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# PROJECT SQUID

TECHNICAL REPORT 37

THE HEAT CONDUCTIVITY, VISCOSITY, SPECIFIC HEAT  
AND PRANDTL NUMBERS FOR THIRTEEN GASES

Frederick G. Keyes

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MASSACHUSETTS INSTITUTE OF TECHNOLOGY  
Cambridge, Massachusetts

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P R O J E C T   S Q U I D

A Cooperative Program  
Of Fundamental Combustion Research  
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THE HEAT CONDUCTIVITY, VISCOSITY, SPECIFIC HEAT  
AND PRANDTL NUMBERS FOR THIRTEEN GASES

by

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## ABSTRACT

The experimental effort under the present contract is especially directed to obtaining measurements of heat conductivity at temperatures above the upper range of reported data. No measurements to temperatures approaching  $1000^{\circ}\text{C}$  are given in this report. However the execution of the design of the equipment is proceeding satisfactorily, and the necessary extensive theometric investigation will presently be in operation.

The results of several years of conductivity measurements for a number of gases are brought together in this report in the form of tables for thirteen gases, computed from formulations which include all available information. Data for the first temperature range in the case of the mixture  $\text{N}_2\text{-CO}_2$  are also given. Viscosities and specific heats are also included in the tables, all for zero pressure.

LIST OF SYMBOLS

R	gas constant $8.3144 \cdot 10^7$ ergs per $^{\circ}$ K per mole
$\bar{R}$	gas constant per unit weight
k	gas constant per molecule
M	molecular weight
N	number of molecules per unit weight or per mole
$n, n_1, n_2$	number of moles of species 1, 2, etc.
$x_1, x_2$	mole fractions of species 1, 2, etc.
p	pressure
v	volume of unit mass
E	energy
T	degrees Kelvin, $(273.16 + t^{\circ} \text{C})$
$\epsilon$	$T^{-1}$
$B_0$	second virial coefficient; $\Upsilon_0$ temperature portion
$\bar{A}$	virial constant divided by R
r	linear distance
$r_0$	distance from origin to intersection of potential curve with r axis
$\alpha_1, \alpha_2$	proportionality factors for rotational and vibrational energy transfer
b, $\beta$	van der Waals b from critical data; from p-v-T data
K	Enskog's function
$a_0, a, a_1$	constants of a viscosity formula (1)
$c_0, c, c_1$	constants of a heat conductivity formula
$C_p^0$	specific heat at "zero" pressure
$C_p$	specific heat at pressure p
$C_v$	specific heat at constant volume
$\rho$	density
$\lambda$	heat conductivity or coef. of $r^{-12}$ in L-J* intermolecular potential
$\eta$	viscosity
$\epsilon$	molecular potential energy at minimum
$\mu$	coefficient of $r^{-6}$ in the L-J* intermolecular potential
$\sigma$	molecular diameter

\*Lennard-Jones

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INTRODUCTION

The material contained in the present report brings together the results of an attempt to review critically the data found in the literature for the heat conductivity of the following gases: helium, argon, hydrogen, nitrogen, carbon monoxide, nitric oxide, oxygen, carbon dioxide, steam, nitrous oxide, ammonia, methane, and the natural mixture, air.

In the case of argon, nitrogen, oxygen, carbon dioxide, steam, ammonia, methane and air, new measurements have been carried out using the method of concentric cylinders described in detail in an earlier report. The new measurements were all carried out above  $0^{\circ}\text{C}$  and to about  $350^{\circ}\text{C}$ , the greater part under the Office of Naval Research, M.I.T. Contract N5ori-78. In some cases additional measurements are needed at low temperatures and the equipment for the work is now in operation under O.N.R., M.I.T. Contract N5ori-07855. The main tabulations in this report are for low, or formally, "zero" pressure values.

Pressure effects for heat conductivity have been measured for a few gases. In the case of viscosity some pressure effects have been reported in the literature. The specific heat of gases under pressure can be computed conveniently to moderate pressures in most cases, and the p-v-T data needed have been reformulated in the case of most gases and cover a considerable pressure and temperature.

The heat conductivity of mixtures is discussed only for the  $\text{N}_2\text{-CO}_2$  case for which well verified new measurements are now available to about  $350^{\circ}\text{C}$ , carried out under a project supported by the American Society of Mechanical Engineers. The existing theory does not account for the unexpected reversal of the sign of the deviation from the linear composition rule as the temperature increases.

The viscosity properties of mixtures appear to be less complex than for heat conductivity, and the predictions of theory seem to accord tolerably well with the facts. The specific heat pressure effects theory for mixtures is in principle solved and can be dealt with with reasonable assurance. This subject will be reported upon in detail separately. The three properties, heat conductivity, viscosity, and specific heat at constant pressure, are listed in Table 6 for each  $50^{\circ}\text{C}$  from low temperatures to  $1000^{\circ}\text{C}$ . Since extrapolation had to be invoked for tabulation to the latter temperature, each underlined figure in the tables denotes extrapolation by means of the formulating equation. The corresponding Prandtl numbers are also tabulated for each gas.

Following prolonged consideration, apparatus for carrying out measurements at higher temperatures, approximately  $1000^{\circ}\text{C}$ , has been designed and is now under construction. The high temperature apparatus cannot be used for measurements under pressures greater than atmospheric, whereas the low temperature and intermediate temperature equipment does make possible measurements under considerable pressure.

The conductivity data for each substance has been formulated in relation to temperature by using a three-constant empirical equation reminiscent of the two-constant Sutherland form, long in use for correlating viscosity data. The equation serves well for the monatomic and diatomic gases, perhaps less satisfactorily for carbon dioxide, and certainly not well without amendment for methane where the energy transport of nine normal modes of vibrational energy is in question. The data to be secured at higher temperatures will be valuable as a means of understanding more completely the role of vibrational energy transport in the case of those molecules whose vibrational frequencies are known.

The kinetic theory correlation of heat conductivity data requires a knowledge of the viscosity and its temperature dependence which explains the effort given to reviewing the reported data. Accordingly while no new measurements have been undertaken, the data for this property have been

brought together for painstaking correlation. In this report data are tabulated for the viscosity of the gases whose conductivities have been listed, and over the same temperature range, namely to 1000°C.

The heat capacity at constant volume is another property required for the interpretation and formulation of heat conductivity in current kinetic theory. Accordingly the constant pressure specific heats per mole for zero pressure are also listed, and finally the so-called Prandtl number  $(c_p \eta / \lambda)_0$ , where  $c_p$  represents heat capacity,  $\eta$  viscosity, and  $\lambda$  heat conduction.

#### Comments on the Tables of Heat Conductivity, Viscosity, and Heat Capacity

The new measurements of heat conductivity which have been made in connection with the material tabulated in this report are for argon, nitrogen, oxygen, carbon dioxide, steam, ammonia, methane and air, extending from room temperature to about 350°C (1). New measurements are also desirable at low temperatures for most gases in order to obtain the factual basis needed to gain greater insight into the mechanism of transfer of molecular rotational energy. The translational energy transfer mechanism given by the kinetic theory is well substantiated by the existing facts for monatomic gases.

It is well known that rotational energy, of the diatomic gases for example, is nearly fully excited at room temperature. At lower temperatures the rotational increment in the case of the specific heat diminishes progressively to zero, leaving the molecule in a state equivalent to that of a monatomic gas with constant volume specific heat  $3/2 R$  per mole. The only diatomic gas whose zero rotational state is substantially zero under accessible experimental conditions is hydrogen. In this case the zero rotational state appears to leave the hydrogen molecule in the condition of a true monatomic gas from the point of view of the heat conductivity; namely it obeys the relation  $\lambda = 2.5 C_v \eta$ , where  $\lambda$  is the heat conductivity,  $C_v$  the constant volume specific heat, and  $\eta$  the viscosity. The course of the above ratio is represented in fig. 1. Further details about this relationship will be given below.

