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THE THERMODYNAMICS OF THE TEFLON-FLUOROCARBON VAPOR SYSTEM

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The RAND Corporation
SANTA MONICA • CALIFORNIA

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PREFACE

This study was done at the request of the Scientific Advisor to the Physics Division, Research Directorate,* Air Force Special Weapons Center, Kirtland Air Force Base, New Mexico.

It is a contribution to a better understanding of the complex problems involved in the physics of re-entry bodies. Teflon is the sixth of a series of ablative materials to be investigated by means of mathematical techniques similar to those used at RAND in the parametric study of certain low-molecular-weight compounds as nuclear rocket propellants.

The results of the investigation of graphite, polystyrene, polyethylene, phenol-formaldehyde resin, and polyamide resin, the first five materials to be studied in the series, are reported in RAND Memoranda RM-3326-PR, *The Thermodynamics of the Graphite-Carbon Vapor System*, RM-3708-PR, *The Thermodynamics of the Polystyrene-Hydrocarbon Vapor System*, RM-3709-PR, *The Thermodynamics of the Polyethylene-Hydrocarbon Vapor System*, RM-3988-PR, *The Thermodynamics of the Phenol-Formaldehyde Resin: Carbon-Hydrogen-Oxygen Vapor System*, and RM-4404-PR, *The Thermodynamics of the Polyamide Resin (Nylon-6): Carbon-Hydrogen-Oxygen-Nitrogen Vapor System*.

Other materials to be investigated are ceramics such as silicon dioxide.

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SUMMARY

The purpose of this study is the thermodynamic investigation of Teflon over a range of temperatures up to 6000°K and pressures up to 10^5 atmospheres.

Two sets of equilibrium composition equations are used--one representing a pure gas phase, the other a heterogeneous system of gas and solid carbon. The gas phase of the heterogeneous chemical system, like the homogeneous gas phase, comprises 14 gaseous carbon fluorine, and fluorocarbon species.

The results of the computational program are presented in both tabular and graphic form. The latter is a conventional Mollier diagram in which specific enthalpy is plotted against specific entropy, with cross plots of temperature, pressure, and molecular weight.

ACKNOWLEDGMENTS

This study involved considerable hand and machine computation. The efforts of the following RAND Physics Department staff members are gratefully acknowledged: Donald A. Brown, for his extensive liaison and computational work; and Elizabeth J. Force, for her meticulous graphical presentation of the tabulated results.

CONTENTS

I. INTRODUCTION

This study considers a chemical system that under certain conditions of temperature and pressure is a pure gas mixture and under others is a disperse system, or smoke. In this case the smoke is a gas that contains a condensed phase, solid carbon or graphite, symbolized by C_s.

In deriving the computations, the following assumptions have been made:

(1) Thermal equilibrium is maintained between the solid particles and the gas phase.

(2) The pressure due to the thermal motion of the solid particles can be neglected.

(3) The gas phase obeys the ideal-gas law.

(4) The molar volume of solid carbon is essentially constant, that is, independent of temperature and pressure.

II. COMPOSITION EQUATIONS

In this study it is assumed that the gas or smoke formed by heating polytetrafluoroethylene, whose molecular formula is $[C_2F_4]_x$ or, simply, CF_2, at various pressures up to a temperature of 6000°K is a mixture of C_s (graphite), C (gas), F_2, F, and 11 other carbon and fluorocarbon chemical species for which thermochemical data are available. The presence or absence of a condensed phase makes it necessary to consider two distinct sets of chemical equations.

A. Solid carbon present. In terms of C_s and F_2 as independent components, the chemical equations for the dependent, or derived, species are given by the expression

$$a_iC_s + b_iF_2 = C_{a_i}F_{2b_i}, \tag{1}$$

where a_i has the integral values 0, 1, 2, ..., and b_i has the half-integral values 0, 1/2, 1, 3/2, ...

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

$$n_s = 1 - \sum^{13} a_in_i, \tag{2}$$

and

$$n_{F_2} = 1 - \sum^{13} b_in_i, \tag{3}$$

where n_s is the number of moles of C_s, a_i is the coefficient of C_s on the left-hand side of Eq. (1), n_{F_2} is the number of moles of F_2, b_i is the coefficient of F_2 on the left-hand side of Eq. (1), and n_i is the corresponding number of moles of component i.

The equilibrium equations are obtained by considering the free energy F of the system and the partial molar free energy or chemical potential $\mu_j = \partial F/\partial n_j$ of each component. The chemical potential is a function of the state and composition of the system. For an ideal gas

$$\mu_i = \mu_i^o + RT \ln (n_i P/n), \quad i = F_2, 1, \ldots, 13, \tag{4}$$

where μ_i^o is the chemical potential of component i in the standard state of unit partial pressure, R is the gas constant, T is the temperature, P is the pressure, and n is the total number of moles of gas in the mixture.

The chemical potential for graphite is given by

$$\mu_s = \mu_s^o + (P - 1)\bar{V}_s, \tag{5}$$

where μ_s^o is the standard molar free energy for graphite, $\bar{V}_s$ is the molar volume of graphite, and P is the pressure of the system.

The condition for chemical equilibrium is that for all possible reactions represented by Eq. (1),

$$\Delta F = \sum \mu_j \, \Delta n_j = 0, \quad j = C_s, F_2, 1, \ldots, 13, \tag{6}$$

at constant temperature and pressure. Equations (4) and (5) may, therefore, be combined to give

$$RT \ln (n_i P/n) = a_i \mu_s^o + b_i \mu_{F_2}^o - \mu_i^o + a_i (P - 1)\bar{V}_s + b_i \, RT \ln (n_{F_2} P/n). \tag{7}$$

Because the equilibrium constants K_i associated with the chemical reactions (1) are defined by the relation

$$\Delta F^o = \mu_i^o - a_i \mu_s^o - b_i \mu_{F_2}^o = - RT \ln K_i, \tag{8}$$

Eq. (7) may be written in the form

$$\ln (n_i P/n) = \ln K_i + a_i (P - 1)\bar{V}_s/RT + b_i \ln (n_{F_2} P/n), \qquad (9)$$

or

$$n_i = K_i \exp \left[a_i(P - 1)\bar{V}_s/RT\right] (P/n)^{b_i - 1} (n_{F_2})^{b_i}. \qquad (10)$$

Equations (2), (3), and (10) form a system of 15 non-linear equations in 15 unknowns which can be solved by a process of iteration.

B. Solid carbon absent. In terms of C (gas) and F_2 as independent components, the chemical equations for the dependent, or derived, species are given by the expression

$$a_j C + b_j F_2 = C_{a_j} F_{2b_j}, \qquad (11)$$

where a_j has the integral values 0, 1, 2, ..., and b_j has the half-integral values 0, 1/2, 1, 3/2, ...

The mass-balance equations are

$$n_C = 1 - \sum^{12} a_j n_j, \qquad (12)$$

and

$$n_{F_2} = 1 - \sum^{12} b_j n_j, \qquad (13)$$

where n_C is the number of moles of C, a_j is the coefficient of C on the left-hand side of Eq. (11), n_{F_2} is the number of moles of F_2, b_j is the coefficient of F_2 on the left-hand side of Eq. (11), and n_j is the corresponding number of moles of component j.

