00091	.03933	.00208	.00056
2500	1.613	.37696	.18532	.18668	.00158	.00002	.00014	.24066	.00005	.00850	.00006	.00003
1700	0.2452	.37897	.18942	.18948	.00001	-------	-------	.24200	-------	.00013	-------	-------
1000	0.02682	.37899	.18950	.18950	-------	-------	-------	.24201	-------	-------	-------	-------
r = 1.75 (47.47 percent fuel by weight)												
3363	20.41	0.32229	0.23008	0.14591	0.01162	0.00038	0.00172	0.23954	0.00085	0.04526	0.00157	0.00073
3000	8.797	.32804	.23736	.15763	.00528	.00011	.00062	.24418	.00029	.02584	.00042	.00023
2200	1.484	.33347	.24906	.16654	.00019	-------	.00001	.24843	-------	.00230	-------	-------
1500	0.2652	.33389	.25041	.16694	-------	-------	-------	.24874	-------	.00002	-------	-------
800	0.02142	.33389	.25042	.16695	-------	-------	-------	.24875	-------	-------	-------	-------
r = 2.00 (50.81 percent fuel by weight)												
3192	20.41	0.29198	0.28066	0.13912	0.00572	0.00009	0.00071	0.24838	0.00037	0.03215	0.00046	0.00037
2900	10.86	.29495	.28759	.14446	.00264	.00002	.00027	.25104	.00013	.01864	.00013	.00013
2000	1.560	.29827	.29793	.14910	.00003	-------	-------	.25395	-------	.00071	-------	-------
1300	0.2445	.29838	.29838	.14919	-------	-------	-------	.25405	-------	-------	-------	-------
800	0.03633	.29838	.29838	.14919	-------	-------	-------	.25405	-------	-------	-------	-------
r = 2.50 (56.35 percent fuel by weight)												
2856	20.41	0.24419	0.36056	0.12079	0.00119	-------	0.00011	0.25985	0.00006	0.01315	0.00003	0.00007
2500	9.998	.24540	.36590	.12239	.00030	-------	.00002	.26117	.00001	.00480	-------	.00001
1600	1.316	.24604	.36905	.12302	-------	-------	-------	.26186	-------	.00003	-------	-------
1200	0.4030	.24605	.36907	.12302	-------	-------	-------	.26186	-------	-------	-------	-------
800	0.08399	.24605	.36907	.12302	-------	-------	-------	.26186	-------	-------	-------	-------

NACA

TABLE V - EQUILIBRIUM COMPOSITION IN COMBUSTION CHAMBER AND FOLLOWING AN ISENTROPIC EXPANSION TO ASSIGNED EXIT TEMPERATURES FOR COMMERCIAL FUEL

[Commercial fuel: 36.3 percent NH_3, 54.85 percent N_2H_4, and 8.85 percent $N_2H_4 \cdot H_2O$ by weight; oxidant: OF_2.]

Temperature T (°K)	Pressure P (atm)	Equilibrium composition (mole fraction)										
		HF	H_2	H_2O	OH	O_2	NO	N_2	F	H	O	N
r = 0.50 (20.78 percent fuel by weight)												
3885	20.41	0.55883	0.00393	0.01089	0.02730	0.08709	0.02759	0.11560	0.06703	0.01793	0.08080	0.00300
3600	9.928	.58690	.00259	.01019	.02189	.10182	.02445	.12036	.05129	.01184	.06691	.00177
2900	1.443	.64784	.00053	.00733	.00858	.14214	.01466	.13184	.01816	.00219	.02648	.00025
2300	0.3023	.67573	.00004	.00475	.00176	.16562	.00611	.13889	.00298	.00012	.00398	.00001
1400	0.03334	.68095	-------	.00426	.00001	.17221	.00030	.14227	-------	-------	-------	-------
r = 0.75 (28.36 percent fuel by weight)												
3842	20.41	0.51040	0.03207	0.06705	0.05301	0.04122	0.02130	0.15492	0.01888	0.04726	0.05083	0.00305
3500	8.341	.53189	.02636	.08316	.04615	.04776	.01783	.16177	.01127	.03306	.03918	.00157
2900	1.428	.56417	.01323	.11877	.02789	.05978	.01091	.17351	.00317	.01102	.01726	.00029
2300	0.2500	.58216	.00233	.14714	.00829	.06974	.00454	.18163	.00039	.00093	.00284	.00001
1500	0.03103	.58572	.00001	.15465	.00014	.07437	.00038	.18472	-------	-------	.00001	-------
r = 1.00 (stoichiometric, 34.69 percent fuel by weight)												
3747	20.41	0.44875	0.07242	0.11775	0.04907	0.01659	0.01377	0.18547	0.00828	0.05908	0.02632	0.00248
3400	7.790	.46551	.06289	.14538	.04014	.01635	.01042	.19331	.00459	.04186	.01832	.00123
2800	1.152	.49216	.03834	.20373	.02027	.01222	.00471	.20647	.00107	.01488	.00596	.00020
2300	0.2238	.50720	.01485	.24759	.00585	.00544	.00138	.21421	.00014	.00249	.00084	.00002
1600	0.02984	.51292	.00063	.26878	.00011	.00027	.00004	.21725	-------	.00001	-------	-------
r = 1.25 (40.05 percent fuel by weight)												
3627	20.41	0.39622	0.12218	0.14830	0.03482	0.00536	0.00755	0.20851	0.00384	0.06004	0.01140	0.00178
3300	8.336	.40796	.11633	.17443	.02499	.00371	.00476	.21562	.00195	.04299	.00642	.00084
2700	1.509	.42462	.10852	.21613	.00701	.00058	.00093	.22589	.00027	.01519	.00076	.00010
2000	0.2697	.43026	.11058	.22865	.00018	-------	.00001	.22927	-------	.00104	-------	-------
1100	0.01980	.43053	.11106	.22899	-------	-------	-------	.22941	-------	-------	-------	-------

