

Pressure-Volume-Temperature Data for Oxygen

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To satisfy the demand for data on oxygen at higher pressures, an equation has been developed that represents the available experimental data within the accuracy of the observed values. Values of the virial coefficients are given for densities in Amagat units in the temperature range -200° to $+200^{\circ}$ C. Values of pressure in pounds per square inch² are tabulated corresponding to temperatures from -50° to $+150^{\circ}$ F and densities up to 320 times the density at 70° F and 1 atmosphere. These data are also presented in a chart, with pV/RT and pressure as coordinates.

I. Equation of State

The use of progressively higher pressures in high-pressure containers has developed a need for data on oxygen at pressures and densities higher than those at present tabulated. Although an equation for representing the properties of oxygen has been published by Millar and Sullivan [1]¹, that equation is not adequate for the present purpose. Hence an equation has been devised that represents all available experimental PVT data at densities up to the critical density within the limit of experimental accuracy. The equation is of the Kamerlingh Onnes type. Exponential functions of temperature replace the functions used by that author. This equation has the form

$$pV/RT = 1 + B/V + C/V^2 + D/V^4, \quad (1)$$

where the virial coefficients have the following values:

$$B = (B_1/T)(1 - \exp(-M/T)) + B_2$$

$$C = (C_1/T)(1 - \exp(-M/T)^3) + C_2$$

$$D = (E_1/T)(1 - \exp(-M/T)^7) + D_2$$

The omission of the term in $1/V^3$ is in accordance with the practice of Kamerlingh Onnes.¹ The quantities B_1 , B_2 , C_1 , C_2 , D_1 , D_2 , and M are constants. The exponent of (M/T) is in each case, equal to $(2n-1)$ where n is the exponent of V . The practice of Kammerlingh Onnes has been

to add terms containing higher powers of V for making the equation applicable at higher densities. No attempt has been made to see whether the form of temperature function used here could be extended to such additional terms.

A study of charts of pV versus $1/V$ for several substances shows that a linear relation exists between the minimum values of pV for the various isotherms and their corresponding values of density. If this linear relation may be extrapolated to low temperatures where the minimum occurs in the region of the subcooled liquid and cannot be reproduced experimentally, then since the density of the condensed phase is finite, the minimum value of pV should also be finite, even though negative at the lower temperatures. The form of temperature functions used in eq 1 have been designed such that their product with T remains finite as T approaches zero; and in this respect are considered to be better than those used for butadiene [2], although the constants for the second virial can be chosen so that over a wide temperature range the two functions will give values very closely in agreement. The form $B_1/T^4 + B_2$, which was used for the third virial in the equation for butadiene, becomes at high temperatures a close approximation to the form used here.

The value of M was determined by a method of successive approximations. The procedure consisted in assuming a value for M , solving for B_1 and B_2 from values of the second virial derived from the experimental data at two temperatures,

¹ Figures in brackets indicate the literature references at the end of this paper.

those chosen being 0° and 100° C, and calculating the value of the second virial at a third temperature. Successive values of M were chosen until the calculated value of the second virial at the third temperature, in this case the critical temperature, agreed with that derived from experimental data. The value obtained for M was near $1.25T_c$ and hence the number 192.838 was adopted for M . This is five-fourths of 154.27°K, the number reported by the Leiden laboratory for the critical temperature. In consideration of the law of corresponding states, the quantity $1.25T_c$ should be sufficiently approximate to make a good initial choice for fitting data to other substances, although the exact value five-fourths is no longer considered significant.

Although coefficients were determined for the three terms to represent all the observed data for oxygen within the limit of experimental accuracy, yet at the lowest temperatures the choice of a smaller value of M would improve slightly the agreement between calculated and observed values. But this change would be at the expense of excessive deviations at higher temperatures. A similar situation was found in attempts to apply the equation to nitrogen.² On the other hand, the data for nitrogen above 100° C indicate a larger value of M . This emphasizes the fact that, although eq 1 covers the entire range of data on oxygen, it is only empirical and is applicable to a limited temperature range.

For convenience in computation, the Napierian number e is replaced by the base 10 giving

$$B = (B_1/T)(1 - 10^{-b}) + B_2$$

$$C = (C_1/T)(1 - 10^{-c}) + C_2$$

$$D = (D_1/T)(1 - 10^{-d}) + D_2$$

The numerical values to be used are as follows:

$$B_1 = -1.04472 \quad B_2 = 0.0009878$$

$$C_1 = 647.93 \times 10^{-6} \quad C_2 = 1.426 \times 10^{-6}$$

$$D_1 = -1133.9 \times 10^{-12} \quad D_2 = 5.55 \times 10^{-12}$$

$$T = {}^{\circ}\text{C} + 273.16$$

² The constants used for nitrogen were $B_1 = -0.008223$, $B_2 = 0.001208$, and $M = 157.45 = (5/4) T_c$, where T_c was assumed to be 125.96°K, and V is in Amagat units. A very good representation of the data in International Critical Tables [3] up to 100° C is obtained, but at 400° C the second virial coefficient is in error by about 0.0002, i. e., about 20 percent. If the exponent is increased to about $-1.8 T_c/T$ the experimental data above -100° C are very well represented but not those at lower temperatures.

$$b = 0.434294(M/T) = 83.7484/T$$

$$c = 0.434294(M/T)^3 = 3.1143 \times 10^6 / T^3$$

$$d = 0.434294(M/T)^7 = 43.06 \times 10^{14} / T^7,$$

where

$$0.434294 = \log_{10} e$$

and where in the right-hand side of the equation, the temperature T is expressed in degrees Kelvin, and the volume V , in Amagat units, that is, the ratio of the volume at the specified state to the volume at 0° C and 1 atm. Since the fraction pV/RT is dimensionless in form, its value is independent of the units, and it may be expressed in any units so long as they are consistent.

