U.S. AIR FORCE

Project RAND

RESEARCH MEMORANDUM

This is a working paper. It may be expanded, modified, or withdrawn at any time. The views, conclusions, and recommendations expressed herein do not necessarily reflect the official views or policies of the United States Air Force.

The RAND *Corporation*

SANTA MONICA • CALIFORNIA

DISCLAIMER

DISCLAIMER

Portions of this document may be illegible in electronic image products. Images are produced from the best available original document.

U. S. AIR FORCE

PROJECT RAND

RESEARCH MEMORANDUM

A PARAMETRIC STUDY OF CERTAIN LOW-MOLECULAR-WEIGHT
COMPOUNDS AS NUCLEAR ROCKET PROPELLANTS
V. METHANE

F. J. Krieger

RM-2807-PR

August 1961

Assigned to_____ _____

The RAND *Corporation*

241 002

page blank

SUMMARY

The purpose of this study is the parametric investigation of a series of low-molecular-weight, high-hydrogen-content compounds as propellants for nuclear-powered rockets. The chemical compounds include hydrogen (H_2), ammonia (NH_3), water (H_2O), lithium hydride (LiH), methane (CH_4), and methanol (CH_3OH).

A two-part computational program was carried out for each compound; the results are presented in both tabular and graphic form. The results of the first part of the program are presented in static form, that is, by the conventional Mollier diagram, in which specific enthalpy is plotted against specific entropy, with cross plots of temperature, pressure, and molecular weight. The results of the second part of the program are presented in dynamic form by a series of diagrams in which specific impulse is plotted against pressure, with cross plots of chamber temperature, exhaust temperature, and rocket-nozzle area. It was assumed that the propellant gas, starting with a nonzero chamber velocity, maintained instantaneous chemical equilibrium composition as it expanded isentropically through a de Laval nozzle. The general procedure, here, is an extension of that described in Ref. 1.

Because of the voluminous nature of the computations and the graphical presentation of the information derived, the results of the investigation are issued as separate research memoranda, one for each propellant. This study presents the results for methane. The others currently available in the series are as follows:

RM-2400 A Parametric Study of Certain Low-Molecular-Weight
     Compounds as Nuclear Rocket Propellants:
     I. Hydrogen

ACKNOWLEDGMENTS

This study involved a considerable amount of hand and machine computation. The efforts of the following RAND staff members are gratefully acknowledged: Herschel E. Kanter, of the Computer Sciences Department, for adapting the problem to the IBM 704 computer; Donald A. Brown, of the Physics Department, for his extensive liaison and computational work; and Elizabeth J. Force, of the Physics Department, for her meticulous graphical presentation of the tabulated results.

page blank

CONTENTS

page blank

LIST OF TABLES

page blank

LIST OF FIGURES

I. INTRODUCTION

This study will consider a disperse system, or smoke—that is, an expanding propellant gas that contains a condensed phase, which in this case is solid carbon, C_s.

If temperature equilibrium is maintained between solid and gas during expansion, the condensed particles contribute markedly to the heat capacity, but negligibly to the work done in expansion. This effect must be taken into consideration in the thermodynamic equations that lead to the expression for specific impulse.

The following assumptions have been used: (1) Thermal equilibrium is maintained between the solid particles and the gas phase. (2) The solid particles have the same velocity as the gas at all stages of the expansion. (3) The volume of the solid particles is negligible compared with that of the gas. (4) The pressure due to the thermal motion of the solid particles can be neglected. (5) The gas phase obeys the laws of perfect gases.

page blank

II. COMPOSITION EQUATIONS

In this study it is assumed that the propellant gas formed by heating methane (CH_4) in a nuclear reactor, or other device, is a mixture of the following sixteen chemical species: H, H_2, C_s (graphite), C (gas), CH, CH_2, CH_3, CH_4, C_2, C_2H, C_2H_2, C_2H_4, C_2H_6, C_3, C_3H_4, and C_3H_6. The presence or absence of a condensed phase makes it necessary to consider two distinct sets of chemical equations.

I. <u>Solid carbon present</u>. In terms of H_2 and C_s as independent components, the chemical equations for the dependent, or derived, components are

$$H = 1/2 \; H_2, \tag{1}$$

$$C = C_s, \tag{2}$$

$$C_2 = 2 \; C_s, \tag{3}$$

$$C_3 = 3 \; C_s, \tag{4}$$

$$CH = C_s + 1/2 \; H_2, \tag{5}$$

$$CH_2 = C_s + H_2, \tag{6}$$

$$CH_3 = C_s + 3/2 \; H_2, \tag{7}$$

$$CH_4 = C_s + 2 \; H_2, \tag{8}$$

$$C_2H = 2 \; C_s + 1/2 \; H_2, \tag{9}$$

$$C_2H_2 = 2 \; C_s + H_2, \tag{10}$$

$$C_2H_4 = 2 \; C_s + 2 \; H_2, \tag{11}$$

$$C_2H_6 = 2 \; C_s + 3 \; H_2, \tag{12}$$

$$C_3H_4 = 3 \; C_s + 2 \; H_2, \tag{13}$$

$$C_3H_6 = 3 \; C_s + 3 \; H_2. \tag{14}$$

The equations required to determine the equilibrium composition of the nonhomogeneous gas mixture are obtained from mass-balance and equilibrium considerations. The following equations are derived from mass-balance considerations:

$$n_{H_2} = 2 - \frac{1}{2}n_H - \frac{1}{2}n_{CH} - n_{CH_2} - \frac{3}{2}n_{CH_3} - 2n_{CH_4} - \frac{1}{2}n_{C_2H}$$

$$- n_{C_2H_2} - 2n_{C_2H_4} - 3n_{C_2H_6} - 2n_{C_3H_4} - 3n_{C_3H_6} \, , \qquad (15)$$

$$n_{C_s} = 1 - n_C - n_{CH} - n_{CH_2} - n_{CH_3} - n_{CH_4} - 2n_{C_2} - 2n_{C_2H} - 2n_{C_2H_2}$$

$$- 2n_{C_2H_4} - 2n_{C_2H_6} - 3n_{C_3} - 3n_{C_3H_4} - 3n_{C_3H_6} \, , \qquad (16)$$

where n_i (i = H, H_2, etc.) is the number of moles of component i.

The equations obtained from equilibrium considerations are the following:

$$n_H = K_H (P/n)^{-1/2} n_{H_2}^{1/2} \, , \qquad (17)$$

$$n_C = K_C (P/n)^{-1} \, , \qquad (18)$$

$$n_{C_2} = K_{C_2} (P/n)^{-1} \, , \qquad (19)$$

$$n_{C_3} = K_{C_3} (P/n)^{-1} \, , \qquad (20)$$

$$n_{CH} = K_{CH}(P/n)^{-1/2}n_{H_2}^{1/2}, \qquad (21)$$

$$n_{CH_2} = K_{CH_2}n_{H_2}, \qquad (22)$$

$$n_{CH_3} = K_{CH_3}(P/n)^{1/2}n_{H_2}^{3/2}, \qquad (23)$$

$$n_{CH_4} = K_{CH_4}(P/n)n_{H_2}^{2}, \qquad (24)$$

$$n_{C_2H} = K_{C_2H}(P/n)^{-1/2}n_{H_2}^{1/2}, \qquad (25)$$

$$n_{C_2H_2} = K_{C_2H_2}n_{H_2}, \qquad (26)$$

$$n_{C_2H_4} = K_{C_2H_4}(P/n)n_{H_2}^{2}, \qquad (27)$$

$$n_{C_2H_6} = K_{C_2H_6}(P/n)^{2}n_{H_2}^{3}, \qquad (28)$$

$$n_{C_3H_4} = K_{C_3H_4}(P/n)n_{H_2}^{2}, \qquad (29)$$

$$n_{C_3H_6} = K_{C_3H_6}(P/n)^{2}n_{H_2}^{3}, \qquad (30)$$

where n is the total number of moles of gaseous components in the equilibrium mixture, P is the total pressure in atmospheres, and K_1 is the thermodynamic equilibrium constant of component i. The equilibrium constants are determined by means of the relation

$$\Delta F^{O} = - RT \ln K, \qquad (31)$$

where ΔF^{O} is the standard free-energy change that accompanies the chemical reactions (1) through (14), R is the gas constant, and T is the absolute temperature.

II. <u>Solid carbon absent</u>. In terms of H_2 and C as independent components, the chemical equations for the dependent, or derived, components are the same as Eqs. (1) through (14) except that C_s is replaced by C (gas) and Eq. (2) disappears. The mass-balance equations are

$$n_{H_2} = 2 - \frac{1}{2}n_H - \frac{1}{2}n_{CH} - n_{CH_2} - \frac{3}{2}n_{CH_3} - 2n_{CH_4} - \frac{1}{2}n_{C_2H}$$

$$- n_{C_2H_2} - 2n_{C_2H_4} - 3n_{C_2H_6} - 2n_{C_3H_4} - 3n_{C_3H_6} , \qquad (32)$$

$$n_C = 1 - n_{CH} - n_{CH_2} - n_{CH_3} - n_{CH_4} - 2n_{C_2} - 2n_{C_2H} - 2n_{C_2H_2}$$

$$- 2n_{C_2H_4} - 2n_{C_2H_6} - 3n_{C_3} - 3n_{C_3H_4} - 3n_{C_3H_6} . \qquad (33)$$

The equilibrium equations are the following:

$$n_H = K_H(P/n)^{-1/2} n_{H_2}^{1/2} , \qquad (34)$$

$$n_{C_2} = K_{C_2}(P/n) n_C^2 , \qquad (35)$$

$$n_{C_3} = K_{C_3}(P/n)^2 n_C^3 , \qquad (36)$$

$$n_{CH} = K_{CH}(P/n)^{1/2} n_C n_{H_2}^{1/2} , \qquad (37)$$

$$n_{CH_2} = K_{CH_2}(P/n) n_C n_{H_2} , \qquad (38)$$

$$n_{CH_3} = K_{CH_3}(P/n)^{3/2} n_C n_{H_2}^{3/2} , \qquad (39)$$

$$n_{CH_4} = K_{CH_4}(P/n)^2 n_C n_{H_2}^2 , \qquad (40)$$

$$n_{C_2H} = K_{C_2H}(P/n)^{3/2}n_C^2 n_{H_2}^{1/2}, \tag{41}$$

$$n_{C_2H_2} = K_{C_2H_2}(P/n)^2 n_C^2 n_{H_2}, \tag{42}$$

$$n_{C_2H_4} = K_{C_2H_4}(P/n)^3 n_C^2 n_{H_2}^2, \tag{43}$$

$$n_{C_2H_6} = K_{C_2H_6}(P/n)^4 n_C^2 n_{H_2}^3, \tag{44}$$

$$n_{C_3H_4} = K_{C_3H_4}(P/n)^4 n_C^3 n_{H_2}^2, \tag{45}$$

$$n_{C_3H_6} = K_{C_3H_6}(P/n)^5 n_C^3 n_{H_2}^3, \tag{46}$$

where n is the total number of moles of gas in the equilibrium mixture, P is the total pressure in atmospheres, and K_i is the thermodynamic equilibrium constant of component i as defined in Eq. (31). These values of K_i are quite different from those in Eqs. (17) through (30) because of the reactions with which they are associated.

page blank

III. THERMODYNAMIC EQUATIONS

The molecular weight of the gas mixture is given by the relation

$$M = \frac{16.043}{\bar{n}} , \qquad (47)$$

where 16.043 is the molecular weight of methane and $\bar{n}$ is the total number of moles in the gas mixture, including C_s.

The specific entropy of the gas mixture at any point in the expansion process is given by the expression

$$s = \frac{1}{16.043} \left\{ \sum n_i \left[S^o_i - R \ln (n_i/n) - R \ln P \right] + n_{C_s} S^o_{C_s} \right\} , \qquad (48)$$

where s is the entropy in calories per degree per gram, S^o_i is the standard entropy per mole of component i at a given temperature, n_i is the mole number of component i, n is the total number of moles of gas in the mixture, P is the total pressure in atmospheres, and R is the gas constant. The summation is over gaseous species only. The contribution of the solid carbon is given by the last term and assumes that the volume of C_s is negligible.

The specific enthalpy of the gas mixture is given by the expression

$$h = \frac{1}{16.043} \left\{ \sum n_i H^o_i + n_{C_s} H^o_{C_s} \right\} , \qquad (49)$$

where h is the enthalpy in calories per gram, and n_i and H^o_i are the mole number and the heat content per mole, respectively, of component i at a given temperature. Again the summation is over gaseous species only.

In Eqs. (48) and (49) it is assumed that solid carbon is in thermal equilibrium with the gas phase. By equating the change in kinetic energy of the expanding gas to its change in enthalpy, the velocity v at any point in the expansion, assuming no slippage of the solid phase, is found to be

$$v = \left[v_c^2 + 2J(h_c - h) \right]^{1/2} , \qquad (50)$$

where h is the specific enthalpy, J is the mechanical equivalent of heat, and the subscript c refers to the chamber conditions.

Specific impulse I and velocity v are related by means of the simple expression

$$I = v/g , \qquad (51)$$

where g is the acceleration of gravity. This concept of specific impulse assumes complete or perfect expansion of the propellant gas.

IV. MASS-FLOW EQUATIONS

As the propellant gas expands through the rocket nozzle, its mass-flow rate $\dot{m}$ in grams per second may be defined by the expression

$$\dot{m} = \rho A v , \qquad (52)$$

where ρ is the density of the gas in grams per cubic centimeter, A is the cross-sectional area of the nozzle in square centimeters, and v is the velocity in centimeters per second. The ideal gas equation may be written in the form

$$P = \frac{\rho}{M} RT , \qquad (53)$$

where P is the absolute pressure in atmospheres, ρ is the density and M the molecular weight of the gas, R is the gas constant, and T is the absolute temperature in degrees Kelvin. Equations (52) and (53) may be combined to give the expression

$$A = \frac{\dot{m}RT}{PMv} \qquad (54)$$

for the area associated with a given mass-flow rate at any point in the nozzle.

page blank

V. BASIC DATA

The pertinent thermodynamic properties (heat content, entropy, and free energy) for this study were either (1) taken in toto from established sources (H, H_2, C_s, C, CH), or (2) obtained by extending existing tables (C_2H_2, C_2H_4, C_2H_6, C_3H_4, C_3H_6), or (3) computed anew from fundamental data (CH_2, CH_3, CH_4, C_2, C_2H, C_3). The heats of formation at $0°K$ (i.e., H_0^0) were either taken directly from the References, or derived from established values at $298.16°K$, or estimated. The values of the heats of formation and the sources of the thermodynamic properties are listed in the following table.

