RESEARCH MEMORANDUM

THEORETICAL PERFORMANCE OF LIQUID AMMONIA AND LIQUID FLUORINE AS A ROCKET PROPELLANT

By Sanford Gordon and Vearl N. Huff

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NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

WASHINGTON

March 16, 1953
Declassified December 1, 1953

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SUMMARY

Theoretical values of performance parameters for liquid ammonia and liquid fluorine as a rocket propellant 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, ratio of nozzle-exit area to throat area, specific heat at constant pressure, coefficient of viscosity, and coefficient of thermal conductivity.

The maximum value of specific impulse was 311.5 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.

INTRODUCTION

Liquid ammonia and liquid fluorine are of interest as a rocket propellant because of high performance. Extensive data exist in the literature on their availability and cost, and on their physical, chemical, and handling properties.

The performance of liquid ammonia and liquid fluorine has been reported in the literature by a number of organizations, such as Jet Propulsion Lab., C.I.T.; Reaction Motors, Inc.; Battelle Memorial Institute; and the NACA. Additional performance calculations for this propellant were made at the NACA Lewis laboratory as part of a series of calculations on propellants containing the chemical elements hydrogen, fluorine, and nitrogen (ref. 1) to provide a comparison with the performance of other propellants based on the same thermodynamic data and computed to the same degree of accuracy, and to provide several parameters not previously published.

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, ratio of nozzle-exit area to throat area, specific heat at constant pressure, coefficient of viscosity, and coefficient of thermal conductivity.

So that data based on the assumptions of equilibrium and frozen composition during the expansion process could be compared, several additional calculations were made assuming frozen composition.

SYMBOLS

The following symbols are used in this report:

A number of equivalent formulas (a function of pressure and molecular weight; see ref. 5)

a local velocity of sound, ft/sec

C_F coefficient of thrust

C_p^o molar specific heat at constant pressure, cal/(mole)(^oK)

c_p specific heat at constant pressure, cal/(gm)(^oK)

c_v specific heat at constant volume, cal/(gm)(^oK)

c^* characteristic velocity, ft/sec

D_A $\left(\frac{\partial \log A}{\partial \log T}\right)_s$

D_i $\left(\frac{\partial \log p_i}{\partial \log T}\right)_s$

g acceleration due to gravity, 32.174 ft/sec^2

H_T^o sum of sensible enthalpy and chemical energy, cal/mole

h sum of sensible enthalpy and chemical energy per unit weight, $\frac{\sum_i n_i(H_T^o)_i}{nM}$, cal/g

I	specific impulse, lb-sec/lb
k	coefficient of thermal conductivity, cal/(sec)(cm)($^{\circ}$K)
M	molecular weight, g/mole
n	number of moles
P	pressure
p	partial pressure
R	universal gas constant (consistent units)
r	equivalence ratio, ratio of number of fluorine atoms to hydrogen atoms
S	nozzle area, sq ft
T	temperature, $^{\circ}$K
w	rate of flow, lb/sec
Y_A	$\left(\frac{\partial \log A}{\partial \log T}\right)_P$
Y_i	$\left(\frac{\partial \log n_i}{\partial \log T}\right)_P$
γ_s	$\left(\frac{\partial \log P}{\partial \log \rho}\right)_s$
μ	coefficient of viscosity, g/(cm)(sec) = poise
ρ	density, g/cu cm

Subscripts:

c	combustion chamber
e	nozzle exit
frozen	composition assumed frozen
i	product of combustion
max	maximum

P constant pressure

s constant entropy

t nozzle throat

x any point in nozzle

CALCULATION OF PERFORMANCE DATA

Calculations of the performance data were made with a Bell computer and an IBM Card-Programmed Electronic Calculator as described in reference 1. The assumptions, thermodynamic data, and transport properties used for the calculations are the same as those of reference 1.

The products of combustion were assumed to be ideal gases and included the following substances: hydrogen fluoride HF, hydrogen H_2, nitrogen N_2, fluorine F_2, atomic fluorine F, atomic hydrogen H, and atomic nitrogen N. The dissociation energy of F_2 was taken to be 35.6 kilocalories per mole (ref. 2). Physical and thermochemical properties of the propellants were taken from references 2 to 5 and are given in table I.

Procedure for combustion conditions. - For each of ten equivalence ratios, combustion temperature, equilibrium composition, enthalpy, mean molecular weight, derivative of the logarithm of pressure with respect to the logarithm of density at constant entropy γ_s, specific heat at constant pressure, coefficient of viscosity, coefficient of thermal conductivity, and entropy of the combustion products were computed at a combustion pressure of 300 pounds per square inch absolute (20.41 atm).

Procedure for exit conditions. - Equilibrium composition, mean molecular weight, pressure, derivative of the logarithm of pressure with respect to the logarithm of density at constant entropy γ_s, enthalpy of the products of combustion, specific heat at constant pressure, coefficient of viscosity, and coefficient of thermal conductivity were computed for each equivalence ratio by assuming isentropic expansion for four assigned exit temperatures selected to cover the exit pressure range from the nozzle-throat pressure to about 0.1 atmosphere.

Interpolation. - Parameters for pressures at and near the nozzle throat and for pressures corresponding to altitudes of 0, 10,000, 20,000, 30,000, 40,000, and 50,000 feet were interpolated by means of cubic equations between each pair of the assigned exit temperatures. The functions and their first derivatives used in the interpolations are described in reference 1.

The errors due to interpolation were checked for several cases. The values presented for all performance parameters appear to be correctly interpolated or in error at most by one or two units in the last place tabulated.

Formulas. - The formulas used in computing the various parameters are given in reference 1 and are summarized as follows:

Specific impulse, lb-sec/lb

$$I = 294.98 \sqrt{\frac{h_c - h_e}{1000}} \tag{1}$$

Throat area per unit flow rate, (sq ft)(sec)/lb (pressure in atm)

$$S_t/w = \frac{1.3144\ T_t}{P_t\ M_t\ a} \tag{2}$$

Characteristic velocity, ft/sec (P_c = 300 lb/sq in. abs)

$$\begin{aligned} c^* &= g\ P_c\ S_t/w \\ &= 1.3899 \times 10^6\ S_t/w \end{aligned} \tag{3}$$

Coefficient of thrust

$$C_F = Ig/c^* = 32.174\ I/c^* \tag{4}$$

Nozzle-exit area per unit flow rate, (sq ft)(sec)/lb (pressure in atm)

$$S_e/w = \frac{0.040853\ T_e}{P_e\ M_e\ I} \tag{5}$$

Ratio of nozzle-exit area to throat area

$$S_e/S_t = \frac{S_e/w}{S_t/w} \tag{6}$$

Specific heat at constant pressure, cal/(g)(^{o}K)

$$c_p = \frac{1}{nMT}\left[T \sum_i n_i(C_p^o)_i + \sum_i n_i(H_T^o)_i\, Y_i - \sum_i n_i(H_T^o)_i\, Y_A\right] \tag{7}$$

Derivative of logarithm of pressure with respect to logarithm of density at constant entropy

$$\gamma_s = \frac{\sum_i p_i\, D_i}{P\,(D_A-1)} \tag{8}$$

Coefficient of viscosity, poise

$$\mu = \frac{PM}{\sum_i \frac{p_i}{(\mu_i/M_i)}} \tag{9}$$

Coefficient of thermal conductivity, cal/(sec)(cm)(^{o}K)

$$k = \mu \left(c_p + \frac{5}{4}\,\frac{R}{M}\right) \tag{10}$$

When composition is assumed to be frozen, equations (7) and (8) become

Specific heat at constant pressure assuming frozen composition cal/(g)(^{o}K)

$$(c_p)_{frozen} = \frac{\sum_i n_i(C_p^o)_i}{nM} \tag{11}$$

Derivative of logarithm of pressure with respect to logarithm of density at constant entropy assuming frozen composition

$$(\gamma_s)_{frozen} = \frac{(c_p)_{frozen}}{(c_p)_{frozen} - \frac{R}{M}} = \left(\frac{c_p}{c_v}\right)_{frozen} \tag{12}$$

The values of viscosity and thermal conductivity for mixtures of combustion gases calculated by means of equations (9) and (10) are only approximate. When more reliable transport properties for the various products of combustion become available, a more rigorous procedure for computing the properties of mixtures may also be justified.

THEORETICAL PERFORMANCE DATA

The calculated values of the various performance parameters for a combustion pressure of 300 pounds per square inch absolute and at exit pressures corresponding to altitudes of 0, 10,000, 20,000, 30,000, 40,000, and 50,000 feet are given in table II for ten equivalence ratios. The values of pressure corresponding to the assigned altitudes were taken from reference 6. As an aid to engine design, the values of the parameters within the rocket nozzle for 80, 90, 100, 110, and 120 percent of the throat pressure are tabulated in table III. Equilibrium composition, γ_s, specific heat at constant pressure, coefficient of viscosity, coefficient of thermal conductivity, and mean molecular weight in the combustion chamber and at assigned exit temperatures are given in table IV. The mole fraction of F_2 was always less than 0.00002 and therefore was not tabulated in table IV.

