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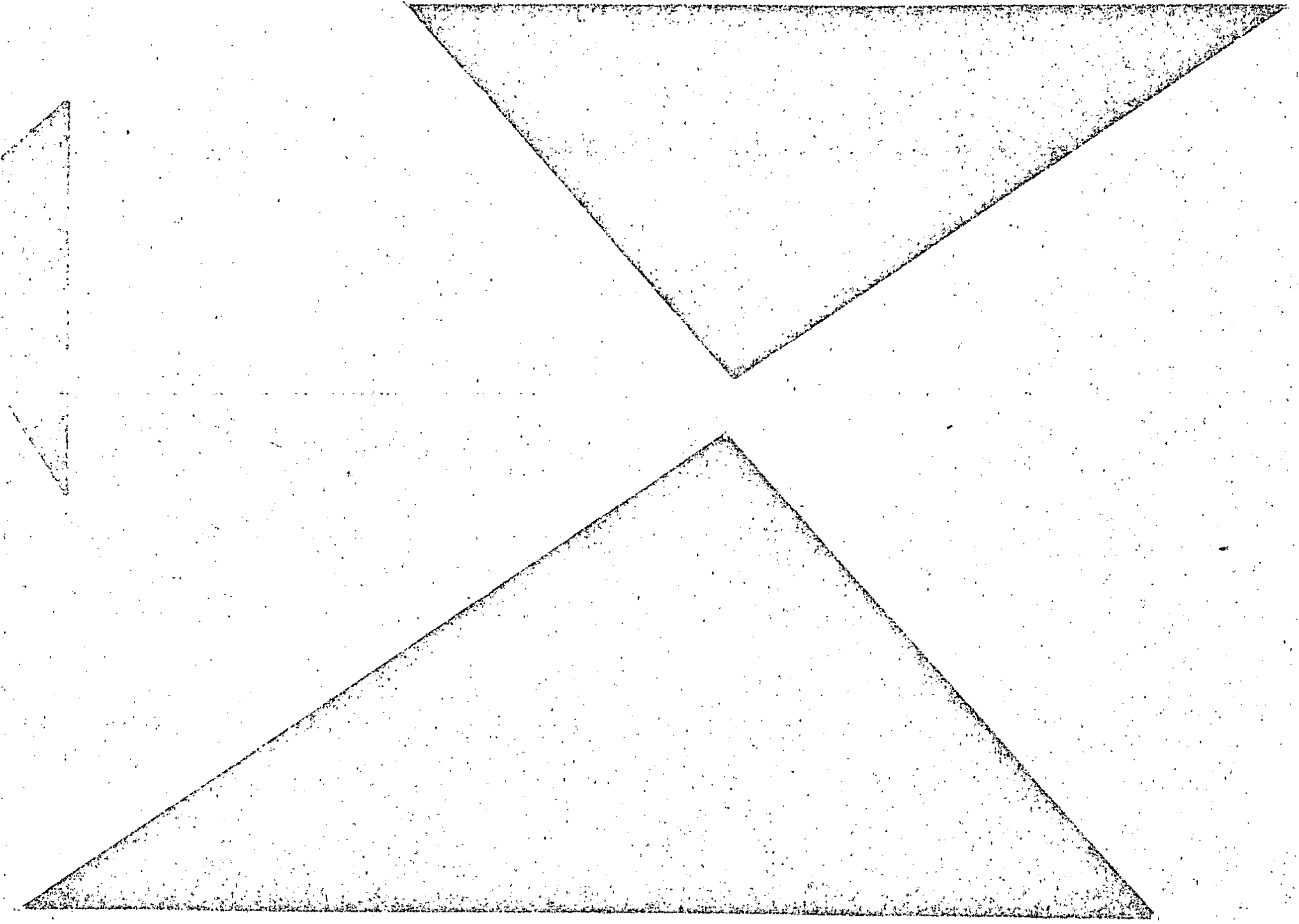

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THERMODYNAMIC PROPERTIES OF OXYGEN AND NITROGEN

III

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I. ABSTRACT

During the third quarter (Jan. 1 to April 1, 1972) work on the project has concentrated on the equation of state for nitrogen. The final equation for nitrogen has now been determined. The details of this work are documented in the doctoral dissertation of Richard T. Jacobsen [50].

In the work on the equation of state for nitrogen new coefficients were determined by constraining the critical point to selected critical point parameters. Comparisons of this new equation with all the P-ρ-T data have been made, as well as comparisons to all other thermodynamic data reported in the literature. The extrapolation of the equation of state was studied for vapor to higher temperatures and lower temperatures, and for the liquid surface to the saturated liquid and the fusion lines. A new vapor pressure equation was also determined which was constrained to the same critical temperature, pressure, and slope (dP/dT) as the equation of state.

Work on the equation of state for oxygen included studies for improving the equation at the critical point. However, a satisfactory equation has not as yet been determined which fits the selected parameters for the critical point. Comparisons of velocity of sound data for oxygen were also made between values calculated with the equation of state reported in the January 1, 1972 Progress Report [51] and experimental data.

Functions for the calculation of the derived thermodynamic properties using the equation of state are given in this report, together with the derivative and integral functions for the calculation of the thermodynamic properties using the equations of state. Summary tables of the thermodynamic properties of nitrogen and oxygen are also included to serve as a check for those preparing computer programs using the equations of state.

II. THERMODYNAMIC PROPERTIES OF NITROGEN

A. Final Equation of State

The final equation of state determined for nitrogen has the same form as reported in the January 1, 1972 Progress Report [51] on this project. This equation is given below with the coefficients for nitrogen in Table I.

$$
\begin{aligned}
P = {} & \rho RT + \rho^2(N_1T + N_2T^{\frac{1}{2}} + N_3 + N_4/T + N_5/T^2) \\
& + \rho^3(N_6T + N_7 + N_8/T + N_9/T^2) \\
& + \rho^4(N_{10}T + N_{11} + N_{12}/T) + \rho^5(N_{13}) \\
& + \rho^6(N_{14}/T + N_{15}/T^2) + \rho^7(N_{16}/T) \\
& + \rho^8(N_{17}/T + N_{18}/T^2) + \rho^9(N_{19}/T^2) \\
& + \rho^3(N_{20}/T^2 + N_{21}/T^3)\ \exp\ (-\gamma\rho^2) \\
& + \rho^5(N_{22}/T^2 + N_{23}/T^4)\ \exp\ (-\gamma\rho^2) \\
& + \rho^7(N_{24}/T^2 + N_{25}/T^3)\ \exp\ (-\gamma\rho^2) \\
& + \rho^9(N_{26}/T^2 + N_{27}/T^4)\ \exp\ (-\gamma\rho^2) \\
& + \rho^{11}(N_{28}/T^2 + N_{29}/T^3)\ \exp\ (-\gamma\rho^2) \\
& + \rho^{13}(N_{30}/T^2 + N_{31}/T^3 + N_{32}/T^4)\ \exp\ (-\gamma\rho^2) \qquad (1)
\end{aligned}
$$

TABLE I

COEFFICIENTS FOR THE EQUATION OF STATE (1) FOR NITROGEN*

Coefficient	Numerical Value	Coefficient	Numerical Value
N_1	$0.136224769272827 \times 10^{-2}$	N_{17}	$-0.111614119537424 \times 10^{-5}$
N_2	0.107032469908591	N_{18}	$0.368796562233495 \times 10^{-3}$
N_3	$-0.243900721871413 \times 10^{1}$	N_{19}	$-0.201317691347729 \times 10^{-5}$
N_4	$0.341007449376470 \times 10^{2}$	N_{20}	$-0.169717444755949 \times 10^{5}$
N_5	$-0.422374309466167 \times 10^{4}$	N_{21}	$-0.119719240044192 \times 10^{6}$
N_6	$0.105098600246494 \times 10^{-3}$	N_{22}	$-0.975218272038281 \times 10^{2}$
N_7	$-0.112594826522081 \times 10^{-1}$	N_{23}	$0.554639713151323 \times 10^{5}$
N_8	$0.142600789270907 \times 10^{-3}$	N_{24}	-0.179920450443470
N_9	$0.184698501609007 \times 10^{5}$	N_{25}	$-0.256582926077184 \times 10^{1}$
N_{10}	$0.811140082588776 \times 10^{-7}$	N_{26}	$-0.413707715090789 \times 10^{-3}$
N_{11}	$0.233011645038006 \times 10^{-2}$	N_{27}	-0.256245415300293
N_{12}	-0.507752586350986	N_{28}	$-0.124222373740063 \times 10^{-6}$
N_{13}	$0.485027881931214 \times 10^{-4}$	N_{29}	$0.103556535840165 \times 10^{-4}$
N_{14}	$-0.113656764115364 \times 10^{-2}$	N_{30}	$-0.538699166558303 \times 10^{-9}$
N_{15}	-0.707430273540575	N_{31}	$-0.757415412839596 \times 10^{-8}$
N_{16}	$0.751706648852680 \times 10^{-4}$	N_{32}	$0.585367172069521 \times 10^{-7}$

$\gamma = 0.0056$;   R = 0.0820539 liter-atm/mole-K

*Coefficients are for temperature in degrees Kelvin, pressure in atmospheres, and density in moles/liter.

1. Critical Point Parameters

The values of pressure and temperature at the critical point of nitrogen were selected as 33.555 atm. and 126.20 K. These values are consistent with the critical point measurements of White et al. [52] and to the vapor pressure formulation discussed in section IIB. (The critical pressure and temperature reported in [52] are 33.54 ± .02 atm. and 125.26 ± .04 degrees Kelvin, respectively.) The critical point density was determined as 11.21 moles/liter by the method of rectilinear diameters using values of density for the saturated liquid and saturated vapor calculated by the simultaneous solution of the vapor pressure equation and an equation of state each fit to the appropriate data. The final coefficients of the equation of state were determined by a weighted least squares fit using the criteria outlined in the January 1 Progress Report [51], and constrained to the critical point data given above using a procedure suggested by McCarty [53].

2. Comparisons of the P-ρ-T Data to the Equation of State

The accuracy of the equation of state (1) is illustrated in reference [50] by comparison of the deviations between the experimental P-ρ-T data for nitrogen and other thermodynamic property measurements with the equation of state. The deviations between the equation and the P-ρ-T data are essentially the same as the deviations for the equation reported in the January 1, 1972 Progress Report [51] and are not repeated here.

The equation of state generally shows agreement with the P-ρ-T data within the experimental uncertainty of the measured values, except in the vicinity of the critical point, in the low temperature liquid region and in the high pressure supercritical region, where some systematic deviations are found, similar to the deviations in these regions illustrated in [51]. Table II lists the root mean square deviations in pressure and in density for the various P-ρ-T data sets.

3. Comparisons of the Equation of State with Velocity of Sound Data

The velocity of sound measurements reported in the literature for nitrogen have been compared with values of the velocity of sound calculated with the equation of state, and the comparisons of data from [44], [46], [47], and [49] are given in Table III. These data sets have been selected as representative, and include measured values for the low temperature liquid, saturated liquid, saturated vapor, and vapor at high pressures. In general, the velocity of sound data for the vapor compare well with values calculated from the equation of state, whereas the comparisons of data for the liquid show larger deviations.

4. Extrapolation of the Equation of State

The P-ρ-T data for the saturated liquid and the freezing line were excluded in the determination of the coefficients of the equation of state (1) for nitrogen as given in Table I. Extrapolations of the equation of state to the saturated liquid and the saturated solid lines have been made and are compared with the experimental data available for these conditions in Figure 1. The P-ρ-T values calculated for these comparisons were determined using the vapor pressure equation (5) given in section II-B to calculate the pressure corresponding to the data temperature.

Extrapolation of the equation of state to the melting curve was made using the Simon melting curve equation (2) as reported by Grilly and Mills [39] with appropriate temperature corrections. The Simon equation for nitrogen is

$$P = a + bT^c, \qquad (2)$$

where a = -1579.08, b = 0.926302, and c = 1.795, with pressures in atmospheres and temperatures in degrees K. Densities at the melting curve calculated from the equation of state at pressures determined from the Simon equation for various temperatures are compared with the measured values of Grilly and Mills [39] in Figure 2.