The equilibrium equations are given by the expression

$$n_j = K_j (P/n)^{a_j + b_j - 1} (n_C)^{a_j} (n_{F_2})^{b_j}, \qquad (14)$$

where n is the total number of moles of gas in the equilibrium mixture, P is the total pressure in atmospheres, and K_j is the thermodynamic equilibrium constant of component j. These values of K_j are quite different from those in Eq. (10) because of the reactions with which they are associated.

III. THERMODYNAMIC EQUATIONS

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

$$M = \frac{50.011}{\bar{n}}, \tag{15}$$

where 50.011 is the formula weight of the input material CF_2 and $\bar{n}$ is the total number of moles in the gas-solid mixture.

The specific free energy (in calories per gram) of the gas mixture is given by the expression

$$f = \frac{1}{50.011}\left\{\sum^{g} n_i[\mu_i^o + RT \ln (n_i P/n)] + n_s[\mu_s^o + c(P - 1)\bar{V}_s]\right\}, \tag{16}$$

which is derived from Eqs. (4) and (5). The summation is over all gaseous species. The constant c = 0.0242172 converts cc-atmospheres to calories.

The specific entropy (in calories per degree per gram) of the gas mixture is given by the expression

$$s = \frac{1}{50.011}\left\{\sum^{g} n_i[S_i^o - R \ln (n_i P/n)] + n_s[S_s^o - c\alpha_V(P - 1)\bar{V}_s]\right\}, \tag{17}$$

where S_i^o and S_s^o are the standard molar entropy of component i and graphite, respectively, at a given temperature, and α_V is the volume coefficient of thermal expansion of graphite.

The specific enthalpy (in calories per gram) of the gas mixture is given by the expression

$$h = \frac{1}{50.011}\left\{\sum^{g} n_i H_i^o + n_s[H_s^o + c(1 - \alpha_V T)(P - 1)\bar{V}_s]\right\}, \tag{18}$$

where H_i^o and H_s^o are the standard molar heat content of component i and graphite, respectively, at a given temperature.

The specific internal energy (in calories per gram) of the gas mixture is given by the expression

$$u = \frac{1}{50.011}\left\{\sum^{g} n_i(H_i^o - RT) + n_s\left[H_s^o - c[1 + (P - 1)\alpha_v T]\bar{V}_s\right]\right\}. \qquad (19)$$

The terms representing the increase in a thermodynamic property from one atmosphere to P atmospheres for graphite, namely,

$$\Delta F = (P - 1)\bar{V}_s, \qquad (20)$$

$$\Delta S = - \alpha_v(P - 1)\bar{V}_s, \qquad (21)$$

$$\Delta H = (1 - \alpha_v T)(P - 1)\bar{V}_s, \qquad (22)$$

$$\Delta U = - \alpha_v T(P - 1)\bar{V}_s, \qquad (23)$$

are readily derived from the differential formulas relating the various thermodynamic functions. Each of the above terms must be multiplied by the factor c = 0.0242172 to convert it from cc-atmospheres to calories.

The specific volume of the gas mixture (in cubic centimeters per gram) is given by the expression

$$v = \frac{1}{50.011}\left\{nRT/P + n_s\bar{V}_s\right\}, \qquad (24)$$

where the first term in the brackets is the volume of the gas phase and the second term is that of the solid phase.

IV. BASIC DATA

The pertinent thermodynamic properties (heat content, entropy, free energy, and heat of formation) for the 15 chemical species considered in this study were taken for the most part from JANAF Thermochemical Data.[1] The molecular weights and heats of formation of the various chemical species are listed in the following table.

Species	Molecular Weight	Heat of Formation at 0^oK (cal/mole)	Reference
C_s (graphite)	12.011	0	1
C	12.011	169,576	1
C_2	24.022	197,000	1
C_3	36.033	188,104	1
C_4	48.044	240,500	1
C_5	60.055	240,298	1
CF	31.011	73,536	1
CF_2	50.011	-30,100	1
CF_3	69.011	-115,077	1
CF_4	88.011	-219,071	1
C_2F	43.022	64,670	2
C_2F_2	62.022	-51,930	1
C_2F_4	100.022	-154,179	1
F	19.000	18,357	1
F_2	38.000	0	1

The molar volume of graphite ($\bar{V}_s$ = 5.5524 cc) was derived from a mean density of 2.1632 gm/cc based on measurements of 49 samples at the Los Alamos Scientific Laboratory.[3]

The volume coefficient of thermal expansion for graphite is given by the expression

$$\alpha_v = \frac{1}{v}\left[\frac{\partial v}{\partial T}\right]_p = (18.80 + 0.001875T) \times 10^{-6} \text{ cc/cc-deg} \qquad (25)$$

for $T > 773^oK$. This expression was derived from data on the linear coefficient of expansion of lampblack obtained at the National Carbon Research Laboratories.[4]

Two values of the gas constant were used: R = 1.98726 cal/deg-mole and R = 82.0597 cc-atm/deg-mole. Their ratio gives the conversion factor c = 0.0242172 cal/cc-atm.

V. COMPUTATIONAL PROCEDURE

The two sets of equilibrium composition equations--the one involving solid carbon and the other gaseous species only--represent two mutually exclusive contiguous regions. It is expedient to determine the border line between the two regions, that is, the conditions of temperature and pressure under which solid carbon just vanished.

This can be done by making use of the fact that under certain conditions the value of n_s in Eq. (2) changes sign. Thus, for a specified pressure, a temperature interval can be found in which the change of sign occurs. If this interval is divided into, say, three equally spaced temperatures, the sublimation temperature of graphite (that is, the temperature at which graphite disappears) at any desired pressure may be determined by interpolation.

VI. RESULTS

The results of this study are presented numerically in Tables 1 and 2 and graphically in Figs. 1, 2, and 3. Figure 1 is a conventional Mollier diagram for Teflon; specific enthalpy is plotted against specific entropy, with cross plots of temperature and pressure. The temperatures range from 6000°K to 500°K, the pressures from 10^5 atm to 10^{-8} atm. The dotted line demarcates the pure gas phase from the smoke. Figure 2 is a cross plot of molecular weight on the basic framework of Fig. 1. Figure 3 is a plot of volume versus temperature with cross plots of constant pressure. Of particular interest is the anomalous character of the gas/smoke interface at pressures below 10^{-3} atm.

The variation of sublimation temperature with pressure for Teflon, polyethylene, and graphite is shown in Fig. 4. For Teflon at 10^{-3} atm the sublimation temperature is 1640°K, at 1 atm it is 2028°K, while at 10^3 atm it is 2650°K. It is interesting to note that for polyethylene,[4] a chemical analogue of Teflon, the corresponding temperatures are 2912°K, 3365°K, and 3799°K, respectively, while for graphite[5] they are 3151°K, 4127°K, and 5908°K, respectively.

All the computations required to obtain the results in Tables 1 and 2 were made on the RAND IBM 7040/7044 computer. In the tables the numbers are represented in "floating decimal" notation; the first five digits indicate the decimal form of the number, and the last two digits indicate a power of 10. Thus, 12345 05 represents 0.12345×10^5 and 12345-05 represents 0.12345×10^{-5}.

