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PRESSURE-VOLUME-TEMPERATURE RELATIONS IN CO_2 AT ELEVATED TEMPERATURES AND PRESSURES*

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ABSTRACT. Carbon dioxide is probably the second most geologically important gas. Interpretation of hydrothermal systems and work on the stability of carbonate minerals has been greatly hampered by a lack of information concerning properties of carbon dioxide. Measurements are presented in this paper of the pressure-volume-temperature relations of carbon dioxide gas to maximum temperatures of 1000°C. and pressures of 1400 bars. The technique and the equipment involved in making the measurements is discussed.

INTRODUCTION

Among the gases of greatest interest to geologists, CO_2 ranks second in importance to water. Most volcanic gases contain at least 20 percent by weight of carbon dioxide. By analogy we may assume that similar amounts of CO_2 are contained in ore-forming solutions. This CO_2 will probably lower the critical temperature of the resultant solution and hence may play a role in determining whether such a solution is gaseous or liquid.

Experimental work by John R. Miller (1952) in the writer's laboratory on the system $CaCO_3$—H_2O—CO_2 was terminated at very modest temperature and pressure limits because of a lack of the fundamental P-V-T relations of CO_2 and for lack of data on the system CO_2—H_2O. Experimental study of many of the most interesting reactions involved in contact metamorphism similarly must await the determination of the properties of CO_2 and CO_2-H_2O mixtures. For these and other reasons, the P-V-T relations of CO_2 have been determined to 1000° C. and 1400 bars, and are recorded in this paper.

A good deal of previous work has been done on CO_2. Most of this has been included in the volume *Carbon Dioxide* (Quinn and Jones, 1935). The important early work is that of Amagat (1880), who measured densities and pressures of the gas up to approximately 200° C. and 1000 bars pressure. This work was published in 1880, and Amagat's measurements above 150° C. at high pressures remain the only work in this portion of the field to the present time. McCormack and Schneider (1950) have recently published the results of some accurate measurements to 50 bars pressure and to 600° C.

The results of some exceedingly precise measurements at temperatures up to 150° C. and pressures to 3000 atmospheres were published by workers at the Van der Waals Laboratory in Amsterdam (Michels and Michels, 1935). Unfortunately, the beautifully precise methods used by the Van der Waals Laboratory are not practical at high temperatures, since mercury, which is used to seal the gas, boils at 375° C. at 1 atmosphere pressure. Moreover, the pressure vessels were not designed to withstand high pressures at high temperatures. The values of density reported in this paper are reproducible to 1 part in 500 where those of the Van der Waals Laboratory have a precision of 1/10,000.

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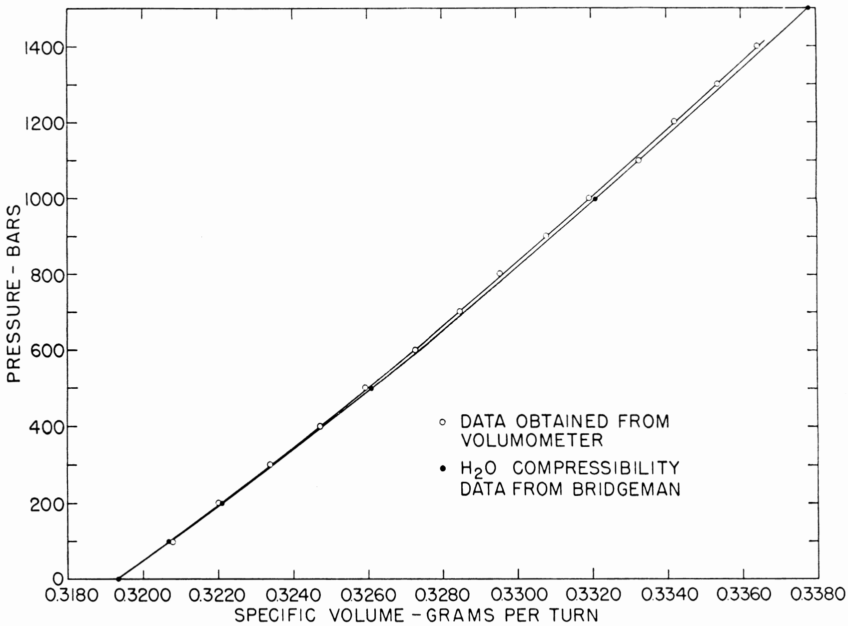
APPARATUS AND TECHNIQUE

The general apparatus and method of measurement utilized in the present investigation have been described in part in an earlier paper (Kennedy. 1950). Some modifications of the method, however, have been made.

The volumometer.—Two volumometers were used in the present work. Their design is based on the volumometers described by Keyes (1933). One of the volumometers has a ½ inch diameter piston and the other a ¼ inch diameter piston. The lead screws of the volumometers were precision lead screws made by the Waltham Machine Works with a maximum tolerance of ±0.0003 in. in total length. Several samples of water from the volumometer were collected and weighed by advancing the lead screw over various portions of its length. They indicated that the lead screw and piston were uniform to within 0.00001 grams/turn.

The larger volumometer was used for measuring the volume of material injected into a bomb and was calibrated by weighing quantities of water



VOLUMOMETER CALIBRATION

Fig. 1.

extruded at various pressures. The calibration, showing grams water expelled per turn, is shown in figure 1. This is compared with a curve, computed from Bridgman's data (1935) on water compressibility, without correcting for the pressure distortion of the volumometer. The difference between the two curves, which amounts to approximately 0.044 percent per 1000 bars pressure rise, is largely due to compression of the volumometer piston. Taking Young's modulus for steel to be 30.0 x 10^6 p.s.i., a correction for compression of the piston amounts to 0.049 percent per 1000 bars; thus the agreement with

Bridgman's data is excellent. Further details concerning the calibration of the volumometer will be presented in a paper now in preparation on density measurements of water.

Bomb.—The bombs used in these measurements were similar in design to those previously described (Kennedy, 1950) with but a minor modification. A tube of stainless steel of 0.25 in. o.d. and 0.06 in. i.d., closed at one end, was threaded through the bottom of the bomb and welded in place. The thermocouple wires, coated with quartz glass, were inserted in the tube so that the thermocouple junction rested near the center of the bomb. By this method uncertainties concerning the temperature of the bomb contents were largely reduced.

Bombs used in these measurements were of the order of 200 to 300 cc capacity.

TEMPERATURE CONTROLS AND MEASUREMENT

The bomb was heated in an electrical furnace 30 inches in length with an inside diameter of 3 inches. The ends of the furnace were stuffed with a mixture of magnesium oxide and asbestos. Exploration of the closed bomb cavity with a thermocouple indicated a temperature inhomogeneity of less than $\pm 0.1°$ C. at 400° C.

