Thermodynamic Data for Carbon Dioxide at High Pressure and Temperature

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During a research program undertaken to investigate the thermodynamic properties of certain mixtures containing carbon dioxide as one component, it was discovered that very few data for pure carbon dioxide were available at temperatures above 150° C. Table I lists recent work on the thermodynamic properties of this vapor. At the period of compilation of these data, the only information available for temperatures above 150° C. was that provided by Sweigert, Weber, and Allen (*44*) [which had been questioned by Granet and Kass (*6*)], the original NBS-NACA values of properties at zero pressure only (*31*), and the experimental investigation of MacCormack and Schneider (*14*) to 50-atm. pressure from which thermodynamic functions were computed (*15*) using the same basic spectroscopic data (*8*) as those used by the National Bureau of Standards. It was therefore decided to tabulate values at much closer temperature and pressure intervals than the data then available, and to extend the tabulation to 200-atm. pressure. This led to the work described below.

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ENTHALPY DATA

If the virial equation

$$PV = A + BP = CP^2 + DP^3 + \ldots \quad (1)$$

is a valid equation of state for the gas, then it is easily shown that the general thermodynamic relation

$$H(P,T) = \int_{T_0}^{T} Cp(0,T)dT + \int_{0}^{P} [V - T(\partial V/\partial T)_p]dP$$

Table I. Some Recent Work on Thermodynamic Properties of Carbon Dioxide

Year	Author(s)	Ref.	Function(s)	Temp., Range, °C.	Pressure Range, Atm.
1935	Michels, A., Michels, C.	(*24*)	PV	0–150	16–250
1935	Michels, A., others	(*26*)	PV	0–150	70–3000
1936	Quinn, E. L., Jones, C. L.	(*38*)	H,S,Cp, etc.	Misc.	Misc.
1937	Michels, A., others	(*25,29*)	PV	0–150	18–3117
1937	Michels, A., others	(*21*)	PV	2.85–40.08	36.32–98.45
1937	Michels, A., others	(*20*)	H,S,etc.	25–150[a]	0–600 amagats
1939	Deming, W. E., Deming, L. S.	(*3*)	f/p	0(5)30(10)50(25)150	1(25)100(50)200..2500
1942	Ellenwood, F. O., others	(*5*)	C_p,C_v	0–4000° F.	0–10000 p.s.i.a.
1942	Maron, S. H., Turnbull, D.	(*16*)	. . .	137,198,258	1000
1942	Meyers, C. H.	(*19*)	P,V	Critical temp.	. . .
1942	Roebuck, J. R., others	(*40*)	. . .	−75(25)0(10)100(25)150(50)300	1–200
1942	Smallwood, J. C.	(*43*)	C_v	. . .	. . .
1944	Reamer, H. H., others	(*39*)	P,V,T	100(60)460° F.	0–10000 p.s.i.a.
1946	N.D.R.C. Summ. Tech. Rep.	(*32*)			
1946	Sweigert, R. L., others	(*44*)	H,S,V	75–1800° F.	0.15–3000 p.s.i.a.
1948	Gratch, S.	(*9*)	Review	0–150	0–3000
1948	de Groot, S. R., Michels, A.	(*10*)	μ,C_p	25–150[a]	0–2000
1948	Michels, A., de Groot, S. R.	(*22*)	H,S,C_p, etc.	25–150[a]	1–600
1948	Michels, A., de Groot, S. R.	(*23*)	H,S,PV, etc.	25–150[a]	1–2000
1949	Gratch, S.	(*8*)	C_p,etc.	100(misc.) 5000° R.	0
1949	Oishi, J.	(*33*)	P,V,T	0,100	0.57 to 1.23
1950	Gratch, S.	(*7*)	C_p	100(misc.) 5000° R.	0
1950	Huggill, J. A. W., others	(*11*)	H,S,V	−80(10)150	1–3000
1950	MacCormack, K. E., Schneider, W. G.	(*14*)	P,V,T	0(50)200(100)600	0–50
1950	MacCormack, K. E., Schneider, W. G.	(*15*)	H,S,Cp,etc.	0(50)200(100)600	0(10)50 and 1
1950	Michels, A., Stryland, J. C.	(*27*)	C_v	20–40	140 to 425 amagats
1950	Michels, A., others	(*28*)	Vapor pressure	−56 to 3	5–37
1950	N.B.S.-N.A.C.A. Tables	(*31*)	H,S,C_p,etc.	60(10)800(50) 2700° K.	0
1951	Kendall, B. J., Sage, B. H.	(*12*)	P,V,T	40–460° F.	200–100000 p.s.i.a.
1951	Schneider, W. G., Chynometh, A.	(*41*)	C_v	Critical temp.	. . .
1952	Granet, I., Kass, P.	(*6*)	C_p	100–1500° F.	0–2000 p.s.i.a.
1952	Masi, J. F., Petkof, B.	(*18*)	C_p	−30,0,50,90	0.5, 1,1.5
1952	Schrock, V. E.	(*42*)	C_p	35–350	1–67
1952	Wentorf, R. H., Jr.	(*45*)	P,V,T	31.02–31.10	72.723–72.974
1953	Price, D.	(*36*)	H,S,PV,Cp,etc.	0–1000	0–40 amagats (< 100)
1953	Woolley, H. W.	(*46*)	C_p/C_v	23.8	0–22.22
1954	Kennedy, G. C.	(*13*)	P,V,T	0(10)1000° K.	25–1400 bars
1954	Masi, J. F.	(*17*)	C_p, review	250–1500° K.	1
1954	Price, D.	(*37*)	H,S,PV,C_p,etc.	100(50)500(100)1000	50–1400 bars
1954	Woolley, H. W.	(*47*)	H,S,C_p	50(10)1000(50)1500(100)5000° K.	0
1955	N.B.S.	(*30*)	H,S,C_p,etc.	50(10)1000(50)1500(100)5000° K.	0–100
1955	Pfefferle, W. C., others	(*34*)	P,V,T	30	3.684–53.633
1955	Price, D.	(*35*)	P,V,H,S	100(50)500(100)1000	50–1400 bars
1956	Baker, H. W.	(*1*)	H	−140	−1400 p.s.i.a.
1956	Din, F., ed.	(*4*)	H,S,V,etc.	−80(10)150,etc.	0.5–3000
1956	Wentorf, R. H., Jr.	(*45*)	P,V,T	31.02–31.10	72.723–72.974
1957	Cook, D.	(*2*)	P,V,T	−60 to 30	0.5–2.5
1957	This work	. . .	H,V	150(10)650	1–200

