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THE THERMODYNAMIC PROPERTIES OF OXYGEN AND NITROGEN

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AN EQUATION OF STATE FOR OXYGEN AND NITROGEN*

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INTRODUCTION

Recent measurements of the thermodynamic properties of oxygen and nitrogen have provided the necessary data to allow the development of a single equation of state for both fluids, which with the appropriate coefficients, describes the P-ρ-T surface for each within the estimated experimental uncertainty of the data. The formulation uses least squares curve fitting of the equation of state to the available experimental data including P-ρ-T data, saturation data, and measured isochoric heat capacities. New vapor pressure equations and equations for the ideal gas-heat capacities for both oxygen and nitrogen have been developed for use in the calculation of derived thermodynamic properties. By the use of a new fitting technique, continuous integration along isothems through the two phase region facilitates the calculation of liquid properties. A further advantage of this formulation is the ease of programming a single equation of state for computer calculations in design work. Details of the work outlined here may be found in [25].

THE EQUATION OF STATE

The coefficients for the equations of state for oxygen and nitrogen given in Table I were determined by simultaneous least squares fits to the data summarized in Table II, to values of isochoric heat capacity, and to saturation density values used to define the criteria for phase equilibrium. The details of the methods used to incorporate heat capacity and saturation data in the fitting procedures are given in [24].

The functional form of the equation of state (1) with 32 terms, was developed by a stepwise multiple regression analysis of the 50 terms considered likely to be appropriate in representing the body of selected data for nitrogen. The coefficients for the equation of state for both fluids as determined by weighted least squares fits to selected data constrained to the appropriate critical point parameters are included in Table I.

$$\begin{aligned}
P = \rho RT &+ \rho^2 \left(N_1 T + N_2 T^{1/2} + N_3 + N_4/T + N_5/T^2\right) \\
&+ \rho^3 \left(N_6 T + N_7 + N_8/T + N_9/T^2\right) + \rho^4 \left(N_{10} T + N_{11} + N_{12}/T\right) \\
&+ \rho^5 \left(N_{13}\right) + \rho^6 \left(N_{14}/T + N_{15}/T^2\right) + \rho^7 \left(N_{16}/T\right) \\
&+ \rho^8 \left(N_{17}/T + N_{18}/T^2\right) + \rho^9 \left(N_{19}/T^2\right) \\
&+ \rho^3 \left(N_{20}/T^2 + N_{21}/T^3\right) \exp\left(-\gamma\rho^2\right) \\
&+ \rho^5 \left(N_{22}/T^2 + N_{23}/T^4\right) \exp\left(-\gamma\rho^2\right) \\
&+ \rho^7 \left(N_{24}/T^2 + N_{25}/T^3\right) \exp\left(-\gamma\rho^2\right) \\
&+ \rho^9 \left(N_{26}/T^2 + N_{27}/T^4\right) \exp\left(-\gamma\rho^2\right) \\
&+ \rho^{11} \left(N_{28}/T^2 + N_{29}/T^3\right) \exp\left(-\gamma\rho^2\right) \\
&+ \rho^{13} \left(N_{30}/T^2 + N_{31}/T^3 + N_{32}/T^4\right) \exp\left(-\gamma\rho^2\right) \qquad (1)
\end{aligned}$$

THE VAPOR PRESSURE EQUATION

The data used in the determination of the vapor pressure equation for oxygen and nitrogen are summarized in Table II.

The vapor pressure equation developed in this work is:

$$\begin{aligned} \ln (P) = {} & N_1/T + N_2 + N_3T + N_4 (T_c - T)^{\alpha} \\ & + N_5T^3 + N_6T^4 + N_7T^5 + N_8T^6 + N_9 \ln (T) \end{aligned} \tag{2}$$

Coefficients for this equation for both fluids are included in Table I.

THE IDEAL GAS HEAT CAPACITY EQUATION

The ideal gas heat capacity equation used in this work is a form suggested by Barieau [23] which has been fitted to the data of Baehr et al. [22].

The equation is:

$$\begin{aligned} Cp^{\circ}/R = {} & N_1/T^3 + N_2/T^2 + N_3/T \\ & + N_4 + N_5T + N_6T^2 + N_7T^3 \\ & + N_8u^2e^u/e^u - 1)^2, \end{aligned} \tag{3}$$

where Cp° is the ideal gas heat capacity, T is the temperature in degrees K, and $u = N_9/T$. The coefficients for this equation for both oxygen and for nitrogen are also given in Table I. The equation is valid for both nitrogen and oxygen for temperatures from 50 to 2000 K.