II. Representation of the Experimental Data

Although this work was undertaken primarily to calculate data for use in the compressed gas industry in the temperature range -50° to 150° F, a much wider range has been covered.

Equation 1 with the constants given in the first section of this paper represents the available data within the experimental error from -145° to 200° C, at densities up to 300 or even more Amagat units. The accuracy with which eq 1 represents the data is shown by figure 1, in which the coordinates are $(V/V_0)(1 - pV/RT)$ versus V_0/V , where V is the specific volume at the pressure p and the temperature T , V_0 is the specific volume at 1 atm and 0° C, and R is the gas constant in appropriate units. The continuous curves represent values calculated from eq 1. The sensitivity of the chart to errors in pressure is variable, with the density becoming infinite at zero density. The effect at -117° C of a 0.2 percent error in the pressure is illustrated by the distance H between the top of the chart and the adjacent dotted curve.

The available measured values of pVT for oxygen are represented by the various points in figure 1. These data are given in International Critical Tables, [3]. They comprise measurements from three sources namely: (1) Holborn and Otto at the Physikalische Technische Reichsanstalt [4], (2) Kamerlingh Onnes and his associates at Leiden [3, 5], Amagat [6].

(1) The first group consists of nine measurements at pressures up to 100 atm at each of the

temperatures 0° , 50° , and 100° C. The points marked by \times represent these measurements in figure 1. The empirical equation represents these measurements with average deviations from the observed pressures of 0.011, 0.043, and 0.017 percent, respectively.

(2) The second group are less precise and probably less accurate. Except for those observations below -117° C, they are represented in figure 1 by the various kinds of circles. Table 1 shows the pressure range covered by these measurements as well as the accuracy with which the empirical equation represents them. The four columns contain respectively the temperature in degrees C, the number of measurements at that temperature,

the pressure range covered in atmospheres, and the average difference between the calculated and observed pressures in percent.

Except for the data at -102.46° C, the average deviations at low temperatures do not exceed those in the temperature range 0° to 20° C, where the equation is more accurately determined by the measurements at the Reichsanstalt. Reference to figure 1 shows that the data at -102.46 deviate consistently from the equation. There is no trend in the deviations at other temperatures to indicate that this is a failure of the equation. It appears rather that the data along this particular isotherm are in error. Likewise the four observed values at -113.97° C and the respective approximate densi-

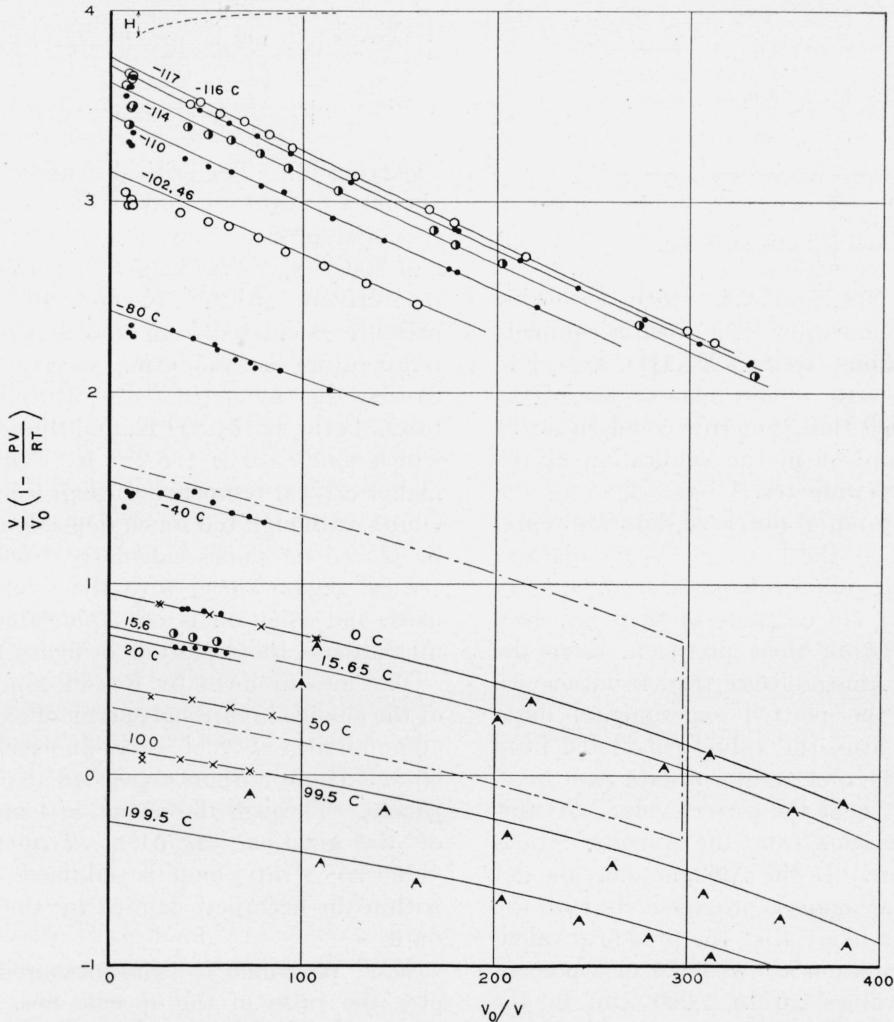


FIGURE 1. Comparison of observed values with values calculated from equation 1.

