

21. Density and Compressibility of Liquids¹

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Symbols

B^*	complex compressibility
B'	Re B^*
B''	Im B^*
c_s	adiabatic velocity of sound
c	velocity of sound
C_P	specific heat at constant pressure
$d_{t_1}^{t_2}$	specific gravity (t_1 is temperature of liquid; t_2 is temperature of standard)
K	instantaneous bulk modulus
K^*	complex bulk modulus
K'	Re K^*
K''	Im K^*
P	pressure
S	entropy
T	absolute temperature
t	Celsius temperature
v	specific volume
v_0	specific volume in reference state
α_P	isobaric coefficient of volume expansivity
β	instantaneous compressibility
β_s	adiabatic compressibility
β_T	isothermal compressibility
ρ	density
ρ_0	density at reference state

21-1. Density of Liquids. Introduction. The density of a homogeneous liquid is defined as the mass per unit volume. The specific volume is the reciprocal of the density. Density can be expressed in either an absolute or a relative scale. The SI (Système International) absolute units are kilograms per cubic meter, and the cgs absolute units are grams per cubic centimeter. Before 1964 the liter was defined as the volume required to contain one kilogram of water at 3.98°C and 760 mm Hg pressure, equal to 1.000028 cubic decimeters. In 1964² the liter was redefined to be exactly equal to the cubic decimeter. This difference of 28 parts per million may be

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² *Proc. 12th General Conf. Weights and Measures*, Paris, p. 21, Oct. 6-13, 1964.

significant in measurements of high accuracy. Accordingly, in order to avoid misunderstanding, it has been recommended that for volume measurements of high accuracy the units be expressed in cubic meters or their submultiples, in lieu of liters or their submultiples. The following tables which express densities in grams per milliliter have not been corrected. In cases where accurate data are required, the original source should be consulted to determine the correct units. Table 21-1 gives the conversion factors for the density units most commonly used.

TABLE 21-1. CONVERSION FACTORS FOR DENSITY UNITS*

Units	kg/m ³ (SI)	g/cm ³ (cgs)	g/ml (old)	lb/ft ³	lb/in ³
1 kg/m ³ (SI)	1	10 ⁻³	1.000028 × 10 ⁻³	6.24280 × 10 ⁻²	3.61273 × 10 ⁻⁵
1 g/cm ³ (cgs)	10 ³	1	1.000028	62.4280	3.61273 × 10 ⁻²
1 g/ml (old)	9.99972 × 10 ²	0.999972	1	62.4262	3.61263 × 10 ⁻²
1 lb/ft ³	16.0185	1.60185 × 10 ⁻²	1.60189 × 10 ⁻²	1	5.75704 × 10 ⁻⁴
1 lb/in ³	2.76799 × 10 ⁴	27.6799	27.6807	1.72800 × 10 ³	1

* Conversions to SI units taken from ASTM Metric Practice Guide, U.S. Department of Commerce, *Natl. Bur. Standards Handbook 102*, 38 (Mar. 10, 1967).

For expressing densities on a relative scale the specific gravity is used. The specific gravity gives the ratio of the density of a liquid at a particular temperature to the density of a standard liquid (usually pure water) at a standard temperature. The conventional symbol for absolute density is ρ or d . The former will be used in this set of tables. The conventional symbol for specific gravity is $d_{t_1}^{t_2}$ where t_1 is the temperature of the liquid and t_2 is the temperature of the standard.

21-2. Methods of Measurement. The pycnometer method is most commonly used when precise density measurements on a particular liquid are desired at fixed temperature.¹ A pycnometer is a vessel made of glass with a low coefficient of expansion whose volume can be determined very precisely in terms of its capacity for a standard liquid. Most pycnometers have a capacity of about 30 ml. The general procedure consists in filling the pycnometer with the unknown liquid, thermostating the system at the desired temperature, determining the volume of the pycnometer occupied by the liquid, and then weighing the pycnometer. For accurate work air buoyancy corrections should be applied. For determining densities of the same sample over a range of temperatures, the dilatometer method is sometimes used. In one variation of this method a secondary standard liquid such as mercury is placed in contact with the liquid sample. As the temperature is raised, the secondary liquid is displaced out of the dilatometer. The weight of the displaced secondary liquid is a measure of the change in volume of the unknown liquid. Another variation of this method involves the observation of the change in level of the unknown liquid in a narrow calibrated capillary attached to the main flask. (The measurements of densities of liquefied gases at or near their boiling points are more complicated, since a closed system may have to be used and significant corrections must be made for the density of the vapor in equilibrium with the liquid.²) Where less accuracy is required, hydrostatic weighing methods³ and hydrometers are expedient. Hydrostatic weigh-

¹ A. Johnson, *J. Research Natl. Bur. Standards* 69C, 1 (1965).

² W. H. Keelson, "Helium," pp. 206ff., American Elsevier Publishing Company, Inc., New York, 1942; E. R. Grilly, E. F. Hammel, and S. G. Sydoriak, *Phys. Rev.* 75, 1103 (1949); E. R. Grilly, *J. Am. Chem. Soc.* 73, 5307 (1951).

³ H. A. Bowman and R. M. Schoonover, *J. Research Natl. Bur. Standards* 71C, 179 (1967). (Although this reference is strictly applicable to solids, many of the procedures described here are also applicable to liquids.)

ing involves obtaining the apparent weight of solids (weights) of known mass and density submerged in the liquid from an analytical (or Westphal) balance on a thin wire or thread. A hydrometer is simply a calibrated float which reads the density directly. The performance of the last two methods is impaired by surface tension. Modifications which avoid this are the flotation and the elastic helix methods. The flotation method involves the adjustment of a submerged weight to the same average density as the density of the unknown liquid. At this point the weight will neither sink nor float. Alternatively, a balance is sometimes obtained by appropriately adjusting the temperature of the liquid. The method is tedious, but high accuracy can be obtained. In one version¹ a known electric current producing a magnetic field is adjusted until an iron weight suspended in the field and submerged in the liquid is stationary. With the elastic helix a weight is suspended in the unknown liquid from a completely submerged coil often made of quartz. The density of the liquid is related to the length of the helix.

The falling-drop method has been used recently on molten metals² and for the isotopic analysis of water.³ This method involves measuring the transit time, usually at terminal velocity, of a drop of liquid sample falling within an immiscible liquid or gas. In another version⁴ the volume of a falling drop of molten metal is determined by measuring the dimensions of its profile from a photograph.

The radiation method,⁵ for which the gamma radiation from an irradiated isotope is claimed to be proportional to its density, has been used successfully on liquids at high temperatures. References⁶ are recommended for more detailed and general discussion on most of the methods mentioned above.

21-3. Reliability. The reliability of the density measurements tabulated is variable. This compilation does not pretend to evaluate for extreme accuracy. Such factors as uncertainty in the temperature scale, possible impurities of the samples, and in some cases even changes in atomic weights must be taken into consideration when applying a critical analysis. The data are given as reported in the original literature or in other standard works and are to be interpreted in the spirit of being representative values. Reference to the original literature is recommended in cases of doubt.