Recently (2, 3) in the case of gaseous viscosity the intermolecular potential form  $E(r) = \lambda r^{-12} - \mu r^{-6}$  has been employed for computing the relevant integrals which arise from the application of the potential in the Maxwell-Boltzmann general transport equation. From the tabulated values of the latter integrals, the viscosity may be readily computed as a function of temperature after finding the value of  $\lambda$  and  $\mu$ , the potential constants, from two pairs of values of viscosity-temperature (4), or independently of viscosity data from accurate second virial coefficients for the gas interpreted through the use of the form  $E(r)$ .

A search of the literature for viscosity data has been followed by a critical examination of the material in the course of which a three-constant empirical form (4) was used for formulation which appears to be sufficient for the representation of the results. The viscosity equation follows:

$$\eta \cdot 10^5 = a_0 \sqrt{T} / 1 + a_1 \cdot 10^{-a_1} T^{-1} \quad (1)$$

where  $a_0$ ,  $a_1$  and  $a_2$  are constants, and  $T$  and  $T^{-1}$  are respectively thermodynamic temperature and its reciprocal ( $T^{-1}$ ).

An interesting example of the applicability of equation (1) is the case of air where considerable data by a number of different observers exist. The temperature range of data runs from  $90^\circ$  to  $1845^\circ\text{K}$ . Figure 2 gives a survey of the data from  $51^\circ$  to  $1572^\circ\text{C}$ , relative to a line determined from the constants of equation 1 using the data from  $90^\circ$  to  $300^\circ\text{K}$ . It is evident that the higher temperature data are well represented by virtual extrapolation from the low temperature region. In the case of argon similar extrapolation does not proceed as satisfactorily and the viscosity by extrapolation is smaller by about 7 per cent at  $1600^\circ\text{K}$  relative to the data reported by Vasilescu (5). The viscosity of carbon dioxide by similar extrapolation failed by much less at high temperature while the low temperature nitrogen values of viscosity extrapolated with the equation about as satisfactorily as did air.

The application of the collision integrals for computing the viscosity of carbon dioxide indicates a systematic drift of the constants  $\epsilon/k$  and  $r_0 = (\lambda/\mu)^{1/6}$ \* in the direction of a trend to smaller values with rising temperatures. For example selecting the values of the constants from the low temperature experimental data for the viscosity of  $\text{CO}_2$  as given by Hirschfelder, Bird and Spatz (3) leads to viscosity values at 1000°K and higher, about 3 per cent larger than the reported data of Vasilesco and somewhat greater in the case of Bremond. Figure 3 gives a survey of the relationships. In the absence of reliable measurements of viscosity at high temperatures in the case of non-polar molecules, the collision integral tables provide a valuable means of extrapolation to high temperatures using the constants derived from lower temperature viscosity values.

The Tabulated Data The constants of the formulating equation for heat conductivity are contained in the table 1. The equation is of the same form as equation 1, with  $c_0$  substituted for  $a_0$ ,  $c$  for  $a$ , and  $c_1$  for  $a_1$ .

The heat conductivity at "zero" pressure can be represented to the accuracy of the data in the case of all the monatomic and diatomic gases. It appears also to be satisfactory for carbon dioxide and steam, but not as satisfactory for methane. The representation of the conductivity of the more complex molecules by an analytical form in the case of molecules having many modes of vibration may understandably not be as simple as it is for the diatomic molecules whose vibrational frequencies are of high frequency. The contribution of this vibrational energy transport is small until high temperatures are reached. In the case of a molecule of which methane is an example, having relatively simple structure, there are

\* The potential  $E(r) = \lambda r^{-12} - \mu r^{-6}$  may be expressed in terms of  $r_0$  and  $\epsilon/k$  where  $r_0$  is the distance along the  $r$  axis or abscissae to the point of intersection of the potential curve, while  $\epsilon$  is the value of  $E(r)$  at the minimum of the potential curve and  $k$  is the gas constant per molecule. Using these values  $E(r)$  may be written  $E(r) = -4\epsilon \left[ (r_0/r)^{12} - (r_0/r)^6 \right]$  and  $r_0 = (\lambda/\mu)^{1/6}$   $\epsilon = (\mu^2/4\lambda)$ .

(3n-6) normal modes and the fraction of vibrational energy to be transported is much greater than for carbon dioxide.

The kinetic theory as already stated leads to the following equation for heat conductivity:

$$\lambda = \text{constant} \times C_v \times \eta \quad (2)$$

where  $C_v$  is the constant volume specific heat and  $\eta$  the viscosity. The "constant" depends on the particular model considered, but all plausible models lead to a value not far from  $5/2$ .

In the case of the monatomic gases the available data indicates that the specific heat at "zero" pressure conforms to the prediction of the kinetic theory; namely  $3/2 R$ , where  $R$  is the universal gas constant. The viscosity is however temperature dependent for all molecules, and in the case of field free reflecting spheres varies as the square root of the thermodynamic temperature. Where the intermolecular field is of the van der Waals type, the Sutherland equation is obtained. In all cases examined, however, a modified Sutherland form appears to represent the observed data over long ranges of temperature as indicated in the case of air.

It appears therefore that the dependence of the heat conductivity upon temperature in the case of monatomic gases is identical with the temperature dependence exhibited by the viscosity. It has not been found possible, however, to represent the whole temperature range of available viscosity data for argon with a single form (table 2). The heat conductivity data for argon which have been augmented by new measurements are nevertheless representable by the form, equation 1, but the constants are not identical with the viscosity constants. The same situation exists qualitatively with respect to helium. Admittedly the heat conductivities are much less accurately known than the viscosities, but the temperature dependence of the viscosity values appears more complex in the case of helium and argon than the viscosity of the diatomic gases. It is evident that the situation can be clarified only by further measurements of the heat conductivity of argon and helium at lower temperatures, and possibly also of the viscosity.

In the case of diatomic gases there are two degrees of rotational energy and one degree of vibrational energy (  $(3n-5)$  normal modes) for a linear molecule of  $n$  atoms. The vibrational energy does not however become appreciable until above room temperature. For hydrogen the variation of the rotational energy is from small values at low temperatures to full excitation in the accessible measurement range in consequence of the very small moment of inertia of the rotating molecule. This latter circumstance is fortunate because it leads to some insight into the transfer of the energy of rotation in heat conduction.

The assumption was made long ago by Eucken (6) that the same form of expression, equation 2, held for the rotational energy and vibrational energy as for the translational energy. Employing this assumption, the following equation could be written:

$$\lambda = 5/2 C_t \eta + \alpha_1 C_r \eta + \alpha_2 C_{vib} \eta$$

$$\text{or } \lambda/\eta = 5/2 C_t + \alpha_1 (C_r/C_t) C_t + \alpha_2 (C_{vib}/C_t) C_t \quad (3)$$

On this basis we would be constrained to write the specific heat  $C_v$  as  $C_v = C_t(1 + \beta)$  where  $C_t$  is the translational part of the specific heat and  $\beta$  is the ratio of the sum of the rotational and vibrational energy to the translational component. Except as an approximation it is well known that such a summation is never justified.

On the basis of the foregoing we may now write the following equation embodying the Eucken assumption:

$$F = \lambda/C_v \eta = \left[ 1/(1 + \beta) \right] (5/2 + \alpha_1 \beta_r + \alpha_2 \beta_{vib}) \quad (4)$$

where  $\beta_r$  represents  $C_r/C_t$  in equation 3 and similarly  $\beta_{vib}$  represents  $C_{vib}/C_t$ . It will be observed that the kinetic theory gives no information regarding the quantities  $\alpha_1$  or  $\alpha_2$ . Moreover the empirical determination of  $\alpha_1$  and  $\alpha_2$  is at present beset with difficulties due to the lack of accurate data at low and at high temperatures. The device to be described

below can be justified as a special means for correlating present data for practical purposes pending the accumulation of information in temperature ranges suited to giving significant empirical indication regarding  $\alpha_1$  and  $\alpha_2$  or related quantities.

It is a fact that the heat conductivity of the monatomic and diatomic gases can be favorably correlated as a function of temperature by an equation in form identical with equation 1 (He is a partial exception). Thus for example in the case of air the available data prior to 1951 extended from  $-183^\circ$  to about  $300^\circ\text{C}$ , and the constants of the formulation are given in table 1. Recently new values were obtained by Glassman and Bonilla\* to high temperatures and it was found that values computed using the constants for air were in agreement with the results deduced from the high temperature measurements to about 3 per cent at  $2500^\circ\text{K}$ . In this instance the vibrational component is not large relative to the sum of the translational and vibrational components even at the latter temperature.