Parameters. - The parameters are plotted in figures 1 to 9. Curves of specific impulse for the six altitudes are shown in figure 1 plotted against weight percent fuel. The maximum value of specific impulse for the sea-level curve is 311.5 pound-seconds per pound at 24.1 percent of fuel by weight.

The maximum values of specific impulse and the weight percentages at which they occur were obtained by numerical differentiation of the calculated values and are shown in figure 2 as functions of altitude. The maximum specific impulse increases 22 percent for a change in altitude from sea level to 50,000 feet.

Curves of combustion-chamber temperature and nozzle-exit temperature for the six altitudes are presented in figure 3 as functions of weight percent fuel. The maximum combustion temperature obtained was 4310° K at 21.4 percent fuel by weight. The maximums of the exit temperature curves occur near the stoichiometric ratio.

Characteristic velocity and coefficient of thrust are plotted in figure 4 and ratios of the area at the nozzle exit to the area at the throat are shown in figure 5 as functions of weight percent fuel.

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

Curves of specific heat at constant pressure, coefficient of viscosity, and coefficient of thermal conductivity for six pressures are plotted in figures 7 to 9 as functions of weight percent fuel.

Frozen composition. - In order to compare data based on the assumptions of equilibrium and frozen composition during the expansion process, several additional calculations were made assuming frozen composition. These are presented in the following table together with corresponding equilibrium data for the stoichiometric equivalence ratio and expansion to two altitudes:

Parameters	Altitude			
	Sea level		50,000 feet	
	Equilibrium	Frozen	Equilibrium	Frozen
I, lb-sec/lb	311.0	287.9	379.2	336.2
c^*, ft/sec	7019	6690	7019	6690
C_F	1.426	1.385	1.738	1.617
S_e/S_t	3.908	3.131	18.71	12.90
T_e, ^oK	3113	2026	2130	1122
M_e	20.72	19.10	21.14	19.10

The percentage differences in these parameters for frozen and equilibrium composition are considerably higher for expansion to 50,000 feet than for expansion to sea level.

For a combustion-chamber pressure of 300 pounds per square inch absolute and an exit pressure of 1 atmosphere, the values of maximum specific impulse are 311.5 pound-seconds per pound at 24.1 percent fuel by weight for equilibrium composition during expansion and 290.0 pound-seconds per pound at 25.7 percent fuel by weight for frozen composition during expansion.

Chamber pressure effect. - According to NACA data for liquid hydrazine with liquid fluorine, the parameters c^*, C_F, and S_e/S_t are very nearly linear with the logarithm of chamber pressure for a fixed equivalence ratio and expansion ratio. For the stoichiometric equivalence ratio, increasing chamber pressure by a factor of 2 resulted in a change of +1.0 percent for c^*, and changes of -0.1 percent for C_F and -1.0 percent for S_e/S_t for an expansion ratio of 20.41; and changes of -0.6 percent for C_F and -3.3 percent for S_e/S_t for an expansion ratio of 326.6. It is expected that the values of c^*, C_F, and S_e/S_t given in this report for liquid ammonia with liquid fluorine for a chamber pressure of 300 pounds per square inch absolute may be used at other chamber pressures with similar small differences. Greater precision can be obtained by additional performance computations for other chamber pressures.

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REFERENCES

1. Gordon, Sanford, and Huff, Vearl N.: Theoretical Performance of Liquid Hydrogen and Liquid Fluorine as a Rocket Propellant. NACA RM E52L11, 1953.

2. Rossini, Frederick D., Wagman, Donald D., Evans, William H., Levine, Samuel, and Jaffe, Irving: Selected Values of Chemical Thermodynamic Properties. Nat. Bur. Standards Circular No. 500, Dept. Commerce, Feb. 1952.

3. Hodgman, Charles D.: Handbook of Chemistry and Physics. Thirty-Third ed., Chem. Rubber Publishing Co., 1951-1952.

4. Kilner, Scott B., Randolph, Carl L., Jr., and Gillespie, Rollin W.: The Density of Liquid Fluorine. Jour. Am. Chem. Soc., vol. 74, no. 4, Feb. 20, 1952, pp. 1086-1087.

5. Huff, Vearl N., Gordon, Sanford, and Morrell, Virginia E.: General Method and Thermodynamic Tables for Computation of Equilibrium Composition and Temperature of Chemical Reactions. NACA Rep. 1037, 1951. (Supersedes NACA TN's 2113 and 2161.)

6. Diehl, Walter S.: Standard Atmosphere - Tables and Data. NACA Rep. 218, 1925.

TABLE I. - PROPERTIES OF LIQUID PROPELLANTS

[Temperatures in superscripts, °C.]

Properties ↓ / Propellant →	Ammonia	Fluorine
Molecular weight, M	17.032	38.00
Density, g/cc	[a]$0.68^{-33.4}$	[b]1.54^{-196}
Freezing point, °C	[c]-77.76	[c]-217.96
Boiling point, °C	[c]-33.43	[c]-187.92
Viscosity, centipoises	[a]$0.255^{-33.5}$	--------
Enthalpy of formation at boiling point from elements at 25 °C, ΔH_f, kcal/mole	[d]-17.14	[d]-3.030
Enthalpy of vaporization, ΔH, kcal/mole	[c]$5.581^{-33.43}$	[c]$1.51^{-187.92}$
Enthalpy of fusion, ΔH, kcal/mole	[c]$1.351^{-77.76}$	[c]$0.372^{-217.96}$

[a]Reference 3.
[b]Reference 4.
[c]Reference 2.
[d]Reference 5.

TABLE II. - CALCULATED PERFORMANCE OF LIQUID AMMONIA WITH LIQUID FLUORINE

[Combustion-chamber pressure, 300 lb/sq in. absolute.]

Propellant			Combustion chamber		Characteristic velocity, c*, ft/sec	Nozzle exit						
Equivalence ratio, r	Weight-percent fuel	[a]Density, g/cc	Temperature, T_c, °K	Mean molecular weight, M_c		Altitude, ft	Pressure, P, atm	Temperature, T_e, °K	Mean molecular weight, M_e	Ratio of nozzle-exit area to throat area, S_e/S_t	Coefficient of thrust, C_F	Specific impulse, I, lb-sec/lb
1.2	19.94	1.230	4290	19.78	6867	0	1.0	2639	20.84	3.488	1.407	300.3
						10,000	.6876	2405	20.84	4.435	1.467	313.0
						20,000	.4594	2173	20.84	5.775	1.523	325.0
						30,000	.2968	1943	20.84	7.725	1.576	336.3
						40,000	.1852	1718	20.84	10.62	1.625	346.8
						50,000	.1149	1515	20.84	14.70	1.667	355.9
1.1	21.36	1.212	4310	19.48	6959	0	1.0	2970	20.94	3.766	1.421	307.2
						10,000	.6876	2741	20.97	4.828	1.486	321.3
						20,000	.4594	2494	20.98	6.312	1.547	334.5
						30,000	.2968	2244	20.98	8.473	1.605	347.1
						40,000	.1852	1997	20.98	11.69	1.659	358.7
						50,000	.1149	1770	20.98	16.24	1.706	368.9
1.0	23.01	1.193	4295	19.10	7019	0	1.0	3113	20.72	3.908	1.426	311.0
						10,000	.6876	2962	20.85	5.128	1.494	325.8
						20,000	.4594	2791	20.97	6.886	1.560	340.3
						30,000	.2968	2590	21.06	9.464	1.624	354.2
						40,000	.1852	2363	21.12	13.30	1.684	367.5
						50,000	.1149	2130	21.14	18.71	1.738	379.2
0.9	24.93	1.171	4236	18.65	7046	0	1.0	2957	20.09	3.812	1.421	311.2
						10,000	.6876	2783	20.19	4.960	1.487	325.7
						20,000	.4594	2590	20.28	6.597	1.551	339.6
						30,000	.2968	2376	20.34	8.987	1.612	353.0
						40,000	.1852	2147	20.38	12.54	1.669	365.6
						50,000	.1149	1923	20.39	17.56	1.720	376.7
0.8	27.19	1.146	4121	18.13	7025	0	1.0	2745	19.37	3.707	1.415	308.9
						10,000	.6876	2567	19.45	4.804	1.479	323.0
						20,000	.4594	2373	19.51	6.362	1.541	336.4
						30,000	.2968	2162	19.55	8.628	1.599	349.2
						40,000	.1852	1942	19.57	11.99	1.654	361.2
						50,000	.1149	1731	19.57	16.73	1.703	371.8

[a]Based on F_2 density of 1.54 at -196° C and NH_3 density of 0.68 at -33.4° C.