21-4. Selected Reference Works with Density Data

- "International Critical Tables," McGraw-Hill Book Company, New York, 1928.
 Landolt-Börnstein: "Zahlenwerte und Funktionen aus Physik, Chemie, Astronomie, Geophysik, Technik," 6th ed., Springer Verlag, Berlin, 1950—
 Timmermans, J.: "Physico-chemical Constants of Pure Organic Compounds," American Elsevier Publishing Company, Inc., New York, vol. 1, 1950; vol. 2, supplement, 1965.
 Timmermans, J.: "The Physico-chemical Constants of Binary Systems in Concentrated Solutions," 4 vols., Interscience Publishers, Inc., New York, 1959-1960.
 Mellor, J. W.: "Comprehensive Treatise of Inorganic and Theoretical Chemistry," Longmans, Green & Co., Ltd., London, 16 vols., 1921-1937; supplements, 1956-1967.
 Simons, J. H., ed.: "Fluorine Chemistry," Academic Press, Inc., New York, 1950.
 Lyon, R. N., ed.: "Liquid Metals Handbook," U.S. Atomic Energy Commission and Bureau of Ships, Chap. 2, 1952; Sodium-NaK Supplement, 1955.

¹ F. J. Millero, Jr., *Rev. Sci. Instr.* **38**, 1441 (1967).

² Y. V. Naidich and V. N. Eremenko, *Fiz. Metal. i Metalloved.* (USSR) **11**, 883 (1961); English translation in *Phys. Metals Metallog.* **11**(6), 62 (1961).

³ M. Pascalau, L. Blaga, and L. Blaga, *J. Sci. Instr.* **43**, 310 (1966).

⁴ A. E. El-Mehairy and R. G. Ward, *Trans. Met. Soc. AIME* **227**, 1226 (1963).

⁵ I. G. Dillon, P. A. Nelson, and B. S. Swanson, *J. Chem. Phys.* **44**, 4229 (1966); *Rev. Sci. Instr.* **37**, 614 (1966).

⁶ P. Hidnert and E. L. Peffer, *Natl. Bur. Standards Circ.* 487 (Mar. 15, 1950); N. Bauer, Chap. 6 in "Physical Methods of Organic Chemistry," vol. I, A. Weissberger, ed., Interscience Publishers, Inc., New York, 1949; J. Reilly and W. N. Rae, "Physico-chemical Methods," vol. I, pp. 609-628, D. Van Nostrand Company, Inc., Princeton, N.J., 1953.

Stewart, R. B., and V. J. Johnson, eds.: "Compendium of the Properties of Materials at Low Temperature" (Phase I), Wright Air Force Development Division Technical Report, 1961.

Morey, G. W.: "The Properties of Glass," Reinhold Book Corporation, New York, 1954.

Janz, G. J.: "Molten Salts Handbook," Academic Press, Inc., New York, 1967.

Janz, G. J., F. W. Dampier, G. R. Lakshminarayanan, P. K. Lorenz, and R. P. T. Tomkins: Molten Salts: vol 1, Electrical Conductance, Density, and Viscosity Data, *Natl. Bur. Standards Ref. Data Ser.* 15. October, 1968.

The following contain tabulated sheets published periodically:

Zwolinski, B. J.: "Selected Values of Properties of Hydrocarbons and Related Compounds,"¹ Thermodynamics Research Center, Texas A&M University, College Station, Texas, 1966—.

Zwolinski, B. J.: "Selected Values of Properties of Chemical Compounds," Thermodynamics Research Center, Texas A&M University, College Station, Texas, 1966—.

Zwolinski, B. J.: "Selected Data on Thermodynamics and Spectroscopy," Thermodynamics Research Center, Texas A&M University College Station, Texas, 1969—.

21-5. Density of Water. A rather complete analysis of all the investigations of the physical properties of water is given by N. Ernest Dorsey.² He points out that the data from which the density tables are made up do not take into consideration the isotope effect. Because of this there may be uncertainties of the order of 8 parts in 10^7 introduced when the densities of samples from various sources are considered. The removal of deuterium from an average sample of distilled water increases the density by about 17 parts per million. There is also some reason to believe that the polymerization is a factor in the variability of the physical properties of water. Values of the density of water as a function of temperature are presented in Table 21-2.

¹ American Petroleum Institute Project 44.

² N. Ernest Dorsey, "Properties of Ordinary Water Substance," Reinhold Book Corporation, New York, 1948.

TABLE 21-2. DENSITY OF PURE AIR-FREE H₂O AT ATMOSPHERIC PRESSURE
($\rho = \text{g/ml}^*$; $t = ^\circ\text{C}$)

Range 0-40°C†										
t	ρ	t	ρ	t	ρ	t	ρ	t	ρ	
0	0.9998676	5	0.9999919	10	0.9997281	15	0.9991286	20	0.9982336	
1	0.9999265	6	0.9999683	11	0.9996336	16	0.9989721	21	0.9980221	
2	0.9999678	7	0.9999297	12	0.9995261	17	0.9988041	22	0.9978003	
3	0.9999922	8	0.9998765	13	0.9994059	18	0.9986248	23	0.9975684	
4	1.0000	9	0.9998092	14	0.9992732	19	0.9984346	24	0.9973266	
t	0.0	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
15	0.9991286	1134	0982	0828	0674	0518	0360	0202	0043	9882
16	0.9989721	9558	9394	9229	9062	8895	8726	8557	8386	8214
17	0.9988041	7867	7691	7515	7337	7158	6979	6798	6616	6433
18	0.9986248	6063	5877	5689	5501	5311	5120	4928	4735	4541
19	0.9984346	4150	3953	3754	3555	3355	3153	2950	2747	2542
20	0.9982336	2130	1922	1713	1503	1292	1080	0867	0653	0438
21	0.9980221	0004	9786	9567	9346	9125	8903	8679	8455	8230
22	0.9978003	7776	7547	7318	7088	6856	6624	6390	6156	5921
23	0.9975684	5447	5208	4969	4729	4487	4245	4002	3758	3512
24	0.9973266	3019	2771	2522	2272	2021	1769	1516	1262	1007
25	0.9970751	0494	0237	9978	9718	9458	9196	8934	8671	8406
t	ρ	t	ρ	t	ρ					
26	0.9968141	31	0.9953722	36	0.9937159					
27	0.9965437	32	0.9950575	37	0.9933604					
28	0.9962642	33	0.9947344	38	0.9929970					
29	0.9959757	34	0.9944030	39	0.9926260					
30	0.9956783	35	0.9940635	40	0.9922473					
Range 40-100°C‡										
t	ρ	t	ρ	t	ρ					
40	0.99224	65	0.98059	90	0.96534					
45	0.99024	70	0.97781	95	0.96192					
50	0.98807	75	0.97489	100	0.95838					
55	0.98573	80	0.97183							
60	0.98324	85	0.96865							
Range 100-370°C§										
t	ρ	t	ρ	t	ρ					
100	0.95841	190	0.87639	280	0.75063					
110	0.95099	200	0.86492	290	0.73237					
120	0.94317	210	0.85290	300	0.71266					
130	0.93494	220	0.84031	310	0.69118					
140	0.92629	230	0.82712	320	0.66747					
150	0.91721	240	0.81330	330	0.64095					
160	0.90771	250	0.79881	340	0.61071					
170	0.89776	260	0.78368	350	0.57497					
180	0.88733	270	0.76769	360	0.52872					