For methane the situation is quantitatively different for the molecule has 9 normal modes of vibration and appreciable amounts of vibrational energy appear below  $273^\circ\text{K}$  while at  $800^\circ\text{K}$  the vibrational energy exceeds the total of translational and rotational energy. It is found that representation by the type of formula satisfactory for the diatomic gases fails for methane.

To represent the methane data, the lowest available temperature data were used to determine the constants  $c_0$ ,  $c$  and  $c_1$  representing the heat conductivity in the region where translational and rotational energy transfer are almost wholly dominant. Utilizing the higher temperature values of the heat conductivity, it then becomes possible to compute the quantity  $\alpha_2$  from equation 3 for each temperature of heat conductivity observation. Empirically it appears that  $\alpha_2$  is proportional to Kelvin temperature as given in the note under table 1. A similar procedure was employed to represent

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\* Preprint only available; Heat Transfer Symposium, Am.Inst.Ch. Eng. Dec. 1951.

the higher temperature values for  $N_2O$ . It is believed that in view of the linear relation between  $\alpha_2$  and temperature, extrapolation to higher temperatures might be made with confidence.

Pressure Effects The theory of the pressure effect for both viscosity and heat conductivity has been given by Enskog (7) using the van der Waals concept of the intermolecular field. The application to heat conductivity was discussed in a recent paper (8) in which it was shown that to a first approximation the Enskog form, equation 4, represented the new data for  $N_2$  and  $CO_2$  at low pressures. Moreover in the case of  $N_2 - CO_2$  mixtures, first order pressure effects could be simply computed.

$$\lambda_p/\lambda_o = 1/K + 6/5 b\rho + 0.7574 b^2\rho^2K \quad (4)$$

$$K = 1 + 5/8 b\rho + 0.29 b^2\rho^2$$

In equation 4, b represents the van der Waals quantity four-fold the volume of the molecules of unit mass of gaseous substances or  $2/3 N\pi\sigma^3$  where  $\sigma$  represents the molecular diameter,  $\rho$  representing the density. The values of b however obtained from reliable p-v-T data proved to be smaller, 0.63 to 1, relative to b from the pressure coefficient for low pressures using equation 4. To the first power of pressure equation 4 may be written

$$\lambda_p/\lambda_o = 1 + 0.575 b (M/R) p \zeta \quad (5)$$

where M is the molecular weight, R the gas constant per mole (82.06 for cc per mole, atm,  $^{\circ}K$ ), b is the van der Waals four-fold volume of the molecules and  $\zeta$  denotes  $T^{-1}$ . Values of the coefficient (0.575 b M/R) will be found in table 3 for several gases.

The pressure effect equation for viscosity is given by Enskog (8) for viscosity and is in form identical with equation 4 above, except that the factor 6/5 before  $b\rho$  becomes 4/5. The first order equation for viscosity therefore becomes

$$\eta_p/\eta_0 = 1 + 0.175 b (M/R) p \quad (6)$$

Table 4 gives the pressure coefficient  $0.175 b (M/R)$  for several gases.

The pressure effect to pressures of 100 atm for viscosity have been reported upon by E. W. Comings, B. J. Mayland and R. S. Egly (9) and measurements of thermal conductivity of gases at similar high pressure have been made by J. M. Lenoir (10). In both these reports the correlation of pressure effects suggested by the van der Waals corresponding states theory is discussed. The relation of these results to the measurements of F. G. Keyes and D. J. Sandell, Jr. (11) for  $CO_2$  and  $N_2$  have also been cited (8) and the measurements of both groups of independent observers shown to be in good accord, in the case of heat conductivity of nitrogen to about 200 atm. The measurements did not extend to as high pressures in the case of the pressure effect for  $CO_2$  reported by Keyes (8). For steam the pressure effect found by Keyes and Sandell is less than reported by D.L. Timroth and Vargaftig (12).

The pressure effect for heat capacity rests on an assured basis. For "zero" pressure,  $C_p^0$ , the heat capacity of a binary or multicomponent mixture is given by the linear relation following equations where  $x_1, x_2, \dots$  represent mole fractions.

$$\begin{aligned} [C_p^0] &= C_p^0 (1) x_1 + C_p^0 (2) x_2 \\ [C_p^0] &= \sum_1^n C_p^0 (1) x_1 \end{aligned} \quad (7)$$

A pure gas under pressure is governed by the following thermodynamic equations:

$$\begin{aligned} C_p &= C_p^0 - \int_0^p T (\partial^2 v / \partial T^2) dp \\ C_p &= C_v^0 + T (\partial p / \partial T) \cdot (\partial v / \partial T) + \int_0^v T (\partial^2 p / \partial T^2) dv \end{aligned} \quad (8)$$

The second members of equation 8 require a knowledge of the equation of state of the pure gases and in the case of mixtures the equation of state of every mixture of interest. The application of equations 8 will be discussed for the case of a first approximation.

The equation of state to a first approximation may be written:

$$p = \bar{R}T/(v - B_0) \quad (9)$$

where  $\bar{R}$  represents the gas constant divided by the molecular weight,  $v$  representing the volume of unit weight and  $B_0$  a temperature function (second virial coefficient).

The form of  $B_0$  has been shown to be as follows in mole units for many gases (13, 14, 15) (He, N,  $H_2$  are exceptions) including polar gases.

$$B_0 = \beta - \psi_0$$

$$\psi_0 = \bar{A} e^{-c_2 \tau^2} \quad (10)$$

where  $\beta = 2/3 N\pi \sigma^3$  corresponding to van der Waals  $b$ , and  $\bar{A} = A/R$ ,  $\bar{A}$  is a constant and  $c_2$  likewise. The equation for  $C_p$  then becomes:

$$C_p = C_p^0 + 2\tau\psi_0 (1 + 5c_2\tau^2 + 2c_2\tau^4) \quad (11)$$

where  $\tau$  represents reciprocal temperature.

In the case of mixtures  $[B_0]$  may be assumed given by the following expression (16, 17)

$$[B_0] = \sum n_1 \left[ \sum \beta_1 x_1 - \left( \sum A_1^{1/2} x_1 \right)^2 / R \right] \tau e^{-\sum (c_2(1)^{1/2} x_1)^2 \tau^2} \quad (12)$$

where  $x_1, x_2 \dots$  are the mole fractions and  $n_1, n_2, n_3 \dots$  the number of moles of species 1, 2, ...

The equation 12 for high temperatures becomes

$$[B_0] = \sum n_1 \left[ \sum \beta_1 x_1 - (\sum A_1^{1/2} x_1)^2 / R T \right],$$

which can be shown to follow from the assumption that  $\beta_{12} = 1/2 (\beta_1 + \beta_2)$ ,

$$A_{12} = (A_1 A_2)^{1/2}.$$

The Heat Conductivity of Mixtures There are a number of heat conductivity measurements for binary mixtures, (twenty) to be found in the literature, and A. L. Lindsay and L. A. Bromley (18) have developed a formula which represents the mixtures with tolerable accuracy. There appear to be no measurements reported for ternary or higher order mixtures.

The measurements made under the present general program were supported and sponsored by the American Society of Mechanical Engineers (8) referred to briefly above. During the past year the earlier measurements have been repeated, and with extension to higher temperatures (550°C). The results are exhibited graphically in fig. 4. It will be observed that relative to a linear relation between composition and heat conductivity, the sign of the deviation changes. The Enskog theoretical formula fails to reproduce the shift in sign as does also the Lindsay and Bromley formula.

Each mixture composition is representable by the same type of equation used to represent the pure gases. The direct plot, fig. 5, of  $c_0$  and  $c$  versus composition is non-linear and inconvenient for composition interpolation or to extrapolate to higher temperatures. The equation can also be expressed in the form  $\sqrt{T}/\lambda = 1/c_0 + c/c_0 e^{-c_1}$  and from the insert plot on fig. 5 it appears that the values of  $1/c_0$  and  $c/c_0$  for pure gases and mixtures are approximately linear in composition for  $N_2$ - $CO_2$ . When higher temperature data are available it will be of interest to determine whether the linear relationship for the  $1/c_0$ 's and the  $c/c_0$ 's predict the measured values with tolerable accuracy.

