GEORGIA INSTITUTE OF TECHNOLOGY
Engineering Experiment Station

PROJECT INITIATION

Date: **July 22, 1969**

Project Title: **Correlation of Vapor Pressure of Pure Substances of Cryogenic Interest**

Project No.: **A-1194**

Project Director: **Dr. W. T. Ziegler**

Sponsor: **National Bureau of Standards, U. S. Department of Commerce**

Effective . . . . **July 1, 1969** . . . . Estimated to run until: . . . **February 28, 1970** . . . . .

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Final Report - 6 copies
Reports due upon completion of work

Contact Person: For Technical Matters:
Mr. Dudley B. Chelton

For Administrative Matters:
Mr. Boyd L. Green, Contracting Officer
National Bureau of Standards
Boulder, Colorado 80302

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PROJECT TERMINATION

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PROJECT NO: A-1194

PROJECT DIRECTOR: Dr. W. T. Ziegler

SPONSOR: National Bureau of Standards, U. S. Department of Commerce

TERMINATION EFFECTIVE: ___May 31, 1970___

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Final report mailed 7/31/70.

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July 31, 1970

U. S. Department of Commerce
National Bureau of Standards
Boulder, Colorado 80302

Attention: Mr. Merle V. Gibson
Contract Specialist
Contracting Office
NBS

Subject: Final Report
NBS Contract No. CST-7973

Gentlemen:

The subject contract was concerned with the calculation of the vapor pressure and heats of vaporization and sublimation of neon from its normal boiling point $(27.1°K)$ to temperatures at which the vapor pressure is less than 10^{-12} torr. The calculations were to be based on published thermodynamic data. This work has been completed and a technical report covering it has been issued entitled:

Calculation of the Vapor Pressure and Heats of Vaporization and Sublimation of Liquids and Solids Below One Atmosphere Pressure. IX. Neon. W. T. Ziegler, G.N.Brown and J.D.Garber. Technical Report No. 1, Project A-1194, Engineering Experiment Station, Georgia Institute of Technology, Atlanta, Georgia 30332, May 1, 1970. Contract No. CST-7973, National Bureau of Standards, U.S. Department of Commerce, Boulder, Colorado 80302.

The contract called for submission of 400 copies of the complete report to the sponsor. A total of 375 copies of the report were transmitted to the sponsor in May, 1970. The remaining copies were retained by us (with the permission of Mr. M.J.Hiza, Cryogenic Engineering Laboratory, NBS, Boulder, Colo.) for distribution to individuals having special need for the report.

Shortly after the report was issued a number of typographical errors and minor omissions were found in the report. These do not affect the conclusions or results reported. We have prepared a set of corrections for the report and are sending you 400 copies of these corrections for attachment to the original report. We suggest that these be transmitted to Mr. M. J.Hiza to whom we understand the original report was sent by your office.

The transmittal of the original report and the correction sheets complete the work to be done under this contract.

Very truly yours,

W. T. Ziegler,
Project Director

APPROVED:

Frederick Bellinger
Chemical Sciences & Materials Division

Comment on and Corrections to Neon Vapor Pressure Report
(July 27, 1970)

Recently we issued the following report:

Calculation of the Vapor Pressure and Heats of Vaporization and Sublimation of Liquids and Solids Below One Atmosphere Pressure. IX. Neon. W. T. Ziegler, G. N. Brown and J. D. Garber, Technical Report No. 1, Project No. A-1194, Engineering Experiment Station, Georgia Institute of Technology, Atlanta, Georgia 30332 May 1, 1970. Contract No. CST-7973, National Bureau of Standards, U.S. Department of Commerce, Boulder, Colorado, 80302.

We have discovered a number of typographical errors and omissions in this report and wish to correct these herewith. Please send any additional errors or corrections noted to Dr. W. T. Ziegler, School of Chemical Engineering, Georgia Institute of Technology, Atlanta, Georgia 30332.

Comment

Page 20, Table VI. The calculations presented in this Table are based on thermodynamic relations, hence the temperature scale strictly speaking is the thermodynamic Kelvin scale. However, since all fixed points used were on the IPTS-68 scale, the calculations are reported as being on this scale over the range 30 to 13.81 K the lowest defined temperature of the IPTS-68. Temperatures in Table VI below this temperature are therefore not on IPTS-68. This comment applies to other portions of the report as well.

Corrections

Page i, line 8 from bottom, write calorimetric

Page 8, Table III, write 325.02 ± 0.10

Page 9, line 8 from top, write -- liquid density data --

Page 10, line 7 from bottom, write 80.06 for 80.66

Page 11, Table IV, last line, for 20 write 21 and add 20.5, 415.53; 20, 415.59

Page 15, Equation (13), for B_1^*, B_{II}^4, B_{III}^4 and B_o write B_I^*, B_{II}^*, B_{III}^* B_o^*, respectively

Page 19, line 14 from top, write --- one part $\underline{in}$ 10^4

Page 27, line 12 from bottom, for 11 points write 14 points
line 4 from bottom, write 759.991

Page 28, bottom line, write Grilly[22]

Page 29, Figure 1, change Eq. (15) to 16 and 16 to 15.

Page 31, line 2 from bottom, for _is_ write _of_

Page 32, line 6 from bottom, insert _an_ before estimate

Page 34, line 9 from bottom, insert _been_ after also

Page 38, Ref. 43, write I-VI for I-IV
       Ref. 47, write No. 64d for No. 64b

Page 40, line 3 from bottom, insert the words: have been made before Cath

Page 41, line 5 from bottom, write They combined ---

Page 48, line 11 from top, write: The vapor pressure of liquid and
       solid^{22} Ne ----
       line 4 from bottom, after Roth insert the words: for
       naturally occurring neon --

TECHNICAL REPORT NO. 1

PROJECT NO. A-1194

CALCULATION OF THE VAPOR PRESSURE AND HEATS OF VAPORIZATION

AND SUBLIMATION OF LIQUIDS AND SOLIDS BELOW ONE ATMOSPHERE

PRESSURE. IX. NEON

by

W. T. Ziegler, G. N. Brown, and J. D. Garber

May 1, 1970

1970

Engineering Experiment Station

GEORGIA INSTITUTE OF TECHNOLOGY

Atlanta, Georgia

TECHNICAL REPORT NO. 1

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PRESSURE.   IX.   NEON

by

W. T. Ziegler, G. N. Brown, and J. D. Garber

May 1, 1970

ABSTRACT

The "best" available experimental thermal data, together with suitable thermodynamic relations, have been used to compute the vapor pressure and heats of vaporization and sublimation of naturally occurring neon from 30 to 2.5 K. Calculations are presented in tabular form from 30 to 27.102 K (the normal boiling point) in 0.5 K intervals, from 27.102 to 24.552 K (the triple point) in 0.1 degree intervals and from the triple point to 2.5 K in 0.2 degree intervals on the International Practical Temperature Scale of 1968 (IPTS-68). These tabular values have also been fitted by means of empirical equations.

Comparison of the computed vapor pressure values with the best available experimental vapor pressure data indicates that the computed values represent the experimental data to within 0.01 K over the experimental range 20-30 K. In view of this agreement it is believed that the computed values provide the best estimate of the vapor pressure of solid neon presently available for temperatures below 20 K.

The calormetric entropy of neon as an ideal gas at 27.102 K and one atm. pressure has been determined to be 23.138 ± 0.16 e.u. which may be compared with the statistical value of 23.034 e.u. The heat of sublimation at 0 K was computed to be 449.1 cal/mole.

The vapor pressure measurements of Bigeleisen and Roth (J. Chem. Phys. 35 (1), 68 (1961)) for naturally occurring neon and the neon isotopes ^{20}Ne and ^{22}Ne have been converted to IPTS-68, permitting their vapor pressure data for these isotopes to be used on this temperature scale.

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I. INTRODUCTION

The purpose of the present work was to calculate the vapor pressure and heats of vaporization and sublimation of neon from the normal boiling point (T = 27.102 K) to 2.5 K using the thermodynamic relations developed in earlier work. (The word neon used without qualification implies naturally occurring neon.) The available experimental vapor pressure data for neon have been compared with the computed values. The present work is concerned primarily with naturally occurring neon, although some comments are made about the vapor pressure of the neon isotopes ^{20}Ne and ^{22}Ne.

The thermodynamic relations used have been described in another place.[49] Similar thermodynamic relations have been used by other investigators.[38, 39, 40, 41, 46] These relations have been used earlier to compute the vapor pressures and heats at vaporization and sublimation of parahydrogen, oxygen, ethylene, methane, nitrogen, fluorine, carbon dioxide, carbon monoxide, ethane, argon, krypton, and xenon from the normal boiling point to temperatures at which the vapor pressure is below about 10^{-20} torr. References to these calculations can be found in the report dealing with xenon.[50] (Note: These reports may be obtained from the Clearinghouse for Federal Scientific and Technical Information, Springfield, Virginia 22151.)

The thermodynamic data for neon needed for the computations are: (1) the heat capacity and volume of the saturated condensed phase as a function of temperature over the range of interest; (2) the heat of fusion and one heat of vaporization or sublimation at a known temperature and pressure (e.g., the normal boiling point); (3) the triple point temperature; (4) the heat capacity of the gas phase or thermodynamic functions of the ideal gas; (5) an equation of state for the gas phase. These thermodynamic data have been

used to compute the vapor pressure and heats of vaporization and sublimation of naturally occurring neon from its normal boiling point (27.102 K) to 2.5 K, where its vapor pressure is computed to be 1.01×10^{-35} torr. The computed results have been compared with the available experimental vapor pressure data. No experimentally determined heats of vaporization and sublimation are available. In addition, a comparison has been made between the "third law" entropy calculated from calorimetric data and the entropy calculated using statistical mechanics.

All temperatures reported in the present paper are on the International Practical Temperature Scale of 1968 (IPTS-68)[1] unless otherwise stated. Conversion between IPTS-68 and the U. S. National Bureau of Standards scale of 1955 (NBS-55) was made by means of the relation

$$T_{68} - T_{55} = a_o + a_1 T_{68} + a_2 T_{68}^2 + a_3 T_{68}^3 \qquad (1)$$

where

$$a_o = -1.28575025 \times 10^{-1}$$
$$a_1 = 1.77953796 \times 10^{-2}$$
$$a_2 = -7.53758741 \times 10^{-4}$$
$$a_3 = 1.04020979 \times 10^{-5}$$

The equation was obtained by a least squares fit of the values given by Bedford, et al[3] (their Table 2) using the values given for 17-29 K inclusive. The maximum difference between the two scales in this region is 9 millidegrees at 20 K.