TABLE 21-2. DENSITY OF PURE AIR-FREE H₂O AT
ATMOSPHERIC PRESSURE (Continued)
Range 0 to -13°C¶

<i>t</i>	ρ	<i>t</i>	ρ	<i>t</i>	ρ
0	0.999868	-5	0.999176	-10	0.997935
-1	0.999773	-6	0.998950	-11	0.997636
-2	0.999673	-7	0.998720	-12	0.997292
-3	0.999553	-8	0.998501	-13	0.997292
-4	0.999380	-9	0.998249		

For a comparative study and density values over this range expressed in SI units, see P. H. Bigg, *Brit. J. Appl. Phys.* **18**, 521 (1967).

* These data have not been corrected in terms of the new definition of the liter (Sec. 21-1). For the conversion factor, see Table 21-1.

† L. W. Tilton and J. K. Taylor, *J. Research Natl. Bur. Standards* **18**, 205 (1937).

‡ V. Stott and P. H. Bigg, "International Critical Tables," vol. 3, p. 24, McGraw-Hill Book Company, New York, 1928.

§ F. G. Keyes and L. B. Smith, *Mech. Eng.* **53**, 132 (1931).

¶ J. F. Mohler, *Phys. Rev.* **35**, 236 (1912).

TABLE 21-3. DENSITY OF D₂O (100% D₂O WITH NORMAL OXYGEN ISOTOPE COMPOSITION)
($\rho = \text{g/ml}^*$; $t = ^\circ\text{C}$)
Range 3.8–20°C†

t	ρ
3.8	1.10533
5	1.10549
10	1.10588
15	1.10577
20	1.10527

Range 20–100°C‡

t	ρ	t	ρ	t	ρ
20	1.10530	50	1.09562	80	1.07815
25	1.10437	55	1.09316	85	1.07467
30	1.10315	60	1.09051	90	1.07104
35	1.10167	65	1.08766	95	1.06729
40	1.09989	70	1.08466	100	1.06339
45	1.09786	75	1.08148		

Range 90–250°C§

t	ρ	t	ρ	t	ρ
90	1.0708	150	1.0167	210	0.943
100	1.0630	160	1.0058	220	0.928
110	1.0547	170	0.9950	230	0.913
120	1.0459	180	0.9826	240	0.897
130	1.0366	190	0.970	250	0.881
140	1.0268	200	0.957		

For additional data on H₂O¹⁸, D₂O, and D₂O¹⁸, see: F. Steckel and S. Szapiro, *Trans. Faraday Soc.* **59**, 331 (1963).

* These data have not been corrected in terms of the new definition of the liter (Sec. 21-1). For the conversion factor, see Table 21-1.

† T. L.-Chang and J. Y. Chien, *J. Am. Chem. Soc.* **63**, 1709 (1941).

‡ R. Schrader and K. Wirtz, *Z. Naturforsch.* **6a**, 220 (1951).

§ J. R. Heiks, M. K. Barnett, L. V. Jones, and E. Orban, *J. Phys. Chem.* **58**, 488 (1954).

The maximum density of D₂O has been determined to be 1.10596 g/ml at 11.23°C. K. Stokland, E. Ronaess, and L. Tronstad, *Trans. Faraday Soc.* **35**, 312 (1938). This is based on a value for d_{20}^{20} of 1.10764. L. Tronstad and Brun, *Trans. Faraday Soc.* **34**, 766 (1938). See H. L. Johnston, *J. Am. Chem. Soc.* **61**, 878 (1939), for a discussion of these values.

The density of H₂O and D₂O at 370°C are approximately the same. E. H. Riesenfeld and T. L.-Chang, *Z. physik. Chem.* **B30**, 61 (1935); **B28**, 408 (1935).

TABLE 21-4. DENSITY OF MERCURY (Hg)
 ($\rho = \text{g. ml}^*$; $t = ^\circ\text{C}$)
 Range -38.87 to $100^\circ\text{C}^\dagger$

t	ρ	t	ρ
-38.87	13.691 ₉	24	13.536 ₄
-30	13.669 ₃	25	13.534 ₀
-20	13.645 ₃	30	13.521 ₈
-10	13.620 ₂	35	13.509 ₆
0	13.595 ₃	40	13.497 ₃
5	13.583 ₂	45	13.485 ₁
10	13.570 ₉	50	13.472 ₉
15	13.558 ₆	55	13.460 ₈
16	13.556 ₂	60	13.448 ₆
17	13.553 ₇	65	13.436 ₅
18	13.551 ₃	70	13.424 ₃
19	13.548 ₃	75	13.412 ₂
20	13.546 ₃	80	13.400 ₁
21	13.543 ₉	85	13.388 ₀
22	13.541 ₃	90	13.375 ₉
23	13.538 ₉	95	13.363 ₉
		100	13.351 ₈

Range $100-360^\circ\text{C}^\ddagger$

t	ρ	t	ρ	t	ρ
100	13.3518	200	13.113	300	12.875
120	13.304	220	13.065	320	12.827
140	13.256	240	13.018	340	12.779
160	13.208	260	12.970	357.1	12.737
180	13.160	280	12.922		

* These data have not been corrected in terms of the new definition of the liter (Sec. 21-1). For the conversion factor, see Table 21-1.

† Stott and Bigg, "International Critical Tables," vol. 2, p. 457, McGraw-Hill Book Company, New York, 1928; Sears, *Proc. Phys. Soc. (London)* **26**, 95 (1913).

‡ G. M. C. Kaye and T. H. Laby, "Tables of Physical and Chemical Constants," 10th ed., Longmans, Green & Co., Ltd., London, 1948; Chappuis, "Travaux et mémoires du bureau international des poids et mesures," vol. 16, 1917.

TABLE 21-5. DENSITY OF METHYL ALCOHOL (CH₃OH)
(ρ = g/ml*; t = °C)

Density at Fixed Points

t	ρ
0	0.809985†
5	0.80535†
25	0.78654†
25	0.78655‡
30	0.78181†

Density as a Function of Temperature

Range 0-60°C§	
t	ρ
0	0.80999
5	0.80536
10	0.80070
15	0.79602
20	0.79132
25	0.78660
30	0.78186
35	0.77710
40	0.77232
45	0.76753
50	0.76270
60	0.75300

These data fit a formula

$$\rho = 0.80999 - 0.0009253t - 0.00000041t^2 \quad (21-1)$$

Range -94.5 to 15°C¶

$$\rho = 0.81015 - 0.0010041t - 0.000001802t^2 - 0.00000001657t^3 \quad (21-2)$$

* These data have not been corrected in terms of the new definition of the liter (Sec. 21-1). For the conversion factor, see Table 21-1.