In addition to the extrapolation of the equation of state in the liquid range it is also desirable to extrapolate the vapor data to higher and lower temperatures. At both high and low temperatures, the dominant terms in the equation of state are $\rho RT + \rho^2(N_1T + N_2T^{\frac{1}{2}} + N_3 + N_4/T + N_5/T^2)$. With equation (1) expanded as a power series (i.e., a virial equation), the second virial coefficient becomes,

$$B(T) = (N_1T + N_2T^{\frac{1}{2}} + N_3 + N_4/T + N_5/T^2)RT, \qquad (3)$$

where the N_i are the coefficients from Table I, and T is the temperature in degrees K. Hence, the dominant terms are the contributions from first and second virial terms.

The contribution for the ideal gas and second virial terms taken from equation (1) is as follows:

$$\text{Percent P} = (\mathcal{P}/P_{eqn}) \times 100 \qquad (4)$$

where $\mathcal{P}$ is the contribution to the calculated pressure attributed to the sum of the ideal gas and second virial term [$\mathcal{P} = \rho RT + B(T)\rho^2/RT$] and P_{eqn} is the pressure calculated from equation (1) at the specified temperature T, and density ρ. Figures 3 and 4 illustrate Percent P as the contribution of these terms. Figure 5 is a similar comparison showing the percentage contribution of the ideal gas term alone for the low temperature vapor. The contribution here is determined from equation (4) with $\mathcal{P} = \rho RT$.

Examination of Figures 3, 4, and 5 indicates that the extrapolation of the equation of state for the vapor at high and low temperatures is reasonable and for the higher temperature is limited by the accuracy of the second virial coefficient as predicted by equation (3). Figure 6 is a comparison of values from equation (3) with the experimental virial coefficients from the references cited. The accuracy of the second virial coefficient from equation (1), as illustrated in Figure 6, indicates that the extrapolation of the equation of state from 1000 K to 2000 K for pressures to 300 atmospheres is reasonable. Figure 5 indicates that equation (1) may also be extrapolated to lower temperatures for the gas to the saturated vapor line.

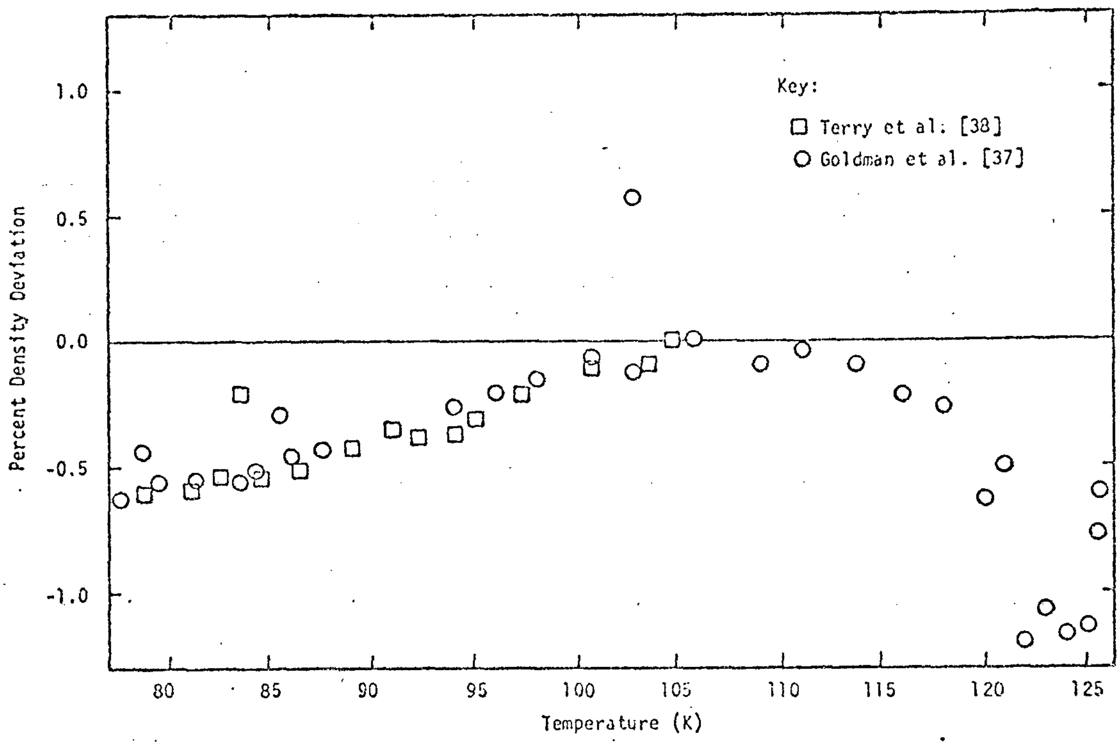

Figure 1 .--Deviations of Equation of State from Liquid P-ρ-T Data at the Vapor Pressure.

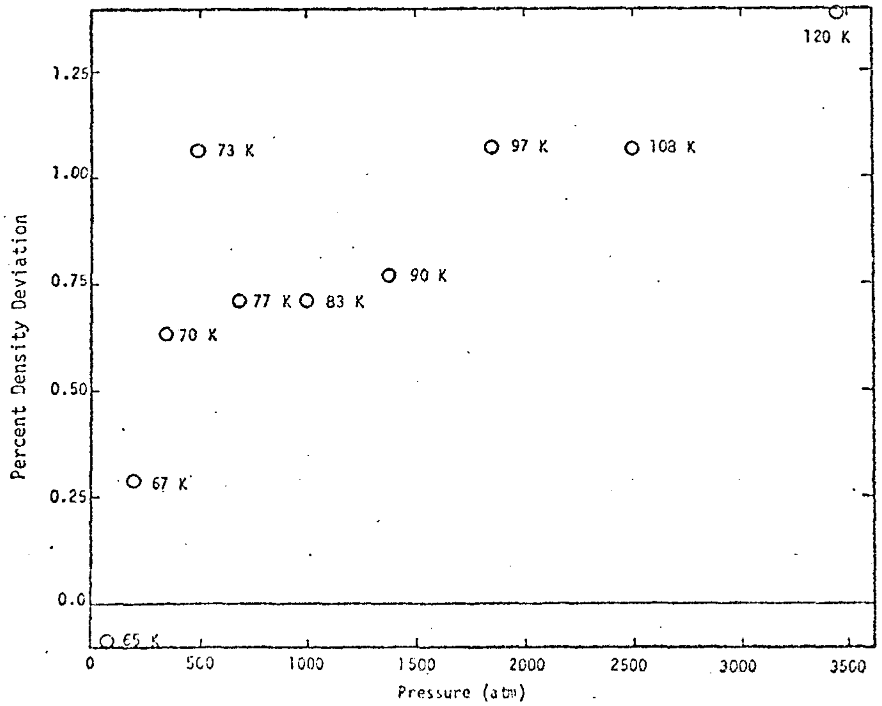

Figure 2.--Deviations of Equation (1) from Liquid P-ρ-T Data on the Freezing Line from [39]. (Nominal temperatures are given beside each point).

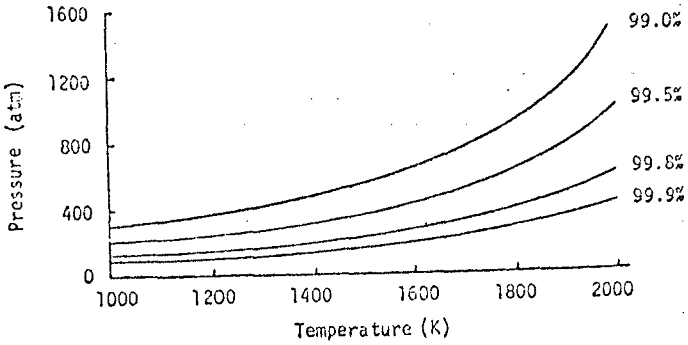

Figure 3 --Percentage Contribution of First and Second Virial Terms to Pressure from Eqn. (1) at High Temperature.

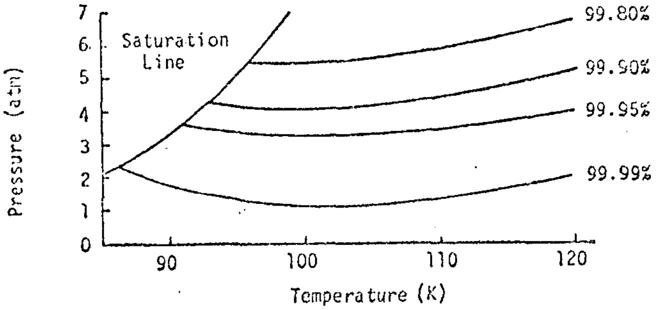

Figure 4 --Percentage Contribution of First and Second Virial Terms to Pressure from Eqn. (1) at Low Temperature.

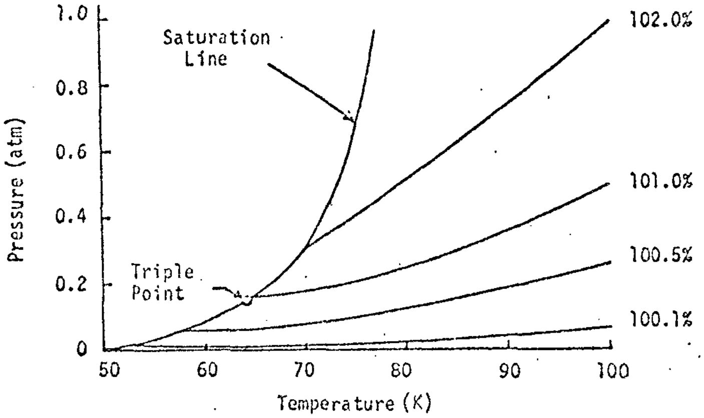

Figure 5 --Percentage Contribution of First Virial (ideal gas) Term to Pressure from Eqn. (1) at Low Temperature.

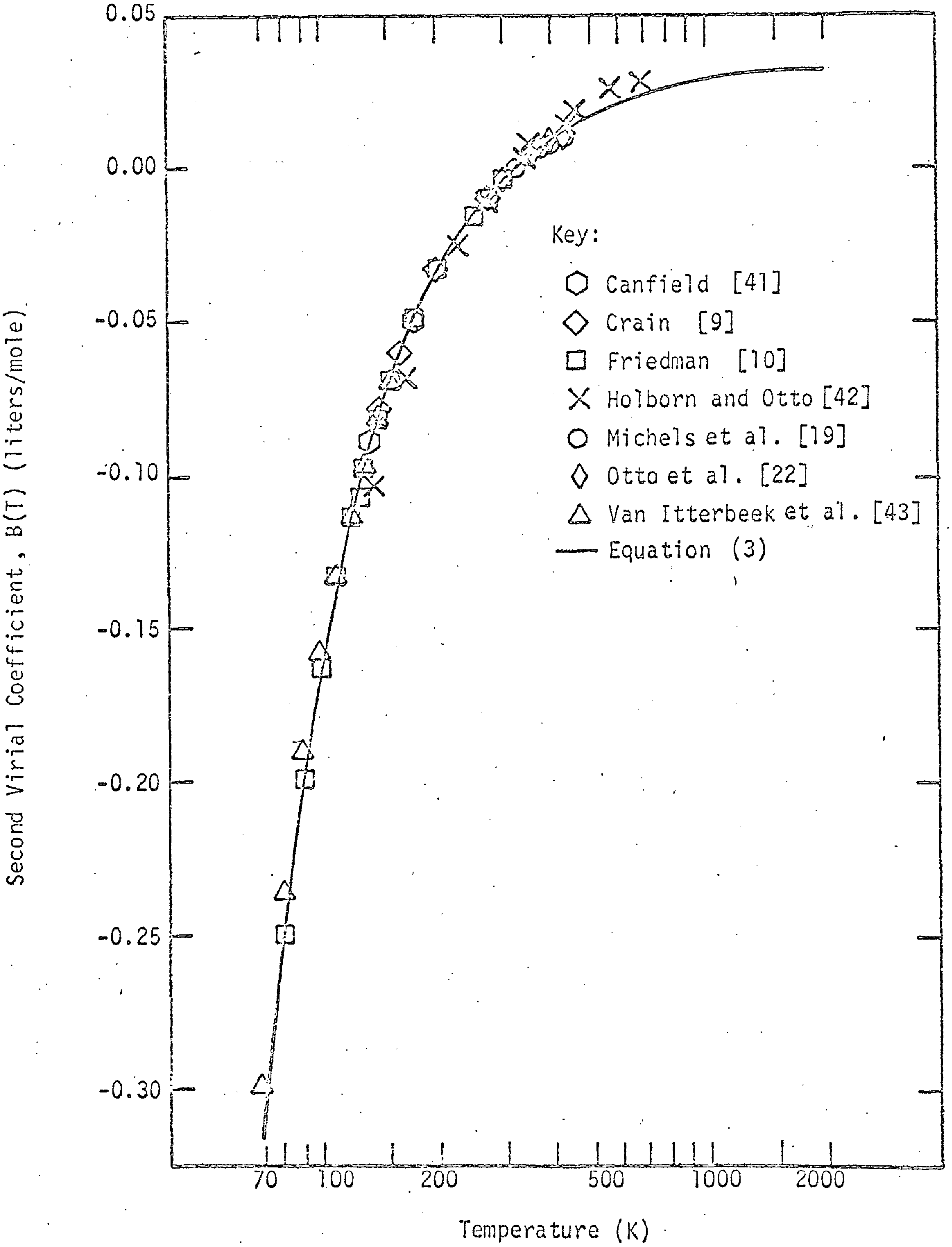

Figure 6.--Comparison of Second Virial Coefficient from Equation (3) to Experimental Values from the Sources Indicated.