Component	Molecular Weight	Heat of Formation at $0°K$ (cal/mole)	Source of Thermo-dynamic Properties
H	1.008	51,620 (Ref. 2)	(Refs. 2, 3)
H_2	2.016	0	(Refs. 2, 4)
C_s(graphite)	12.011	0	(Refs. 2, 5)
C (gas)	12.011	170,391 (Ref. 2)	(Refs. 2, 3)
CH	13.019	141,300 (derived from Ref.2)	(Ref. 6)
CH_2	14.027	92,500 (estimated)	(Refs. 7, 8)
CH_3	15.035	32,910 (derived from Ref.2)	(Refs. 7, 8)
CH_4	16.043	-15,987 (Ref. 2)	(Refs. 2, 7)
C_2	24.022	200,200 (Ref. 9)	(Ref. 10)
C_2H	25.030	104,000 (estimated)	(Ref. 11)
C_2H_2	26.038	54,329 (Ref. 12)	(Ref. 12)
C_2H_4	28.054	14,522 (Ref. 2)	(Ref. 13)
C_2H_6	30.070	-16,517 (Ref. 2)	(Ref. 14)
C_3	36.033	212,300 (Ref. 9)	(Ref. 7)
C_3H_4	40.065	46,017 (Ref. 12)	(Ref. 12)
C_3H_6	42.081	8,468 (derived from Refs. 13, 15)	(Ref. 13)

The pertinent physical constants have the following values: The acceleration of gravity $g = 980.665$ cm/sec^2; the gas constant $R = 82.0567$ cm^3 atm/deg-mole; the mechanical equivalent of heat $J = 4.1840$ abs joules/cal.

Substituting the above numerical values of the physical constants into Eqs. (50) and (51) gives the following working equation:

$$I = \left[I_c^2 + 87.0122(h_c - h) \right]^{1/2}. \tag{55}$$

By letting $\dot{m} = 1000$ gm/sec, Eq. (54) becomes

$$A = \frac{83.6745T}{PMI}. \tag{56}$$

VI. COMPUTATIONAL PROCEDURE

In general, the composition of the expanding gas can be determined at any temperature and pressure by solving Eqs. (15) through (30) when solid carbon is present and Eqs. (32) through (46) when it is absent. The entropy of the system, the expansion of which is assumed to be isentropic, can be determined from the initial chamber conditions by means of Eq. (48). Once the value of the entropy has been established, Eq. (48) can be used to determine the pressure at any temperature and composition. The velocity of the expanding gas at any point can be computed by means of Eq. (50). The chamber velocity v_c can be determined from the following considerations.

If, for a given mass-flow rate $\dot{m}$, a plot of area A versus temperature T is made for various temperatures between T_c and T_e, a smooth curve having a well-defined minimum is obtained. This point of minimum area A_t corresponds to the throat of the nozzle. It can be readily shown that the differential form of Eq. (54) is

$$\frac{d \ln A}{d \ln T} = 1 - \frac{d \ln P}{d \ln T} - \frac{d \ln M}{d \ln T} - \frac{d \ln v}{d \ln T} . \qquad (57)$$

The nozzle throat temperature T_t is defined as the temperature for which the right-hand member of Eq. (57) is zero.

The chamber velocity v_c, which by its nature is not zero, can therefore be computed from Eq. (54) when the arbitrary--but realistic--design condition

$$A_c = 2A_t \qquad (58)$$

is satisfied. Because A_t cannot be determined explicitly, an iterative method, such as that described in Ref. 1, must be used.

In practice, it was found expedient (1) to write the expression

$$2 = \frac{A_c}{A} \equiv \frac{T_c P M v}{T P_c M_c v_c} \equiv \frac{T_c P M}{T P_c M_c} \left[1 + \frac{87.0122(h_c - h)}{I_c^2} \right]^{1/2} , \quad (59)$$

which reduces to

$$I_c^2 = \frac{87.0122(h_c - h)}{4X^2 - 1} , \quad (60)$$

where

$$X = \frac{T P_c M_c}{I_c P M} ;$$

(2) to determine the values of I_c that satisfy Eq. (60) for a series of equally spaced values of $T \leq T_c$; and (3) to determine by interpolation the value of T (i.e., T_t) that maximizes I_c in step (2).

VII. RESULTS

The results of the first part of this study are presented numerically in Table 1 and graphically in Figs. 1 and 1a, which are conventional Mollier diagrams for methane; specific enthalpy is plotted against specific entropy, with cross plots of temperature, pressure, and molecular weight. The temperatures range from $5000^{\circ}K$ to $100^{\circ}K$; the pressures range from 10^{5} atm to 10^{-8} atm. The dotted line (....) demarcates the pure gas phase (above) from the smoke (below).

The results of the second part of this study, presented numerically in Tables 2 through 6, assumed (1) a mass-flow rate of 1000 gm/sec, (2) initial chamber pressures ranging from 10^{3} to 10^{-1} atm, (3) initial chamber temperatures ranging from $5000^{\circ}K$ to $2000^{\circ}K$, and (4) the initial chamber conditions found in Table 1. The results are presented graphically in Figs. 2 through 6, respectively. In these diagrams specific impulse is plotted against pressure, with cross plots of temperature and nozzle area. Initial chamber temperature T_c and pressure P_c are considered parameters. T_e is the downstream or exhaust temperature. The area A is based on a mass-flow rate of 1000 gm/sec. In Tables 2 through 6 and in the corresponding figures the dotted line (....) demarcates the pure gas phase from the smoke.

All the computations required to obtain the results in Tables 1 through 6 were made on the RAND JOHNNIAC computer and/or the RAND IBM 704 computer. The latter machine, using a different program based on Ref. 16, served as a check on the former, particularly in the critical phase-change areas of temperature and pressure where smoke begins to form.

In the tables the numbers are presented in "floating decimal" notation; the first two digits, minus 50, indicate a power of 10 and the next five digits indicate the decimal form of the number. Thus 5512345 represents 0.12345×10^5 and 4512345 represents 0.12345×10^{-5}.

Table 1

SUMMARY OF COMPUTED VALUES OF SPECIFIC ENTROPY, SPECIFIC ENTHALPY,
MOLECULAR WEIGHT, MOLES OF GAS, AND MOLES OF SOLID CARBON
FOR METHANE AT VARIOUS TEMPERATURES AND PRESSURES

Pressure, P (atm)	Entropy, s (cal/ deg-gm)	Enthalpy, h (cal/gm)	Molecular Weight, M	Moles of Gas, n	Moles of Solid, n_s
		5000 °K			
5610000	5151437	5474722	5210433	5115377	0000000
5510000	5159087	5487874	5181824	5119606	0000000
5410000	5168212	5510335	5170716	5122686	0000000
5310000	5182421	5513882	5157499	5127901	0000000
5210000	5210703	5521534	5142036	5138164	0000000
5110000	5213539	5529493	5133528	5147848	0000000
5010000	5215272	5531144	5132203	5149817	0000000
4910000	5216723	5531277	5132097	5149982	0000000
4810000	5218151	5531289	5132087	5149998	0000000
4710000	5219578	5531291	5132086	5149999	0000000
4610000	5221004	5531291	5132086	5149999	0000000
4510000	5222430	5531291	5132086	5150000	0000000
4410000	5223856	5531291	5132086	5150000	0000000
4310000	5225282	5531291	5132086	5150000	0000000
		4500 °K			
5610000	5149104	5463654	5211112	5114437	0000000
5510000	5156582	5475983	5185827	5118692	0000000
5410000	5164771	5487000	5175082	5121367	0000000
5310000	5175911	5510785	5165108	5124640	0000000
5210000	5194896	5515766	5150583	5131716	0000000
5110000	5212375	5524003	5137844	5142392	0000000
5010000	5214967	5529706	5132697	5149064	0000000
4910000	5216546	5530438	5132135	5149922	0000000
4810000	5217984	5530496	5132090	5149992	0000000
4710000	5219411	5530501	5132086	5149999	0000000
4610000	5220837	5530502	5132086	5149999	0000000
4510000	5222263	5530502	5132086	5150000	0000000
4410000	5223690	5530502	5132086	5150000	0000000
4310000	5225116	5530502	5132086	5150000	0000000

Table 1--continued

Pressure, P (atm)	Entropy, s (cal/ deg-gm)	Enthalpy, h (cal/gm)	Molecular Weight, M	Moles of Gas, n	Moles of Solid, n_s
			4000°K		
5610000	5146489	5452553	5211944	5113432	0000000
5510000	5153803	5464189	5191218	5117587	0000000
5410000	5161575	5473410	5178775	5120365	0000000
5310000	5170491	5484774	5171733	5122364	0000000
5210000	5184149	5511190	5160764	5126402	0000000
5110000	5210720	5516972	5146414	5134564	0000000
5010000	5213732	5524526	5136383	5144094	0000000
4910000	5216243	5529162	5132497	5149367	0000000
4810000	5217790	5529671	5132118	5149948	0000000
4710000	5219225	5529711	5132089	5149995	0000000
4610000	5220652	5529715	5132086	5149999	0000000
4510000	5222078	5529715	5132086	5149999	0000000
4410000	5223504	5529715	5132086	5150000	0000000
4310000	5224930	5529715	5132086	5150000	0000000
			3700°K		
5610000	5144768	5445930	5212513	5112821	0000000
5510000	5151888	5456824	5195835	5116740	0000000
5410000	5159697	5466180	5180866	5119838	0000000
5310000	5167699	5474018	5174933	5121409	0000000
5210000	5178802	5491292	5166682	5124058	0000000
5110000	5197390	5513193	5153519	5129976	0000000
5010000	5212480	5519706	5141221	5138919	0000000
4910000	5215548	5526508	5134173	5146945	0000000
4810000	5217624	5529035	5132239	5149762	0000000
4710000	5219099	5529226	5132099	5149979	0000000
4610000	5220529	5529242	5132087	5149997	0000000
4510000	5221956	5529244	5132086	5149999	0000000
4410000	5223382	5529244	5132086	5149999	0000000
4310000	5224808	5529244	5132086	5150000	0000000
			3600°K		
5610000	5144168	5443738	5212712	5112620	0000000
5510000	5151193	5454286	5197716	5116417	0000000
5455332	5153285	5457340	5191663	5117502	4445000
5410000	5158661	5462402	5177976	5119663	4991015
5310036	5166822	5470851	5175862	5121147	4488000
5310000	5166836	5470865	5175854	5121149	0000000
5210000	5177217	5485508	5168492	5123423	0000000

Table 1--continued

Pressure, P (atm)	Entropy, s (cal/ deg-gm)	Enthalpy, h (cal/gm)	Molecular Weight, M	Moles of Gas, n	Moles of Solid, n_s
5110000	5194270	5512055	5156161	5128566	0000000
5010000	5212064	5518188	5143158	5137172	0000000
4910000	5215100	5524875	5135412	5145303	0000000
4810000	5217530	5528694	5132372	5149557	0000000
4710000	5219052	5529056	5132108	5149964	0000000
4610000	5220486	5529084	5132088	5149996	0000000
4510000	5221913	5529087	5132086	5149999	0000000
4410000	5223339	5529087	5132086	5149999	0000000
4310000	5224765	5529087	5132086	5149999	0000000

$3500°K$

Pressure, P (atm)	Entropy, s (cal/ deg-gm)	Enthalpy, h (cal/gm)	Molecular Weight, M	Moles of Gas, n	Moles of Solid, n_s
5610000	5143554	5441559	5212915	5112422	0000000
5510556	5150274	5451410	5210045	5115970	4370000
5510000	5150437	5451604	5199228	5116087	4880523
5410000	5157480	5458212	5174118	5119507	5021379
5310000	5165118	5464767	5171158	5120836	5017088
5218648	5172711	5475742	5172354	5122172	4471000
5210000	5175729	5480224	5170191	5122856	0000000
5110000	5191296	5510999	5158855	5127258	0000000
5010000	5211644	5516695	5145341	5135383	0000000
4910000	5214585	5523047	5136947	5143421	0000000
4810000	5217376	5528146	5132656	5149125	0000000
4710000	5219001	5528874	5132127	5149935	0000000
4610000	5220441	5528925	5132089	5149993	0000000
4510000	5221868	5528930	5132086	5149999	0000000
4410000	5223295	5528930	5132086	5149999	0000000
4310000	5224721	5528930	5132086	5150000	0000000

$3000°K$

Pressure, P (atm)	Entropy, s (cal/ deg-gm)	Enthalpy, h (cal/gm)	Molecular Weight, M	Moles of Gas, n	Moles of Solid, n_s
5610000	5140277	5430922	5212054	5111496	0000000
5538612	5142419	5433151	5213040	5112302	4438000
5510000	5145671	5436094	5191324	5114944	5026224
5410000	5152264	5441202	5163422	5118873	5064218
5310000	5158594	5443425	5158574	5120035	5073533
5210000	5165516	5446824	5157751	5120591	5071880
5110000	5175001	5457192	5156960	5121929	5062353
5010000	5192115	5488363	5154958	5125893	5032975
4927305	5210810	5512294	5153037	5130248	4455000
4910000	5212034	5514762	5147414	5133835	0000000

Table 1--continued

Pressure, P (atm)	Entropy, s (cal/ deg-gm)	Enthalpy, h (cal/gm)	Molecular Weight, M	Moles of Gas, n	Moles of Solid, n_s
4810000	5214767	5519752	5139501	5140613	0000000
4710000	5217871	5525327	5134193	5146918	0000000
4610000	5220135	5527940	5132234	5149769	0000000
4510000	5221622	5528132	5132097	5149981	0000000
4410000	5223053	5528147	5132086	5149998	0000000
4310000	5224480	5528148	5132086	5149999	0000000

2500 °K

Pressure, P (atm)	Entropy, s (cal/ deg-gm)	Enthalpy, h (cal/gm)	Molecular Weight, M	Moles of Gas, n	Moles of Solid, n_s
5599998	5136629	5420907	5214938	5110739	0000000
5572579	5137195	5421252	5214761	5110868	4489000
5510000	5141249	5423927	5196027	5113700	5030063
5410000	5147922	5429246	5162891	5118023	5074850
5310000	5154281	5431511	5155291	5119754	5092610
5210000	5160240	5432192	5154277	5120052	5095049
5110000	5166507	5433495	5153909	5120259	5094989
5010000	5173969	5437539	5153083	5120833	5093888
4910000	5185179	5450188	5150690	5122617	5090318
4810000	5210669	5486326	5144919	5127709	5080056
4710000	5213949	5514556	5137946	5136021	5062572
4610000	5216384	5517897	5135831	5140292	5044812
4522971	5218656	5521679	5136610	5143820	4492000
4510000	5219922	5523689	5134867	5146011	0000000
4410000	5222649	5527060	5132305	5149660	0000000
4310000	5224187	5527348	5132101	5149975	0000000