The thermodynamic relations used are presented in Section II. The experimental data for neon are reviewed in Section III and the best values selected for the various physical quantities needed in the calculations are given. The calculations of vapor pressure and heats of vaporization and

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sublimation are presented in Section IV, together with a discussion of the agreement between the computed and experimental data. Some comments and calculations pertaining to the vapor pressures of the neon isotopes are given in Section V. Conclusions and recommendations regarding the use of the computed results are given in Section VI.

II. THERMODYNAMIC RELATIONS

A. Variation of Heat of Vaporization and Sublimation with Temperature

By performing an enthalpy cycle between two points, (P,T) and P_1,T_1), on the vapor pressure curve of a pure substance it can be shown[49] that the heat of vaporization or sublimation at the temperature T can be computed from Equation (2).*

$$(\Delta H_v)_T = (\Delta H_v)_{T_1} + \int_T^{T_1} c_s' \, dT + \sum_T^{T_1} (\Delta H_{tr})'$$
$$- \left[(H^o - H_o^o)_{T_1}'' - (H^o - H_o^o)_{T_-}'' \right] - RT_1\delta_1 + RT\delta + \int_P^{P_1} v_s' \, dP \qquad (2)$$

In this equation the quantity δ is given by the relation,

$$\delta = \left[H(P,T) - H^o(T) \right]'' / (RT) \qquad (3)$$

and δ_1 is the value of δ at the point (P_1,T_1). The prime (') and double prime (") symbols refer to the condensed and vapor phases, respectively. The evaluation of the right-hand side of Equation (3) requires an equation of state for the vapor. If a virial form of the equation of state is used, namely

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*All symbols are defined in Appendix A.

$$PV = RT\left(1 + \frac{B}{V} + \frac{C}{V^2} + --\right) \qquad (4)$$

where the second and third virial coefficients, B and C, are assumed to be functions of temperature only, then one obtains

$$\delta = \left(B - T\frac{dB}{dT}\right)/V + \left(C - \tfrac{1}{2}T\frac{dC}{dT}\right)/V^2 + -- \qquad (5)$$

For temperatures below the triple point, $(\Delta H_v)_T$ in Equation (2) is the heat of sublimation rather than the heat of vaporization. The evaluation of the last two terms of Equation (2) requires a value of the vapor pressure at T. If vapor pressure calculations are made by an iterative procedure these also provide the pressure necessary to compute the last two terms of Equation (2).

B. Vapor Pressure Relations

From a known point (P_1, T_1) on the vapor pressure curve, the vapor pressure at any other point (P,T) can be calculated from the previously derived relation[49]

$$\ln P = \ln P_1 - (\Delta H_v)_{T_1} (T_1 - T)/RTT_1 + \left[(H^o - H^o_o)''_{T_1} - (H^o - H^o_o)''_T \right]/RT$$

$$-\left[(S^o)''_{T_1} - (S^o)''_T \right]/R - \left(\int_T^{T_1} c'_s\, dT \right)/RT - \left(\sum_T^{T_1} (\Delta H_{tr})' \right)/RT$$

$$+ \left(\int_T^{T_1} c'_s\, dT/T \right)/R + \left(\sum_T^{T_1} (\Delta H_{tr})'/T_{tr} \right)/R + \delta_1(T_1 - T)/T$$

$$- \epsilon_1 + \epsilon - \left(\int_P^{P_1} v'_s\, dP \right)/RT \qquad (6)$$

where

$$\epsilon = \left[H^o(T) - H(P,T) \right]''/RT - \left[S^o(P,T) - S(P,T) \right]''/R \qquad (7)$$

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and ϵ_1 is the value of ϵ at (P_1, T_1). If the virial form of the equation of state is assumed, i.e., Equation (4), then ϵ becomes,

$$\epsilon = \ln (PV/RT) - 2B/V - 3C/2V^2 + --\qquad(8)$$

Equation (6), which can be considered to be an integration of the Clapeyron equation, can be solved if the appropriate thermodynamic data are available. These data are ΔH_v at (P_1, T_1); the heat capacities and molar volumes of the saturated condensed phases; the temperatures and heat of transition of all condensed phase transitions; an equation of state for the real gas; the requisite molecular structure data for the ideal gas. Solution of Equation (6) requires an iterative procedure since the last two terms are pressure dependent.

Equation (6) can be rearranged as follows:

$$(\Delta H_v)_{T_1} = \left\{ RT \ln P_1/P + \left[(H^o - H_o^o)_{T_1}'' - (H^o - H_o^o)_{T}'' \right] \right.$$

$$- \int_T^{T_1} c_s' \, dT - \sum_T^{T_1} (\Delta H_{tr})' - T \left[(S^o)_{T_1}'' - (S^o)_{T}'' \right]$$

$$+ T \int_T^{T_1} c_s' \, dT/T + T \sum_T^{T_1} (\Delta H_{tr})'/T_{tr}$$

$$\left. + R(T_1 - T)\delta_1 - RT\epsilon_1 + RT\epsilon - \int_P^{P_1} v_s' \, dP \right\} T_1/(T_1 - T) \qquad(9)$$

Equation (9) may be used to examine the thermodynamic consistency of the experimental thermal, equation of state and vapor pressure data by computing $(\Delta H_v)_{T_1}$ for the various experimental (P,T) points. It may also be used to

compute the heat of vaporization at a given point (P_1, T_1) (say the normal boiling point or triple point) from two points (P_1, T_1) and (P, T) on the vapor pressure curve. Neither of these uses of Equation (9) requires an iterative procedure in the calculations.

III. EXPERIMENTAL DATA FOR NEON

A. Introduction

Calculations of the vapor pressure of naturally occurring neon from Equation (6) and the heats of vaporization and sublimation from Equation (2) from the normal boiling point (27.102 K) to 2.5 K were made using the following data: molecular weight; the temperature of the normal boiling point and triple point; the heat of vaporization at the normal boiling point; the molar heat capacity and molar volume of the saturated condensed phase; the second virial coefficient of the gas. The ideal gas was assumed to have a constant molar heat capacity of $5R/2$.

The available thermophysical property data for neon were analyzed and a selection was made of the "best" values of the necessary and related data for neon. The values selected for use in computing the final values of vapor pressure and heats of vaporization and sublimation (Table VI) are given in Table I. All temperatures refer to the IPTS-68 scale.

TABLE I

SELECTED PHYSICAL PROPERTIES OF NEON

Property	Selected Value	Table No. or Section
Molecular weight	20.179	Section III B
Normal boiling point (nbp)	27.102 K	Section III C
Triple point (tp)	24.552 K	Section III D
Heat of vaporization (nbp)	416.2 cal/gm mole	Section III E
Heat of fusion	80.11 cal/gm mole	Section III F
Heat capacity of ideal gas	5 R/2 (C_p^o)	
Heat capacity of saturated condensed phases	Polynomials for different temperature intervals	Section III G
Molar volumes of saturated condensed phases	Polynomials for liquid and solid densities	Section III H
Second virial coefficient	Lennard-Jones 6-12 potential function $\sigma = 2.782$ Å, $e/k =$ 34.82 K with quantum corrections Eq. (13)	Section III I

B. Isotopic Composition and Molecular Weight

According to Remy[43] the International Atomic Weight Table 1968 gives the molecular weight of naturally occurring neon as 20.179 $\pm$ 0.003. The choice of this value is based upon the recent mass-spectrometric work of Eberhardt, Eugster and Marti[13] and Walton and Cameron[48] who give the abundances shown in Table II. The masses (on C - 12 scale) used by both sets of investigators are those of König, et al.[36]

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TABLE II

ISOTOPIC COMPOSITION OF NATURALLY OCCURRING NEON

Isotope	Abundance[48]	Abundance[13]	Mass[36]
^{20}Ne	90.514 ± 0.031	90.50 ± 0.07	19.9924
^{21}Ne	0.266 ± 0.005	0.268 ± 0.002	20.9939
^{22}Ne	9.220 ± 0.029	9.23 ± 0.07	21.9914
Average mol. weight	20.1794 ± 0.0030	20.179 ± 0.002	

C. Normal Boiling Point

The normal boiling point (P = 760 torr) of naturally occurring neon has
been taken to be 27.102 K (IPTS-68).[1] Grilly[21] has reported a temperature
of 27.099 K and Furukawa[17] has obtained a value of 27.103 K.

D. Triple Point Temperature and Pressure

The triple point temperature and pressure of naturally occurring neon have
been determined by a number of investigators. Their results are given in
Table III. Correction to IPTS-68 has been made, where possible, using the
conversion relations given by Bedford, et al.[3]

TABLE III

TRIPLE POINT TEMPERATURE AND PRESSURE

Reported Temperature K	Temp. Scale	Temp. on IPTS-68	Reported Pressure (Torr)	Investigator
24.544 ± 0.004	NBS-55	24.552	324.78 ± 0.36	Grilly[21]
24.553	NBS-55	24.561	325.02 ± 010	Furukawa[17]
24.57	Ref. 11		323.5	Crommelin and Gibson[11]
24.59	Ref. 11*		325.06 ± 0.01	Bigeleisen and Roth[4]

*The reference given by Bigeleisen and Roth is apparently in error

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The value selected for the triple point temperature in the calculations of Section IV is that of Grilly[21], 24.552 K. The vapor pressure data of Furukawa[17] became available to us only after these calculations were completed.

E. Heat of Vaporization

The heats of vaporization and sublimation of neon appear not to have been measured directly. Grilly[21] has presented a summary of heats of vaporization calculated from the Clapeyron equation, using his own and other vapor pressure relations, together with the saturated vapor and liquid data of Mathias, et al.[37] No corrections to a common temperature scale were applied by him. Unfortunately, the density measurements of Mathias, et al.[37] are on the then current Leiden scale with T_o = 273.09 K. Futhermore, Mathias, et al.[37] state that the normal boiling point of neon on their temperature scale is 27.17 K, whereas the normal boiling point on the NBS-55 scale of Grilly is 27.092 K.