TABLE II. - CALCULATED PERFORMANCE OF LIQUID AMMONIA WITH LIQUID FLUORINE - Concluded

[Combustion-chamber pressure, 300 lb/sq in. absolute.]

Propellant			Combustion chamber		Characteristic velocity, c*, ft/sec	Nozzle exit						
Equivalence ratio, r	Weight-percent fuel	[a]Density, g/cc	Temperature, T_c, °K	Mean molecular weight, M_c		Altitude, ft	Pressure, P, atm	Temperature, T_e, °K	Mean molecular weight, Me	Ratio of nozzle-exit area to throat area, S_e/S_t	Coefficient of thrust, C_F	Specific impulse, I, lb-sec/lb
0.7	29.92	1.117	3942	17.53	6955	0	1.0	2511	18.57	3.620	1.410	304.9
						10,000	.6876	2330	18.62	4.666	1.473	318.4
						20,000	.4594	2136	18.65	6.145	1.532	331.3
						30,000	.2968	1932	18.66	8.291	1.589	343.5
						40,000	.1852	1724	18.67	11.47	1.642	354.9
						50,000	.1149	1530	18.67	15.96	1.688	364.9
0.6	33.24	1.084	3705	16.88	6846	0	1.0	2232	17.64	3.510	1.405	298.9
						10,000	.6876	2052	17.66	4.496	1.465	311.8
						20,000	.4594	1867	17.66	5.889	1.522	324.0
						30,000	.2968	1678	17.67	7.913	1.576	335.5
						40,000	.1852	1491	17.67	10.92	1.627	346.2
						50,000	.1149	1318	17.67	15.15	1.671	355.5
0.5	37.41	1.045	3403	16.12	6680	0	1.0	1900	16.55	3.367	1.396	289.8
						10,000	.6876	1735	16.56	4.293	1.454	301.9
						20,000	.4594	1570	16.56	5.602	1.508	313.2
						30,000	.2968	1405	16.56	7.504	1.560	323.8
						40,000	.1852	1243	16.56	10.32	1.607	333.7
						50,000	.1149	1095	16.56	14.29	1.649	342.3
0.4	42.76	0.999	2990	15.17	6388	0	1.0	1530	15.32	3.224	1.387	275.4
						10,000	.6876	1391	15.32	4.098	1.442	286.3
						20,000	.4594	1253	15.32	5.333	1.494	296.7
						30,000	.2968	1116	15.32	7.121	1.543	306.3
						40,000	.1852	983	15.32	9.766	1.588	315.3
						50,000	.1149	863	15.32	13.48	1.627	323.1
0.3	49.90	0.944	2374	13.92	5854	0	1.0	1126	13.93	3.116	1.383	251.6
						10,000	.6876	1018	13.93	3.946	1.436	261.3
						20,000	.4594	913	13.93	5.116	1.486	270.4
						30,000	.2968	809	13.93	6.807	1.533	278.9
						40,000	.1852	710	13.93	9.304	1.576	286.7
						50,000	.1149	620	13.93	12.81	1.613	293.5

[a]Based on F_2 density of 1.54 at -196° C and NH_3 density of 0.68 at -33.4° C.

TABLE III. - CALCULATED PARAMETERS AT PRESSURES NEAR NOZZLE THROAT FOR LIQUID AMMONIA WITH LIQUID FLUORINE

[Combustion-chamber pressure, 300 lb/sq in. absolute.]

Equivalence ratio, r	Weight-percent fuel	$\frac{P_x}{P_t}$	Pressure, P_x, atm	Temperature, T_x, °K	Mean molecular weight, M_x	Ratio of nozzle area to throat area, S_x/S_t	Coefficient of thrust, C_F	Specific impulse, I, lb-sec/lb
1.2	19.94	1.2	13.98	4114	20.01	1.0343	0.5508	117.6
		1.1	12.82	4075	20.07	1.0080	.6090	130.0
		1.0	11.65	4031	20.12	1.0000	.6662	142.2
		.9	10.49	3983	20.18	1.0080	.7235	154.4
		.8	9.320	3929	20.25	1.0319	.7816	166.8
1.1	21.36	1.2	14.06	4154	19.72	1.0366	0.5455	118.0
		1.1	12.89	4115	19.77	1.0089	.6040	130.6
		1.0	11.72	4073	19.83	1.0000	.6615	143.1
		.9	10.54	4027	19.89	1.0077	.7191	155.5
		.8	9.372	3978	19.96	1.0320	.7775	168.2
1.0	23.01	1.2	14.06	4138	19.33	1.0358	0.5450	118.9
		1.1	12.89	4102	19.38	1.0085	.6035	131.7
		1.0	11.72	4062	19.44	1.0000	.6611	144.2
		.9	10.55	4019	19.50	1.0080	.7187	156.8
		.8	9.376	3972	19.57	1.0326	.7771	169.5
0.9	24.93	1.2	14.04	4074	18.87	1.0353	0.5467	119.7
		1.1	12.87	4037	18.92	1.0083	.6052	132.5
		1.0	11.70	3997	18.97	1.0000	.6626	145.1
		.9	10.53	3952	19.03	1.0080	.7201	157.7
		.8	9.359	3903	19.09	1.0324	.7785	170.5
0.8	27.19	1.2	13.97	3947	18.32	1.0345	0.5516	120.4
		1.1	12.81	3907	18.37	1.0081	.6097	133.1
		1.0	11.65	3864	18.42	1.0000	.6669	145.6
		.9	10.48	3816	18.47	1.0078	.7241	158.1
		.8	9.317	3763	18.53	1.0318	.7822	170.8

TABLE III. - CALCULATED PARAMETERS AT PRESSURES NEAR NOZZLE THROAT FOR LIQUID AMMONIA WITH LIQUID FLUORINE - Concluded

[Combustion-chamber pressure, 300 lb/sq in. absolute.]

Equivalence ratio, r	Weight-percent fuel	$\frac{P_x}{P_t}$	Pressure, P_x, atm	Temperature, T_x, ^oK	Mean molecular weight, M_x	Ratio of nozzle area to throat area, S_x/S_t	Coefficient of thrust, C_F	Specific impulse, I, lb-sec/lb
0.7	29.92	1.2	13.90	3756	17.71	1.0337	0.5572	120.5
		1.1	12.74	3714	17.75	1.0080	.6150	133.0
		1.0	11.59	3668	17.80	1.0000	.6719	145.3
		.9	10.43	3618	17.84	1.0077	.7288	157.6
		.8	9.268	3562	17.89	1.0313	.7866	170.1
0.6	33.24	1.2	13.84	3511	17.03	1.0330	0.5622	119.6
		1.1	12.68	3468	17.06	1.0078	.6197	131.9
		1.0	11.53	3421	17.10	1.0000	.6764	143.9
		.9	10.38	3370	17.14	1.0076	.7330	156.0
		.8	9.224	3312	17.18	1.0307	.7905	168.2
0.5	37.41	1.2	13.74	3200	16.23	1.0319	0.5693	118.2
		1.1	12.59	3156	16.26	1.0076	.6264	130.1
		1.0	11.45	3108	16.28	1.0000	.6827	141.7
		.9	10.30	3055	16.31	1.0073	.7389	153.4
		.8	9.160	2995	16.34	1.0297	.7959	165.2
0.4	42.76	1.2	13.55	2771	15.23	1.0301	0.5837	115.9
		1.1	12.42	2725	15.24	1.0072	.6400	127.1
		1.0	11.29	2675	15.25	1.0000	.6954	138.1
		.9	10.16	2619	15.26	1.0070	.7508	149.1
		.8	9.033	2557	15.27	1.0282	.8071	160.2
0.3	49.90	1.2	13.32	2154	13.93	1.0283	0.6020	109.5
		1.1	12.21	2111	13.93	1.0068	.6572	119.6
		1.0	11.10	2064	13.93	1.0000	.7117	129.5
		.9	9.991	2013	13.93	1.0067	.7662	139.4
		.8	8.881	1958	13.93	1.0272	.8214	149.4

TABLE IV - PROPERTIES AND COMPOSITION IN COMBUSTION CHAMBER AND FOLLOWING AN ISENTROPIC EXPANSION TO ASSIGNED EXIT TEMPERATURES FOR LIQUID AMMONIA WITH LIQUID FLUORINE

[Combustion-chamber pressure, 300 lb/sq. in absolute.]

