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**Thermodynamic Properties of
Fluid ^4He in the 75 to 300 K and
2- to 20-kbar Range**

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THERMODYNAMIC PROPERTIES OF FLUID ^4He IN THE
75 TO 300 K AND 2- TO 20-kbar RANGE

by

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ABSTRACT

Helium is the simplest noble gas and is the second most abundant element in the universe. Helium properties are required for the use of helium in energy technologies, basic physical research studies, and astrophysical modeling. This report summarizes new pressure, volume, temperature, and sound velocity measurements on ^4He in the ranges 75 to 300 K and 2 to 20 kbar. From an equation of state (EOS) fitted to these data, we calculate and tabulate the thermodynamic quantities: volume V , sound velocity v_s , thermal expansivity α_p , heat capacity at constant pressure C_p , the ratio of specific heats γ , adiabatic compressibility χ_s , and molar entropy S . Computer-drawn graphs of the isothermal pressure variation of these quantities are presented and the precision of the fits to the data is discussed. Comparison with other measurements is described in the limited region of overlap, that is, at less than 10 kbar and near room temperature.

INTRODUCTION

Helium, the lightest noble gas, has been the subject of a number of studies of P , V , T , and derived thermodynamic properties.¹⁻⁴ With few exceptions, these studies have been limited to pressures below 1 kbar [1 kbar = 10^8 Pa], where leak-tight seals in experimental apparatus are not a severe problem. Stewart⁵ reported measurements in solid helium along the 4 K isotherm to 20 kbar. Tsiklis, Maslennikova, and Gluvka⁶ have reported compressibility measurements in helium fluid to 7 kbar in the temperature range 293-323 K. Sound velocity measurements in fluid helium along the 298 K isotherm up to 10 kbar were reported by Nishitake and Hanayama.⁷

We report simultaneous measurements of P , V , T , and longitudinal sound velocity v_s in helium fluid over the pressure and temperature ranges 3-20 kbar and 75-300 K. Some 670 data sets⁸ provide the basis for a double-process least-squares fit of the data to an equation of state (EOS) of the Benedict⁹ type. Although this equation of state was developed for a diatomic gas, the results of the fit over the full pressure and temperature range of the ⁴He data are quite satisfactory with percent deviations of 0.30 in volume and 0.51 in sound velocity. These results are compared with sound-velocity measurements⁷ to 10 kbar and molar-volume measurements⁶ to 7 kbar near room temperature. At lower temperatures and higher pressures the present data are unique.

The piston-cylinder apparatus used to seal and compress helium has been described in detail elsewhere.¹⁰⁻¹⁴ Measurements of molar volume V and sound velocity v_s are made simultaneously at various pressures P along an isotherm T . A fixed-path sound cell and pulse-timing measurements are used to provide an independent sound velocity measurement. The Bridgman unsupported area seals on the movable piston and the fixed buffer rod were made with either indium or teflon in the low- and high-temperature range, respectively. Such seals were found to hold against helium for many pressure cycles with no noticeable leakage.

Errors in these measurements and further particulars of the apparatus used are discussed in Ref. 14. The corrected pressures are considered accurate to a few tenths of 1% at low pressures, increasing to about 0.5% at higher pressures. Errors in temperature at ambient and 75 K are known to be within ± 0.05 K, but at intermediate temperatures the accuracy, including drift during a run, is estimated to be ± 0.5 K. Volumes are estimated to be known to 0.4%, the error becomes somewhat larger at pressures and temperatures farther from the normalizing point, 2 kbar and 275 K. Sound velocities were found to scatter from a power-law least-squares fit by $\pm 0.5\%$.

EQUATION-OF-STATE DEVELOPMENT

We have discussed the usefulness of the Benedict⁹ type EOS for fitting P - V - T and v_s measurements on the diatomic molecules nitrogen,¹¹ hydrogen,¹³ and deuterium.¹² This equation,

$$V = (A + BT + CT^{-1/2}) P^{-1/3} + (D + ET) P^{-2/3} + (F + GT + HT^{-1/2} + JT^{-1}) P^{-1} \quad (\text{cm}^3 \text{ mole}^{-1}), \quad (1)$$

is applied to data on monotomic ^4He and is found quite satisfactory over the full range of experimental conditions. Knowledge of the heat capacity C_p over the full temperature range at our normalization pressure of 2 kbar is required to relate the sound velocity data to the EOS of Eq. (1). As discussed in Ref. 14, the data of McCarty¹ were extrapolated to give,

$$C_{p=2} = 0.073960T - 3.8754T^{1/2} + 91.968 - 523.31T^{-1/2} + 1299.1T^{-1} \quad (2) \\ (\text{J mole}^{-1} \text{ K}^{-1}).$$

These results are used in the relation for the heat capacity,

$$C_p = C_{p=2}(T) - T \int_{p=2}^P \left(\frac{\partial^2 V}{\partial T^2} \right)_P dP, \quad (3)$$

and, in turn, in the relation for the sound velocity,

$$\frac{1}{v_s} = \frac{M^{1/2}}{V} \left\{ - \left(\frac{\partial V}{\partial P} \right)_T - \frac{T \left[\left(\frac{\partial V}{\partial T} \right)_P \right]^2}{C_p} \right\}^{1/2}. \quad (4)$$

The resulting best fit of the 670 data points is shown in Table I Column 1, labeled 148-L. Also shown in Table I is the calculated percent deviation of the full data set in V and v_s from the EOS.

The 146-A fit is to an earlier set of only the P - V - T data from a single-process least-squares fit to Eq. (1). The earlier data set contained several measurements that were later corrected. This result indicates the large deviation in fitted parameters that can occur when v_s is not used with P , V , and T in a double-process least-squares fit. The constants H and J tend to be closely correlated, and the lower magnitude of these constants is usually a good indication of the quality of the fit; compare 148-L, 146-A and 147-F in Table I.

TABLE I
CONSTANTS OF EQ. (1) AND PERCENT DEVIATIONS OF THE DATA POINTS FOUND
BY A DOUBLE-PROCESS LEAST-SQUARES FIT TO 670 DATA POINTS. SEVERAL
OTHER FITS ARE LISTED AND DISCUSSED IN THE TEXT.

	148-L	146-A	147-F
A	+ 22.575	+ 24.50	+ 22.46
B	+ 0.0064655	- 0.0007730	+ 0.003621
C	- 7.2645	- 14.34	+ 0.1783
D	- 12.483	- 16.93	- 15.44
E	- 0.024549	- 0.002649	- 0.007290
F	+ 1.0596	- 16.93	+ 8.528
G	+ 0.10604	+ 0.1062	+ 0.08314
H	- 19.641	+ 360.9	- 77.17
J	+189.84	-1557.	+352.5
% Var V	0.30	--	0.29
% Var v_s	0.51	--	0.53

The fit 147-F was made with the parameter G fixed as the constant in the ideal gas equation. In this case there are smaller variations of the constants from the fit 148-L and a somewhat improved fit to the volume data at the expense of the fit to the sound velocity data. This is likely related to the well known difficulty of the ideal gas law to predict sound velocities in real gases.

The quality of the fit 148-L along several isotherms is shown in the pairs of Figs. 1-5. For each selected isotherm the percent deviation of the sound velocity and the volume is shown as a function of pressure.

DERIVED THERMODYNAMIC VALUES

As described in an earlier report,¹⁵ the volume-explicit EOS of Eq. (1) is convenient for the derivation of other thermodynamic quantities. These are summarized below.