Table 1

SUMMARY OF COMPUTED VALUES OF VOLUME, MOLECULAR WEIGHT, MOLES OF GAS, AND MOLES OF SOLID CARBON FOR TEFLON AT VARIOUS TEMPERATURES AND PRESSURES

Temperature, T (°K)	Pressure, P (atm)	Log Volume, v (cc/gm)	Molecular Weight, M	Moles of Gas, n	Moles of Solid, n_s
6000 04	10000 06	-11069 01	62976 02	79413 00	
6000 04	10000 05	43910-01	44501 02	11238 01	
6000 04	10000 04	11827 01	32329 02	15469 01	
6000 04	10000 03	23350 01	22766 02	21967 01	
6000 04	10000 02	34431 01	17749 02	28177 01	
6000 04	10000 01	44671 01	16796 02	29776 01	
6000 04	10000-00	54700 01	16683 02	29977 01	
6000 04	10000-01	64703 01	16672 02	29998 01	
6000 04	10000-0[illegible]	74703 01	16670 02	30000 01	
6000 04	10000-03	84703 01	16670 02	30000 01	
6000 04	10000-04	94703 01	16670 02	30000 01	
6000 04	10000-05	10470 02	16670 02	30000 01	
6000 04	10000-06	11470 02	16670 02	30000 01	
6000 04	10000-07	12470 02	16670 02	30000 01	
5500 04	10000 06	-11702 01	66785 02	74883 00	
5500 04	10000 05	-61395-01	51986 02	96201 00	
5500 04	10000 04	11080 01	35195 02	14210 01	
5500 04	10000 03	22187 01	27274 02	18337 01	
5500 04	10000 02	33689 01	19301 02	25911 01	
5500 04	10000 01	44233 01	17027 02	29371 01	
5500 04	10000-00	54316 01	16708 02	29933 01	
5500 04	10000-01	64325 01	16674 02	29993 01	
5500 04	10000-02	74325 01	16671 02	29999 01	
5500 04	10000-03	84325 01	16670 02	30000 01	
5500 04	10000-04	94325 01	16670 02	30000 01	
5500 04	10000-05	10433 02	16670 02	30000 01	
5500 04	10000-06	11433 02	16670 02	30000 01	
5500 04	10000-07	12433 02	16670 02	30000 01	
5000 04	10000 06	-12309 01	69818 02	71631 00	
5000 04	10000 05	-16758-00	60351 02	82867 00	
5000 04	10000 04	10164 01	39514 02	12657 01	
5000 04	10000 03	21129 01	31635 02	15809 01	
5000 04	10000 02	32509 01	23026 02	21719 01	
5000 04	10000 01	43609 01	17873 02	27982 01	
5000 04	10000-00	53877 01	16805 02	29759 01	
5000 04	10000-01	63908 01	16684 02	29976 01	
5000 04	10000-02	73911 01	16672 02	29998 01	

Table 1--continued

Temperature, T (°K)	Pressure, P (atm)	Log Volume, v (cc/gm)	Molecular Weight, M	Moles of Gas, n	Moles of Solid, n_s
5000 04	10000-03	83912 01	16670 02	30000 01	
5000 04	10000-04	93912 01	16670 02	30000 01	
5000 04	10000-05	10391 02	16670 02	30000 01	
5000 04	10000-06	11391 02	16670 02	30000 01	
5000 04	10000-07	12391 02	16670 02	30000 01	
4500 04	10000 06	-12902 01	72030 02	69430 00	
4500 04	10000 05	-25954-00	67124 02	74505 00	
4500 04	10000 04	86792 00	50052 02	99917 00	
4500 04	10000 03	20289 01	34553 02	14474 01	
4500 04	10000 02	31039 01	29069 02	17204 01	
4500 04	10000 01	42487 01	20829 02	24011 01	
4500 04	10000-00	53286 01	17328 02	28862 01	
4500 04	10000-01	63437 01	16737 02	29881 01	
4500 04	10000-02	73452 01	16677 02	29988 01	
4500 04	10000-03	83454 01	16671 02	29999 01	
4500 04	10000-04	93454 01	16670 02	30000 01	
4500 04	10000-05	10345 02	16670 02	30000 01	
4500 04	10000-06	11345 02	16670 02	30000 01	
4500 04	10000-07	12345 02	16670 02	30000 01	
4000 04	10000 06	-13501 01	73501 02	68042 00	
4000 04	10000 05	-33757-00	71411 02	70033 00	
4000 04	10000 04	71386 00	63435 02	78838 00	
4000 04	10000 03	19047 01	40882 02	12233 01	
4000 04	10000 02	29957 01	33147 02	15088 01	
4000 04	10000 01	40749 01	27627 02	18102 01	
4000 04	10000-00	52105 01	20216 02	24738 01	
4000 04	10000-01	62808 01	17193 02	29088 01	
4000 04	10000-02	72930 01	16719 02	29912 01	
4000 04	10000-03	82941 01	16675 02	29991 01	
4000 04	10000-04	92942 01	16671 02	29999 01	
4000 04	10000-05	10294 02	16670 02	30000 01	
4000 04	10000-06	11294 02	16670 02	30000 01	
4000 04	10000-07	12294 02	16670 02	30000 01	
3500 04	10000 06	-14132 01	74368 02	67248 00	
3500 04	10000 05	-40890-00	73637 02	67916 00	
3500 04	10000 04	60546 00	71243 02	70198 00	
3500 04	10000 03	16756 01	60617 02	82503 00	
3500 04	10000 02	28884 01	37134 02	13468 01	
3500 04	10000 01	39408 01	32916 02	15194 01	
3500 04	10000-00	50091 01	28125 02	17782 01	

Table 1--continued

Temperature, T (°K)	Pressure, P (atm)	Log Volume, v (cc/gm)	Moleculer Weight, M	Moles of Gas, n	Moles of Solid, n_s
3500 04	10000-01	61365 01	20976 02	23842 01	
3500 04	10000-02	72161 01	17464 02	28637 01	
3500 04	10000-03	82345 01	16737 02	29880 01	
3500 04	10000-04	92361 01	16677 02	29989 01	
3500 04	10000-05	10236 02	16671 02	29999 01	
3500 04	10000-06	11236 02	16670 02	30000 01	
3500 04	10000-07	12236 02	16670 02	30000 01	
3000 04	10000 06	-14827 01	74802 02	66858 00	
3000 04	10000 05	-48146-00	74594 02	67044 00	
3000 04	10000 04	52146 00	74096 02	67495 00	
3000 04	10000 03	15330 01	72153 02	69313 00	
3000 04	10000 02	25955 01	62480 02	80043 00	
3000 04	10000 01	38175 01	37477 02	13345 01	
3000 04	10000-00	48691 01	33280 02	15028 01	
3000 04	10000-01	59036 01	30739 02	16269 01	
3000 04	10000-02	70176 01	23638 02	21157 01	
3000 04	10000-03	81078 01	19205 02	26041 01	
3000 04	10000-04	91620 01	16953 02	29500 01	
3000 04	10000-05	10169 02	16691 02	29962 01	
3000 04	10000-06	11169 02	16672 02	29996 01	
3000 04	10000-07	12169 02	16671 02	30000 01	
2500 04	10000 06	-15628 01	74971 02	66708 00	
2500 04	69283 05	-14034 01	74964 02	66713 00	16391-06
2500 04	10000 05	-57811 00	54566 02	54287 00	37365-00
2500 04	10000 04	39002-00	61003 02	59227 00	22753-00
2500 04	25448 03	10327 01	74764 02	66892 00	-46194-06
2500 04	10000 03	14390 01	74660 02	66985 00	
2500 04	10000 02	24435 01	73883 02	67689 00	
2500 04	10000 01	34691 01	69657 02	71796 00	
2500 04	10000-00	46171 01	49537 02	10096 01	
2500 04	10000-01	57835 01	33774 02	14808 01	
2500 04	10000-02	67929 01	33050 02	15132 01	
2500 04	17377-03	75730 01	31560 02	15847 01	-59605-07
2500 04	10000-03	78418 01	26801 02	16935 01	17245-00
2500 04	10000-04	89265 01	20258 02	20583 01	41037-00
2500 04	38213-05	93922 01	21763 02	22980 01	43958-06
2500 04	10000-05	10010 02	20059 02	24933 01	
2500 04	10000-06	11074 02	17299 02	28909 01	
2500 04	10000-07	12089 02	16702 02	29943 01	