TABLE V - EQUILIBRIUM COMPOSITION IN COMBUSTION CHAMBER AND FOLLOWING AN ISENTROPIC EXPANSION TO ASSIGNED EXIT TEMPERATURES FOR COMMERCIAL FUEL - Concluded

[Commercial fuel: 36.3 percent NH_3, 54.85 percent N_2H_4, and 8.85 percent $N_2H_4 \cdot H_2O$ by weight; oxidant: OF_2.]

Temperature T (°K)	Pressure P (atm)	Equilibrium composition (mole fraction)										
		HF	H_2	H_2O	OH	O_2	NO	N_2	F	H	O	N
r = 1.50 (44.66 percent fuel by weight)												
3474	20.41	0.35203	0.17887	0.16004	0.02020	0.00138	0.00349	0.22534	0.00167	0.05191	0.00399	0.00108
3200	10.27	.35853	.18021	.17526	.01301	.00071	.00194	.23003	.00082	.03709	.00189	.00052
2400	1.505	.36891	.18937	.19761	.00095	.00001	.00007	.23739	.00002	.00563	.00002	.00001
1700	0.2874	.37017	.19215	.19933	.00001	-------	-------	.23822	-------	.00012	-------	-------
1000	0.03120	.37019	.19222	.19935	-------	-------	-------	.23823	-------	-------	-------	-------
r = 1.75 (48.65 percent fuel by weight)												
3295	20.41	0.31473	0.23639	0.15879	0.01003	0.00030	0.00140	0.23735	0.00066	0.03865	0.00114	0.00055
3000	10.42	.31888	.24203	.16773	.00511	.00010	.00059	.24075	.00025	.02397	.00037	.00021
2200	1.786	.32379	.25288	.17635	.00018	-------	.00001	.24467	-------	.00211	-------	-------
1400	0.2374	.32417	.25412	.17675	-------	-------	-------	.24496	-------	.00001	-------	-------
800	0.02547	.32417	.25412	.17675	-------	-------	-------	.24496	-------	-------	-------	-------
r = 2.00 (52.15 percent fuel by weight)												
3104	20.41	0.28311	0.28861	0.15103	0.00447	0.00006	0.00051	0.24592	0.00024	0.02551	0.00028	0.00025
2800	10.71	.28556	.29494	.15559	.00183	.00001	.00017	.24816	.00007	.01353	.00006	.00007
1900	1.524	.28786	.30267	.15889	.00001	-------	-------	.25021	-------	.00035	-------	-------
1200	0.2160	.28791	.30289	.15893	-------	-------	-------	.25026	-------	-------	-------	-------
800	0.04424	.28791	.30289	.15893	-------	-------	-------	.25026	-------	-------	-------	-------
r = 2.50 (57.99 percent fuel by weight)												
2730	20.41	0.23331	0.36926	0.13125	0.00072	-------	0.00006	0.25682	0.00003	0.00850	0.00001	0.00004
2400	10.55	.23406	.37284	.13227	.00017	-------	.00001	.25766	-------	.00298	-------	.00001
1500	1.293	.23443	.37482	.13266	-------	-------	-------	.25808	-------	.00001	-------	-------
1200	0.5179	.23444	.37482	.13266	-------	-------	-------	.25808	-------	-------	-------	-------
800	0.1074	.23444	.37482	.13266	-------	-------	-------	.25808	-------	-------	-------	-------