† A. Rakowski and A. B. Frost. *Trans. Inst. Pure Chem. Reagents U.S.S.R.* 9(334). 95 (1930).

‡ R. E. Gibson, *J. Am. Chem. Soc.* 57, 1551 (1935).

§ Brunel and Van Bibber, "International Critical Tables," vol. 3, p. 27, McGraw-Hill Book Company, New York, 1928.

¶ J. Timmermans, *Sci. Proc. Roy. Dublin Soc.* 13, 310 (1912).

TABLE 2I-6. DENSITY OF ETHYL ALCOHOL (C₂H₅OH) $(\rho = \text{g/ml}^a; t = \text{°C})$

Density at Fixed Points

t	ρ
0	0.806300 ^b
25	0.785063 ^b
25	0.78506 ^c
50	0.763137 ^b

Density as a Function of Temperature

Range 10-40°C^d

t	ρ
10	0.79784
15	0.79360
20	0.78934
25	0.78506
30	0.78075
35	0.77641
40	0.77203

These data fit a formula

$$\rho = 0.78506 - 0.0008591(t - 25) - 0.00000056(t - 25)^2 - 0.000000005(t - 25)^3 \quad (2I-3)$$

Range 45-78°C^e

t	ρ
45	0.76773
50	0.76329
60	0.75423
70	0.74491
78	0.73720

These data fit a formula

$$\rho = 0.80625 - 0.0008461t + 0.000000160t^2 - 0.0000000085t^3 \quad (2I-4)$$

Range below 0°C^f

t	ρ
-59	0.856
-78	0.872

^a These data have not been corrected in terms of the new definition of the liter (Sec. 2I-1). For the conversion factor, see Table 2I-1.

^b Kretschmer, Nowakowska, and Wieba, *J. Am. Chem. Soc.* **70**, 1785 (1948).

^c N. S. Osborne, E. C. McKelvey, and H. W. Bearce, *Natl. Bur. Standards (U.S.) Bull.* **9**, 327 (1913).

^d N. S. Osborne, E. C. McKelvey, and H. W. Bearce, *Natl. Bur. Standards (U.S.) Bull.* **9**, 327 (1913).

^e Brunel and Van Bibber, "International Critical Tables," vol. 3, p. 27, McGraw-Hill Book Company, New York, 1928.

^f Beilstein, "Organische Chemie," vol. 1, p. 148, 1928.

TABLE 21-7. DENSITIES OF SELECTED INORGANIC LIQUIDS
(Range 0-50°C; ρ = g/ml; t = °C; pressure atmospheric)

Substance	Formula	t	ρ	Year	Ref.
Antimony pentachloride.....	SbCl ₅	20	2.336	1915	1
Antimony pentafluoride.....	SbF ₅	23	2.99	1904	2
Arsenic tribromide.....	AsBr ₃	25	3.540	1893	3
Arsenic trichloride.....	AsCl ₃	20	2.161	1880	3
Arsenic trifluoride.....	AsF ₃	20	2.590	1880	3
Boron tribromide.....	BBr ₃	0	2.650	1893	4
Boron trichloride.....	BCl ₃	11	1.3493	1927	5
Boron triiodide.....	BI ₃	50	3.3	1891	6
Bromine pentafluoride.....	BrF ₅	25	2.4604	1954	7
Bromine trifluoride.....	BrF ₃	25	2.8030	1954	7
Carbonyl chloride.....	COCl ₂	0	1.4187	1946	8
Dicarbon tetrachloride.....	C ₂ Cl ₄	20	1.6226	1880	9
Carbon disulfide.....	CS ₂	20	1.2632	1926	10
Carbon oxysulfide.....	COS	0	1.073	1932	11
Carbon selenide sulfide.....	CSeS	20	1.9874	1929	12
Carbon suboxide.....	C ₃ O ₂	0	1.114	1908	13
Carbon tetrachloride.....	CCl ₄	20	1.5940	1938	14
Chlorine dioxide.....	ClO ₂	0	1.642	1930	15
Perchloric acid.....	HClO ₄	20	1.7676	1906	16
Chlorosulfonic acid.....	HCISO ₃	20	1.753	1912	17
Chlorine trifluoride.....	ClF ₃	0	1.891	1950	18
Chromium oxychloride.....	CrO ₂ Cl ₂	20	1.923	1880	3
Germanium oxychloride.....	GeOCl ₂	20	2.057	1931	19
Germanium tetrachloride.....	GeCl ₄	20	1.879	1926	20
Bromogermane.....	GeH ₃ Br	29.5	2.34	1929	21
Dibromogermane.....	GeH ₂ Br ₂	0	2.80	1929	21
Trichlorogermane.....	GeHCl ₃	0	1.93	1926	20
Hydrazine.....	NH ₂ NH ₂	0	0.9816	1950	22
Hydrogen disulfide.....	H ₂ S ₂	25	1.3270	1930	23
Hydrogen fluoride.....	HF	0	1.0015	1933	24
Hydrogen pentasulfide.....	H ₂ S ₅	16	1.67	1928	25
Hydrogen peroxide.....	H ₂ O ₂	19.9	1.4419	1920	26
Hydrogen trisulfide.....	H ₂ S ₃	15	1.496	1908	27
Iodine heptafluoride.....	IF ₇	6	2.8	1930	28
Iodine pentafluoride.....	IF ₅	0	3.29	1933	29
Iron pentacarbonyl.....	Fe(CO) ₅	18	1.4644	1891	30
Lead tetrachloride.....	PbCl ₄	0	3.18	1893	31
Molybdenum fluoride.....	MoF ₆	27	2.503	1931	32
Nickel carbonyl.....	Ni(CO) ₄	20	1.310	1891	3
Nitric acid (100%).....	HNO ₃	20	1.502	1919	3
Nitrogen dioxide.....	NO ₂	20	1.348	1919	3
Dinitrogen oxide.....	N ₂ O	0	1.450	1888	3
Osmium tetroxide.....	OsO ₄	43	4.322	1931	33
Phosphorus tribromide.....	PBr ₃	20	2.877	1845	3
Phosphorus trichloride.....	PCl ₃	20	1.575	1880	3
Phosphorus oxychloride.....	POCl ₃	20	1.675	1880	3

TABLE 21-7. DENSITIES OF SELECTED INORGANIC LIQUIDS (Continued)