TABLE II

ROOT MEAN SQUARE DEVIATIONS IN DENSITY AND PRESSURE OF P-ρ-T DATA FROM THE EQUATION OF STATE

Source	RMS Deviation in Density (percent)	RMS Deviation in Pressure (percent)
Data used in the Determination of the Equation of State		
Canfield [8]	0.14	0.22
Cockett et al. [30] *	0.25	7.12
Crain [9]	0.08	0.11
Friedman [10]	0.24	0.14
Golubev and Dobrovolskii [32] *	0.35	5.52
Gibbons [31] *	0.16	7.90
Holborn and Otto [14]	0.07	0.07
Michels et al. [19]	0.02	0.02
Michels et al. [20]	0.05	0.15
Otto et al. [22]	0.01	0.01
Robertson and Babb [23]	0.08	0.22
Saurel [24]	0.07	0.09
Weber [36] *	0.30	0.84
Data not used in the Determination of the Equation of State		
Amagat [1]	0.17	0.21
Amagat [2]	0.14	0.40
Bartlett et al. [4]	0.32	0.48
Bartlett et al. [5]	0.15	0.42
Benedict [6]	0.31	3.29
Benedict [7]	0.24	1.34
Hall and Canfield [11]	0.42	0.36
Heuse and Otto [12]	0.01	0.01
Holborn and Otto [13]	0.08	0.08
Holborn and Otto [15]	0.42	0.33
Malbrunot [18]	0.46	0.89
Malbrunot and Vodar [17]	0.40	0.83
Miller et al. [21]	0.26	0.30
Kamerlingh Onnes and van Urk [16]	0.20	0.14
Streett and Staveley [33]*	0.31	28.90
Tsiklis [28]	0.47	1.81
Tsiklis and Polyakov [27]	0.29	1.08
Van Itterbeek and Verbeke [34], [35]*	0.37	19.63
Verschoyle [29]	0.13	0.14

*Data for the liquid phase.

TABLE III

COMPARISONS OF SELECTED MEASURED VALUES OF SONIC VELOCITY FOR NITROGEN TO CALCULATED VALUES

Pressure (atm)	Temperature (K)	Experimental Velocity of Sound (meters/sec)	$\frac{W_{data} - W_{calc}}{W_{data}} \times 100$ (percent)
Low Temperature Liquid Data of [44]			
84.3	113.6	589	0.22
68.3	109.2	617	2.02
104.7	113.4	634	2.15
104.7	113.6	631	1.95
42.2	104.8	614	0.66
43.6	105.0	616	1.00
57.1	105.9	629	1.23
94.8	110.2	646	1.81
126.8	113.8	659	1.82
104.7	109.5	666	1.84
8.5	90.6	725	- 2.38
8.5	90.6	726	- 2.24
46.9	85.5	819	- 2.89
86.0	87.6	836	- 1.17
136.9	91.0	850	0.16
38.4	84.3	822	- 3.72
84.3	87.7	834	- 1.12
134.3	90.6	853	0.30
8.2	81.0	826	- 6.76
1.6	77.6	851	- 9.89
8.1	75.3	883	-10.87
52.0	77.5	897	- 6.64
116.6	81.0	917	- 2.39
61.5	77.6	902	- 6.30
121.9	80.9	920	- 2.47
1.7	73.6	896	-12.82
112.6	75.0	959	- 5.97
111.5	75.0	959	- 5.93
120.0	73.8	975	- 6.35
Saturated Liquid Data of [46]			
0.18	65.4	968	-27.17
0.22	66.4	959	-24.81
0.29	68.1	942	-21.37
0.38	70.0	924	-18.21
0.50	71.9	905	-15.64
0.68	74.2	881	-13.17
0.85	76.0	864	-11.44
1.26	79.3	831	- 8.99
1.29	79.6	829	- 8.77
1.39	80.3	822	- 8.31
1.81	82.7	796	- 6.95
1.89	83.2	791	- 6.70
2.25	84.9	772	- 5.85
2.66	86.7	755	- 4.93
2.70	86.9	753	- 4.79
2.82	87.4	748	- 4.54
3.05	88.2	739	- 4.26
3.96	91.3	705	- 3.27
4.61	93.1	685	- 2.72
6.39	97.4	636	- 1.74
7.38	99.4	612	- 1.47
8.34	101.2	590	- 1.36
9.86	103.7	559	- 1.22
13.4	108.7	493	- 1.50
14.7	110.2	472	- 1.73
17.1	112.9	434	- 2.32
19.1	115.0	403	- 3.05
21.4	117.1	369	- 4.22
23.9	119.3	329	- 6.31
24.1	119.4	327	- 6.12
25.0	120.2	313	- 6.92
26.4	121.2	290	- 9.09
28.0	122.4	265	-10.49
30.6	124.3	220	-14.77
30.7	124.3	219	-14.79
31.9	125.1	191	-20.16
32.4	125.5	183	-19.51
Saturated Vapor Data of [47]			
1.24	79.2	177	0.46
1.13	78.4	177	0.78
1.07	78.0	176	0.39
0.50	71.9	171	0.45

TABLE III--continued

Pressure (atm)	Temperature (K)	Experimental Velocity of Sound (meters/sec)	$\frac{W_{data} - W_{calc}}{W_{data}} \times 100$ (percent)
High Pressure Data of [49]			
600	298.14	655	-0.90
1000	298.14	844	-0.36
1500	298.14	1030	0.35
2000	298.14	1170	-0.03
2500	298.14	1296	0.39
3000	298.14	1398	0.23
3250	298.14	1445	0.23
3500	298.14	1500	0.94
3750	298.14	1545	1.11
200	323.14	440	0.37
600	323.14	650	-0.59
1000	323.14	830	-0.38
1500	323.14	1010	0.08
2000	323.14	1160	0.69
2500	323.14	1280	0.59
3000	323.14	1380	0.23
3500	323.14	1480	0.75
600	348.14	655	0.73
1000	348.14	825	0.26
1500	348.14	1000	0.46
2000	348.14	1140	0.30
2500	348.14	1262	0.42
3000	348.14	1370	0.64
3500	348.14	1463	0.63
200	373.15	462	0.02
600	373.15	648	-0.19
1000	373.15	820	0.57
1500	373.15	985	0.08
2200	373.15	1130	-3.90
2500	373.15	1248	0.40
3000	373.15	1354	0.48
3500	373.15	1442	0.12
200	398.16	476	0.55
600	398.16	654	0.60
1000	398.16	818	0.98
1500	398.16	978	0.29
2200	398.16	1115	-4.20
2500	398.16	1232	0.05
3000	398.16	1338	0.19
200	423.17	486	0.30
600	423.17	658	0.86
1000	423.17	810	0.43
1500	423.17	972	0.41
2200	423.17	1107	-4.12
2500	423.17	1223	0.15
3000	423.17	1330	0.39
3500	423.17	1420	0.16
4000	423.17	1480	-1.47
200	448.18	500	0.92
600	448.18	660	0.68
1000	448.18	810	0.69
1500	448.18	960	-0.25
2200	448.18	1098	-4.23
2500	448.18	1216	0.29
3000	448.18	1325	0.72
3500	448.18	1410	0.13
4000	448.18	1435	-4.00

B. Vapor Pressure Equation

A new vapor pressure equation has been determined for nitrogen as follows:

$$\ln(P) = N_1/T + N_2 + N_3T + N_4(T_c - T)^{1.95} + N_5T^3 + N_6T^4 + N_7T^5 + N_8T^6 + N_9 \ln(T) \qquad (5)$$

where T_c = 126.20 K (the critical point temperature), T is the saturation temperature in degrees K, and P the vapor pressure in atmospheres. The coefficients for the equation for temperature are given in Table IV.

A comparison of the vapor pressure equation (5) with the selected data used to determine the coefficients is given in Figure 7. This equation has been constrained to the critical point temperature of 126.20 K, the critical pressure of 33.555 atm., and the slope dP/dT of 1.6569 atm/K, which is equal to the value of $(\partial P/\partial T)_\rho$ at the critical point from the equation of state (1).

C. Conclusions and Recommendations on Studies of the Equation of State for Nitrogen

The results of this study are summarized below:

1. The equation of state (1) developed in this work represents the experimental P-ρ-T data in the liquid and vapor phases for pressures from 0 to 10,000 atmospheres and for temperatures of 65 K to 1073 K. The equation may be extrapolated to 2000 K at pressures below 300 atmospheres with an accuracy of at least ± 1 percent. The equation may also be extrapolated to lower temperatures for the vapor with an accuracy of at least ± 2 percent down to 20 K at very low pressures. It is estimated that the accuracy of the equation of state is within 0.5 percent in the liquid region, except in the vicinity of the critical point. At temperatures above the critical temperature for pressures up to 1000 atmospheres, the accuracy is generally within 0.1 percent except in the region near the critical point between temperatures of 126.2 K and 150 K and at pressures between 30 and 150 atmospheres where the density deviations from experimental data are as large as 0.7 percent. In the range from 1000 to 10,000 atmospheres the accuracy is estimated to be within 0.3 percent of the data used in the formulation, but deviations in density as large as 12 percent are evident in comparisons to other data in this range.

TABLE IV

COEFFICIENTS FOR NITROGEN VAPOR PRESSURE EQUATION (5)*

Coefficient	Numerical Value	Coefficient	Numerical Value
N_1	$0.8394409444 \times 10^{4}$	N_6	$-0.5944544662 \times 10^{-5}$
N_2	$-0.1890045259 \times 10^{4}$	N_7	$0.2715433932 \times 10^{-7}$
N_3	$-0.7282229165 \times 10^{1}$	N_8	$-0.4879535904 \times 10^{-10}$
N_4	$0.1022850966 \times 10^{-1}$	N_9	$0.5095360824 \times 10^{3}$
N_5	$0.5556063825 \times 10^{-3}$		

*Coefficients are for temperature in degrees Kelvin, and pressure in atmospheres.