Table 1--continued

Temperature, T (°K)	Pressure, P (atm)	Log Volume, v (cc/gm)	Molecular Weight, M	Moles of Gas, n	Moles of Solid, n_s
2000 04	10000 06	-13015 01	58584 02	57323 00	28043-00
2000 04	10000 05	-65836 00	50255 02	50252 00	49262-00
2000 04	10000 04	23330-00	50502 02	50502 00	48525-00
2000 04	10000 03	12292 01	51523 02	51499 00	45566-00
2000 04	10000 02	22539 01	55073 02	54666 00	36143-00
2000 04	10000 01	33234 01	69397 02	64159 00	79053-01
2000 04	68297 00	35066 01	74842 02	66822 00	-00000 00
2000 04	10000-00	43434 01	74430 02	67192 00	
2000 04	10000-01	53595 01	71715 02	69735 00	
2000 04	10000-02	64627 01	56556 02	88428 00	
2000 04	10000-03	76813 01	34188 02	14628 01	
2000 04	10000-04	86924 01	33328 02	15006 01	
2000 04	22550-05	93412 01	33173 02	15076 01	-14901-06
2000 04	10000-05	97369 01	25421 02	16627 01	30468-00
2000 04	10000-06	10805 02	17898 02	19429 01	85141 00
2000 04	10000-07	11818 02	17018 02	20062 01	93250 00
1500 04	10000 06	-11742 01	50293 02	50281 00	49158-00
1500 04	10000 05	-74818 00	50013 02	50002 00	49994-00
1500 04	10000 04	10931-00	50014 02	50004 00	49989-00
1500 04	10000 03	10922 01	50021 02	50011 00	49969-00
1500 04	10000 02	20906 01	50043 02	50033 00	49902-00
1500 04	10000 01	30910 01	50113 02	50104 00	49692-00
1500 04	10000-00	40930 01	50336 02	50326 00	49028-00
1500 04	10000-01	50990 01	51052 02	51030 00	46931-00
1500 04	10000-02	61175 01	53446 02	53251 00	40322-00
1500 04	10000-03	71703 01	62429 02	60132 00	19977-00
1500 04	33336-04	76940 01	74701 02	66948 00	-92387-06
1500 04	10000-04	82199 01	74183 02	67415 00	
1500 04	10000-05	92474 01	69629 02	71825 00	
1500 04	10000-06	10414 02	47452 02	10539 01	
1500 04	10000-07	11565 02	33492 02	14932 01	
1000 04	10000 06	-11958 01	50011 02	50000 00	49999-00
1000 04	10000 05	-86153 00	50011 02	50000 00	50000 00
1000 04	10000 04	-57531-01	50011 02	50000 00	50000 00
1000 04	10000 03	91696 00	50011 02	50000 00	50000-00
1000 04	10000 02	19143 01	50011 02	50000 00	50000-00
1000 04	10000 01	29141 01	50011 02	50000 00	50000-00
1000 04	10000-00	39140 01	50011 02	50000 00	50000-00
1000 04	10000-01	49140 01	50011 02	50000 00	50000-00
1000 04	10000-02	59140 01	50011 02	50000 00	50000-00

Table 1--continued

Temperature, T (°K)	Pressure, P (atm)	Log Volume, v (cc/gm)	Molecular Weight, M	Moles of Gas, n	Moles of Solid, n_s
1000 04	10000-03	69140 01	50011 02	50000 00	49999-00
1000 04	10000-04	79140 01	50012 02	50001 00	49996-00
1000 04	10000-05	89141 01	50016 02	50005 00	49986-00
1000 04	10000-06	99142 01	50026 02	50015 00	49956-00
1000 04	10000-07	10914 02	50057 02	50047 00	49861-00
5000 03	10000 06	-12247 01	50011 02	50000-00	50000 00
5000 03	10000 05	-10153 01	50011 02	50000-00	50000 00
5000 03	10000 04	-33188-00	50011 02	50000 00	50000 00
5000 03	10000 03	61884 00	50011 02	50000 00	50000 00
5000 03	10000 02	16136 01	50011 02	50000-00	50000 00
5000 03	10000 01	26131 01	50011 02	50000 00	50000 00
5000 03	10000-00	36130 01	50011 02	50000 00	50000 00
5000 03	10000-01	46130 01	50011 02	50000-00	50000 00
5000 03	10000-02	56130 01	50011 02	50000-00	50000 00
5000 03	10000-03	66130 01	50011 02	50000 00	50000 00
5000 03	10000-04	76130 01	50011 02	50000 00	50000 00
5000 03	10000-05	86130 01	50011 02	50000-00	50000 00
5000 03	10000-06	96130 01	50011 02	50000-00	50000 00
5000 03	10000-07	10613 02	50011 02	50000 00	50000 00