Substance	Formula	<i>t</i>	ρ	Year	Ref.
Rhenium hexafluoride.....	ReF ₆	18.8	3.616	1934	34
Rhenium oxytetrafluoride.....	ReOF ₄	39.7	3.717	1934	34
Selenic acid.....	H ₂ SeO ₄	15	2.602	1889	35
Selenium monochloride.....	Se ₂ Cl ₂	17.5	2.906	1884	36
Selenium oxychloride.....	SeOCl ₂	20	2.434	1931	37
Selenium oxyfluoride.....	SeOF ₂	20	2.67	1928	38
Selenium tetrafluoride.....	SeF ₄	20	2.77	1928	39
Tribromosilane.....	SiHBr ₃	17	2.7	1880	40
Tribromochlorosilane.....	SiBr ₃ Cl	20	2.434	1887	41
Trichlorosilane.....	SiHCl ₃	20	1.34	1905	42
Triiodosilane.....	SiHI ₃	23	3.286	1908	43
Trisilane.....	Si ₃ H ₈	0	0.725	1916	44
Tetrasilane.....	Si ₄ H ₁₀	0	0.79	1916	44
Silicon tetrabromide.....	SiBr ₄	18.6	2.7889	1931	45
Silicon tetrachloride.....	SiCl ₄	20	1.4812	1926	46
Stannic chloride.....	SnCl ₄	20	2.229	1932	47
Sulfuric acid.....	H ₂ SO ₄	20	1.834	1923	3
Sulfur dichloride.....	SCl ₂	19	1.606	1908	48
Sulfur monobromide.....	S ₂ Br ₂	20	2.6355	1903	49
Sulfur monochloride.....	S ₂ Cl ₂	20	1.678	1880	3
Sulfur trioxide.....	SO ₂	20.46	1.9207	1941	50
Disulfur decafluoride.....	S ₂ F ₁₀	0	2.08	1934	51
Sulfuryl chloride.....	SO ₂ Cl ₂	20	1.673	1897	3
Sulfuryl chloride fluoride.....	SO ₂ FCl	0	1.623	1936	52
Thionyl bromide.....	SOBr ₂	18	2.68	1893	53
Thionyl chloride.....	SOCl ₂	20	1.638	1880	3
Thiocarbonyl tetrabromide.....	CSBr ₄	20	3.0240	1929	54
Thiocarbonyl tetrachloride.....	CSCl ₄	20	1.6996	1929	54
Trithiocarbonic acid.....	H ₂ CS ₃	17	1.47	1928	25
Pyrosulfurylchloride.....	S ₂ O ₃ Cl ₂	20	1.837	1912	17
Thallium-mercury amalgam.....	Tl ₂ Hg ₃	25	12.94	1928	55
Titanium tetrachloride.....	TiCl ₄	20	1.730	1932	47
Tungsten hexafluoride.....	WF ₆	19	3.419	1931	32
Vanadium oxytrichloride.....	VOCl ₃	20	1.828	1910	3

For general references, see Sec. 21-4.

For data on molten optical glasses, see: L. Sharsis, and S. Spinner, *J. Research Natl. Bur. Standards* **46**, 176 (1951).

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TABLE 21-8. LIQUID DENSITIES OF ELEMENTARY AND INORGANIC SUBSTANCES WHICH ARE NORMALLY GASEOUS UNDER STANDARD CONDITIONS (Range below 0°C; ρ = g/ml; t = °C; pressure atmospheric*)

Substance	Formula	t	ρ	Year	Ref.
Air.....	20.9% oxygen	-194	0.92	....	1
	53.6% oxygen	-194	1.015	....	1
	72.15% oxygen	-194	1.068	....	1
	94.4% oxygen	-194	1.133	....	1
Ammonia.....	NH ₃	-40	0.6900	1923	24
Argon.....	Ar	-189.38 (T.P.)	1.4195	1940	2
		-183.15	1.3740	1912	14
Boron trifluoride.....	BF ₃	-101.0 (N.B.P.)	1.595	1932	3
Diborane.....	B ₂ H ₆	-108.2	0.4542	1941	4
Carbon dioxide.....	CO ₂	-56.6 (T.P.)	1.179	1928	5
Carbon monoxide.....	CO	-195.08 (ortho- baric)	0.80640	1936	6
Chlorine.....	Cl ₂	-33.7 (N.B.P.)	1.568	1909	7
		-40	1.574	1926	8
Fluorine.....	F ₂	-195.94	1.562 ₂	1954	9
Hydrogen bromide.....	HBr	-68.7	2.157	1906	10
Hydrogen chloride.....	HCl	-85.8	1.1937	1906	10
Hydrogen iodide.....	HI	-35.7 (N.B.P.)	2.799	1906	10
Hydrogen selenide.....	H ₂ Se	-42	2.12	1902	13
		-27 (orthobaric)	1.061	1032	12
Hydrogen sulfide.....	H ₂ S	-60.1 (N.B.P.)	0.964	1906	10
		-63	0.9539	1932	11
Hydrogen telluride.....	H ₂ Te	-17.7	2.701	1932	12
Krypton.....	Kr	-157.21 (T.P.)	2.4525	1940	2
Neon.....	Ne	-245.9 (N.B.P.)	1.204	1915	14
Nitric oxide.....	NO	-150.2 (N.B.P.)	1.269	1910	16
		-153.6	1.227	1932	17
Nitrogen.....	N ₂	-195.84 (N.B.P.)	0.808 ₄	1915	14
		-198.3	0.8297	1902	15
Nitrous oxide.....	N ₂ O	-89.4 (N.B.P.)	1.2257	1904	18
Dinitrogen trioxide.....	N ₂ O ₃	-8	1.464	1888	19
Nitrogen tetroxide.....	N ₂ O ₄	-5	1.5035	1888	19
Oxygen.....	O ₂	-182.97 (N.B.P.)	1.144 ₇	1911	14
		-182.5	1.1181	1904	20
		-195.0	1.1953	1930	21
Ozone.....	O ₃	-112.4 (N.B.P.)	1.63	1924	14
Radon.....	Rn	-62 (N.B.P.)	4.40	1912	14
Silicane.....	SiH ₄	-185	0.68	1916	22
Disilicane.....	Si ₂ H ₆	-25	0.69	1916	22
Sulfur dioxide.....	SO ₂	-10	1.4601	1899	22
Uranium hexafluoride.....	UF ₆	-209.11 (T.P.)	3.630	1949	23
Xenon.....	Xe	-111.80 (T.P.)	3.0506	1932	2
		-106.9 (N.B.P.)	3.063	1912	14

N.B.P. = normal boiling point; T.P. = triple point.

See Table 21-9 for liquid hydrogen and liquid helium.

* Unless specified as orthobaric (i.e., corresponding to thermodynamic equilibrium of coexistent liquid and vapor phases) or T.P.