CRITICAL POINT CONSTANTS AND CONSTRAINTS

The equation of state and vapor pressure equation have been constrained at the critical point to provide consistency for thermodynamic property calculations. The value of $(\partial P/\partial T)_\rho$ was determined from the equation of state (1) constrained to the critical pressure, temperature and density with both $(\partial P/\partial \rho)_T$ and $(\partial^2 P/\partial \rho^2)_T$ constrained to have a value of zero at the critical point. This calculated value of $(\partial P/\partial T)_\rho$ the critical temperature, and the critical pressure were used as contraints in the determination of the vapor pressure equation. The critical point values for oxygen and nitrogen are given in Table I.

COMPARISONS OF THE EQUATIONS OF STATE TO EXPERIMENTAL DATA

Comparisons to P-ρ-T Data for Nitrogen

For nitrogen, the equation of state (1) generally shows agreement with the selected P-ρ-T data within the experimental uncertainty of the measured values, except in the vicinity of the critical point, and in the low temperature liquid and the high pressure supercritical regions. Large deviations in calculated density values from experimental measurements near the critical point may be attributable to the large experimental uncertainties for data in this region or to difficulties in fitting the equation of state. There is a lack of agreement among various experimental data for the liquid and for the supercritical values at pressures above 1000 atmospheres. Critical evaluation of the data in these ranges allowed the selection of data for the determination of the equation of state on the basis of agreement with measurements in adjacent or coincident regions and the precision of the individual data sets. The equation of state (1) for nitrogen 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. 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. Table III illustrates the root mean square deviations in density and in pressure for the selected P-ρ-T data sets used in the determination of the coefficients of the equation of state for nitrogen.

Comparisons to P-ρ-T Data for Oxygen

The equation of state for oxygen generally shows agreement with the P-ρ-T data within the experimental uncertainty of the measured values. The equation is valid for the liquid to within 0.1 percent in density, for the vapor at temperatures below the critical temperature to within 0.2 percent, for states at temperatures above the critical temperature to 250 K to within 0.2 percent, and for the supercritical states between 250 and 300 K to within 0.1 percent. In the immediate vicinity of the critical point calculated density values may be in error as much as 3 percent as a result of difficulties in fitting the equation of state in this region. Small systematic deviations of density values calculated using the equation of state (1) from experimental values are present for isotherms above the critical temperature extending to at least 250 K.

Table III includes the root mean square deviations in density and in pressure for the selected P-ρ-T data sets used in the determination of the coefficients for the equation of state for oxygen.

Comparisons to Vapor Pressure Data

The vapor pressure equation (2) with coefficients for nitrogen from Table I represents the selected data to within about ± 0.01 K over the entire range between the triple point and the critical point. Equation (2) with coefficients for oxygen from Table I represents the selected vapor pressure data from the triple point to 90 K within ± 0.10 K, and those data from 90 K to the critical point within ± 0.01 K.

THERMODYNAMIC PROPERTY CALCULATIONS

Values of C_p and C_v calculated by integration along isotherms using equation (1) and equation (3) with coefficients from Table I are illustrated for nitrogen in Figure 1 and for oxygen in Figure 2. Comparisons of calculated heat capacity values with the available experimental measurements indicate proper behavior of the derivative functions of the equation of state except for the region near the critical point and for the liquid in the immediate vicinity of the saturation line. Abbreviated tables of properties of nitrogen and oxygen are presented in Tables IV and V to provide for verification of calculated property values using this formulation.