Mathias, et al.[37] have reported the density of the saturated vapor and liquid at 27.15 K (their scale) to be 0.00939 and 1.20421 gm/cc, respectively. These densities give saturated molar volumes V^G = 2149.0, V^L = 16.76 cc/mole and ΔV = 2132.2 cc/mole. If we assign to these volumes the temperature 27.102 - 0.02 = 27.082 K(IPTS-68) or 27.072 K on Grilly's temperature scale (NBS-55) and use Grilly's vapor pressure equation at T = 27.072 K to compute P and dP/dT, we obtain P = 755.45 torr and dP/dT = 228.49 torr/deg. K. Calculations of ΔH_V at 27.082 K (IPTS-68) using these quantities in the exact Clapeyron equation gives ΔH_V = 420.3 cal/gm mole. This value may be compared with the value of 429 cal/mole computed by Grilly[21] (his Table 1). It is clear that correction of the density data of Mathias, et al. to the NBS-55 or IPTS-68 is quite significant. The heat of vaporization computed in this manner is not significantly different if the vapor pressure equation of

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Furukawa (Equations (17) and (18)) is used. Heats of vaporization computed by earlier investigators have not been considered because of the uncertainty in the temperature scales, or the vapor pressure relations used by them.

In the absence of any directly determined heats of vaporization it was decided to make use of Equation (9) to compute $(\Delta H_v)_{T_1}$ at the normal boiling point using the vapor pressure equations of Grilly for the liquid and solid region. This was accomplished by first computing the vapor pressure from these equations at 0.5 degree intervals from 27 to 20 K on the IPTS-68. These vapor pressure data, together with other required data from Table 1, were then used to compute $(\Delta H_v)_{nbp}$ for each of these vapor pressure data. The results are shown in Table IV. Except for the value of $(\Delta H_v)_{T_1}$ computed for T = 27 K, the $(\Delta H_v)_{nbp}$ is seen to be very nearly constant at about 416 cal/mole. (An exactly constant value would have implied a thermodynamically consistent set of input data). A value of $(\Delta H_v)_{nbp}$ = 416.2 cal/mole was chosen as the "best" value for making all subsequent calculations of pressure and heats of vaporization and sublimation from Equations (2) and (6).

F. Heat of Fusion

The heat of fusion of naturally occurring neon has been measured by Clusius[9] and by Fagerström.[15] The value found by Clusius is 80.1 cal/gm mole (average of 80.13 and 80.66) and by Fagerström is 335.2±1 joule/mole (80.11 cal/gm mole) (average of 334.65 and 335.75 joules/mole). The value used in the calculations in Section IV was 80.11 cal/gm mole.

G. Heat Capacity of Saturated Liquid and Solid Neon

1. Heat Capacity of Saturated Liquid Neon

The heat capacity data of Fagerström and Hollis Hallett[14,15] (8 points, range 24.90-26.84 K), of Clusius[9] (4 points, range 25.7-26.8 K) and of

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TABLE IV

HEAT OF VAPORIZATION AT T = 27.102 K CALCULATED
USING GRILLY VAPOR PRESSURE EQUATIONS AND EQUATION (9)

T,K IPST-68	$(\Delta H_v)_{T_1}$ (T_1 = 27.102 K) cal/gm mole
27	404.53[a]
26.5	414.69
26	415.62
25.5	415.96
25	416.13
24.552 (tp)	416.22
24.5	416.34
24	415.92
23.5	415.67
23	415.53
22.5	415.46
22	415.44
21.5	415.45
20	415.48

[a]This value is less accurate than the others because the calculation of $(\Delta H_v)_{T_1}$ is sensitive to the temperature difference (27.102 - T).

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Gladun[19] (4 points, range 25.2-26.89 K) were fitted over the temperature range from 26.89 K to 24.90 by a least squares procedure to an equation of the form

$$c_s' = A_o + A_1 T \qquad (10)$$

where c_s' is in cal/gm mole K, and T is in deg. K. As the data showed considerable scatter a higher degree polynomial fit was not warranted. The resulting coefficients are $A_o = 4.54002982$; $A_1 = 1.70883090 \times 10^{-1}$. The root mean square deviation was 2.865×10^{-1}, with an average deviation of 2.57 per cent and a maximum deviation of 6.02 per cent.

2. Heat Capacity of Saturated Solid Neon

The heat capacity data of Fagerström and Hollis Hallett[14,15] of Fenichel and Serin[16,44] and of Clusius[9,10] were fitted by a least squares method to equations of the form

$$c_s'/T = A_o + A_1 T + A_2 T^2 + \text{---} \qquad (11)$$

where c_s' is in cal/gm mole K, and T is in deg. K.

The data were divided into four temperature ranges and each fitted to an equation of the above form. The temperature ranges and data used were: 1.4 to 3.7 K (Ref. 14, 15, 16, 44); 3.5 to 7 K (Ref. 14, 15, 16, 44); 6 to 12 K (Ref. 9, 10, 14, 15, 16, 44); 11 to triple point (Ref. 9, 10, 14, 15, 16). The coefficients of Equation (11) are shown in Table V.

TABLE V

COEFFICIENTS OF HEAT CAPACITY POLYNOMIALS FOR SOLID NEON

Coefficient				
A_o	$-2.19498554(-3)$[a]	$-9.05430264(-3)$	$-4.74058032(-2)$	$5.29204534(-1)$
A_1	$3.52005379(-3)$	$1.53573461(-3)$	$1.13757340(-2)$	$-1.35935957(-1)$
A_2	$-6.99263388(-4)$	$1.49763187(-3)$	$1.34084385(-3)$	$1.58053082(-2)$
A_3	$3.23342346(-4)$	0	$-6.73066720(-5)$	$-7.25372972(-4)$
A_4	0	0	0	$1.18248541(-5)$
Temp. range used in L. S. fit (K)	$1.4-3.7$	$3.5-7$	$6-12$	$11-tp$
Deviation (rms)	$8.72\ (-4)$	$6.57\ (-3)$	$2.52\ (-2)$	$1.20\ (-1)$
Temp. range used in vapor pressure calculations (K)	$1.4-3.6$	$3.6-6.5$	$6.5-11.5$	$11.5-tp$

---

[a] Number in parentheses indicates power of 10 by which entry is to be multiplied.

H. Molar Volumes of Saturated Liquid and Solid Neon

1. Molar Volume of Saturated Liquid

Gladun[20] has determined the density of liquid neon along the saturation line from 25.20 K to 43.14 K. The data reported by him over the range 25.20 to 30.39 K (11 points) were fitted by a least squares procedure to an equation of the form

$$d \text{ (gm/cc)} = A_o + A_1 T + A_2 T^2 \qquad\qquad (12)$$

with a maximum deviation of 0.25 per cent. Gladun stated that the data of Mathias, et al.[37] agree with his measurements to 0.1 per cent over this range. The constants of the resulting equation are

$$A_o = 1.35434387; \ A_1 = 6.56596362 \times 10^{-3}; \ A_2 = -4.42948907 \times 10^{-4}.$$

The temperature scale used by Gladun was that of Grilly[21], hence T is on the NBS-55 scale. Corection of those data to IPST-68 was not made. Molar volumes were obtained using a molecular weight of 20.179.

2. Molar Volume of Saturated Solid

Batchelder, Losee and Simmons[2] have determined the density of crystalline neon by x-ray diffraction over the range 3 to 23.5 K. Their smoothed data at one degree intervals over the range 3 to 23 K were fitted by a least squares procedure to the empirical equation of the same form as Equation (12) with a maximum deviation of 0.41 per cent.

The constants found were: $A_o = 1.49981922$; $A_1 = 2.66914437 \times 10^{-3}$; $A_2 = -2.26846097 \times 10^{-4}$.

I. Second Virial Coefficient

The second and third virial coefficients of neon have not been measured below 44 K. In making the various vapor pressure calculations shown in the present work only the second virial coefficient has been used. Since for the purposes of the present calculations it was desirable to have an analytical expression for the second virial coefficient B (in cc/mole) for the temperatures below the normal boiling point (27.102 K) it was decided to use a Lennard-Jones 6-12 intermolecular potential function to compute B as a function temperature. As neon exhibits quantum effects in this temperature range it was also desirable to have a set of parameters which were adjusted for these effects. A detailed discussion of the choice of the Lennard-Jones parameters used and comparison of the second virial coefficient computed from these parameters with the available experimental data is shown in Appendix B.

The second virial coefficient and its temperature derivative used in Equations (2), (6) and (9) have been computed using the Lennard-Jones 6-12 potential parameters of Sullivan and Sonntag[45], namely, $\sigma = 2.782$ Å, $e/k = 34.82$ K. The calculations were made using the expression[24] for the second virial coefficient

$$\frac{B}{b_o} = B^*_{CL} + (\Lambda^*)^2 B^*_1 + (\Lambda^*)^4 B^4_{II} + (\Lambda^*)^6 B^4_{III} - (\Lambda^*)^3 B_o \qquad (13)$$

where the negative sign of the last term implies a Bose-Einstein gas molecule. In this expression

$$b_o = \frac{2}{3} \pi N_o \sigma^3 \qquad (13.1)$$

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$$\left(\Lambda^*\right)^2 = \frac{h^2}{k \, (\sigma)^2 m \, (e/k)} \tag{13.2}$$

The value of Λ^* used was 0.5934139.

$$B^*_o = \frac{3}{32(\pi)^{5/2}} \, (T^*)^{-3/2} \tag{13.3}$$

where $T^* = T/(e/k)$ \hfill (13.4)

Quantum corrections through B^*_{III} have been made using the infinite series expressions for B^*_I and B^*_{II} given in Hirschfelder, Curtiss and Bird[24] (p 1119) and the expression for B^*_{III} given by Kihara[33,34]

$$B^*_{III} = \sum_{j=o}^{\infty} b^{(j)}_{III} \, (T^*)^{-\left(\frac{2j+11}{4}\right)} \tag{13.5}$$

with $o \leqq j \leqq 41$.

The necessary values of $b^{(j)}_{CL}$, $b^{(j)}_I$, $b^{(j)}_{II}$ and $b^{(j)}_{III}$ were taken from Kirk.[35] Calculations of B were made as a function of temperature from 120 to 30 K at ten degree intervals and from 30 to 15 K at one degree intervals. The numerical values of B so computed are given in Table IX, Appendix B. These results are shown in Figure 2, (Appendix B), together with the experimental data of Sullivan and Sonntag and the experimental work of other investigators.

The second virial coefficient values computed at one degree intervals were fitted by a least squares procedure to an empirical expression to form

$$B \text{ (cc/mole)} = A_o + \frac{A_1}{T} + \frac{A_2}{T^2} + \frac{A_3}{T^3} \tag{14}$$

It was found that a third degree expression adequately represented the second virial coefficients over the range 15-30 K. The final expression

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used in Equations (2), (6) and (9) made use of the constants

$$A_o = 2.74929435 \times 10^1$$

$$A_1 = -2.79414498 \times 10^3$$

$$A_2 = -6.17987439 \times 10^3$$

$$A_3 = -3.08651215 \times 10^5$$

The maximum deviation was 0.01 per cent.