The furnace temperature was regulated by means of an alternating current bridge and phase-shifting thyratron circuit. Xenon-filled, tantalum anode thyratron tubes were used, with a maximum output of approximately 6 amperes at 200 volts. Temperature regulation over most of the range was to within $\pm 0.5°$ C., though at no time in the course of the measurements was it necessary to hold the temperature at a given value for a long time.

Temperatures were measured by determining the e.m.f. of a platinum-platinum 10% rhodium thermocouple on a shielded, type K potentiometer. Four thermocouples were made up from the same spools of 0.020″ wire obtained from Baker & Co., Newark, New Jersey. They were annealed for 50 minutes at 1400°C. and then compared with each other by placing the junctions of the couples in four closely spaced holes drilled in a stainless steel block. The block was then heated in the center of the 30 in. furnace, used to heat the bomb. The couples agreed with each other to $\pm 0.05°$ C. in the region from room temperature to 1000° C. One of these couples was then calibrated against the boiling points of water and sulfur, and the freezing points of antimony, copper, and gold. A second thermocouple was calibrated at the National Bureau of Standards. The Bureau of Standards certified the e.m.f. of this thermocouple at the thermometric fixed points, the freezing points of zinc, antimony, silver, and gold. The accuracy of this certification was 2 microvolts, about $\pm 0.2°$ C. In addition they certified 15 corresponding values of e.m.f. and temperature to an accuracy of $\pm 0.3°$ C. in the range 0 to 1100° C. and from $\pm 0.3°$ C. at 1100° C. to $\pm 2°$ C. at 1450° C. The two thermocouple calibrations agreed with each other within the limits of accuracy of certification. The two calibrated thermocouples were then placed to one side and only used when the four thermocouples were compared against each other. One of the thermocouples, after over a year of use at temperatures below 1000° C., showed a drift in calibration of less than 0.1° C.

Pressure measurement.—Three Bourdon tube gauges, manufactured by the Heise Bourdon Tube Co., were used in the present work. The gauges covered the ranges 0-100 bars, 0-500 bars and 0-1400 bars. Gauge dials were graduated in 1000, 1000 and 1400 scale divisions respectively. The gauges were calibrated by the manufacturer against a dead weight gauge and gave a maximum uncertainty in the readings over most of the range of approximately one scale division owing to hysteresis. At the highest pressures, 1400 bars, hysteresis became slightly greater. After a good deal of work had been done, it became apparent that some drift of a few tenths of one percent in the calibration of the gauges had taken place. Consequently the dead weight piston gauge, previously described by Benedict (1939), was set up and the gauges were thereafter checked on the dead weight tester at regular intervals. The earlier work was then systematically re-examined and appropriate corrections made.

CARBON DIOXIDE GAS SUPPLY

The carbon dioxide gas used in the experiment was made by New England Alcohol Co., a subsidiary of Monsanto Chemical Co., and supplied through the New England Gas Products Co. The CO_2 gas is supplied as "bone dry" and has a purity of 99.6 percent top sample. As the gas in a cylinder is used the purity increased to better than 99.9 percent when 50 percent of the tank has been expended. It was thus standard practice to bleed off the top portion of the tank and use the bottom half for the gas measurements. No correction was made for impurities in the gas; nitrogen is the major impurity.

Although the gas was supplied as "water free," small droplets of water and oil were soon detected in the supply line extending from the carbon dioxide cylinder to the bomb. A trap was therefore installed in the system and the gas passed through several inches of loosely packed anhydrous magnesium perchlorate before it was loaded into the apparatus. This effectively removed traces of oil and moisture from the gas.

EXPERIMENTAL METHOD

Two different methods were used to obtain the present data. A set of measurements at 25, 50, and 75 bars pressure and measurements at gas densities of less than 0.10 g/cc along the 150° C. isotherm were obtained by injecting known quantities of gas, via the capillary tubing, into the bomb. The volumometer was maintained in an ice bath and was always read at 0°C. and 100 bars pressure before and after gas was injected into the bomb. The schematic diagram of the apparatus is shown in figure 2. For example, a point on the 50 bar curve is obtained in the following fashion: The system is first flushed several times with carbon dioxide. Needle valves no. 3 and no. 4 are then opened and the volumometer allowed to fill with gas at tank pressure. Tank pressure, the pressure of gas over liquid CO_2, ranged from 55 to 70 bars depending on room temperature. The gas condenses in the cold volumometer, which fills rapidly, though about ½ hour usually is required before the volumometer returns to 0°C. as considerable latent heat of condensation is liberated. Next V-4 is closed, V-2 is opened, and the piston in the volumometer is advanced until Gauge no. 1 reads the desired pressure, 50 bars. V-2 is then closed and the piston advanced until Gauge no. 2 reads 100 bars. At this point, the piston position is read. V-1 and V-2 are then

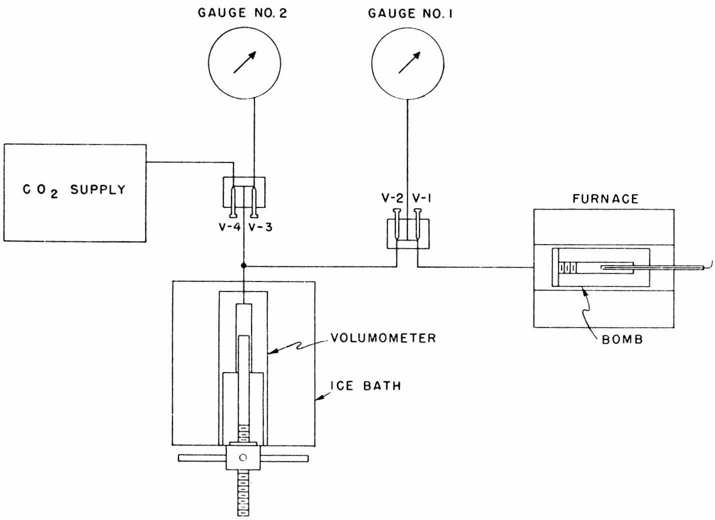


FIG. 2 SCHEMATIC DIAGRAM OF APPARATUS

opened, allowing gas to flow into the bomb. The volumometer piston is again advanced until Gauge no. 1 reads the desired 50 bars. About 15 minutes is required at this point for attainment of equilibrium between the gas and the bomb. V-2 is then closed and the piston advanced until Gauge no. 2 reads 100 bars. The final position of the piston is then read. The difference in cc between the two piston settings, multiplied by the density of CO_2 gas at 0°C. and 100 bars, 0.9690 g/cc, gives the amount of gas forced into the bomb. No corrections are made for the amount of gas required to deflect the gauge, fill the valve block, or fill the capillary tubing between gauge and volumometer, for the pressures on this part of the system are the same before and after the piston settings are read. The only correction that might be made is that for the volume of the capillary tubing between V-1 and the bomb. The tubing is of 0.100 in. outside diameter, 0.019 in. inside diameter, and 14 in. in length. This volume amounts to approximately 0.06 cc and is negligible in terms of the volume of the bombs (200 to 300 cc). Consequently these corrections were not made.