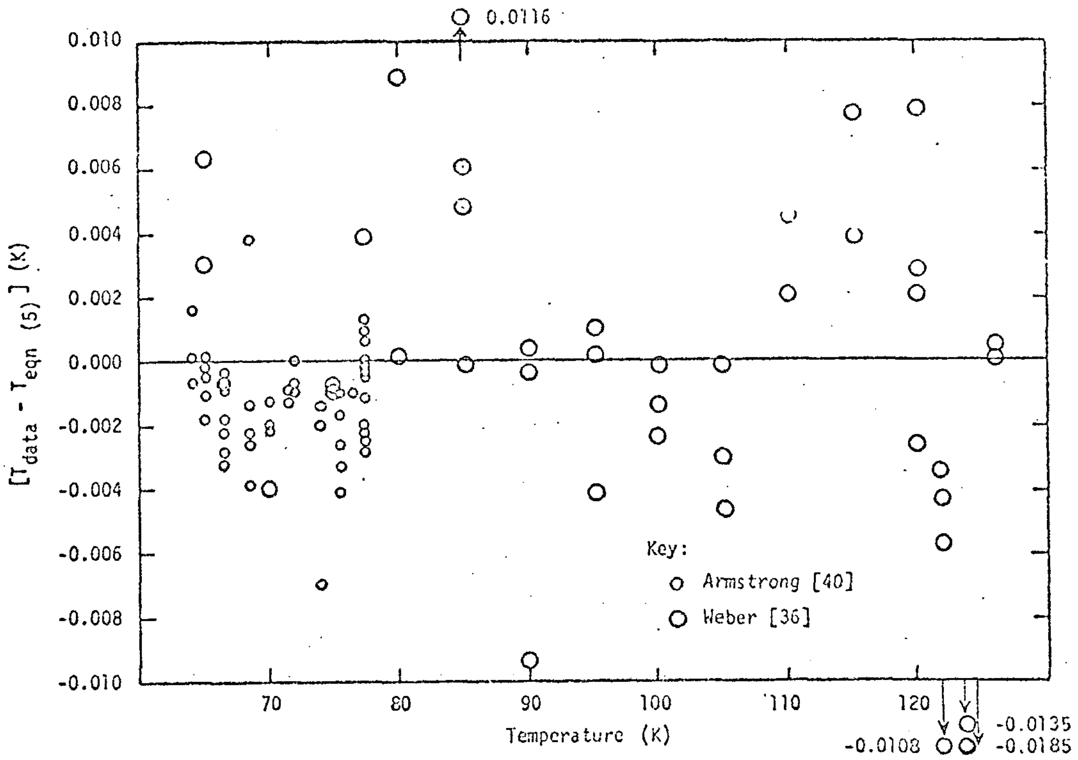

Figure 7.--Deviations of Nitrogen Vapor Pressure Equation (5) from Selected Vapor Pressure Data.

2. The vapor pressure equation (5) represents the selected data used in the formulation of the equation generally within an accuracy of 0.01 K between the triple point and the critical point.

3. Values of the heat capacity, enthalpy, and latent heats of vaporization are presented in reference [1] with comparisons to available measured calorimetric data. Although the paucity of these measurements make it difficult to define the accuracy of the equation of state (1) for the calculation of heat capacity values, these comparisons further indicate that the behavior of the isobaric calculated values is thermodynamically correct.

Suggestions for further research are presented below:

1. The work reported here is essentially complete within the limits imposed by the availability of experimental data to describe the thermodynamic properties of nitrogen. However, the lack of agreement of the various P-ρ-T data in the liquid region suggests the need for further measurement of the properties of the liquid.

2. The use of a single equation of state for the P-ρ-T surface appears to be accompanied by fitting problems near the critical point which propagate to temperatures above the critical value. It is suggested that new methods of accomodating the requirements of the P-ρ-T surface in this region for the least squares determination of the equation of state be explored.

3. A detailed study of the sonic velocity data should be made to complete the analysis of this data and to identify the cause of the large deviations of calculated velocity of sound values from experimental measurements in the liquid region.

4. The consistency of the vapor pressure equation, melting equation, and equation of state in the region of the triple point should be investigated.

5. The simultaneous fitting procedures developed in this work are applicable to other fluids for which the appropriate data are available.

III. THERMODYNAMIC PROPERTIES OF OXYGEN

Interim Equation of State

The equation of state presented in the Jan. 1, 1972 Progress Report [51] has not been superseded, to date. The equation of state for oxygen ~~from [51] is the same as (1).~~ The coefficients presented in [51] for oxygen are reprinted in Table V for convenience. (The multiplier for N_{24} as reported in [51] as "10^{1}" was incorrect. The multiplier should have been "10^{-1}", as given in Table V.) Studies for improving the fit of the equation of state (1) for oxygen at the critical point have not, as yet, resulted in an improved equation.

During the third quarter comparisons of velocity of sound data for oxygen with values calculated from the equation of state (1) with the coefficients from Table V have been completed. The comparisons of data from [45], [46], [47], and [48] are given in Table VI. These data sets have been selected as representative and include measured values for the liquid at moderate and high pressures, and the saturated liquid and saturated vapor.

These comparisons indicate that the equation is sufficiently accurate for obtaining good values of the velocity of sound for the liquid at moderate pressures and for the saturated liquid and the saturated vapor. However, the comparisons to measured velocity of sound values at high pressures for the liquid indicate a deviation between the calculated and measured values which is probably greater than the uncertainty of the measured values. This is to be expected since the P-ρ-T values and the C_V data used in the determination of the coefficients of the equation of state were for pressures below 350 atmospheres. Very few measurements of velocity of sound for oxygen in the vapor phase are available from the literature.

Table V

Coefficients for the Equation of State (1) for Oxygen*

$N_1 = -0.170887398436657 \times 10^{-2}$
$N_2 = 0.233008642369091$
$N_3 = -0.433993811662375 \times 10^{1}$
$N_4 = 0.177172970652312 \times 10^{3}$

$N_5 = -0.120035790297848 \times 10^{5}$
$N_6 = 0.768602601713339 \times 10^{-4}$
$N_7 = -0.838050060230444 \times 10^{-2}$
$N_8 = -0.112945718198605 \times 10^{2}$

$N_9 = 0.249933236222486 \times 10^{4}$
$N_{10} = -0.392210483256747 \times 10^{-5}$
$N_{11} = 0.412792194660784 \times 10^{-2}$
$N_{12} = 0.385058781582990 \times 10^{-2}$

$N_{13} = -0.286274514156647 \times 10^{-4}$
$N_{14} = -0.656972420621184 \times 10^{-4}$
$N_{15} = -0.868270744076546 \times 10^{-1}$
$N_{16} = 0.248888126044600 \times 10^{-5}$

$N_{17} = -0.480347612728966 \times 10^{-8}$
$N_{18} = 0.698141409980872 \times 10^{-4}$
$N_{19} = -0.851009706892387 \times 10^{-6}$
$N_{20} = 0.171174677742300 \times 10^{4}$

$N_{21} = -0.337130293024023 \times 10^{6}$
$N_{22} = -0.120824987128239 \times 10^{2}$
$N_{23} = 0.748250739682284 \times 10^{5}$
$N_{24} = -0.104770899761072 \times 10^{-1}$

$N_{25} = 0.145048005360464 \times 10^{1}$
$N_{26} = -0.782522681423924 \times 10^{-4}$
$N_{27} = -0.325891488829226$
$N_{28} = 0.413896845058343 \times 10^{-8}$

$N_{29} = 0.879581917933464 \times 10^{-5}$
$N_{30} = -0.947485588746460 \times 10^{-10}$
$N_{31} = -0.251031994074357 \times 10^{-8}$
$N_{32} = -0.535541160709992 \times 10^{-7}$

$\gamma = 0.0056$ $R = 0.0820535$ liter-atm/mol-K

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*Coefficients are for temperatures in degrees Kelvin, pressures in atmospheres, and density in moles/liter.

TABLE VI

COMPARISONS OF SELECTED MEASURED VALUES OF SONIC VELOCITY FOR OXYGEN TO CALCULATED VALUES

Pressure (atm)	Temperature (K)	Experimental Velocity of Sound (meters/sec)	$\frac{W_{data} - W_{calc}}{W_{data}} \times 100$ (percent)
High Pressure Liquid Data of [48]			
913	67.5	1331	7.58
848	67.5	1317	7.30
755	67.5	1297	6.84
654	67.5	1274	6.28
553	67.5	1249	5.61
450	67.5	1223	4.82
351	67.5	1197	3.96
250	67.5	1168	2.77
150	67.5	1138	1.50
53	67.5	1106	-0.13
916	73.4	1304	6.43
848	73.4	1289	6.20
752	73.4	1267	5.78
651	73.4	1242	5.27
551	73.4	1217	4.78
451	73.4	1190	4.12
353	73.4	1160	3.26
253	73.4	1131	2.44
152	73.4	1098	1.40
51	73.4	1063	0.16
940	77.7	1289	5.94
849	77.7	1269	5.67
756	77.7	1246	5.25
648	77.7	1220	4.82
552	77.7	1195	4.38
451	77.7	1167	3.81
355	77.7	1137	3.09
251	77.7	1104	2.27
152	77.7	1068	1.20
49	77.7	1029	0.04
921	83.8	1257	5.42
851	83.8	1241	5.23
756	83.8	1217	4.84
652	83.8	1190	4.40
553	83.8	1161	3.78
454	83.8	1131	3.23
349	83.8	1098	2.59
253	83.8	1064	1.83
153	83.8	1027	1.06
59	83.8	987	0.20
930	90.4	1229	5.18
871	90.4	1215	4.98
754	90.4	1184	4.47
653	90.4	1156	4.04
555	90.4	1126	3.47
454	90.4	1094	2.89
351	90.4	1059	2.26
251	90.4	1021	1.56
154	90.4	980	0.77
65	90.4	940	0.14
Moderate Pressure Liquid Data of [45]			
6.3	77.3	1010	-0.95
12.5	77.3	1013	-0.85
15.8	77.3	1014	-0.80
19.7	77.3	1018	-0.54
23.9	77.3	1019	-0.50
27.8	77.3	1022	-0.37
31.5	77.3	1022	-0.44
34.7	77.3	1023	-0.40
45.4	77.3	1028	-0.23
53.2	77.3	1032	-0.05
55.1	77.3	1032	-0.08
59.8	77.3	1035	0.07
62.2	77.3	1036	0.14
64.0	77.3	1037	0.13
70.1	77.3	1039	0.23
71.1	77.3	1040	0.25
3.8	90.3	905	-0.79
10.2	90.3	908	-0.75
14.6	90.3	912	-0.57
18.8	90.3	913	-0.64
23.6	90.3	917	-0.48
29.4	90.3	920	-0.41
36.5	90.3	923	-0.47
38.3	90.3	926	-0.25
45.5	90.3	929	-0.26

TABLE VI--continued

Pressure (atm)	Temperature (K)	Experimental Velocity of Sound (meters/sec)	$\frac{W_{data} - W_{calc}}{W_{data}} \times 100$ (percent)
49.6	90.3	930	-0.26
55.2	90.3	935	-0.03
58.3	90.3	938	0.13
61.9	90.3	939	0.16
66.2	90.3	940	-0.02
68.3	90.3	942	0.18
71.2	90.3	945	0.29
Saturated Liquid Data of [46]			
0.0095	61.1	1134	-2.60
0.0097	61.2	1133	-2.60
0.015	63.1	1119	-2.10
0.02	65.0	1105	-1.40
0.06	69.8	1068	-1.10
0.08	71.5	1055	-1.00
0.12	74.1	1035	-0.90
0.17	76.1	1019	-0.89
0.22	77.8	1005	-0.86
0.23	78.1	1003	-0.82
0.33	80.8	982	-0.83
0.48	83.7	959	-0.80
0.69	86.8	934	-0.76
0.95	89.7	910	-0.72
1.30	92.6	886	-0.67
1.80	96.0	859	-0.50
2.20	98.7	834	-0.56
3.00	102.2	805	-0.40
3.80	105.3	777	-0.50
4.50	107.6	756	-0.44
5.50	110.5	730	-0.35
6.90	113.7	701	-0.24
8.30	116.7	672	-0.27
8.90	117.9	660	-0.13
9.80	119.6	646	0.14
11.60	122.4	617	0.22
13.70	125.6	586	0.40
16.20	128.7	552	0.52
18.90	131.9	517	0.39
21.80	134.9	484	0.50
25.00	137.8	449	0.46
28.40	140.7	413	0.38
32.20	143.7	374	0.03
36.70	146.8	330	-0.20
42.40	150.5	266	-3.65
44.40	151.6	247	-3.96
46.00	152.5	229	-5.05
47.40	153.3	212	-6.15
48.40	153.9	198	-8.30
Saturated Vapor Data of [47]			
1.01	90.3	178	0.06
0.67	86.5	174	-0.70
0.43	82.8	171	-0.20
0.24	78.4	167	-0.51

IV. IDEAL GAS HEAT CAPACITY

An equation for the ideal gas heat capacity, C_p^o, from [50] is,

$$C_p^o/R = N_1/T^3 + N_2/T^2 + N_3/T + N_4 + N_5T + N_6T^2 + N_7T^3 + N_8u^2e^u/(e^u - 1)^2 \qquad (6)$$

where T is the temperature and $u = N_9/T$.