[a]Tabulated principally at 25° C. intervals.

reduces to

$$H(P,T) = H(0,T) + (B - TdB/dT)P + (C - TdC/dT)P^2/2 + (D - TdD/dT)P^3/3 + \dots \quad (2)$$

so that, from a knowledge of the zero pressure function $H(0,T)$, the virial coefficients and their temperature derivatives, the enthalpy at any pressure, P, and temperature, T, can readily be computed. The actual form used for the computation of the enthalpy data was

$$H(P,T) = H(0,T) + (B - TdB/dT)P - c \quad (3)$$

i.e., it has been assumed that all virial coefficients higher than the second are negligible. This assumption was postulated by Schneider (*14*) from experimental work and has also been shown to be valid by analysis of a few compressibility measurements made by the author in a similar pressure and temperature range. In Equation 3, c is a correction factor inserted so that the zero of enthalpy occurs at 0° C. and 1 atm.

$$c = \int_0^1 \{V - T(\partial V/\partial T)_p\} dP \text{ at } T = T_0 = 273.16^\circ\text{K}.$$

According to MacCormack and Schneider (*15*), $c = -12.53$ cal. per mole.

The zero pressure data of Gratch (*8*) as tabulated by Woolley (*31*) have been interpolated to give values of $H(0,T)$ for every 10° from 150° to 650° C. Values of the function $B - TdB/dT$ were then determined for temperatures of 150°, 200°, 300°, 400°, 500°, and 600° C. by fitting the data of MacCormack and Schneider (*15*) to Equation 3. Values of $B - TdB/dT$ for all other temperatures were found by interpolation of these values. The enthalpy function $H(P,T)$ was then calculated for all pressures and temperatures by applying Equation 3. These values are reproduced in Table II.