NACA

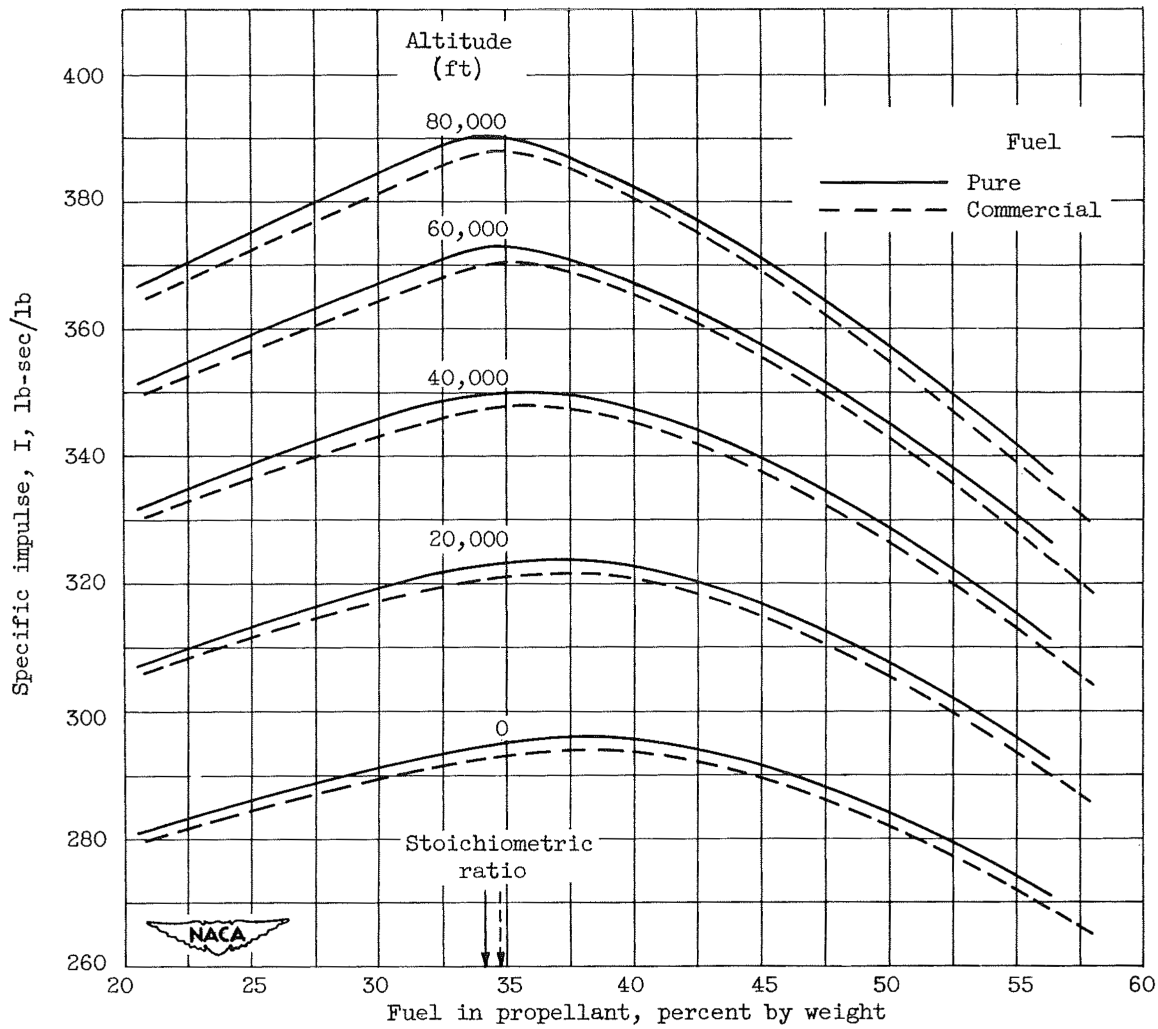


Figure 1. - Theoretical specific impulse of mixtures of liquid ammonia and hydrazine with liquid oxygen bifluoride. Pure fuel: 36.3 percent ammonia, 63.7 percent hydrazine by weight; commercial fuel: 36.3 percent ammonia, 54.85 percent hydrazine, 8.85 percent hydrazine hydrate by weight; isentropic expansion assuming equilibrium composition; combustion-chamber pressure, 300 pounds per square inch absolute; exit pressure corresponding to altitude indicated.