The density of gas at 0°C. and 100 bars in the volumometer was determined by measuring with the volumometer the quantity of gas required to bring a bomb at 0°C., of known volume, to a set of pressures and corresponding densities reported by Michels for 0°C. Michels gives values of densities for 0°C. for the pressure range 16.55 bars to 33.42 bars. The results of Michel's and others are reported in Amagat units, i.e. the ratio of the density of carbon dioxide to its density at 0°C. and 1 atmosphere pressure. In this paper, where densities are reported in g/cc, an Amagat unit is assumed to be 0.0019767 g/cc (Quinn and Jones, 1936, p. 35). Using this conversion factor, Amagat's density for carbon dioxide at 0°C. and 100 bars pressure is approximately 0.9775 g/cc. This differs sharply from the writer's present value of 0.9690. These grossly differing values are not as alarming as first appears. Amagat's value probably is somewhat in error; on the other hand, it seems likely that the writer's volumometer, though in an ice bath, was not exactly at 0°C. The piston of the volumometer projects from the ice bath to a driving screw, and some heat conducted down the piston may well hold the contents of the volumometer slightly above 0°C. The density of carbon dioxide changes very rapidly with temperature in this region, and if the volumometer were as much as 1°C. above 0°C. most of the difference between the two values would be accounted for. The exact conditions of the volumometer need not be precisely known, however. For the purpose of the present work, it need only be known that steady state conditions hold and that the CO_2 liquid at 100 bars pressure as it emerges from the volumometer has a density of 0.9690 g/cc. This was amply proved by repeated checks of the data of Michels and his co-workers.

The previously described method of measuring gas densities is a slow and tedious one, largely because of the sharp temperature changes which take place in both the pressure gauge and the volumometer as the CO_2 liquid vaporizes and condenses under the abrupt pressure changes involved. Consequently much time is spent waiting for temperature to equalize over the various parts of the apparatus external to the furnace.

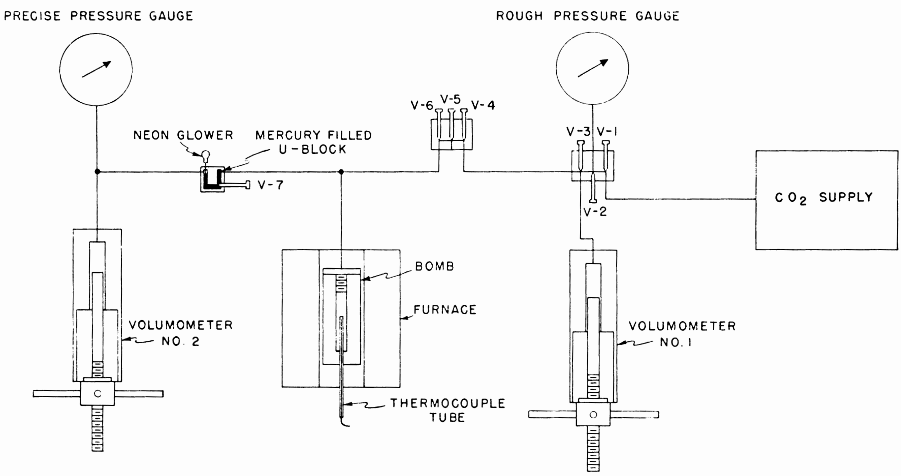


FIG. 3 SCHEMATIC DIAGRAM OF APPARATUS

Because of these difficulties, a second method was devised, the apparatus of which is shown in figure 3. This apparatus is designed to measure P and T on a constant quantity of gas under approximately constant volume conditions. As temperature and pressure changes affect the volume of a bomb, it is impossible to make measurements under precisely constant volume conditions.

The essential difference in this apparatus from that of figure 2 is in the use of an insulated needle connected with a neon glower to locate the surface of mercury in a U block. V-7 in the U block is closed and the piston in volumometer no. 1 is advanced until a quantity of gas, which is not measured, is introduced in the bomb. The piston in volumometer no. 2 is then advanced until the two pressure gauges are at approximately the same value. V-6 is next closed, V-7 opened, and volumometer no. 2 is adjusted so that the level of mercury is exactly at the tip of the insulated needle as indicated by the neon glower. The bomb is slowly heated and a plot of pressure versus temperature made. The piston in volumometer no. 2 is advanced for each reading to restore the level of mercury in the U block to its proper position at the tip of the insulated needle. By this method the contents of the bomb remain the same throughout the heating cycle, and the fluid required to deflect the pressure gauge, in this case kerosene, is supplied from the volumometer. No correction was made for compressibility of mercury in the U block, as this is negligible. Great care was exercised in the construction of the apparatus, particularly in construction of the T joint, where the capillary tubing from the bomb, the U block, and the loading apparatus meet, so that this part of the apparatus would be of minimum volume. Total volume of the tubing and connections between the bomb and the surface of the mercury is approximately 0.10 cc which contrasts favorably with the volume of the bomb, approximately 200 cc.

For each filling of this apparatus, the pressure measured at 150° C. can be used to find the density in Amagat units (A.U.) of the CO_2 at this pressure and 150° C. This information can be obtained from Michels' density-pressure data for the 150° C. isotherm. The density of the gas in the bomb can be then determined in g/cc by

$$d(g/cc) = d(A.U.)\ d_N(g/cc)$$

where

d_N is the gas density at N. T. P.

For CO_2, $d_N = 0.0019767$ g/cc.

For a fixed quantity of gas, the density will vary with T and P inversely as the bomb volume varies. Hence d for any pair of values of T_2 and P_2 can be determined from d(150°, P.) provided the thermal expansion and pressure dilation of the bomb are known.

The major advantage of the latter method of determining P-V-T relations is that it is unnecessary to know the volume of the bomb used in the measurements or to meter the amount of gas injected into the bomb. It is necessary, however, to have an accurate reference isotherm such as the 150° C. isotherm supplied by Michels. Michels' data, however, extend only to gas densities as low as 0.03706 g/cm and reference data at much lower densities are needed. These low density reference data were obtained by the first described method, that of injecting known quantities of gas into a bomb of known volume.