Fig. 1a.
Percentage deviation of the sound velocity values from the least-squares fit to Eq. (1) for fluid ^4He data at $T = 295.1$ K.

Fig. 1b.
Percentage deviation of the molar volume values from the least-squares fit to Eq. (1) for fluid ^4He data at $T = 295.1$ K.

Fig. 2a.

Percentage deviation of the sound velocity values from the least-squares fit to Eq. (1) for fluid ^4He data at $T = 248.8 \text{ K}$.

Fig. 2b.

Percentage deviation of the molar volume values from the least-squares fit to Eq. (1) for fluid ^4He data at $T = 248.8 \text{ K}$.

Fig. 3a.
Percentage deviation of the sound velocity values from the least-squares fit to Eq. (1) for fluid ^4He data at $T = 200.8 \text{ K}$.

Fig. 3b.
Percentage deviation of the molar volume values from the least-squares fit to Eq. (1) for fluid ^4He data at $T = 200.8 \text{ K}$.

Fig. 4a.

Percentage deviation of the sound velocity values from the least-squares fit to Eq. (1) for fluid ^4He data at $T = 152.1$ K.

Fig. 4b.

Percentage deviation of the molar volume values from the least-squares fit to Eq. (1) for fluid ^4He data at $T = 152.1$ K.

Fig. 5a.
Percentage deviation of the sound velocity values from the least-squares fit to Eq. (1) for fluid ^4He data at $T = 97.2 \text{ K}$.

Fig. 5b.
Percentage deviation of the molar volume values from the least-squares fit to Eq. (1) for fluid ^4He data at $T = 97.2 \text{ K}$.

$$\text{Isobaric thermal expansion coefficient: } \alpha_p = - \frac{1}{V} \left(\frac{\partial V}{\partial T} \right)_p \quad (5)$$

$$\text{Isothermal compressibility: } \chi_T = - \frac{1}{V} \left(\frac{\partial V}{\partial P} \right)_T \quad (6)$$

$$\text{Ratio of heat capacities: } \gamma = \frac{C_p}{C_v} = \frac{\chi_T}{\chi_s} \quad (7)$$

$$\text{Adiabatic compressibility: } \chi_s = - \frac{1}{V} \left(\frac{\partial V}{\partial P} \right)_s = \frac{1}{\rho v_s^2} \quad (8)$$

The heat capacities are determined from Eqs. (2), (3), and (7). The molar entropy is found from the thermodynamic relation

$$S(P_0, T) - S(P, T) = \int_{P_0}^P \left(\frac{\partial V}{\partial T} \right)_P dP \quad (9)$$

and a relation for the entropy at the normalizing pressure of 2 kbar. Tabular values of entropy are available from Ref. 1 and these were fitted, as described in Ref. 14, to give

$$S_{p=2} = -58.598 + 21.314 \ln T \quad (10)$$

A FORTRAN program, as described in Ref. 15, was modified to provide the listing in Table II of the quantities V , v_s , α_p , C_p , T , χ_s , and S at 25-K and 0.5-kbar increments. These values as a function of pressure along an isotherm are also graphically displayed in Figs. 6-14. The special font used in these figures was selected to indicate that these curves all refer to values calculated from our EOS.

TABLE II

CALCULATED VALUES FROM E O C FOR HELIUM AT 75.0 K.

PRESS.	VOL.	V(C)	ALPHA	C(P)	GAMMA	CH(C)	ENTROPY
KBAR	CC-MOLE	KM ³	K	J-MOLE-K		KBAR	J-MOLE-K
2.00	13.245	1.592	2.260E-03	20.790	1.299	1.306E-01	33.45
2.50	12.302	1.744	2.486E-03	20.117	1.291	1.010E-01	31.75
3.00	11.609	1.875	2.218E-03	19.605	1.265	8.247E-02	30.35
3.50	11.069	1.991	2.016E-03	19.202	1.252	6.976E-02	29.16
4.00	10.630	2.095	1.857E-03	18.977	1.241	6.051E-02	28.11
4.50	10.263	2.190	1.730E-03	18.612	1.231	5.348E-02	27.17
5.00	9.949	2.277	1.625E-03	18.392	1.223	4.796E-02	26.33
5.50	9.676	2.357	1.537E-03	18.210	1.216	4.250E-02	25.55
6.00	9.435	2.433	1.462E-03	18.056	1.210	3.932E-02	24.83
6.50	9.219	2.504	1.397E-03	17.929	1.205	3.673E-02	24.17
7.00	9.025	2.571	1.341E-03	17.820	1.200	3.410E-02	23.54
7.50	8.849	2.635	1.291E-03	17.729	1.196	3.193E-02	22.96
8.00	8.689	2.696	1.247E-03	17.654	1.192	2.986E-02	22.40
8.50	8.539	2.754	1.208E-03	17.592	1.189	2.812E-02	21.87
9.00	8.402	2.810	1.173E-03	17.541	1.186	2.658E-02	21.37
9.50	8.274	2.864	1.141E-03	17.500	1.183	2.520E-02	20.89
10.00	8.155	2.916	1.112E-03	17.469	1.180	2.397E-02	20.42
10.50	8.043	2.965	1.085E-03	17.444	1.179	2.285E-02	19.99
11.00	7.938	3.014	1.061E-03	17.427	1.176	2.183E-02	19.55
11.50	7.839	3.060	1.038E-03	17.416	1.174	2.091E-02	19.14
12.00	7.745	3.106	1.017E-03	17.411	1.172	2.006E-02	18.74
12.50	7.656	3.150	9.982E-04	17.411	1.170	1.928E-02	18.35
13.00	7.572	3.193	9.803E-04	17.416	1.169	1.856E-02	17.97
13.50	7.492	3.234	9.637E-04	17.425	1.167	1.789E-02	17.60
14.00	7.416	3.275	9.482E-04	17.439	1.166	1.727E-02	17.25
14.50	7.343	3.315	9.336E-04	17.455	1.165	1.670E-02	16.90
15.00	7.273	3.353	9.199E-04	17.475	1.163	1.616E-02	16.56
15.50	7.206	3.391	9.071E-04	17.499	1.162	1.565E-02	16.23
16.00	7.142	3.428	8.950E-04	17.524	1.161	1.518E-02	15.91
16.50	7.080	3.464	8.836E-04	17.553	1.160	1.474E-02	15.59
17.00	7.020	3.500	8.727E-04	17.584	1.159	1.432E-02	15.29
17.50	6.963	3.535	8.625E-04	17.617	1.158	1.393E-02	14.99
18.00	6.908	3.569	8.528E-04	17.653	1.158	1.355E-02	14.69
18.50	6.855	3.602	8.436E-04	17.690	1.157	1.320E-02	14.39
19.00	6.803	3.635	8.348E-04	17.729	1.156	1.287E-02	14.10
19.50	6.754	3.667	8.265E-04	17.770	1.155	1.255E-02	13.82
20.00	6.705	3.699	8.185E-04	17.812	1.154	1.225E-02	13.55
20.50	6.659	3.730	8.109E-04	17.856	1.154	1.196E-02	13.27
21.00	6.614	3.760	8.036E-04	17.902	1.153	1.168E-02	13.01
21.50	6.570	3.791	7.967E-04	17.949	1.153	1.142E-02	12.74
22.00	6.527	3.820	7.900E-04	17.996	1.152	1.117E-02	12.48
22.50	6.486	3.849	7.837E-04	18.045	1.151	1.093E-02	12.23

TABLE II (continued)

CALCULATED VALUES FROM E O S FOR HELIUM AT 100.0 K.