The data of Table II are compared with other work in Table III. Despite the numerous tabulations of thermodynamic functions listed in Table I, only MacCormack and Schneider listed zero pressure values in 1952, apart from the source values (*31*). The comparison in Table III for zero pressure shows that good agreement in the data is obtained.

The agreement of the data for higher pressures is fairly satisfactory except possibly for the highest pressures at 150° C. The divergence in values here can be taken as indicative of the uncertainty existing in the virial coefficients and shows that high

Table II. Enthalpy of Carbon Dioxide

(Units: Calories per mole. Enthalpy zero, 0° C., 1 atm.)

T., °C.	Pressure, Atmospheres									
	0	1	2	3	4	5	10	15	20	25	30
150	1415.0	1410.1	1405.2	1400.3	1395.4	1390.5	1365.9	1341.4	1316.8	1292.3	1267.8
160	1515.9	1511.3	1506.6	1502.0	1497.3	1492.7	1469.4	1446.1	1442.9	1399.6	1376.3
170	1617.6	1613.2	1608.8	1604.3	1599.9	1595.5	1573.3	1551.2	1529.0	1506.9	1484.7
180	1720.1	1715.9	1711.7	1707.5	1703.3	1699.1	1678.0	1656.9	1635.8	1614.8	1593.7
190	1823.4	1819.4	1815.4	1811.4	1807.3	1803.3	1783.2	1763.1	1743.1	1723.0	1702.9
200	1927.4	1923.6	1919.8	1915.9	1912.1	1908.3	1889.1	1869.9	1850.7	1831.6	1812.4
210	2032.2	2028.5	2024.9	2021.2	2017.6	2013.9	1995.7	1977.4	1959.2	1940.9	1922.6
220	2137.7	2134.2	2130.7	2127.2	2123.7	2120.3	2102.9	2085.5	2068.1	2050.7	2033.3
230	2243.9	2240.6	2237.3	2233.9	2230.6	2227.3	2210.7	2194.1	2177.6	2161.0	2144.4
240	2350.9	2347.7	2344.5	2341.4	2338.2	2335.0	2319.2	2303.4	2287.5	2271.7	2255.9
250	2458.5	2455.5	2452.4	2449.4	2446.4	2443.3	2428.2	2413.0	2397.9	2382.8	2367.6
260	2566.8	2563.9	2561.0	2558.0	2555.1	2552.2	2537.7	2523.2	2508.6	2494.1	2479.6
270	2675.7	2672.9	2670.1	2667.3	2664.6	2661.8	2647.8	2633.9	2620.0	2606.1	2592.1
280	2785.3	2782.6	2779.9	2777.3	2774.6	2771.9	2785.6	2745.2	2731.8	2718.4	2705.7
290	2895.5	2893.0	2890.4	2887.8	2885.3	2882.7	2869.9	2857.1	2844.3	2831.5	2818.7
300	3006.5	3004.0	3001.5	2999.1	2996.6	2994.1	2981.8	2969.5	2957.2	2944.9	2932.5
310	3117.9	3115.5	3113.1	3110.8	3108.4	3106.0	3094.0	3082.1	3070.2	3058.2	3046.3
320	3230.0	3227.7	3225.5	3223.2	3220.9	3218.6	3207.1	3195.7	3184.2	3172.7	3161.3
330	3342.7	3340.5	3338.3	3336.1	3333.9	3331.7	3320.7	3309.7	3298.8	3287.8	3276.8
340	3455.8	3453.7	3451.6	3449.4	3447.3	3445.2	3434.7	3424.1	3413.6	3403.1	3392.5
350	3569.6	3567.6	3565.5	3563.5	3561.5	3559.5	3549.4	3539.3	3529.2	3519.1	3509.0