J. Vapor Pressure of Neon

The vapor pressure of naturally occurring neon in the liquid state near and below the normal boiling point and in the solid state has been measured by a number of investigators. The vapor pressures of the neon isotopes ^{20}Ne and ^{22}Ne have also been determined. These measurements are discussed in some detail in Appendix C.

The most extensive measurements of the vapor pressure of naturally occurring neon made in recent years are those of Grilly[21] who determined the vapor pressure of neon (0.235 mole per cent ^{21}Ne, 8.86 mole per cent ^{22}Ne and 0.08 mole per cent N_2) in the liquid range (61 data points from 24.544 to 44.384 K and in the solid range (20 data points) from 20.301 to 24.544 K on the NBS-55 temperature scale (T_{55}). He represented these data for the solid by the equation

$$\log_{10} P \text{ (torr)} = 6.89224 - 110.809\ T_{55}^{-1} + 5.4348 \times 10^{-3}\ T_{55} \tag{15}$$

with a r.m.s. deviation of 0.21 per cent and a maximum deviation of 0.47 per cent in P. Grilly represented his vapor pressure data for the liquid over the range 24.544 to 44.384 K by the equation

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$$\log_{10} P \text{ (torr)} = 7.46116 - 106.090\, T_{55}^{-1} - 3.56616 \times 10^{-2} T_{55}$$

$$+ 4.11092 \times 10^{-4} T_{55}^2 \qquad (16)$$

with a r.m.s. deviation of 0.085 per cent and a maximum deviation of 0.23 per cent in P. The normal boiling point derived from this equation is 27.092 K (NBS-55).

Dr. Grilly[22] kindly provided us with the original experimental data on which Equations (15) and (16) were based. These data, converted to IPTS-68, are shown in Table X, Appendix C.

Dr. George T. Furukawa[17] (U. S. National Bureau of Standards, Washington, D. C.) has recently completed measurements of the vapor pressure of naturally occurring liquid neon (relative isotopic abundance ^{20}Ne, 90.5 per cent; ^{21}Ne, 0.26 per cent; ^{22}Ne, 9.26 per cent) from the triple point to slightly above the normal boiling point. The 96 data points were fitted by him using a least squares procedure to obtain the equation

$$\ln P \text{ (torr)} = A_1 \ln T + A_2/T + A_3 + A_4 T + A_5 T^2 \qquad (17)$$

where T is on the IPTS-68.

Dr. Furukawa kindly allowed us to use this equation. The exact values of the constants (given to 16 significant figures, see Appendix C) were approximated by the following values

$$
\begin{aligned}
A_1 &= -7.650560763 \times 10^2 \\
A_2 &= -6.759780756 \times 10^3 \\
A_3 &= +2.11405696 \times 10^3 \\
A_4 &= +2.984887506 \times 10^1 \\
A_5 &= -1.941182548 \times 10^{-1}
\end{aligned}
\qquad (18)
$$

Values of vapor pressure calculated from Equations (17) and (18) are shown in Table X, Appendix C.

IV. CALCULATIONS

A. Introduction

The vapor pressure and heat of vaporization of naturally occurring liquid neon have been computed by means of Equations (6) and (2) from 30 K to the normal boiling point (27.102 K) at 0.5 degree intervals and from the normal boiling point to the triple point (24.552 K) at 0.1 degree intervals. The results are shown in Table VI. Similar calculations have been made for solid neon from the triple point to 2.5 K at 0.2 degree intervals. These results are also shown in Table VI. The temperature scale is IPTS-68. The calculations were made using the input data given in Table I. The iterative calculations were made so that each final pressure given in Table VI differed from the previous iteration by less than one part 10^4.

The integral involving the molar volume of the condensed phase was evaluated as follows. For the liquid range between T_1 and P_1 (n.b.p.) and P,T

$$\int_P^{P_1} v_s' \, dP = (v_s')_{av} (P_1 - P) \qquad (19)$$

where $(v_s')_{av} = \dfrac{(v_s')_{T_1} + (v_s')_T}{2}$. The molar volume $(v_s')_{T_1}$ and $(v_s')_T$ of liquid neon at T_1 and T, were obtained from Equation (12) using the empirical parameters for the liquid.

TABLE VI

CALCULATED VAPOR PRESSURE AND HEATS OF VAPORIZATION AND SUBLIMATION OF
NATURALLY OCCURRING NEON

Temperature (K, IPTS-68)	Pressure (torr)	Heat of Vaporization (cal/gm mole K)
	- - - Liquid - - -	
30.000	1.6718 (3)[a]	396.50
29.500	1.4756 (3)	400.24
29.000	1.2967 (3)	403.83
28.500	1.1344 (3)	407.28
28.000	9.8760 (2)	410.59
27.500	8.5540 (2)	413.76
27.102	7.6000 (2)	416.20
27.100	7.5954 (2)	416.21
27.000	7.3689 (2)	416.81
26.900	7.1475 (2)	417.41
26.800	6.9311 (2)	418.00
26.700	6.7197 (2)	418.58
26.600	6.5132 (2)	419.16
26.500	6.3115 (2)	419.73
26.400	6.1146 (2)	420.30
26.300	5.9223 (2)	420.87
26.200	5.7347 (2)	421.43
26.100	5.5515 (2)	421.99
26.000	5.3729 (2)	422.54

[a] Number in parentheses indicates power of 10 by which entry is to
be multiplied.

TABLE VI (Continued)

Temperature (K, IPTS-68)	Pressure (torr)	Heat of Vaporization (cal/gm mole K)
25.900	5.1986 (2)	423.08
25.800	5.0287 (2)	423.63
25.700	4.8631 (2)	424.16
25.600	4.7016 (2)	424.70
25.500	4.5442 (2)	425.22
25.400	4.3909 (2)	425.75
25.300	4.2416 (2)	426.27
25.200	4.0962 (2)	426.78
25.100	3.9546 (2)	427.29
25.000	3.8168 (2)	427.80
24.900	3.6828 (2)	428.30
24.800	3.5524 (2)	428.80
24.700	3.4255 (2)	429.29
24.600	3.3022 (2)	429.78
24.561	3.2550 (2)	429.97
24.552 (tp)	3.2442 (2)	430.01
- - - Solid - - -		
24.552 (tp)	3.2442 (2)	510.12
24.500	3.1710 (2)	510.29
24.300	2.9018 (2)	510.90
24.100	2.6517 (2)	511.45
24.000	2.5335 (2)	511.71
23.900	2.4197 (2)	511.96
23.700	2.2047 (2)	512.42
23.500	2.0058 (2)	512.84
23.300	1.8220 (2)	513.22
23.100	1.6524 (2)	513.56

TABLE VI (Continued)

Temperature (K, IPTS-68)	Pressure (torr)		Heat of Vaporization (cal/gm mole K)
23.000	1.5727	(2)	513.71
22.900	1.4961	(2)	513.86
22.700	1.3524	(2)	514.13
22.500	1.2203	(2)	514.37
22.300	1.0992	(2)	514.57
22.100	9.883	(1)	514.75
22.000	9.365	(1)	514.83
21.900	8.870	(1)	514.89
21.700	7.945	(1)	515.02
21.500	7.102	(1)	515.12
21.300	6.336	(1)	515.20
21.100	5.640	(1)	515.25
21.000	5.318	(1)	515.27
20.900	5.011	(1)	515.29
20.700	4.441	(1)	515.30
20.500	3.928	(1)	515.29
20.300	3.465	(1)	515.27
20.100	3.050	(1)	515.23
20.000	2.859	(1)	515.20
19.900	2.678	(1)	515.17
19.700	2.345	(1)	515.09
19.500	2.048	(1)	515.0
19.300	1.784	(1)	514.9
19.100	1.549	(1)	514.8
19.000	1.442	(1)	514.7
18.900	1.342	(1)	514.6
18.700	1.158	(1)	514.5
18.500	9.971		514.3

TABLE VI (Continued

Temperature (K, IPTS-68)	Pressure (torr)	Heat of Vaporization (cal/gm mole K)
18.300	8.555	514.1
18.100	7.317	513.9
18.000	6.758	513.8
17.900	6.236	513.7
17.700	5.296	513.5
17.500	4.481	513.3
17.300	3.778	513.0
17.100	3.173	512.8
17.000	2.903	512.7
16.900	2.654	512.5
16.700	2.210	512.2
16.500	1.833	511.9
16.300	1.513	511.6
16.100	1.244	511.3
16.000	1.126	511.1
15.900	1.017	511.0
15.700	8.279 (-1)	510.6
15.500	6.703 (-1)	510.3
15.300	5.398 (-1)	509.9
15.100	4.323 (-1)	509.5
15.000	3.861 (-1)	509.3
14.900	3.442 (-1)	509.1
14.700	2.724 (-1)	508.7
14.500	2.143 (-1)	508.3
14.300	1.675 (-1)	507.8
14.100	1.300 (-1)	507.4
14.000	1.142 (-1)	507.1
13.900	1.002 (-1)	506.9

TABLE VI (Continued)

Temperature (K, IPTS-68)	Pressure (torr)	Heat of Vaporization (cal/gm mole K)
13.700	7.664 (-2)	506.4
13.500	5.819 (-2)	505.9
13.300	4.383 (-2)	505.4
13.100	3.274 (-2)	504.9
13.000	2.820 (-2)	504.6
12.900	2.424 (-2)	504.4
12.700	1.778 (-2)	503.8
12.500	1.292 (-2)	503.2
12.300	9.297 (-3)	502.7
12.100	6.619 (-3)	502.1
12.000	5.562 (-3)	501.8
11.900	4.661 (-3)	501.5
11.700	3.244 (-3)	500.9
11.500	2.231 (-3)	500.3
11.300	1.515 (-3)	499.6
11.100	1.015 (-3)	499.0
11.000	8.262 (-4)	498.7
10.900	6.702 (-4)	498.3
10.700	4.361 (-4)	497.7
10.500	2.793 (-4)	497.0
10.300	1.759 (-4)	496.2
10.100	1.089 (-4)	495.5
10.000	8.508 (-5)	495.2
9.900	6.615 (-5)	494.8
9.700	3.940 (-5)	494.1
9.500	2.298 (-5)	493.3
9.300	1.311 (-5)	492.6
9.100	7.299 (-6)	491.8

TABLE VI (Continued)