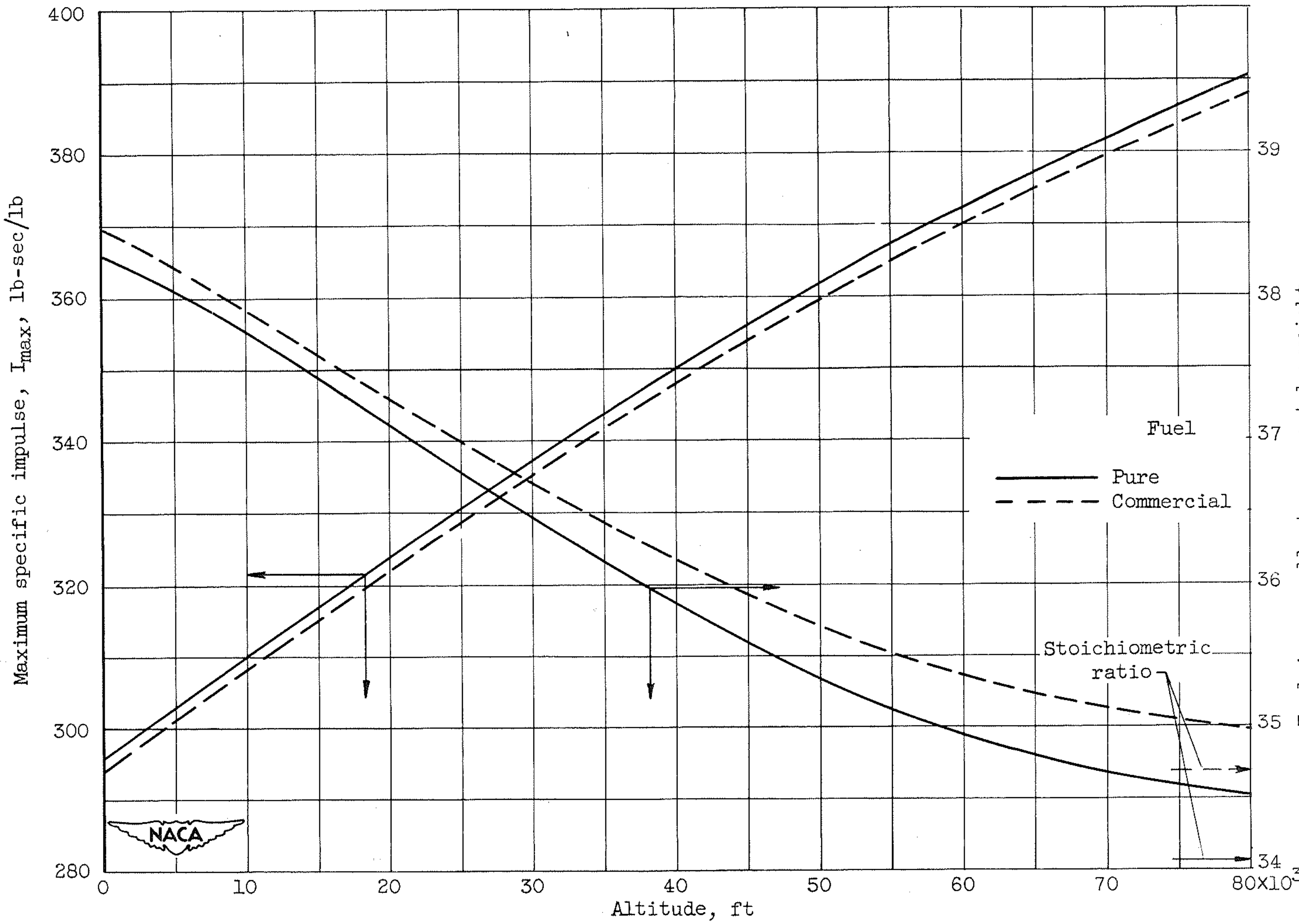


Figure 2. - Maximum theoretical specific impulse and corresponding weight percent of fuel in propellant of mixtures of liquid ammonia and hydrazine with liquid oxygen bifluoride. Pure fuel: 36.3 percent ammonia, 63.7 percent hydrazine by weight; commercial fuel: 36.3 percent ammonia, 54.85 percent hydrazine, 8.85 percent hydrazine hydrate by weight; isentropic expansion assuming equilibrium composition; combustion-chamber pressure, 300 pounds per square inch absolute; exit pressure corresponding to altitude indicated.