360	3683.6	3681.7	3679.7	3677.8	3675.9	3673.9	3664.2	3654.5	3644.8	3635.1	3625.4
370	3798.5	3796.6	3794.8	3792.9	3791.1	3789.2	3779.9	3770.6	3761.3	3752.0	3742.7
380	3914.1	3912.3	3910.5	3908.9	3906.9	3905.1	3896.2	3887.2	3878.3	3869.4	3860.4
390	4030.7	4029.0	4027.3	4025.6	4023.9	4022.2	4013.6	4005.0	3996.5	3987.9	3979.3
400	4147.4	4145.7	4144.1	4142.5	4140.8	4139.2	4131.0	4122.8	4114.5	4106.3	4098.1
410	4264.3	4262.7	4261.1	4259.5	4258.0	4256.4	4248.5	4240.6	4232.8	4224.9	4217.0
420	4381.8	4380.3	4378.8	4377.3	4375.8	4374.3	4366.8	4359.3	4351.7	4344.2	4336.7
430	4499.9	4498.5	4497.0	4495.6	4494.2	4492.7	4485.5	4478.3	4471.1	4463.9	4456.7
440	4619.4	4618.0	4616.6	4615.2	4613.8	4612.5	4605.6	4598.7	4591.7	4584.8	4577.9
450	4737.9	4736.6	4735.2	4733.9	4732.6	4731.3	4724.7	4718.0	4711.4	4704.8	4698.2
460	4856.9	4855.7	4854.4	4853.1	4851.9	4850.6	4844.3	4837.9	4831.6	4825.3	4818.9
470	4976.5	4975.3	4974.1	4972.9	4971.7	4970.5	4964.4	4958.3	4952.3	4946.2	4940.2
480	5096.7	5095.5	5094.3	5093.2	5092.0	5090.9	5085.1	5079.3	5073.5	5067.7	5061.9
490	5211.9	5210.8	5209.7	5208.6	5207.5	5206.4	5200.8	5195.3	5189.7	5184.2	5178.6
500	5338.6	5337.5	5336.4	5335.4	5334.3	5333.2	5327.9	5322.6	5317.3	5312.0	5307.0
510	5459.9	5458.9	5457.9	5456.9	5455.9	5454.8	5449.8	5444.7	5430.7	5434.6	5429.5
520	5582.6	5581.7	5580.7	5579.7	5578.7	5577.8	5572.9	5568.1	5563.3	5558.4	5553.6
530	5705.5	5704.5	5703.6	5702.7	5701.8	5700.9	5696.3	5691.7	5687.1	5682.5	5677.9
540	5828.1	5827.3	5826.4	5825.5	5824.6	5823.8	5819.4	5815.0	5810.6	5806.2	5801.8
550	5951.4	5950.6	5949.8	5948.9	5948.1	5947.3	5943.1	5938.9	5934.7	5930.6	5926.4
560	6075.1	6074.3	6073.5	6072.7	6071.9	6071.1	6067.2	6063.2	6059.2	6055.3	6051.3
570	6199.1	6198.4	6197.6	6196.9	6196.1	6195.4	6191.6	6187.9	6184.1	6180.4	6176.6
580	6323.6	6322.9	6322.1	6321.4	6320.7	6320.0	6316.5	6312.9	6309.4	6505.8	6302.3
590	6448.4	6447.7	6447.0	6446.3	6445.7	6445.0	6441.7	6438.3	6435.0	6431.6	6428.3
600	6573.5	6572.9	6572.2	6571.6	6571.0	6570.3	6567.2	6564.0	6560.9	6557.7	6554.5
610	6699.1	6698.5	6697.9	6697.3	6696.7	6696.1	6693.1	6690.2	6687.2	6684.3	6681.3
620	6824.9	6824.3	6823.8	6823.2	6822.6	6822.1	6819.3	6816.6	6813.8	6811.0	6808.3
630	6951.1	6950.6	6950.1	6949.6	6949.0	6948.5	6945.9	6943.4	6940.8	6938.2	6935.6
640	7077.8	7077.4	7076.9	7076.4	7075.9	7075.4	7073.0	7070.6	7068.2	7065.8	7063.4
650	7204.5	7204.1	7203.6	7203.2	7202.8	7202.3	7200.1	7197.9	7195.6	7193.4	7191.2