TABLE I

COEFFICIENTS FOR EQUATIONS

Equation of State (1)*

Nitrogen	Oxygen
$N_1 = 0.136224769272827 \times 10^{-2}$	$N_1 = -0.430904539116151 \times 10^{-2}$
$N_2 = 0.107032469908591$	$N_2 = 0.352017371210142$
$N_3 = -0.243900721871413 \times 10^{1}$	$N_3 = -0.583622146387697 \times 10^{1}$
$N_4 = 0.341007449376470 \times 10^{2}$	$N_4 = 0.243509085365005 \times 10^{3}$
$N_5 = -0.422374309466167 \times 10^{4}$	$N_5 = -0.124636118754359 \times 10^{5}$
$N_6 = 0.105098600246494 \times 10^{-3}$	$N_6 = 0.120808823909537 \times 10^{-3}$
$N_7 = -0.112594826522081 \times 10^{-1}$	$N_7 = -0.550317003134120 \times 10^{-1}$
$N_8 = 0.142600789270907 \times 10^{-3}$	$N_8 = -0.107757858055132 \times 10^{-3}$
$N_9 = 0.184698501609007 \times 10^{5}$	$N_9 = 0.278535713206315 \times 10^{4}$
$N_{10} = 0.811140082588776 \times 10^{-7}$	$N_{10} = -0.704063168225340 \times 10^{-5}$
$N_{11} = 0.233011645038006 \times 10^{-2}$	$N_{11} = 0.734267224770646 \times 10^{-2}$
$N_{12} = -0.507752586350986$	$N_{12} = -0.593869823298574$
$N_{13} = 0.485027881931214 \times 10^{-4}$	$N_{13} = -0.636168419089612 \times 10^{-4}$
$N_{14} = -0.113656764115364 \times 10^{-2}$	$N_{14} = 0.330340156388619 \times 10^{-3}$
$N_{15} = -0.707430273540575$	$N_{15} = -0.857692988384297 \times 10^{-1}$
$N_{16} = 0.751706648852680 \times 10^{-4}$	$N_{16} = -0.754619159849318 \times 10^{-5}$
$N_{17} = -0.111614119537424 \times 10^{-5}$	$N_{17} = 0.996438361098119 \times 10^{-7}$
$N_{18} = 0.368796562233495 \times 10^{-3}$	$N_{18} = 0.624681098557646 \times 10^{-4}$
$N_{19} = -0.201317691347729 \times 10^{-5}$	$N_{19} = -0.731698500361039 \times 10^{-6}$
$N_{20} = -0.169717444755949 \times 10^{5}$	$N_{20} = 0.117348522089476 \times 10^{4}$
$N_{21} = -0.119719240044192 \times 10^{6}$	$N_{21} = -0.398781039076253 \times 10^{6}$
$N_{22} = -0.975218272038281 \times 10^{2}$	$N_{22} = -0.166821139899919 \times 10^{2}$
$N_{23} = 0.554639713151823 \times 10^{5}$	$N_{23} = 0.109498608452644 \times 10^{6}$
$N_{24} = -0.179920450443470$	$N_{24} = -0.178433458562360 \times 10^{-1}$
$N_{25} = -0.256582926077184 \times 10^{1}$	$N_{25} = 0.187525619791366 \times 10^{1}$
$N_{26} = -0.413707715090789 \times 10^{-3}$	$N_{26} = -0.941017857952665 \times 10^{-4}$
$N_{27} = -0.256245415300293$	$N_{27} = -0.575396819330284$
$N_{28} = -0.124222373740063 \times 10^{-6}$	$N_{28} = -0.207155723961989 \times 10^{-7}$
$N_{29} = 0.103556535840165 \times 10^{-4}$	$N_{29} = 0.157471345490601 \times 10^{-4}$
$N_{30} = -0.538699166558303 \times 10^{-9}$	$N_{30} = -0.107579209254507 \times 10^{-9}$
$N_{31} = -0.757415412839596 \times 10^{-8}$	$N_{31} = -0.700238600921750 \times 10^{-8}$
$N_{32} = 0.585367172069521 \times 10^{-7}$	$N_{32} = 0.343548518746171 \times 10^{-7}$

$\gamma = 0.0056$; $R = 0.820539$ liter-atm/mole-K

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

Vapor Pressure Equation (2)**

Nitrogen	Oxygen
$N_1 = 0.8394409444 \times 10^{4}$	$N_1 = -0.5581932039 \times 10^{3}$
$N_2 = -0.1890045259 \times 10^{4}$	$N_2 = -0.1211887103 \times 10^{3}$
$N_3 = -0.7282229165 \times 10^{1}$	$N_3 = -0.8345621163 \times 10^{-1}$
$N_4 = 0.1022850966 \times 10^{-1}$	$N_4 = 0.2660364433 \times 10^{-2}$
$N_5 = 0.5556063825 \times 10^{-3}$	$N_5 = 0.1687502383 \times 10^{-4}$
$N_6 = -0.5944544662 \times 10^{-5}$	$N_6 = -0.2126247712 \times 10^{-6}$
$N_7 = 0.2715433932 \times 10^{-7}$	$N_7 = 0.9574109678 \times 10^{-9}$
$N_8 = -0.4879535904 \times 10^{-10}$	$N_8 = -0.1661764045 \times 10^{-11}$
$N_9 = 0.5095360824 \times 10^{3}$	$N_9 = 0.2754560571 \times 10^{2}$
$\alpha = 1.95000$	$\alpha = 1.91576$