The coefficients for equation (6) with values of T in degrees Kelvin for nitrogen and oxygen are given in Tables VII and VIII, respectively. These coefficients were determined by a least squares fit of the data from [54].

TABLE VII

COEFFICIENTS FOR THE IDEAL HEAT CAPACITY EQUATION (6) FOR NITROGEN

Coefficient	Numerical Value	Coefficient	Numerical Value
N_1	$-0.7352104012 \times 10^{3}$	N_6	$0.1746508498 \times 10^{-7}$
N_2	$0.3422399804 \times 10^{2}$	N_7	$-0.3568920335 \times 10^{-11}$
N_3	-0.5576482846	N_8	$0.1005387228 \times 10^{1}$
N_4	$0.3504042283 \times 10^{1}$	N_9	3353.4061
N_5	$-0.1733901851 \times 10^{-4}$		

TABLE VIII

COEFFICIENTS FOR THE IDEAL HEAT CAPACITY EQUATION (6) FOR OXYGEN

Coefficient	Numerical Value	Coefficient	Numerical Value
N_1	$-0.186442361 \times 10^{3}$	N_6	$-0.111035799 \times 10^{-7}$
N_2	$0.207840241 \times 10^{2}$	N_7	$0.208612876 \times 10^{-10}$
N_3	-0.342642911	N_8	$0.101894691 \times 10^{1}$
N_4	$0.350297163 \times 10^{1}$	N_9	2239.18105
N_5	$0.205866482 \times 10^{-6}$		

A comparison between the values of C_p^o/R for nitrogen from [54] and values calculated from equation (6) with coefficients from Table VII indicated exact agreement to the five significant figures, given in [54], except above 1200 K. From 1200 K to 2000 K the difference between the values from equation (6) and from [54] is no more than ± 0.0001. The equation for nitrogen is applicable for temperatures from 50 to 2000 K. The values of C_p^o/R for oxygen calculated from equation (6) with coefficients from Table VIII exhibit a maximum deviation from the values reported in [54] of ± 0.0002 from 30 to 600 K, the range of applicability of the equation for oxygen.

For the calculation of thermodynamic properties described in section V of this report, the reference entropy, $S^o_{T_o}$, and reference enthalpy, $H^o_{T_o}$, for oxygen and nitrogen for the ideal gas at T_o = 298.15 K and P_o = 1 atmosphere are given in Table IX. The values of $H^o_{T_o}$ are taken from the values of $(H^o - H^o_o)$ in [55] with H^o_o = 0.0.

TABLE IX

IDEAL GAS REFERENCE STATES FOR THERMODYNAMIC PROPERTY CALCULATIONS FROM [55]

(T_o = 298.15 K, P_o = 1 atm.)

	$S^o_{T_o}$ (joules/mole-K)	$H^o_{T_o}$ (joules/mole)
Nitrogen	191.502 ± 0.025	8669 ± 3
Oxygen	205.037 ± 0.033	8682 ± 4

V. CALCULATION OF THERMODYNAMIC PROPERTIES USING THE EQUATION OF STATE (1)

Derived Thermodynamic Properties

The values of density, enthalpy, entropy, C_v, C_p, and velocity of sound at various pressures and temperatures are calculated from the equation of state (1), and the ideal gas heat capacity equation (6). The vapor pressure equation, (5), and the Simon melting curve equation, (2), were used to identify the temperature of the phase changes from vapor to liquid, and liquid to solid, respectively, for each isobar. The integral representations for the properties are continuously integrated through the two-phase region to calculate properties in the liquid range. This is made possible by the fitting procedures employed in the development of the equation of state as described in [51] in which the conditions for two-phase equilibrium were included in the least squares determination of the coefficients for the equation of state (1). The thermodynamic formulations for the calculation of the thermodynamic property tables of section VI were taken from [57]. These relations are summarized in the following paragraphs. Functions for the integrals and derivatives of the equation of state required to perform these calculations are given in V-B.

The entropy of any thermodynamic state was calculated from

$$S(T,\rho) = S^{o}_{T_o} + \int_{T_o}^{T} (C^{o}_{p}/T)dT - R\ln(RT\rho) + \int_{0}^{\rho} [R/\rho - (1/\rho^2)(\partial P/\partial T)_{\rho}]_T \, d\rho. \qquad (7)$$

The functions for evaluation of the integrals $\int (C^{o}_{p}/T)dT$ and $\int [(R/\rho) - (1/\rho^2)(\partial P/\partial T)_{\rho}]_T$ are given in V-B. The functions for the isochore derivative $(\partial P/\partial T)_{\rho}$ of the equation of state are included in V-B.

The enthalpy of any state may be calculated from

$$H(T,\rho) = H^{o}_{T_o} + T\int_{0}^{\rho} [(P/T\rho^2) - (1/\rho^2)(\partial P/\partial T)_{\rho}]_T \, d\rho + (P - \rho RT)/\rho + \int_{T_o}^{T} C^{o}_{p} \, dT. \qquad (8)$$

However, it is convenient to replace the first integral term in (8) as follows:

$$T \int_0^\rho [(P/T\rho^2) - (1/\rho^2)(\partial P/\partial T)_\rho]_T \, d\rho$$

$$\equiv T \int_0^\rho [(R/\rho) - (1/\rho^2)(\partial P/\partial T)_\rho]_T \, d\rho$$

$$+ \int_0^\rho [(P/\rho^2) - (RT/\rho)]_T \, d\rho. \qquad (9)$$

By substitution of the identity of (9) in equation (8), the expression for enthalpy is given as

$$H(T,\rho) = H^0_{T_0} + T \int_0^\rho [(R/\rho) - (1/\rho^2)(\partial P/\partial T)_\rho]_T \, d\rho$$

$$+ \int_0^\rho [(P/\rho^2) - (RT/\rho)]_T \, d\rho + (P - \rho RT)/\rho$$

$$+ \int_{T_0}^T C^0_p \, dT. \qquad (10)$$

The evaluations of the integrals and isochore derivative are given in V-B. The internal energy of a fluid state may be calculated from

$$U(T,\rho) = H(T,\rho) - P/\rho. \qquad (11)$$

The specific heat at constant volume, C_V, of liquid and gas phase points was calculated using the relation

$$C_V(T,\rho) = (C^0_p - R) - \int_0^\rho (T/\rho^2) \, [\partial^2 P/\partial T^2)_\rho] \, d\rho \qquad (12)$$

where C^0_p at temperature, T, is calculated from equation (6). The specific heat at constant pressure, C_p, is given by

$$C_p(T,\rho) = C_V(T,\rho) + [(T/\rho^2)(\partial P/\partial T)^2_\rho/(\partial P/\partial \rho)_T]. \qquad (13)$$

It is notable that the calculation of properties from the equation developed in this work is considerably simplified from the prior methods of [56] and [57] by the continuous integration along isotherms through the two phase region due to the imposing of the requirements for phase equilibrium in the determination of the equation of state.

Sample tables of thermodynamic properties of nitrogen and oxygen are presented in Section VI.

The Equation of State

Equation (1) may be written in the form:

$$P = \rho RT + \sum_{i=1}^{32} N_i X_i \qquad (14)$$

where the N_i are listed in Table I or V and the X_i are as follows:

$X_1 = \rho^2 T$
$X_2 = \rho^2 T^{1/2}$
$X_3 = \rho^2$
$X_4 = \rho^2/T$
$X_5 = \rho^2/T^2$
$X_6 = \rho^3 T$
$X_7 = \rho^3$
$X_8 = \rho^3/T$
$X_9 = \rho^3/T^2$
$X_{10} = \rho^4 T$
$X_{11} = \rho^4$
$X_{12} = \rho^4/T$
$X_{13} = \rho^5$
$X_{14} = \rho^6/T$
$X_{15} = \rho^6/T^2$
$X_{16} = \rho^7/T$
$X_{17} = \rho^8/T$
$X_{18} = \rho^8/T^2$
$X_{19} = \rho^9/T^2$
$X_{20} = \rho^3 F/T^2$
$X_{21} = \rho^3 F/T^3$
$X_{22} = \rho^5 F/T^2$
$X_{23} = \rho^5\ F/T^4$
$X_{24} = \rho^7\ F/T^2$
$X_{25} = \rho^7\ F/T^3$
$X_{26} = \rho^9\ F/T^2$
$X_{27} = \rho^9\ F/T^4$
$X_{28} = \rho^{11} F/T^2$
$X_{29} = \rho^{11} F/T^3$
$X_{30} = \rho^{13} F/T^2$
$X_{31} = \rho^{13} F/T^3$
$X_{32} = \rho^{13} F/T^4$

$$F = \exp(-0.0056\ \rho^2)$$

The Isotherm Derivative

The isotherm derivative of the equation of state (1) may be represented as:

$$(\partial P/\partial \rho)_T = RT + \sum_{i=1}^{32} N_i X_i \qquad (15)$$

where the N_i are given in Table I or V and the X_i are as follows:

$X_1 = 2\rho T$
$X_2 = 2\rho T^{1/2}$
$X_3 = 2\rho$
$X_4 = 2\rho/T$
$X_5 = 2\rho/T^2$
$X_6 = 3\rho^2 T$
$X_7 = 3\rho^2$
$X_8 = 3\rho^2/T$
$X_9 = 3\rho^2/T^2$
$X_{10} = 4\rho^3 T$
$X_{11} = 4\rho^3$
$X_{12} = 4\rho^3/T$
$X_{13} = 5\rho^4$
$X_{14} = 6\rho^5/T$
$X_{15} = 6\rho^5/T^2$
$X_{16} = 7\rho^6/T$
$X_{17} = 8\rho^7/T$
$X_{18} = 8\rho^7/T^2$
$X_{19} = 9\rho^8/T^2$
$X_{20} = F_{21}/T^2$
$X_{21} = F_{21}/T^3$
$X_{22} = F_{22}/T^2$
$X_{23} = F_{22}/T^4$
$X_{24} = F_{23}/T^2$
$X_{25} = F_{23}/T^3$
$X_{26} = F_{24}/T^2$
$X_{27} = F_{24}/T^4$
$X_{28} = F_{25}/T^2$
$X_{29} = F_{25}/T^3$
$X_{30} = F_{26}/T^2$
$X_{31} = F_{26}/T^3$
$X_{32} = F_{26}/T^4$

$$F = \exp(-0.0056\ \rho^2)$$
$$F_1 = 2F\rho(-0.0056)$$
$$F_{21} = 3F\rho^2 + F_1\rho^3$$
$$F_{22} = 5F\rho^4 + F_1\rho^5$$
$$F_{23} = 7F\rho^6 + F_1\rho^7$$
$$F_{24} = 9F\rho^8 + F_1\rho^9$$
$$F_{25} = 11F\rho^{10} + F_1\rho^{11}$$
$$F_{26} = 13F\rho^{12} + F_1\rho^{13}$$

The Isochore Derivative

The isochore derivative of the equation of state (1) may be written as:

$$(\partial P/\partial T)_\rho = \rho R + \sum_{i=1}^{32} N_i X_i \qquad (16)$$

where the N_i are given in Table I or V and the X_i are as follows:

$X_1 = \rho^2$
$X_2 = \rho^2/(2T^{1/2})$
$X_3 = 0.0$
$X_4 = -\rho^2/T^2$
$X_5 = -2\rho^2/T^3$
$X_6 = \rho^3$
$X_7 = 0.0$
$X_8 = -\rho^3/T^2$
$X_9 = -2\rho^3/T^3$
$X_{10} = \rho^4$
$X_{11} = 0.0$
$X_{12} = -\rho^4/T^2$
$X_{13} = 0.0$
$X_{14} = -\rho^6/T^2$
$X_{15} = -2\rho^6/T^3$
$X_{16} = -\rho^7/T^2$
$X_{17} = -\rho^8/T^2$
$X_{18} = -2\rho^8/T^3$
$X_{19} = -2\rho^9/T^3$
$X_{20} = -2\rho^3F/T^3$
$X_{21} = -3\rho^3F/T^4$
$X_{22} = -2\rho^5F/T^3$
$X_{23} = -4\rho^5F/T^5$
$X_{24} = -2\rho^7F/T^3$
$X_{25} = -3\rho^7F/T^4$
$X_{26} = -2\rho^9F/T^3$
$X_{27} = -4\rho^9F/T^5$
$X_{28} = -2\rho^{11}F/T^3$
$X_{29} = -3\rho^{11}F/T^4$
$X_{30} = -2\rho^{13}F/T^3$
$X_{31} = -3\rho^{13}F/T^4$
$X_{32} = -4\rho^{13}F/T^5$

$$F = \exp(-0.0056\ \rho^2)$$

The Evaluation of Integrals

The integral, $\int[R/\rho - (1/\rho^2)(\partial P/\partial T)_\rho]_T\, d\rho$ may be written as:

$$\sum_{i=1}^{32} N_i Y_i \qquad (17)$$

where the N_i are listed in Table I or V and the Y_i are listed below:

$Y_1 = -\rho$
$Y_2 = -\rho/(2T^{1/2})$
$Y_3 = 0.0$
$Y_4 = \rho/T^2$
$Y_5 = 2\rho/T^3$
$Y_6 = -\rho^2/2$
$Y_7 = 0.0$
$Y_8 = \rho^2/(2T^2)$
$Y_9 = \rho^2/T^3$
$Y_{10} = -\rho^3/3$
$Y_{11} = 0.0$
$Y_{12} = \rho^3/(3T^2)$
$Y_{13} = 0.0$
$Y_{14} = \rho^5/(5T^2)$
$Y_{15} = 2\rho^5/(5T^3)$
$Y_{16} = \rho^6/(6T^2)$
$Y_{17} = \rho^7/(7T^2)$
$Y_{18} = 2\rho^7/(7T^3)$
$Y_{19} = \rho^8/(4T^3)$
$Y_{20} = 2G_1/T^3$
$Y_{21} = 3G_1/T^4$
$Y_{22} = 2G_2/T^3$
$Y_{23} = 4G_2/T^5$
$Y_{24} = 2G_3/T^3$
$Y_{25} = 3G_3/T^4$
$Y_{26} = 2G_4/T^3$
$Y_{27} = 4G_4/T^5$
$Y_{28} = 2G_5/T^3$
$Y_{29} = 3G_5/T^4$
$Y_{30} = 2G_6/T^3$
$Y_{31} = 3G_6/T^4$
$Y_{32} = 4G_6/T^5$

where the G_i and F are listed in Table X.

The integral $\int [(P/\rho^2) - (RT/\rho)]_T \, d\rho$ may be written as:

$$\sum_{i=1}^{32} N_i Y_i \tag{18}$$

where the N_i are listed in Table I or V and the Y_i are listed below:

$Y_1 = \rho T$
$Y_2 = \rho T^{1/2}$
$Y_3 = \rho$
$Y_4 = \rho/T$
$Y_5 = \rho/T^2$
$Y_6 = \rho^2 T/2$
$Y_7 = \rho^2/2$
$Y_8 = \rho^2/(2T)$
$Y_9 = \rho^2/(2T^2)$
$Y_{10} = \rho^3 T/3$
$Y_{11} = \rho^3/3$
$Y_{12} = \rho^3/(3T)$
$Y_{13} = \rho^4/4$
$Y_{14} = \rho^5/(5T)$
$Y_{15} = \rho^5/(5T^2)$
$Y_{16} = \rho^6/(6T)$
$Y_{17} = \rho^7/(7T)$
$Y_{18} = \rho^7/(7T^2)$
$Y_{19} = \rho^8/(8T^2)$
$Y_{20} = G_1/T^2$
$Y_{21} = G_1/T^3$
$Y_{22} = G_2/T^2$
$Y_{23} = G_2/T^4$
$Y_{24} = G_3/T^2$
$Y_{25} = G_3/T^3$
$Y_{26} = G_4/T^2$
$Y_{27} = G_4/T^4$
$Y_{28} = G_5/T^2$
$Y_{29} = G_5/T^3$
$Y_{30} = G_6/T^2$
$Y_{31} = G_6/T^3$
$Y_{32} = G_6/T^4$

where the G_i and F are listed in Table X.

The integral, $\int [(T/\rho^2)(\partial^2 P/\partial T^2)_\rho]_T \, d\rho$ may be written as:

$$\sum_{i=1}^{32} N_i Y_i \tag{19}$$

where the N_i are listed in Table I or V and the Y_i are listed below:

$Y_1 = 0.0$
$Y_2 = \rho/(4T^{1/2})$
$Y_3 = 0.0$
$Y_4 = 2\rho/T^2$
$Y_5 = 6\rho/T^3$
$Y_6 = 0.0$
$Y_7 = 0.0$
$Y_8 = \rho^2/T^2$
$Y_9 = 3\rho^2/T^3$
$Y_{10} = 0.0$
$Y_{11} = 0.0$
$Y_{12} = (2\rho^3)/(3T^2)$
$Y_{13} = 0.0$
$Y_{14} = (2\rho^5)/(5T^2)$
$Y_{15} = (6\rho^5)/(5T^3)$
$Y_{16} = \rho^6/(3T^2)$
$Y_{17} = (2\rho^7)/(7T^2)$
$Y_{18} = (6\rho^7)/(7T^3)$
$Y_{19} = (3\rho^8)/(4T^3)$
$Y_{20} = 6G_1/T^3$
$Y_{21} = 12G_1/T^4$
$Y_{22} = 6G_2/T^3$
$Y_{23} = 20G_2/T^5$
$Y_{24} = 6G_3/T^3$
$Y_{25} = 12G_3/T^4$
$Y_{26} = 6G_4/T^3$
$Y_{27} = 20G_4/T^5$
$Y_{28} = 6G_5/T^3$
$Y_{29} = 12G_5/T^4$
$Y_{30} = 6G_6/T^3$
$Y_{31} = 12G_6/T^4$
$Y_{32} = 20G_6/T^5$

where the G_i and F are listed in Table X.

TABLE X

FUNCTIONS FOR DERIVATIVES OF THE EQUATION OF STATE

$F = \exp(-0.0056\rho^2)$
$G_1 = F/[2(-0.0056)]$
$G_2 = (F\rho^2 - 2G_1)/[2(-0.0056)]$
$G_3 = (F\rho^4 - 4G_2)/[2(-0.0056)]$
$G_4 = (F\rho^6 - 6G_3)/[2(-0.0056)]$
$G_5 = (F\rho^8 - 8G_4)/[2(-0.0056)]$
$G_6 = (F\rho^{10} - 10G_5)/[2(-0.0056)]$

The integral $\int C_p^o \, dT$ may be written as:

$$\sum_{i=1}^{8} N_i Y_i \tag{20}$$

where the N_i are listed in Table VII or VIII and the Y_i are given below:

$Y_1 = -1/(2T^2)$

$Y_2 = -1/T$

$Y_3 = \ln(T)$

$Y_4 = T$

$Y_5 = T^2/2$

$Y_6 = T^3/3$

$Y_7 = T^4/4$

$Y_8 = UT/[\exp(U)-1]$

$U = N_9/T$ (N_9 from Table VII or VIII)

The integral $\int (C_p^o/T) \, dT$ may be written as:

$$\sum_{i=1}^{8} N_i Y_i \tag{21}$$

where the N_i are listed in Table VII or VIII and the Y_i are given below:

$Y_1 = -1/(3T^3)$

$Y_2 = -1/(2T^2)$

$Y_3 = -1/T$

$Y_4 = \ln(T)$

$Y_5 = T$

$Y_6 = T^2/2$

$Y_7 = T^3/3$

$Y_8 = U/(EU-1)-\ln[1-(1/EU)]$

$U = N_9/T$ (N_9 from Table VII or VIII)

$EU = \exp(U)$

VI. SUMMARY TABLES [These tables are included as a check for those preparing computer programs using the equation of state (1) with coefficients from Table I for the calculation of thermodynamic properties.]

THERMODYNAMIC PROPERTIES OF NITROGEN

[T in degrees K, P in atm., ρ in mol/liter, h in J/mol, s in J/(mol K), C_v in J/(mol K), C_p in J/(mol K), Vel. Sound in M/sec]