PRESS.	VOL.	V(S)	ALPHA	C(P)	GAMMA	CHI(S)	ENTROPY
KBAR	CC/MOLE	KM/S	/K	J/MOLE-K		/KBAR	J/MOLE-K
2.00	14.239	1.615	2.882E-03	21.220	1.408	1.365E-01	39.50
2.50	13.101	1.760	2.511E-03	20.913	1.374	1.057E-01	37.66
3.00	12.279	1.886	2.241E-03	20.687	1.346	8.623E-02	36.16
3.50	11.647	1.998	2.035E-03	20.516	1.323	7.239E-02	34.89
4.00	11.140	2.099	1.872E-03	20.383	1.303	6.317E-02	33.78
4.50	10.720	2.191	1.740E-03	20.280	1.287	5.579E-02	32.79
5.00	10.364	2.276	1.631E-03	20.199	1.273	4.992E-02	31.90
5.50	10.057	2.355	1.538E-03	20.135	1.261	4.529E-02	31.09
6.00	9.797	2.429	1.459E-03	20.087	1.250	4.143E-02	30.35
6.50	9.549	2.499	1.391E-03	20.050	1.241	3.813E-02	29.66
7.00	9.333	2.565	1.331E-03	20.023	1.233	3.543E-02	29.02
7.50	9.139	2.628	1.278E-03	20.005	1.226	3.305E-02	28.42
8.00	8.962	2.688	1.231E-03	19.994	1.219	3.098E-02	27.85
8.50	8.799	2.746	1.189E-03	19.989	1.213	2.916E-02	27.31
9.00	8.650	2.801	1.151E-03	19.989	1.208	2.755E-02	26.80
9.50	8.511	2.854	1.116E-03	19.994	1.203	2.611E-02	26.32
10.00	8.382	2.905	1.085E-03	20.003	1.199	2.482E-02	25.95
10.50	8.261	2.954	1.056E-03	20.016	1.195	2.365E-02	25.41
11.00	8.148	3.002	1.030E-03	20.032	1.191	2.259E-02	24.93
11.50	8.042	3.048	1.006E-03	20.051	1.188	2.163E-02	24.57
12.00	7.941	3.093	9.831E-04	20.073	1.184	2.074E-02	24.17
12.50	7.847	3.136	9.622E-04	20.097	1.181	1.993E-02	23.79
13.00	7.757	3.179	9.428E-04	20.123	1.179	1.918E-02	23.42
13.50	7.671	3.220	9.247E-04	20.151	1.176	1.848E-02	23.06
14.00	7.590	3.260	9.077E-04	20.181	1.174	1.784E-02	22.71
14.50	7.512	3.300	8.918E-04	20.212	1.172	1.724E-02	22.37
15.00	7.438	3.338	8.769E-04	20.245	1.169	1.668E-02	22.04
15.50	7.367	3.376	8.629E-04	20.279	1.167	1.615E-02	21.71
16.00	7.299	3.412	8.496E-04	20.315	1.166	1.566E-02	21.40
16.50	7.234	3.448	8.371E-04	20.352	1.164	1.520E-02	21.09
17.00	7.171	3.484	8.252E-04	20.389	1.162	1.476E-02	20.79
17.50	7.111	3.518	8.140E-04	20.429	1.161	1.435E-02	20.50
18.00	7.052	3.552	8.034E-04	20.467	1.159	1.396E-02	20.22
18.50	6.996	3.585	7.932E-04	20.507	1.158	1.360E-02	19.94
19.00	6.942	3.618	7.836E-04	20.548	1.157	1.325E-02	19.66
19.50	6.890	3.650	7.744E-04	20.590	1.155	1.292E-02	19.39
20.00	6.839	3.682	7.656E-04	20.633	1.154	1.261E-02	19.13
20.50	6.790	3.713	7.573E-04	20.676	1.153	1.231E-02	18.87
21.00	6.743	3.742	7.493E-04	20.719	1.152	1.202E-02	18.61
21.50	6.697	3.773	7.416E-04	20.763	1.151	1.175E-02	18.36
22.00	6.652	3.803	7.343E-04	20.808	1.150	1.149E-02	18.12
22.50	6.609	3.832	7.272E-04	20.853	1.149	1.125E-02	17.87

TABLE II (continued)

CALCULATED VALUES FROM E O S FOR HELIUM AT 125.0 K.

PRESS.	VOL.	V(S)	ALPHA	C(P)	GAMMA	CHI(S)	ENTROPY
KBAR	CC/MOLE	KM/S	°K	J/MOLE-K		KBAR	J/MOLE-K
2.00	15.281	1.621	2.763E-03	21.427	1.469	1.452E-01	44.26
2.50	13.935	1.761	2.421E-03	21.271	1.429	1.122E-01	42.39
3.00	12.976	1.884	2.169E-03	21.161	1.395	9.136E-02	40.84
3.50	12.247	1.993	1.974E-03	21.082	1.367	7.701E-02	39.53
4.00	11.667	2.092	1.818E-03	21.026	1.344	6.657E-02	38.50
4.50	11.191	2.184	1.691E-03	20.985	1.325	5.864E-02	37.40
5.00	10.790	2.269	1.585E-03	20.957	1.308	5.241E-02	36.50
5.50	10.446	2.347	1.495E-03	20.939	1.294	4.740E-02	35.69
6.00	10.146	2.420	1.418E-03	20.929	1.281	4.327E-02	34.94
6.50	9.881	2.490	1.350E-03	20.926	1.270	3.991E-02	34.24
7.00	9.644	2.556	1.291E-03	20.928	1.261	3.699E-02	33.60
7.50	9.431	2.613	1.239E-03	20.934	1.252	3.435E-02	33.00
8.00	9.238	2.673	1.193E-03	20.945	1.244	3.215E-02	32.43
8.50	9.061	2.737	1.151E-03	20.959	1.237	3.023E-02	31.89
9.00	8.899	2.792	1.113E-03	20.975	1.230	2.852E-02	31.39
9.50	8.748	2.845	1.079E-03	20.994	1.224	2.700E-02	30.90
10.00	8.608	2.896	1.047E-03	21.015	1.219	2.564E-02	30.44
10.50	8.479	2.946	1.019E-03	21.039	1.214	2.441E-02	30.00
11.00	8.357	2.994	9.932E-04	21.063	1.210	2.329E-02	29.59
11.50	8.243	3.040	9.679E-04	21.090	1.205	2.228E-02	29.17
12.00	8.135	3.085	9.453E-04	21.117	1.202	2.135E-02	28.78
12.50	8.034	3.129	9.243E-04	21.146	1.199	2.050E-02	28.40
13.00	7.938	3.172	9.048E-04	21.176	1.195	1.971E-02	28.04
13.50	7.847	3.214	8.866E-04	21.207	1.191	1.898E-02	27.69
14.00	7.760	3.254	8.695E-04	21.239	1.189	1.831E-02	27.34
14.50	7.679	3.294	8.534E-04	21.271	1.186	1.768E-02	27.01
15.00	7.599	3.332	8.384E-04	21.304	1.183	1.710E-02	26.69
15.50	7.524	3.370	8.242E-04	21.338	1.181	1.655E-02	26.37
16.00	7.452	3.407	8.108E-04	21.373	1.179	1.604E-02	26.06
16.50	7.383	3.443	7.981E-04	21.408	1.177	1.556E-02	25.77
17.00	7.317	3.479	7.861E-04	21.443	1.175	1.510E-02	25.48
17.50	7.253	3.514	7.748E-04	21.479	1.173	1.468E-02	25.19
18.00	7.192	3.548	7.640E-04	21.515	1.171	1.427E-02	24.91
18.50	7.133	3.581	7.537E-04	21.552	1.169	1.389E-02	24.64
19.00	7.076	3.614	7.439E-04	21.589	1.168	1.353E-02	24.39
19.50	7.021	3.647	7.346E-04	21.626	1.166	1.319E-02	24.12
20.00	6.968	3.679	7.257E-04	21.664	1.165	1.287E-02	23.86
20.50	6.917	3.710	7.172E-04	21.701	1.163	1.256E-02	23.61
21.00	6.867	3.740	7.090E-04	21.740	1.162	1.226E-02	23.36
21.50	6.819	3.771	7.012E-04	21.778	1.161	1.198E-02	23.12
22.00	6.772	3.800	6.937E-04	21.816	1.159	1.171E-02	22.89
22.50	6.727	3.830	6.866E-04	21.855	1.158	1.146E-02	22.65