In both methods it is necessary to make corrections for thermal expansion and pressure dilation of the bomb. The thermal expansion correction is very straightforward and, for instance, with bombs of type 347 stainless steel, amounts to

20° – 100°C., 0.3576%
20° – 500°C., 2.520%
20° – 1000°C., 5.703%

Only an approximation can be made for the correction due to pressure dilation of the bomb.

Change in radius of the bomb under pressure was computed from the following formula:

$$\Delta r = \frac{a^2P}{(b^2-a^2)E}\left\{(1+\mu)\frac{b^2}{r} + (1-\mu)r\right\}$$

and at $r = a$

$$\Delta a = \frac{a^2P}{(b^2-a^2)E}\left\{(1+\mu)\frac{b^2}{a} + (1-\mu)a\right\}$$

where Δr is the change in internal radius, μ is Poisson's ratio 0.30, $E = 30X10^6$ p.s.i., P is internal pressure, a is internal radius and b is external radius. This formula is applicable to an infinitely long tube under pressure. In this particular case the ends of the bomb and the longitudinal stresses present will partially restrain deformation and the actual volume change will be somewhat less than computed. The total volume change of the bomb due to pressure has a maximum value of 0.084 percent per 1000 atmospheres, and as this is within the limits of error in reading the pressure gauges, further refinements were deemed unnecessary. It was assumed that Poisson's ratio and Young's modulus of the bomb metal remained approximately constant over the operating temperature. This is a fair approximation over much of the temperature range, but at the highest temperatures this must remain only an assumption.

RESULTS

Curves determined by simultaneous measurements of P and T were plotted for a large number of different d values in the bomb. In total, several thousand measurements were made. These were smoothed and corrected for bomb expansion to make the best isochore for each bomb filling. Isobars and isotherms were then constructed and smoothed graphically to make the best fit to the values taken from the isochores. Density values in g/cc were read directly from the isobaric plots. Tables of differences between adjacent values were then made up along the isobars and the last figure in the density value was adjusted to give smooth differences. These final values are the ones reported in the accompanying table 2 (p. 236ff.).

All the values in the accompanying table were determined, as indicated above, from the isochore data obtained by the second method described in this paper. However, the first and second methods described gave essentially identical results. The smoothed values obtained by the "constant volume" method, expressed to four places, are shown in the following table 1. These are compared with the direct values obtained by the volumometer.

TABLE 1
Comparison of Results from Constant Volume Method with Results by Volumometer

	25 bars		50 bars		75 bars	
T° C.	Volumometer	Constant volume	Volumometer	Constant volume	Volumometer	Constant volume
200	.02881	.0288				
300	.02326	.0233	.04682	.0468		
400	.01960	.0197	.03927	.0393	.05909	.0591
500	.01705	.0171	.03390	.0340	.05089	.0509
600	.01511	.0151	.03008	.0301	.04500	.0449
700	.01348	.0135	.02693	.0269	.04031	.0402
800	.01221	.0122	.02442	.0244	.03666	.0364
900	.01122	.0112	.02234	.0223		

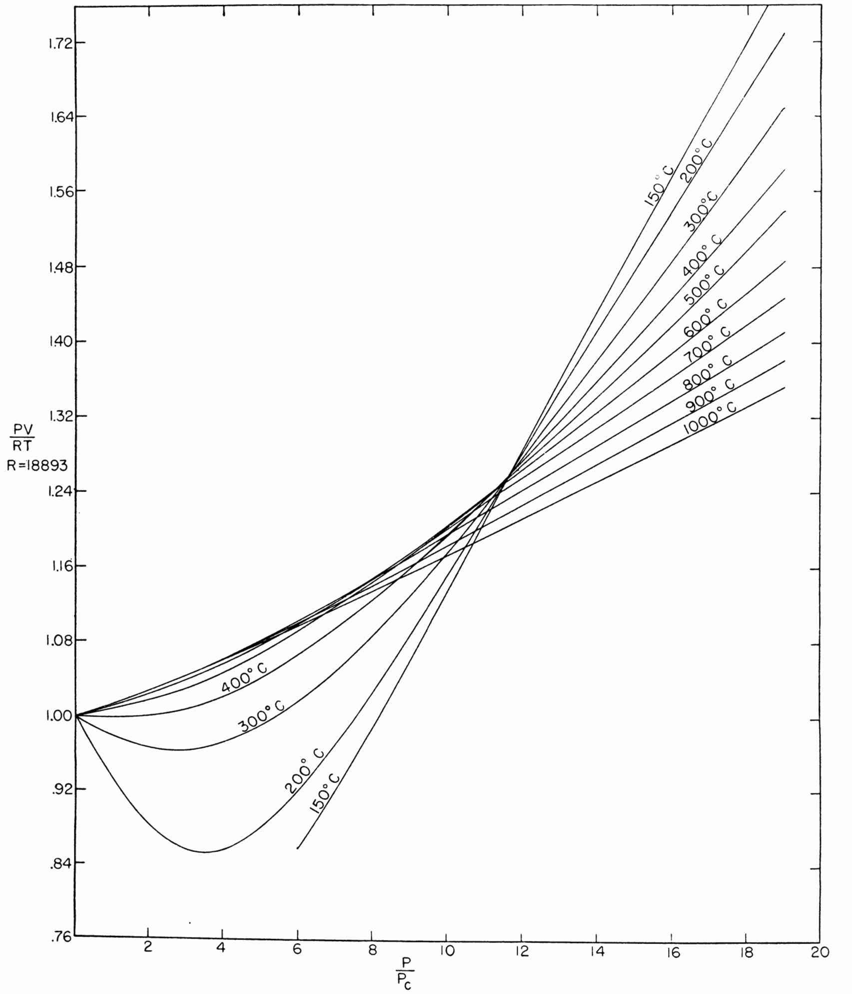


Fig. 4. Deviation from ideality of carbon dioxide plotted against the reduced pressure.