Temperature, T, °K	Pressure, P, atm	γ_s, $\left(\frac{\partial \log P}{\partial \log \rho}\right)_s$	Specific heat at constant pressure, c_p, cal/(g)(°K)	Coefficient of viscosity, μ, micropoise	Coefficient of thermal conductivity, k, microcal/(sec)(cm)(°K)	Mean molecular weight, M	Equilibrium composition, mole fraction					
							HF	H_2	N_2	F	H	N
r = 1.2 (19.94 percent fuel by weight)												
4290	20.41	1.1631	1.5160	1830	3003	19.784	0.64316	0.00531	0.11148	0.19048	0.04095	0.00862
4000	10.88	1.1667	1.2640	1736	2408	20.163	.67551	.00303	.11516	.17413	.02648	.00570
2900	1.484	1.3065	.4137	1332	710	20.828	.73108	.00001	.12178	.14659	.00030	.00024
2300	.5753	1.3357	.3796	1092	545	20.837	.73171	.00000	.12195	.14632	.00000	.00001
1400	.08555	1.3674	.3584	710	339	20.846	.73201	.00000	.12200	.14557	.00000	.00000
r = 1.1 (21.36 percent fuel by weight)												
4310	20.41	1.1565	1.7479	1824	3421	19.476	0.65593	0.00978	0.11742	0.15013	0.05731	0.00943
4000	9.877	1.1549	1.5461	1727	2885	19.928	.69616	.00649	.12189	.12863	.04068	.00615
3000	1.053	1.2503	.5172	1369	870	20.935	.78559	.00014	.13104	.08090	.00184	.00048
2600	.5472	1.3095	.4033	1209	631	20.979	.78926	.00000	.13153	.07904	.00010	.00007
1700	.09820	1.3452	.3692	834	407	20.982	.78948	.00000	.13158	.07892	.00000	.00000
r = 1.0 (23.01 percent fuel by weight)												
4295	20.41	1.1544	1.8403	1801	3549	19.100	0.66410	0.01747	0.12436	0.10986	0.07494	0.00927
4000	10.06	1.1512	1.6815	1710	3092	19.533	.70403	.01407	.12879	.08749	.05935	.00626
3000	.7550	1.1789	.8340	1361	1297	20.823	.82458	.00393	.14034	.01921	.01135	.00059
2900	.5921	1.1892	.7505	1322	1149	20.902	.83223	.00319	.14097	.01480	.00841	.00040
2100	.1080	1.3024	.4085	998	525	21.145	.85635	.00019	.14281	.00052	.00013	.00000
r = 0.9 (24.93 percent fuel by weight)												
4236	20.41	1.1571	1.7461	1755	3299	18.650	0.66526	0.03109	0.13232	0.07167	0.09137	0.00830
4000	11.79	1.1563	1.5943	1682	2902	18.966	.69434	.02949	.13581	.05507	.07936	.00594
2900	.8825	1.2099	.6990	1295	1065	20.127	.79178	.03460	.14711	.00350	.02268	.00034
2700	.5768	1.2310	.6002	1218	880	20.234	.79812	.03786	.14799	.00139	.01451	.00014
1900	.1092	1.3151	.4095	896	476	20.392	.80576	.04451	.14922	.00000	.00051	.00000
r = 0.8 (27.19 percent fuel by weight)												
4121	20.41	1.1660	1.5221	1680	2788	18.126	0.65503	0.05572	0.14145	0.03954	0.10175	0.00650
3900	12.61	1.1684	1.3702	1610	2424	18.377	.67604	.05733	.14448	.02816	.08954	.00445
2800	1.125	1.2204	.6837	1224	994	19.344	.74015	.08219	.15434	.00111	.02204	.00018
2500	.5977	1.2500	.5601	1111	764	19.475	.74605	.08858	.15546	.00023	.00965	.00004
1700	.1068	1.3283	.4116	796	429	19.571	.74995	.09367	.15624	.00000	.00014	.00000

TABLE IV - PROPERTIES AND COMPOSITION IN COMBUSTION CHAMBER AND FOLLOWING AN ISENTROPIC EXPANSION TO ASSIGNED EXIT TEMPERATURES FOR LIQUID AMMONIA WITH LIQUID FLUORINE - Concluded

[Combustion-chamber pressure, 300 lb/sq. in absolute.]

Temperature, T, ^{o}K	Pressure, P, atm	γ_s, $\left(\frac{\partial \log P}{\partial \log \rho}\right)_s$	Specific heat at constant pressure, c_p, cal/(g)(^{o}K)	Coefficient of viscosity, μ, micropoise	Coefficient of thermal conductivity, k, microcal/(sec)(cm)(^{o}K)	Mean molecular weight, M	Equilibrium composition, mole fraction: HF	H_2	N_2	F	H	N
r = 0.7 (29.92 percent fuel by weight)												
3942	20.41	1.1789	1.3079	1573	2281	17.535	0.62902	0.09785	0.15189	0.01776	0.09926	0.00421
3700	12.38	1.1833	1.1744	1495	1965	17.766	.64432	.10444	.15477	.01100	.08297	.00251
2600	1.203	1.2407	.6222	1115	843	18.542	.68370	.14014	.16281	.00023	.01306	.00005
2200	.5253	1.2848	.4973	968	611	18.638	.68748	.14585	.16369	.00002	.00296	.00000
1500	.1062	1.3405	.4192	698	385	18.666	.68852	.14753	.16393	.00000	.00002	.00000
r = 0.6 (33.24 percent fuel by weight)												
3705	20.41	1.1914	1.1515	1439	1869	16.877	0.58656	0.16038	0.16369	0.00640	0.08093	0.00205
3400	11.04	1.1980	1.0086	1342	1548	17.116	.59838	.17281	.16657	.00299	.05830	.00096
2300	1.150	1.2768	.5425	972	665	17.630	.61940	.20445	.17206	.00002	.00407	.00001
2000	.6154	1.3062	.4858	865	542	17.658	.62040	.20633	.17233	.00000	.00094	.00000
1300	.1089	1.3527	.4314	602	344	17.666	.62069	.20690	.17241	.00000	.00000	.00000
r = 0.5 (37.41 percent fuel by weight)												
3403	20.41	1.2062	.9930	1281	1470	16.116	0.52925	0.24081	0.17665	0.00167	0.05096	0.00065
3100	11.26	1.2175	.8573	1189	1201	16.287	.53591	.25273	.17871	.00064	.03173	.00028
2100	1.532	1.3000	.5287	867	589	16.546	.54509	.27189	.18170	.00000	.00131	.00000
1700	.6326	1.3281	.4865	730	464	16.556	.54543	.27267	.18181	.00000	.00010	.00000
1200	.1621	1.3589	.4545	547	331	16.557	.54545	.27273	.18182	.00000	.00000	.00000
r = 0.4 (42.76 percent fuel by weight)												
2990	20.41	1.2352	.7992	1093	1053	15.168	0.45676	0.33310	0.19034	0.00021	0.01947	0.00013
2700	11.84	1.2551	.6980	1009	869	15.246	.45924	.33971	.19136	.00006	.00959	.00003
1700	1.524	1.3283	.5254	699	481	15.319	.46152	.34611	.19230	.00000	.00007	.00000
1300	.5298	1.3519	.4984	563	372	15.320	.46154	.34615	.19231	.00000	.00000	.00000
1200	.3903	1.3584	.4916	528	345	15.320	.46154	.34615	.19231	.00000	.00000	.00000
r = 0.3 (49.90 percent fuel by weight)												
2374	20.41	1.2899	.6488	856	708	13.917	0.36697	0.42713	0.20387	0.00000	0.00202	0.00000
2100	11.95	1.3068	.6121	779	616	13.927	.36724	.42815	.20402	.00000	.00059	.00000
1200	1.272	1.3579	.5412	505	363	13.931	.36735	.42857	.20408	.00000	.00000	.00000
1000	.6428	1.3714	.5268	437	308	13.931	.36735	.42857	.20408	.00000	.00000	.00000
700	.1765	1.3893	.5091	329	226	13.931	.36735	.42857	.20408	.00000	.00000	.00000