T., °C.	35	40	45	50	60	70	80	90	100	110	125	150	175	200
150	1243.2	1218.7	1194.2	1169.6	1120	1071	1022	973	924	875	802	679	556	433
160	1353.1	1329.8	1306.5	1283.3	1237	1190	1144	1097	1051	1004	934	818	702	585
170	1462.6	1440.4	1414.2	1396.1	1352	1307	1263	1219	1175	1064	1004	953	842	731
180	1572.6	1551.5	1530.5	1509.4	1467	1425	1383	1341	1299	1256	1193	1088	982	877
190	1682.8	1662.7	1642.6	1622.5	1582	1542	1502	1462	1422	1381	1321	1221	1120	1020
200	1793.2	1774.1	1754.9	1735.7	1697	1659	1621	1582	1544	1506	1448	1352	1256	1161
210	1904.4	1886.1	1867.9	1849.6	1813	1777	1740	1704	1667	1630	1576	1484	1391	1302
220	2015.8	1998.4	1981.0	1963.6	1929	1894	1859	1824	1790	1755	1703	1616	1529	1442
230	2127.8	2111.2	2094.6	2078.1	2045	2012	1979	1945	1912	1879	1829	1746	1663	1581
240	2240.1	2224.2	2208.4	2192.6	2161	2129	2098	2066	2034	2003	1955	1876	1797	1718
250	2352.5	2337.3	2332.2	2307.0	2277	2246	2216	2186	2156	2125	2080	2004	1928	1853
260	2465.0	2450.5	2436.0	2421.4	2392	2363	2334	2305	2276	2247	2203	2131	2058	1985
270	2578.2	2564.3	2550.4	2536.4	2509	2481	2453	2425	2397	2369	2328	2258	2188	2119
280	2691.7	2678.3	2665.0	2561.6	2625	2598	2571	2545	2518	2491	2451	2384	2317	2251
290	2805.9	2793.1	2780.3	2767.5	2742	2716	2691	2665	2639	2614	2575	2511	2446	2383
300	2920.2	2907.9	2895.6	2883.3	2859	2834	2809	2785	2760	2736	2698	2637	2575	2514
310	3034.3	3022.4	3010.4	2998.5	2975	2951	2927	2903	2879	2855	2819	2760	2700	2640
320	3149.8	3138.4	3126.9	3115.4	3093	3070	3047	3024	3001	2978	2944	2886	2829	2772
330	3265.8	3254.8	3243.8	3232.8	3211	3189	3167	3145	3123	3101	3068	3013	2958	2903
340	3382.0	3371.4	3360.9	3350.3	3329	3308	3287	3266	3245	3224	3192	3139	3087	3034
350	3498.9	3488.8	3478.7	3468.6	3448	3428	3408	3388	3368	3347	3317	3267	3216	3166
360	3615.8	3606.1	3596.4	3586.7	3567	3548	3529	3509	3490	3471	3441	3393	3344	3296
370	3733.4	3724.1	3714.8	3705.5	3687	3668	3650	3631	3612	3594	3565	3519	3473	3426
380	3851.5	3842.6	3833.6	3824.7	3807	3789	3771	3753	3735	3717	3691	3646	3601	3557
390	3970.8	3962.2	3953.6	3945.0	3928	3911	3894	3876	3859	3842	3816	3774	3731	3688
400	4089.9	4081.7	4073.5	4065.3	4049	4032	4016	4000	3983	3967	3942	3901	3860	3819
410	4209.1	4201.3	4193.4	4185.5	4170	4154	4138	4122	4107	4091	4066	4027	3988	3949
420	4329.2	4321.7	4314.2	4306.7	4292	4277	4262	4247	4232	4217	4194	4157	4119	4082
430	4449.5	4442.3	4435.1	4427.9	4414	4399	4385	4370	4356	4341	4320	4284	4248	4212
440	4571.0	4564.1	4557.2	4550.3	4537	4523	4509	4495	4481	4467	4447	4412	4378	4343
450	4691.6	4685.0	4678.4	4671.8	4658	4645	4632	4619	4606	4592	4573	4540	4507	4473
460	4812.6	4806.3	4799.9	4793.6	4781	4768	4756	4743	4730	4718	4699	4667	4635	4604
470	4934.1	4928.0	4922.0	4915.9	4904	4892	4880	4867	4855	4843	4825	4795	4764	4734
480	5056.1	5050.3	5044.5	5038.7	5027	5015	5004	4992	4981	4969	4952	4923	4894	4965
490	5173.1	5167.5	5162.0	5156.5	5145	5134	5123	5112	5101	5090	5073	5046	5018	4990
500	5301.4	5296.1	5290.8	5285.5	5275	5264	5254	5243	5232	5222	5206	5179	5153	5126
510	5424.5	5419.4	5414.3	5409.3	5399	5389	5379	5369	5359	5348	5338	5308	5283	5258
520	5548.7	5543.9	5539.0	5534.2	5525	5515	5505	5495	5486	5476	5462	5438	5414	5389
530	5673.3	5668.7	5664.1	5659.5	5650	5641	5632	5623	5613	5604	5590	5567	5545	5522
540	5797.5	5793.1	5788.7	5784.3	5776	5767	5758	5749	5740	5733	5719	5698	5676	5654
550	5922.2	5918.1	5913.9	5909.7	5901	5893	5885	5876	5868	5860	5847	5826	5805	5785
560	6047.3	6043.4	6039.4	6035.5	6028	6020	6012	6004	5996	5988	5976	5956	5936	5917
570	6172.9	6169.1	6165.4	6161.6	6154	6147	6139	6132	6124	6117	6105	6087	6068	6049
580	6298.7	6295.2	6291.6	6288.1	6281	6274	6267	6260	6253	6245	6235	6217	6199	6182
590	6424.9	6421.6	6418.2	6414.9	6408	6401	6395	6388	6381	6375	6365	6348	6331	6314
600	6551.4	6548.2	6545.1	6541.9	6536	6529	6523	6517	6510	6504	6495	6479	6463	6447
610	6678.3	6675.4	6672.4	6669.5	6664	6658	6652	6646	6640	6634	6625	6610	6595	6581
620	6805.5	6802.7	6800.0	6797.2	6792	6786	6781	6775	6770	6764	6756	6742	6728	6714
630	6933.1	6930.5	6927.9	6925.4	6920	6915	6910	6905	6900	6894	6887	6874	6861	6848
640	7061.0	7058.6	7056.2	7053.8	7049	7044	7039	7035	7030	7025	7018	7006	6994	6982
650	7188.9	7186.7	7184.5	7182.3	7178	7173	7169	7164	7160	7156	7149	7138	7127	7115