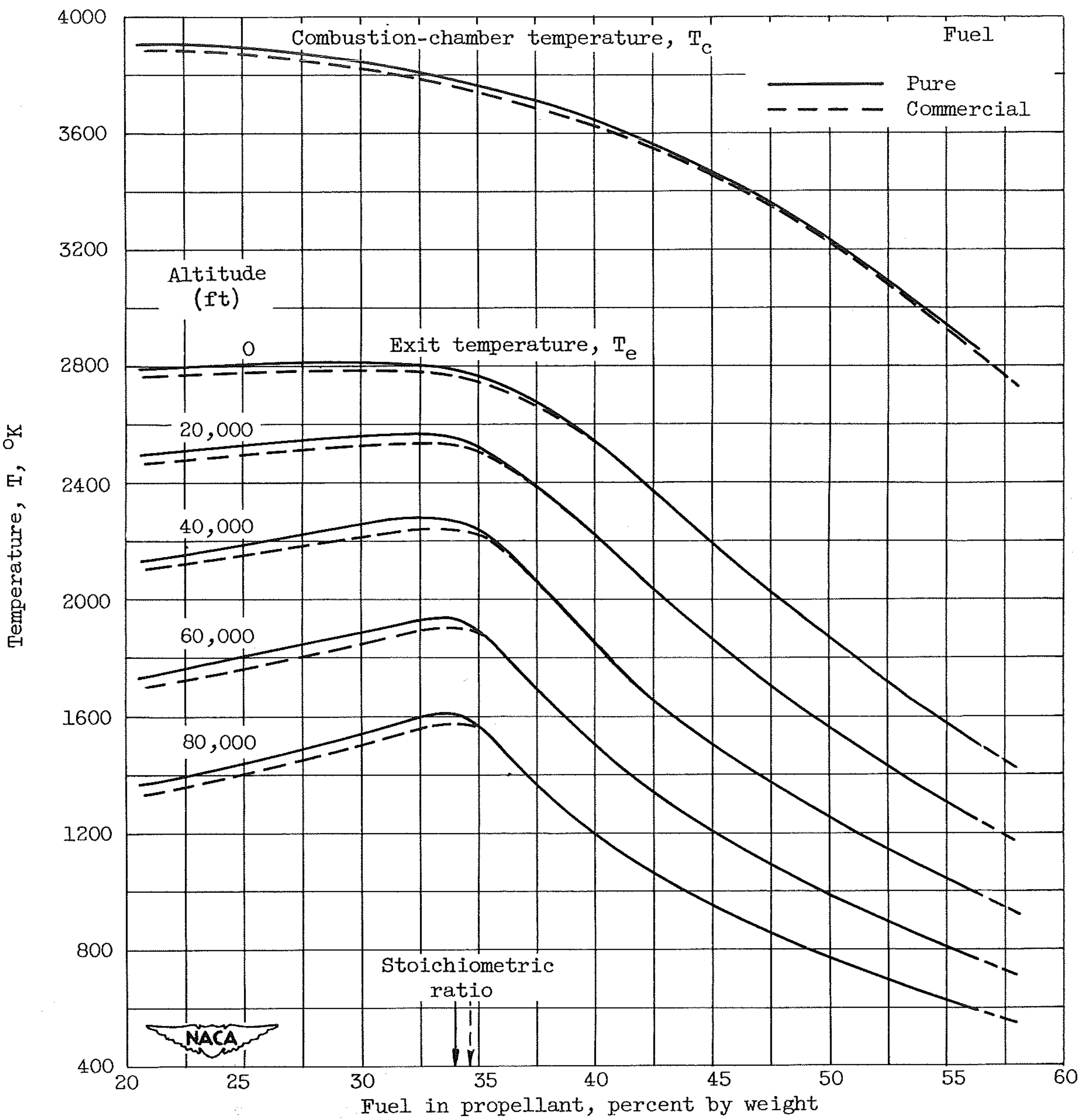


Figure 3. - Theoretical combustion-chamber temperature and nozzle-exit temperature of mixtures of liquid ammonia and hydrazine with liquid oxygen bifluoride. Pure fuel: 36.3 percent ammonia, 63.7 percent hydrazine by weight; commercial fuel: 36.3 percent ammonia, 54.85 percent hydrazine, 8.85 percent hydrazine hydrate by weight; isentropic expansion assuming equilibrium composition; combustion-chamber pressure, 300 pounds per square inch absolute; exit pressure corresponding to altitude indicated.