TABLE II (continued)

CALCULATED VALUES FROM E D 3 FOR HELIUM AT 150.0 K.

PRESS.	VOL.	V(S)	ALPHA	C(P)	GAMMA	CHI(S)	ENTROPY
KBAR	CC-MOLE	KM/SEC	/K	J/MOLE-K		/KBAR	J/MOLE-K
2.00	16.344	1.627	2.614E-03	21.490	1.505	1.543E-01	48.17
2.50	14.784	1.761	2.306E-03	21.407	1.463	1.190E-01	46.27
3.00	13.683	1.881	2.074E-03	21.353	1.423	9.663E-02	44.71
3.50	12.853	1.988	1.893E-03	21.313	1.399	8.123E-02	43.40
4.00	12.199	2.086	1.748E-03	21.296	1.375	7.003E-02	42.26
4.50	11.665	2.176	1.628E-03	21.284	1.354	6.153E-02	41.26
5.00	11.219	2.260	1.528E-03	21.280	1.336	5.437E-02	40.36
5.50	10.837	2.339	1.442E-03	21.282	1.321	4.951E-02	39.54
6.00	10.505	2.412	1.368E-03	21.283	1.307	4.510E-02	38.79
6.50	10.214	2.482	1.304E-03	21.293	1.295	4.142E-02	38.10
7.00	9.955	2.548	1.247E-03	21.312	1.285	3.830E-02	37.46
7.50	9.723	2.611	1.197E-03	21.328	1.275	3.562E-02	36.85
8.00	9.512	2.672	1.152E-03	21.346	1.266	3.330E-02	36.29
8.50	9.321	2.729	1.111E-03	21.366	1.259	3.126E-02	35.76
9.00	9.145	2.785	1.075E-03	21.388	1.251	2.946E-02	35.25
9.50	8.983	2.838	1.041E-03	21.411	1.245	2.785E-02	34.77
10.00	8.833	2.890	1.011E-03	21.435	1.239	2.642E-02	34.32
10.50	8.693	2.940	9.829E-04	21.461	1.234	2.513E-02	33.89
11.00	8.563	2.988	9.571E-04	21.487	1.229	2.396E-02	33.46
11.50	8.441	3.035	9.333E-04	21.514	1.224	2.299E-02	33.06
12.00	8.326	3.081	9.112E-04	21.542	1.220	2.192E-02	32.67
12.50	8.218	3.125	8.906E-04	21.571	1.216	2.102E-02	32.30
13.00	8.116	3.168	8.714E-04	21.600	1.212	2.020E-02	31.94
13.50	8.019	3.210	8.535E-04	21.629	1.208	1.944E-02	31.59
14.00	7.927	3.251	8.367E-04	21.659	1.205	1.874E-02	31.26
14.50	7.840	3.291	8.210E-04	21.690	1.202	1.809E-02	30.93
15.00	7.757	3.330	8.061E-04	21.720	1.199	1.748E-02	30.61
15.50	7.677	3.369	7.922E-04	21.751	1.197	1.691E-02	30.30
16.00	7.601	3.406	7.799E-04	21.782	1.194	1.637E-02	30.00
16.50	7.529	3.442	7.684E-04	21.814	1.192	1.587E-02	29.71
17.00	7.459	3.478	7.546E-04	21.846	1.189	1.540E-02	29.43
17.50	7.392	3.513	7.434E-04	21.879	1.187	1.496E-02	29.15
18.00	7.328	3.548	7.327E-04	21.910	1.185	1.454E-02	28.88
18.50	7.266	3.582	7.225E-04	21.942	1.183	1.415E-02	28.61
19.00	7.206	3.615	7.129E-04	21.974	1.181	1.378E-02	28.35
19.50	7.148	3.648	7.036E-04	22.007	1.180	1.342E-02	28.10
20.00	7.093	3.680	6.948E-04	22.040	1.179	1.309E-02	27.85
20.50	7.039	3.711	6.864E-04	22.072	1.177	1.277E-02	27.61
21.00	6.987	3.742	6.783E-04	22.105	1.175	1.246E-02	27.37
21.50	6.937	3.773	6.706E-04	22.138	1.174	1.217E-02	27.13
22.00	6.889	3.803	6.632E-04	22.171	1.172	1.190E-02	26.90
22.50	6.840	3.833	6.560E-04	22.204	1.171	1.163E-02	26.67

TABLE II (continued)

CALCULATED VALUES FROM E D S FOR HELIUM AT 175.0 K.