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Table 1. Equation Constants for Heat Conductivity at Low Pressure

Units: cal per cm per sec per °C.

	$c_0 \cdot 10^5$	c	$c_1$	Temp. range deg K
He	2.350	43.5	10	15 - 375
A	0.388	186.7	10	90 - 620
H <sub>2</sub>	3.760	166.0	10	90 - 595
CO	0.586	218.0	7.8	90 - 375
N <sub>2</sub>	0.604	224.0	12	90 - 773
NO	0.646	264.9	12	130 - 377
O <sub>2</sub>	0.673	266.0	10	90 - 375
H <sub>2</sub> O	1.546	1737.0	12	373 - 823
N <sub>2</sub> O(a)*	1.248	1523.0	10	
CO <sub>2</sub> (c)	3.333	4433.0	10	190 - 592
NH <sub>3</sub> (b)*	2.110	1719.0	12	215 - 347
CH <sub>4</sub>	0.877	307.0	10	96 - 201
Air	0.632	245.0	12	90 - 584

$$(a) \text{ N}_2\text{O} \quad 190\text{-}378^\circ\text{K} \quad 10^5 \lambda = \frac{1.248 \sqrt{T}}{1 + 1523 \beta / 10^{10} \beta} + \frac{1.555 \times 10^{-3} T \beta_{\text{vib}} C_v \eta \cdot 10^5}{1 + \beta}$$

$$(b) \text{ CH}_4 \quad 96\text{-}574^\circ\text{K} \quad 10^5 \lambda = \frac{0.877 \sqrt{T}}{1 + 307 \beta / 10^{10} \beta} + \frac{2.23 \times 10^{-3} T \beta_{\text{vib}} C_v \eta \cdot 10^5}{1 + \beta}$$

(c) The correlation of values of NH<sub>3</sub> to higher temperatures has not been completed.

\* The temperature course of the heat conductivity of N<sub>2</sub>O and CH<sub>4</sub> is not well represented by the form of equation 1 over the entire range. Experience indicates however that the equation is satisfactory until the vibrational degrees of freedom begin to be appreciably excited. The second terms of the right hand members of the above equations were formulated from the available specific heat and viscosity data. It will be noted that the coefficient  $\alpha_2$  of equation 3 is proportional to temperature, and not constant as generally assumed.

Table 2 Equation Constants for Viscosity at Low Pressure

Unit:  $10^5$  poises

	$a_0 \cdot 10^5$	a	$a_1$	Temp. range deg K
He (a)				
A (a)				
H <sub>2</sub> (a)				
CO	1.495	143.2	6	80 - 550
N <sub>2</sub> (b)	1.418	116.4	5	81 - 1695
NO	1.587	127.6	0	118 - 300
O <sub>2</sub>	1.739	142.0	5	72 - 550
H <sub>2</sub> O	1.501	446.8	0	373 - 873
N <sub>2</sub> O	1.531	239.4	2	185 - 550
CO <sub>2</sub>	1.554	246.0	3	198 - 1686
NH <sub>3</sub>	1.715	667.1	20	194 - 680
CH <sub>4</sub>	1.103	232.5	12.5	78 - 373
Air	1.488	122.1	5	79 - 1845

(a) The viscosity data for helium, argon and hydrogen cannot be represented by the formula over the whole range of temperature using a single set of constants. The information following is the best that can be provided at this time.

He 1.64-20°K  $10^5 \eta = 0.848 \sqrt{T} / (1 + 1.5936)$

He 20-140°K  $\log (10^5 \eta) = 1.722 + 0.6268 \log T$

He 140-373°K  $10^5 \eta = 1.805 \sqrt{T} / (1 + 2536/10^{506})$

A 55-273°K  $10^5 \eta = 2.173 \sqrt{T} / (1 + 218.46/10^{146})$ ; deviation 2.2 per cent at 55°K; about 0.6 per cent otherwise.  
Johnston and Grilly maximum deviation 0.36 per cent.

A 180-1873°K  $10^5 \eta = 1.910 \sqrt{T} / (1 + 136.66)$ . Largest deviation 1.5 per cent for Kopsch data, 140-294°K.

H<sub>2</sub> 14-90°K  $10^5 \eta = (0.507 \sqrt{T}) / (1 + 21.86)$

H<sub>2</sub> 90-550°K  $10^5 \eta = (0.623 \sqrt{T}) / (1 + (70.86/10^{17.36}))$

(b) The equation which best represents Vasilesco's data is

$$10^5 \eta = (1.411 \sqrt{T}) / (1 + (115.86/10^{56}))$$

Table 3 Heat Conductivity Pressure Coefficients

Gas	$\frac{\lambda - \lambda_0}{\lambda_0}$
N <sub>2</sub>	0.462 p <sup>β</sup>
CO <sub>2</sub>	0.86 p <sup>β</sup>
CH <sub>4</sub>	0.723 p <sup>β</sup>

The above coefficients deduced from data are each much larger than follow from using the values of  $\beta$  derived from p-v-T data in Enskog's theoretical coefficient, namely

$$\frac{23}{40} \frac{M}{R} \beta.$$

Table 4 Viscosity Pressure Coefficients

Gas	$\frac{\eta - \eta_0}{\eta_0}$
H <sub>2</sub>	0.0734 p <sup>β</sup>
N <sub>2</sub>	0.302 p <sup>β</sup>
CO <sub>2</sub>	0.935 p <sup>β</sup>
CH <sub>4</sub>	0.497 p <sup>β</sup>

The above coefficients are not reconcilable with the observed coefficients for heat conductivity in terms of Enskog's equations. The ratio of the coefficients should be less by the order of a third for the viscosity.

Table 5 Values of Equation of State Virial Constants

Units: atm, cc per gm, °K.

	$B$	$\bar{A}$	$C_2 \cdot 10^5$	$\bar{R}$
$N_2^*$				
$CO_2$	1.767	1106	0.1727	1.8644
$H_2O$	2.061	2902	1.7094	4.5547
$NH_3$	2.124	2010	0.8956	4.8178

\* The equation obtained for  $N_2$  for the virial coefficient is:

$$B_0 T^{1/4} = 10.08 - 766.115 \underline{B}^{3/4} - 1.7545 \underline{B}^{15/4}$$

Table 6 The Heat Conductivity, Viscosity, Specific Heat and Prandtl Numbers for Thirteen Gases

Units for conductivity: calories (4.186 ergs) per cm. per sec.  
per °C. x  $10^5$

Units for viscosity: poises x  $10^5$

Units for specific heat: calories (4.186 ergs) per mole per °C.

Underlined figures signify extrapolated values.

Table 6

<u>t °C</u>	<u>He (4.003)</u>				<u>A (39.944)</u>			
	<u><math>\lambda \cdot 10^5</math></u>	<u><math>\eta \cdot 10^5</math></u>	<u><math>C_p^o</math></u>	<u>Pr</u>	<u><math>\lambda \cdot 10^5</math></u>	<u><math>\eta \cdot 10^5</math></u>	<u><math>C_p^o</math></u>	<u>Pr</u>
-200	13.99	7.77	4.97	0.69	<u>1.16</u>	6.36	4.97	0.68
-150	20.14	10.77	4.97	.66	1.91	10.20	4.97	.66
-100	25.31	13.57	4.97	.67	2.62	13.97	4.97	.66
-50	29.81	16.13	4.97	.67	3.31	17.58	4.97	.66
0	33.83	18.56	4.97	.68	3.93	20.93	4.97	.66
50	37.49	20.97	4.97	.69	4.54	24.13	4.97	.66
100	40.86	23.29	4.97	.71	5.09	27.00	4.97	.66
150	<u>43.99</u>	<u>25.57</u>	4.97	.72	5.63	29.70	4.97	.66
200	<u>46.94</u>	<u>27.73</u>	4.97	.73	6.13	32.24	4.97	.65
250	<u>49.72</u>	<u>29.77</u>	4.97	.74	6.62	34.64	4.97	.65
300	<u>52.37</u>	<u>31.82</u>	4.97	.75	7.08	36.93	4.97	.65
350	<u>54.89</u>	<u>33.76</u>	4.97	.76	<u>7.52</u>	39.11	4.97	.65
400	<u>57.39</u>	<u>35.63</u>	4.97	.77	<u>7.94</u>	41.20	4.97	.64
450	<u>59.71</u>	<u>37.45</u>	4.97	.78	<u>8.35</u>	43.20	4.97	.64
500	<u>61.96</u>	<u>39.22</u>	4.97	.79	<u>8.75</u>	45.13	4.97	.64
600	<u>66.23</u>	<u>42.60</u>	4.97	.80	<u>9.49</u>	48.80	4.97	.64
700	<u>70.24</u>	<u>45.81</u>	4.97	.81	<u>10.20</u>	52.25	4.97	.64
800	<u>74.04</u>	<u>48.86</u>	4.97	.82	<u>10.87</u>	55.50	4.97	.64
900	<u>77.66</u>	<u>51.78</u>	4.97	.83	<u>11.50</u>	58.60	4.97	.63
1000	<u>81.12</u>	<u>54.59</u>	4.97	.83	<u>12.11</u>	61.54	4.97	.63