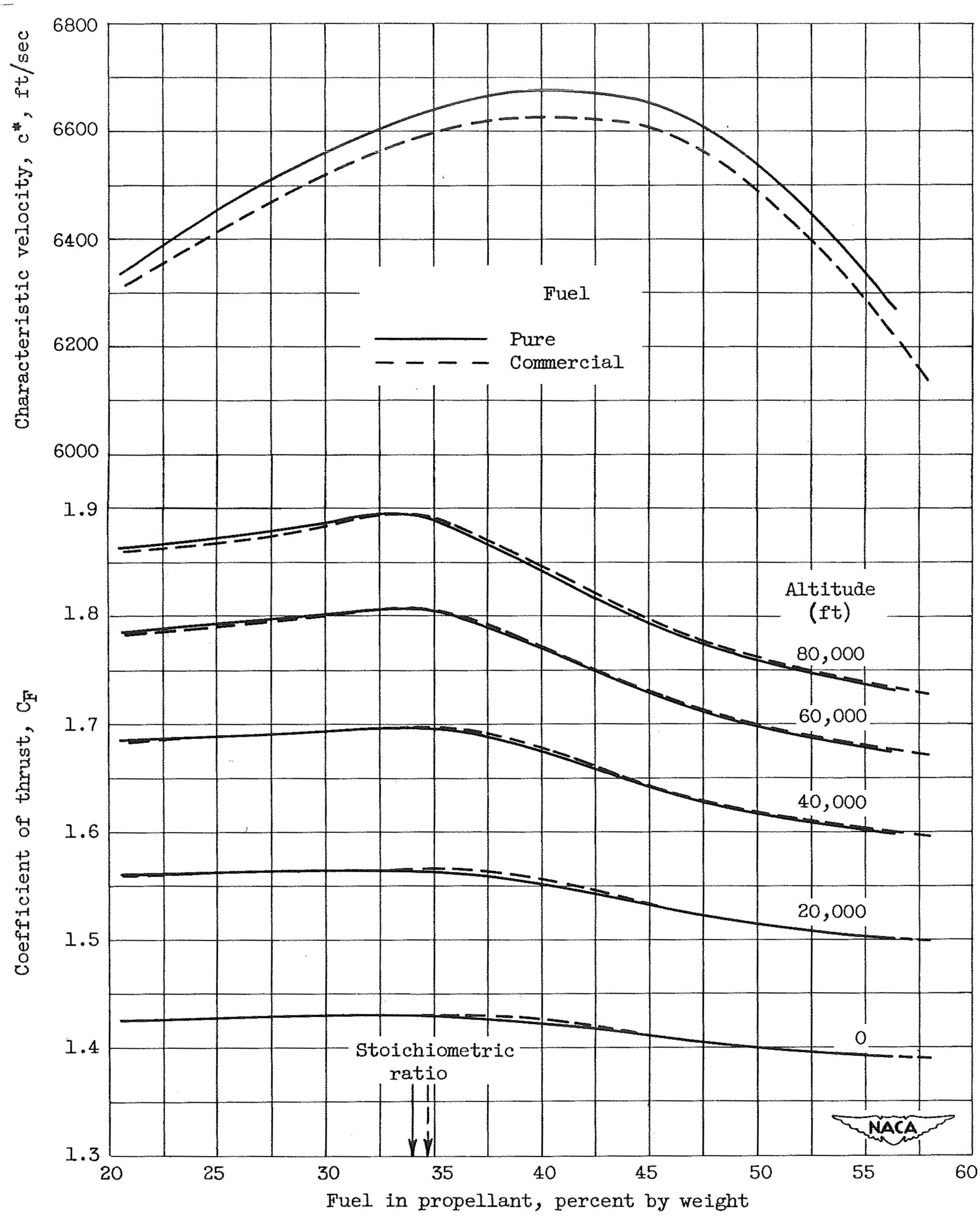


Figure 4. - Theoretical characteristic velocity and coefficient of thrust of mixtures of liquid ammonia and hydrazine with liquid oxygen bifluoride. Pure fuel: 36.3 percent ammonia, 63.7 percent hydrazine by weight; commercial fuel: 36.3 percent ammonia, 54.85 percent hydrazine, 8.85 percent hydrazine hydrate by weight; isentropic expansion assuming equilibrium composition; combustion-chamber pressure, 300 pounds per square inch absolute; exit pressure corresponding to altitude indicated.