precision is necessary if accurate virial derivatives are to be obtained. The estimated uncertainty of these values is given in Table IV; with the exception mentioned above, all the published values fall inside the limits assigned in Table IV.

VOLUMETRIC BEHAVIOR

Values are given, in Table V, of the first and second virial coefficients for the temperature range 150° to 650° C., so that volumetric data can readily be obtained by applying the virial equation

$$PV = A + BP \tag{4}$$

These values were obtained by interpolation of those quoted by MacCormack and Schneider (*14*) for six temperatures from 150° to 650° C. A few compressibility measurements made by the author in this temperature range gave virial values in excellent agreement with those quoted in Table V. Since completion of this work, a discussion of such data has appeared (*30*) which will enable the agreement between the values of MacCormack and Schneider (*14*) and other data to be assessed. The fuller

Table III. Comparison of Enthalpy Data[a] for Carbon Dioxide

Temp., °C.	Pressure, Atm. 0	1	10	50	100	Source
150	1414.99	1410.1	1365.9	1169.6	924	This
	1415.05	1410.1	1366.0	1169.7		(*16*)
		1414.9	1384.1	1209.8	930	(*11*)
		1409.8		1162.9	897	(*23*)
		1397.6	1369.9		892.6	(*30*)
200	1927.42	1923.6	1889.1	1735.7	1544	This
	1927.48	1923.6		1735.8		(*16*)
		1928.5	1893.7		1517.5	(*30*)
250		2455.5	2428.2	2156		This
		2461.5	2433.8		2116.8	(*30*)
300	3006.46	3004.0	2891.8	2883.3	2760	This
	3006.59	3004.1		2880.8		(*16*)
		3011.9	2988.1		2729.7	(*30*)
350		3567.6	3549.4		3368	This
		2478.0	3558.0		3343.1	(*30*)
400	4147.38	4145.7	4131.0	4065.3	3983	This
	4147.22	4145.6		4065.7		(*16*)
		4156.7	4141.0		3959.7	(*30*)
450		4736.6	4724.7		4606	This
		4749.0	4735.4		4783.4	(*30*)
500	5338.55	5337.5	5327.9	5385.5	5232	This
	5339.15	5338.1		5286.0		(*16*)
		5352.5	5341.1		5211.4	(*30*)
550		5950.6	5943.1		5868	This
		5967.8	5958.5		5846.7	(*30*)
600	6573.50	6572.9	6567.2	6541.9	6510	This
	6573.73	6573.1		6542.3		(*16*)
		6591.7	6584.1		6487.5	(*30*)
650		7204.1	7200.1		7160	This
		7224.7	7218.3		7134.8	(*30*)