\times , Values observed by Holborn and Otto [4]; various circles, values observed by Ornes et al [5]; Δ , values observed by Amagat [6]; continuous curves calculated from eq 1; $--$, height H between this curve and top of the chart indicates the effect of 0.2 percent error in pressure; $- -$, boundary of field covered by table 4.

TABLE 1. Comparison of values from empirical equation with measurements at Leiden

Temperature °C	Number measure	Pressure range	Average deviation <i>Percent</i>
-145.39	2	atm 3 to 5	0.10
-137.87	2	5	.08
-124.95	5	3 to 6	.04
-118.58	3	4 to 6	.03
-117.01	4	4 to 6	.11
-116.99	12	20 to 52	.14
-116.01	17	4 to 55	^a .09
-113.97	12	20 to 60	^b .07
-113.94	3	5 to 6	.13
-109.90	3	5 to 7	.09
-109.97	10	20 to 61	.14
-102.49	4	5 to 7	.11
-102.46	8	20 to 60	.23
-80.03	8	21 to 62	.13
-80.00	3	6 to 8	.08
-40.05	7	21 to 61	.09
-70.01	4	6 to 9	.06
-0	5	36 to 54	.05
15.6	3	34 to 56	.17
20	6	34 to 60	.11

^a One measured value has been excluded. If this value is included the average deviation becomes 0.18%.

^b Four measured values have been excluded, see text.

ties of 167, 202, 274, and 334, which, according to Leiden Communication 169a, form a complete series of observations (series XXXIII), appear to be even more in error. The relative size of the deviations are such that the error could either be in the temperature or in the calibration of the small end of the piezometer.

(3) The third group of observed data are represented in figure 1 by the letter A. A comparison of these data with values calculated from eq 1 are given in table 2. No estimate of their accuracy can be deduced from their precision, since the values given by Amagat were read from smooth curves through the plotted experimental data. However at 100 atm, the values calculated from eq 1 agree with the first groups of data and therefore must be very near the correct value. At this pressure, the deviation from the Amagat data is 0.3 to 0.9 percent. If the Amagat data do not contain errors that increase progressively with the pressure, it seems likely that the pressures calculated from the equation are within 1 or 2 percent of the correct values up to 1,000 atm in the temperature range 0° to 200° C.

There appear to have been no new data on the critical constants for oxygen since the review by

TABLE 2. Comparison of values from eq 1 with measurements of Amagat

The body of the table contains the percentage by which the observed pressure exceeds the calculated value.

Pressure	Temperature, °C.				
	0	15.6	15.65	99.5	199.5
atm	<i>Percent</i>	<i>Percent</i>	<i>Percent</i>	<i>Percent</i>	<i>Percent</i>
100	0.3	-----	0.6	0.9	-----
200	.7	-----	.6	.9	0.4
300	.1	-----	.5	1.0	.6
400	-.5	-----	0	1.9	.8
500	-1.2	-----	-0.4	2.2	1.1
600	-1.5	-----	-.7	2.2	1.2
700	-1.4	-----	-.7	2.4	1.3
800	-0.9	-----	-.7	2.3	1.2
900	-0.4	-----	-.4	2.0	1.1
1,000	0	0.3	-----	1.8	-----
1,200	0.5	.9	-----	-----	-----
1,400	1.1	1.2	-----	-----	-----
1,600	1.9	1.7	-----	-----	-----
1,800	2.5	2.5	-----	-----	-----
2,000	3.3	3.0	-----	-----	-----

Pickering [7]. The critical density as reported is about 301 Amagat units. The critical temperature and pressure reported by Onnes, Dorsman, and Holst [8], whose values Pickering chooses, are respectively 154.27° K and 49.71 atm. The pressure calculated from eq 1 at this density and temperature is 48.3 atm., whereas at the same density the calculated temperature corresponding to 49.71 atm. is 154.89° K, and the temperature at which $dp/dV=0$ is 155.27° K. This indicates a higher critical temperature than that reported by Onnes, although too much dependence should not be placed on slopes calculated from eq 1 in the critical region since, with the number of terms used, the equation is not applicable at densities much above those plotted in figure 1.

The measurement by Rossini and Frandsen [9] of the change in internal energy of oxygen between 40 and 0 atm at 28° C gives an excellent check on eq 1. Those authors report 40 (6.51)=260.4 int j/mole. Through the use of eq 1 and integration of the relation $(\partial E/\partial V)_T=T(\partial p/\partial T)_V-p$, the value 258.8 int j/mole is obtained, which is well within the accuracy claimed for the experimental data.