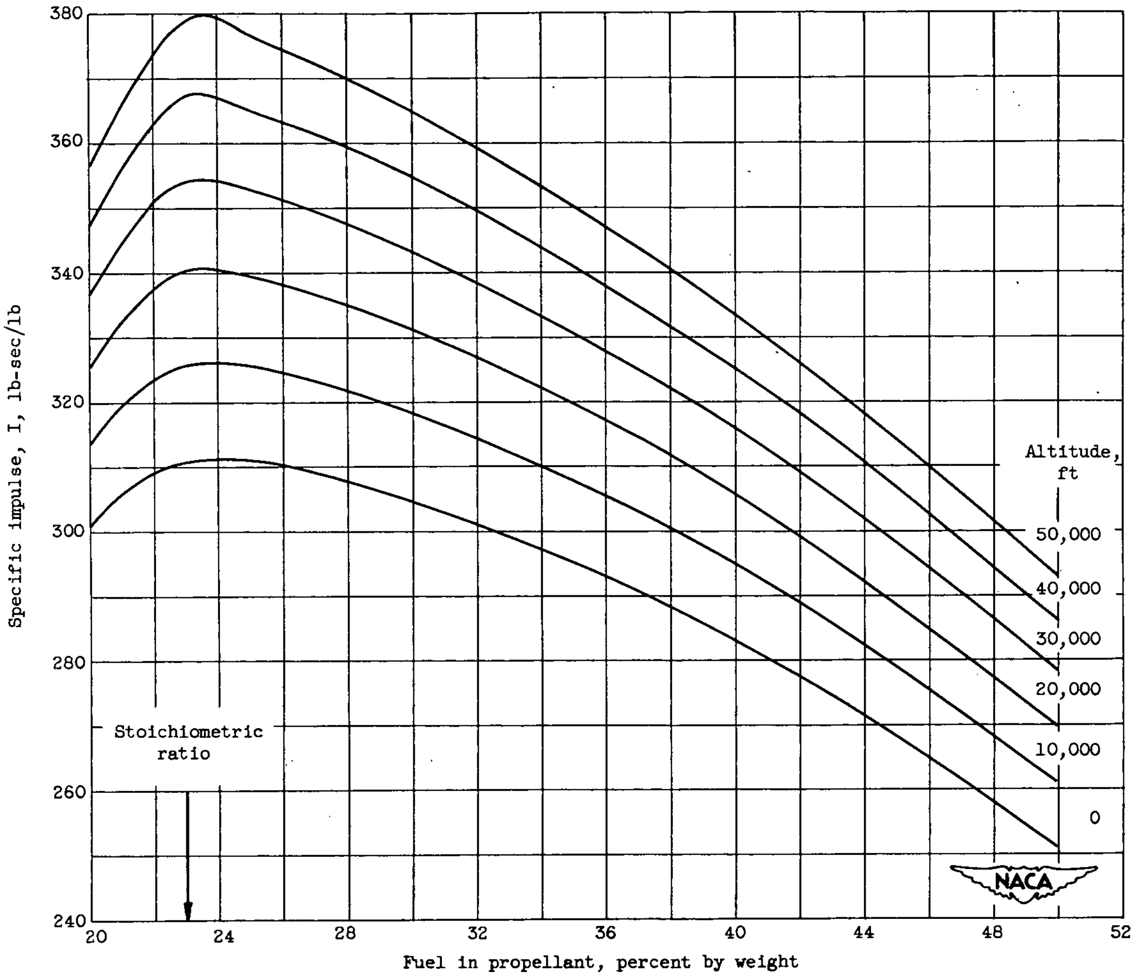

Figure 1. - Theoretical specific impulse of liquid ammonia with liquid fluorine. Isentropic expansion assuming equilibrium composition; combustion-chamber pressure, 300 pounds per square inch absolute; exit pressure corresponding to altitude indicated.

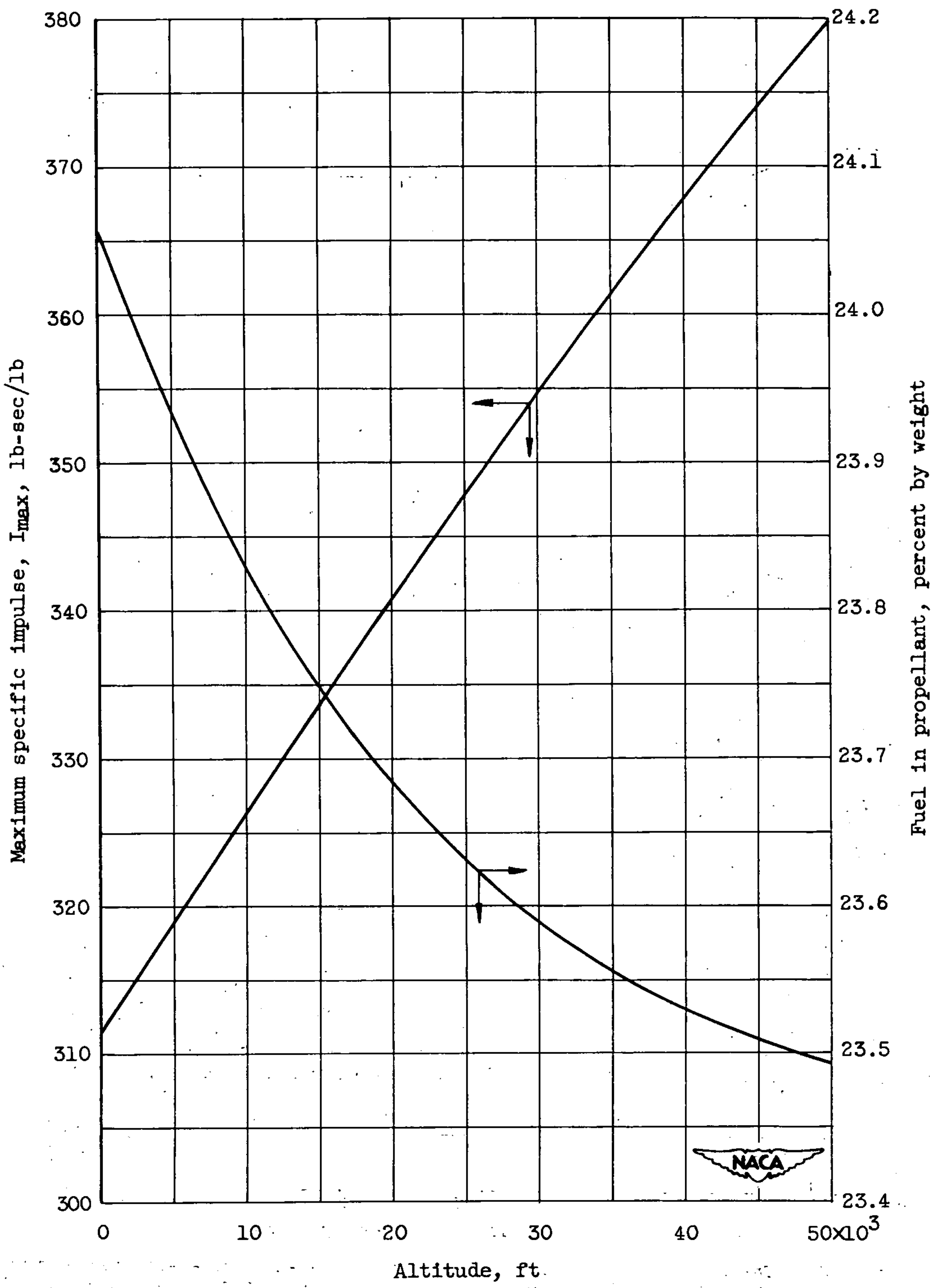

Figure 2. - Maximum theoretical specific impulse and corresponding weight percent of fuel in propellant of liquid ammonia with liquid fluorine. Isentropic expansion assuming equilibrium composition; combustion-chamber pressure, 300 pounds per square inch absolute; exit pressure corresponding to altitude indicated.