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TABLE 2I-9. DENSITIES OF CRYOGENIC LIQUIDS

Helium (isotope 4) ^a	
	N.B.P. = 4.216 K
	$T = 4.20$ K; pressure = 1 atm; $\rho = 0.1251$ g/ml
	$T_{\lambda} = 2.186$ K; pressure = 38.3 mm Hg; $\rho = 0.1462$ g/ml
	$T_{\lambda} = 2.178$ K; pressure = 1 atm; $\rho = 0.1473$ g/ml
Helium (isotope 3) ^b	
	$T = 3.20$ K (N.B.P.); $\rho = 0.0570$ g/ml
Normal hydrogen (isotope 1) ^c	
	$T = 20.39$ K (N.B.P.); $\rho = 0.07098$ g/ml
Parahydrogen (isotope 1) ^d	
	$T = 20.27$ K (N.B.P.); $\rho = 0.07076$ g/ml
Hydrogen deuteride (HD) ^e	
	$T = 16.604$ K (T.P.); pressure = 92.8 mm Hg; $\rho = 0.1234$ g/ml
Deuterium (isotope 2) ^f	
	$T = 18.72$ K (T.P.); pressure = 128.5 mm Hg; $\rho = 0.1730$ g/ml
Tritium (isotope 3) ^g	
	$T = 25.04$ K (N.B.P.); $\rho = 0.2571$ g/ml

General reference: R. B. Stewart and V. J. Johnson, eds., "A Compendium of the Properties of Materials at Low Temperature" (Phase I), Wright Air Force Development Division Technical Report, 1961.

N.B.P. = normal boiling point; T.P. = triple point.

For a discussion of the provisional temperature scale in the liquid-hydrogen region see ref. ^a and H. J. Hoge and F. G. Brickwedde, *J. Research Natl. Bur. Standards* **22**, 351 (1939).

^a W. H. Keesom, "Helium," pp. 207, 226, 240, American Elsevier Publishing Company, Inc., New York, 1940. The temperature scale in the liquid-helium range must be considered when evaluating the reported results of density measurements. A discussion of the problems involved and the most recent conventions adopted is given in C. F. Squire, "Low Temperature Physics," p. 25, McGraw-Hill Book Company, 1953.

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TABLE 21-10. DENSITIES OF SELECTED ORGANIC LIQUIDS
 (Range 0 to 25°C; ρ = g/ml*; t = °C; pressure atmospheric)

Substance	Formula	t	ρ	Year	Ref.
Acetic acid.....	CH ₃ ·CO ₂ H	20	1.04926	1930	1
Acetone.....	CH ₃ ·CO·CH ₃	20	0.79053	1930	2
Alcohol, amyl.....	C ₅ H ₁₁ OH	15	0.81837	1932	3
Alcohol, <i>n</i> -butyl.....	C ₄ H ₉ OH	25	0.80567	1943	4
Alcohol, ethyl†					
Alcohol, methyl‡					
Alcohol, <i>n</i> -propyl.....	C ₃ H ₇ OH	20	0.8035	1949	5
Alcohol, isopropyl.....	(CH ₃) ₂ ·CHOH	25	0.78087	1935	6
Aniline.....	C ₆ H ₅ NH ₂	20	1.02173	1949	7
Benzene.....	C ₆ H ₆	20	0.87903	1946	8
Bromobenzene.....	C ₆ H ₅ Br	20	1.49519	1930	9
Bromoform.....	CHBr ₃	20	2.8905	1935	10
Carbon disulfide.....	CS ₂	20	1.2632	1926	11
Carbon tetrachloride....	CCl ₄	20	1.5940	1938	12
Chloroform.....	CHCl ₃	20	1.48913	1930	9
Chlorobenzene.....	C ₆ H ₅ Cl	20	1.10617	1930	9
Cyclohexane.....	C ₆ H ₁₂	20	0.77853	1946	8
Cyclopentane.....	C ₅ H ₁₀	20	0.74538	1946	8
Diethyl ether.....	(C ₂ H ₅) ₂ O	15	0.71925	1928	13
Ethyl acetate.....	CH ₃ ·CO ₂ C ₂ H ₅	25	0.89468	1937	14
Ethyl formate.....	H·CO ₂ C ₂ H ₅	15	0.92892	1932	15
Formic acid.....	H·CO ₂ H	15	1.22647	1930	1
Glycerol (glycerin).....	CH ₂ OH·CHOH·CH ₂ OH	20	1.2613	1937	16
Glycol, ethylene.....	(CH ₂ OH) ₂	15	1.11710	1935	17
<i>n</i> -Heptane.....	<i>n</i> -C ₇ H ₁₆	20	0.68367	1946	8
Heptene-1.....	CH ₂ =CH—(CH ₂) ₄ —CH ₃	20	0.6972	1946	19
<i>n</i> -Hexane.....	<i>n</i> -C ₆ H ₁₄	20	0.6595	1946	18
Hexene-1.....	CH ₂ =CH—(CH ₂) ₃ —CH ₃	20	0.6736	1946	19
Hydrogen cyanide.....	HCN	20	0.6876	1932	20
Iodobenzene.....	C ₆ H ₅ I	30	1.81548	1932	21
Isoprene.....	CH ₂ =C(CH ₃)—CH=CH ₂	20	0.6805	1936	22
Methyl formate.....	H·CO ₂ CH ₃	20	0.97421	1930	1
Methyl iodide.....	CH ₃ I	15	2.29300	1934	23
Nicotine.....	C ₅ H ₇ N·C ₄ H ₇ N(CH ₃)	20	1.0093	1925	24
Nitrobenzene.....	C ₆ H ₅ NO ₂	25	1.1983	1944	25
Nitroglycerin.....	NH ₂ NO ₂ ·CHNO ₂ ·CH ₂ NO ₂	15	1.5964	1930	26
<i>n</i> -Nonane.....	<i>n</i> -C ₉ H ₂₀	20	0.7174	1946	18
<i>n</i> -Octane.....	<i>n</i> -C ₈ H ₁₈	20	0.70252	1946	8
<i>n</i> -Pentane.....	<i>n</i> -C ₅ H ₁₂	20	0.62619	1947	27
Isopentane.....	iso-C ₅ H ₁₂	20	0.61963	1947	27
Pentene-1.....	CH ₂ =CH—CH ₂ —CH ₂ —CH ₃	20	0.6406	1946	19
<i>n</i> -Propylbenzene.....	C ₆ H ₅ - <i>n</i> -C ₃ H ₇	20	0.8618	1946	28
Toluene.....	C ₆ H ₅ —CH ₃	20	0.86683	1946	8

For extensive data on hydrocarbons see: A. F. Forziati and F. D. Rossini, *J. Research Natl. Bur. Standards* **43**, 473 (1949); A. F. Forziati, D. L. Camin, and F. D. Rossini, *J. Research Natl. Bur. Standards* **45**, 406 (1950).

For general references, see Sec. 21-4.

* These data have not been corrected in terms of the new definition of the liter (Sec. 21-1). For the conversion factor, see Table 21-1.

† See Table 21-6.

‡ See Table 21-5.