E. J. Workman [10] has measured in a calorimeter the ratio of the specific heat of oxygen at various pressures up to 130 kg/cm² to the specific heat at 1 atm. A comparative method was used in which the same stream of gas was passed twice

through the calorimeter. Measurements were made at two temperatures, 26° and 60° C, respectively. Through differentiation of eq 1 and assumption that C_p for 1 atm is 7.05 cal/° C mole, the value of this ratio was calculated for the pressure 50 kg/cm.² The third and higher virials were neglected; at the higher pressures it might be necessary to include calculations based on the third virial. The values for the ratio calculated for 26° and 60° C are, respectively, 1.102 and 1.076, whereas Workman gives 1.088 and 1.063, respectively. The cause for this discrepancy of over 1 percent is suggested by Workman's statement [10, p. 1352] as follows: "For example, we can be reasonably certain that in the present apparatus the net heat transfer q arises from an excessive heat conduction along the line leading from the low pressure bath to the heat interchanger." Heat transfer at this place would always be in the direction to yield a low value for the ratio of specific heats.

Equation 1 leads to a value of 94.9×10^{-5} for the second virial coefficient for oxygen at 0° C. This is in very good agreement with C. S. Cragoe's [11] estimate $(95.1 \pm 0.9) \times 10^{-5}$. The value of pV/RT at 0° C and 1 atm derived from eq 1 is therefore $1 - 94.9 \times 10^{-5}$, or 0.9999051. Cragoe has shown this value to be consistent with measurements at pressures of 1 atm or less. The use of $RT_0 = 22.4140$ liter atm per mole as given by him leads to a weight of 1.42904 g for the normal liter. This value was chosen by Pickering [12] in his review of the experimental data on the weight of the normal liter.

Equation 1 has been compared with the Beattie Bridgeman equation [13]. The agreement is very close. For unit Amagat density in the temperature range -140° to +200° C, the deviation for pV/RT at the two extreme temperatures is 8 parts in 100,000, this being the maximum deviation. At 0° C, where eq 1 is in agreement with Cragoe's estimated value [11], the Beattie Bridgeman equation gives a value of pV/RT , which is 5 parts in 100,000 smaller. At higher densities, eq 1 is in slightly better agreement with the experimental data.

It may be of interest to note that the value of pV/RT calculated from eq 1 for saturated oxygen vapor at the normal boiling point (-183.0° C) is 0.9713, which is probably as good a value as any now available.

PVT Data for Oxygen

III. Virial Coefficients

Instead of a complete table of pressures over the whole range -200° to +200° C, for which eq 1 might be used, values of the second virial coefficient B are given in table 3 for every 10 deg C, and values of the higher virial coefficients C and D are given graphically for the same temperature range in figures 2 and 3, respectively. These values are for use with the density in Amagat units. If the density in grams per liter is desired,

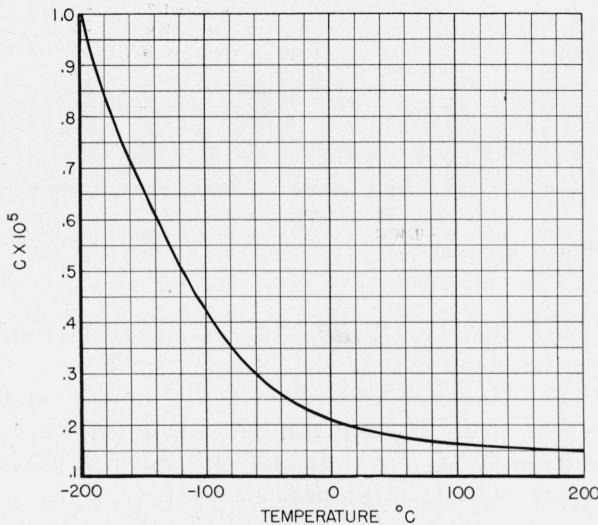


FIGURE 2. Values of the third virial coefficient C plotted as a function of temperature.

To be used with densities in Amagat units.

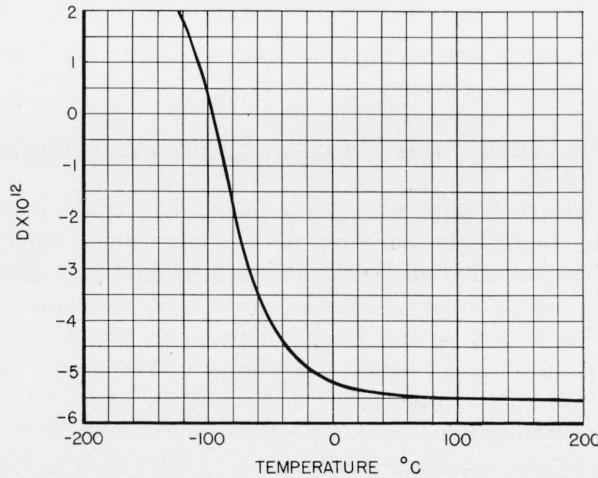


FIGURE 3. Values of the virial coefficient D plotted as a function of temperature.

To be used with densities in Amagat units.

the density in Amagat units should be multiplied by the density at 0° C and 1 atm, 1.42904 g/liter.