Table 6 - continued

<u>t<sup>o</sup>C</u>	<u>H<sub>2</sub>(2.016)</u>				<u>CO (28.010)</u>			
	<u>λ.10<sup>5</sup></u>	<u>η.10<sup>5</sup></u>	<u>c<sub>p</sub><sup>o</sup></u>	<u>Pr</u>	<u>λ.10<sup>5</sup></u>	<u>η.10<sup>5</sup></u>	<u>c<sub>p</sub><sup>o</sup></u>	<u>Pr</u>
-200	12.13	3.41	5.09	0.71	1.51	4.88	6.95	0.80
-150	19.73	4.88	5.73	.70	2.57	8.14	6.95	.78
-100	26.94	6.19	6.31	.72	3.62	11.16	6.95	.77
-50	33.66	7.36	6.67	.72	4.61	13.93	6.95	.75
0	39.92	8.41	6.84	.71	5.55	16.49	6.95	.74
50	45.77	9.38	6.93	.70	6.44	18.87	6.97	.73
100	51.26	10.28	6.96	.69	7.28	21.08	6.99	.72
150	56.45	11.12	6.98	.68	<u>8.08</u>	23.16	7.02	.72
200	61.35	11.91	6.99	.67	<u>8.84</u>	25.13	7.08	.72
250	66.03	12.66	7.00	.67	<u>9.56</u>	27.00	7.14	.72
300	70.48	<u>13.37</u>	7.00	.66	<u>10.26</u>	<u>28.77</u>	7.22	.72
350	<u>74.74</u>	<u>14.05</u>	7.01	.65	<u>10.93</u>	<u>30.47</u>	7.30	.73
400	<u>78.84</u>	<u>14.71</u>	7.03	.65	<u>11.57</u>	<u>32.10</u>	7.39	.73
450	<u>82.72</u>	<u>15.33</u>	7.05	.65	<u>12.18</u>	<u>33.66</u>	7.47	.74
500	<u>86.52</u>	<u>15.94</u>	7.07	.65	<u>12.78</u>	<u>35.17</u>	7.56	.74
600	<u>93.81</u>	<u>17.09</u>	7.12	.64	<u>13.91</u>	<u>38.04</u>	7.72	.75
700	<u>100.6</u>	<u>18.17</u>	7.20	.65	<u>14.99</u>	<u>40.73</u>	7.87	.76
800	<u>107.0</u>	<u>19.19</u>	7.29	.65	<u>16.00</u>	<u>43.28</u>	7.99	.77
900	<u>113.1</u>	<u>20.16</u>	7.38	.65	<u>16.97</u>	<u>45.69</u>	8.10	.78
1000	<u>119.0</u>	<u>21.09</u>	7.48	.66	<u>17.89</u>	<u>48.00</u>	8.20	.79

Table 6 - continued

<u>t<sup>o</sup>C</u>	<u>N<sub>2</sub> (28.016)</u>				<u>NO (30.008)</u>			
	<u>λ.10<sup>5</sup></u>	<u>η.10<sup>5</sup></u>	<u>c<sub>p</sub><sup>o</sup></u>	<u>Pr</u>	<u>λ.10<sup>5</sup></u>	<u>η.10<sup>5</sup></u>	<u>c<sub>p</sub><sup>o</sup></u>	<u>Pr</u>
-200	1.67	5.14	6.95	0.76	<u>1.59</u>	<u>4.95</u>	7.80	0.81
-150	2.72	8.46	6.95	.77	2.64	8.65	7.60	.83
-100	3.78	11.45	6.95	.75	3.69	12.02	7.37	.80
-50	4.78	14.17	6.95	.74	4.71	15.08	7.24	.77
0	5.74	16.64	6.95	.72	5.69	17.88	7.16	.75
50	6.64	18.92	6.96	.71	6.63	20.45	7.14	.73
100	7.49	21.03	6.97	.70	<u>7.52</u>	22.85	7.15	.72
150	8.31	23.01	7.00	.69	<u>8.38</u>	25.08	7.19	.72
200	9.09	24.87	7.03	.69	<u>9.20</u>	27.19	7.25	.71
250	9.83	26.64	7.09	.69	<u>9.98</u>	29.18	7.33	.71
300	10.54	28.31	7.15	.69	<u>10.74</u>	<u>31.08</u>	7.43	.72
350	11.22	29.91	7.22	.69	<u>11.46</u>	<u>32.88</u>	7.52	.72
400	11.88	31.45	7.29	.69	<u>12.17</u>	<u>34.61</u>	7.61	.72
450	<u>12.52</u>	32.92	7.37	.69	<u>12.84</u>	<u>36.28</u>	7.71	.73
500	<u>13.13</u>	34.34	7.45	.70	<u>13.50</u>	<u>37.88</u>	7.79	.73
600	<u>14.30</u>	37.03	7.61	.70	<u>14.75</u>	<u>40.92</u>	7.96	.74
700	<u>15.40</u>	39.56	7.75	.71	<u>15.94</u>	<u>43.77</u>	8.10	.74
800	<u>16.45</u>	41.95	7.88	.72	<u>17.06</u>	<u>46.46</u>	8.22	.75
900	<u>17.44</u>	44.22	8.00	.72	<u>18.13</u>	<u>49.02</u>	8.32	.75
1000	<u>18.39</u>	46.39	8.10	.73	<u>19.15</u>	<u>51.47</u>	8.41	.75

Table 6 - continued

<u>t<sup>o</sup>C</u>	<u>O<sub>2</sub> (32.000)</u>				<u>H<sub>2</sub>O (18.016)</u>			
	<u>λ.10<sup>5</sup></u>	<u>η.10<sup>5</sup></u>	<u>c<sub>p</sub><sup>o</sup></u>	<u>Pr</u>	<u>λ.10<sup>5</sup></u>	<u>η.10<sup>5</sup></u>	<u>c<sub>p</sub><sup>o</sup></u>	<u>Pr</u>
-200	1.58	5.60	6.95	0.77				
-150	2.68	9.41	6.95	.76				
-100	3.78	12.95	6.95	.75				
-50	4.84	16.19	6.96	.73				
0	5.87	19.18	6.99	.71	<u>3.79</u>	<u>9.41</u>	7.99	1.10
50	6.85	21.95	7.05	.71	<u>4.68</u>	<u>11.33</u>	8.04	1.08
100	7.78	24.54	7.13	.70	5.61	13.20	8.12	1.06
150	<u>8.67</u>	26.97	7.24	.70	6.56	15.02	8.22	1.05
200	<u>9.53</u>	29.26	7.36	.71	7.54	16.79	8.33	1.03
250	<u>10.35</u>	31.43	7.48	.71	8.52	18.52	8.45	1.02
300	<u>11.14</u>	<u>33.50</u>	7.60	.71	9.52	20.19	8.57	1.01
350	<u>11.90</u>	<u>35.48</u>	7.70	.72	10.52	21.82	8.70	1.00
400	<u>12.64</u>	<u>37.37</u>	7.81	.72	11.54	23.41	8.84	1.00
450	<u>13.34</u>	<u>39.19</u>	7.90	.73	12.55	24.95	8.98	0.99
500	<u>14.03</u>	<u>40.95</u>	7.99	.73	13.57	26.45	9.12	.99
600	<u>15.34</u>	<u>44.28</u>	8.14	.73	<u>15.60</u>	29.34	9.40	.98
700	<u>16.57</u>	<u>47.41</u>	8.26	.74	<u>17.63</u>	<u>32.09</u>	9.69	.98
800	<u>17.74</u>	<u>50.37</u>	8.36	.74	<u>19.65</u>	<u>34.72</u>	9.98	.98
900	<u>18.86</u>	<u>53.19</u>	8.44	.74	<u>21.64</u>	<u>37.23</u>	10.27	.98
1000	<u>19.92</u>	<u>55.88</u>	8.50	.75	<u>23.62</u>	<u>39.65</u>	10.56	.98