PRESS.	VOL.	V(S)	ALPHA	C(P)	GAMMA	CHI(S)	ENTROPY
KBAR	CC/MOLE	KM/S	/K	J/MOLE-K		/KBAR	J/MOLE-K
2.00	17.416	1.634	2.467E-03	21.471	1.530	1.630E-01	51.48
2.50	15.638	1.764	2.189E-03	21.428	1.488	1.255E-01	49.57
3.00	14.394	1.881	1.978E-03	21.403	1.453	1.017E-01	48.01
3.50	13.463	1.986	1.812E-03	21.390	1.424	8.526E-02	46.70
4.00	12.732	2.083	1.677E-03	21.386	1.399	7.333E-02	45.56
4.50	12.140	2.172	1.565E-03	21.388	1.379	6.429E-02	44.55
5.00	11.646	2.255	1.470E-03	21.395	1.360	5.721E-02	43.65
5.50	11.227	2.333	1.390E-03	21.406	1.344	5.152E-02	42.83
6.00	10.864	2.407	1.320E-03	21.420	1.330	4.686E-02	42.08
6.50	10.547	2.477	1.259E-03	21.436	1.317	4.296E-02	41.39
7.00	10.265	2.543	1.205E-03	21.454	1.306	3.966E-02	40.75
7.50	10.013	2.606	1.156E-03	21.473	1.296	3.683E-02	40.15
8.00	9.785	2.667	1.113E-03	21.494	1.287	3.439E-02	39.59
8.50	9.579	2.725	1.074E-03	21.516	1.279	3.224E-02	39.06
9.00	9.390	2.781	1.039E-03	21.539	1.271	3.034E-02	38.56
9.50	9.216	2.834	1.007E-03	21.563	1.265	2.866E-02	38.09
10.00	9.055	2.886	9.776E-04	21.587	1.258	2.716E-02	37.63
10.50	8.906	2.937	9.505E-04	21.612	1.253	2.580E-02	37.20
11.00	8.767	2.985	9.256E-04	21.638	1.247	2.458E-02	36.79
11.50	8.637	3.033	9.025E-04	21.664	1.242	2.346E-02	36.39
12.00	8.515	3.079	8.811E-04	21.690	1.238	2.245E-02	36.01
12.50	8.400	3.123	8.611E-04	21.717	1.233	2.152E-02	35.64
13.00	8.292	3.167	8.425E-04	21.744	1.229	2.066E-02	35.28
13.50	8.189	3.209	8.251E-04	21.771	1.226	1.987E-02	34.94
14.00	8.092	3.250	8.087E-04	21.798	1.222	1.914E-02	34.61
14.50	8.000	3.291	7.934E-04	21.826	1.219	1.846E-02	34.29
15.00	7.912	3.330	7.789E-04	21.853	1.216	1.782E-02	33.97
15.50	7.829	3.369	7.652E-04	21.881	1.213	1.723E-02	33.67
16.00	7.748	3.406	7.524E-04	21.909	1.210	1.668E-02	33.37
16.50	7.672	3.443	7.401E-04	21.937	1.207	1.616E-02	33.09
17.00	7.599	3.480	7.286E-04	21.965	1.205	1.568E-02	32.81
17.50	7.529	3.515	7.176E-04	21.994	1.203	1.522E-02	32.53
18.00	7.461	3.550	7.071E-04	22.022	1.200	1.479E-02	32.27
18.50	7.396	3.584	6.972E-04	22.050	1.198	1.438E-02	32.00
19.00	7.333	3.618	6.877E-04	22.078	1.196	1.400E-02	31.75
19.50	7.273	3.651	6.787E-04	22.107	1.195	1.363E-02	31.50
20.00	7.215	3.684	6.700E-04	22.135	1.193	1.328E-02	31.26
20.50	7.158	3.716	6.617E-04	22.164	1.191	1.295E-02	31.02
21.00	7.104	3.747	6.538E-04	22.192	1.189	1.264E-02	30.79
21.50	7.052	3.778	6.462E-04	22.220	1.188	1.234E-02	30.55
22.00	7.001	3.809	6.390E-04	22.249	1.186	1.206E-02	30.33
22.50	6.951	3.839	6.320E-04	22.277	1.185	1.179E-02	30.10

TABLE II (continued)

CALCULATED VALUES FROM E O O FOR HELIUM AT 200.0 K.

PRESS.	VOL.	V(O)	ALPHA	C(P)	GRAMMA	CHICKS	ENTROPY
KBAR	CM/MOLE	KM/S	°K	J/MOLE-K		KBAR	J/MOLE-K
2.00	18.492	1.644	2.330E-03	21.410	1.549	1.709E-01	54.35
2.50	16.495	1.771	2.079E-03	21.389	1.507	1.314E-01	52.43
3.00	15.106	1.824	1.887E-03	21.380	1.473	1.063E-01	50.87
3.50	14.072	1.987	1.734E-03	21.380	1.444	8.902E-02	49.55
4.00	13.266	2.082	1.608E-03	21.386	1.420	7.642E-02	48.41
4.50	12.615	2.171	1.504E-03	21.395	1.399	6.689E-02	47.41
5.00	12.074	2.253	1.416E-03	21.408	1.381	5.941E-02	46.51
5.50	11.617	2.331	1.340E-03	21.423	1.364	5.342E-02	45.69
6.00	11.222	2.404	1.274E-03	21.440	1.350	4.851E-02	44.95
6.50	10.878	2.474	1.216E-03	21.458	1.337	4.441E-02	44.26
7.00	10.573	2.540	1.164E-03	21.477	1.326	4.094E-02	43.62
7.50	10.302	2.603	1.119E-03	21.498	1.316	3.797E-02	43.02
8.00	10.057	2.664	1.077E-03	21.519	1.307	3.540E-02	42.47
8.50	9.835	2.722	1.040E-03	21.541	1.298	3.316E-02	41.94
9.00	9.633	2.778	1.006E-03	21.564	1.290	3.112E-02	41.44
9.50	9.447	2.832	9.756E-04	21.587	1.283	2.942E-02	40.97
10.00	9.275	2.885	9.474E-04	21.610	1.277	2.785E-02	40.52
10.50	9.117	2.935	9.213E-04	21.634	1.271	2.644E-02	40.09
11.00	8.969	2.984	8.973E-04	21.657	1.265	2.516E-02	39.68
11.50	8.831	3.032	8.750E-04	21.682	1.260	2.400E-02	39.28
12.00	8.701	3.078	8.543E-04	21.706	1.255	2.294E-02	38.91
12.50	8.580	3.123	8.351E-04	21.730	1.251	2.198E-02	38.54
13.00	8.465	3.167	8.170E-04	21.755	1.246	2.109E-02	38.19
13.50	8.357	3.210	8.002E-04	21.780	1.242	2.027E-02	37.85
14.00	8.255	3.251	7.843E-04	21.804	1.239	1.951E-02	37.52
14.50	8.158	3.292	7.694E-04	21.829	1.235	1.880E-02	37.20
15.00	8.065	3.332	7.554E-04	21.854	1.232	1.815E-02	36.89
15.50	7.977	3.371	7.421E-04	21.879	1.229	1.754E-02	36.59
16.00	7.893	3.409	7.296E-04	21.904	1.226	1.697E-02	36.30
16.50	7.813	3.447	7.177E-04	21.929	1.223	1.643E-02	36.02
17.00	7.736	3.483	7.064E-04	21.954	1.221	1.593E-02	35.74
17.50	7.662	3.519	6.957E-04	21.979	1.218	1.546E-02	35.47
18.00	7.592	3.554	6.856E-04	22.004	1.216	1.501E-02	35.21
18.50	7.524	3.589	6.759E-04	22.029	1.214	1.459E-02	34.95
19.00	7.458	3.623	6.666E-04	22.054	1.212	1.420E-02	34.70
19.50	7.395	3.656	6.578E-04	22.079	1.210	1.382E-02	34.45
20.00	7.334	3.689	6.494E-04	22.104	1.208	1.346E-02	34.21
20.50	7.276	3.722	6.413E-04	22.129	1.206	1.312E-02	33.97
21.00	7.219	3.753	6.336E-04	22.153	1.204	1.280E-02	33.74
21.50	7.165	3.785	6.261E-04	22.179	1.203	1.250E-02	33.52
22.00	7.112	3.816	6.190E-04	22.203	1.201	1.220E-02	33.30
22.50	7.060	3.846	6.122E-04	22.228	1.200	1.193E-02	33.09

TABLE II (continued)

CALCULATED VALUES FROM E O S FOR HELIUM AT 225.0 K.