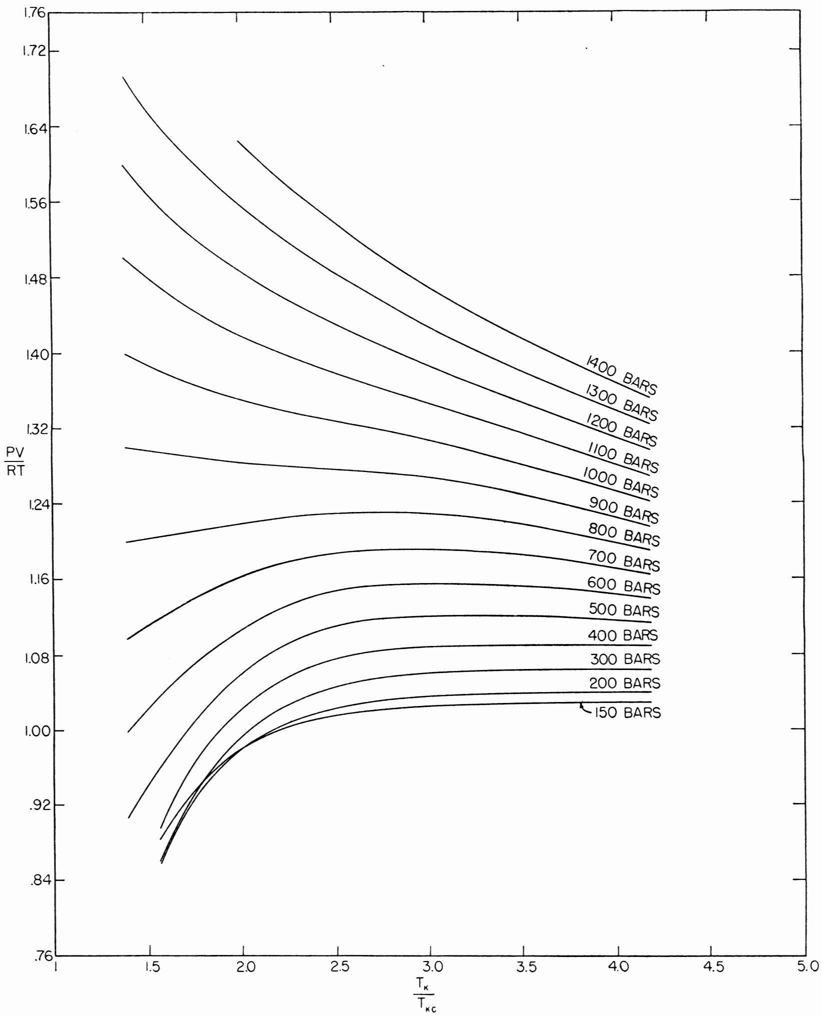


Fig. 5. Deviation from ideality of carbon dioxide plotted against reduced temperature.

The agreement between the two sets of results is satisfactory.

Little can be said about the accuracy of these measurements. Throughout the region where the present body of data overlaps that of Michels and of McCormack and Schneider, the two sets of data agree to 0.0001 g/cc or 0.2 percent, whichever is the larger. At high temperatures, the lack of any body of data for comparison and the possibility of reaction between bomb wall and gas makes all claims to accuracy somewhat meaningless. The writer is, furthermore, in the embarrassing position of having claimed accuracies at high temperatures in an earlier paper on P-V-T relations of water which later proved to be unjustifiable, largely because of reaction between the water gas and the bomb alloy. The reproducibility of the present set of data is high, and the smoothed values reported in the tables differ from the experimentally determined values by 0.4 percent or .0002 g/cc, whichever is the greater, for the largest changes introduced by the smoothing procedure.

The present results are summarized and presented in figure 4 and figure 5. In these figures the deviation from the ideal gas law is shown. In figure 4, the value PV/RT is plotted against the reduced pressure, P/Pc, where P is the P observed and Pc is the critical pressure of 73.82 bars. In figure 5, the value PV/RT is plotted against T/T_c where T is the temperature, on the Kelvin scale and Tc is the critical temperature, 304.2° K.

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Table 2
Density CO_2 in g/cc
Pressure in Bars

T°C.	25	50	75	100	150	200	250	300	350	400	450
0	.0601	.947	.954	.969	.997	1.0170	1.0350	1.0530	1.0670	1.0792	1.0900
10	.0561	.864	.891	.914	.950	.9770	1.0000	1.0190	1.0350	1.0502	1.0635
20	.0527	.1423	.810	.855	.901	.9335	.9600	.9832	1.0030	1.0200	1.0351
30	.0499	.1251	.655	.782	.850	.8887	.9190	.9460	.9685	.9882	1.0054
40	.0476	.1135	.2305	.638	.785	.8415	.8771	.9077	.9339	.9559	.9755
50	.0456	.1052	.1932	.3901	.705	.7855	.8347	.8687	.8990	.9233	.9451
60	.0437	.0984	.1726	.2868	.604	.7240	.7889	.8292	.8634	.8905	.9139
70	.0421	.0930	.1584	.2478	.504	.6605	.7379	.7882	.8270	.8575	.8821
80	.0405	.0883	.1469	.2215	.430	.5935	.6872	.7466	.7898	.8243	.8516
90	.0391	.0845	.1381	.2019	.373	.5325	.6359	.7040	.7522	.7909	.8212
100	.0378	.0810	.1305	.1877	.333	.4815	.5880	.6630	.7160	.7571	.7911
110	.0366	.0778	.1239	.1765	.304	.4378	.5443	.6230	.6805	.7250	.7613
120	.0354	.0749	.1187	.1673	.280	.4015	.5053	.5855	.6460	.6938	.7321
130	.0344	.0722	.1141	.1595	.262	.3718	.4718	.5517	.6129	.6642	.7048
140	.0334	.0697	.1094	.1525	.2465	.3470	.4419	.5200	.5824	.6352	.6771
150	.0325	.0674	.1054	.1461	.2337	.3267	.4151	.4925	.5549	.6079	.6501
160	.0316	.0653	.1018	.1403	.2229	.3089	.3918	.4680	.5293	.5822	.6253
170	.0308	.0633	.0985	.1352	.2136	.2925	.3720	.4447	.5070	.5587	.6025
180	.0301	.0616	.0954	.1303	.2050	.2805	.3553	.4252	.4867	.5377	.5820
190	.0294	.0601	.0925	.1259	.1972	.2693	.3407	.4070	.4677	.5185	.5628
200	.0288	.0586	.0898	.1220	.1900	.2591	.3271	.3907	.4491	.5006	.5443
210	.0281	.0571	.0873	.1184	.1839	.2497	.3149	.3757	.4327	.4830	.5269
220	.0275	.0556	.0851	.1151	.1780	.2411	.3033	.3621	.4172	.4673	.5107
230	.0269	.0542	.0829	.1120	.1726	.2333	.2927	.3494	.4030	.4517	.4956
240	.0263	.0529	.0808	.1092	.1675	.2260	.2831	.3380	.3896	.4370	.4810
250	.0257	.0518	.0788	.1065	.1629	.2192	.2743	.3274	.3773	.4237	.4672
260	.0252	.0507	.0770	.1040	.1586	.2130	.2663	.3179	.3660	.4111	.4540
270	.0246	.0496	.0752	.1017	.1546	.2073	.2588	.3089	.3554	.3994	.4414
280	.0242	.0486	.0736	.0994	.1507	.2020	.2518	.3003	.3455	.3886	.4293
290	.0237	.0477	.0721	.0972	.1470	.1970	.2450	.2925	.3364	.3786	.4178
300	.0233	.0468	.0707	.0951	.1434	.1923	.2388	.2850	.3279	.3691	.4072
310	.0229	.0459	.0693	.0930	.1402	.1879	.2330	.2781	.3200	.3600	.3975
320	.0225	.0451	.0679	.0910	.1372	.1837	.2276	.2716	.3127	.3514	.3885
330	.0221	.0443	.0667	.0892	.1344	.1798	.2226	.2653	.3057	.3433	.3800