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

Ideal Gas Heat Capacity Equation (3)***

Nitrogen	Oxygen
$N_1 = -0.735210401157252 \times 10^{3}$	$N_1 = -0.498199853711943 \times 10^{4}$
$N_2 = 0.342239980411978 \times 10^{2}$	$N_2 = 0.230247779995218 \times 10^{3}$
$N_3 = -0.557648284567620$	$N_3 = -0.345565323510732 \times 10^{1}$
$N_4 = 0.350404228308756 \times 10^{1}$	$N_4 = 0.352187677367116 \times 10^{1}$
$N_5 = -0.173390185081005 \times 10^{-4}$	$N_5 = -0.435420216024420 \times 10^{-4}$
$N_6 = 0.174650849766463 \times 10^{-7}$	$N_6 = 0.134635345013162 \times 10^{-7}$
$N_7 = -0.356892033544348 \times 10^{-11}$	$N_7 = 0.162059825959105 \times 10^{-10}$
$N_8 = 0.100538722808834 \times 10^{1}$	$N_8 = 0.103146851572565 \times 10^{1}$
$N_9 = 0.335340610000000 \times 10^{4}$	$N_9 = 0.223918105000000 \times 10^{4}$

***Coefficients are for temperature in degrees Kelvin.

Critical Point Constants and Constraints

Nitrogen	Oxygen
$T_c = 126.20$ K	$T_c = 154.581$ K
$P_c = 33.555$ atm	$P_c = 49.77$ atm
$\rho_c = 11.21$ moles/liter	$\rho_c = 13.63$ moles/liter
$(\partial P/\partial \rho)_T = 0$	$(\partial P/\partial \rho)_T = 0$
$(\partial^2 P/\partial \rho^2)_T = 0$	$(\partial^2 P/\partial \rho^2)_T = 0$
$(\partial P/\partial T)_\rho = 1.6569$ atm/K	$(\partial P/\partial T)_\rho = 1.9689$ atm/K

TABLE II

SUMMARY OF DATA USED IN THE DETERMINATION OF EQUATIONS OF STATE, VAPOR PRESSURE EQUATIONS, AND IDEAL GAS HEAT CAPACITY EQUATIONS

P-ρ-T Data Used in the Determination of Equations of State

Nitrogen				Oxygen			
Source	Temperature Range (K)	Pressure Range (atm)	Number of Data Points	Source	Temperature Range (K)	Pressure Range (atm)	Number of Data Points
Canfield [1]	133 - 273	2 - 300	152	Michels et al. [14]	273 - 323	22 - 135	40
Cockett et al. [2]	85 - 120	50 - 200	63	Nijhoff and Keesom [15]	120 - 233	3 - 9	43
Crain [3]	143 - 273	2 - 500	90	Weber [16]	56 - 300	0.5 - 358	1482
Friedman [4]	80 - 300	1 - 200	201				
Gibbons [5]	72 - 77	22 - 124	17				
Golubev and Dobrovolskii [6]	78 - 133	49 - 484	59				
Holborn and Otto [7]	273 - 673	20 - 99	66				
Michels et al. [8]	273 - 423	20 - 80	56				
Michels et al. [9]	273 - 423	200 - 3000	147				
Otto et al [10]	298 - 423	45 - 400	63				
Robertson and Babb [11]	308 - 673	1600 - 10,000	170				
Saurel [12]	423 - 1073	10 - 900	87				
Weber [13]	80 - 140	30 - 266	76				

Data Used in the Determination of the Vapor Pressure Equations

Nitrogen			Oxygen		
Source	Temperature Range (K)	Number of Data Points	Source	Temperature Range (K)	Number of Data Points
Armstrong [17]	66 - 77	74	Hoge [18]	95.76 - 154.575	96
Weber [13]	65 - 126	47	Muijlwijk et al. [19]	65.257 - 96.118	33
			Myers [20]	55 - 95	41
			Weber [22]	113.994 - 154.304	20