At 150° C., and 150 atm., H = 679 (This) and 683 (*11*). At 150° C., and 200 atm., H = 433 (This), 459 (*11*), and 374 (*23*).

[a]Enthalpy unit, cal./mole.
Enthalpy zero, 0° C. 1 atm.
One amagat unit of energy = RT_0/A_0 = 539.02 cal./mole.
R = 1.98718 cal./mole °K. T_0 = 273.16° K.
A_0 = volume per mole of CO_2/volume per mole perfect gas.

Table IV. Estimated Uncertainties in Values of Table II for the Enthalpy of Carbon Dioxide Vapor[a]

(Cal./Mole)

Pressure Atm.	Temp., °C. 150	200	250	300	400	500	600
1	0.15	0.15	0.15	0.18	0.20	0.25	0.30
10	2.6	2.1	1.8	1.4	1.0	0.8	0.6
50	13	10	7.7	6.5	4.1	2.7	1.8
100	25	20	15	13	8	6	3.5
150	38	30	23	19.5	12	9	5.3
200	51	40	30	26	16	11	7

[a]These uncertainties are those introduced in interpolation of original NBS zero pressure data (*31*) and in estimation of coefficients $B\text{-}TdB/dT$ at various temperatures from a plot of values deduced from Equation 3. Zero pressure data have been revised (*47*) since this material was completed, and uncertainties do not include differences between two sets of zero-pressure tabulations (*31,47*).

Table V. Virial Coefficients of Carbon Dioxide Interpolated from the Work of MacCormack and Schneider (*15*).

	A_T[a]		$PV(P = 50)$[a]		$-10^3 B_T$[a]	
T., °C.	McC&S	This	McC&S	This	McC&S	This
150	1.560050	1.560050	1.44640	1.446400	2.273	2.273
160	. . .	1.596917	. . .	1.491267	. . .	2.113
170	. . .	1.633784	. . .	1.535784	. . .	1.951
180	. . .	1.670560	. . .	1.582050	. . .	1.772
190	. . .	1.707517	. . .	1.624017	. . .	1.670
200	1.744383	1.744380	1.66785	1.667880	1.531	1.530
210	. . .	1.781250	. . .	1.710000	. . .	1.425
220	. . .	1.818120	. . .	1.752070	. . .	1.321
230	. . .	1.854980	. . .	1.793580	. . .	1.228
240	. . .	1.891850	. . .	1.835500	. . .	1.127
250	. . .	1.928720	. . .	1.877070	. . .	1.033
260	. . .	1.965580	. . .	1.918430	. . .	0.943
270	. . .	2.002450	. . .	1.959750	. . .	0.854
280	. . .	2.039320	. . .	2.007270	. . .	0.781
290	. . .	2.076183	. . .	2.041583	. . .	0.692
300	2.113050	2.113050	2.08257	2.082400	0.610	0.613
310	. . .	2.149920	. . .	2.122870	. . .	0.541
320	. . .	2.186783	. . .	2.163333	. . .	0.469
330	. . .	2.223650	. . .	2.203650	. . .	0.400
340	. . .	2.260520	. . .	2.243720	. . .	0.336
350	. . .	2.297380	. . .	2.283180	. . .	0.284
360	. . .	2.335250	. . .	2.322400	. . .	0.237
370	. . .	2.371117	. . .	2.360417	. . .	0.194
380	. . .	2.407983	. . .	2.400533	. . .	0.149
390	. . .	2.444850	. . .	2.439500	. . .	0.107
					$10^3 B_T$[a]	
400	2.481717	2.481720	2.47818	2.478220	-0.071	-0.070
410	. . .	2.518584	. . .	2.517134	. . .	-0.029
420	. . .	2.555450	. . .	2.555900	. . .	-0.009
430	. . .	2.592320	. . .	2.594620	. . .	0.046
440	. . .	2.629184	. . .	2.633284	. . .	0.082
450	. . .	2.666050	. . .	2.673900	. . .	0.117
460	. . .	2.702910	. . .	2.710410	. . .	0.150
470	. . .	2.739784	. . .	2.748934	. . .	0.183
480	. . .	2.776650	. . .	2.787300	. . .	0.213
490	. . .	2.815317	. . .	2.825717	. . .	0.244
500	2.850384	2.850383	2.86400	2.864033	0.272	0.273
510	. . .	2.887250	. . .	2.902350	. . .	0.302
520	. . .	2.924120	. . .	2.904620	. . .	0.330
530	. . .	2.960383	. . .	2.978383	. . .	0.362
540	. . .	2.997850	. . .	3.017350	. . .	0.391
550	. . .	3.034717	. . .	3.055467	. . .	0.415
560	. . .	3.071583	. . .	3.036983	. . .	0.442
570	. . .	3.108449	. . .	3.131849	. . .	0.468
580	. . .	3.145317	. . .	3.170017	. . .	0.494
590	. . .	3.182183	. . .	3.208133	. . .	0.519
600	3.219050	3.219050	3.2465	3.246250	0.544	0.544
610	. . .	3.255917	. . .	3.284367	. . .	0.569
620	. . .	3.292784	. . .	3.322434	. . .	0.593
630	. . .	3.329650	. . .	3.360550	. . .	0.618
640	. . .	3.366517	. . .	3.398567	. . .	0.641
650	. . .	3.403384	. . .	3.436634	. . .	0.665