TABLE 3. *Values of the second virial coefficient B, multiplied by 1,000, for use in eq 1*
(Quadratic interpolation should be used)

Temperature	Temperature, ° C				
	0	10	20	30	40
°C					
-100.....	-3.0644	-3.4514	-3.8966	-4.4123	-5.0140
-0.....	-0.9488	-1.0743	-1.2123	-1.3647	-1.5333
0.....	-0.9488	-0.8345	-0.7299	-0.6340	-0.5461
100.....	-1.1420	-0.0904	-0.0423	+0.0027	+0.0447
200.....	+2.488				
	50	60	70	80	90
-100.....	-5.7225	-6.5648	-7.5774	-8.8112	-10.3388
-0.....	-1.7208	-1.9299	-2.1642	-2.4278	-2.7247
0.....	-0.4650	-0.3902	-0.3210	-0.2569	-0.1974
100.....	.0842	.1213	.1561	.1888	.2197

The quantity pV/RT is dimensionless, and for the left-hand side of the equation, p , V , and T may be in any units as long as the proper value of R is used. If p is in atmospheres, V in Amagat units, and $T=0^\circ\text{C}+273.16$, the value of R is $1/(0.999051)$ (273.16), or 0.00366434.

At low pressures the third and fourth terms are negligibly small, and when the temperature and a pressure not much over 1 atm are given, p/RT may be substituted for $1/V$ in the second term, and

$$pV/RT = 1 - Bp/RT, \quad (2)$$

becomes a convenient approximation to eq 1 at such low pressures.

IV. Table and Chart in Engineering Units

In the compressed gas industry, it is customary to express pressures in pounds per square inch, temperatures in degrees Fahrenheit, and densities in units similar to Amagat units, i. e., the ratio of the density at the given condition to the density at 70° F and 1 atm (14.696 lb/in.²). When eq 1 is reduced to these units, the constants represented by letters are

$$B_1 = -1.74509$$

$$B_2 = 0.0009167$$

$$C_1 = 1004.37 \times 10^{-6}$$

$$C_2 = 1.2280 \times 10^{-6}$$

$$D_1 = -1513.68 \times 10^{-12}$$

$$D_2 = 4.1160 \times 10^{-12}$$

$$\begin{aligned} b &= 150.747/T \\ c &= 18.163 \times 10^6 / T^3 \\ d &= 2636 \times 10^{14} / T^7 \end{aligned}$$

$$\begin{aligned} T &= ^\circ\text{F} + 459.688 \\ R &= 0.0277631 \end{aligned}$$

Table 4 contains pressures that were calculated with the use of these constants in eq 1. Temperatures are given at the ends of the rows; densities are given at the heads of the columns, and pressures in the body of the table. The units are as described in the preceding paragraph except in the third section of the table where a unit of 10 lb/in.² is used to avoid carrying pressures to an unnecessary number of places. An attempt has been made to give a number of decimal places comparable with the accuracy of the experimental data, although some of the values may be given to an extra place.

If the number of pounds mass of gas per cubic foot is desired, the densities in the units given should be multiplied by the density at 70° F and 1 atm, namely 0.082787 lb/ft³. This factor is deduced from three data, namely: (1) the value 0.99933 for pV/RT at 70° F and 1 atm calculated from eq 1, (2) the value 22.4140 liter atm per scale assumed for RT at the ice point, (3) the value 273.16° K assumed for the temperature of the ice point.

The range covered by this table and the extent to which the equation is supported by experimental data in this region is illustrated in figure 1 by an area bounded on the left by the left-hand boundary of the chart, on the right by a vertical dot-dash straight line, and above and below by dot-dash curves.

A chart (fig. 4) has also been prepared that reproduces the data given in table 4 in a form that permits the rapid solution of practical problems. This chart is being printed in a larger size, together with similar charts for nitrogen and hydrogen, and with instructions for their use, as Bureau Miscellaneous Publication M191. The coordinates of the chart are $Z=pV/RT$ versus pressure.

On this chart, figure 4, pressures are expressed in pounds per square inch absolute and temperatures in degrees Fahrenheit. Densities are expressed as the ratio of the density at the specified condition to that calculated from the equation for 70° F and 1 atm., i. e., 0.082787 lb/ft³. Readings from the chart indicate that it is drawn to represent the equation within 5 lb/in.² and within 0.0005 for the value of pV/RT . The quantity

TABLE 4. *Absolute pressures for oxygen at various temperatures and densities*Densities referred to the density at 70° F and 1 atm as unity; density at 70° F and 1 atm=0.082787 lb/ft.³