Data Used in the Determination of the Ideal Gas Heat Capacity Equations

Nitrogen			Oxygen		
Source	Temperature Range (K)	Number of Data Points	Source	Temperature Range (K)	Number of Data Points
Baehr et al. [22]	50 - 2000	116	Baehr et al. [22]	50 - 2000	116

TABLE III

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

Nitrogen			Oxygen		
Source	RMS Deviation in Density (percent)	RMS Deviation in Pressure (percent)	Source	RMS Deviation in Density (percent)	RMS Deviation in Pressure (percent)
Canfield [1]	0.166	0.225	Michels et al. [14]	0.071	0.068
Cockett et al. [2]	0.260	7.077	Nijhoff and Keesom [15]	0.079	0.076
Crain [3]	0.077	0.114	Weber [16]	0.302	1.692
Friedman [4]	0.552	0.116			
Gibbons [5]	0.161	7.901			
Golubev and Dobrovolskii [6]	0.352	5.522			
Holborn and Otto [7]	0.066	0.068			
Michels et al. [8]	0.015	0.016			
Michels et al. [9]	0.053	0.149			
Otto et al. [10]	0.011	0.012			
Robertson and Babb [11]	0.077	0.224			
Saurel [12]	0.074	0.093			
Weber [13]	0.496	0.813			

TABLE IV

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	-4086.	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	898.
*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	23.68	-1773.	97.19	26.15	67.96	562.
100	0.1243	2856.	159.40	21.05	30.02	202.	*103.937	1.492	2466.	137.97	24.12	45.28	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	410.
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	0.01218	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	15.08	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	308.
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	64989.	213.56	27.56	35.87	896.
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.	72.68	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	1226.
150	23.74	1095.	106.76	25.88	48.35	738.	150	28.28	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	41.98	958.
300	12.96	7594.	137.21	22.45	38.27	547.	300	20.48	8475.	128.25	23.96	37.84	846.
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	10.56	25740.	162.44	24.01	33.71	836.
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	1665.	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	30.09	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.