[a]A_T, B_T, PV are in amagat units. A_0 = 1.00705.
[b]Normal volume = 22258.2 cc./mole.

discussion of the NBS tabulation by Masi (*30*) has not yet appeared.

OTHER WORK

Since the above computations were completed, extensive tables of thermodynamic properties (*4*, *30*, *35-37*) have appeared. Some (*4,30*) are revisions of tables (*11,31*) incorporated in the comparisons above, while the data of Price (*35-37*) are based upon volumetric determinations of Kennedy (*13*). Values given by Kennedy do not appear to be sufficiently accurate for comparison of virial coefficients with those of Table V. The newer tabulation (*30*) contains zero pressure values for carbon dioxide (*47*) which differ from the original data (*31*). The second portion of Table III compares the data of Table II and (*30*). Except at the higher pressures and at 150° C. agreement to 1% exists.

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Measurement of the Thermal Properties of Carbonaceous Materials

The companion article on "Heat Transfer and Thermal Stresses in Carbonization of Briquets" appears in the July issue of *Industrial and Engineering Chemistry*, Vol. 51, page 833.

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Many processes for the treatment of coal involve thermal conversion. In process development, thermal data on the materials are desirable. This work was designed to supply such thermal data for carbonaceous materials. Heat capacity measurements were made on a bituminous coal from the Pittsburgh seam and its low-temperature char. Thermal conductivity was measured on a coal-char-pitch briquet. Finally, an estimate was made of the heat transfer film coefficient from a fluidized heating medium to a spherical briquet. This latter work was carried out so that the thermal parameters could be applied to the calculation of heating rates for carbonaceous briquets, an application which is described in an article in the July issue of I/EC on heat transfer in the carbonization of briquets (*17*).

LITERATURE SURVEY

The heat capacity data for coal and coke were reviewed by Clendenin and others (*3*). A correlation equation for the specific heat capacity of moisture-free coal is presented, based on data for 23 American bituminous coals. The equation expresses heat capacity as a linear function of temperature and volatile matter content, but is not expected to hold into the temperature range in which coal becomes plastic. In fact, the very limited data included in the correlation for temperatures above 100° C. make its use above about 150° C. an unjustifiable extrapolation.

The heat capacity of a material undergoing thermal decomposition such as bituminous coal in the plastic range loses