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TABLE 21-11. DENSITIES OF SELECTED FLUOROCARBON
AND CHLOROFUORO LIQUIDS
(Range all temperatures; $\rho = \text{g/ml}$; $t = ^\circ\text{C}$)

Substance	Index	t	ρ	Year	Ref.
<i>n</i> -Butforane.....	C ₄ F ₁₀	20.8	1.47 (orthobaric)	1939	1
Cyclopentforane.....	C ₅ F ₁₀	20	1.648	1947	2
Ethforane.....	C ₂ F ₆	-78.2	1.61	1933	3
Ethforene.....	C ₂ F ₄	-76.3	1.519	1933	3
Fluoroform.....	CF ₃ H	-84.4	1.465	1936	4
Freon-11.....	CCl ₃ F	15	1.4995	1940	5
Freon-12.....	CCl ₂ F ₂	20	1.326 (orthobaric)	1942	6
Freon-13.....	CClF ₃	-130	1.726	1931	7
Freon-21.....	CHCl ₂ F	15	1.3906 (orthobaric)	1940	5
Freon-22.....	CHClF ₂	20	1.2130	1940	5
Freon-112.....	C ₂ Cl ₄ F ₂	25	1.6447	1934	8
Hexforanes (mixture)...	C ₆ F ₁₄	20	1.697	1947	2
Methforane.....	CF ₄	-130	1.62	1933	3
Octforanes (mixture)....	C ₈ F ₁₈	20	1.802	1947	2
<i>n</i> -Pentforane.....	C ₅ F ₁₂	20	1.634	1947	2
Propforane.....	C ₃ F ₈	0.2	1.45 (orthobaric)	1939	1
Benzo trifluoride.....	C ₆ H ₅ CF ₃	30	1.1762	1953	9
<i>p</i> -Fluorotoluene.....	CH ₃ C ₆ H ₄ F	30	0.9869	1953	9
<i>p</i> -Fluorobromobenzene..	BrC ₆ H ₄ F	30	1.5859	1953	9

General reference: J. H. Simons, ed., "Fluorine Chemistry," vol. I, Academic Press, Inc., New York, 1950.

Pressure is atmospheric unless indicated as orthobaric conditions.

References for Table 21-11

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21-6. Volume of Liquids as a Function of Pressure and Temperature. Introduction. The density of a liquid in equilibrium must be a single-valued function of temperature and pressure, though this is not necessarily true for solids. Thermal equilibrium can be attained in all liquids within a reasonable length of time, but for polymers and other glass-forming liquids the viscosities may be so high that the reported "equilibrium" values of density often depend on the temperature and pressure history of the sample. Based on the extrapolation of observations at higher temperatures, it is assumed that such systems are approaching a true equilibrium state, but approaching it so slowly that changes cannot be detected. An example is optical glass near room temperature.

In the following tables equilibrium¹ specific volumes of selected liquids are listed at various pressures and temperatures. These data were all determined by experimental measurement. The range of pressures is from 1 to 50,000 atm (or to the freezing point). The range of temperatures is from 0 to 200°C (in a few cases there are points outside this range). In addition a compilation of many other liquids for which high-pressure data are available is given with references.

In the tables the volume as a function of pressure and temperature is expressed in one of three ways:

1. Specific volume at a pressure and temperature.
2. Relative volume v/v_0 , where v is the specific volume at the particular pressure and temperature and v_0 is the specific volume in the reference state (usually 0°C and 760 mm). Reference values are taken from the previous tables of this section, where appropriate data are available. The others are taken from: J. Timmermans, "Physico-chemical Constants of Pure Organic Compounds," American Elsevier Publishing Company, Inc., New York, 1950.
3. The change in volume of a given mass of liquid from a reference pressure of 5,000 kg/cm² along each experimental isotherm. All the data in the very high pressure range (5,000 to 50,000 kg/cm²) are expressed in this way.

From these data, isothermal compressibilities may be found (Sec. 21-12) and also isobaric thermal expansions if the volumes are known for more than one temperature. Other thermodynamic parameters, such as specific heats, have been directly determined as a function of pressure in very few cases and have to be inferred from the volume relations by indirect methods. No attempt is made here to give any of these values. References to the general subject of high pressures are cited below.²

21-7. Equations of State for Liquids. From PVT (pressure-volume-temperature) data equilibrium equations of state may be obtained. An explicit, meaningful equation of state in closed form applicable over wide ranges of both temperature and pressure is usually difficult to obtain from experimental data. An empirical relation can always be obtained from a statistical fit to a polynomial of the form

$$v = \sum_{i=0}^{\infty} \sum_{j=0}^{\infty} A_{ij} t^i P^j \quad (21-5)$$

truncated to delete insignificant terms. Over more limited ranges, volume isobars often approximate linear dependence on temperature. The Tait equation,

$$\frac{v_0 - v}{v_0} = c \log_{10} \left(1 + \frac{P}{b} \right) \quad (21-6)$$

¹ Except, possibly, for glycerin at low temperatures, or high pressures (Table 21-24).

² P. W. Bridgman, "The Physics of High Pressure," G. Bell & Sons, Ltd., London, 1952; *Revs. Modern Phys.* **18**, 1 (1946); J. Timmermans, "Les Constantes physiques des composés organiques cristallisés," Masson et Cie., Paris, 1953.

is probably the most familiar semiempirical relation¹ used to approximate the volume isotherms. A statistical fit is facilitated because of the implication of linearity between bulk modulus and pressure,² which can be seen when Eq. (21-6) is converted to the following form:³

$$-v_0 \left(\frac{\partial P}{\partial v} \right)_T = 2.302 \frac{b + P}{c} \quad (21-7)$$

The constants b and c have been interpreted⁴ in terms of the internal pressure and cohesive energy density. At high pressures the applicability of the Tait equation would appear to be limited in view of the fact that it predicts negative volumes at pressures exceeding a certain value. In practice this limitation is usually not serious because this value is in the order of several hundred million atmospheres.

Theoretical relations based on molecular structure are not very reliable in estimating PVT behavior. Considerable discussion on PVT estimation methods and their reliability is given by Bondi.⁵

21-8. Experimental Methods for Studying Compressibility of Liquids. A thorough description of the techniques employed in the experimental determination of the volume of liquids as a function of pressure and temperature is given by P. W. Bridgman in his text.⁶ Even more extensive details are given in his original publications. The siphon method, which was used in the pressure range 1 to 12,000 atm, is described in *Proc. Am. Acad. Arts Sci.* **66**, 185 (1931). The differential method, which was used in the pressure range 5,000 to 50,000 atm, is described in *Proc. Am. Acad. Arts Sci.* **74**, 21 (1940), and **74**, 399 (1942).

For more recent surveys with respect to liquids, see W. A. Steel and W. Webb, chap. 4i in "High Pressure Physics and Chemistry," vol. 1, R. S. Bradley, ed., Academic Press, Inc., New York, 1963. Recently the specific volumes of water⁷ and mercury⁸ have been evaluated from velocity of sound data. This involves the evaluation of the adiabatic compressibility as usual (see Sec. 21-12). After the adiabatic compressibility is converted to the corresponding isothermal, the specific volume is evaluated by numerical integration. The data obtained from this technique are claimed to be even more accurate than those obtained directly from equilibrium measurements. Shock waves⁹ are often used to obtain data at high pressures. For a review of nonequilibrium methods commonly used on polymer and glass-forming liquids, see R. S. Marvin and J. E. McKinney, chap. 9 in "Physical Acoustics," vol. 2B, W. P. Mason, ed., Academic Press, Inc., New York, 1965.