PRESS.	VOL.	VIS	ALPHA	C(P)	GAMMA	CHICKS	ENTROPY
KBAR	CC/MOLE	KM/S	°K	J/MOLE-K		°KBAR	J/MOLE-K
2.00	19.569	1.657	2.204E-03	21.331	1.563	1.730E-01	56.86
2.50	17.353	1.730	1.978E-03	21.324	1.523	1.369E-01	54.95
3.00	15.819	1.890	1.802E-03	21.325	1.490	1.106E-01	53.38
3.50	14.682	1.991	1.661E-03	21.331	1.462	9.249E-02	52.07
4.00	13.799	2.085	1.545E-03	21.342	1.433	7.930E-02	50.93
4.50	13.099	2.172	1.447E-03	21.355	1.417	6.930E-02	49.92
5.00	12.501	2.254	1.365E-03	21.371	1.399	6.147E-02	49.03
5.50	12.005	2.331	1.293E-03	21.387	1.383	5.519E-02	48.21
6.00	11.579	2.404	1.231E-03	21.406	1.368	5.005E-02	47.47
6.50	11.208	2.473	1.176E-03	21.425	1.356	4.577E-02	46.79
7.00	10.881	2.540	1.127E-03	21.444	1.344	4.215E-02	46.15
7.50	10.589	2.603	1.084E-03	21.465	1.334	3.905E-02	45.56
8.00	10.327	2.664	1.044E-03	21.485	1.324	3.637E-02	45.00
8.50	10.090	2.722	1.003E-03	21.506	1.316	3.403E-02	44.48
9.00	9.874	2.778	9.766E-04	21.528	1.308	3.196E-02	43.98
9.50	9.677	2.832	9.470E-04	21.550	1.301	3.013E-02	43.51
10.00	9.494	2.885	9.199E-04	21.571	1.294	2.850E-02	43.06
10.50	9.326	2.936	8.943E-04	21.593	1.288	2.703E-02	42.64
11.00	9.169	2.985	8.717E-04	21.616	1.282	2.571E-02	42.23
11.50	9.023	3.033	8.503E-04	21.639	1.277	2.451E-02	41.84
12.00	8.886	3.079	8.302E-04	21.660	1.272	2.341E-02	41.46
12.50	8.759	3.125	8.117E-04	21.683	1.267	2.241E-02	41.10
13.00	8.638	3.169	7.943E-04	21.705	1.263	2.149E-02	40.75
13.50	8.524	3.212	7.780E-04	21.727	1.259	2.064E-02	40.41
14.00	8.416	3.254	7.627E-04	21.750	1.255	1.986E-02	40.09
14.50	8.314	3.295	7.483E-04	21.772	1.251	1.913E-02	39.77
15.00	8.217	3.335	7.347E-04	21.795	1.248	1.845E-02	39.46
15.50	8.124	3.375	7.218E-04	21.817	1.245	1.782E-02	39.17
16.00	8.036	3.413	7.096E-04	21.839	1.242	1.723E-02	38.88
16.50	7.952	3.451	6.981E-04	21.862	1.239	1.668E-02	38.60
17.00	7.872	3.488	6.872E-04	21.884	1.236	1.617E-02	38.32
17.50	7.795	3.524	6.768E-04	21.906	1.234	1.568E-02	38.05
18.00	7.721	3.560	6.669E-04	21.928	1.231	1.522E-02	37.79
18.50	7.650	3.595	6.575E-04	21.950	1.229	1.479E-02	37.54
19.00	7.582	3.629	6.485E-04	21.973	1.227	1.438E-02	37.29
19.50	7.516	3.663	6.399E-04	21.995	1.225	1.400E-02	37.05
20.00	7.453	3.696	6.316E-04	22.017	1.223	1.363E-02	36.81
20.50	7.392	3.729	6.236E-04	22.039	1.221	1.328E-02	36.58
21.00	7.333	3.761	6.162E-04	22.061	1.219	1.295E-02	36.35
21.50	7.276	3.793	6.090E-04	22.082	1.218	1.264E-02	36.12
22.00	7.221	3.824	6.021E-04	22.104	1.216	1.234E-02	35.90
22.50	7.169	3.855	5.954E-04	22.126	1.214	1.205E-02	35.69

TABLE II (continued)

CALCULATED VALUES FROM E D 3 FOR HELIUM AT 250.0 K.

PRESS.	VOL.	ρ	ALPHA	C_P	GAMMA	CHICKS	ENTROPY
KBAR	CC/MOLE	KM ³ /C	°K	J/MOLE-K		°KBAR	J/MOLE-K
2.00	20.649	1.672	2.090E-03	21.250	1.575	1.845E-01	59.11
2.50	19.211	1.791	1.884E-03	21.251	1.536	1.419E-01	57.19
3.00	16.531	1.899	1.723E-03	21.253	1.504	1.146E-01	55.63
3.50	15.291	1.998	1.593E-03	21.269	1.476	9.571E-02	54.31
4.00	14.332	2.090	1.485E-03	21.282	1.453	8.197E-02	53.17
4.50	13.562	2.176	1.394E-03	21.297	1.433	7.155E-02	52.17
5.00	12.927	2.257	1.317E-03	21.314	1.415	6.340E-02	51.27
5.50	12.393	2.333	1.250E-03	21.331	1.399	5.686E-02	50.46
6.00	11.935	2.406	1.191E-03	21.350	1.385	5.151E-02	49.72
6.50	11.537	2.475	1.139E-03	21.369	1.372	4.705E-02	49.04
7.00	11.197	2.541	1.093E-03	21.389	1.361	4.329E-02	48.40
7.50	10.875	2.604	1.051E-03	21.407	1.350	4.006E-02	47.81
8.00	10.596	2.665	1.014E-03	21.427	1.341	3.728E-02	47.26
8.50	10.344	2.723	9.799E-04	21.447	1.332	3.485E-02	46.74
9.00	10.115	2.780	9.490E-04	21.468	1.324	3.271E-02	46.25
9.50	9.905	2.834	9.207E-04	21.489	1.317	3.081E-02	45.79
10.00	9.712	2.887	8.946E-04	21.509	1.310	2.912E-02	45.33
10.50	9.534	2.938	8.706E-04	21.529	1.304	2.760E-02	44.91
11.00	9.369	2.987	8.484E-04	21.549	1.298	2.623E-02	44.50
11.50	9.214	3.035	8.278E-04	21.569	1.293	2.499E-02	44.11
12.00	9.070	3.082	8.085E-04	21.590	1.289	2.386E-02	43.74
12.50	8.935	3.128	7.906E-04	21.610	1.283	2.282E-02	43.39
13.00	8.809	3.172	7.738E-04	21.631	1.279	2.187E-02	43.03
13.50	8.689	3.215	7.580E-04	21.651	1.275	2.100E-02	42.70
14.00	8.576	3.258	7.432E-04	21.671	1.271	2.019E-02	42.37
14.50	8.469	3.299	7.293E-04	21.692	1.267	1.944E-02	42.06
15.00	8.367	3.340	7.161E-04	21.712	1.264	1.874E-02	41.76
15.50	8.270	3.379	7.037E-04	21.732	1.260	1.809E-02	41.46
16.00	8.178	3.418	6.919E-04	21.752	1.257	1.749E-02	41.17
16.50	8.090	3.456	6.807E-04	21.772	1.254	1.692E-02	40.89
17.00	8.006	3.494	6.701E-04	21.792	1.252	1.639E-02	40.62
17.50	7.926	3.530	6.600E-04	21.812	1.249	1.589E-02	40.36
18.00	7.849	3.566	6.504E-04	21.832	1.247	1.542E-02	40.10
18.50	7.775	3.601	6.412E-04	21.852	1.244	1.498E-02	39.85
19.00	7.704	3.636	6.325E-04	21.872	1.242	1.456E-02	39.60
19.50	7.636	3.670	6.241E-04	21.891	1.240	1.416E-02	39.36
20.00	7.570	3.704	6.161E-04	21.911	1.238	1.379E-02	39.12
20.50	7.507	3.737	6.084E-04	21.931	1.236	1.343E-02	38.89
21.00	7.445	3.769	6.011E-04	21.950	1.234	1.309E-02	38.67
21.50	7.386	3.801	5.941E-04	21.969	1.232	1.277E-02	38.45
22.00	7.329	3.833	5.873E-04	21.989	1.231	1.246E-02	38.23
22.50	7.274	3.864	5.808E-04	22.008	1.229	1.217E-02	38.01

TABLE II (continued)

CALCULATED VALUES FROM E O 3 FOR HELIUM AT 275.0 K.