Temperature (K, IPTS-68)	Pressure (torr)	Heat of Vaporization (cal/gm mole K)
9.000	5.396 (-6)	491.4
8.900	3.963 (-6)	491.0
8.700	2.095 (-6)	490.2
8.500	1.075 (-6)	489.4
8.300	5.353 (-7)	488.6
8.100	2.578 (-7)	487.7
8.000	1.765 (-7)	487.3
7.900	1.198 (-7)	486.9
7.700	5.356 (-8)	486.0
7.500	2.298 (-8)	485.2
7.300	9.425 (-9)	484.3
7.100	3.683 (-9)	483.4
7.000	2.258 (-9)	483.0
6.900	1.365 (-9)	482.5
6.700	4.780 (-10)	481.7
6.500	1.572 (-10)	480.7
6.300	4.829 (-11)	479.8
6.100	1.376 (-11)	478.9
6.000	7.125 (-12)	478.4
5.900	3.610 (-12)	478.0
5.700	8.648 (-13)	477.0
5.500	1.873 (-13)	476.1
5.300	3.625 (-14)	475.2
5.100	6.190 (-15)	474.2
5.000	2.429 (-15)	473.7
4.900	9.185 (-16)	473.2
4.700	1.164 (-16)	472.2
4.500	1.233 (-17)	471.3

TABLE VI (Continued)

Temperature (K, IPTS-68)	Pressure (torr)	Heat of Vaporization (cal/gm mole K)
4.300	1.065 (-18)	470.3
4.100	7.283 (-20)	469.4
4.000	1.726 (-20)	468.9
3.900	3.807 (-21)	468.4
3.700	1.456 (-22)	467.4
3.500	3.867 (-24)	466.4
3.300	6.669 (-26)	465.5
3.100	6.878 (-28)	464.5
3.000	5.579 (-29)	464.0
2.900	3.816 (-30)	463.5
2.700	9.934 (-33)	462.5
2.500	1.013 (-35)	461.5

For temperatures below the triple point the integral was divided into two parts

$$\int_P^{P_1} v'_s \, dP = (v'_s)_{av} (P_1 - P_{tp}) + (v'_s)^s_{av} (P_{tp} - P) \tag{20}$$

where $(v'_s)^s_{av}$ was evaluated from Equation (12) using the empirical parameters for the solid.

All calculations in Table VI have been made using a gas imperfection correction based on the second virial coefficient only. Hence, the computed values of the vapor pressure above the normal boiling point may be slightly in error because of the failure to include higher virial coefficients.

The computed vapor pressures given in Table VI for the range 27.102 K to the triple point (11 points: 27.102, 27.0, 26.8, --- 24.6 K) have been fitted by a least squares method to the equation

$$\ln P \text{ (torr)} = A_o + \frac{A_1}{T} + \frac{A_2}{T^2} + -- + \frac{A_n}{T^n} \tag{21}$$

The values of the constants are

$$A_o = 1.45683287 \times 10^1$$

$$A_1 = -2.08649277 \times 10^2$$

$$A_2 = -1.73607188 \times 10^2 \tag{22}$$

The root mean square deviation is 4.45×10^{-3} torr. The vapor pressure of neon computed from this equation at 27.102 K is 799.991 torr. Higher order polynomials gave only slightly smaller r.m.s. deviations.

Two vapor pressure equations of the above form were fitted to the values given in Table VI for the vapor pressure of solid neon. The first of these

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covered the range 24.552 (tp) to 12.5 K (32 points, 24.552, 24.5, 24.1, 23.7 ---, 12.5 K). A fourth degree polynomial with the values of the constants

$$A_o = 1.72295003 \times 10^1$$

$$A_1 = -3.08555051 \times 10^2$$

$$A_2 = 9.86024302 \times 10^2 \qquad (23)$$

$$A_3 = -9.06932715 \times 10^3$$

$$A_4 = 3.51416575 \times 10^4$$

was selected. This gave a r.m.s. deviation of 2.66×10^{-2} torr. The triple point pressure computed from this equation is 324.32 torr. The maximum error in pressure is 0.03 per cent at 12.5 K.

The second vapor pressure equation for solid neon was fitted from 13.3 to 3.7 K (25 points, 13.3, 12.9, -- 3.7 K). A third degree polynomial with the constants

$$A_o = 1.65060974 \times 10^1$$

$$A_1 = -2.69940222 \times 10^2$$

$$A_2 = 1.28274063 \times 10^2 \qquad (24)$$

$$A_3 = -1.62408198 \times 10^2$$

was selected. A maximum error of about 0.65 per cent in P was found. This occurred at 13.3 K and 4.5 K.

B. Comparison of Computed and Experimental Vapor Pressures

The computed vapor pressures of naturally occurring neon given in Table VI have been compared in Figure 1 with the experimental vapor pressure data of Grilly[21] (See Table X, Appendix C) and with the vapor pressure equations
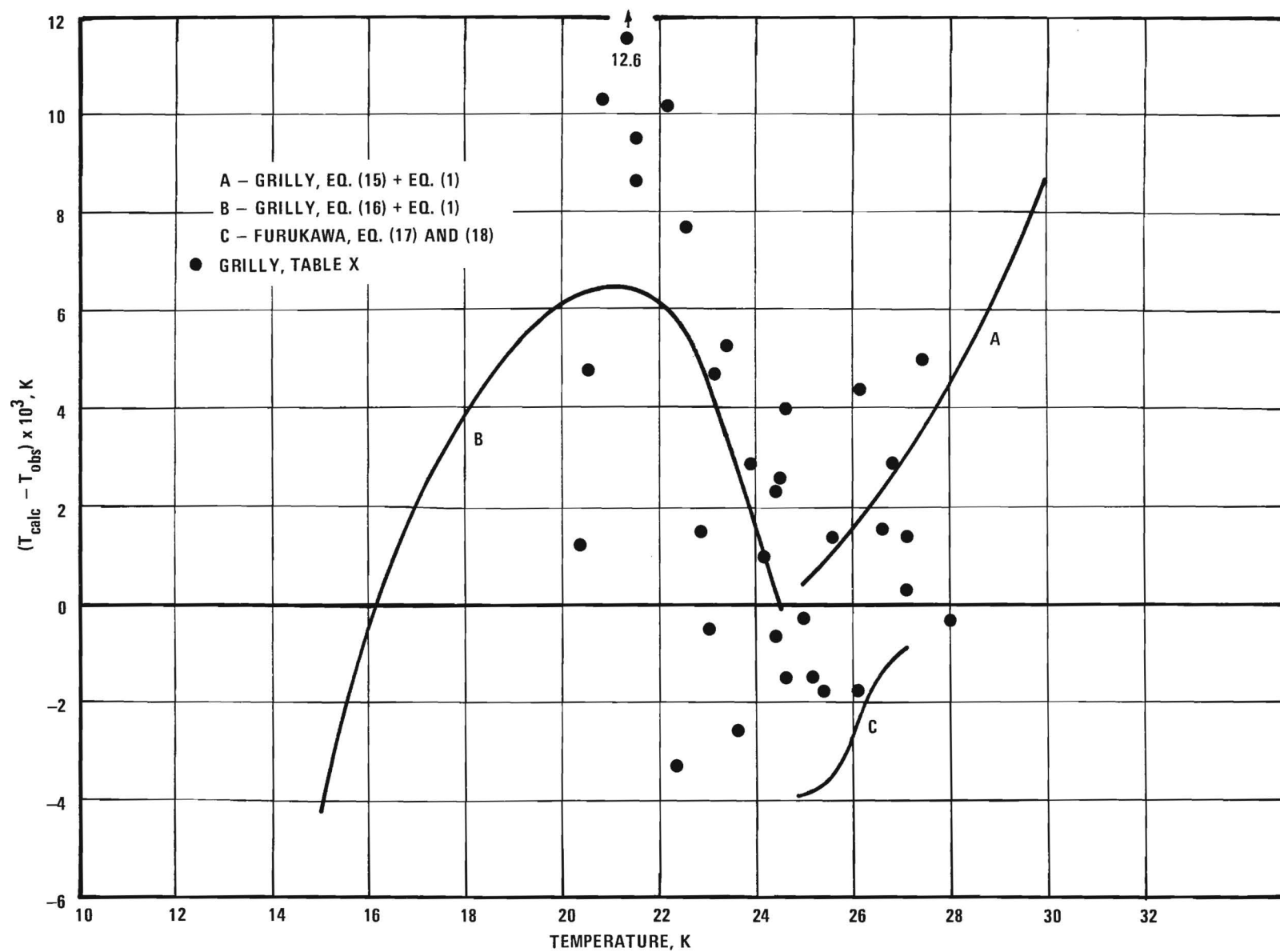
Figure 1. Comparison of Calculated and Experimental Vapor Pressure of Neon. All Temperatures on IPTS-68.

for the liquid and solid developed by him to represent these data (Equations
(15) and (16), Section III J). All temperatures of Grilly have been conver-
ted from the NBS-55 scale to IPTS-68 by means of Equation (1).

The comparison between the computed and experimental vapor pressures
shown in Figure 1 was made by examining the difference $(T_{calc} - T_{obs})$ as
a function of temperature. (Numerical values of $(T_{calc} - T_{obs})$ shown in
Figure 1 are given in Appendix C.) Here T_{obs} is the observed temperature
(converted to IPTS-68) corresponding to the experimentally observed vapor
pressure, and T_{calc} is the temperature which corresponds to this same
observed pressure as determined by interpolation in Table VI. Consideration
of Figure 1 shows that over the temperature range of Gilly's vapor pressure
equations below the normal boiling point (27.1 to 20.3 K) the maximum value
of $(T_{calc} - T_{obs})$ is about 7 millidegrees. The $(T_{calc} - T_{obs})$ values computed
for the actual vapor pressure data show somewhat larger deviations. It is
also to be noted that the vapor pressures computed by extrapolation of his
vapor pressure equation for the solid to 15 K and those of Table VI agree to
within a few millidegrees.

Also shown in Figure 1 is a comparison between experimental measurements
of Furukawa[17] as represented by Equations (17) and (18). The computed values
of vapor pressures given in Table VI are seen to agree with Furukawa's values
to about 4 millidegrees.

The vapor pressure measurements of other investigators have not been
included in Figure 1 because of the uncertainty as to how to convert their
temperature scales to IPTS-68. Grilly[21] has published a comparison of his
equation with the experimental data of earlier investigators in a manner
somewhat similar to that given in Figure 1. However, he did not convert
these data to a uniform temperature scale.

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In view of the agreement between the vapor pressures given in Table VI over the temperature range 27.1 to 20.3 K with the best available experimental data it is believed that the values of the vapor pressure of solid neon computed in Table VI below 20 K represent the best presently available estimate of these vapor pressures. The values of the vapor pressure in Table VI are given to more significant figures than the input experimental data warrant, but are given to provide sufficient significant figures to permit interpolation.