2000 °K

Pressure, P (atm)	Entropy, s (cal/ deg-gm)	Enthalpy, h (cal/gm)	Molecular Weight, M	Moles of Gas, n	Moles of Solid, n_s
5610670	5132469	5411755	5215708	5110213	4471000
5610000	5132560	5411772	5215584	5110252	4841532
5510000	5136662	5413626	5211178	5112249	5021022
5410000	5143211	5418701	5172039	5116178	5060910
5310000	5150438	5422885	5156240	5119286	5092394
5210000	5156498	5423763	5153816	5119925	5098850
5110000	5162280	5423932	5153537	5120008	5099577
5010000	5168117	5424181	5153449	5120050	5099647
4910000	5174727	5424938	5153252	5120162	5099633
4810000	5181215	5427331	5152648	5120515	5099563
4710000	5190962	5434864	5150825	5121625	5099338
4610000	5210895	5457728	5146023	5124992	5098655
4510000	5214304	5510963	5137883	5132638	5097097
4410000	5217381	5515054	5133260	5138657	5095766
4310000	5218973	5515986	5132472	5139968	5094371

Table 1--continued

Pressure, P (atm)	Entropy, s (cal/ deg-gm)	Enthalpy, h (cal/gm)	Molecular Weight, M	Moles of Gas, n	Moles of Solid, n_s
		1500°K			
5610117	5128019	5338725	5216015	5110017	4489000
5599999	5128034	5338745	5216004	5110020	4733845
5510000	5131502	5346219	5213628	5110892	4987964
5410000	5136671	5373391	5210060	5112978	5029691
5310000	5144645	5412913	5166544	5117056	5070522
5210000	5152209	5416316	5155201	5119531	5095307
5110000	5158243	5416892	5153655	5119950	5099495
5010000	5163985	5416956	5153494	5119995	5099945
4910000	5169698	5416971	5153476	5120001	5099990
4810000	5175421	5416997	5153467	5120005	5099995
4710000	5181182	5417077	5153446	5120017	5099995
4610000	5187065	5417322	5153378	5120055	5099995
4510000	5193335	5418126	5153166	5120175	5099995
4410000	5210083	5420680	5152505	5120555	5099994
4310000	5211216	5428684	5150529	5121750	5099989
		1000°K			
5610000	5122804	-5326271	5216042	5110000	0000000
5552368	5123605	-5326270	5216042	5110000	4420000
5510000	5125755	-5325399	5215639	5110129	4912898
5410000	5129132	-5320957	5214595	5110495	4949569
5310000	5133685	-5266277	5212194	5111577	5015777
5210000	5141275	5332642	5184294	5114516	5045160
5110000	5151321	5385688	5159500	5118481	5084813
5010000	5158615	5410347	5154161	5119810	5098104
4910000	5164525	5410574	5153546	5119980	5099805
4810000	5170251	5410598	5153483	5119998	5099980
4710000	5175957	5410600	5153477	5119999	5099998
4610000	5181662	5410600	5153476	5119999	5099999
4510000	5187366	5410600	5153476	5120000	5099999
4410000	5193071	5410601	5153476	5120000	5099999
4310000	5198776	5410602	5153476	5120000	5110000
		500°K			
5487419	5119597	-5372491	5216043	5099999	4320000
5399999	5122286	-5372472	5216034	5110002	4727036
5310000	5125155	-5372394	5216012	5110009	4795436
5199999	5128063	-5372144	5215945	5110030	4830493
5110000	5131090	-5371340	5215739	5110096	4896525

Table 1--continued

Pressure, P (atm)	Entropy, s (cal/ deg-gm)	Enthalpy, h (cal/gm)	Molecular Weight, M	Moles of Gas, n	Moles of Solid, n_s
5010000	5134496	-5368828	5215120	5110305	4930514
4910000	5139091	-5360943	5213456	5110960	4996094
4810000	5147165	-5337361	5210128	5112919	5029198
4710000	5161087	5311100	5167150	5116945	5069455
4610000	5172521	5341890	5155308	5119503	5095031
4510000	5179236	5347230	5153667	5119946	5099467
4410000	5185050	5347806	5153495	5119994	5099946
4310000	5190765	5347864	5153478	5119999	5099994

$300^\circ K$

Pressure, P (atm)	Entropy, s (cal/ deg-gm)	Enthalpy, h (cal/gm)	Molecular Weight, M	Moles of Gas, n	Moles of Solid, n_s
5414239	5118777	-5384640	5216043	5110000	0000000
5399999	5119215	-5384640	5216042	5110000	4418000
5310000	5122067	-5384640	5216042	5110000	4518100
5210000	5124919	-5384639	5216042	5110000	4561000
5099999	5127772	-5384638	5216042	5110000	4619410
4999999	5130625	-5384633	5216041	5110000	4661410
4899999	5133483	-5384618	5216036	5110001	4719419
4810000	5136352	-5384572	5216023	5110006	4761408
4710000	5139256	-5384423	5215980	5110019	4819419
4610000	5142275	-5383955	5215848	5110061	4861407
4510000	5145654	-5382473	5215443	5110194	4919415
4410000	5150168	-5377799	5214291	5110612	4961292
4310000	5158159	-5363362	5211614	5111906	5019062

$100^\circ K$

Pressure, P (atm)	Entropy, s (cal/ deg-gm)	Enthalpy, h (cal/gm)	Molecular Weight, M	Moles of Gas, n	Moles of Solid, n_s
5159228*	5120006*	-5394719	5216043	5110000	0000000
5099999	5122262	-5394719	5216043	5110000	0000000
4999999	5125114	-5394719	5216043	5110000	0000000
4899999	5127967	-5394719	5216043	5110000	0000000
4799999	5130819	-5394719	5216043	5110000	0000000
4699999	5133671	-5394719	5216043	5110000	0000000
4599999	5136523	-5394719	5216043	5110000	0000000
4510000	5139375	-5394719	5216043	5110000	0000000
4410000	5142227	-5394719	5216043	5110000	0000000
4310000	5145079	-5394719	5216043	5110000	0000000

Table 2

SUMMARY OF COMPUTED VALUES FOR THE ISENTROPIC EXPANSION OF METHANE
THROUGH A NOZZLE, ASSUMING INSTANTANEOUS CHEMICAL EQUILIBRIUM,
A MASS FLOW RATE OF 1000 GM/SEC, AND AN INITIAL CHAMBER
PRESSURE OF 1000 ATMOSPHERES

Temperature, T ($^{\circ}$K)	Pressure, P (atm)	Specific Impulse, I (sec)	Nozzle Area, A (cm^2)
545000	5399995	5283943	5070481
544900	5385571	5316084	5041990
544800	5372907	5321158	5036576
544700	5361836	5325246	5035265
544600	5352192	5328772	5035750
544500	5343832	5331922	5037392
544400	5336618	5334798	5039988
544300	5330422	5337463	5043513
544200	5325130	5339958	5048034
544100	5320632	5342313	5053696
544000	5316834	5344550	5060707
543900	5313644	5346683	5069361
543800	5310984	5348727	5080041
543700	5287808	5350690	5093260
543600	5269680	5352580	5110968
543500	5246767	5355588	5115767
543400	5229729	5358725	5124136
543300	5218745	5361660	5137201
543200	5211772	5364393	5157440
543100	5173948	5366926	5188408
543000	5146736	5369249	5213476
542900	5129816	5371368	5220276
542800	5119240	5373294	5230061
542700	5112574	5375044	5243873
542600	5083336	5376632	5262983
542500	5056093	5378067	5288829
542400	5038357	5379361	5312309
542300	5026643	5380527	5316767
542200	5018772	5381582	5322485
542100	5013391	5382541	5329745
542000	4996365	5383421	5338949
541900	4969630	5384236	5350704
541800	4950302	5385002	5365882
541700	4936188	5385730	5385745
541600	4925830	5386429	5411213
541500	4918202	5387105	5414802
541400	4912612	5387761	5419788
541300	4885612	5388401	5426874

Table 2--continued

Temperature, T (^{o}K)	Pressure, P (atm)	Specific Impulse, I (sec)	Nozzle Area, A (cm^2)
541200	4856729	5389026	5437173
541100	4836548	5389635	5452528
541000	4822747	5390232	5476208
539000	4813549	5390816	5511437
538000	4776313	5391392	5517922
537000	4739345	5391974	5530125
536000	4715980	5392649	5562118
535000	4628564	5393692	5626794
534000	4494451	5395229	5754508
533000	4220596	5397047	6013986
532000	3731168	5398885	6438655
531000	3477520	5399437	6667660
544500	5399983	5277208	5064962
544400	5384289	5315308	5037902
544300	5370714	5320238	5033307
544200	5359026	5324192	5032514
544100	5349009	5327590	5033418
544000	5340473	5330618	5035466
543900	5333236	5333375	5038509
543800	5327134	5335921	5042560
543700	5322020	5338297	5047734
543600	5316772	5341100	5057754
543500	5310965	5345025	5083368
543400	5271119	5348595	5112218
543300	5245889	5351859	5118071
543200	5229591	5354839	5126788
543100	5219158	5357552	5139556
543000	5212525	5359999	5157780
542900	5182947	5362199	5183197
542800	5155719	5364172	5211789
542700	5137987	5365946	5216434
542600	5126291	5367543	5222533
542500	5118472	5368979	5230388
542400	5113160	5370275	5240362
542300	5094904	5371449	5252897
542200	5069086	5372521	5268584
542100	5050623	5373511	5288218
542000	5037193	5374433	5311298
541900	5027280	5375303	5314467
541800	5019906	5376132	5318579
541700	5014409	5376929	5323990
541600	5010320	5377699	5331212
541500	4972847	5378446	5341061
541400	4950504	5379173	5354766

Table 2--continued

Temperature, T ($^{\circ}$K)	Pressure, P (atm)	Specific Impulse, I (sec)	Nozzle Area, A (cm^2)
541300	4934278	5379882	5374258
541200	4922700	5380573	5410260
541100	4914605	5381248	5414493
541000	4890640	5381909	5421050
539000	4853587	5382561	5431756
538000	4829505	5383218	5450701
537000	4814028	5383930	5491524
536000	4744174	5384859	5523738
535000	4654805	5386193	5614282
534000	4514929	5387875	5734617
533000	4232659	5389741	5987737
532000	3811079	5391516	6411064
531000	3612468	5391944	6545493
544000	5399920	5271499	5059465
543900	5382974	5314563	5034222
543800	5368553	5319313	5030380
543700	5356341	5323102	5030032
543600	5340944	5328063	5034460
543500	5327289	5333202	5045211
543400	5318066	5337601	5061889
543300	5311918	5341462	5086645
543200	5278745	5344882	5112244
543100	5252346	5347921	5117304
543000	5235207	5350610	5124251
542900	5224019	5352989	5133561
542800	5216634	5355098	5145782
542700	5211690	5356977	5161542
542600	5183334	5358661	5181543
542500	5160192	5360174	5210656
542400	5143962	5361541	5213761
542300	5132393	5362787	5217598
542200	5124005	5363934	5222353
542100	5117838	5365002	5228277
542000	5113243	5366008	5235747
541900	5097852	5366964	5245324
541800	5071740	5367880	5257786
541700	5052072	5368764	5274227
541600	5037344	5369621	5296210
541500	5026367	5370453	5312622
541400	5018272	5371262	5316805
541300	5012387	5372050	5322761
541200	4981842	5372820	5331450
541100	4952418	5373573	5344515
541000	4932216	5374316	5365082

Table 2--continued

Temperature, T (°K)	Pressure, P (atm)	Specific Impulse, I (sec)	Nozzle Area, A (cm^2)
539000	4918605	5375063	5410003
538000	4896259	5375853	5416846
537000	4833052	5376785	5434984
536000	4793836	5378002	5511565
535000	4692656	5379543	5585496
534000	4522900	5381321	5722553
533000	4253367	5383216	5953335
532000	3856410	5384872	6322517
531000	3716456	5385218	6437191
543500	5410000	5260697	5065097
543400	5368261	5317738	5033715
543300	5346406	5324272	5037113
543200	5331582	5329261	5045913
543100	5321621	5333352	5059219
543000	5314970	5336791	5077385
542900	5310506	5339729	5110114
542800	5274765	5342271	5113145
542700	5253906	5344499	5116944
542600	5239337	5346475	5121646
542500	5229011	5348239	5127409
542400	5221571	5349830	5134455
542300	5216131	5351281	5143073
542200	5212096	5352620	5153690
542100	5190688	5353871	5166882
542000	5167752	5355051	5183516
541900	5150257	5356176	5210487
541800	5136922	5357256	5213271
541700	5126813	5358297	5216951
541600	5119211	5359306	5221883
541500	5113532	5360284	5228640
541400	5093379	5361236	5238107
541300	5062849	5362165	5251725
541200	5041015	5363078	5271957
541100	5025684	5363983	5310346
541000	5015112	5364903	5315652
539000	4979952	5365878	5325881
538000	4935063	5366974	5350249
537000	4911079	5368266	5412995
536000	4820671	5369787	5453782
535000	4717340	5371509	5545900
534000	4541070	5373369	5712487
533000	4311527	5375270	5924453
532000	3987389	5376674	6215700
531000	3844900	5376981	6315089

Table 2--continued

Temperature, T (°K)	Pressure, P (atm)	Specific Impulse, I (sec)	Nozzle Area, A (cm²)
543000	5410000	5257726	5068564
542900	5372167	5315174	5036231
542800	5352594	5320398	5036742
542700	5338692	5324311	5041314
542600	5328713	5327495	5048220
542500	5321465	5330189	5057217
542400	5316129	5332532	5068480
542300	5312154	5334615	5082407
542200	5291582	5336500	5099674
542100	5268829	5338235	5112123
542000	5251420	5339854	5114855
541900	5238046	5341381	5118387
541800	5227806	5342835	5123028
541700	5220025	5344229	5129228
541600	5214173	5345574	5137664
541500	5198061	5346879	5149488
541400	5165913	5348155	5166627
541300	5142670	5349415	5192558
541200	5126269	5350676	5213406
541100	5115068	5351960	5220599
541000	5077953	5353299	5234537
539000	5034540	5354725	5266136
538000	5012259	5356261	5315360
537000	4931519	5357919	5347418
536000	4850318	5359695	5422417
535000	4739221	5361566	5520264
534000	4598844	5363487	5651341
533000	4346197	5365326	5861177
532000	4149840	5366324	6031591
531000	4030272	5366653	6125849
542500	5410000	5253044	5062705
542400	5375181	5312820	5033758
542300	5356557	5317197	5032523
542200	5342443	5320574	5035017
542100	5331697	5323411	5039638
542000	5323468	5325904	5046321
541900	5317154	5328160	5055544
541800	5312339	5330244	5068184
541700	5287066	5332199	5085662
541600	5260027	5334053	5111027
541500	5240145	5335833	5114615
541400	5225831	5337560	5120064
541300	5215816	5339255	5128774
541200	5190872	5340937	5143620
541100	5147961	5342624	5171138