Table 6 - continued

<u>t<sup>o</sup>C</u>	<u>N<sub>2</sub>O (44.016)</u>				<u>CO<sub>2</sub> (44.010)</u>			
	<u>λ.10<sup>5</sup></u>	<u>η.10<sup>5</sup></u>	<u>c<sub>p</sub><sup>o</sup></u>	<u>Pr</u>	<u>λ.10<sup>5</sup></u>	<u>η.10<sup>5</sup></u>	<u>c<sub>p</sub><sup>o</sup></u>	<u>Pr</u>
-150	1.23	<u>5.92</u>	7.14	0.78				
-100	1.93	8.59	7.68	.78	<u>1.87</u>	<u>8.65</u>	7.40	0.78
-50	2.73	11.15	8.33	.77	2.63	11.22	8.13	.79
0	3.63	13.59	8.95	.76	3.46	13.68	8.67	.78
50	4.63	15.91	9.53	.74	4.35	16.01	9.15	.77
100	5.71	18.10	10.02	.72	5.29	18.22	9.64	.75
150	<u>6.88</u>	20.19	10.43	.70	6.27	20.34	10.09	.74
200	<u>8.11</u>	22.19	10.83	.67	7.30	22.35	10.48	.73
250	<u>9.42</u>	24.10	11.18	.65	8.36	24.28	10.84	.72
300	<u>10.80</u>	25.92	11.52	.63	9.46	26.13	11.17	.70
350	<u>12.24</u>	<u>27.67</u>	11.80	.61	<u>10.58</u>	27.90	11.46	.69
400	<u>13.75</u>	<u>29.35</u>	12.07	.59	<u>11.73</u>	29.61	11.73	.67
450	<u>15.32</u>	<u>30.98</u>	12.32	.57	<u>12.91</u>	31.26	11.97	.66
500	<u>16.92</u>	<u>32.55</u>	12.55	.55	<u>14.10</u>	32.85	12.20	.65
600	<u>20.24</u>	<u>35.55</u>	12.97	.52	<u>16.55</u>	35.88	12.60	.62
700	<u>23.75</u>	<u>38.37</u>	13.30	.49	<u>19.07</u>	38.83	12.93	.60
800	<u>27.44</u>	<u>41.04</u>	13.59	.46	<u>21.63</u>	41.46	13.20	.57
900	<u>31.24</u>	<u>43.58</u>	13.84	.44	<u>24.24</u>	44.04	13.44	.55
1000	<u>35.14</u>	<u>46.01</u>	14.06	.42	<u>26.89</u>	46.51	13.64	.54

Table 6 - continued

t <sup>o</sup> C	<u>NH<sub>3</sub> (17.032)</u>				<u>CH<sub>4</sub> (16.042)</u>			
	<u>λ.10<sup>5</sup></u>	<u>η.10<sup>5</sup></u>	<u>C<sub>p</sub><sup>o</sup></u>	<u>Pr</u>	<u>λ.10<sup>5</sup></u>	<u>η.10<sup>5</sup></u>	<u>C<sub>p</sub><sup>o</sup></u>	<u>Pr</u>
-200					1.85	3.00	7.96	0.80
-150					3.17	4.91	7.95	.77
-100	<u>2.93</u>	5.71	7.99	0.92	4.52	6.79	7.98	.75
-50	4.03	7.47	8.11	.89	5.88	8.60	8.12	.74
0	5.21	9.25	8.34	.87	7.28	10.32	8.36	.74
50	6.45	11.05	8.63	.86	8.81	11.96	8.75	.74
100	7.92*	12.84	8.97	.86	10.56	13.51	9.36	.75
150	9.66	14.62	9.34	.87	12.55	<u>14.99</u>	10.04	.75
200	11.58	16.37	9.72	.88	14.82	<u>16.41</u>	10.73	.74
250	13.67	<u>18.10</u>	10.10	.89	17.41	<u>17.76</u>	11.40	.72
300	15.93	<u>19.80</u>	10.47	.90	20.26	<u>19.06</u>	12.09	.71
350	18.39	<u>21.47</u>	10.84	.90	<u>23.39</u>	<u>20.30</u>	12.79	.69
400	21.03	<u>23.11</u>	11.21	.91	<u>26.82</u>	<u>21.50</u>	13.39	.67
450	D	<u>24.72</u>	11.56		<u>30.50</u>	<u>22.66</u>	13.99	.65
500	E	<u>26.31</u>	11.92		<u>34.53</u>	<u>23.78</u>	14.57	.63
600	C	<u>29.39</u>	12.59		<u>43.50</u>	<u>25.92</u>	15.64	.58
700	O	<u>32.35</u>	13.22		<u>53.60</u>	<u>27.93</u>	16.60	.54
800	M	<u>35.22</u>	13.81		<u>64.78</u>	<u>29.84</u>	17.46	.50
900	P	<u>37.98</u>	14.35		<u>77.03</u>	<u>31.66</u>	18.24	.47
1000	O S E S	<u>40.65</u>	14.84		<u>90.38</u>	<u>33.40</u>	18.96	.44

\* Heat Conductivity values above 315<sup>o</sup> K have been extrapolated graphically.

Table 6 - continued

Air (28.964)

<u>t °C</u>	<u><math>\lambda \cdot 10^5</math></u>	<u><math>\eta \cdot 10^5</math></u>	<u><math>c_p^\circ</math></u>	<u>Pr</u>
-200	1.64	5.25	6.93	0.77
-150	2.71	8.68	6.93	.77
-100	3.77	11.80	6.93	.75
-50	4.79	14.63	6.94	.73
0	5.77	17.22	6.94	.72
50	6.70	19.60	6.96	.70
100	7.59	21.82	6.99	.69
150	8.43	23.90	7.03	.69
200	9.24	25.85	7.08	.68
250	10.01	27.71	7.15	.68
300	10.75	29.47	7.22	.68
350	<u>11.47</u>	31.15	7.30	.68
400	<u>12.15</u>	32.76	7.38	.69
450	<u>12.82</u>	34.31	7.46	.69
500	<u>13.46</u>	35.80	7.54	.69
600	<u>14.68</u>	38.64	7.69	.70
700	<u>15.84</u>	41.30	7.83	.71
800	<u>16.94</u>	43.81	7.95	.71
900	<u>17.98</u>	46.20	8.06	.72
1000	<u>18.98</u>	48.49	8.15	.72