TABLE V

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	T	ρ	h	s	C_v	C_p	Vel. Sound
Pressure 0.10 atm.							Pressure 1 atm.						
*54.360	40.87	-6237	66.41	33.20	54.49	1252.	*54.371	40.88	-6235	66.41	33.22	54.50	1252.
60	40.07	-5928	71.82	34.59	54.95	1162.	60	40.07	-5926	71.81	34.60	54.95	1162.
70	38.65	-5382	80.24	33.18	54.23	1063.	70	38.65	-5380	80.23	33.19	54.23	1063.
*72.77	38.25	-5232	82.34	32.65	54.12	1040.	80	37.20	-4839	87.45	31.39	54.09	983.
*72.77	0.01685	2098	182.97	20.99	29.53	162.	90	35.69	-4296	93.85	29.98	54.68	905.
80	0.01530	2311	185.76	20.92	29.40	170.	*90.191	35.66	-4285	93.97	29.96	54.70	903.
90	0.01358	2605	189.22	20.87	29.29	181.	*90.191	0.13968	2544	169.65	21.56	31.05	178.
100	0.01222	2897	192.30	20.84	29.23	190.	100	0.12484	2845	172.82	21.26	30.37	188.
120	0.01017	3481	197.62	20.81	29.17	209.	120	0.10300	3446	178.29	20.98	29.74	207.
140	0.00871	4064	202.12	20.81	29.15	226.	140	0.08784	4037	182.85	20.89	29.48	225.
160	0.00762	4647	206.01	20.80	29.14	241.	160	0.07663	4626	186.78	20.85	29.36	241.
200	0.00610	5813	212.51	20.82	29.14	270.	200	0.06112	5798	193.32	20.84	29.27	269.
250	0.00488	7271	219.02	20.89	29.21	301.	250	0.04881	7261	199.85	20.90	29.28	301.
300	0.00406	8736	224.36	21.07	29.39	330.	300	0.04065	8728	205.20	21.08	29.44	330.
Pressure 10 atm.							Pressure 20 atm.						
*54.475	40.89	-6211	66.43	33.43	54.54	1249.	*54.591	40.91	-6185	66.46	33.66	54.58	1247.
60	40.10	-5908	71.73	34.71	54.93	1162.	60	40.14	-5888	71.65	34.83	54.91	1163.
70	38.70	-5363	80.14	33.26	54.17	1065.	70	38.74	-5343	80.05	33.35	54.10	1068.
80	37.26	-4823	87.36	31.45	54.00	987.	80	37.31	-4804	87.25	31.52	53.89	990.
90	35.75	-4280	93.74	30.04	54.53	909.	90	35.82	-4263	93.62	30.10	54.38	914.
100	34.15	-3730	99.54	28.93	55.73	827.	100	34.24	-3714	99.40	28.99	55.48	833.
*119.851	30.47	-2575	110.06	27.35	61.89	641.	120	30.61	-2560	109.91	27.37	61.06	651.
*119.851	1.21681	3003	156.58	23.66	40.35	189.	*133.018	27.44	-1703	116.67	26.89	72.85	502.
120	1.21421	3009	156.63	23.64	40.27	189.	*133.018	2.50971	2972	151.81	25.43	54.25	187.
140	0.96355	3740	162.28	21.94	34.13	214.	140	2.22335	3316	154.33	23.95	45.30	199.
160	0.81299	4399	166.68	21.36	32.06	234.	160	1.75704	4115	159.68	22.14	36.56	226.
200	0.62865	5646	173.64	21.03	30.59	266.	200	1.29957	5471	167.26	21.27	32.30	263.
250	0.49422	7159	180.40	21.01	30.03	301.	250	1.00224	7044	174.29	21.13	30.90	300.
300	0.40864	8657	185.86	21.17	29.93	330.	300	0.82203	8577	179.88	21.26	30.48	330.
Pressure 40 atm.							Pressure 100 atm.						
*54.823	40.94	-6132	66.52	34.09	54.66	1242	*55.512	41.04	-5974	66.69	35.21	54.84	1231.
60	40.21	-5848	71.47	35.06	54.86	1166.	60	40.43	-5728	70.96	35.69	54.75	1173.
70	38.83	-5304	79.86	33.51	53.97	1072.	70	39.09	-5186	79.31	33.94	53.63	1087.
80	37.42	-4766	87.04	31.66	53.70	997.	80	37.73	-4653	86.44	32.03	53.17	1017.
90	35.95	-4228	93.38	30.23	54.08	923.	90	36.34	-4121	92.70	30.59	53.32	948.
100	34.41	-3683	99.12	29.11	55.01	845.	100	34.89	-3585	98.34	29.47	53.86	878.
120	30.92	-2546	109.48	27.44	59.53	673.	120	31.73	-2487	108.35	27.73	56.39	728.
140	26.04	-1223	119.64	26.75	77.99	456.	140	27.92	-1303	117.46	26.48	63.07	565.
*149.001	21.72	- 335	125.77	28.16	150.54	297.	160	22.47	123	126.95	26.16	84.01	383.
*149.001	6.22794	2426	144.30	29.70	160.66	178.	200	8.819	3810	147.68	23.78	60.85	260.
160	4.38968	3362	150.39	24.90	59.21	207.	250	5.537	6124	158.09	21.97	39.15	305.
200	2.79171	5098	160.16	21.80	36.69	258.	300	4.263	7959	164.79	21.90	35.01	340.
250	2.06066	6812	167.82	21.36	32.78	299.							
300	1.66237	9417	173.68	21.44	31.61	332.							
Pressure 200 atm.							Pressure 300 atm.						
*54.648	41.21	-5711	67.00	36.60	54.98	1224.	*57.766	41.38	-5448	67.31	37.52	54.96	1226.
60	40.77	-5527	70.15	36.58	54.63	1188.	60	41.10	-5325	69.39	37.31	54.58	1206.
70	39.50	-4988	78.46	34.55	53.16	1112.	70	39.88	-4789	77.66	35.06	52.79	1137.
80	38.22	-4461	85.50	32.57	52.46	1048.	80	38.67	-4266	84.64	33.03	51.91	1078.
90	36.92	-3937	91.67	31.12	52.34	987.	90	37.44	-3749	90.74	31.61	51.62	1021.
100	35.58	-3413	97.19	30.02	52.51	924.	100	36.19	-3233	96.17	30.54	51.56	963.
120	32.80	-2355	106.83	28.29	53.43	797.	120	33.65	-2201	105.58	28.88	51.72	850.
140	29.75	-1268	115.21	26.87	55.54	670.	140	31.01	-1161	113.59	27.49	52.31	741.
160	26.29	- 123	122.85	25.73	59.23	550.	160	28.20	- 105	120.64	26.29	53.36	641.
200	18.26	2391	136.85	24.15	63.85	381.	200	22.28	2064	132.74	24.48	54.48	493.
250	11.48	5184	149.38	22.70	47.63	350.	250	16.05	4667	144.38	23.28	48.53	420.
300	8.55	7331	157.24	22.49	39.64	370.	300	12.30	6917	152.60	23.03	42.03	414.