Table 2

SUMMARY OF COMPUTED VALUES OF DENSITY, ENTHALPY, ENERGY, AND ENTROPY FOR TEFLON AT VARIOUS TEMPERATURES AND PRESSURES

Temperature, T (°K)	Pressure, P (atm)	Density, d (gm/cc)	Enthalpy h (cal/gm)	Energy, u (cal/gm)	Entropy, s (cal/deg-gm)
6000 04	10000 06	12791 02	31808 03	12874 03	14497 01
6000 04	10000 05	90384 00	10173 04	74932 03	16509 01
6000 04	10000 04	65662-01	19048 04	15360 04	19225 01
6000 04	10000 03	46239-02	36646 04	31409 04	23829 01
6000 04	10000 02	36048-03	54402 04	47684 04	29125 01
6000 04	10000 01	34113-04	58940 04	51841 04	32554 01
6000 04	10000-00	33884-05	59506 04	52359 04	35385 01
6000 04	10000-01	33861-06	59564 04	52412 04	38139 01
6000 04	10000-02	33858-07	59570 04	52418 04	40885 01
6000 04	10000-03	33858-08	59571 04	52418 04	43630 01
6000 04	10000-04	33858-09	59571 04	52418 04	46375 01
6000 04	10000-05	33858-10	59571 04	52418 04	49120 01
6000 04	10000-06	33858-11	59571 04	52418 04	51865 01
6000 04	10000-07	33858-12	59571 04	52418 04	54609 01
5500 04	10000 06	14798 02	48584 02	-11507 03	14028 01
5500 04	10000 05	11518 01	51663 03	30638 03	15638 01
5500 04	10000 04	77981-01	14430 04	11325 04	18423 01
5500 04	10000 03	60430-02	24811 04	20804 04	21771 01
5500 04	10000 02	42765-03	46241 04	40578 04	27698 01
5500 04	10000 01	37727-04	56243 04	49824 04	32083 01
5500 04	10000-00	37019-05	57835 04	51294 04	35094 01
5500 04	10000-01	36944-06	58005 04	51450 04	37868 01
5500 04	10000-02	36937-07	58022 04	51466 04	40615 01
5500 04	10000-03	36936-08	58024 04	51467 04	43360 01
5500 04	10000-04	36936-09	58024 04	51467 04	46105 01
5500 04	10000-05	36936-10	58024 04	51467 04	48850 01
5500 04	10000-06	36936-11	58024 04	51467 04	51595 01
5500 04	10000-07	36936-12	58024 04	51467 04	54340 01
5000 04	10000 06	17016 02	-19526 03	-33757 03	13564 01
5000 04	10000 05	14709 01	63930 02	-10071 03	14776 01
5000 04	10000 04	96304-01	96246 03	71099 03	17504 01
5000 04	10000 03	77103-02	16314 04	13173 04	20159 01
5000 04	10000 02	56120-03	32490 04	28175 04	25069 01
5000 04	10000 01	43560-04	50649 04	45089 04	31009 01
5000 04	10000-00	40958-05	55798 04	49886 04	34705 01
5000 04	10000-01	40663-06	56412 04	50456 04	37564 01
5000 04	10000-02	40633-07	56474 04	50514 04	40320 01

Table 2--continued

Temperature, T (°K)	Pressure, P (atm)	Density, d (gm/cc)	Enthalpy, h (cal/gm)	Energy, u (cal/gm)	Entropy, s (cal/deg-gm)
5000 04	10000-03	40630-08	56480 04	50520 04	43066 01
5000 04	10000-04	40630-09	56481 04	50520 04	45811 01
5000 04	10000-05	40630-10	56481 04	50520 04	48556 01
5000 04	10000-06	40630-11	56481 04	50520 04	51301 01
5000 04	10000-07	40630-12	56481 04	50520 04	54046 01
4500 04	10000 06	19506 02	-41635 03	-54050 03	13098 01
4500 04	10000 05	18178 01	-29116 03	-42438 03	14029 01
4500 04	10000 04	13554-00	25478 03	76116 02	16010 01
4500 04	10000 03	93570-02	11453 04	88653 03	19138 01
4500 04	10000 02	78721-03	18223 04	15147 04	22072 01
4500 04	10000 01	56406-04	37312 04	33019 04	28181 01
4500 04	10000-00	46924-05	51642 04	46481 04	33821 01
4500 04	10000-01	45324-06	54602 04	49259 04	37182 01
4500 04	10000-02	45162-07	54908 04	49545 04	39990 01
4500 04	10000-03	45146-08	54938 04	49574 04	42742 01
4500 04	10000-04	45144-09	54941 04	49577 04	45487 01
4500 04	10000-05	45144-10	54942 04	49577 04	48232 01
4500 04	10000-06	45144-11	54942 04	49577 04	50977 01
4500 04	10000-07	45144-12	54942 04	49577 04	53722 01
4000 04	10000 06	22392 02	-61773 03	-72588 03	12624 01
4000 04	10000 05	21756 01	-56420 03	-67552 03	13388 01
4000 04	10000 04	19326-00	-36205 03	-48736 03	14563 01
4000 04	10000 03	12455-01	53533 03	34089 03	17688 01
4000 04	10000 02	10098-02	10988 04	85900 03	20383 01
4000 04	10000 01	84167-04	18927 04	16050 04	23854 01
4000 04	10000-00	61590-05	37688 04	33756 04	30501 01
4000 04	10000-01	52379-06	50738 04	46114 04	36259 01
4000 04	10000-02	50937-07	53156 04	48401 04	39576 01
4000 04	10000-03	50802-08	53384 04	48617 04	42375 01
4000 04	10000-04	50789-09	53406 04	48638 04	45125 01
4000 04	10000-05	50787-10	53408 04	48640 04	47871 01
4000 04	10000-06	50787-11	53409 04	48640 04	50616 01
4000 04	10000-07	50787-12	53409 04	48640 04	53361 01
3500 04	10000 06	25893 02	-80226 03	-89578 03	12132 01
3500 04	10000 05	25639 01	-78253 03	-87699 03	12806 01
3500 04	10000 04	24805-00	-72438 03	-82201 03	13602 01
3500 04	10000 03	21106-01	-45476 03	-56951 03	15054 01
3500 04	10000 02	12929-02	60564 03	41834 03	19054 01
3500 04	10000 01	11461-03	94835 03	73704 03	21367 01
3500 04	10000-00	97925-05	16346 04	13872 04	24806 01

Table 2--continued

Temperature, T (°K)	Pressure, P (atm)	Density, d (gm/cc)	Enthalpy, h (cal/gm)	Energy, u (cal/gm)	Entropy, s (cal/deg-gm)
3500 04	10000-01	73034-06	33252 04	29936 04	31537 01
3500 04	10000-02	60806-07	47789 04	43807 04	38111 01
3500 04	10000-03	58276-08	51535 04	47379 04	41879 01
3500 04	10000-04	58065-09	51850 04	47679 04	44710 01
3500 04	10000-05	58045-10	51880 04	47708 04	47462 01
3500 04	10000-06	58043-11	51883 04	47710 04	50208 01
3500 04	10000-07	58043-12	51883 04	47711 04	52953 01
3000 04	10000 06	30385 02	-97310 03	-10528 04	11605 01
3000 04	10000 05	30301 01	-96723 03	-10471 04	12238 01
3000 04	10000 04	30098-00	-95381 03	-10343 04	12897 01
3000 04	10000 03	29309-01	-90931 03	-99193 03	13670 01
3000 04	10000 02	25380-02	-67848 03	-77390 03	15108 01
3000 04	10000 01	15223-03	40963 03	25055 03	19676 01
3000 04	10000-00	13518-04	73872 03	55958 03	22104 01
3000 04	10000-01	12487-05	10620 04	86807 03	24597 01
3000 04	10000-02	96018-07	23798 04	21276 04	30676 01
3000 04	10000-03	78012-08	38057 04	34953 04	37595 01
3000 04	10000-04	68863-09	48861 04	45345 04	43767 01
3000 04	10000-05	67801-10	50256 04	46684 04	46960 01
3000 04	10000-06	67724-11	50355 04	46779 04	49737 01
3000 04	10000-07	67717-12	50365 04	46788 04	52485 01
2500 04	10000 06	36544 02	-11341 04	-12003 04	11019 01
2500 04	69283 05	25317 02	-11339 04	-12002 04	11117 01
2500 04	10000 05	37854 01	-14143 04	-14783 04	10594 01
2500 04	10000 04	40736-00	-13070 04	-13664 04	11570 01
2500 04	25448 03	92742-01	-11280 04	-11945 04	12628 01
2500 04	10000 03	36393-01	-11253 04	-11918 04	12888 01
2500 04	10000 02	36014-02	-11080 04	-11752 04	13572 01
2500 04	10000 01	33954-03	-10193 04	-10906 04	14559 01
2500 04	10000-00	24147-04	-41889 03	-51918 03	17710 01
2500 04	10000-01	16463-05	53018 03	38308 03	22708 01
2500 04	10000-02	16110-06	59952 03	44920 03	24357 01
2500 04	17377-03	26732-07	78930 03	63187 03	26187 01
2500 04	10000-03	14395-07	10082 04	83993 03	27422 01
2500 04	10000-04	11844-08	18843 04	16798 04	32651 01
2500 04	38213-05	40537-09	26984 04	24701 04	36734 01
2500 04	10000-05	97775-10	32791 04	30314 04	40332 01
2500 04	10000-06	84326-11	45436 04	42564 04	47856 01
2500 04	10000-07	81413-12	48689 04	45714 04	51870 01