TABLE 2 *(Continued)*

Density CO_2 in g/cc

Pressure in Bars

T°C.	500	600	700	800	900	1000	1100	1200	1300	1400
0	1.1024	1.1227	1.1405	1.1569	1.1698	1.1841	1.1990	1.2101	1.2211	1.2305
10	1.0759	1.0974	1.1167	1.1340	1.1485	1.1636	1.1788	1.1908	1.2022	1.2127
20	1.0482	1.0719	1.0928	1.1112	1.1272	1.1431	1.1586	1.1716	1.1835	1.1949
30	1.0200	1.0462	1.0689	1.0885	1.1060	1.1226	1.1386	1.1525	1.1650	1.1772
40	.9916	1.0204	1.0450	1.0659	1.0848	1.1022	1.1187	1.1335	1.1466	1.1595
50	.9630	.9945	1.0211	1.0434	1.0637	1.0819	1.0990	1.1146	1.1284	1.1419
60	.9340	.9686	.9973	1.0210	1.0427	1.0617	1.0795	1.0958	1.1104	1.1244
70	.9050	.9427	.9735	.9988	1.0218	1.0417	1.0603	1.0772	1.0926	1.1071
80	.8763	.9168	.9498	.9769	1.0010	1.0219	1.0413	1.0589	1.0750	1.0900
90	.8478	.8911	.9262	.9552	.9804	1.0023	1.0225	1.0409	1.0576	1.0731
100	.8195	.8655	.9038	.9337	.9600	.9830	1.0041	1.0231	1.0405	1.0565
110	.7915	.8402	.8797	.9125	.9398	.9639	.9860	1.0056	1.0236	1.0403
120	.7641	.8159	.8570	.8916	.9199	.9452	.9683	.9884	1.0070	1.0244
130	.7380	.7922	.8347	.8710	.9003	.9268	.9509	.9715	.9907	1.0087
140	.7132	.7693	.8134	.8507	.8812	.9087	.9338	.9549	.9747	.9933
150	.6889	.7469	.7928	.8309	.8628	.8912	.9171	.9386	.9590	.9781
160	.6650	.7255	.7727	.8117	.8450	.8742	.9008	.9228	.9436	.9631
170	.6424	.7051	.7533	.7933	.8277	.8577	.8848	.9074	.9287	.9488
180	.6211	.6853	.7347	.7755	.8109	.8417	.8692	.8924	.9141	.9347
190	.6014	.6665	.7169	.7585	.7947	.8262	.8539	.8777	.8999	.9208
200	.5833	.6485	.6998	.7423	.7789	.8111	.8391	.8634	.8860	.9072
210	.5658	.6315	.6834	.7266	.7636	.7964	.8246	.8495	.8725	.8939
220	.5497	.6153	.6675	.7113	.7486	.7821	.8105	.8359	.8594	.8809
230	.5347	.5998	.6525	.6965	.7341	.7680	.7969	.8226	.8465	.8683
240	.5203	.5850	.6381	.6823	.7200	.7544	.7836	.8097	.8340	.8560
250	.5064	.5709	.6244	.6687	.7065	.7411	.7707	.7971	.8217	.8441
260	.4929	.5573	.6111	.6556	.6935	.7282	.7582	.7849	.8098	.8326
270	.4798	.5443	.5983	.6430	.6810	.7157	.7460	.7730	.7982	.8213
280	.4673	.5320	.5859	.6307	.6688	.7036	.7342	.7613	.7869	.8103
290	.4556	.5202	.5740	.6190	.6570	.6918	.7227	.7500	.7758	.7995
300	.4444	.5088	.5626	.6076	.6457	.6805	.7115	.7390	.7651	.7890
310	.4338	.4978	.5517	.5966	.6347	.6695	.7007	.7282	.7547	.7787
320	.4238	.4873	.5412	.5860	.6241	.6589	.6902	.7178	.7445	.7686
330	.4143	.4772	.5310	.5757	.6139	.6486	.6800	.7077	.7346	.7588

TABLE 2 (*Continued*)