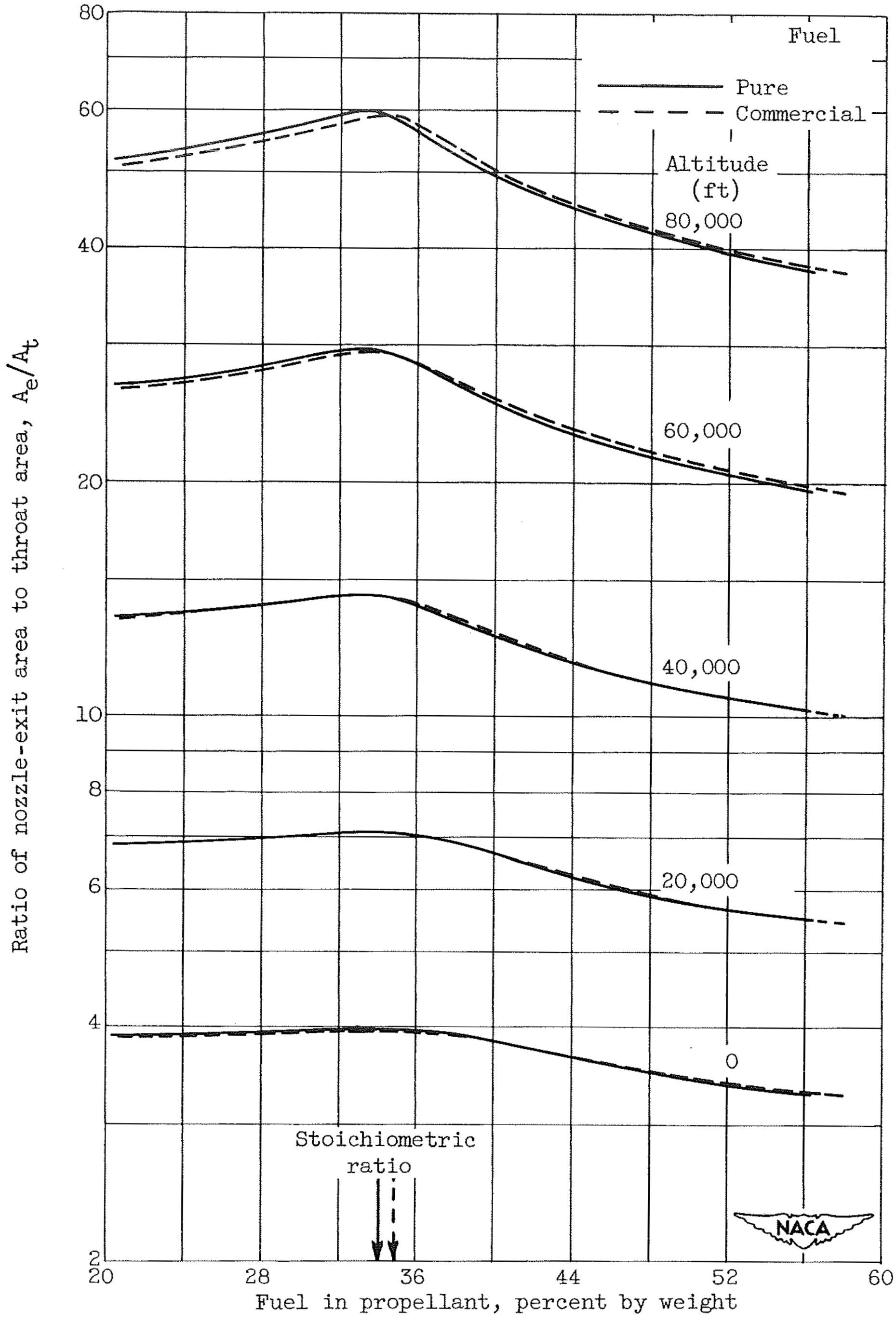
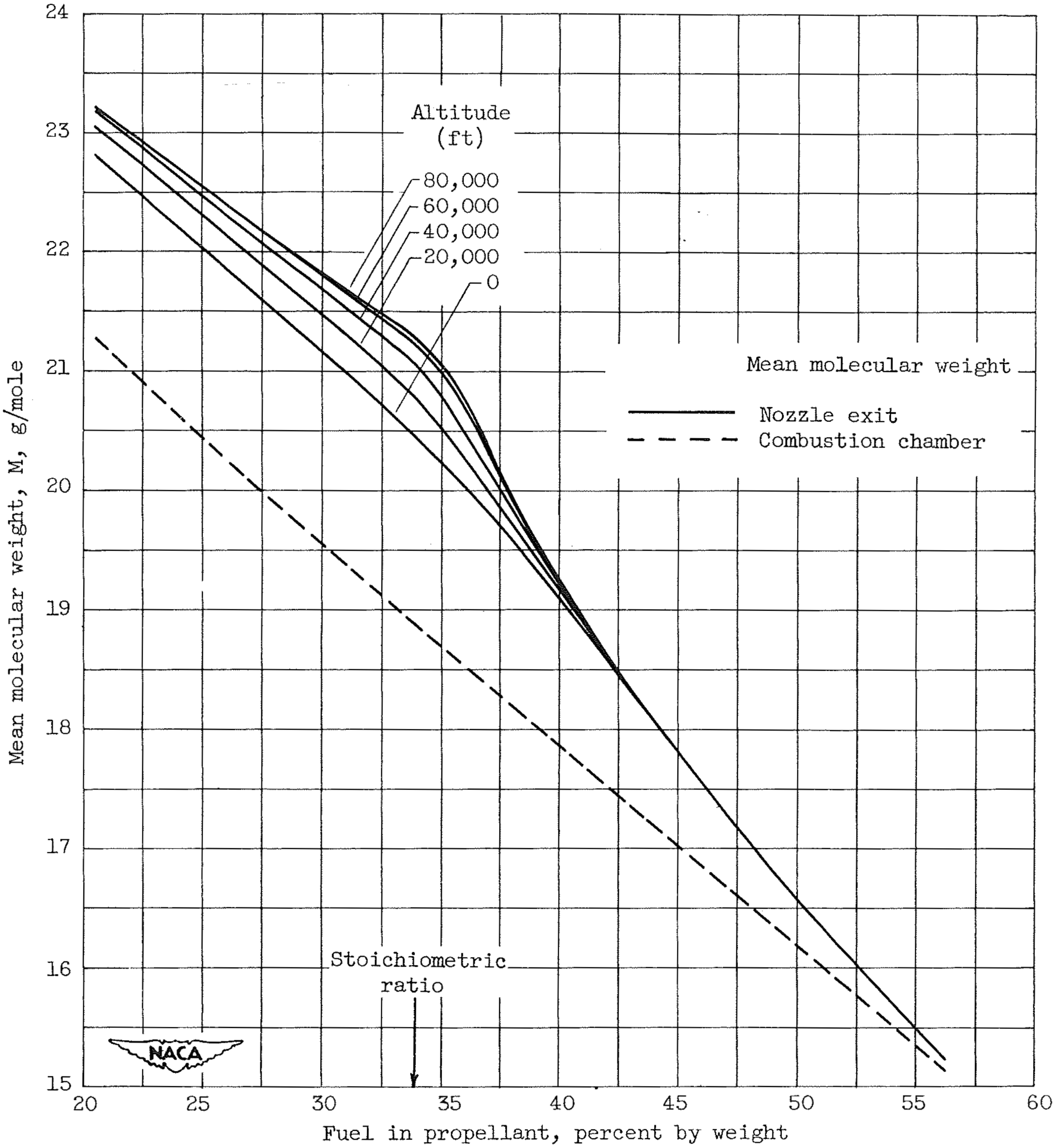
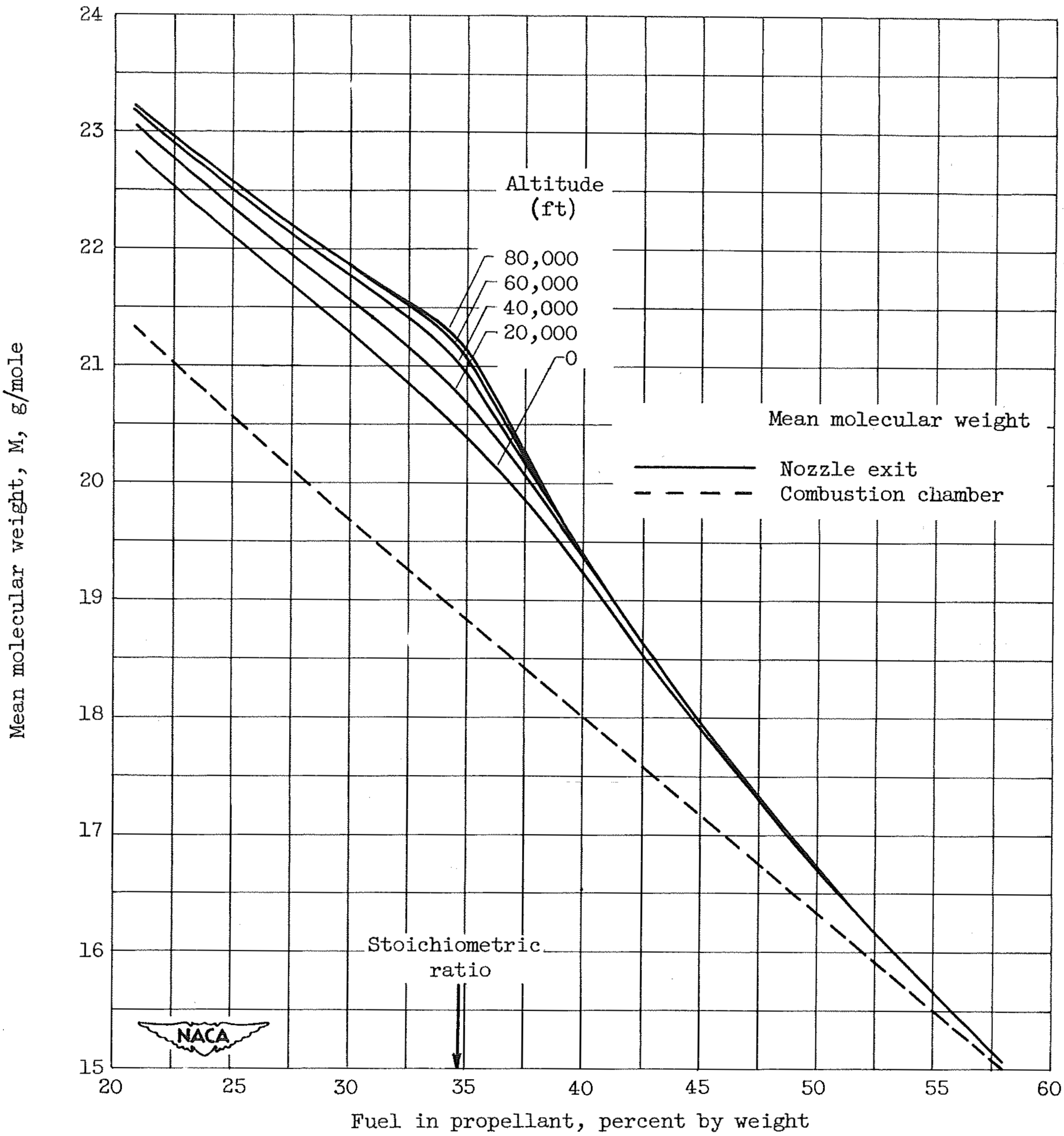