PRESS.	VOL.	W(S)	ALPHA	C(P)	GAMMA	CHI(S)	ENTROPY
KBAR	CC/MOLE	KM/S	/K	J/MOLE-K		/KBAR	J/MOLE-K
2.00	21.726	1.688	1.986E-05	21.178	1.584	1.905E-01	61.13
2.50	19.068	1.803	1.799E-05	21.184	1.547	1.465E-01	59.21
3.00	17.243	1.909	1.651E-05	21.194	1.516	1.182E-01	57.65
3.50	15.900	2.006	1.530E-05	21.208	1.489	9.871E-02	56.34
4.00	14.863	2.097	1.430E-05	21.222	1.466	8.447E-02	55.20
4.50	14.034	2.182	1.345E-05	21.238	1.446	7.367E-02	54.20
5.00	13.352	2.262	1.272E-05	21.255	1.429	6.521E-02	53.30
5.50	12.790	2.337	1.209E-05	21.273	1.413	5.843E-02	52.49
6.00	12.290	2.410	1.154E-05	21.291	1.399	5.289E-02	51.75
6.50	11.865	2.478	1.104E-05	21.309	1.387	4.827E-02	51.07
7.00	11.492	2.544	1.061E-05	21.328	1.376	4.436E-02	50.44
7.50	11.161	2.607	1.021E-05	21.346	1.365	4.103E-02	49.85
8.00	10.864	2.668	9.854E-06	21.365	1.356	3.814E-02	49.30
8.50	10.597	2.726	9.530E-06	21.384	1.347	3.563E-02	48.79
9.00	10.354	2.782	9.234E-06	21.403	1.339	3.342E-02	48.29
9.50	10.133	2.837	8.963E-06	21.422	1.332	3.146E-02	47.82
10.00	9.929	2.890	8.713E-06	21.441	1.325	2.971E-02	47.38
10.50	9.741	2.941	8.483E-06	21.459	1.319	2.814E-02	46.96
11.00	9.567	2.990	8.269E-06	21.478	1.313	2.673E-02	46.55
11.50	9.405	3.039	8.070E-06	21.497	1.308	2.545E-02	46.16
12.00	9.253	3.086	7.885E-06	21.516	1.303	2.428E-02	45.79
12.50	9.112	3.132	7.712E-06	21.535	1.298	2.321E-02	45.43
13.00	8.978	3.176	7.550E-06	21.553	1.294	2.223E-02	45.09
13.50	8.853	3.220	7.398E-06	21.572	1.290	2.133E-02	44.76
14.00	8.735	3.262	7.255E-06	21.590	1.286	2.050E-02	44.43
14.50	8.623	3.304	7.120E-06	21.609	1.282	1.973E-02	44.12
15.00	8.516	3.345	6.992E-06	21.627	1.278	1.902E-02	43.82
15.50	8.415	3.385	6.872E-06	21.645	1.275	1.835E-02	43.53
16.00	8.319	3.424	6.758E-06	21.664	1.272	1.773E-02	43.24
16.50	8.228	3.462	6.649E-06	21.682	1.269	1.715E-02	42.96
17.00	8.140	3.500	6.546E-06	21.700	1.266	1.660E-02	42.69
17.50	8.056	3.537	6.448E-06	21.719	1.264	1.609E-02	42.43
18.00	7.976	3.573	6.355E-06	21.736	1.261	1.561E-02	42.18
18.50	7.899	3.609	6.266E-06	21.754	1.259	1.515E-02	41.92
19.00	7.825	3.644	6.181E-06	21.771	1.256	1.473E-02	41.68
19.50	7.754	3.678	6.100E-06	21.789	1.254	1.432E-02	41.44
20.00	7.686	3.712	6.022E-06	21.807	1.252	1.394E-02	41.21
20.50	7.620	3.745	5.947E-06	21.824	1.250	1.357E-02	40.98
21.00	7.557	3.778	5.876E-06	21.842	1.248	1.323E-02	40.75
21.50	7.495	3.810	5.807E-06	21.859	1.247	1.290E-02	40.53
22.00	7.436	3.842	5.741E-06	21.876	1.245	1.258E-02	40.32
22.50	7.379	3.874	5.678E-06	21.894	1.243	1.229E-02	40.11

TABLE II (continued)

CALCULATED VALUES FROM E O S FOR HELIUM AT 300.0 K.

PRESS.	VOL.	ρ (G)	ALPHA	C_p	GAMMA	CHI(3)	ENTROPY
KBAR	CC/MOLE	KM/C	/K	J/MOLE-K		/KBAR	J/MOLE-K
2.00	22.305	1.705	1.892E-03	21.120	1.592	1.955E-01	62.97
2.50	19.326	1.817	1.721E-03	21.130	1.556	1.508E-01	61.05
3.00	17.954	1.920	1.584E-03	21.142	1.526	1.217E-01	59.49
3.50	16.508	2.016	1.472E-03	21.157	1.500	1.015E-01	58.18
4.00	15.394	2.105	1.379E-03	21.172	1.479	8.662E-02	57.04
4.50	14.506	2.189	1.300E-03	21.189	1.459	7.566E-02	56.04
5.00	13.777	2.268	1.231E-03	21.205	1.441	6.693E-02	55.15
5.50	13.165	2.343	1.171E-03	21.223	1.426	5.993E-02	54.34
6.00	12.644	2.414	1.119E-03	21.240	1.413	5.413E-02	53.60
6.50	12.192	2.483	1.072E-03	21.257	1.400	4.942E-02	52.92
7.00	11.796	2.549	1.030E-03	21.275	1.389	4.539E-02	52.29
7.50	11.445	2.611	9.929E-04	21.293	1.379	4.195E-02	51.71
8.00	11.132	2.671	9.589E-04	21.310	1.370	3.897E-02	51.16
8.50	10.849	2.730	9.279E-04	21.328	1.361	3.638E-02	50.64
9.00	10.593	2.786	8.996E-04	21.346	1.353	3.410E-02	50.15
9.50	10.359	2.840	8.736E-04	21.363	1.346	3.208E-02	49.68
10.00	10.145	2.893	8.497E-04	21.381	1.339	3.028E-02	49.24
10.50	9.947	2.945	8.275E-04	21.398	1.333	2.866E-02	48.82
11.00	9.764	2.994	8.070E-04	21.416	1.327	2.721E-02	48.42
11.50	9.594	3.043	7.879E-04	21.433	1.322	2.589E-02	48.03
12.00	9.435	3.090	7.700E-04	21.450	1.317	2.469E-02	47.66
12.50	9.287	3.136	7.533E-04	21.468	1.312	2.359E-02	47.31
13.00	9.147	3.181	7.377E-04	21.485	1.308	2.259E-02	46.96
13.50	9.016	3.225	7.230E-04	21.502	1.304	2.166E-02	46.63
14.00	8.893	3.268	7.091E-04	21.519	1.300	2.081E-02	46.31
14.50	8.776	3.310	6.961E-04	21.535	1.296	2.002E-02	46.00
15.00	8.665	3.351	6.837E-04	21.552	1.292	1.928E-02	45.70
15.50	8.560	3.391	6.721E-04	21.569	1.289	1.860E-02	45.41
16.00	8.459	3.430	6.610E-04	21.585	1.286	1.796E-02	45.12
16.50	8.364	3.469	6.505E-04	21.602	1.283	1.737E-02	44.85
17.00	8.273	3.507	6.405E-04	21.618	1.280	1.681E-02	44.58
17.50	8.186	3.544	6.310E-04	21.635	1.278	1.628E-02	44.32
18.00	8.103	3.580	6.219E-04	21.651	1.275	1.579E-02	44.06
18.50	8.023	3.616	6.133E-04	21.667	1.273	1.533E-02	43.81
19.00	7.946	3.652	6.050E-04	21.683	1.270	1.489E-02	43.57
19.50	7.872	3.686	5.971E-04	21.699	1.268	1.447E-02	43.33
20.00	7.801	3.721	5.895E-04	21.715	1.266	1.408E-02	43.10
20.50	7.733	3.754	5.823E-04	21.731	1.264	1.371E-02	42.87
21.00	7.667	3.787	5.753E-04	21.747	1.262	1.336E-02	42.65
21.50	7.604	3.820	5.687E-04	21.763	1.260	1.302E-02	42.43
22.00	7.543	3.852	5.623E-04	21.778	1.259	1.270E-02	42.22
22.50	7.483	3.884	5.561E-04	21.794	1.257	1.240E-02	42.01