T	ρ	h	s	C_v	C_p	Vel. Sound	T	ρ	h	s	C_v	C_p	Vel. Sound
Pressure 1 atm.							Pressure 10 atm.						
*63.171	30.98	-4209.	68.01	26.75	54.68	1325.	*63.371	30.99	-4176.	68.06	27.32	54.62	1311.
65	30.73	-4107.	69.59	27.75	55.77	1247.	65	30.77	-4056.	69.46	28.16	55.55	1244.
70	30.02	-3824.	73.78	28.53	57.17	1092.	70	30.07	-3805.	73.64	28.90	56.91	1092.
75	29.25	-3537.	77.75	28.12	57.63	983.	75	29.31	-3519.	77.58	28.45	57.33	985.
*77.347	28.87	-3402.	79.53	27.82	57.80	939.	80	28.51	-3231.	81.29	27.77	57.65	893.
*77.347	0.1647	2163.	151.54	21.59	31.45	175.	90	26.72	-2648.	88.16	26.73	59.44	752.
80	0.1585	2246.	152.59	21.48	31.17	178.	100	24.64	-2032.	94.64	26.23	64.34	617.
90	0.1392	2554.	156.22	21.20	30.44	190.	*103.937	23.65	-1773.	97.19	26.15	67.96	562.
100	0.1243	2856.	159.40	21.05	30.02	202.	*103.937	1.492	2456.	137.97	24.12	45.25	183.
150	0.08173	4336.	171.41	20.84	29.36	249.	150	0.8643	4120.	151.27	21.37	32.17	243.
200	0.06107	5799.	179.83	20.80	29.22	288.	200	0.6228	5674.	160.22	20.99	30.39	287.
300	0.04063	8717.	191.66	20.80	29.15	353.	300	0.4069	8660.	172.34	20.86	29.57	355.
400	0.03046	11635.	200.06	20.91	29.25	408.	400	0.3038	11608.	180.82	20.95	29.46	413.
600	0.02030	17554.	212.05	21.76	30.08	496.	600	0.2022	17554.	192.87	21.78	30.16	499.
800	0.01523	23698.	220.87	23.07	31.38	569.	800	0.1517	23710.	201.71	23.08	31.43	571.
1000	0.01216	30103.	228.02	24.32	32.63	631.	1000	0.1214	30121.	208.86	24.33	32.66	633.
1600	0.007615	50493.	243.94	26.71	35.02	789.	1600	0.07599	50519.	224.80	26.71	35.03	791.
2000	0.006092	64678.	251.85	27.52	35.84	879.	2000	0.06082	64706.	232.71	27.52	35.84	881.
Pressure 40 atm.							Pressure 100 atm.						
*64.035	31.03	-4068.	68.22	29.05	54.38	1271.	*65.346	31.12	-3850.	68.56	31.87	53.82	1217.
65	30.91	-4015.	69.04	29.47	54.86	1235.							
70	30.25	-3737.	73.16	30.05	56.11	1094.	70	30.57	-3597.	72.30	32.03	54.73	1101.
75	29.53	-3455.	77.05	29.45	56.40	993.	75	29.93	-3323.	76.09	31.14	54.86	1012.
80	28.77	-3173.	80.69	28.64	56.55	914.	80	29.25	-3049.	79.63	30.08	54.81	943.
90	27.12	-2604.	87.40	27.37	57.59	781.	90	27.80	-2500.	86.09	28.41	55.07	831.
100	25.26	-2015.	93.59	26.68	60.49	662.	100	26.22	-1944.	91.94	27.41	56.23	733.
150	4.416	3223.	135.33	23.86	52.84	227.	150	15.03	1347.	118.29	25.58	79.33	332.
200	2.653	5246.	147.08	21.61	35.01	286.	200	7.217	4426.	136.27	22.68	45.72	303.
300	1.631	8481.	160.25	21.06	30.95	361.	300	4.040	8168.	151.60	21.39	33.49	380.
400	1.203	11526.	169.02	21.06	30.14	418.	400	2.935	11389.	160.88	21.26	31.37	437.
600	0.7984	17557.	181.24	21.84	30.43	507.	600	1.942	17575.	173.43	21.95	30.91	524.
800	0.5997	23751.	190.14	23.12	31.56	579.	800	1.464	23840.	182.43	23.20	31.81	594.
1000	0.4808	30183.	197.31	24.35	32.74	640.	1000	1.177	30311.	189.65	24.41	32.88	655.
1600	0.3018	50607.	213.27	26.73	35.05	797.	1600	0.7441	50784.	205.64	26.75	35.09	808.
2000	0.2419	64800.	221.18	27.53	35.85	886.	2000	0.5980	64939.	213.56	27.56	35.87	895.
Pressure 400 atm.							Pressure 1000 atm.						
*71.613	31.69	-2757.	70.38	37.20	49.80	1155.	*82.997	32.85	-640.	73.42	33.68	41.54	1285.
75	31.41	-2589.	72.63	35.83	49.59	1118.	85	32.74	-557.	74.41	33.07	41.72	1277.
80	30.97	-2342.	75.87	33.92	49.39	1075.							
90	30.01	-1848.	81.68	31.07	49.29	1012.	90	32.45	-346.	76.81	31.87	42.40	1258.
100	28.98	-1355.	86.87	29.35	49.30	959.	100	31.80	85.	81.36	30.39	43.93	1225.
150	23.74	1095.	106.76	25.88	48.35	738.	150	28.23	2336.	99.61	27.75	44.62	1072.
200	19.07	3441.	120.28	24.05	45.23	612.	200	25.20	4502.	112.09	26.05	41.95	953.
300	12.96	7594.	137.21	22.45	38.27	547.	300	20.48	8475.	128.25	23.96	37.84	845.
400	9.807	11215.	147.66	22.01	34.64	561.	400	17.18	12131.	138.79	23.09	35.51	810.
600	6.741	17866.	161.17	22.41	32.55	620.	600	13.03	19010.	152.76	23.09	33.74	810.
800	5.204	24379.	170.53	23.52	32.76	676.	800	10.55	25740.	162.44	24.01	33.71	835.
1200	3.614	37769.	184.09	25.60	34.20	776.	1200	7.742	39423.	176.29	25.91	34.74	906.
Pressure 4000 atm.							Pressure 10,000 atm.						
*127.569	36.51	8766.	80.05	29.12	33.62	1850.	*191.605	40.76	25634.	87.49	30.22	31.52	2404.
150	35.88	9600.	86.06	31.96	40.00	1771.							
200	34.22	11710.	98.18	31.97	42.70	1565.	200	40.68	25906.	88.87	31.30	33.19	2374.
300	31.32	15782.	114.75	28.55	38.68	1566.	300	39.11	29713.	104.22	32.69	39.87	2214.
400	29.01	19507.	125.48	26.45	36.14	1511.	400	37.36	33624.	115.49	29.98	38.10	2172.
600	25.43	26534.	139.75	25.14	34.63	1450.	600	34.45	40942.	130.36	27.37	35.66	2134.
800	22.70	33472.	149.73	25.47	34.87	1422.	800	32.09	48046.	140.57	27.06	35.59	2104.
1000	20.53	40501.	157.57	26.17	35.43	1413.	1000	30.69	55219.	148.58	27.41	36.18	2082.
1200	18.76	47640.	164.07	26.84	35.94	1415.	1200	28.35	62516.	155.23	27.86	36.78	2068.

* Phase change.

VI. SUMMARY TABLES--continued [These tables are included as a check for those preparing computer programs using the equation of state (1) with coefficients from Table I for the calculation of thermodynamic properties.]

THERMODYNAMIC PROPERTIES OF OXYGEN

[T in degrees K, P in atm., ρ in mol/liter, h in J/mol, s in J/(mol K), C_v in J/(mol K), C_p in J/(mol K), Vel. Sound in M/sec]

T	ρ	h	s	C_v	C_p	Vel. Sound
			Pressure 0.10 atm.			
*54.360	40.87	-6179.	67.18	31.92	53.42	1271.
60	40.07	-5875.	72.50	33.34	53.90	1177.
70	38.65	-5342.	80.72	31.61	52.81	1078.
*72.770	38.25	-5196.	82.77	31.07	52.67	1055.
*72.770	0.01686	2097.	182.96	21.02	29.58	162.
80	0.01531	2311.	185.76	20.94	29.43	170.
90	0.01359	2604.	189.21	20.88	29.31	181.
100	0.01222	2897.	192.30	20.85	29.24	190.
120	0.01017	3481.	197.62	20.82	29.18	209.
140	0.008713	4064.	202.12	20.81	29.15	226.
160	0.007621	4647.	206.01	20.81	29.14	241.
200	0.006095	5813.	212.51	20.82	29.14	270.
250	0.004876	7271.	219.02	20.89	29.21	301.
300	0.004062	8736.	224.36	21.07	29.39	330.
			Pressure 1 atm.			
*54.371	40.88	-6176.	67.19	31.95	53.43	1271.
60	40.07	-5873.	72.49	33.35	53.90	1177.
70	38.65	-5340.	80.72	31.62	52.80	1078.
80	37.21	-4813.	87.75	29.93	52.71	996.
90	35.69	-4282.	94.00	28.85	53.59	914.
*90.188	35.66	-4272.	94.11	28.83	53.61	912.
*90.188	0.1399	2538.	169.59	21.69	31.30	178.
100	0.1249	2841.	172.78	21.35	30.54	188.
120	0.1030	3444.	178.27	21.03	29.82	207.
140	0.08784	4037.	182.85	20.92	29.52	225.
160	0.07663	4626.	186.78	20.86	29.33	241.
200	0.06112	5798.	193.32	20.84	29.27	259.
250	0.04881	7261.	199.85	20.90	29.28	301.
300	0.04065	8729.	205.20	21.08	29.44	330.
			Pressure 10 atm.			
*54.475	40.89	-6153.	67.21	32.19	53.48	1267.
60	40.10	-5855.	72.41	33.48	53.88	1177.
70	38.70	-5322.	80.63	31.71	52.74	1080.
80	37.26	-4796.	87.65	30.00	52.62	999.
90	35.75	-4267.	93.89	28.91	53.44	918.
100	34.15	-3725.	99.59	28.17	54.97	832.
*119.849	30.47	-2580.	110.02	27.13	61.65	642.
*119.849	1.220	2985.	156.44	24.06	41.13	189.
120	1.217	2991.	156.49	24.04	41.04	189.
140	0.9637	3733.	162.22	22.19	34.52	214.
160	0.8126	4397.	166.66	21.52	32.26	234.
200	0.6284	5649.	173.65	21.08	30.63	266.
250	0.4941	7161.	180.40	21.02	30.01	300.
300	0.4086	8658.	185.86	21.16	29.90	330.
			Pressure 20 atm.			
*54.591	40.91	-6127.	67.23	32.46	53.53	1262.
60	40.14	-5835.	72.32	33.62	53.85	1177.
70	38.74	-5303.	80.53	31.81	52.68	1082.
80	37.31	-4778.	87.54	30.08	52.51	1002.
90	35.82	-4249.	93.77	28.98	53.28	922.
100	34.24	-3710.	99.45	28.23	54.72	839.
120	30.60	-2565.	109.87	27.15	60.83	652.
*133.019	27.44	-1710.	116.62	26.87	72.81	502.
*133.019	2.514	2952.	151.67	25.83	54.93	186.
140	2.225	3300.	154.22	24.35	45.98	199.
160	1.756	4110.	159.64	22.42	36.95	225.
200	1.299	5475.	167.27	21.37	32.39	263.
250	1.002	7049.	174.30	21.14	30.68	300.
300	0.8220	8579.	179.89	21.24	30.43	330.
			Pressure 40 atm.			
*54.823	40.94	-6074.	67.29	32.96	53.63	1254.
60	40.21	-5795.	72.15	33.89	53.81	1177.
70	38.83	-5264.	80.35	32.00	52.55	1085.
80	37.42	-4740.	87.33	30.23	52.32	1009.
90	35.95	-4214.	93.53	29.12	52.98	931.
100	34.41	-3679.	99.17	28.36	54.25	850.
120	30.92	-2551.	109.44	27.22	59.30	675.
140	26.04	-1229.	119.59	26.80	78.05	455.
*148.990	21.74	-343.	125.71	28.16	149.59	299.
*148.990	6.206	2423.	144.27	29.62	152.71	178.
160	4.392	3351.	150.31	25.23	59.65	206.
200	2.790	5102.	160.17	21.99	36.90	257.
250	2.060	6820.	167.85	21.39	32.76	299.
300	1.662	8422.	173.69	21.40	31.53	332.
			Pressure 100 atm.			
*55.512	41.04	-5917.	67.45	34.28	53.84	1234.
60	40.43	-5675.	71.64	34.66	53.70	1178.
70	39.09	-5146.	79.80	32.52	52.21	1096.
80	37.73	-4627.	86.73	30.66	51.79	1026.
90	36.34	-4107.	92.85	29.51	52.22	956.
100	34.89	-3581.	98.39	28.73	53.10	883.
120	31.73	-2492.	108.31	27.50	56.15	730.
140	27.92	-1310.	117.41	26.52	63.10	564.
160	22.47	118.	126.92	26.30	84.22	382.
200	8.826	3809.	147.66	24.02	61.10	260.
250	5.536	6134.	158.12	22.04	39.23	305.
300	4.263	7967.	164.82	21.82	34.90	340.
			Pressure 200 atm.			
*56.648	41.21	-5655.	67.73	35.91	54.01	1213.
60	40.77	-5474.	70.83	35.75	53.58	1180.
70	39.50	-4948.	78.94	33.27	51.75	1113.
80	38.22	-4435.	85.80	31.29	51.09	1053.
90	36.92	-3924.	91.82	30.11	51.25	991.
100	35.58	-3409.	97.24	29.31	51.74	927.
120	32.80	-2361.	106.79	28.06	53.20	798.
140	29.75	-1275.	115.16	26.90	55.59	670.
160	26.29	-127.	122.81	25.87	59.37	549.
200	18.26	2393.	136.85	24.34	64.03	380.
250	11.48	5192.	149.41	22.77	47.71	349.
300	8.553	7339.	157.26	22.36	39.54	370.
			Pressure 350 atm.			
*58.319	41.48	-5262.	68.17	37.40	53.94	1199.
60	41.27	-5171.	69.70	37.07	53.53	1188.
70	40.07	-4649.	77.76	34.17	51.23	1138.
80	38.88	-4142.	84.53	32.09	50.31	1090.
90	37.68	-3640.	90.45	30.90	50.23	1037.
100	36.48	-3136.	95.75	30.13	50.42	982.
120	34.03	-2123.	104.98	28.93	50.36	873.
140	31.52	-1102.	112.86	27.78	51.33	770.
160	28.92	-69.	119.75	26.68	51.91	677.
200	23.57	2020.	131.40	24.87	52.17	536.
250	17.75	4541.	142.67	23.54	47.88	456.
300	13.88	6790.	150.89	23.07	42.36	440.

*Phase change.

BIBLIOGRAPHY

References Containing Experimental Data for Nitrogen

Pressure-Density-Temperature Data

Vapor

[1] Amagat, E. H., Mémoire sur la compressibilité des gaz a des pressions élevées, Ann. Chim. et Phys. 19, 345-385 (1880).