*Phase change.

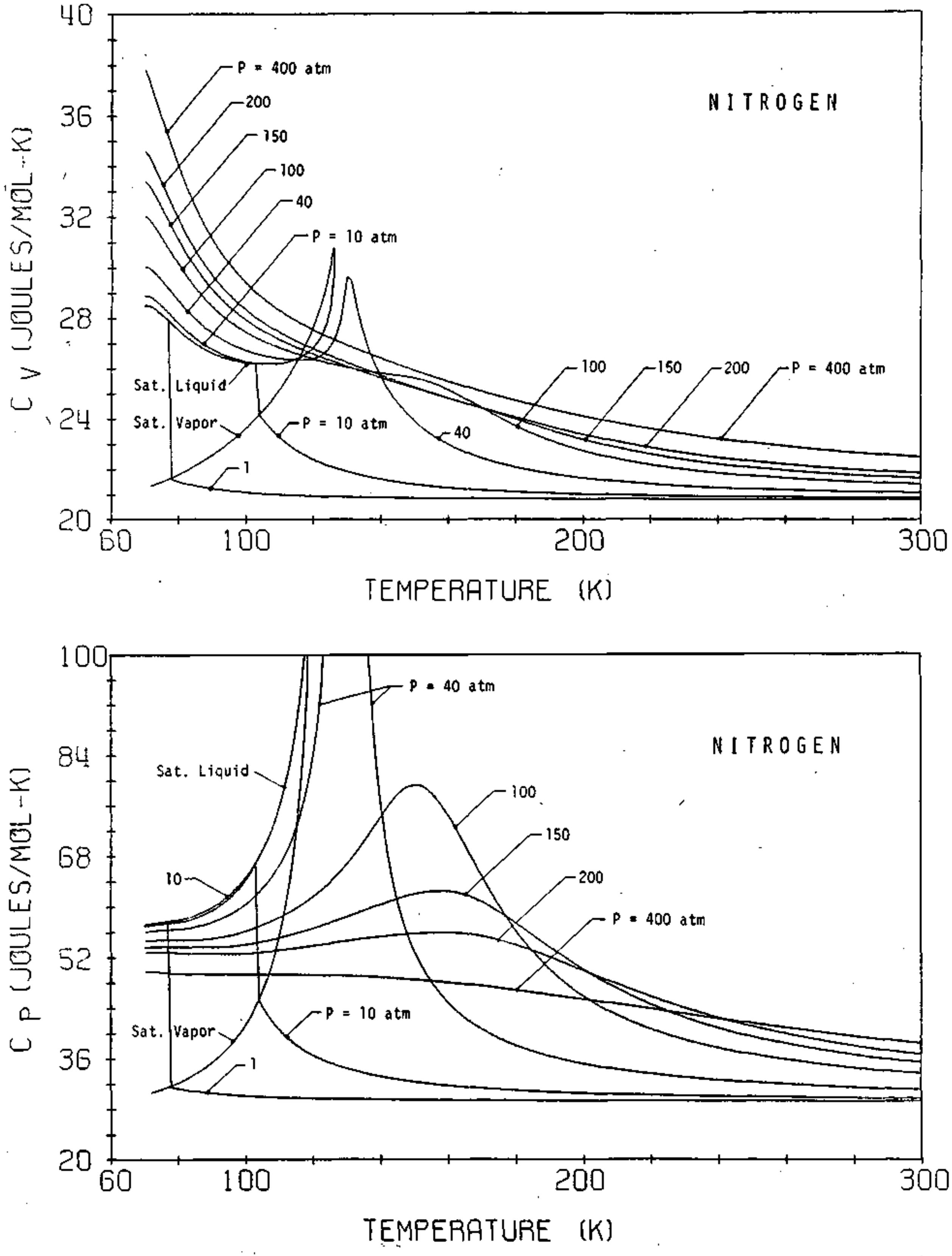

Figure 1. Isochoric and Isobaric Heat Capacities for Nitrogen Calculated with the Equation of State (1) with Coefficients from Table I.