Table 2--continued

Temperature, T ($^{\circ}$K)	Pressure, P (atm)	Specific Impulse, I (sec)	Nozzle Area, A (cm^2)
541000	5122572	5344338	5212811
539000	5090555	5346096	5226515
538000	5029294	5347904	5266297
537000	4969964	5349767	5321688
536000	4910742	5351681	5410532
535000	4785745	5353627	5492227
534000	4625782	5355550	5619591
533000	4427911	5357216	5810517
532000	4316243	5357912	5911090
531000	4210076	5358285	5988806
542000	5410000	5246066	5050427
541900	5371225	5311699	5026767
541800	5349834	5315904	5026851
541700	5334113	5319234	5030750
541600	5322742	5322099	5037805
541500	5314646	5324675	5049138
541400	5290311	5327059	5067346
541300	5252736	5329308	5097718
541200	5228761	5331463	5115142
541100	5214369	5333554	5125434
541000	5164015	5335605	5147351
539000	5124420	5337640	5210117
538000	5076019	5339660	5225897
537000	5017875	5341674	5285053
536000	4928245	5343677	5339823
535000	4825584	5345640	5430707
534000	4711606	5347461	5544102
533000	4550864	5348750	5664187
532000	4472606	5349289	5729149
531000	4345209	5349725	5823200

Table 3

SUMMARY OF COMPUTED VALUES FOR THE ISENTROPIC EXPANSION OF METHANE
THROUGH A NOZZLE, ASSUMING INSTANTANEOUS CHEMICAL EQUILIBRIUM,
A MASS FLOW RATE OF 1000 GM/SEC, AND AN INITIAL CHAMBER
PRESSURE OF 100 ATMOSPHERES

Temperature, T (°K)	Pressure, P (atm)	Specific Impulse, I (sec)	Nozzle Area, A (cm²)
545000	5299999	5293209	5178062
544900	5283799	5318683	5145241
544800	5269819	5324750	5139876
544700	5257824	5329619	5139113
544600	5247580	5333813	5140461
544500	5238886	5337561	5143271
544400	5231552	5340984	5147417
544300	5225405	5344159	5152985
544200	5220290	5347136	5160205
544100	5216063	5349353	5169452
544000	5212600	5352633	5181255
543900	5197867	5355198	5196375
543800	5175216	5357664	5211585
543700	5157153	5360042	5214118
543600	5142917	5362343	5217444
543500	5131816	5364574	5221859
543400	5123257	5366742	5227734
543300	5115928	5363174	5238351
543200	5092661	5372392	5264825
543100	5053168	5375431	5311050
543000	5030214	5378285	5318901
542900	5017031	5380960	5332376
542800	4995243	5383468	5355547
542700	4952800	5385826	5395563
542600	4928993	5388046	5416508
542500	4915777	5390134	5428631
542400	4885123	5392094	5449878
542300	4845597	5393930	5487224
542200	4824337	5395640	5515269
542100	4813037	5397216	5526593
542000	4770862	5398643	5545614
541900	4739627	5399904	5576038
541800	4723134	5410008	5612145
541700	4714222	5410190	5618426
541600	4691792	5410266	5626613
541500	4661208	5410333	5637136
541400	4641334	5410392	5651008
541300	4627777	5410447	5670094

Table 3--continued

Temperature, T (^{O}K)	Pressure, P (atm)	Specific Impulse, I (sec)	Nozzle Area, A (cm^2)
541200	4618350	5410501	5697439
541100	4611817	5410552	5713801
541000	4573613	5410603	5720045
539000	4543958	5410653	5730071
538000	4524961	5410701	5746859
537000	4513322	5410748	5776484
536000	4465488	5410775	5813278
535000	4428633	5410840	5825179
534000	4369755	5410901	5880033
533000	4140943	5411058	6082411
532000	3621043	5411269	6567249
544500	5299998	5282939	5169729
544400	5282060	5317369	5139421
544300	5266879	5323146	5135239
544200	5254112	5327766	5135223
544100	5243445	5331738	5137205
544000	5234602	5335282	5140702
543900	5227322	5338515	5145699
543800	5221380	5341510	5152393
543700	5216571	5344314	5161173
543600	5212714	5346961	5172612
543500	5196527	5349474	5187533
543400	5166647	5352546	5211845
543300	5140313	5356324	5218796
543200	5124099	5359819	5230204
543100	5114283	5363054	5248901
543000	5084347	5366033	5279250
542900	5049752	5368775	5312813
542800	5029352	5371298	5320640
542700	5017335	5373623	5333098
542600	5010261	5375767	5352792
542500	4961033	5377737	5383569
542400	4936570	5379539	5413103
542300	4922153	5381178	5420291
542200	4913627	5382656	5430917
542100	4885567	5383978	5446130
542000	4855073	5385146	5467139
541900	4836380	5386171	5495189
541800	4824616	5387074	5513167
541700	4816963	5387879	5517862
541600	4811807	5388613	5523939
541500	4782126	5389277	5532009
541400	4756574	5389948	5543049
541300	4738317	5390576	5558609

Table 3--continued

Temperature, T ($^{\circ}$K)	Pressure, P (atm)	Specific Impulse, I (sec)	Nozzle Area, A (cm^2)
541200	4725377	5391186	5581138
541100	4716353	5391781	5611466
541000	4710187	5392363	5616628
539000	4660830	5392931	5624910
538000	4634530	5393487	5638773
537000	4618401	5394029	5663288
536000	4589471	5394564	5711082
535000	4534111	5395160	5723815
534000	4429672	5396325	5819747
533000	4184098	5398231	6040017
532000	3653606	5410038	6525950
544000	5310000	5274344	5162759
543900	5280377	5316205	5134730
543800	5264123	5321691	5131509
543700	5250755	5326054	5132080
543600	5239848	5329789	5134563
543500	5228610	5334101	5141776
543400	5217971	5339215	5159583
543300	5211174	5343685	5187956
543200	5169025	5347656	5213240
543100	5142532	5351215	5220124
543000	5126290	5354402	5230591
542900	5116355	5357259	5246261
542800	5110260	5359824	5269379
542700	5065016	5362134	5310297
542600	5041679	5364215	5315098
542500	5027095	5366084	5321816
542400	5017888	5367758	5331025
542300	5012009	5369254	5343378
542200	4982002	5370592	5359618
542100	4956924	5371790	5380576
542000	4940072	5372869	5410733
541900	4928482	5373849	5414147
541800	4920344	5374752	5418529
541700	4914532	5375597	5424218
541600	4910331	5376399	5431722
541500	4872653	5377167	5441864
541400	4850298	5377909	5455900
541300	4834131	5378629	5475791
541200	4822617	5379331	5510464
541100	4814574	5380014	5514757
541000	4790765	5380681	5521363
539000	4754146	5381332	5531969
538000	4730646	5381969	5549800

Table 3--continued

Temperature, T (°K)	Pressure, P (atm)	Specific Impulse, I (sec)	Nozzle Area, A (cm²)
537000	4716123	5332600	5582080
536000	4672382	5383271	5615428
535000	4617078	5394259	5651443
534000	4469011	5385908	5786616
533000	4215577	5387973	6021499
532000	3716459	5390119	6484046
543500	5310000	5262814	5165520
543400	5264722	5319392	5133645
543300	5241662	5326579	5138843
543200	5226793	5332047	5150641
543100	5217294	5336532	5169057
543000	5211269	5340312	5195628
542900	5174362	5343549	5213261
542800	5149764	5346353	5218284
542700	5133796	5348805	5224973
542600	5123300	5350966	5233711
542500	5116310	5352876	5244915
542400	5111580	5354573	5259087
542300	5083255	5356091	5276827
542200	5060450	5357462	5298942
542100	5044203	5358714	5312650
542000	5032426	5359872	5316113
541900	5023757	5360954	5320525
541800	5017323	5361978	5326228
541700	5012534	5362955	5333704
541600	4989750	5363894	5343648
541500	4963343	5364801	5357166
541400	4943915	5365680	5375928
541300	4929807	5366532	5410253
541200	4919741	5367361	5414113
541100	4912704	5368166	5419861
541000	4878884	5368952	5428737
539000	4846696	5369723	5443165
538000	4825807	5370495	5468474
537000	4812420	5371321	5512186
536000	4740287	5372387	5530645
535000	4651578	5373929	5617813
534000	4514259	5375885	5742310
533000	4231091	5378051	6010688
532000	3795510	5380112	6414741
531000	3594227	5380617	6568659
543100	5299999	5260391	5170962
542900	5269708	5316329	5137258
542800	5249297	5321903	5138619

Table 3--continued

Temperature, T (°K)	Pressure, P (atm)	Specific Impulse, I (sec)	Nozzle Area, A (cm²)
542700	5235342	5326020	5144339
542600	5225659	5329329	5152726
542500	5218841	5332095	5163581
542400	5213957	5334472	5177126
542300	5210407	5336562	5193811
542200	5177854	5338434	5211439
542100	5158271	5340141	5213988
542000	5143485	5341720	5217193
541900	5132237	5343198	5221289
541800	5123680	5344595	5226603
541700	5117200	5345925	5233589
541600	5112332	5347197	5242897
541500	5086968	5348419	5255574
541400	5060126	5349594	5273211
541300	5040594	5350730	5298357
541200	5026631	5351833	5313526
541100	5016833	5352912	5319168
541000	5010077	5353989	5328392
539000	4955043	5355106	5345381
538000	4925422	5356342	5383632
537000	4885653	5357806	5420275
536000	4816893	5359565	5479134
535000	4714647	5361585	5564963
534000	4534817	5363776	5717478
533000	4291603	5366018	5936162
532000	3939101	5367750	6239876
531000	3818261	5368111	6341931
542500	5310000	5256412	5167066
542400	5274908	5313507	5136160
542300	5256337	5318028	5134700
542200	5242413	5321472	5137147
542100	5231879	5324334	5141725
542000	5223842	5326821	5148272
541900	5217680	5329048	5157140
541800	5212967	5331082	5168989
541700	5193865	5332967	5184840
541600	5166912	5334733	5210623
541500	5146765	5336402	5213577
541400	5131890	5337992	5217764
541300	5121076	5339524	5223906
541200	5113363	5341020	5233342
541100	5079888	5342510	5248873
541000	5043658	5344038	5277278
539000	5026675	5345660	5313807
538000	4978677	5347425	5329808

Table 3--continued

Temperature, T (°K)	Pressure, P (atm)	Specific Impulse, I (sec)	Nozzle Area, A (cm^2)
537000	4921509	5349362	5386082
536000	4835847	5351466	5438699
535000	4728344	5353699	5534178
534000	4568619	5356000	5689193
533000	4325075	5358240	5913322
532000	4110089	5359611	6117386
531000	3959400	5359982	6214638
542000	5310000	5250967	5158381
541900	5273707	5312227	5131409
541800	5253582	5316493	5130353
541700	5238311	5319850	5133281
541600	5226855	5322717	5138959
541500	5218341	5325273	5147887
541400	5212115	5327621	5161545
541300	5176635	5329828	5182930
541200	5145772	5331950	5211814
541100	5125272	5334032	5218078
541000	5112494	5336118	5230509
539000	5052691	5338248	5259226
538000	5017833	5340437	5313965
537000	4944079	5342695	5343567
536000	4868670	5345018	5420576
535000	4753570	5347381	5518184
534000	4614294	5349730	5642783
533000	4389727	5351874	5837965
532000	4221485	5352896	5991832
531000	4113223	5353305	6073991

Table 4

SUMMARY OF COMPUTED VALUES FOR THE ISENTROPIC EXPANSION OF METHANE
THROUGH A NOZZLE, ASSUMING INSTANTANEOUS CHEMICAL EQUILIBRIUM,
A MASS FLOW RATE OF 1000 GM/SEC, AND AN INITIAL CHAMBER
PRESSURE OF 10 ATMOSPHERES

Temperature, T (^{O}K)	Pressure, P (atm)	Specific Impulse, I (sec)	Nozzle Area, A (cm^2)
545000	5199999	5310898	5291321
544900	5182448	5322582	5251924
544800	5167492	5330064	5246248
544700	5154847	5336058	5246030
544600	5144226	5341216	5248410
544500	5135379	5345818	5252730
544400	5128068	5350016	5258932
544300	5122073	5353903	5267245
544200	5117200	5357541	5278114
544100	5113273	5360974	5292223
544000	5110137	5364234	5311054
543900	5076571	5367349	5313450
543800	5057143	5370338	5316609
543700	5042086	5373220	5320827
543600	5030551	5376009	5326537
543500	5021830	5378718	5334387
543400	5015326	5381359	5345381
543300	5010552	5383940	5361084
543200	4971103	5386472	5384013
543100	4946779	5388959	5411830
543000	4929465	5391498	5417515
542900	4915555	5394746	5432820
542800	4880719	5397825	5461851
542700	4841011	5410075	5511778
542600	4820297	5410356	5522797
542500	4797405	5410626	5545078
542400	4745029	5410886	5591738
542300	4719892	5411139	5619389
542200	4683252	5411385	5642977
542100	4632714	5411626	5710089
542000	4611962	5411862	5725332
541900	4540375	5412093	5768631
541800	4512510	5412318	5820184
541700	4435604	5412535	5864438
541600	4394350	5412742	5922043
541500	4324233	5412932	5977703
541400	4266099	5413095	6025810
541300	4222253	5413218	6069691