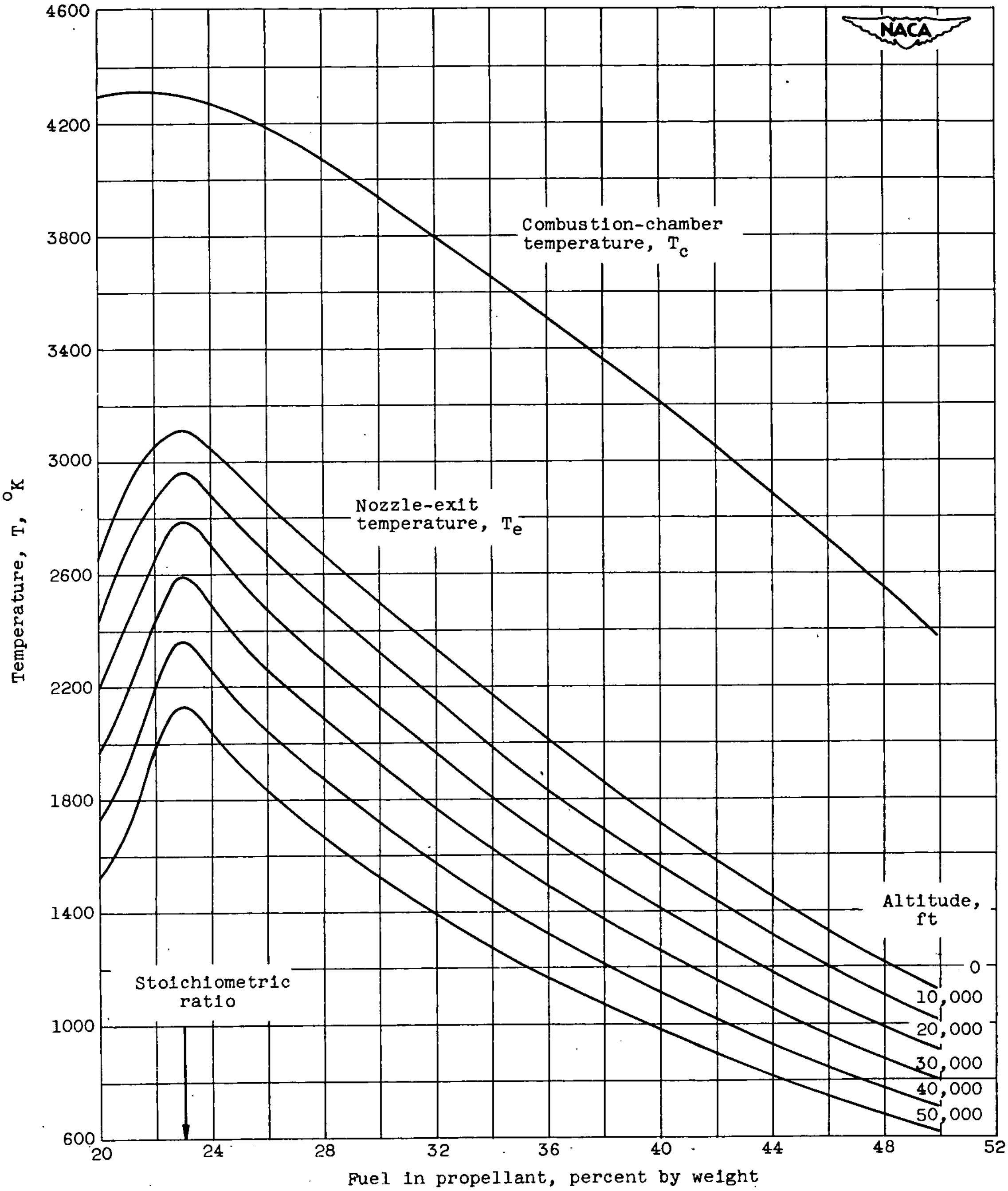

Figure 3. - Theoretical combustion-chamber temperature and nozzle-exit temperature of liquid ammonia with liquid fluorine. Isentropic expansion assuming equilibrium composition; combustion-chamber pressure, 300 pounds per square inch absolute; exit pressure corresponding to altitude indicated.

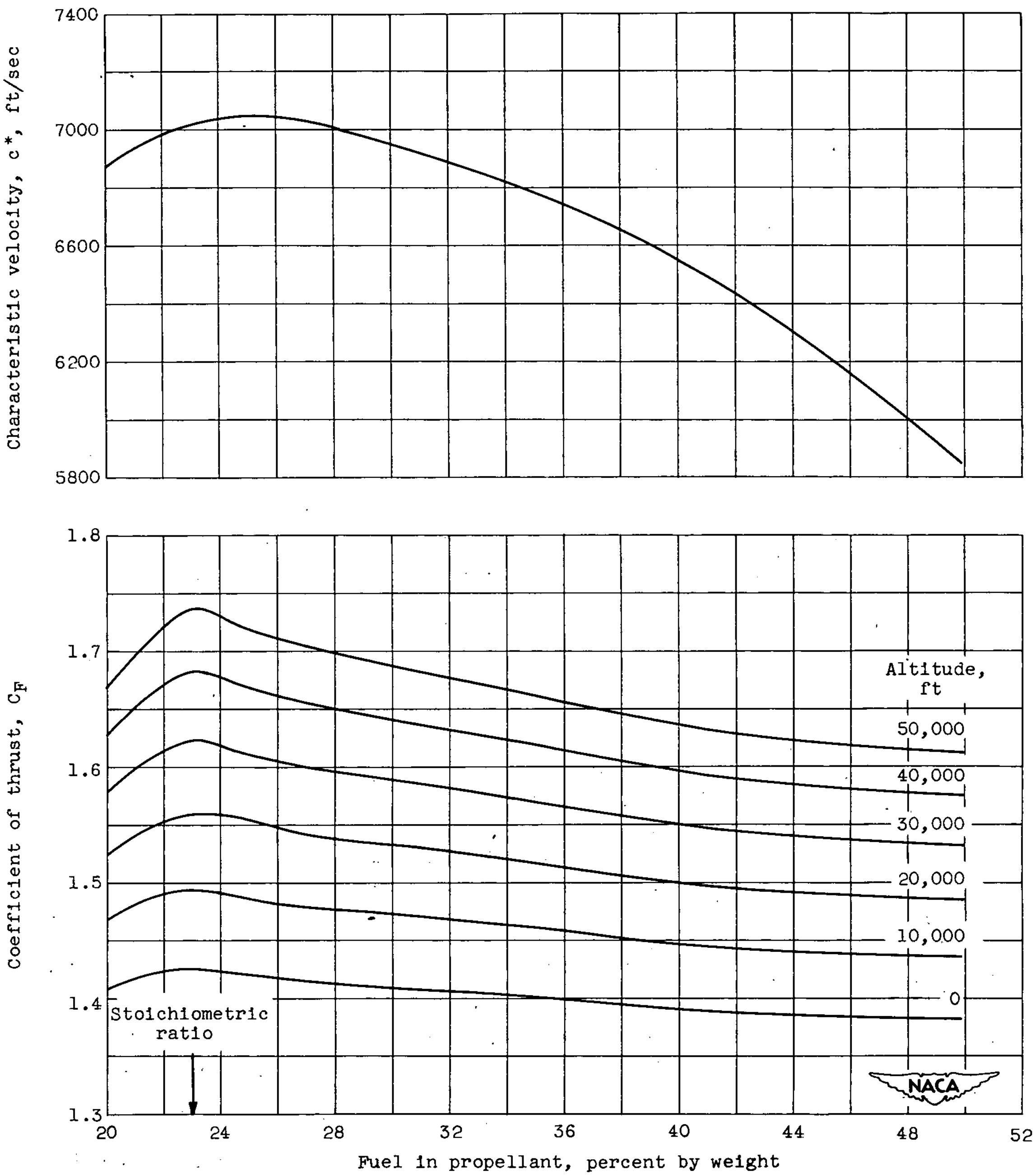

Figure 4. - Theoretical characteristic velocity and coefficient of thrust of liquid ammonia and liquid fluorine. Isentropic expansion assuming equilibrium composition; combustion chamber pressure, 300 pounds per square inch absolute; exit pressure corresponding to altitude indicated.

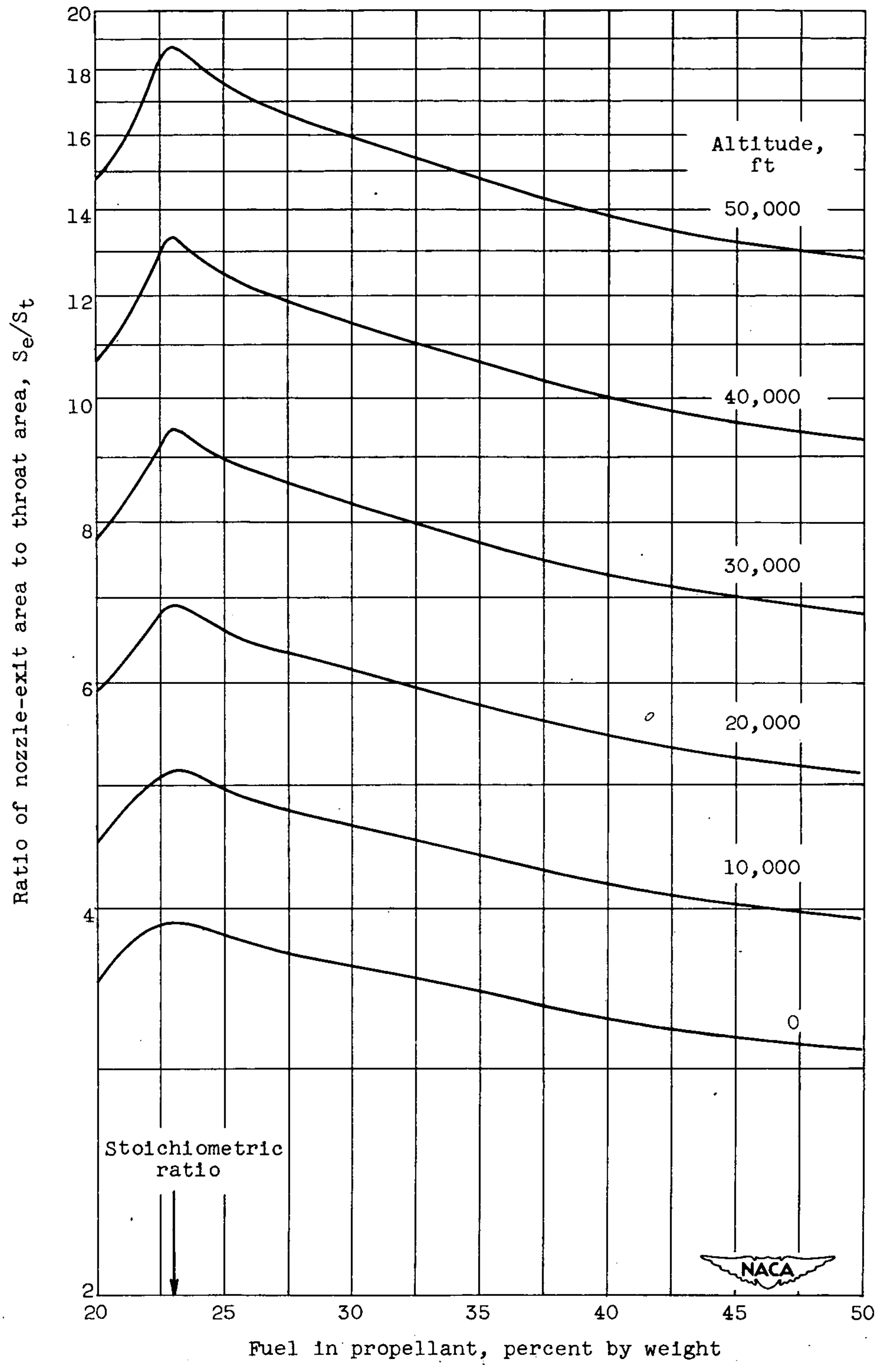

Figure 5. - Theoretical ratios of nozzle-exit area to throat area of liquid ammonia with liquid fluorine. Isentropic expansion assuming equilibrium composition; combustion-chamber pressure, 300 pounds per square inch absolute; exit pressure corresponding to altitude indicated.