Density CO_2 in g/cc

Pressure in Bars

T°C.	25	50	75	100	150	200	250	300	350	400	450
340	.0217	.0435	.0655	.0874	.1318	.1761	.2131	.2595	.2991	.3357	.3716
350	.0213	.0427	.0643	.0857	.1292	.1725	.2137	.2540	.2928	.3284	.3637
360	.0210	.0420	.0631	.0842	.1268	.1690	.2095	.2489	.2867	.3214	.3561
370	.0206	.0413	.0620	.0828	.1245	.1657	.2053	.2440	.2809	.3150	.3488
380	.0203	.0406	.0610	.0814	.1222	.1625	.2015	.2394	.2754	.3090	.3420
390	.0200	.0400	.0600	.0801	.1201	.1594	.1978	.2350	.2701	.3033	.3355
400	.0197	.0393	.0591	.0788	.1178	.1565	.1942	.2308	.2650	.2979	.3293
410	.0194	.0387	.0582	.0774	.1158	.1538	.1909	.2267	.2603	.2928	.3233
420	.0191	.0382	.0573	.0761	.1139	.1512	.1876	.2227	.2557	.2878	.3172
430	.0188	.0376	.0564	.0749	.1121	.1487	.1845	.2189	.2513	.2830	.3117
440	.0185	.0370	.0556	.0737	.1103	.1464	.1815	.2152	.2471	.2784	.3065
450	.0183	.0365	.0547	.0726	.1086	.1441	.1786	.2117	.2431	.2738	.3019
460	.0180	.0360	.0539	.0715	.1070	.1419	.1758	.2083	.2393	.2695	.2974
470	.0178	.0355	.0531	.0705	.1054	.1396	.1732	.2050	.2356	.2652	.2929
480	.0175	.0350	.0524	.0695	.1038	.1374	.1706	.2020	.2320	.2612	.2886
490	.0173	.0345	.0516	.0686	.1023	.1351	.1682	.1991	.2286	.2573	.2843
500	.0171	.0340	.0509	.0677	.1009	.1339	.1658	.1962	.2253	.2536	.2802
510	.0168	.0336	.0502	.0669	.0995	.1319	.1634	.1934	.2202	.2501	.2762
520	.0166	.0331	.0496	.0661	.0982	.1301	.1611	.1907	.2191	.2467	.2724
530	.0164	.0327	.0489	.0652	.0970	.1284	.1589	.1882	.2161	.2434	.2686
540	.0162	.0323	.0483	.0644	.0957	.1267	.1567	.1857	.2132	.2401	.2650
550	.0160	.0319	.0477	.0635	.0945	.1250	.1546	.1833	.2104	.2370	.2614
560	.0158	.0315	.0471	.0628	.0933	.1234	.1526	.1809	.2077	.2339	.2580
570	.0157	.0311	.0465	.0619	.0921	.1219	.1506	.1786	.2051	.2310	.2548
580	.0155	.0308	.0460	.0612	.0909	.1194	.1487	.1763	.2026	.2282	.2517
590	.0153	.0304	.0454	.0604	.0898	.1189	.1468	.1742	.2002	.2254	.2487
600	.0151	.0301	.0449	.0597	.0887	.1174	.1450	.1722	.1979	.2227	.2457
610	.0149	.0297	.0444	.0590	.0876	.1160	.1433	.1702	.1957	.2201	.2428
620	.0148	.0294	.0439	.0583	.0866	.1146	.1416	.1682	.1935	.2175	.2400
630	.0146	.0291	.0434	.0576	.0856	.1133	.1399	.1663	.1914	.2150	.2373
640	.0144	.0287	.0429	.0570	.0847	.1120	.1383	.1644	.1893	.2126	.2346
650	.0143	.0284	.0424	.0563	.0837	.1107	.1368	.1626	.1872	.2102	.2321
660	.0141	.0281	.0419	.0557	.0828	.1095	.1352	.1608	.1852	.2078	.2297
670	.0139	.0278	.0415	.0551	.0819	.1084	.1337	.1590	.1832	.2055	.2273

TABLE 2 *(Continued)*
Density CO_2 in g/cc
Pressure in Bars

T°C.	500	600	700	800	900	1000	1100	1200	1300	1400
340	.4053	.4676	.5212	.5658	.6040	.6387	.6702	.6979	.7249	.7493
350	.3967	.4583	.5117	.5563	.5945	.6291	.6607	.6884	.7155	.7400
360	.3885	.4494	.5025	.5470	.5853	.6199	.6515	.6792	.7063	.7310
370	.3809	.4409	.4935	.5381	.5764	.6110	.6425	.6702	.6974	.7222
380	.3736	.4327	.4848	.5295	.5678	.6024	.6338	.6615	.6887	.7135
390	.3667	.4248	.4765	.5211	.5595	.5940	.6254	.6531	.6803	.7051
400	.3601	.4172	.4684	.5130	.5514	.5859	.6173	.6450	.6722	.6969
410	.3538	.4099	.4605	.5051	.5436	.5780	.6094	.6372	.6643	.6889
420	.3478	.4029	.4530	.4974	.5361	.5703	.6017	.6296	.6566	.6811
430	.3420	.3963	.4459	.4900	.5288	.5629	.5942	.6222	.6492	.6735
440	.3364	.3900	.4391	.4828	.5217	.5557	.5869	.6151	.6420	.6662
450	.3311	.3840	.4325	.4758	.5147	.5487	.5798	.6081	.6350	.6591
460	.3259	.3782	.4260	.4690	.5079	.5419	.5729	.6013	.6281	.6522
470	.3209	.3725	.4197	.4624	.5013	.5353	.5662	.5947	.6214	.6455
480	.3161	.3670	.4136	.4560	.4949	.5289	.5596	.5882	.6148	.6390
490	.3114	.3617	.4077	.4498	.4886	.5226	.5532	.5819	.6084	.6326
500	.3068	.3565	.4020	.4438	.4824	.5165	.5470	.5757	.6021	.6264
510	.3024	.3515	.3965	.4381	.4764	.5105	.5409	.5696	.5959	.6204
520	.2982	.3468	.3913	.4325	.4705	.5046	.5350	.5637	.5899	.6145
530	.2942	.3422	.3863	.4271	.4648	.4988	.5293	.5579	.5841	.6087
540	.2903	.3378	.3815	.4218	.4593	.4932	.5237	.5522	.5784	.6031
550	.2866	.3335	.3768	.4167	.4539	.4877	.5182	.5467	.5728	.5975
560	.2830	.3293	.3723	.4117	.4487	.4823	.5129	.5413	.5673	.5921
570	.2795	.3253	.3679	.4068	.4436	.4770	.5077	.5360	.5620	.5868
580	.2761	.3214	.3636	.4021	.4386	.4719	.5027	.5308	.5568	.5816
590	.2726	.3176	.3594	.3976	.4337	.4669	.4978	.5257	.5517	.5765
600	.2693	.3139	.3553	.3932	.4289	.4620	.4929	.5208	.5467	.5715
610	.2661	.3103	.3513	.3889	.4242	.4572	.4881	.5160	.5418	.5666
620	.2630	.3068	.3474	.3847	.4196	.4525	.4834	.5113	.5370	.5618
630	.2601	.3034	.3437	.3806	.4151	.4479	.4788	.5067	.5323	.5570
640	.2573	.3001	.3401	.3767	.4108	.4435	.4743	.5022	.5277	.5523
650	.2546	.2969	.3366	.3729	.4066	.4392	.4699	.4978	.5232	.5477
660	.2520	.2938	.3331	.3692	.4026	.4350	.4655	.4935	.5187	.5432
670	.2494	.2907	.3297	.3656	.3987	.4309	.4612	.4893	.5144	.5388