[2] Amagat, E. H., Compressibilité des gaz: oxygène, hydrogène, azote et air jusqu' à 3000 atm., Compt. Rend. 107, 522-524 (1888).

[3] Bartlett, E. P., The compressibility isotherms of hydrogen, nitrogen, and mixtures of these gases at 0 degree and pressures to 1000 atmospheres. A correction, J. Am. Chem. Soc. 49, 1955-1957 (1927).

[4] Bartlett, E. P., H. L. Cupples, and T. H. Tremearne, The compressibility isotherms of hydrogen, nitrogen, and a 3:1 mixture of these gases at temperatures between 0 degrees and 400 degrees and at pressures to 1000 atmospheres, J. Am. Chem. Soc. 50, 1275-1288 (1928).

[5] Bartlett, E. P., N. C. Hetherington, H. M. Kvalnes, and T. H. Tremearne, The compressibility isotherms of hydrogen, nitrogen, and a mixture of these gases at temperatures of -70, -50, -25, and -20 degrees and at pressures to 1000 atmospheres, J. Am. Chem. Soc. 52, 1363-1373 (1930).

[6] Benedict, M., Pressure, volume, temperature properties of nitrogen at high density. I. Results obtained with a weight piezometer, J. Am. Chem. Soc. 59, 2224-2233 (1937).

[7] Benedict, M., Pressure, volume, temperature properties of nitrogen at high density. II. Results obtained by a piston displacement method, J. Am. Chem. Soc. 59, 2233-2242 (1937).

[8] Canfield, F. B., Jr., The Compressibility Factors and Second Virial Coefficients for Helium-Nitrogen Mixtures at Low Temperature and High Pressure, Rice University, Houston, Texas, Ph.D. Thesis (1962).

[9] Crain, R. W., Jr., P-V-T Behavior in the Argon-Nitrogen System, University of Michigan, Ann Arbor, Michigan, Ph.D. Thesis (1965).

[10] Friedman, A. S., Pressure-Volume-Temperature Relationships of Gaseous Hydrogen, Nitrogen, and a Hydrogen-Nitrogen Mixture, Ohio State University, Columbus, Ohio, Ph.D. Thesis (1950).

[11] Hall, K. R., and F. B. Canfield, Isotherms for the He-N_2 system at -190 degrees C, -170 degrees C, and -160 degrees C up to 700 atmospheres, Physica 47, 219-226 (1970).

[12] Heuse, W., and J. Otto, Über eine Neubestimmung des Grenzwertes der Ausdehnungs- und Spannungskoeffizienten von Helium, Wasserstoff und Stickstoff, Ann. Physik 2, 1012-1030 (1929).

[13] Holborn, L., and J. Otto, Über die Isothermen von Stickstoff, Sauerstoff und Helium, Z. Physik 10, 367-377 (1922).

[14] Holborn, L. and J. Otto, Über die Isothermen einiger Gase bis 400° und ihre Bedentung für das Gasthermometer, Z. Physik 23, 77-94 (1924).

[15] Holborn, L. and J. Otto, Über die Isothermen von Helium, Stickstoff und Argon unterhalb 0°, Z. Physik 30, 320-328 (1924).

[16] Kamerlingh Onnes, H., and A. Th. van Urk, Isotherms of diatomic substances and their binary mixtures XXVIII. On the isotherms of nitrogen at low temperatures, Communs. Phys. Lab. Univ. of Leiden No. 169-D (1924).

[17] Malbrunot, P., and B. Vodar, Détermination expérimentale de la densité de l'azote jusqu'à 4000 atm et 1000°C, C. R. Acad. Paris, Series B 268, 1337-1340 (1969).

[18] Malbrunot, P., Measure des Paramètres d'Etat des Gaz Denses à Températures Eleveés. Application à l'Azote, University of Paris, Paris, France, Ph.D. Thesis (1970).

[19] Michels, A., H. Wouters, and J. DeBoer, Isotherms of nitrogen between 0 degrees and 150 degrees and at pressures from 20 to 80 atmospheres, Physica 1, 587-594 (1934).

[20] Michels, A., H. Wouters, and J. DeBoer, Isotherms of nitrogen between 200 and 3000 atmospheres and 0 degrees and 150 degrees, Physica 3, 585-589 (1936).

[21] Miller, J. E., L. Stroud, and L. W. Brandt, Compressibility of helium-nitrogen mixtures, J. Chem. and Engr. Data 5, 6-9 (1960).

[22] Otto, J., A. Michels, and H. Wouters, Über Isothermen des Stickstoffes zwischen 0° und 150° bei Drueken bis zu 400 Atmosphären, Physik Z. 35, 97-101 (1934).

[23] Robertson, S. L., and S. E. Babb, Jr., Isotherms of nitrogen to 400 degrees C and 1000 bar, J. Chem. Phys. 50, 4560-4564 (1969).

[24] Saurel, J. R., Determination of the equations of state of compressed gases at elevated temperatures. Application to the study of nitrogen to 1000 kg/CM^2 and 1000 degrees, J. Recherches Centre Natl. Recherches Sci. 42, 21-60 (1958).

[25] Smith, L. B., and R. S. Taylor, The equation of state for pure nitrogen, gas phase, J. Am. Chem. Soc. 45, 2107-2124 (1923).

[26] Townsend, P. W., Pressure-Volume-Temperature Relationships of Binary Gaseous Mixtures, Columbia University, New York, New York, Ph.D. Thesis (1956).

[27] Tsiklis, D. S., and E. V. Polyakov, Measuring the compressibility of gases by the displacement method. Nitrogen compressibility at pressures up to 10,000 atmospheres and temperatures to 400 degrees, Soviet Physics--Doklady 12, 901-904 (1968).

[28] Tsiklis, D. S., Compressibility of nitrogen at pressures up to 10,000 atmospheres, Doklady Akad. Nauk. SSSR 89, 289-290 (1951).

[29] Verschoyle, T. T. H., Isotherms of hydrogen, of nitrogen, and of hydrogen-nitrogen mixtures, at 0 degrees and 20 degrees C, up to a pressure of 200 atmospheres, Proc. Royal Soc. A111, 552-576 (1926).

Liquid

[30] Cockett, A. H., K. Goldman, and N. G. Scrase, The Density of Liquid Nitrogen from 85 to 120 Degrees K and from the Saturation Boundary to 200 Atmospheres, Proceedings of the Second International Cryogenic Engineering Conference, Iliffe Science and Technology Publications, Ltd., Guildford, England, 1968, pp. 276-280.

[31] Gibbons, R. M., The equation of state of neon between 27 and 70 K, Cryogenics 9, 251-260 (1969).

[32] Golubev, I. F., and O. A. Dobrovolskii, Measurement of the density of nitrogen and hydrogen at low temperatures and high pressures by the method of hydrostatic weighing, Gasovaia Promyshlen 9, 43-47 (1964).

[33] Streett, W. B., and L. A. K. Staveley, The P-V-T behavior of liquid nitrogen at temperatures from 77 to 120 degrees K and pressures to 680 atmospheres, Advances in Cryogenic Engineering 13, 363-374 (1968).

[34] Van Itterbeek, A., and O. Verbeke, Density of liquid nitrogen and argon as a function of pressure and temperature, Physica 26, 931-938 (1960).

[35] Van Itterbeek, A., and O. Verbeke, The variation of the density of liquid nitrogen and liquid oxygen as a function of pressure, Cryogenics 2, 79-80 (1961).

[36] Weber, L. A., Some vapor pressure and P-V-T data on nitrogen in the range 65 to 140 K, J. Chem. Thermodyn. 2, 839-846 (1970).

Saturated Liquid

[37] Goldman, K., and N. G. Scrase, Densities of saturated liquid oxygen and nitrogen, Physica 44, 555-586 (1969).

[38] Terry, M. J., J. T. Lynch, M. Bunclark, K. R. Mansell, and L. A. K. Staveley, The densities of liquid argon, krypton, xenon, oxygen, nitrogen, carbon monoxide, methane, and carbon tetrafluoride along the orthobaric liquid curve, J. Chem. Thermodyn. 1, 413-424 (1969).

Liquid on the Freezing Line

[39] Grilly, E. R., and R. L. Mills, Volume change on melting of N_2 up to 3500 kg/cm^2, Physical Review 105, 1140-1145 (1957).

Vapor Pressure Data

[40] Armstrong, G. T., Vapor pressure of nitrogen, Journal of Research of the National Bureau of Standards 53, 263-266 (1954).

NOTE: Reference 36 above also contains Vapor Pressure Data.

Sources of Experimental Second Virial Coefficients

[41] Canfield, F. B., T. W. Leland, and R. Kobayashi, Volumetric behavior of gas mixtures at low temperatures by the Burnett method: the helium-nitrogen system, 0 degrees to -140 degrees C, Adv. in Cryogenic Engr. 8, 146-157 (1962).

[42] Holborn, L., and J. Otto, Über die Isothermen einiger Gase zwischen +400° und -183°, Z. Physik 33, 1-11 (1925).

[43] Van Itterbeek, A., Miss H. Lambert, and G. Forrez, Measurements on the second virial coefficient of nitrogen between 90 and 65 degrees K with use of ultrasonics, Appl. Sci. Research A6, 15-20 (1956).

NOTE: References 9, 10, 19, and 22 above are also sources of Experimental Second Virial Coefficients.

Velocity of Sound Data for Oxygen and Nitrogen

[44] Singer, J. R., and J. H. Lunsford, Ultrasonic attenuation and volume viscosity in liquid nitrogen, J. Chem. Phys. 47, 811-814 (1967).

[45] Van Dael, W., and A. Van Itterbeek, The velocity of sound in dense fluids, in Physics of High Pressures and the Condensed Phase (John Wiley and Sons, Inc., New York, New York, pp. 297-357, 1965).

[46] Van Dael, W., A. Van Itterbeek, A. Cops, and J. Thoen, Sound velocity measurements in liquid argon, oxygen, and nitrogen, Physica 32, 611-620 (1966).

[47] Van Itterbeek, A., Détermenations des grandeurs thérmodynamiques et cinétiques des gaz et des gaz condensés aux basses températures, Nuovo Cimento 7, 218-228 (1950).

[48] Van Itterbeek, A., and W. Van Dael, Velocity of sound in liquid oxygen and liquid nitrogen as a function of temperature and pressure, Physica 28, 861-870 (1962).

[49] Voronov, F. F., L. L. Pitaevokaya, and A. V. Bilevich, Rate of propagation of ultrasound in nitrogen at pressures up to 4 kbar and temperatures in the range 25-175°C, Russian Journal of Physical Chemistry 43, 321-324 (1969).

General References

[50] Jacobsen, R. T., The Thermodynamic Properties of Nitrogen from 64 to 2000 K with Pressures to 10,000 Atmospheres, Washington State University, Pullman, Washington, Ph.D. Thesis (1972).

[51] Stewart, R. B., R. T. Jacobsen, and A. F. Myers, An Equation of State for Oxygen and Nitrogen II, University of Idaho Engineering Experiment Station, Progress Report on Contract NAS 9-12078 to NASA--MSC (January, 1972).

[52] White, D., A. S. Friedman, and H. L. Johnston, The critical temperature and critical pressure of nitrogen, J. Am. Chem. Soc. 73, 5713-5715 (1951).

[53] Private Communication from R. D. McCarty, National Bureau of Standards (1971).

[54] Baehr, H. D., H. Hartmann, H. C. Pohl, and H. Schomacker, Thermodynamische Funktionen idealer Gase für Temperaturen bis 6000°K, (Springer-Verlag, Berlin, Germany, 1968).

[55] CODATA Bulletin 5, International Council of Scientific Unions, Committee on Data for Science and Technology (December 1971).

[56] Coleman, T. C., and R. B. Stewart, The Thermodynamic Properties of Nitrogen, University of Idaho Engineering Experiment Station, Research Report No. 11 (1970).

[57] Stewart, R. B., The Thermodynamic Properties of Oxygen, University of Iowa, Iowa City, Iowa, Ph.D. Thesis (1966).