Table 2--continued

Temperature, T (°K)	Pressure, P (atm)	Density, d (gm/cc)	Enthalpy, h (cal/gm)	Energy, u (cal/gm)	Entropy, s (cal/deg-gm)
2000 04	10000 06	20021 02	-14371 04	-15580 04	96238 00
2000 04	10000 05	45537 01	-16631 04	-17162 04	94995 00
2000 04	10000 04	58439 00	-16685 04	-17099 04	99925 00
2000 04	10000 03	58994-01	-16460 04	-16870 04	10577 01
2000 04	10000 02	55731-02	-15712 04	-16146 04	11434 01
2000 04	10000 01	47494-03	-13472 04	-13982 04	13090 01
2000 04	68297 00	31145-03	-12845 04	-13376 04	13503 01
2000 04	10000-00	45351-04	-12762 04	-13296 04	14056 01
2000 04	10000-01	43697-05	-12229 04	-12783 04	14945 01
2000 04	10000-02	34460-06	-84004 03	-91032 03	17556 01
2000 04	10000-03	20831-07	33528 03	21902 03	24530 01
2000 04	10000-04	20307-08	41038 03	29112 03	26271 01
2000 04	22550-05	45580-09	42821 03	30840 03	27250 01
2000 04	10000-05	18328-09	71293 03	58080 03	29186 01
2000 04	10000-06	15684-10	12291 04	10747 04	33441 01
2000 04	10000-07	15189-11	13648 04	12053 04	35932 01
1500 04	10000 06	14936 02	-17013 04	-18634 04	81309 00
1500 04	10000 05	56000 01	-18228 04	-18660 04	85827 00
1500 04	10000 04	77747 00	-18344 04	-18656 04	90431 00
1500 04	10000 03	80878-01	-18354 04	-18654 04	95020 00
1500 04	10000 02	81169-02	-18350 04	-18649 04	99633 00
1500 04	10000 01	81088-03	-18333 04	-18632 04	10433 01
1500 04	10000-00	80732-04	-18280 04	-18580 04	10927 01
1500 04	10000-01	79620-05	-18113 04	-18417 04	11502 01
1500 04	10000-02	76298-06	-17585 04	-17903 04	12329 01
1500 04	10000-03	67568-07	-15953 04	-16311 04	13930 01
1500 04	33336-04	20231-07	-14339 04	-14738 04	15283 01
1500 04	10000-04	60268-08	-14243 04	-14644 04	15668 01
1500 04	10000-05	56568-09	-13343 04	-13771 04	16899 01
1500 04	10000-06	38551-10	-65084 03	-71365 03	22217 01
1500 04	10000-07	27209-11	24251 03	15351 03	29413 01
1000 04	10000 06	15695 02	-18529 04	-20072 04	68960 00
1000 04	10000 05	72699 01	-19714 04	-20047 04	73785 00
1000 04	10000 04	11416 01	-19833 04	-20045 04	78384 00
1000 04	10000 03	12107-00	-19844 04	-20044 04	82962 00
1000 04	10000 02	12181-01	-19846 04	-20044 04	87537 00
1000 04	10000 01	12188-02	-19846 04	-20044 04	92112 00
1000 04	10000-00	12189-03	-19846 04	-20044 04	96687 00
1000 04	10000-01	12189-04	-19846 04	-20044 04	10126 01
1000 04	10000-02	12189-05	-19846 04	-20044 04	10584 01

Table 2--continued

Temperature, T (°K)	Pressure, P (atm)	Density, d (gm/cc)	Enthalpy, h (cal/gm)	Energy, u (cal/gm)	Entropy, s (cal/deg-gm)
1000 04	10000-03	12189-06	-19846 04	-20044 04	11041 01
1000 04	10000-04	12189-07	-19845 04	-20044 04	11499 01
1000 04	10000-05	12188-08	-19845 04	-20043 04	11957 01
1000 04	10000-06	12185-09	-19842 04	-20041 04	12417 01
1000 04	10000-07	12178-10	-19835 04	-20033 04	12883 01
5000 03	10000 06	16775 02	-19838 04	-21282 04	50857 00
5000 03	10000 05	10359 02	-21036 04	-21270 04	55671 00
5000 03	10000 04	21472 01	-21156 04	-21269 04	60270 00
5000 03	10000 03	24052-00	-21168 04	-21269 04	64847 00
5000 03	10000 02	24345-01	-21169 04	-21269 04	69422 00
5000 03	10000 01	24375-02	-21169 04	-21269 04	73997 00
5000 03	10000-00	24378-03	-21169 04	-21269 04	78572 00
5000 03	10000-01	24378-04	-21169 04	-21269 04	83146 00
5000 03	10000-02	24378-05	-21169 04	-21269 04	87721 00
5000 03	10000-03	24378-06	-21169 04	-21269 04	92296 00
5000 03	10000-04	24378-07	-21169 04	-21269 04	96871 00
5000 03	10000-05	24378-08	-21169 04	-21269 04	10145 01
5000 03	10000-06	24378-09	-21169 04	-21269 04	10602 01
5000 03	10000-07	24378-10	-21169 04	-21269 04	11060 01