Table 2 *(Continued)*
Density CO_2 in g/cc
Pressure in Bars

T°C.	25	50	75	100	150	200	250	300	350	400	450
680	.0138	.0275	.0411	.0545	.0810	.1072	.1323	.1572	.1813	.2033	.2250
690	.0136	.0272	.0407	.0540	.0802	.1060	.1309	.1555	.1794	.2012	.2227
700	.0135	.0269	.0402	.0534	.0794	.1048	.1296	.1538	.1767	.1992	.2205
710	.0133	.0266	.0398	.0529	.0786	.1037	.1283	.1521	.1749	.1972	.2184
720	.0132	.0263	.0394	.0523	.0778	.1026	.1271	.1505	.1732	.1952	.2163
730	.0131	.0261	.0390	.0518	.0770	.1015	.1258	.1489	.1715	.1933	.2142
740	.0130	.0259	.0386	.0513	.0762	.1005	.1246	.1474	.1698	.1914	.2121
750	.0128	.0256	.0382	.0508	.0754	.0995	.1233	.1460	.1682	.1895	.2101
760	.0127	.0253	.0378	.0503	.0746	.0985	.1221	.1445	.1666	.1876	.2082
770	.0126	.0251	.0374	.0498	.0739	.0975	.1208	.1431	.1649	.1858	.2063
780	.0125	.0249	.0371	.0493	.0732	.0966	.1196	.1418	.1634	.1840	.2044
790	.0124	.0246	.0367	.0488	.0725	.0957	.1184	.1404	.1618	.1823	.2026
800	.0122	.0244	.0364	.0484	.0718	.0948	.1173	.1391	.1603	.1806	.2009
810	.0121	.0242	.0360	.0479	.0712	.0939	.1163	.1378	.1598	.1790	.1992
820	.0120	.0239	.0357	.0475	.0705	.0931	.1153	.1365	.1574	.1774	.1974
830	.0119	.0237	.0354	.0471	.0698	.0922	.1143	.1352	.1560	.1759	.1957
840	.0118	.0235	.0351	.0466	.0693	.0914	.1133	.1340	.1546	.1744	.1940
850	.0117	.0233	.0348	.0462	.0686	.0906	.1123	.1328	.1532	.1729	.1924
860	.0116	.0231	.0345	.0458	.0680	.0898	.1113	.1316	.1519	.1714	.1907
870	.0115	.0228	.0342	.0454	.0674	.0890	.1103	.1305	.1506	.1700	.1891
880	.0114	.0226	.0339	.0450	.0669	.0883	.1093	.1294	.1493	.1685	.1874
890	.0113	.0224	.0336	.0446	.0663	.0875	.1083	.1283	.1481	.1671	.1858
900	.0112	.0223	.0333	.0442	.0657	.0868	.1073	.1272	.1468	.1657	.1841
910	.0111	.0221	.0330	.0438	.0652	.0861	.1064	.1261	.1455	.1642	.1825
920	.0110	.0219	.0327	.0434	.0646	.0854	.1054	.1251	.1442	.1629	.1810
930	.0109	.0217	.0324	.0429	.0641	.0846	.1044	.1241	.1429	.1615	.1794
940	.0108	.0215	.0322	.0425	.0635	.0839	.1035	.1231	.1416	.1602	.1779
950	.0107	.0213	.0319	.0422	.0630	.0832	.1026	.1222	.1404	.1589	.1764
960	.0106	.0211	.0317	.0419	.0624	.0825	.1018	.1212	.1392	.1577	.1750
970	.0106	.0209	.0315	.0415	.0619	.0817	.1009	.1203	.1380	.1564	.1736
980	.0105	.0208	.0312	.0412	.0614	.0810	.1001	.1193	.1370	.1552	.1723
990	.0104	.0207	.0309	.0409	.0609	.0804	.0993	.1184	.1360	.1540	.1710
1000	.0103	.0205	.0307	.0407	.0604	.0797	.0986	.1174	.1350	.1527	.1697

TABLE 2 *(Continued)*

Density CO_2 in g/cc

Pressure in Bars

T°C.	500	600	700	800	900	1000	1100	1200	1300	1400
680	.2469	.2877	.3264	.3621	.3949	.4269	.4570	.4851	.5102	.5345
690	.2444	.2848	.3232	.3587	.3912	.4230	.4529	.4810	.5060	.5303
700	.2420	.2819	.3201	.3553	.3876	.4192	.4489	.4770	.5019	.5262
710	.2396	.2791	.3170	.3520	.3841	.4155	.4450	.4730	.4979	.5221
720	.2372	.2764	.3140	.3487	.3807	.4119	.4411	.4691	.4940	.5181
730	.2349	.2737	.3110	.3455	.3774	.4084	.4374	.4653	.4901	.5142
740	.2326	.2711	.3081	.3424	.3742	.4049	.4337	.4615	.4863	.5104
750	.2303	.2685	.3052	.3393	.3711	.4015	.4301	.4578	.4826	.5066
760	.2281	.2660	.3024	.3363	.3680	.3982	.4266	.4542	.4790	.5029
770	.2259	.2636	.2996	.3334	.3649	.3949	.4232	.4506	.4754	.4993
780	.2238	.2613	.2969	.3305	.3619	.3917	.4199	.4471	.4719	.4957
790	.2217	.2590	.2942	.3277	.3589	.3886	.4166	.4437	.4685	.4922
800	.2197	.2567	.2916	.3249	.3560	.3856	.4134	.4403	.4651	.4888
810	.2178	.2545	.2890	.3222	.3531	.3826	.4102	.4370	.4618	.4854
820	.2159	.2523	.2865	.3195	.3503	.3796	.4071	.4338	.4585	.4821
830	.2141	.2502	.2841	.3169	.3475	.3767	.4041	.4306	.4553	.4788
840	.2123	.2481	.2818	.3143	.3448	.3738	.4011	.4275	.4522	.4756
850	.2105	.2461	.2796	.3118	.3422	.3710	.3981	.4245	.4491	.4724
860	.2088	.2441	.2774	.3093	.3396	.3683	.3952	.4215	.4461	.4693
870	.2071	.2422	.2752	.3069	.3370	.3656	.3923	.4186	.4431	.4662
880	.2054	.2403	.2731	.3045	.3345	.3630	.3895	.4157	.4402	.4632
890	.2037	.2384	.2710	.3022	.3320	.3604	.3868	.4129	.4373	.4602
900	.2020	.2365	.2689	.2999	.3296	.3579	.3841	.4102	.4345	.4573
910	.2004	.2346	.2669	.2977	.3272	.3554	.3815	.4075	.4317	.4544
920	.1988	.2328	.2649	.2955	.3248	.3529	.3790	.4048	.4289	.4516
930	.1972	.2310	.2630	.2934	.3225	.3505	.3765	.4022	.4262	.4488
940	.1956	.2293	.2611	.2913	.3202	.3481	.3741	.3996	.4235	.4461
950	.1941	.2276	.2592	.2893	.3180	.3458	.3717	.3971	.4208	.4434
960	.1926	.2259	.2574	.2873	.3159	.3435	.3694	.3946	.4182	.4408
970	.1911	.2242	.2556	.2853	.3138	.3412	.3671	.3921	.4156	.4382
980	.1896	.2226	.2538	.2834	.3118	.3390	.3648	.3897	.4130	.4356
990	.1882	.2210	.2520	.2815	.3098	.3368	.3625	.3873	.4104	.4330
1000	.1868	.2194	.2503	.2796	.3079	.3346	.3603	.3850	.4078	.4305