Figure 5. - Theoretical ratios of nozzle-exit area to throat area of mixtures of liquid ammonia and hydrazine with liquid oxygen bifluoride. Pure fuel: 36.3 percent ammonia, 63.7 percent hydrazine by weight; commercial fuel: 36.3 percent ammonia, 54.85 percent hydrazine, 8.85 percent hydrazine hydrate by weight; isentropic expansion assuming equilibrium composition; combustion-chamber pressure, 300 pounds per square inch absolute; exit pressure corresponding to altitude indicated.



(a) Pure fuel: 36.3 percent ammonia, 63.7 percent hydrazine by weight.

Figure 6. - Theoretical mean molecular weight in the combustion chamber and at the nozzle exit of mixture of liquid ammonia and hydrazine with liquid oxygen bifluoride. Isentropic expansion assuming equilibrium composition. Combustion-chamber pressure, 300 pounds per square inch absolute; exit pressure corresponding to altitude indicated.



(b) Commercial fuel: 36.3 percent ammonia, 54.85 percent hydrazine, 8.85 percent hydrazine hydrate by weight.

Figure 6. - Concluded. Theoretical mean molecular weight in the combustion chamber and at the nozzle exit of mixture of liquid ammonia and hydrazine with liquid oxygen bifluoride. Isentropic expansion assuming equilibrium composition. Combustion-chamber pressure, 300 pounds per square inch absolute; exit pressure corresponding to altitude indicated.