C. Comparison of Computed and Experimental Heats of Vaporization and Sublimation

No direct measurements of heats of vaporization or sublimation of neon were found in the literature. Fagerström and Hollis Hallett[14] have estimated the heat of sublimation at the triple point to be 503.3 cal/mole. Using this value and their heat capacity data they estimated the heat of sublimation of solid neon to be 443.6 cal/mole at 0 K with an estimated error of less than 2 per cent. The corresponding values from Table VI are 510.1 cal/mole at the triple point and 449.1 cal/mole at 0 K.

The heats of vaporization and sublimation given in Table VI have been fitted by a least squares procedure to an equation of the form

$$\Delta H_v (cal/mole) = A_o + A_1 T + A_2 T^2 + --$$ (25)

For the liquid range (14 points, 27.102, 27.00, 26.8, 26.6, ---, 24.6 K) a second degree equation was found to be adequate to represent the heat of vaporization. The constants $A_o = +4.10014396 \times 10^2$, $A_1 = +6.45783223$, $A_2 = -2.29854677 \times 10^{-1}$ gave a r.m.s. deviation is 2.05×10^{-3} cal/mole. For the solid range (58 points, 24.552, 24.5, 24.1, ---, 2.1 K), a third degree

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equation was found to be adequate to represent the heat of sublimation. The constants $A_o = +4.48121436 \times 10^2$, $A_1 = +5.45707298$, $A_2 = -4.83467001 \times 10^{-2}$, $A_4 = -2.85169107 \times 10^{-3}$ gave a r.m.s. deviation of 0.215 cal/mole.

D. Comparison of the Calorimetric and Statistical Entropy of Naturally Occurring Neon as an Ideal Gas

The thermal data used to compute the vapor pressure and heats of vaporization and sublimation given in Table VI were used to compute the calorimetric entropy of the ideal gas at the normal boiling point (27.102 K) and one atm pressure, assuming the entropy of the solid to be zero at 0 K. The results of the calculations are shown in Table VII. The entropy of the solid at 1.4 K has been computed assuming a Debye theta Θ_D = 75.0 K.[14,16] The estimated uncertainties given are based on estimate of the uncertainties in the experimental data.

The entropy of the ideal gas was computed from the statistical mechanical relation

$$(S^o)_{Stat} = R \left[\frac{5}{2} \ln T + \frac{3}{2} \ln M - 1.164862 \right] \quad (26)$$

with M = 20.179.

TABLE VII

COMPARISON OF CALORIMETRIC AND STATISTICAL ENTROPY
OF NEON AS IDEAL GAS AT 27.102 K AND 1 ATM

Temperature Range (K)	Entropy Change (cal/gm mole K)	Estimated Uncertainty cal/gm mole K	
0 - 1.4	0.001	0	θ_D = 75.0 K
1.4 - 3.6	0.018	0	
3.6 - 6.5	0.110	0.001	
6.5 - 11.5	0.568	0.006	
11.5 - 24.552 (tp)	2.783	0.080	
24.552	3.262	0.010	Fusion, $80.11/_{24.552}$
24.552 - 27.102 (nbp)	0.881	0.010	
27.102	15.357	0.037	Vaporization, $416.2/_{27.102}$
27.102	0.158	0.014	Correction for non-ideality
		0.16	
(S^o)Cal.	23.138		
(S^o)Stat	23.034 ± 0.001		

V. VAPOR PRESSURE OF NEON ISOTOPES

The vapor pressures of the neon isotopes have been determined by a number of investigators. (See Appendix C.) In the present work no detailed examination of these data has been made. Bigeleisen and Roth[4] have made measurements of the vapor pressure of naturally occurring neon and the neon isotopes ^{20}Ne and ^{22}Ne at the same temperatures. They reported their measurments in terms of the temperature scale of Crommelin and Gibson.[11] We have converted their pressure measurements for naturally occurring neon to the IPTS-68, as described in Appendix C. The results of this conversion are shown in Table XI, Appendix C.

VI. CONCLUSIONS AND RECOMMENDATIONS

Thermodynamic relations have been used to compute the vapor pressure and heats of vaporization and sublimation of naturally occurring neon from the normal boiling point (27.102 K) to 2.5 K on the IPTS-68. The results of these calculations are presented in Table VI. Three vapor pressure equations, one for the liquid and two for the solid range, have been developed by a least squares procedure to fit these tabular values. Equations have also developed to fit the heat of vaporization of the liquid and the heat of sublimation of the solid.

The computed vapor pressures given in Table VI have been found to be in good agreement with the available experimental data for the liquid and solid down to 20 K. The calorimetric entropy of neon as an ideal gas at 27.102 K and 1 atm pressure was computed to be 23.138 ± 0.16 e.u. from the thermal data used to compute Table VI. The corresponding entropy calculated from statistical mechanics is 23.034 ± 0.001 e.u.

It is concluded that the computed values of the vapor pressure and heats of vaporization and sublimation given in Table VI represent the best experimental data over the range 27.102 to 20 K within 0.01 K and that these values represent the best available estimate below 20 K.

VII. ACKNOWLEDGEMENTS

Respectfully submitted:

Approved:

W. T. Ziegler
Project Director

Frederick Bellinger
Chemical Sciences and Materials Division

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IX. APPENDICES

A. Nomenclature and Physical Constants[*]

B	= second virial coefficient of gas.
C	= third virial coefficient of gas.
c'_s	= molar heat capacity of saturated condensed phase.
d	= density in gm/cc. Eq. (12).
$e/k, \sigma$	= parameters used in the Lennard-Jones (6-12) intermolecular potential function.
h	= Planck's constant = 6.6256×10^{-27} erg-sec/molecule.
$(\Delta H_v)_T$	= heat of vaporization (or sublimation) at T.
(ΔH_{tr})	= heat of transition of condensed phase at transition temperature, T_{tr}. Includes fusion.
$\sum_{T}^{T_1} (\Delta H_{tr})$	= sum of all condensed phase transitions from T through T_1.
$(H^o - H_o^o)''_T$	= enthalpy function for ideal gas at T.
k	= Boltzmann constant = 1.38054×10^{-16} erg/deg. K molecule.
M	= molecular weight.
N_o	= Avogadro's Number = 6.02252×10^{23} molecules/ gm mole.
P	= Pressure.
P_1	= pressure of a known point on the vapor pressure curve.
R	= gas constant = 1.98717 cal/gm mole deg K = 0.082056 cc atm/gm mole deg. K. (1 calorie = 4.1840 ab. joules = 4.1833 int. joules).

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[*] The physical constants used were those adopted for use by the U. S. National Bureau of Standards (NBS Tech. News Bull. 47 175 (1963).

$S^o(P,T)''$ $\qquad$ = entropy of the ideal gas at P and T.

$(S^o)_T''$ $\qquad$ = entropy of ideal gas at P = 1 atm and T.

T $\qquad$ = temperature on the thermodynamic Kelvin scale.

T (IPTS-68) $\qquad$ = temperature on the International Practical Temperature Scale of 1968. (See Ref. 1.)

T_1 $\qquad$ = temperature of a known point on the vapor pressure curve.

T_o $\qquad$ = ice point on thermodynamic scale.

T_{68} $\qquad$ = T (IPTS-68)

T_{55} $\qquad$ = temperature on NBS-55 scale. (See Ref. 3.)

V $\qquad$ = molar volume of gas.

v_s' $\qquad$ = molar volume of saturated condensed phase.

δ $\qquad$ = defined by Equation (3) and Equation (5).

ϵ $\qquad$ = defined by Equation (7) and Equation (8).

Superscripts

' $\qquad$ = condensed phase.

'' $\qquad$ = gas phase.

Subscripts

s $\qquad$ = saturated vapor or condensed state.

v $\qquad$ = vaporization. Also refers to sublimation for temperatures at and below the triple point.

B. Second Virial Coefficient of Neon

The second and third virial coefficients of neon have not been measured below 44 K. Measurements of the second virial coefficient below 140 K (the Boyle temperature for neon is approximately 110 K). Cath and Kamerlingh Onnes[8] (133-53 K); Holborn and Otto[26,27] (123-65.25 K); Sullivan and Sonntag[45] (120-70 K) and Gibbons[18] (70-44 K). These values are shown in Table VIII.

Keesom and Van Lammeren[32] have combined the results of the second
virial coefficient measurements of Cath and Kamerlingh Onnes[8] with measurements
made by them of the effect of pressure on the velocity of sound in neon to
26.25 K to obtain an empirical expression for the second virial coefficient
as a function of temperature. Values of B (expressed in cc/gm mole) calculated
by them are also shown in Table VIII.

As was pointed out in Section III I Sullivan and Sonntag[45] have fitted
their second virial coefficient measurements at 120, 90, 80 and 70 K by a least
squares procedure to a Lennard-Jones 6-12 potential function. They included
the translational quantum corrections corresponding to the terms B_I^*, B_{II}^* and
B_o^* in Equation (13). They obtained the values $\sigma = 2.782$ Å, $e/k = 34.82$ K and
$\Lambda^* = 0.5935$.

Gibbons[18] used the classical Lennard-Jones parameters $\sigma = 2.780$ Å
and $e/k = 34.9$ K given by Hirschfelder, et al.[24] (p 1110) to calculate the
second virial coefficient of neon at his experimental temperatures of 70, 60,
50, 46, and 44 K and found good agreement with his experimental values.
Quantum corrections were not included in these calculations by him.

Nicholson and Schneider[42] have measured the second virial coefficient of
neon over the range 0 to 700°C. The combined these data with the low temperature
data (0° to -150°C) of Holborn and Otto[26] and Kamerlingh Onnes and coworkers[12,28]
and by a least squares method obtained the Lennard-Jones parameters $\sigma = 2.756$ Å
and $e/k = 33.74$ K. The low temperatures values of the second virial coefficient
were corrected for quantum effects before fitting the data.