Temperature	UNIT OF PRESSURE, 1 PSI ABSOLUTE FOR DENSITIES (V_{70}/V)—										
	1	10	20	30	40	50	60	70	80	90	100
° F											
-50	11.3570	112.04	220.79	326.4	429.1	528.9	626.1	720.9	813.3	903.6	991.9
-40	11.6353	114.88	226.62	335.3	441.2	544.5	645.2	743.5	839.7	933.8	1,026.2
-30	11.9136	117.73	232.43	344.3	453.4	560.0	664.1	766.1	866.0	964.0	1,060.3
-20	12.1919	120.57	238.24	353.2	465.5	575.4	683.1	788.7	892.3	994.1	1,094.4
-10	12.4701	123.41	244.05	362.1	477.7	590.9	702.0	811.2	918.5	1,024.2	1,128.4
0	12.7484	126.25	249.86	371.0	489.8	606.4	720.9	833.7	944.7	1,054.2	1,162.4
10	13.0266	129.09	255.66	379.9	501.9	621.8	739.8	856.1	970.9	1,084.1	1,196.2
20	13.3049	131.93	261.46	388.7	513.9	637.2	758.7	878.5	996.9	1,114.0	1,230.0
30	13.5832	134.76	267.25	397.6	526.0	652.6	777.5	900.9	1,022.9	1,143.8	1,263.7
40	13.8614	137.60	273.04	406.5	538.0	667.9	796.3	923.2	1,048.9	1,173.6	1,297.4
50	14.1396	140.43	278.83	415.3	550.0	683.3	815.0	945.5	1,074.9	1,203.3	1,331.0
60	14.4178	143.26	284.61	424.2	562.1	698.6	833.7	967.8	1,100.8	1,233.0	1,364.5
70	14.6960	146.10	290.39	433.0	574.1	713.9	852.5	990.0	1,126.6	1,262.6	1,398.0
80	14.9742	148.93	296.17	441.9	586.1	729.2	871.1	1,012.2	1,152.4	1,292.1	1,431.4
90	15.2524	151.77	301.94	450.7	598.1	744.5	889.8	1,034.3	1,178.2	1,321.6	1,464.8
100	15.5305	154.60	307.71	459.5	610.1	759.7	908.4	1,056.5	1,204.0	1,351.1	1,498.1
110	15.8087	157.43	313.48	468.3	622.1	775.0	927.1	1,078.6	1,229.7	1,380.5	1,531.3
120	16.0869	160.26	319.25	477.1	634.1	790.2	945.7	1,100.7	1,255.4	1,409.9	1,564.5
130	16.3650	163.09	325.02	485.9	646.0	805.4	964.2	1,122.7	1,281.0	1,439.2	1,597.7
140	16.6432	165.92	330.78	494.7	658.0	820.6	982.8	1,144.7	1,306.6	1,468.5	1,630.7
150	16.9213	168.74	336.53	503.5	669.9	835.8	1,001.3	1,166.7	1,332.2	1,497.8	1,663.8
	110	120	130	140	150	160	170	180	190	200	210
-50	1,078.5	1,163.5	1,247.0	1,329	1,411	1,491	1,572	1,651	1,731	1,811	1,891
-40	1,116.8	1,206.1	1,293.9	1,381	1,467	1,552	1,637	1,722	1,807	1,892	1,977
-30	1,155.1	1,248.6	1,340.8	1,432	1,523	1,613	1,703	1,792	1,882	1,972	2,063
-20	1,193.3	1,290.9	1,387.6	1,483	1,579	1,673	1,768	1,862	1,957	2,053	2,149
-10	1,231.4	1,333.2	1,434.1	1,534	1,634	1,734	1,833	1,932	2,032	2,133	2,235
0	1,269.4	1,375.4	1,480.6	1,585	1,690	1,794	1,898	2,002	2,107	2,213	2,320
10	1,307.3	1,417.5	1,527.0	1,636	1,745	1,854	1,962	2,072	2,182	2,293	2,405
20	1,345.1	1,459.4	1,573.3	1,687	1,800	1,913	2,027	2,141	2,257	2,373	2,490
30	1,382.8	1,501.3	1,619.4	1,737	1,855	1,973	2,092	2,211	2,331	2,452	2,575
40	1,420.5	1,543.2	1,665.5	1,788	1,910	2,033	2,156	2,280	2,405	2,532	2,660
50	1,458.1	1,584.9	1,711.4	1,838	1,965	2,092	2,220	2,349	2,479	2,611	2,744
60	1,495.6	1,626.5	1,757.2	1,888	2,019	2,151	2,284	2,418	2,553	2,690	2,828
70	1,533.1	1,668.0	1,803.0	1,938	2,074	2,210	2,348	2,486	2,626	2,768	2,912
80	1,570.5	1,709.5	1,848.7	1,988	2,128	2,270	2,412	2,555	2,700	2,847	2,996
90	1,607.8	1,750.9	1,894.3	2,038	2,183	2,328	2,475	2,623	2,773	2,925	3,080
100	1,645.0	1,792.2	1,939.8	2,088	2,237	2,387	2,539	2,692	2,847	3,004	3,163
110	1,682.2	1,833.5	1,985.2	2,138	2,291	2,446	2,602	2,760	2,920	3,082	3,247
120	1,719.3	1,874.6	2,030.6	2,187	2,345	2,504	2,665	2,828	2,993	3,160	3,330
130	1,756.4	1,915.7	2,075.8	2,237	2,399	2,563	2,728	2,896	3,066	3,238	3,413
140	1,793.4	1,956.7	2,121.0	2,286	2,453	2,621	2,791	2,963	3,139	3,315	3,496
150	1,830.3	1,997.7	2,166.1	2,336	2,507	2,679	2,854	3,031	3,211	3,393	3,578

TABLE 4. *Absolute pressures for oxygen at various temperatures and densities—Continued*