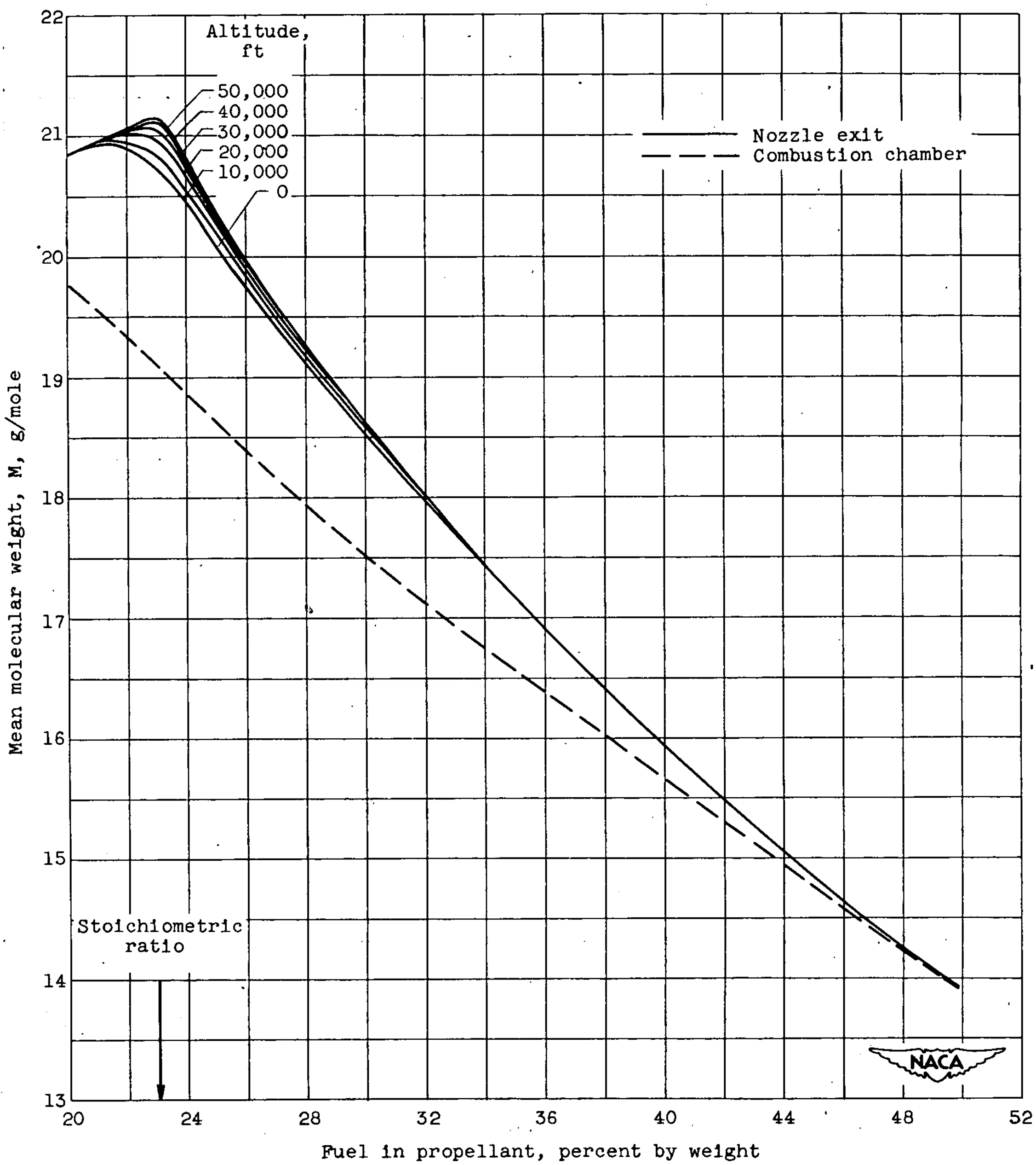

Figure 6. - Theoretical mean molecular weight in combustion chamber and at nozzle exit of liquid ammonia with liquid fluorine. Isentropic expansion assuming equilibrium composition; combustion-chamber pressure, 300 pounds per square inch absolute; exit pressure corresponding to altitude indicated.

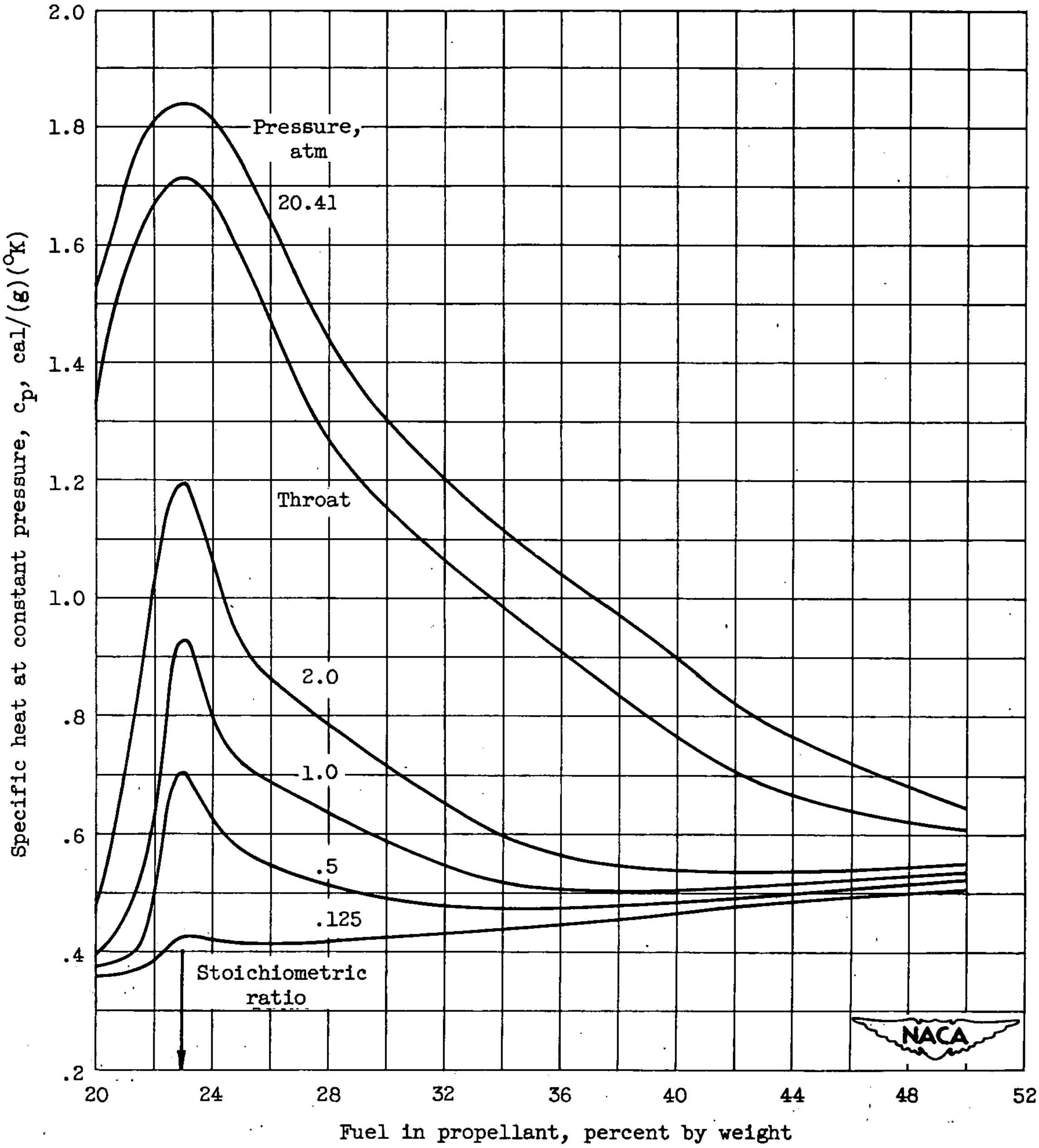

Figure 7. - Theoretical specific heat at constant pressure of combustion products (including energy of dissociation) of liquid ammonia with liquid fluorine. Isentropic expansion assuming equilibrium composition; combustion-chamber pressure, 300 pounds per square inch absolute; exit pressures as indicated.