Table 4--continued

Temperature, T (°K)	Pressure, P (atm)	Specific Impulse, I (sec)	Nozzle Area, A (cm²)
541200	4210247	5413297	6113806
541100	4158764	5413349	6121947
541000	4135753	5413391	6132680
539000	4121285	5413431	6149258
538000	4112084	5413469	6176902
537000	4064503	5413507	6212571
536000	4031735	5413543	6221842
535000	4014058	5413579	6240981
534000	3953696	5413613	6285618
533000	3915957	5413647	6321524
544500	5199999	5293957	5279227
544400	5180030	5320628	5243673
544300	5163509	5327649	5239737
544200	5149946	5333243	5240636
544100	5138900	5338048	5244041
544000	5129986	5342333	5249561
543900	5122857	5346246	5257389
543800	5117213	5349875	5268057
543700	5112794	5353282	5282465
543600	5093745	5356507	5310198
543500	5067644	5359582	5312865
543400	5047997	5362529	5316560
543300	5033442	5365368	5321764
543200	5022846	5368113	5329226
543100	5014130	5371272	5344575
543000	4977193	5374913	5379485
542900	4941569	5378314	5414274
542800	4922035	5381504	5425849
542700	4911465	5384512	5447343
542600	4858353	5387364	5488040
542500	4828963	5390075	5516675
542400	4813961	5392661	5532326
542300	4765034	5395137	5564503
542200	4729144	5397515	5613319
542100	4712526	5399799	5628573
542000	4651617	5410198	5663758
541900	4620484	5410405	5714742
541800	4579411	5410599	5734856
541700	4530967	5410774	5781929
541600	4512760	5410924	5818245
541500	4458940	5411044	5836329
541400	4431538	5411133	5862565
541300	4418996	5411199	5895691
541200	4412077	5411253	5913816

Table 4--continued

Temperature, T (^{o}K)	Pressure, P (atm)	Specific Impulse, I (sec)	Nozzle Area, A (cm^2)
541100	4377007	5411303	5919773
541000	4347877	5411350	5928791
539000	4328583	5411397	5943227
538000	4316231	5411442	5967398
537000	4286640	5411486	6011005
536000	4242626	5411529	6019101
535000	4218881	5411571	6035807
534000	4171761	5411611	6075087
533000	4068885	5411683	6155196
544000	5199999	5282361	5266878
543900	5177395	5318826	5236507
543800	5159254	5325354	5234162
543700	5144840	5330545	5236117
543600	5133511	5335002	5240605
543500	5124716	5338974	5247552
543400	5117973	5342598	5257477
543300	5112872	5345955	5271374
543200	5074891	5350748	5311436
543100	5042695	5355116	5318867
543000	5024078	5359077	5331545
542900	5013451	5362691	5353218
542800	4974429	5366009	5390469
542700	4940743	5369076	5415501
542600	4922035	5371928	5426801
542500	4911774	5374583	5446752
542400	4862128	5377058	5482349
542300	4832387	5379367	5514647
542200	4816721	5381513	5526264
542100	4786037	5383494	5547215
542000	4744581	5385295	5584277
541900	4723627	5386895	5614718
541800	4713054	5388273	5624688
541700	4676394	5389424	5639150
541600	4647527	5390372	5658436
541500	4630994	5391163	5683151
541400	4620701	5391854	5711524
541300	4613850	5392488	5715880
541200	4591366	5393092	5722075
541100	4558818	5393676	5731237
541000	4536636	5394246	5745316
539000	4521877	5394803	5767897
538000	4512423	5395348	5810567
537000	4466308	5395879	5817227
536000	4432608	5396395	5829865

Table 4--continued

Temperature, T (^{o}K)	Pressure, P (atm)	Specific Impulse, I (sec)	Nozzle Area, A (cm^2)
535000	4414350	5396897	5856233
534000	4341571	5397503	5915180
533000	4133537	5399170	6111549
543500	5199999	5265988	5263228
543400	5168632	5319010	5231808
543300	5141546	5327773	5236996
543200	5124860	5334290	5251079
543100	5114751	5339646	5275296
543000	5087223	5344214	5311441
542900	5051530	5348195	5317646
542800	5030457	5351715	5327409
542700	5018027	5354859	5342689
542600	5010697	5357688	5366469
542500	4963810	5360235	5410309
542400	4938361	5362526	5415881
542300	4923324	5364581	5424213
542200	4914404	5366414	5436386
542100	4890824	5368036	5453626
542000	4858687	5369459	5477215
541900	4838901	5370702	5510848
541800	4826392	5371792	5514894
541700	4818221	5372762	5520083
541600	4812696	5373643	5526786
541500	4788367	5374463	5535674
541400	4760890	5375242	5547815
541300	4741245	5375991	5564898
541200	4727317	5376718	5589591
541100	4717603	5377424	5612627
541000	4710966	5378113	5618265
539000	4665479	5378784	5627296
538000	4637168	5379439	5642391
537000	4619804	5380077	5669048
536000	4596210	5380704	5712075
535000	4536339	5381408	5726111
534000	4430636	5382784	5822192
533000	4185808	5384993	6045162
532000	3655312	5387460	6528754
543000	5210000	5260841	5271440
542900	5165710	5317654	5237040
542800	5143780	5323810	5240485
542700	5129596	5328343	5249132
542600	5120311	5331966	5261688
542500	5114155	5334969	5278289

Table 4--continued

Temperature, T (°K)	Pressure, P (atm)	Specific Impulse, I (sec)	Nozzle Area, A (cm²)
542400	5110008	5337516	5299482
542300	5071693	5339717	5312603
542200	5051892	5341650	5315905
542100	5037849	5343375	5320001
542000	5027712	5344939	5325121
541900	5020275	5346378	5331610
541800	5014771	5347719	5339952
541700	5010681	5348983	5350831
541600	4976463	5350187	5365229
541500	4953958	5351337	5384714
541400	4937407	5352441	5411164
541300	4925391	5353505	5414968
541200	4916819	5354531	5420464
541100	4910826	5355523	5428617
541000	4867253	5356484	5441153
539000	4839862	5357421	5461417
538000	4822114	5358349	5496610
537000	4810779	5359329	5516912
536000	4736147	5360573	5541008
535000	4648054	5362381	5622832
534000	4513527	5364689	5752798
533000	4229411	5367233	6013247
532000	3781064	5369650	6420106
531000	3568341	5370253	6610863
542500	5199999	5257064	5267538
542400	5173567	5313959	5236210
542300	5154538	5318613	5235223
542200	5140615	5322119	5238155
542100	5130295	5325003	5243255
542000	5122554	5327488	5250374
541900	5116694	5329696	5259871
541800	5112253	5331700	5272407
541700	5088988	5333548	5288980
541600	5063825	5335270	5311105
541500	5045052	5336885	5314102
541400	5031198	5338410	5318247
541300	5021123	5339858	5324107
541200	5013924	5341239	5332601
541100	4988806	5342565	5345337
541000	4954103	5343857	5365484
539000	4930635	5345152	5410050
538000	4915158	5346533	5417272
537000	4656589	5348158	5437830
536000	4812337	5350172	5513327
535000	4711398	5352555	5610192

Table 4--continued

Temperature, T (°K)	Pressure, P (atm)	Specific Impulse, I (sec)	Nozzle Area, A (cm²)
534000	4527531	5355168	5726711
533000	4267173	5357847	5958834
532000	3912832	5360036	6313840
531000	3748342	5360480	6417838
542000	5199999	5251867	5259953
541900	5174197	5312317	5232341
541800	5154503	5316555	5231040
541700	5139559	5319861	5233664
541600	5128316	5322655	5238791
541500	5119914	5325112	5246621
541400	5113708	5327328	5258024
541300	5091904	5329367	5274657
541200	5059590	5331275	5299511
541100	5036906	5333098	5313847
541000	5021302	5334896	5320499
539000	5010913	5336753	5333615
538000	4945703	5338769	5365561
537000	4913724	5341025	5417104
536000	4824564	5343530	5470822
535000	4720129	5346219	5559567
534000	4547751	5348999	5715637
533000	4314338	5351726	5927850
532000	4018200	5353599	6210755
531000	3899220	5354025	6297297

Table 5

SUMMARY OF COMPUTED VALUES FOR THE ISENTROPIC EXPANSION OF METHANE
THROUGH A NOZZLE, ASSUMING INSTANTANEOUS CHEMICAL EQUILIBRIUM,
A MASS FLOW RATE OF 1000 GM/SEC, AND AN INITIAL CHAMBER
PRESSURE OF 1 ATMOSPHERE

Temperature, T ($^{\circ}$K)	Pressure, P (atm)	Specific Impulse, I (sec)	Nozzle Area, A (cm^2)
545000	5099999	5312298	5410146
544900	5086224	5322984	5361301
544800	5073286	5330507	5352846
544700	5061377	5336844	5350755
544600	5050629	5342510	5351747
544500	5041130	5347728	5354991
544400	5032901	5352611	5360380
544300	5025913	5357229	5368163
544200	5020093	5361623	5378870
544100	5015337	5365823	5393351
544000	5011526	5369849	5411284
543900	4985281	5373716	5413917
543800	4962122	5377434	5417496
543700	4944561	5381009	5422405
543600	4931486	5384446	5429198
543500	4921926	5387747	5438692
543400	4915055	5390916	5452092
543300	4910196	5393954	5471204
543200	4868122	5396866	5498772
543100	4844857	5399663	5513910
543000	4829037	5410236	5519931
542900	4818394	5410499	5529167
542800	4811105	5410768	5545082
542700	4755885	5411106	5588420
542600	4727828	5411424	5617282
542500	4713550	5411726	5634083
542400	4663576	5412018	5668905
542300	4628304	5412304	5714522
542200	4611779	5412588	5732434
542100	4545156	5412870	5778002
542000	4515700	5413151	5820536
541900	4448702	5413432	5860232
541800	4413233	5413713	5920056
541700	4330859	5413993	5977413
541600	4260361	5414272	6035440
541500	4196547	5414548	6119738
541400	4112312	5414820	6213714
541300	4012301	5415086	6312096

Table 5--continued

Temperature, T (^{o}K)	Pressure, P (atm)	Specific Impulse, I (sec)	Nozzle Area, A (cm^2)
541200	3897886	5415338	6413331
541100	3771133	5415564	6516047
541000	3677762	5415730	6612901
539000	3624462	5415806	6636448
538000	3612956	5415842	6660981
544500	5110000	5310830	5391863
544400	5078836	5324458	5349924
544300	5061471	5332936	5345961
544200	5047398	5339701	5347761
544100	5036134	5345510	5352740
544000	5027234	5350684	5360577
543900	5020287	5355391	5371670
543800	5014935	5359734	5386867
543700	5010863	5363782	5410752
543600	4978023	5367583	5413566
543500	4955305	5371174	5417430
543400	4938639	5374587	5422802
543300	4926562	5377853	5430396
543200	4917923	5380996	5441350
543100	4911834	5384043	5457539
543000	4876161	5387015	5482166
542900	4847572	5389932	5512085
542800	4825281	5393519	5522024
542700	4812756	5397082	5542406
542600	4762858	5410045	5582651
542500	4730032	5410368	5616431
542400	4713781	5410679	5633664
542300	4660072	5410981	5671958
542200	4624580	5411276	5716256
542100	4593233	5411567	5739352
542000	4532338	5411853	5810356
541900	4510107	5412136	5830090
541800	4428022	5412416	5898107
541700	4367796	5412692	5936496
541600	4314086	5412964	6015743
541500	4224813	5413229	6079770
541400	4137038	5413485	6147515
541300	4048556	5413724	6232130
541200	3964166	5413933	6321545
541100	3912160	5414084	6410127
541000	3845895	5414163	6424096
539000	3825155	5414207	6439404
538000	3814187	5414244	6461941
537000	3775709	5414279	6510131

Table 5--continued

Temperature, T (°K)	Pressure, P (atm)	Specific Impulse, I (sec)	Nozzle Area, A (cm²)
536000	3737247	5414314	6517607
535000	3716500	5414348	6533045
534000	3663026	5414380	6569054
533000	3619311	5414411	6616866
544000	5110000	5294817	5376051
543900	5075521	5322373	5341120
543800	5056353	5330214	5339273
543700	5041501	5336433	5342517
543600	5030124	5341766	5349060
543500	5021524	5346523	5359111
543400	5015110	5350871	5373738
543300	5010403	5354913	5394873
543200	4970093	5358716	5412571
543100	4946110	5362327	5417158
543000	4929118	5365888	5424621
542900	4915369	5370337	5444769
542800	4879739	5374438	5482338
542700	4840505	5378258	5515365
542600	4820043	5381848	5529237
542500	4796162	5385242	5556975
542400	4744440	5388474	5611449
542300	4719624	5391572	5623933
542200	4682086	5394560	5652536
542100	4632232	5397455	5712228
542000	4611774	5410026	5730479
541900	4539688	5410299	5782061
541800	4512273	5410563	5824013
541700	4434836	5410816	5876389
541600	4391939	5411056	5926089
541500	4323467	5411275	5992079
541400	4263418	5411463	6030743
541300	4221103	5411605	6083717
541200	4196301	5411697	6116703
541100	4155021	5411756	6126617
541000	4133449	5411804	6139628
539000	4119911	5411849	6159685
538000	4111304	5411892	6193107
537000	4060340	5411935	6215208
536000	4029686	5411976	6226404
535000	4013150	5412017	6249504
534000	3950230	5412055	6310335
543500	5099998	5275080	5366276
543400	5071402	5319889	5333606

Table 5--continued

Temperature, T (°K)	Pressure, P (atm)	Specific Impulse, I (sec)	Nozzle Area, A (cm²)
543300	5050106	5327156	5333595
543200	5034508	5332894	5338521
543100	5019669	5339739	5357221
543000	5010835	5345665	5392138
542900	4958902	5350797	5415347
542800	4931562	5355351	5426179
542700	4916632	5359465	5445584
542600	4885943	5363235	5481025
542500	4843448	5366716	5514707
542400	4821421	5369954	5527331
542300	4810265	5372986	5552169
542200	4747690	5375835	5610256
542100	4721475	5378512	5620780
542000	4694065	5381017	5643264
541900	4640482	5383329	5691697
541800	4617475	5385418	5719398
541700	4578282	5387234	5739628
541600	4537989	5388728	5774956
541500	4520585	5389888	5812735
541400	4512365	5390775	5819543
541300	4478984	5391492	5828159
541200	4451296	5392125	5839736
541100	4432889	5392721	5856440
541000	4420470	5393298	5881928
539000	4412222	5393861	5912274
538000	4369407	5394411	5919102
537000	4337047	5394947	5931137
536000	4318226	5395468	5953951
535000	4280714	5395971	6010099
534000	4230191	5396464	6021462
533000	4112965	5397599	6133698
532000	3582514	5410016	6622745
543000	5110000	5260967	5372283
542900	5059458	5319959	5336862
542800	5035408	5327258	5344634
542700	5021142	5332721	5360881
542600	5012674	5337167	5386865
542500	4976493	5340909	5412632
542400	4946599	5344118	5418487
542300	4928752	5346893	5426998
542200	4918038	5349301	5439080
542100	4911556	5351387	5455731
542000	4875812	5353191	5477989
541900	4850909	5354752	5510698