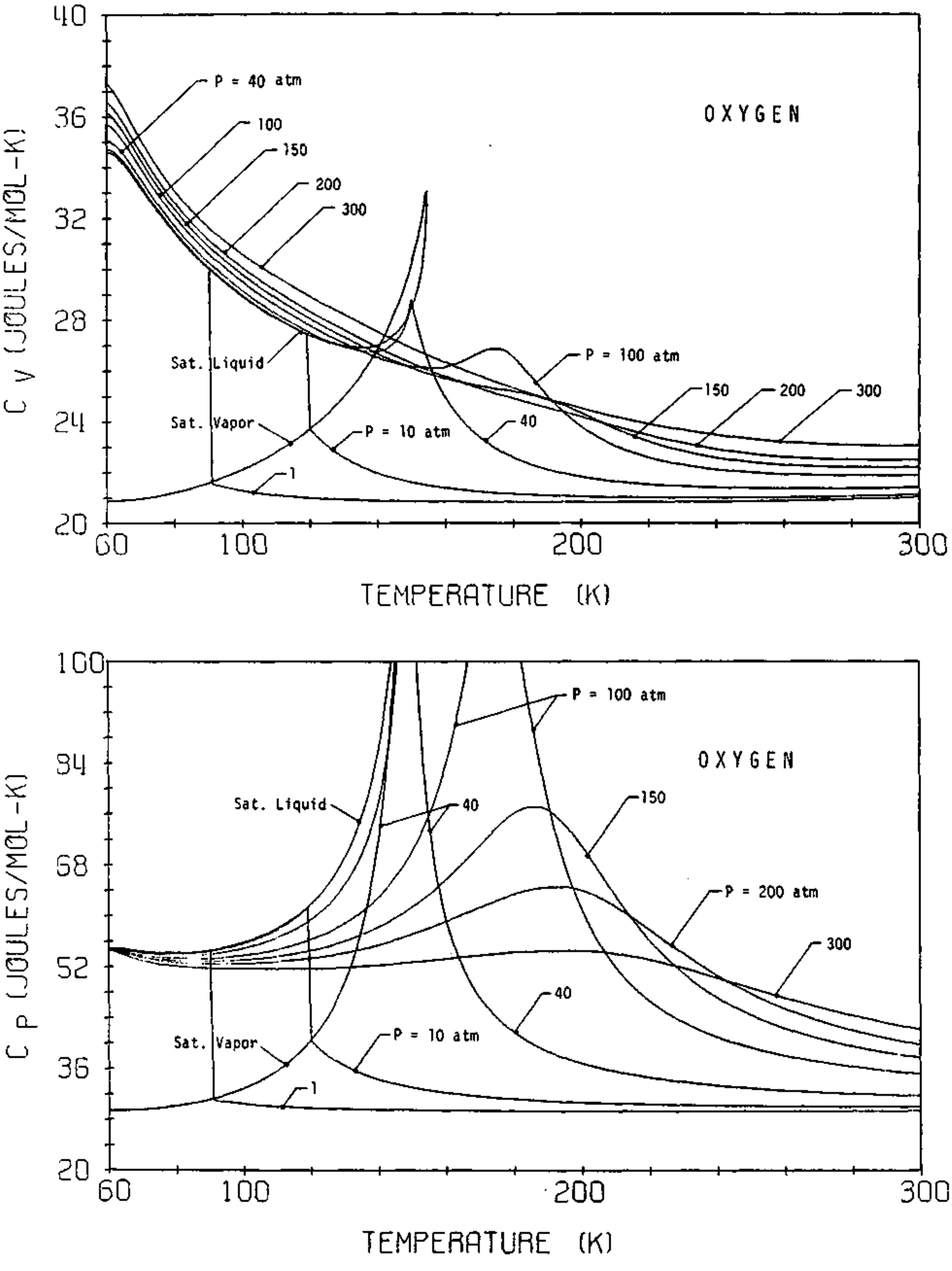

Figure 2. Isochoric and Isobaric Heat Capacities for Oxygen Calculated with the Equation of State (1) with Coefficients from Table I.

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