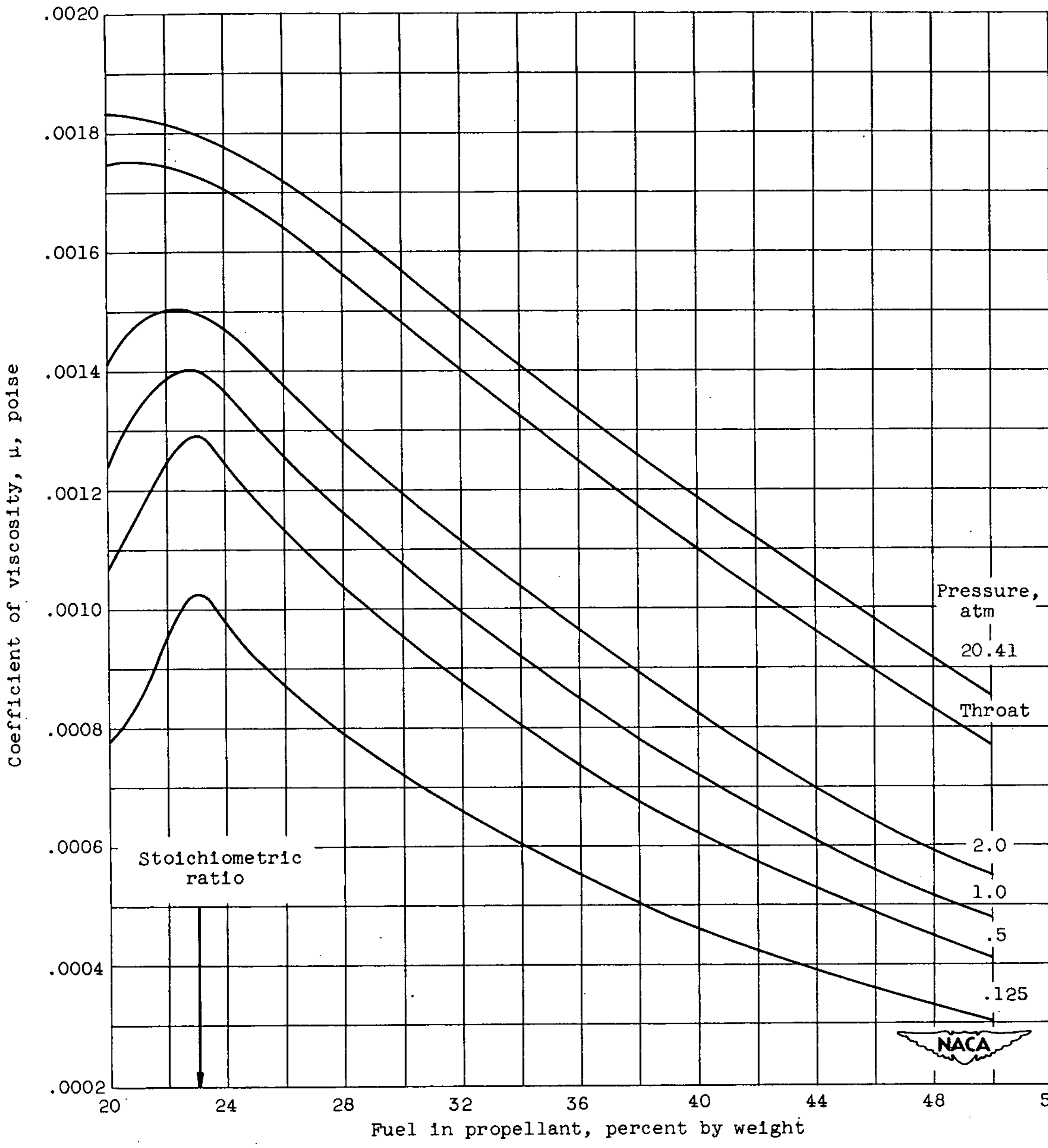

Figure 8. - Theoretical coefficient of viscosity of combustion products of liquid ammonia with liquid fluorine. Isentropic expansion assuming equilibrium composition; combustion-chamber pressure, 300 pounds per square inch absolute; exit pressures as indicated.

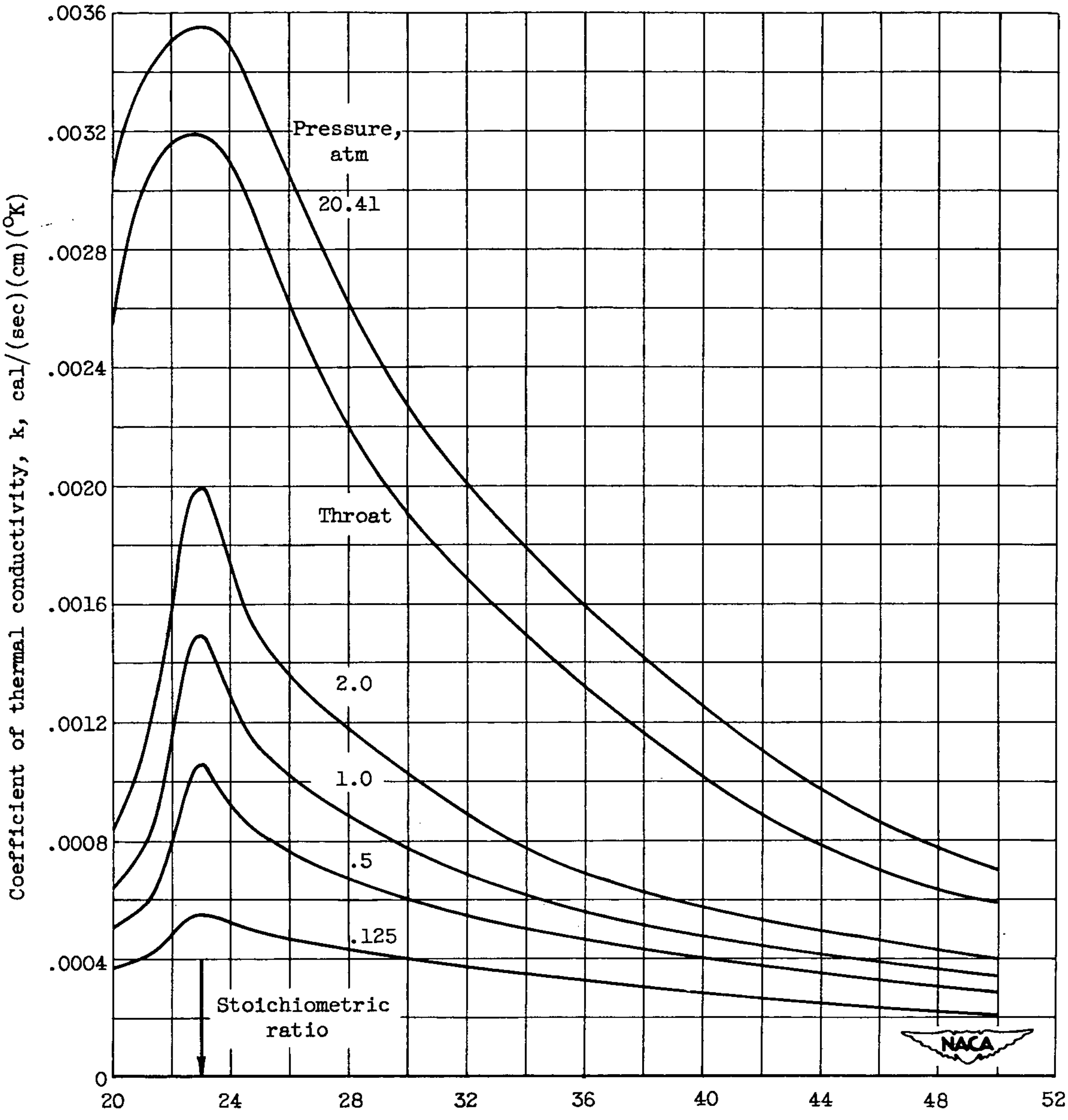

Figure 9. - Theoretical coefficient of thermal conductivity of combustion products of liquid ammonia with liquid fluorine. Isentropic expansion assuming equilibrium composition; combustion-chamber pressure, 300 pounds per square inch absolute; exit pressures as indicated.