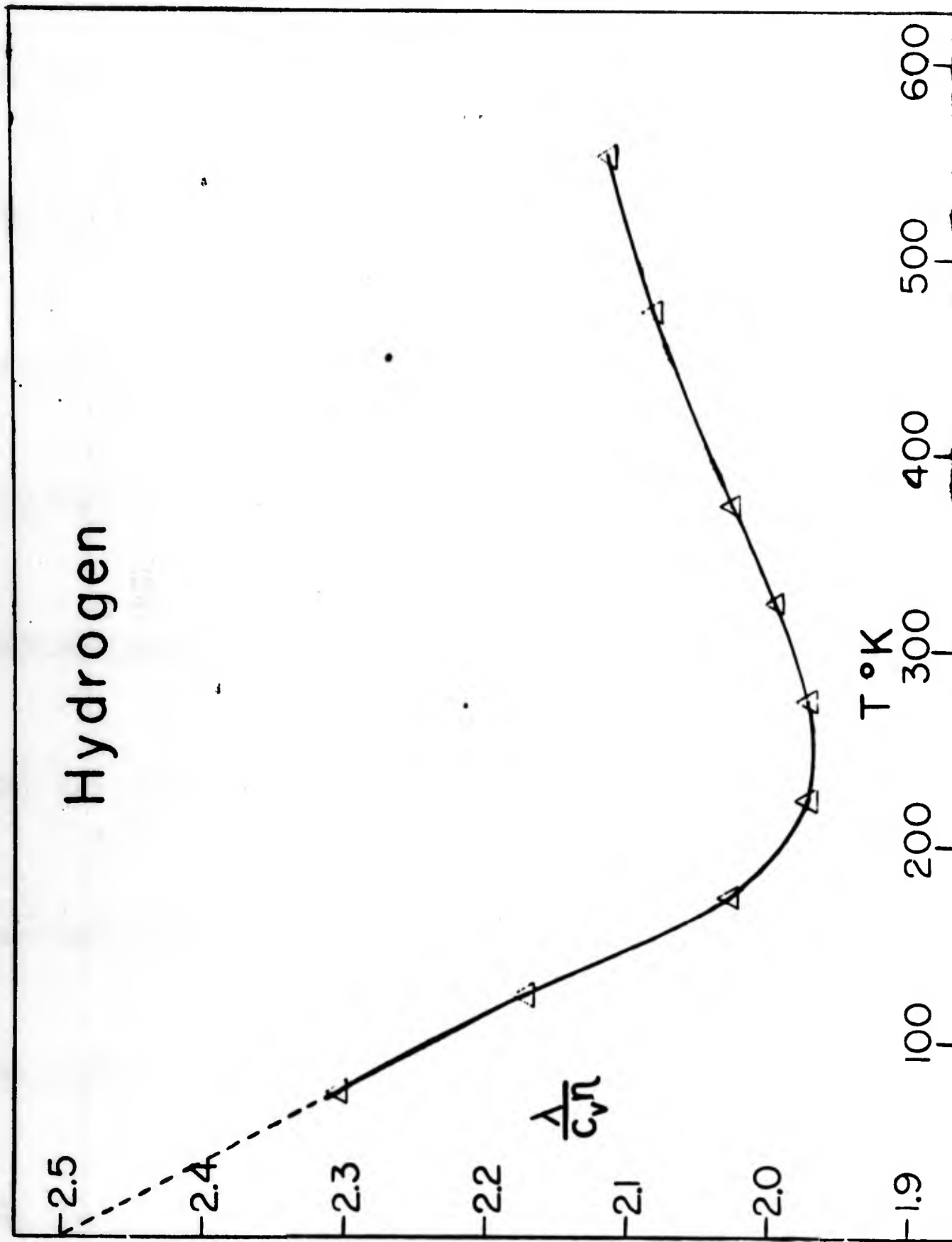


Fig. 1

FIG. 1 VISCOSITY OF AIR

- |   |                            |   |                     |
|---|----------------------------|---|---------------------|
| ○ | VASILESCO                  | ⊙ | BINKELE             |
| x | BREMOND                    | ⊙ | TRAUTZ AND BAUMANN  |
| ⊙ | WILLIAMS                   | ⊙ | TRAUTZ AND STAUF    |
| → | SHILLING AND LAXTON        | ⊙ | TRAUTZ AND NARATH   |
| ← | BRAUNE, BASCHE AND WENTZEL | ⊙ | TRAUTZ AND LUDEWIGS |
| □ | WÖBBER AND MÜLLER          | ⊙ | WEIZEL              |

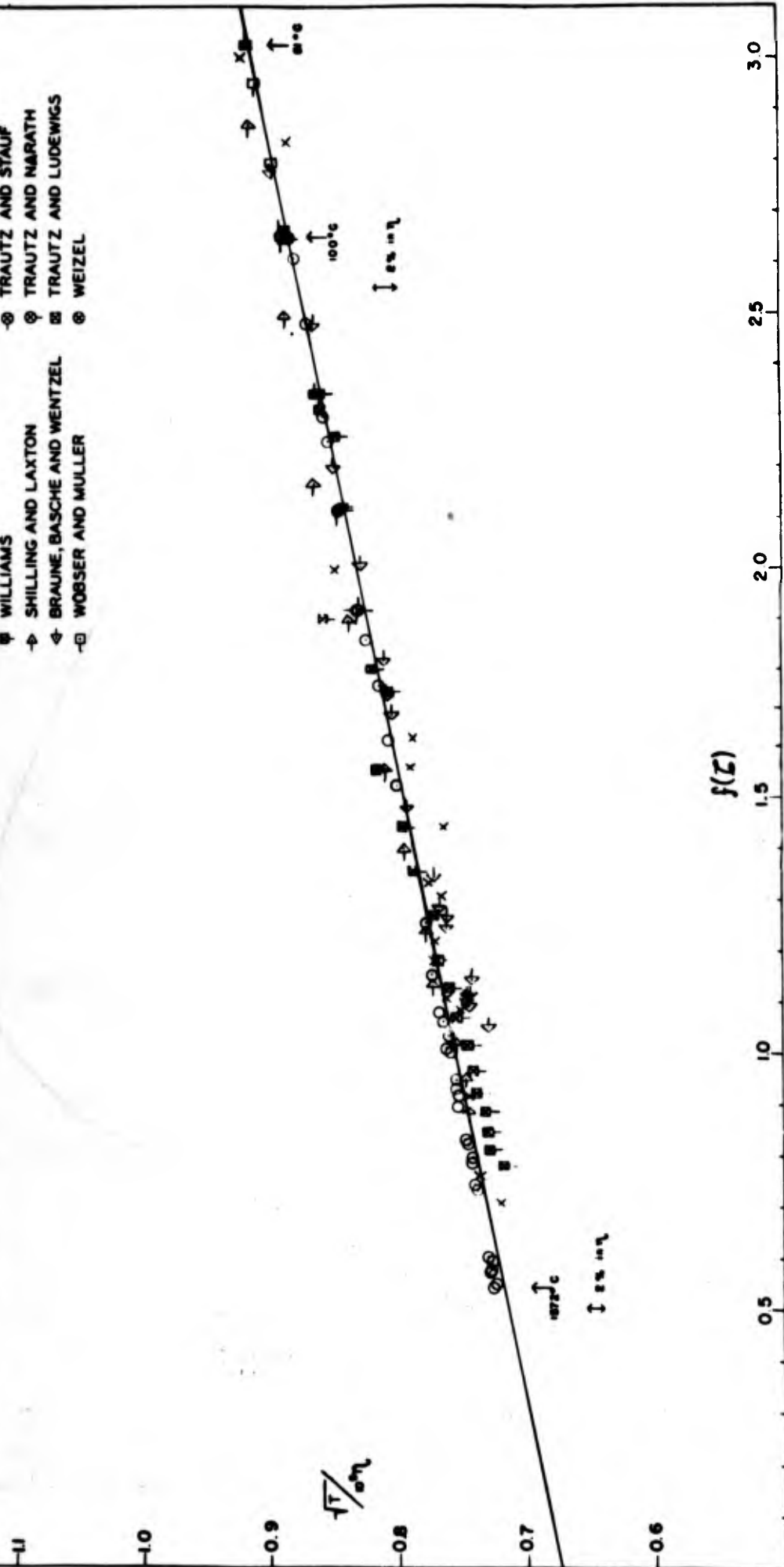


Fig. 2

# VISCOSITY OF CO<sub>2</sub>

- BREMOND
- △ HIRSCHFELDER, BIRD & SPOTZ
- ⊕ ISHIDA
- △ JOHNSTON & McCLOSKEY
- △ LASSALLE
- ▽ MAJUMDAR & VAJIFDAR
- × PHILLIPS
- SUTHERLAND & MAASS
- TRAUTZ & KURZ
- VASILESCO
- WOBSE & MULLER

FIG. 3

$\frac{\eta(\text{calc}) - \eta(\text{obs})}{\eta(\text{obs})} \times 100$   
 PARTS PER HUNDRED