Table 5--continued

Temperature, T (°K)	Pressure, P (atm)	Specific Impulse, I (sec)	Nozzle Area, A (cm²)
541800	4834886	5356116	5514411
541700	4824251	5357328	5519149
541600	4816967	5358431	5525261
541500	4811834	5359455	5533361
541400	4781626	5360425	5544414
541300	4755312	5361354	5559938
541200	4736638	5362252	5582320
541100	4723611	5363120	5611548
541000	4714708	5363963	5616630
539000	4687820	5364781	5624751
538000	4649843	5365575	5638293
537000	4626541	5366348	5662177
536000	4612839	5367108	5710876
535000	4546503	5367987	5724347
534000	4434694	5369701	5823011
533000	4192998	5372307	6048264
532000	3662894	5375155	6528982
542500	5099999	5257355	5367652
542400	5069919	5314961	5335745
542300	5049578	5319981	5336255
542200	5035575	5323683	5340823
542100	5025764	5326665	5347816
542000	5018761	5329183	5357155
541900	5013674	5331379	5369288
541800	4999359	5333345	5385008
541700	4971737	5335140	5410551
541600	4951307	5336802	5413257
541500	4936191	5338358	5416904
541400	4925087	5339825	5421922
541300	4917029	5341215	5428975
541200	4911282	5342539	5439112
541100	4872656	5343801	5454063
541000	4845177	5345011	5476900
539000	4826842	5346176	5511348
538000	4815001	5347313	5517587
537000	4775061	5348476	5529836
536000	4727225	5349890	5566793
535000	4640047	5351983	5633479
534000	4511863	5354730	5772770
533000	4225701	5357762	6018079
532000	3755374	5360651	6434374
531000	3530708	5361413	6627655
542000	5099999	5251997	5360115
541900	5073794	5312436	5332368

Table 5--continued

Temperature, T (°K)	Pressure, P (atm)	Specific Impulse, I (sec)	Nozzle Area, A (cm²)
541800	5054060	5316690	5331194
541700	5039223	5319988	5333907
541600	5028125	5322764	5339078
541500	5019858	5325193	5346879
541400	5013765	5327374	5358089
541300	4993353	5329364	5374131
541200	4961728	5331201	5397360
541100	4939596	5332915	5413180
541000	4924414	5334534	5418499
539000	4914206	5336094	5427296
538000	4874901	5337669	5443762
537000	4831668	5339437	5484642
536000	4780515	5341683	5525540
535000	4682867	5344478	5617370
534000	4520811	5347606	5743154
533000	4247569	5350820	5999804
532000	3837778	5353585	6353636
531000	3693131	5354163	6510339

Table 6

SUMMARY OF COMPUTED VALUES FOR THE ISENTROPIC EXPANSION OF METHANE
THROUGH A NOZZLE, ASSUMING INSTANTANEOUS CHEMICAL EQUILIBRIUM,
A MASS FLOW RATE OF 1000 GM/SEC, AND AN INITIAL CHAMBER
PRESSURE OF 0.1 ATMOSPHERE

Temperature, T (^{o}K)	Pressure, P (atm)	Specific Impulse, I (sec)	Nozzle Area, A (cm^2)
545000	4999998	5313113	5499074
544900	4993815	5318479	5473374
544800	4987535	5322837	5462260
544700	4981088	5326761	5456074
544600	4974378	5330508	5452376
544500	4967329	5334237	5450296
544400	4959903	5338059	5449541
544300	4952150	5342042	5450105
544200	4944242	5346209	5452168
544100	4936466	5350541	5456071
544000	4929158	5354992	5462329
543900	4922606	5359502	5471717
543800	4917002	5364014	5485394
543700	4912414	5368484	5510513
543600	4888093	5372876	5513369
543500	4860805	5377167	5517535
543400	4840865	5381337	5523694
543300	4826771	5385374	5532934
543200	4817122	5389263	5547005
543100	4810714	5392991	5568728
543000	4765800	5396543	5610261
542900	4739825	5399901	5615579
542800	4723870	5410305	5623932
542700	4713480	5410627	5639626
542600	4663382	5411020	5682635
542500	4631298	5411358	5716206
542400	4615804	5411659	5730688
542300	4577793	5411946	5758872
542200	4535776	5412235	5811945
542100	4514937	5412531	5826418
542000	4455496	5412835	5865067
541900	4418028	5413146	5918185
541800	4350281	5413462	5958801
541700	4311785	5413781	6022483
541600	4222627	5414103	6110433
541500	4134469	5414425	6160657
541400	4040095	5414746	6245892
541300	3934034	5415064	6347260

Table 6--continued

Temperature, T ($^\circ$K)	Pressure, P (atm)	Specific Impulse, I (sec)	Nozzle Area, A (cm^2)
541200	3820088	5415377	6469485
541100	3679747	5415680	6615077
541000	3522605	5415963	6745536
539000	3376161	5416189	6911582
544500	4999998	5311838	5497271
544400	4986832	5321713	5459414
544300	4973631	5329114	5450747
544200	4960840	5335636	5448640
544100	4948928	5341676	5450045
544000	4938291	5347381	5454335
543900	4929165	5352816	5461715
543800	4921634	5358011	5472932
543700	4915638	5362985	5489333
543600	4911022	5367750	5511309
543500	4875821	5372315	5514764
543400	4850938	5376684	5519837
543300	4833460	5380860	5527375
543200	4821526	5384842	5538716
543100	4813592	5388623	5555966
543000	4784500	5392197	5582407
542900	4751906	5395556	5612312
542800	4731590	5398701	5618606
542700	4717433	5410215	5631818
542600	4684449	5410602	5664144
542500	4642158	5410942	5712390
542400	4621044	5411255	5723633
542300	4610105	5411558	5746289
542200	4545224	5411861	5796202
542100	4518431	5412169	5821739
542000	4467165	5412482	5854478
541900	4421507	5412799	5915423
541800	4359393	5413120	5950313
541700	4313842	5413443	6019332
541600	4226534	5413766	6089807
541500	4140545	5414089	6152035
541400	4047583	5414409	6239018
541300	3941103	5414726	6339492
541200	3825060	5415037	6456241
541100	3710601	5415336	6611464
544000	5010000	5310724	5485777
543900	4974021	5326002	5446028
543800	4953895	5335297	5444796
543700	4938603	5342684	5449695

Table 6--continued

Temperature, T (°K)	Pressure, P (atm)	Specific Impulse, I (sec)	Nozzle Area, A (cm²)
543600	4927211	5349007	5458939
543500	4918886	5354611	5473062
543400	4912916	5359679	5493629
543300	4887088	5364316	5512326
543200	4857930	5368593	5516600
543100	4838011	5372569	5522818
543000	4824561	5376294	5532004
542900	4815568	5379823	5545896
542800	4796100	5383221	5567702
542700	4748230	5387627	5613065
542600	4724054	5391658	5625107
542500	4711768	5395419	5648641
542400	4655565	5399004	5696602
542300	4624898	5410248	5720019
542200	4610422	5410589	5744027
542100	4540138	5410925	5810445
542000	4514000	5411259	5827186
541900	4443492	5411591	5878993
541800	4411812	5411919	5926120
541700	4327473	5412246	6010038
541600	4253436	5412569	6045911
541500	4184636	5412888	6125662
541400	4110617	5413200	6218018
541300	4010314	5413505	6316252
541200	3877918	5413795	6418759
541100	3750866	5414059	6524985
541000	3644675	5414261	6624836
539000	3611566	5414359	6684887
543500	4999998	5286047	5475065
543400	4970071	5323207	5438036
543300	4948202	5331721	5438680
543200	4932467	5338445	5445231
543100	4921355	5344217	5456976
543000	4913670	5349384	5475798
542900	4880698	5354600	5511301
542800	4841560	5360275	5520240
542700	4820983	5365361	5537084
542600	4810322	5370012	5569659
542500	4749180	5374321	5613460
542400	4722516	5378363	5626943
542300	4698101	5382198	5656406
542200	4640250	5385868	5712484
542100	4615377	5389405	5729555

Table 6--continued

Temperature, T (°K)	Pressure, P (atm)	Specific Impulse, I (sec)	Nozzle Area, A (cm²)
542000	4554046	5392830	5775785
541900	4517255	5396155	5821325
541800	4449412	5399386	5866713
541700	4412547	5410252	5923471
541600	4328044	5410554	5993583
541500	4255340	5410843	6042168
541400	4199443	5411111	6120839
541300	4117959	5411346	6210256
541200	4040934	5411525	6240206
541100	4015189	5411633	6297622
541000	3981767	5411693	6316368
539000	3947844	5411740	6325070
538000	3927126	5411784	6339157
537000	3914478	5411827	6363959
536000	3871234	5411869	6411103
535000	3831555	5411909	6420816
534000	3812053	5411948	6443456
533000	3736906	5411985	6510611
543000	5010000	5263135	5472345
542900	4954233	5323256	5436505
542800	4928982	5332099	5449328
542700	4915224	5338846	5476536
542600	4878364	5344474	5512689
542500	4839433	5349366	5522000
542400	4819331	5353727	5539618
542300	4791977	5357684	5574014
542200	4742344	5361314	5614351
542100	4718846	5364665	5628872
542000	4681298	5367757	5660087
541900	4634292	5370585	5712822
541800	4614420	5373125	5727534
541700	4562523	5375330	5757573
541600	4529257	5377146	5811208
541500	4515342	5378550	5819566
541400	4490181	5379607	5830564
541300	4457008	5380443	5844376
541200	4436889	5381169	5862713
541100	4423630	5381846	5888993
541000	4414704	5382499	5912898
539000	4387798	5383135	5919292
538000	4349857	5383755	5929976
537000	4326612	5384359	5948787
536000	4313092	5384945	5984411
535000	4257986	5385510	6015777
534000	4221815	5386060	6033305

Table 6--continued

Temperature, T (^{O}K)	Pressure, P (atm)	Specific Impulse, I (sec)	Nozzle Area, A (cm^2)
533000	4111373	5387256	6143405
532000	3576516	5390128	6627649
542500	5010000	5256992	5469143
542400	4962083	5317130	5435635
542300	4939103	5323113	5440177
542200	4925067	5327464	5450382
542100	4916407	5330882	5465224
542000	4910976	5333663	5485026
541900	4874930	5335980	5511054
541800	4851987	5337957	5514292
541700	4836440	5339686	5518405
541600	4825622	5341241	5523699
541500	4817917	5342669	5530703
541400	4812372	5344006	5540234
541300	4783877	5345273	5553565
541200	4755568	5346482	5572693
541100	4735810	5347638	5610086
541000	4722307	5348749	5614387
539000	4713318	5349818	5621223
538000	4675566	5350847	5632572
537000	4640189	5351842	5652543
536000	4619280	5352822	5691944
535000	4564902	5354009	5721826
534000	4441070	5356268	5823675
533000	4210433	5359455	6051214
532000	3676290	5362823	6527969
542000	5010000	5252080	5460118
541900	4972297	5312791	5432159
541800	4952249	5317119	5431492
541700	4937597	5320427	5434636
541600	4926839	5323186	5440229
541500	4918915	5325589	5448488
541400	4913106	5327741	5460241
541300	4888965	5329703	5476965
541200	4858951	5331514	5510105
541100	4837979	5333197	5513648
541000	4823637	5334775	5519029
539000	4814077	5336264	5527566
538000	4779265	5337684	5541843
537000	4740815	5339078	5568338
536000	4716487	5340648	5613714
535000	4629135	5342986	5657169
534000	4495672	5346244	5811059
533000	4220846	5349875	6026829

Table 6--continued

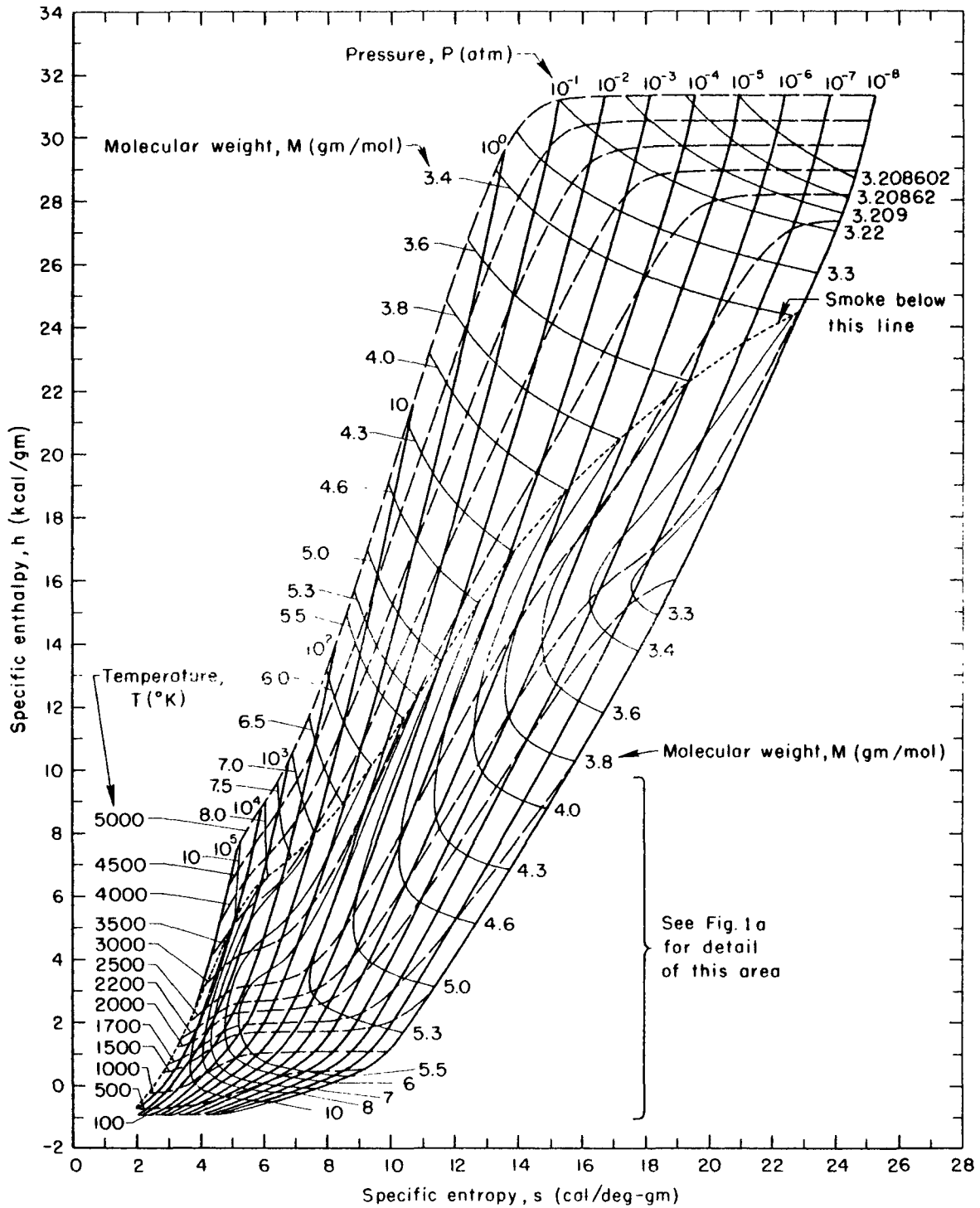| Temperature, T ($^\circ$K)	Pressure, P (atm)	Specific Impulse, I (sec)	Nozzle Area, A (cm^2)
532000	3732107	5353355	6469419
531000	3483720	5354363	6711459