	UNIT OF PRESSURE, 10 PSI ABSOLUTE, FOR DENSITIES (V_{70}/V)—										
	220	230	240	250	260	270	280	290	300	310	320
-50	197.1	205.3	213.6	222	231	240	249	258	267	278	288
-40	206.3	215.1	223.9	233	242	252	261	271	282	293	304
-30	215.5	224.8	234.3	244	254	264	274	285	296	308	319
-20	224.6	234.5	244.6	255	265	276	287	298	310	322	335
-10	233.8	244.2	254.8	266	277	288	300	312	324	337	350
0	242.8	253.9	265.0	276	288	300	312	325	338	352	366
10	252.0	263.5	275.3	287	300	312	325	339	352	367	381
20	261.0	273.1	285.4	298	311	324	338	352	366	381	397
30	270.0	282.7	295.6	309	322	336	350	365	380	396	412
40	279.0	292.2	305.7	319	334	348	363	378	394	411	427
50	288.0	301.8	315.8	330	345	360	376	391	408	425	443
60	296.9	311.3	325.9	341	356	372	388	405	422	440	458
70	305.9	320.8	335.9	351	367	384	400	418	436	454	473
80	314.8	330.2	346.0	362	379	396	413	431	449	469	488
90	323.7	339.7	356.0	373	390	407	425	444	463	483	504
100	332.6	349.1	366.0	383	401	419	438	457	477	497	519
110	341.4	358.5	376.0	394	412	431	450	470	491	512	534
120	350.3	367.9	385.9	404	423	443	463	483	504	526	549
130	359.1	377.3	395.9	415	434	454	475	496	518	541	564
140	367.9	386.7	405.8	425	446	466	488	509	532	555	579
150	376.7	396.0	415.7	436	457	478	500	522	545	569	594

pV/RT or Z is independent of the units of p , V , and T as long as the appropriate value of R is used. The value of Z at $70^\circ F$ and 1 atm is 0.99933; at $32^\circ F$ and 1 atm, 0.999051. For the units given in the chart, the value of R is 0.0277631. RT is then 0.0277631 ($^\circ F + 459.69$). The use of the chart is best illustrated by the following example:

An oxygen cylinder of 1.528 ft^3 internal volume is designed to be filled at $70^\circ F$ to a gage pressure of 2,000 lb/in.².

- To what pressure may it be filled at $60^\circ F$?
- If properly filled, what will the pressure be if the temperature of the tank should rise to $130^\circ F$?
- How many cubic feet of oxygen under the standard condition of 1 atm and $70^\circ F$, will the cylinder deliver, and what weight will be delivered?
- At $70^\circ F$ what will the pressure be after 100 ft³ have been delivered?

Solution:

(a) For the purpose of reading on the chart, we may assume that 2,000 lb/in.² gage is equivalent to 2,015 lb/in.² abs. The point on the chart at $70^\circ F$

and 2,015 lb/in.² abs corresponds to a density of 145.5 and to a value of Z or pV/RT of 0.9415. If we follow the line of constant density for 145.5 down to $60^\circ F$, the pressure read directly from the chart is 1,960 lb/in.² abs, or 1,945 lb/in.² gage, i.e., the filling pressure at $60^\circ F$. For a more accurate estimate of the filling pressure, we note that at the same point on the chart the value of Z or pV/RT is 0.9335. We now have at $70^\circ F$, $p_1V/RT_1 = 2015V_1/R(70+459.69) = 0.9415$, and at $60^\circ F$, $p_2V_2/R(60+459.69) = 0.9335$. Since $V_1 = V_2$, this leads to $p_1T_2/p_2T_1 = 0.9415/0.9335$ or $p_2 = 2015(519.69)0.9335/529.69(0.9415) = 1960.2$ lb/in.² abs, or 1945.2 lb/in.² gage. The direct reading of the chart is in this case in agreement with the more accurate calculated value, although an error in the direct reading as large as 5 lb/in.² may be expected.

(b) If we follow the line of constant density for 145.5 up to $130^\circ F$, the pressure read directly from the chart is 2,330 lb/in.² abs.

(c) The number of cubic feet under standard conditions in the tank = $145.5(1.528) = 222.3$ ft³