T °K

2000

1500

1000

500

0

Fig. 3

# HEAT CONDUCTIVITY OF N<sub>2</sub>-CO<sub>2</sub>

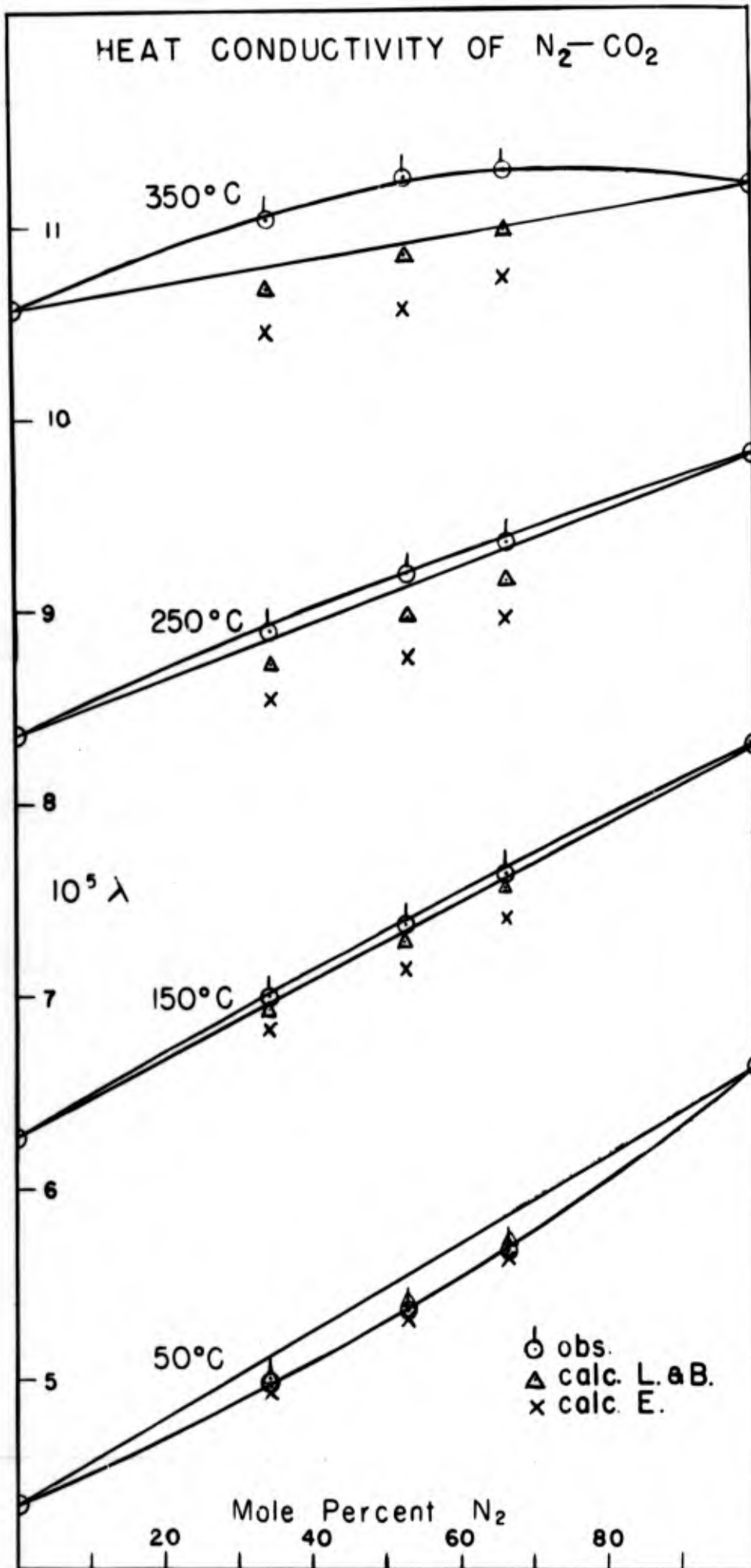
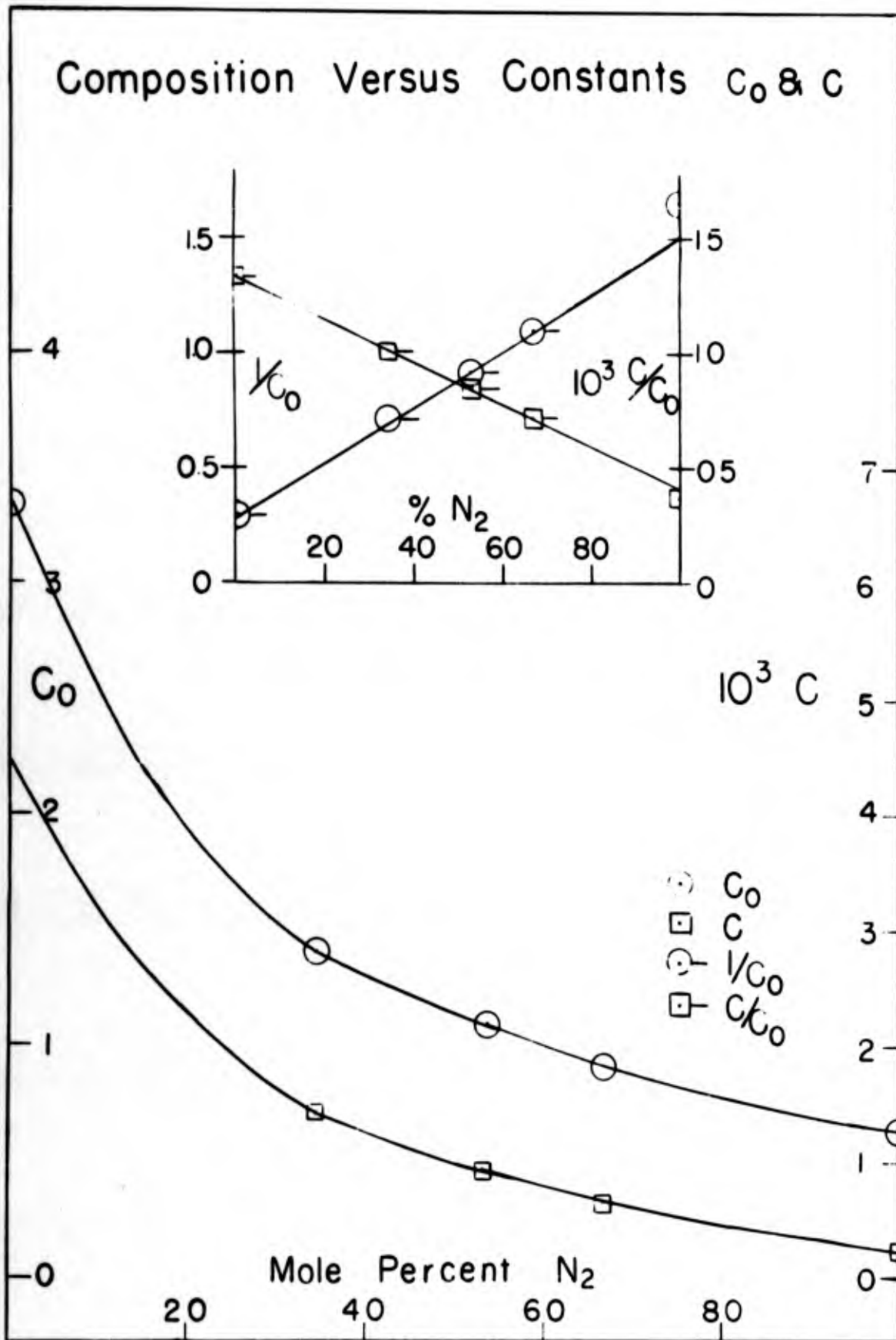


Fig. 4



**Fig. 8.** Graph of the constants  $C_0$ ,  $C$ , with  $C_1 = 11$  for the mixtures,  $C_1 = 12$  for  $N_2$ , and  $C_1 = 10$  for  $CO_2$ .  
 (a) Direct plot of  $C_0$  and  $C$  versus composition.  
 (b) Small plot of  $1/C_0$  and  $C/C_0$  versus composition.

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