Fig. 6.

Molar volume of fluid ^4He vs pressure along five isotherms computed from Eq. (1) using the 148-L set of constants in Table I. Solid line, 300 K; dotted line, 250 K; dashed line, 200 K; short-dashed line, 150 K; and dash-dot line, 100 K.

Fig. 7.

Sound velocity of fluid ^4He vs pressure along five isotherms computed from Eqs. (1), (2), (3), and (4) using the 148-L set of constants in Table I. Symbols are the same as in Fig. 6.

Fig. 8.

Isobaric thermal expansion coefficient of fluid ^4He vs pressure along five isotherms computed from Eqs. (1) and (5). Symbols are the same as in Fig. 6.

Fig. 9.

Heat capacity at constant pressure of fluid ^4He vs pressure along five isotherms computed from Eqs. (1), (2), and (3). Symbols are the same as in Fig. 6.

Fig. 10.

Heat capacity at constant volume of fluid ^4He vs pressure along five isotherms computed from Eqs. (1), (3), and (7). Symbols are the same as in Fig. 6.

Fig. 11.

Specific heat ratio of fluid ^4He vs pressure along five isotherms computed from the EOS. Symbols are the same as in Fig. 6.

Fig. 12.

Isothermal compressibility coefficient of fluid ^4He vs pressure along five isotherms computed from Eqs. (1), (7), and (8). Symbols are the same as in Fig. 6.

Fig. 13.

Adiabatic compressibility coefficient of fluid ^4He vs pressure along five isotherms computed from Eqs. (1) and (8). Symbols are the same as in Fig. 6.

Fig. 14.

Molar entropy of fluid ^4He pressure along five isotherms computed from the EOS. Symbols are the same as in Fig. 6.

COMPARISONS WITH PREVIOUS RESULTS

The compressibility measurements of Tsiklis, Maslennikova and Gluvka⁶ were made in the range 293–323 K up to 7 kbar. At 2 kbar the molar volume is 22.510 cm^3 from our EOS and 22.56 cm^3 from Ref. 6. At higher pressures the agreement is not so good, being 15.249 compared with 15.40 cm^3 at 4 kbar and 11.713 compared with 11.98 cm^3 at 7 kbar. The errors in molar volume reported in Ref. 6 of 0.5% to 0.3% with increasing pressure, combined with our errors, do not allow the data at the higher pressures to be reconciled. Other comparisons are given in Ref. 14.

Ultrasonic measurements have been made along a single isotherm by Nishitake and Hanayama⁷ up to 10 kbar at 298.2 K, up to 4 kbar over the range 298–473 K by Pitaevskaya and Bilevich,¹⁶ and up to 3.5 kbar at 298.2 K by Vereshchagin et al.¹⁷ The values in Ref. 7 are within the reported errors of 3% in sound velocity, i.e., 0.5% smaller than our value at 3 kbar and 1.3% smaller at 10 kbar. At 2 and 4 kbar the data in Ref. 16 are 3.2% lower and 0.9% lower respectively. At the higher pressure of Ref. 16, we are

in approximate agreement within the combined errors of $\pm 0.8\%$. In the small region of overlap, the values of Ref. 17 are within their stated error of 2% of those reported here.

Few theoretical calculations of the EOS for helium have been made, but a recent EOS computed from a modified Lennard-Jones potential has been reported by Ashurst.¹⁸ Comparison is shown in Table III. His sound velocities deviate from ours by almost 8% over the temperature and pressure range of the data. At low pressures, however, where the potential has been adjusted, the agreement is very good. The errors in molar volume diminish with increasing pressure, apparently in response to an adjustment of the theory to fit the compressibilities at low pressure. As in the case of hydrogen,^{15,18} the calculated molar volume and sound velocity generally do not agree with the experimental values within the estimated errors of measurements, though for helium the large differences in molar volume at low pressure are hard to understand.

From our data for helium and deuterium,¹² we can test the kinetic theory scaling law for the case where the velocity-of-sound ratio v_{D_2}/v_{He} is about unity. At 300 K the ratio is 1.202 at 20 kbar and 1.192 at 4 kbar, a variation of less than 1% over the pressure range. At 100 K and 4 kbar the ratio is 1.28 and varies between 1.19 and 1.28 over the full data range. The variation is greater in the calculated values of Ref. 18 and the magnitude of the ratio is outside the limits of kinetic theory.

TABLE III
VOLUME AND SOUND VELOCITY FROM PRESENT EOS COMPARED
WITH VALUES FROM REF. 18

T K	P kbar	$V_{present}$ cm ³ mole ⁻¹	$V_{Ashurst}$ cm ³ mole ⁻¹	v_s present km s ⁻¹	v_s Ashurst km s ⁻¹
298	4 kbar	15.355	14.71	2.104	2.108
298	10	10.129	9.86	2.893	3.000
298	20	7.793	7.72	3.720	3.973
100	4	11.140	10.63	2.099	2.093
100	10	8.382	8.09	2.905	3.024
100	20	6.839	6.80	3.682	3.955

These results compare favorably with a recent computation by Gavrilov and Ivashchenko,⁴ where deviations of 2.2% and 3.2% are reported, respectively, for compressibility and sound velocity against measurements up to 1 kbar. Since there is no direct overlap of measurements the close fit of our extrapolated EOS to lower pressure results is gratifying.

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