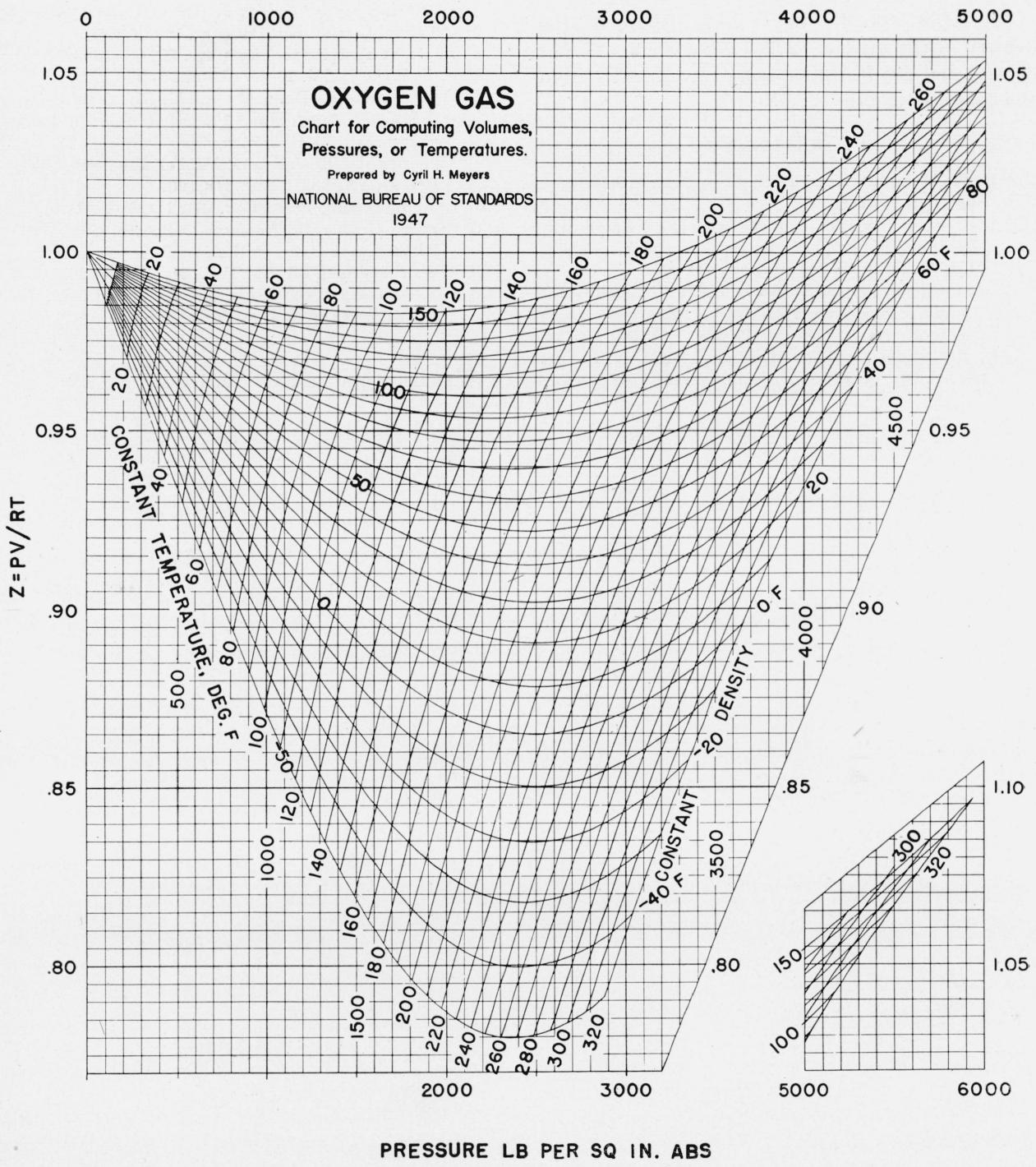


FIGURE 4. Chart of PVT for oxygen in the temperature range -50° to $+150^{\circ}$ F.

The number of cubic feet delivered is $222.3 - 1.528 = 220.8$ ft³. The weight delivered is $220.8 \times 0.082787 = 18.28$ lb.

(d) After 100 ft³ have been delivered, the density in the tank is $122.3/1.528 = 80.0$. At this density and 70° F, the pressure read directly from the chart is 1,130 lb/in.² abs.

V. References

- [1] R. W. Millar and John D. Sullivan, Bur. Mines Tech. Pap. 424 (1928).
- [2] R. B. Scott, Cyril H. Meyers, Robert D. Rands, Jr., Ferdinand G. Brickwedde, and Norman Bekkedahl, J. Research NBS **35**, 39 (1945) RP1661.
- [3] International Critical Tables, **3**, 8 and 9 (McGraw-Hill Book Co. Inc., New York, N. Y., 1926).
- [4] L. Holborn and J. Otto, Z. Physik. **10**, 367 (1922).
- [5] C. A. Crommelin, J. P. Martinez, and H. K. Onnes, Proc. Roy. Acad. Sci. Amsterdam **22**, 108 (1920); Leiden Comm. No. 154a (1918); H. K. Onnes and C. A. Crommelin, Proc. Roy. Acad. Sci. Amsterdam **18**, 515 (1915); Th van Urk & P. G. Nijhoff, Proc. 4th Int. Cong. Refrig. **1**, 65a and 73a (1924); or Leiden Comm. No. 169a and 169c (1924).
- [6] E. H. Amagat, Ann. chim. phys. **29**, 68 (1893).
- [7] S. F. Pickering, J. Phys. Chem. **28**, 97 (1924).
- [8] H. K. Onnes, C. Dorsman, and G. Holst, Proc. Roy. Acad. Sci. Amsterdam **17**, 950 (1915); or Leiden Comm. No. 145b.
- [9] Frederick D. Rossini and Mikkel Frandsen, BS J. Research **9**, 733 (1932) RP 503.
- [10] E. J. Workman, Phys. Rev. **37**₂, 1,345 (1931).
- [11] Carl S. Cragoe, J. Research NBS **26**, 495 (1941) RP1393.
- [12] S. F. Pickering, BS Sci. Pap. **21**, 141 (1926) S529.
- [13] J. A. Beattie and O. C. Bridgeman, J. Am. Chem. Soc. **50**, 3,136 (1928).

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