TABLE VIII

EXPERIMENTAL VALUES OF THE SECOND VIRIAL COEFFICIENT
OF NEON

T K	B (expt.) cc/mole	Reference
70	-17.05	Gibbons[18]
60	-24.91	
50	-35.41	
46	-42.17	
44	-46.14	
70	-15.92	Sullivan and Sonntag[45]
80	-10.72	
100	- 3.61	
120	+ 0.99	
65.25	-20.9	Holborn and Otto[26,27]
90.65	- 8.18	
123.15	+ 0.10	
173.15	6.44	
133.15	1.8	Cath and Kamerlingh Onnes[8]
123.15	0.4	
113.15	- 1.1	
103.15	- 3.1	
93.15	- 5.6	
83.15	- 9.0	
73.15	-13.4	
63.15	-20.2	
53.15	-33.4	

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TABLE VIII (Continued)

T K	B (expt.) cc/mole	Reference
26.25	-128.1	Keesom and Van Lammeren[32]
27.80	-114.2	
30	- 98.7	
40	- 55.6	
50	- 34.8	
60	- 22.9	
70	- 15.3	
80	- 10.3	

We have computed the second virial coefficient as a function of temperature using these three sets of σ and e/k parameters by means of Equation (13). All quantum corrections shown in Equation (13) were used, Λ^* being taken equal to 0.5934139. Calculations were made at ten degree intervals over the range 120 to 30 K and at one degree intervals over the range 30 to 15 K. The results of these calculations are shown in Table IX. As is pointed out in Section III. E., Mathias, et al.[37] have determined the density of saturated neon vapor at 27.15 K (their temperature scale) or 27.082 K (IPTS-68) to be 0.00939 gm/cc or (V = 2149.0 cc/mole). Unfortunately, they did not give a pressure measurement at this temperature. We have calculated a pressure of 755.45 torr (T = 27.082 K, IPTS-68) using Grilly's vapor pressure equation. We may compute a value of B at this temperature from the relation

$$B = V(\frac{PV}{RT} - 1) \qquad (27)$$

Setting V = 2149.0 cc/mole, P = 755.45 torr, R = 82.056 cc atm/mole K and T = 27.082 gives B = -83.3 ± 2 cc/mole. The uncertainty of ± 2 cc/mole corresponds to an assumed uncertainty of $\pm 10^{-5}$ gm/cc in the density measurement. It seems likely that the uncertainty actually is considerably larger than this as the computed value of B is quite sensitive to the precise temperatures and pressure chosen.

The experimentally measured values of the second virial coefficient of neon given in Table VIII are plotted in Figure 2 along with the theoretical curve based on the Lennard-Jones model using the parameters of Sullivan and Sonntag.
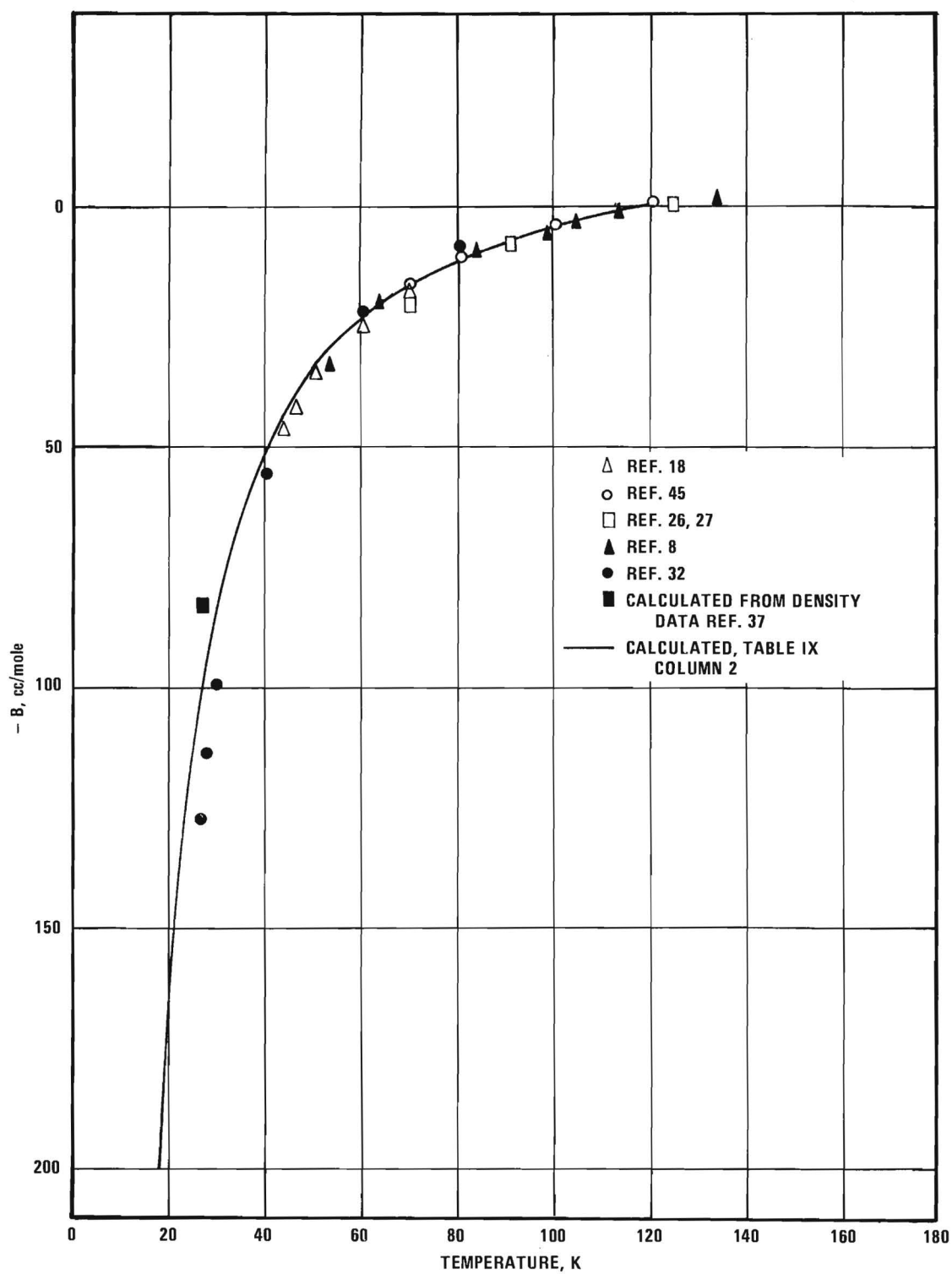
Figure 2. Comparison of Computed and Experimental Second Virial Coefficients of Neon.

TABLE IX

SECOND VIRIAL COEFFICIENT OF NEON CALCULATED
USING VARIOUS LENNARD-JONES (6-12) PARAMETERS

Temp. K	B cc/mole		
	σ = 2.782 Å e/k = 34.82 K Ref. 45	σ = 2.780 Å e/k = 34.90 K Ref. 25	σ = 2.756 Å e/k = 33.74 K Ref. 42
120	0.562	0.511	1.201
100	- 3.795	- 3.849	- 2.862
80	- 10.711	- 10.770	- 9.310
70	- 15.904	- 15.967	- 14.149
60	- 23.138	- 23.208	- 20.884
50	- 33.854	- 33.934	- 30.847
40	- 51.233	- 51.334	- 46.967
30	- 83.950	- 84.097	- 77.179
29	- 88.861	- 89.016	- 81.700
28	- 94.238	- 94.401	- 86.644
27	-100.148	-100.322	- 92.074
26	-106.673	-106.858	- 98.063
25	-113.911	-114.110	-104.699
24	-121.985	-122.200	-112.092
23	-131.043	-131.276	-120.375
22	-141.272	-141.527	-129.714
21	-152.907	-153.188	-140.319
20	-166.249	-166.560	-152.456
19	-181.686	-182.035	-166.471
18	-199.732	-200.128	-182.816
17	-221.071	-221.524	-202.091
16	-246.633	-247.159	-225.110
15	-277.705	-278.323	-252.993

C. Experimental Vapor Pressure Data for Neon and Neon Isotopes

Vapor Pressure of Neon

The vapor pressure of neon in the temperature range near and below the normal boiling point has been determined by Crommelin and Gibson[11] (15.47-27.30 K), Henning and Otto[23] (22.07-27.50 K), and Keesom and Haantjes[29,30] (15.08 to 20.45 K). Verschaffelt[47] has developed a vapor pressure equation to fit the data reported by Crommelin and Gibson. The experimental data reported by these investigators has not been used in the present work because of the uncertainty in how to convert the temperature scales used to the IPTS-68.

Grilly[21] (see Section III J) has measured the vapor pressure of liquid neon over the range 24.544 to 44.384 K (61 data points NBS-55 scale) and of solid neon over the range 20.301 to 24.544 K (20 data points). He represented these data by empirical equations given in Section III J (Equations 15 and 16). Dr. Grilly[22] kindly provided us with the actual data points used in fitting these equations. These observed pressures converted to IPTS-68 by means of Equation (1) are shown in Table X.

Dr. George T. Furukawa[17] (National Bureau of Standards, Washington, D. C.) (see Section III J) has recently completed measurements of the vapor pressure of neon from the triple point to slightly above the normal boiling point. The 96 data points were fitted by him using a least squares method to obtain Eq. (17) (Section III J) in which the constants have the values.

$$
\begin{aligned}
A_1 &= -7.650560763129046 \times 10^2 \\
A_2 &= -6.759780755738651 \times 10^3 \qquad\qquad (28) \\
A_3 &= +2.114056959820131 \times 10^3
\end{aligned}
$$

$$A_4 = +2.984887505912452 \times 10^1$$
$$A_5 = -1.941182548307838 \times 10^{-1} \qquad (28)$$

According to Dr. Furukawa these constants give a computed pressure of 736.6461[+] torr at 27.00 K (IPTS-68). We have used Eq. (17) with the above constants rounded to 10 significant figures (see Eq. (18), Section III J) to compute the values given in Table X. These approximate constants give a pressure of 736.6461017 torr at 27.00 K. The agreement between these two values at 27.00 K suggested that the approximate constants may be used in place of the more exact constants.