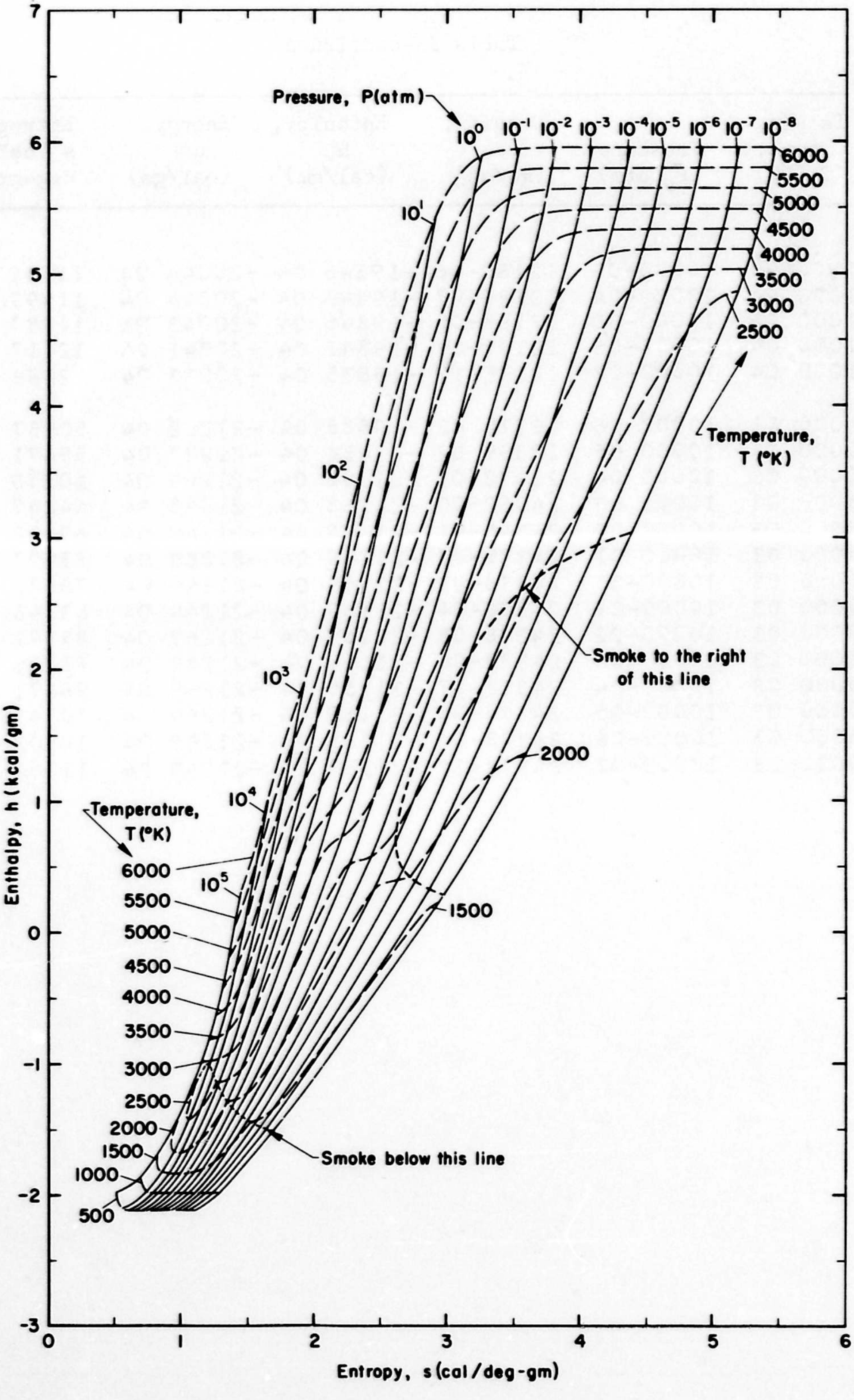

Fig. 1—Enthalpy versus entropy for Teflon with cross plots of temperature and pressure

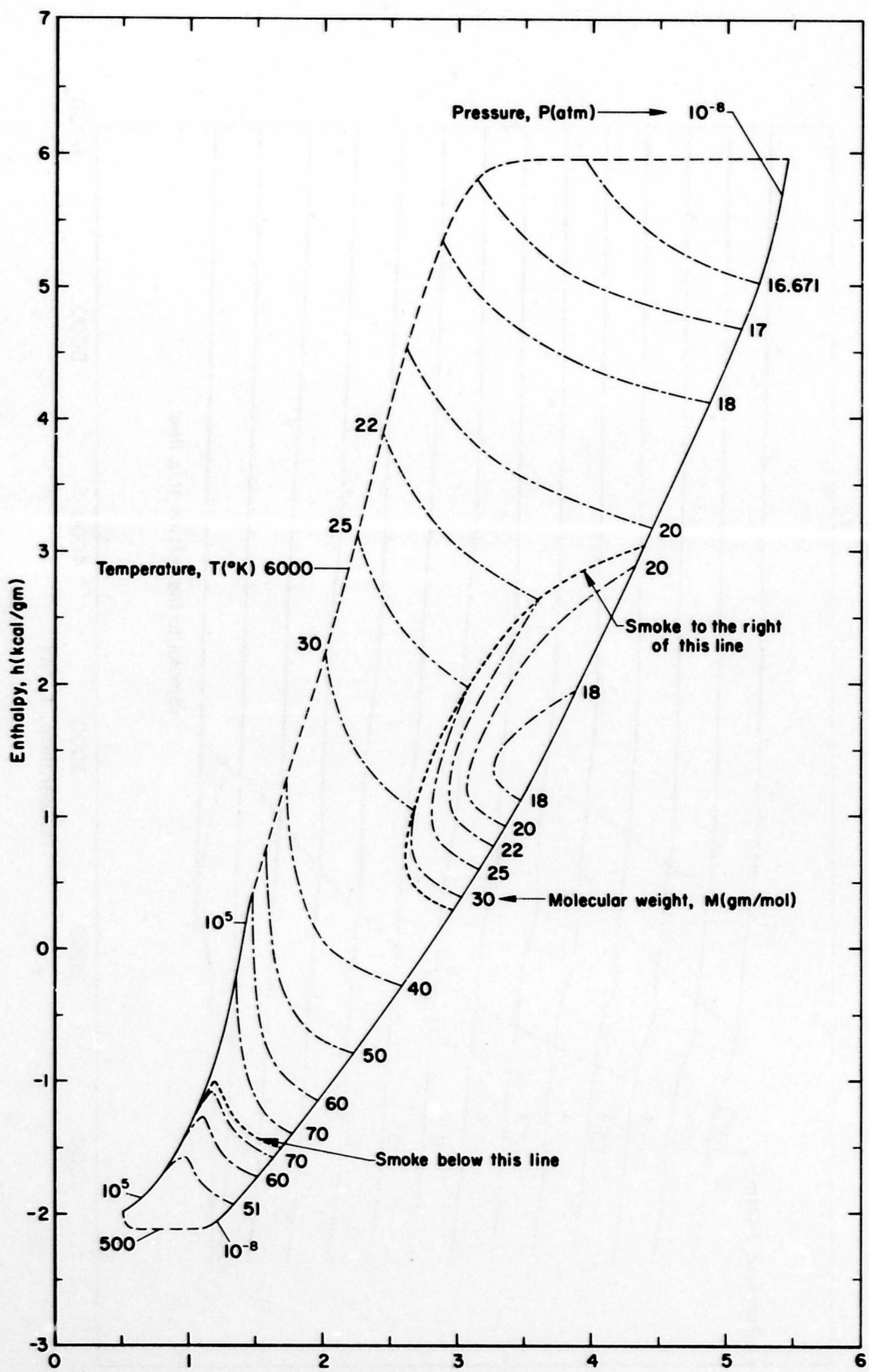

Fig. 2—Enthalpy versus entropy for Teflon with cross plots of constant molecular weight