Fig. I — Specific enthalpy versus specific entropy for methane with
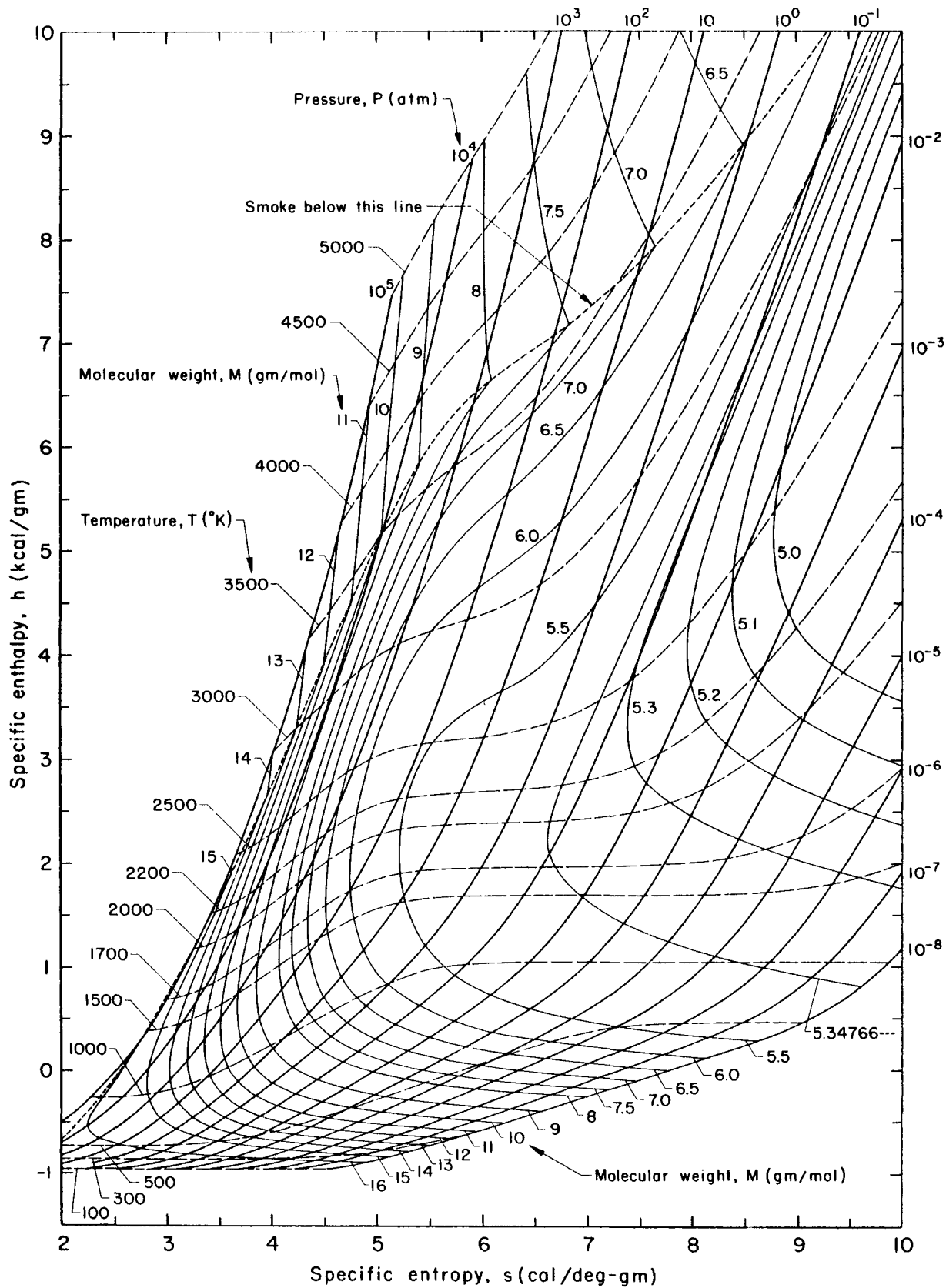cross plots of temperature, pressure and molecular weight
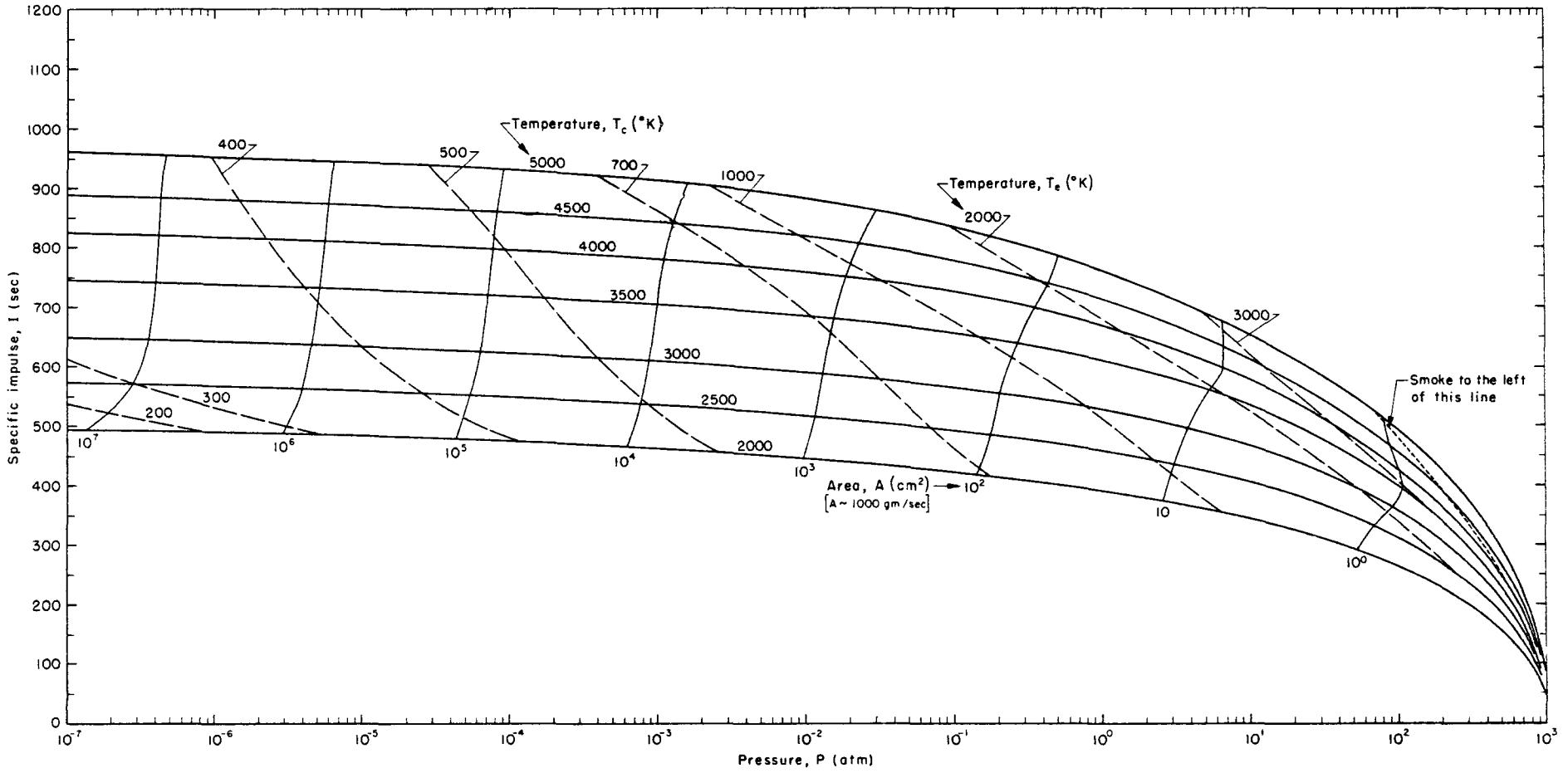
Fig. 1a — Detail of Fig. 1