Vapor Pressure of the Isotopes of Neon

The vapor pressure liquid and solid of ^{20}Ne and ^{22}Ne, as well as various isotopic mixtures, have been reported by Keesom and Haantjes,[30,31] by Boato and coworkers[6,7], by Bigeleisen and Roth[4] and Bigeleisen.[5]

In the present paper we have considered only certain aspects of the paper of Bigeleisen and Roth. These investigators made measurements of the vapor pressures of naturally occurring neon, ^{20}Ne and ^{22}Ne at the same temperatures. They made no direct temperature measurements, but reported their temperatures in terms of the vapor pressure-temperature relations of Crommelin and Gibson of the University of Leiden. (Unfortunately, the reference they cited for the Crommelin-Gibson scale is incorrect. Presumably they have in mind the measurements given by Crommelin and Gibson, Phys. Lab., Univ. Leiden 185b (Ref. 11). We have converted the vapor pressure measurements of Bigeleisen and Roth to IPTS-68 by means of Grilly's vapor pressure relations (Equations 15 and 16, Section III J). The results of these calculations are shown in Table XI. The very significant differences in IPTS-68 and the Crommelin-Gibson scale, as reported by Bigeleisen and Roth, is evident. The excellent

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TABLE X

EXPERIMENTAL VAPOR PRESSURE OF NEON

Observed Temperature (K)(IPTS-68)	Observed Pressure (torr)	$(T_{calc} - T_{obs}) \times 10^3$ (K)
Grilly,[21] vapor pressure equations Eq. (15) and (16).	- - - Liquid - - -	
30.000	1.6755 (3)	+8.8
29.500	1.4784 (3)	+7.5
29.000	1.2990 (3)	+6.6
28.500	1.1361 (3)	+5.4
28.000	9.8885 (2)	+4.5
27.500	8.5631 (2)	+3.6
27.000	7.3753 (2)	+2.8
26.500	6.3158 (2)	+2.1
26.000	5.3755 (2)	+1.5
25.500	4.5456 (2)	+0.9
25.000	3.8173 (2)	+0.4
	- - - Solid - - -	
24.552 (tp)	3.2442 (2)	-0.1
24.500	3.1701 (2)	-0.1
24.000	2.5353 (2)	+1.5
23.500	2.0089 (2)	+3.3
23.000	1.5762 (2)	+4.5
22.500	1.2238 (2)	+5.6
22.000	9.3962 (1)	+6.1
21.500	7.1282 (1)	+6.5
21.000	5.3386 (1)	+6.5
20.500	3.9436 (1)	+6.4
20.000	2.8703 (1)	+6.0
19.500	2.0561 (1)	+5.8

TABLE X (Continued)

Observed Temperature (K)(IPTS-68)	Observed Pressure (torr)	$(T_{calc} - T_{obs}) \times 10^3$ (K)
Grilly,[21] vapor pressure equations, Eq. (15) and (16).	- - - Solid - - -	
19.000	1.4478 (1)	+5.2
18.500	1.0007 (1)	+4.7
18.000	6.7790	+3.9
17.500	4.4932	+3.2
17.000	2.9084	+2.1
16.500	1.8345	+0.9
16.000	1.1248	-1.1
15.500	6.6869 (-1)	-2.2
15.000	3.8421 (-1)	-4.3
Grilly experimental data[22]	- - - Liquid - - -	
27.997	9.867 (2)	-0.3
27.440	8.4172 (2)	+5.0
27.090	7.5761 (2)	+1.4
27.090	7.5736 (2)	+0.3
26.758	6.8482 (2)	+2.9
26.634	6.5864 (2)	+1.5
26.084	5.5312 (2)	+4.4
26.039	5.4396 (2)	-1.8
25.585	4.6729 (2)	+1.4
25.442	4.4514 (2)	-1.8
25.138	4.0054 (2)	-1.5
24.962	3.7648 (2)	-0.3
24.682	3.4011 (2)	-1.5
24.587	3.2912 (2)	+4.0

TABLE X (Continued)

Observed Temperature (K)(IPTS-68)	Observed Pressure (torr)	$(T_{calc} - T_{obs}) \times 10^3$ (K)
- - - Solid - - -		
24.552 (tp)	3.2478 (2)	+2.6
24.485	3.1532 (2)	+2.3
24.485	3.1491 (2)	-0.7
24.226	2.8084 (2)	+1.0
24.110	2.6638 (2)	-0.1
23.857	2.3755 (2)	+2.9
23.633	2.1340 (2)	-2.6
23.464	1.9770 (2)	+5.3
23.051	1.6163 (2)	+4.7
22.938	1.5241 (2)	-0.5
22.851	1.4606 (2)	+1.5
22.542	1.2519 (2)	+7.7
22.475	1.2022 (2)	-3.6
22.165	1.0288 (2)	+10.2
21.475	7.040 (1)	+9.5
21.475	7.037 (1)	+8.7
21.313	6.430 (1)	+12.6
20.884	4.994 (1)	+10.3
20.492	3.920 (1)	+4.8
20.310	3.490 (1)	+1.2

Furukawa[17] Equations (17) and (18)

	- - - Liquid - - -	
27.102	7.5973 (2)	-1.2
27.000	7.3664 (2)	-1.2
26.800	6.9287 (2)	-1.1
26.600	6.5104 (2)	-1.4
26.400	6.1111 (2)	-1.8
26.200	5.7304 (2)	-2.2

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TABLE X (Continued)

Observed Temperature (K)(IPTS-68)	Observed Pressure (torr)	$(T_{calc} - T_{obs}) \times 10^3$ (K)
26.000	5.3681 (2)	-2.7
25.800	5.0235 (2)	-3.1
25.600	4.6961 (2)	-3.4
25.400	4.3854 (2)	-3.7
25.200	4.0907 (2)	-3.8
25.000	3.8115 (2)	-3.9
24.800	3.5472 (2)	-4.0
24.600	3.2971 (2)	-4.2
24.561 (tp)	3.2500 (2)	-4.2

agreement of the triple point pressure found by Bigeleisen and Roth with that reported by Grilly and Furukawa (see Table III, Section III D) suggests that the pressure measurements of Bigeleisen and Roth are of good accuracy. Since Bigeleisen and Roth reported the vapor pressure of the neon isotopes ^{20}Ne and ^{22}Ne at the same temperatures as those given in Table XI for the naturally occurring neon, this table of temperatures can be taken to represent their values for the vapor pressures of ^{20}Ne and ^{22}Ne on the IPTS-68.

TABLE XI

CONVERSION OF VAPOR PRESSURE MEASUREMENTS OF BIGELEISEN AND ROTH OF
NATURALLY OCCURRING NEON

Reported Pressure (torr)	Reported Temperature [a] (K) C and G Scale	Computed Temperature [b] (K) IPTS-68
	- - - Solid - - -	
1.53	16.42	16.311
1.99	16.66	16.586
2.03	16.67	16.607
2.06	16.69	16.623
2.07	16.70	16.628
2.21	16.76	16.698
2.63	16.93	16.888
2.70	16.96	16.917
3.10	17.10	17.071
3.14	17.11	17.086
3.41	17.20	17.179
3.57	17.25	17.232
3.58	17.26	17.235
3.59	17.26	17.238
4.49	17.50	17.499
4.91	17.60	17.605

[a] This temperature is reported by Bigeleisen and Roth[4] to be on the scale of Crommelin and Gibson (presumably of given Ref. 11)

[b] Temperatures on IPTS-68 were computed from pressure given in Column 1 using Equations (15) and (16) (Section III J) of Grilly[21] converted to IPTS-68. Temperatures below 20.3°K represent an extrapolation of Eq. (15).

TABLE XI (Continued)

Reported Pressure (torr)	Reported Temperature [a] (K) C and G Scale	Computed Temperature [b] (K) IPTS-68
5.04	17.63	17.637
6.10	17.86	17.869
6.26	17.89	17.901
6.53	17.94	17.953
6.56	17.95	17.959
6.64	17.96	17.974
8.50	18.28	18.287
9.50	18.43	18.431
9.51	18.44	18.433
16.14	19.12	19.152
16.35	19.14	19.170
16.43	19.14	19.177
16.45	19.15	19.179
16.45	19.15	19.179
16.79	19.18	19.208
17.04	19.21	19.229
17.31	19.23	19.251
17.72	19.26	19.285
29.18	19.98	20.025
29.36	19.99	20.035
29.43	19.99	20.038
29.52	20.00	20.043
34.41	20.24	20.282
39.64	20.46	20.508
39.84	20.47	20.516
40.05	20.48	20.525
44.82	20.65	20.708

TABLE XI (Continued)

Reported Pressure (torr)	Reported Temperature [a] (K) C and G Scale	Computed Temperature [b] (K) IPTS-68
51.19	20.87	20.929
51.43	20.88	20.937
56.28	21.03	21.089
57.93	21.07	21.139
58.14	21.08	21.145
79.42	21.62	21.693
79.86	21.63	21.703
89.49	21.83	21.910
90.11	21.84	21.922
90.32	21.87	21.927
105.66	22.14	22.219
105.91	22.14	22.223
106.73	22.16	22.238
107.74	22.18	22.256
108.13	22.18	22.263
111.00	22.24	22.312
111.50	22.25	22.321
112.57	22.27	22.339
139.57	22.75	22.757
144.09	22.82	22.820
145.36	22.83	22.857
147.03	22.86	22.860
147.88	22.87	22.872
147.95	22.88	22.872
159.28	23.04	23.021
159.30	23.04	23.021
159.39	23.04	23.022
160.49	23.06	23.036

TABLE XI (Continued)

Reported Pressure (torr)	Reported Temperature [a] (K) C and G Scale	Computed Temperature [b] (K) IPTS-68
168.47	23.16	23.135
168.49	23.16	23.135
168.57	23.17	23.136
168.76	23.17	23.138
168.82	23.17	23.139
207.29	23.60	23.566
208.93	23.61	23.582
209.59	23.62	23.589
224.92	23.77	23.740
224.95	23.77	23.740
249.92	24.01	23.968
250.40	24.01	23.972
274.81	24.22	24.178
274.90	24.22	24.178
274.95	24.22	24.179
294.32	24.36	24.331
311.51	24.49	24.460
311.70	24.50	24.461
312.12	24.50	24.464
- - - Liquid - - -		
327.90	24.61	24.581
331.77	24.64	24.613
335.40	24.68	24.643
336.36	24.69	24.650
336.43	24.69	24.651
336.79	24.69	24.654
343.59	24.75	24.709
344.02	24.75	24.712

TABLE XI (Continued)

Reported Pressure (torr)	Reported Temperature [a] (K) C and G Scale	Computed Temperature [b] (K) IPTS-68
344.41	24.76	24.715
395.61	25.17	25.101
396.02	25.17	25.104
449.27	25.54	25.466
449.83	25.55	25.470
480.31	25.75	25.662
480.74	25.76	25.665
605.95	26.43	26.370
605.97	26.43	26.370
623.74	26.52	26.461
677.06	26.80	26.722
677.88	26.81	26.726
778.47	27.25	27.179
778.80	27.25	27.180
1035	28.20	28.162
1144	28.57	28.526
1175	28.66	28.624
1183	28.69	28.649
1185	28.70	28.656
1292	29.01	28.980
1580	29.74	29.764
1600	29.81	29.814
1613	29.83	29.847
1619	29.84	29.862
1635	29.90	29.901
1721	30.11	30.110