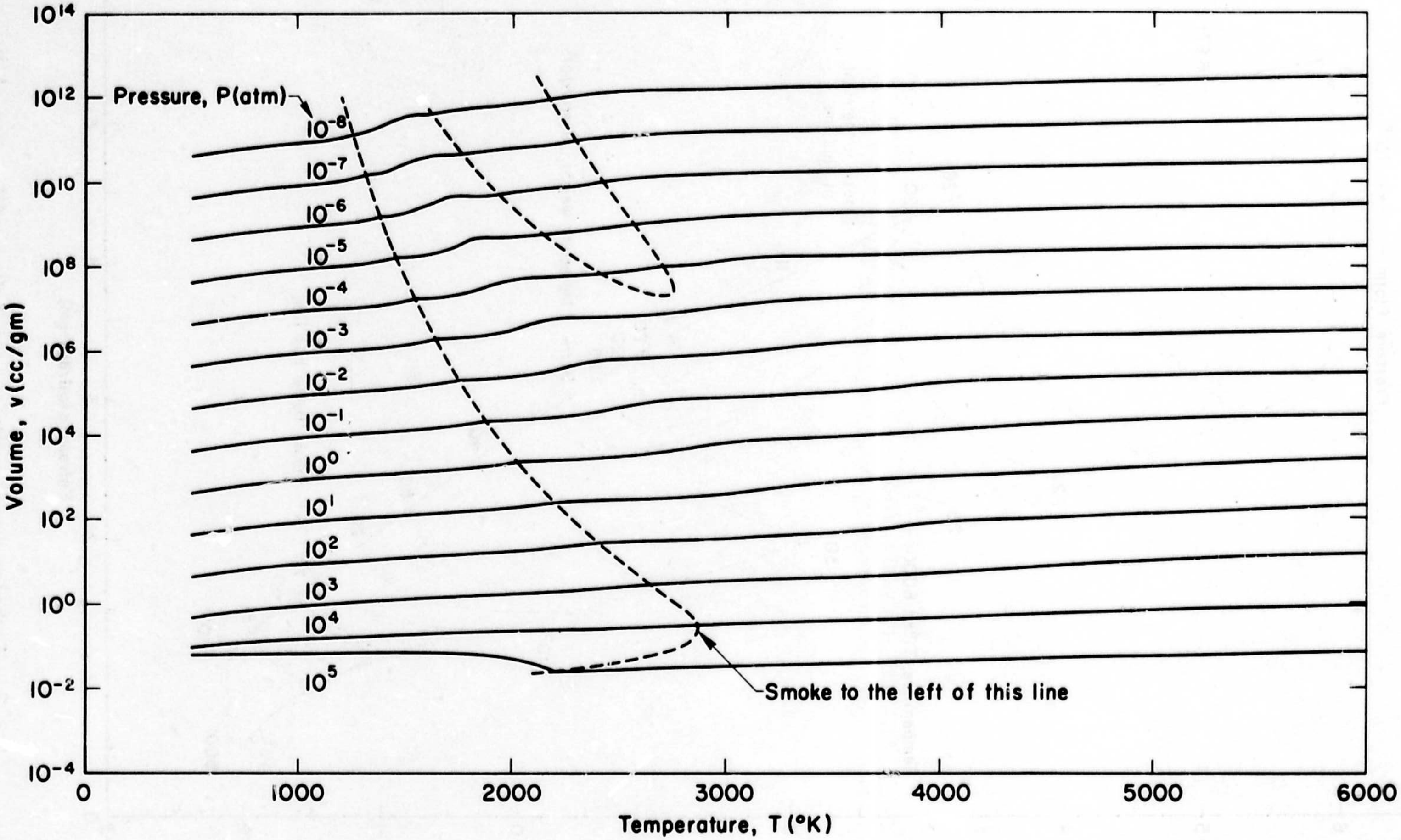

Fig. 3—Volume versus temperature for Teflon with cross plots of constant pressure

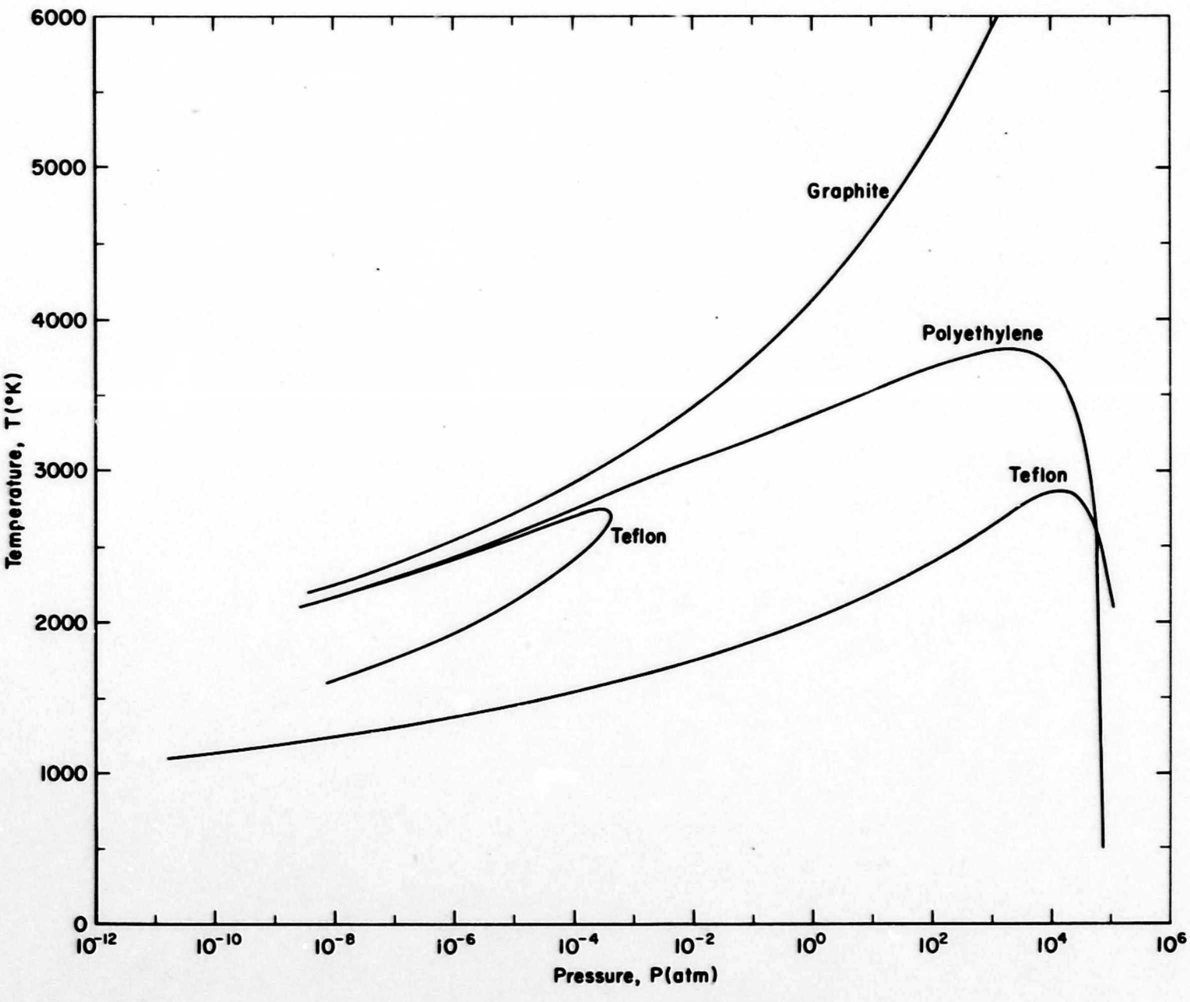

Fig. 4—Sublimation temperature for Teflon, polyethylene, and graphite at various pressures

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