Fig. 2 — Specific impulse versus pressure for the isentropic expansion of methane through a rocket nozzle, assuming a chamber pressure of 10^3 atmospheres and various chamber temperatures
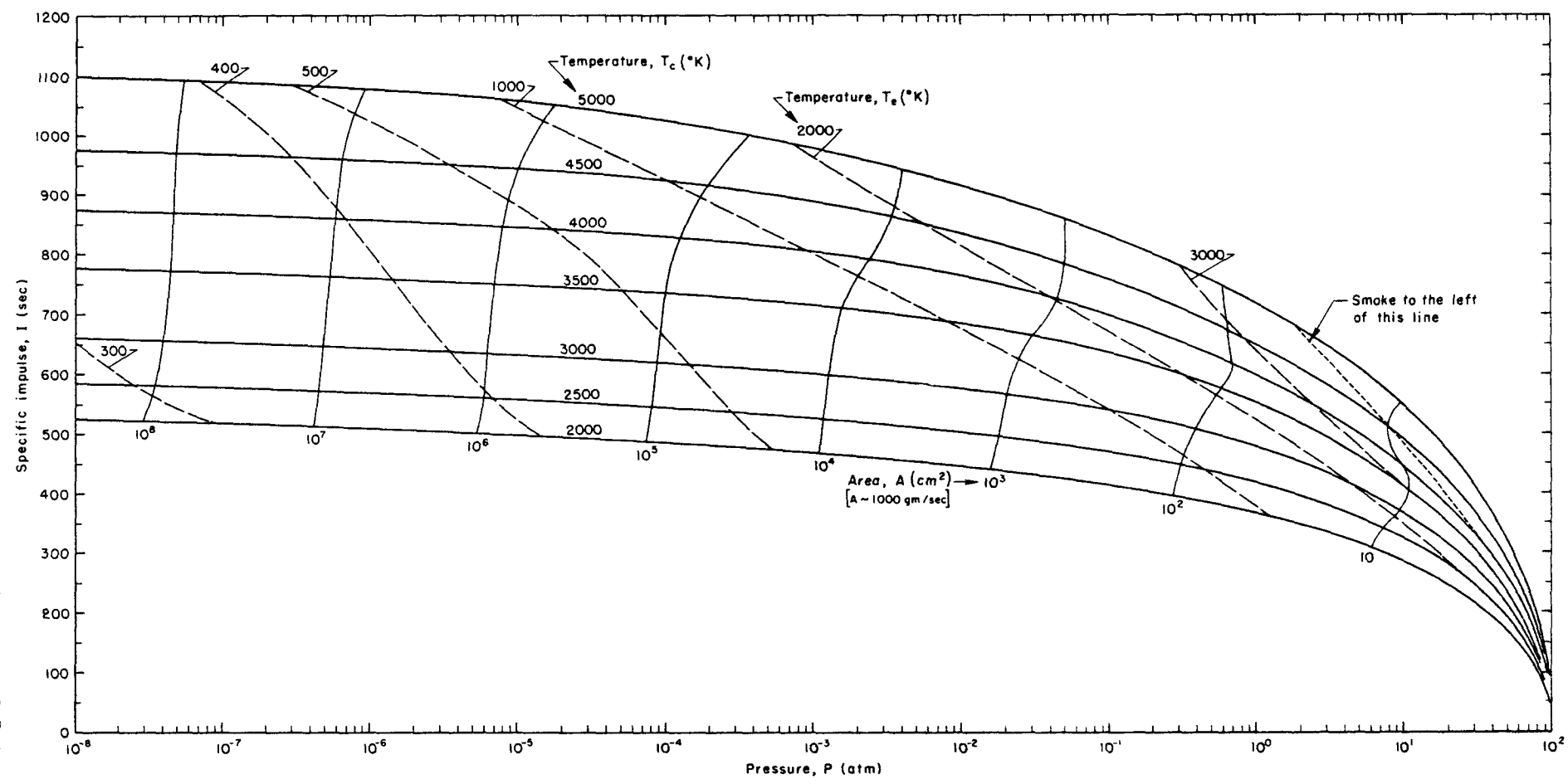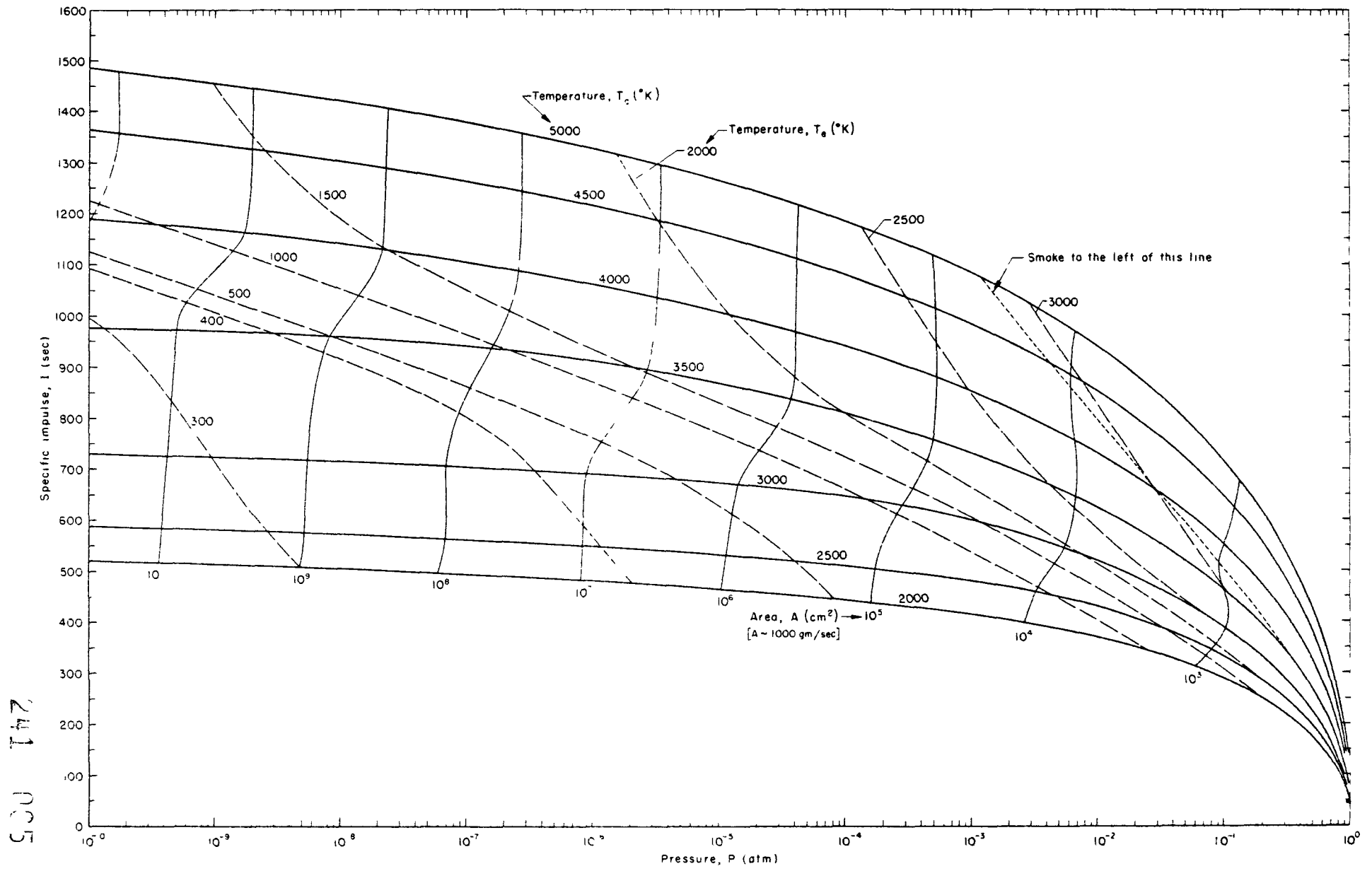
Fig. 3—Specific impulse versus pressure for the isentropic expansion of methane through a rocket nozzle, assuming a chamber pressure of 10^2 atmospheres and various chamber temperatures
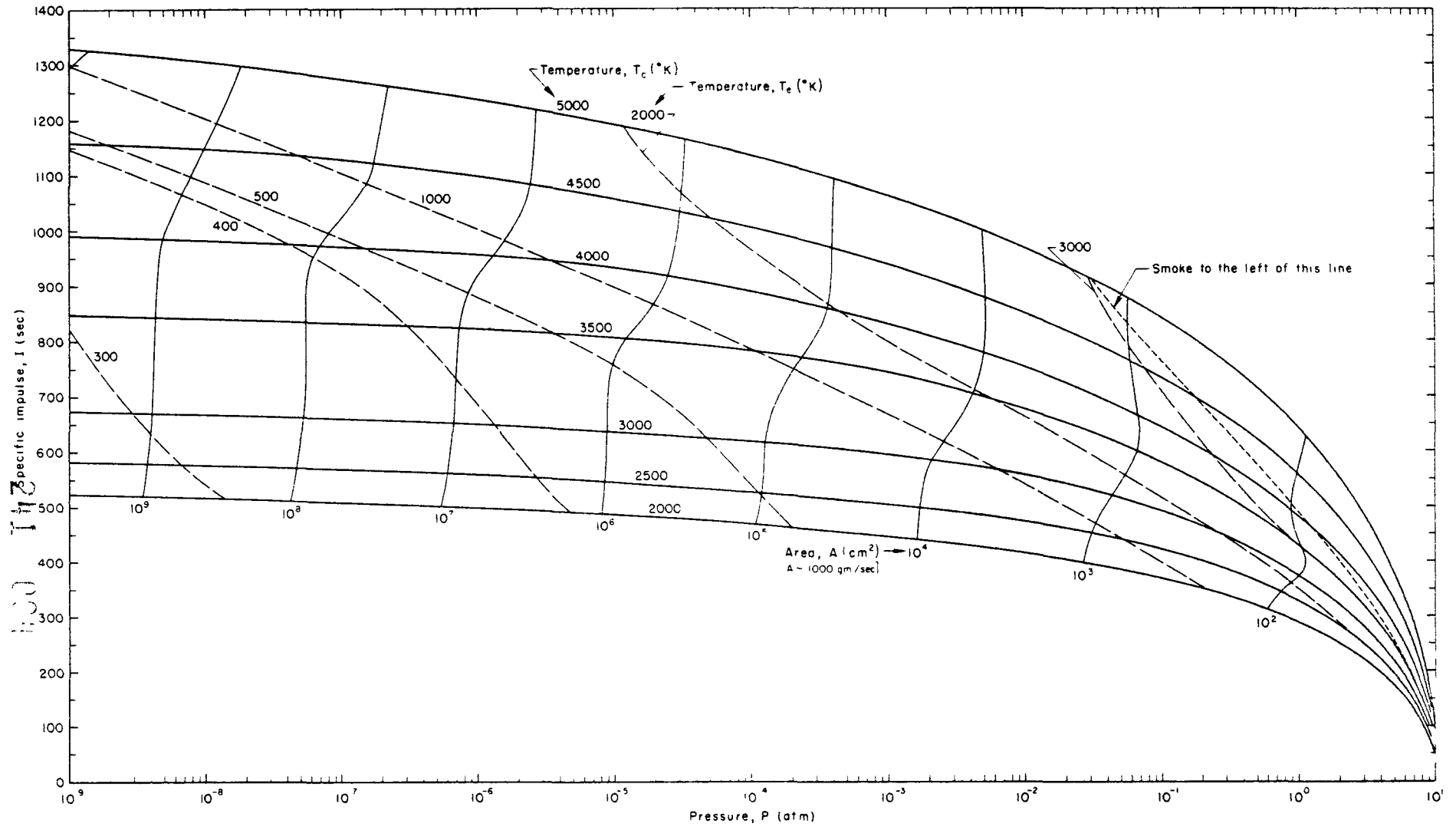
Fig 4—Specific impulse versus pressure for the isentropic expansion of methane through a rocket nozzle, assuming a chamber pressure of 10 atmospheres and various chamber temperatures

Fig 5 — Specific impulse versus pressure for the isentropic expansion of methane through a rocket nozzle, assuming a chamber pressure of 1 atmosphere and various chamber temperatures
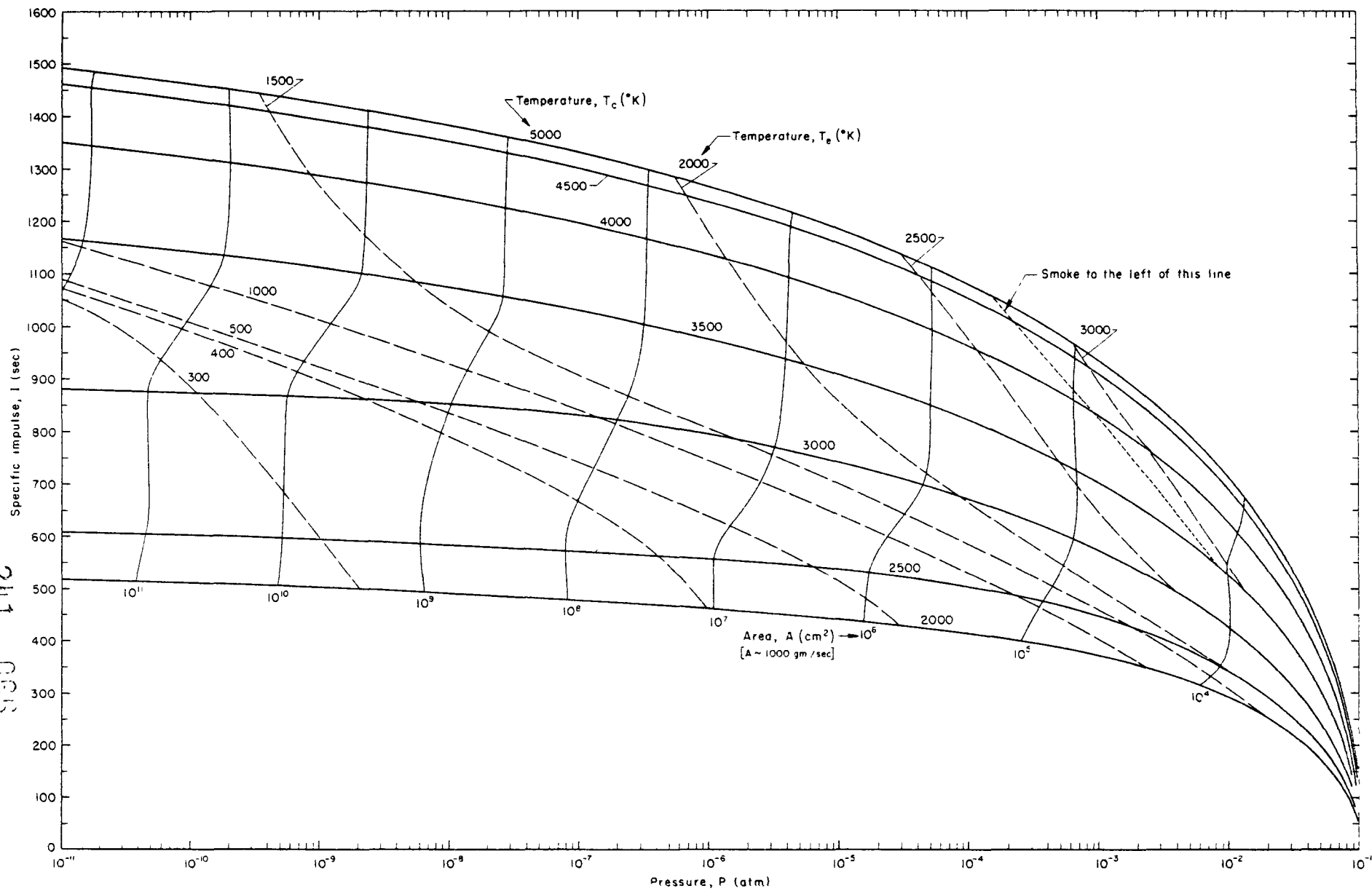
Fig. 6 —Specific impulse versus pressure for the isentropic expansion of methane through a rocket nozzle, assuming a chamber pressure of 10^{-1} atmosphere and various chamber temperatures

Temperature, T_c (°K)

Temperature, T_e (°K)

Smoke to the left of this line

Area, A (cm²) ⟶ 10^6
[A ∼ 1000 gm /sec]

Specific impulse, I (sec)

Pressure, P (atm)

page blank

REFERENCES

1. Krieger, F. J., _Chemical Kinetics and Rocket Nozzle Design_, The RAND Corporation, Report R-203, August 15, 1950; also published in _Journal of the American Rocket Society_, November, 1951, pp. 179-185.

2. _Selected Values of Chemical Thermodynamic Properties_, Series III, National Bureau of Standards, June 30, 1948; March 1, 1954.

3. Kolsky, H. G., _The Thermodynamic Properties of 54 Elements Considered as Ideal Monatomic Gases_, Los Alamos Scientific Laboratory, Report LA-2110, December 20, 1956.

4. Huff, V. N., S. Gordon, and V. E. Morrell, _General Method and Thermodynamic Tables for Computation of Equilibrium Composition and Temperature of Chemical Reactions_, NACA Report 1037, 1951.

5. Fickett, W., and R. D. Cowan, "Values of Thermodynamic Functions to $12,000^{\circ}K$ for Several Substances," _The Journal of Chemical Physics_, Vol. 23, No. 7, July, 1955, pp. 1349-1350.

6. Glatt, L., J. H. Adams, and H. L. Johnston, _Thermodynamic Properties of $C^{12}H^1$ and $N^{14}H^1$ in the Ideal Gas State_, The Ohio State University, Technical Report 11, Project RF-316.

7. Herzberg, Gerhard, _Infrared and Raman Spectra of Polyatomic Molecules_, D. Van Nostrand Co., Inc., New York, 1945.

8. Gurvich, A. M., and A. V. Frost, "Structure, Normal Vibration Frequencies, and Thermodynamic Functions of the Methyl, Methylene, Methyne, and Dicarbon Free Radicals," _Ucheniye Zapiski Moskovskogo Universiteta_, No. 64, 1953, pp. 129-143.

9. Glockler, George, "The Heat of Sublimation of Graphite and the Composition of Carbon Vapor," _The Journal of Chemical Physics_, Vol. 22, No. 2, February, 1954, pp. 159-161.

10. Herzberg, Gerhard, _Molecular Spectra and Molecular Structure I. Spectra of Diatomic Molecules_, 2nd ed., D. Van Nostrand Co., Inc., New York, 1950.

11. Plooster, M. N., and T. B. Reed, "Carbon-Hydrogen-Acetylene Equilibrium at High Temperatures," _The Journal of Chemical Physics_, Vol. 31, No. 1, July, 1959, pp. 66-72.

12. Wagman, D. D., J. E. Kilpatrick, K. S. Pitzer, and F. D. Rossini, "Heats, Equilibrium Constants, and Free Energies of Formation of the Acetylene Hydrocarbons through the Pentynes to $1,500^{\circ}K$," _Journal of Research of the National Bureau of Standards_, Vol. 35, No. 6, December, 1945, pp. 467-496.

13. Kilpatrick, J. E., and K. S. Pitzer, "Heat Content, Free-Energy Function, Entropy, and Heat Capacity of Ethylene, Propylene, and the Four Butenes to 1,500°K," Journal of Research of the National Bureau of Standards, Vol. 37, No. 3, September, 1946, pp. 163-171.

14. Brickwedde, F. G., M. Moskow, and J. G. Aston, "Equilibrium Constants of Some Reactions Involved in the Production of 1,3-Butadiene," Journal of Research of the National Bureau of Standards, Vol. 37, No. 5, November, 1946, pp. 263-279.

15. Prosen, E. J., and F. D. Rossini, "Heats of Formation, Hydrogenation, and Combustion of the Monoolefin Hydrocarbons through the Hexenes, and of the Higher 1-Alkenes, in the Gaseous State at 25°C," Journal of Research of the National Bureau of Standards, Vol. 36, No. 3, March, 1946, pp. 269-275.

16. White, W. B., S. M. Johnson, and G. B. Dantzig, "Chemical Equilibrium in Complex Mixtures," The Journal of Chemical Physics, Vol. 28, No. 5, May, 1958, pp. 751-755.