21-9. General Features of the Behavior of Liquids under Pressure¹⁰

1. Mercury is the least compressible of all liquids (in the range -30 to 200°C). In the nonmetallic group glycerin is the least compressible liquid.

2. At pressures above 10,000 atm, the relative volume change for all liquids is about the same.

¹ For critiques and comparative studies, see: J. R. MacDonald, *Revs. Modern Phys.* **38**, 669 (1966); A. T. J. Hayward, *Brit. J. Appl. Phys.* **18**, 965 (1967).

² L. A. Wood, *J. Polymer Sci. B (Polymer Letters)* **2**, 703 (1964).

³ This definition of the bulk modulus is not fully equivalent to that given in Sec. 21-12 (Eq. 21-9) at isothermal conditions.

⁴ M. A. Cook and L. A. Rogers, *J. Appl. Phys.* **34**, 2330 (1963).

⁵ A. Bondi, "Physical Properties of Molecular Crystals, Liquids, and Glasses," Chap. 8, John Wiley & Sons, Inc., New York, 1968.

⁶ P. W. Bridgman, "The Physics of High Pressure," *op. cit.*

⁷ R. Vedam and G. Holton, *J. Acoust. Soc. Am.* **43**, 108 (1968).

⁸ L. A. Davis and R. B. Gordon, *J. Chem. Phys.* **46**, 2650 (1967).

⁹ G. E. Duvall and G. R. Fowles, Chap. 9 in "High Pressure Physics and Chemistry," vol. 2, R. S. Bradley, ed., Academic Press, Inc., New York, 1963.

¹⁰ P. W. Bridgman, "The Physics of High Pressure," *op. cit.*; W. A. Steel and W. Webb, chap. 4i in "High Pressure Physics and Chemistry," vol. 1, *op. cit.*

3. The melting curve appears to exist up to the highest pressures experimentally obtainable with no indication of either a critical point or a maximum. However, at very high pressures, the viscosity of some liquids becomes so large that the approach to true equilibrium takes place infinitely slowly and a subcooling phenomenon appears.

4. The difference in volume between the solid and the liquid phase tends to decrease with increasing pressure but does not seem to approach zero at any finite pressure.

5. Differences in specific volumes among isomers (i.e., compounds having the same chemical formula but different structural formulas) tend to disappear at around 12,000 atm.

6. The compressibility decreases with increasing pressure, the rate of decrease becoming smaller with increasing pressure.

7. The compressibility increases with increasing temperature; this increase is less at higher pressures.

8. The volume isobars are more nearly linear than the isotherms; however, the bulk modulus often approximates a linear function of pressure. (This dependence is predicted by the Tait equation. See previous section.)

9. The sign of $(\partial^2 v / \partial T^2)_p$ changes from plus to minus with increasing temperature at constant pressure at pressures above about 3,000 to 4,000 atm.

10. The quantity $(\partial p / \partial T)_v$ decreases with increasing volume, but is not a function of volume alone.

11. The isothermal compressibility is unbounded at the critical point.¹

21-10. Units and Conversion Factors. The SI unit of pressure is the newton per square meter, and the cgs unit is the dyne per square centimeter. The bulk modulus is expressed in pressure units, and the compressibility, in reciprocal pressure units. Table 21-12 gives the conversion factors for the pressure units.

¹ See for example: P. A. Egelstaff, "An Introduction to the Liquid State," chap. 15, Academic Press, Inc., New York and London, 1967; P. A. Egelstaff and J. W. Ring, in "Physics of Simple Liquids," H. V. N. Temperley, J. S. Rowlinson, and G. S. Ruchbrooke, eds., North-Holland Publishing Company, Amsterdam, 1968.

TABLE 2-12. CONVERSION FACTORS FOR PRESSURE OR BULK MODULUS UNITS*

Units	N/m ² (SI)	bar	atm	cm Hg	dyn/cm ² (cgs)	kg/cm ²	psi	torr
1 N/m ² (SI)	1	10 ⁻⁵	9.86923 × 10 ⁻⁶	7.50064 × 10 ⁻⁴	10	1.01972 × 10 ⁻⁵	1.45038 × 10 ⁻⁴	7.50064 × 10 ⁻³
1 bar	10 ⁵	1	0.986923	75.0064	10 ⁶	1.01972	14.5038	7.50064 × 10 ²
1 atm	1.01325 × 10 ⁵	1.01325	1	76.0002	1.01325 × 10 ⁶	1.03323	14.6960	7.60002 × 10 ²
1 cm Hg (0°C)	1.33322 × 10 ³	1.33322 × 10 ⁻²	1.31579 × 10 ⁻²	1	1.33322 × 10 ³	1.35951 × 10 ⁻²	0.193367	10
1 dyn/cm ² (cgs)	10 ⁻¹	10 ⁻⁶	9.86923 × 10 ⁻⁷	7.50064 × 10 ⁻³	1	1.01972 × 10 ⁻⁶	1.45038 × 10 ⁻⁵	7.50064 × 10 ⁻⁴
1 kg/cm ²	9.80665 × 10 ⁴	0.980665	0.967841	73.5561	9.80665 × 10 ⁴	1	14.2233	7.35561 × 10 ²
1 psi	6.89476 × 10 ³	6.89476 × 10 ⁻²	6.80460 × 10 ⁻²	5.17151	6.89476 × 10 ³	7.03070 × 10 ⁻²	1	51.7151
1 torr (mm Hg at 0°C)	1.33322 × 10 ²	1.33322 × 10 ⁻³	1.31579 × 10 ⁻³	10 ⁻¹	1.33322 × 10	1.35951 × 10 ⁻³	1.93367 × 10 ⁻²	1

* Conversion to SI units taken from ASTM Metric Practice Guide, U.S. Department of Commerce, *Natl. Bur. Standards Handbook 102*, 39 (Mar. 10, 1967).

TABLE 2I-13. SPECIFIC VOLUME OF PURE AIR-FREE H₂O AS A FUNCTION OF PRESSURE AND TEMPERATURETemp. range -20 to 100°C; * pressure range 1-12,000 kg/cm²; specific volume in ml/g

p , kg/cm ²	-20°C	-15°C	-10°C	-5°C	0°C	20°C	40°C	60°C	80°C	100°C
1	1.0001	1.0018	1.0079	1.0171	1.0284	1.0435
500	0.9770	0.9819	0.9880	0.9959	1.0063	1.0183
1,000	0.9566	0.9576	0.9632	0.9706	0.9786	0.9883	0.9993
1,500	0.9370	0.9380	0.9394	0.9409	0.9476	0.9550	0.9632	0.9724	0.9826
2,000	0.9203	0.9214	0.9228	0.9246	0.9261	0.9328	0.9408	0.9492	0.9582	0.9679
2,500	0.9061	0.9080	0.9097	0.9116	0.9132	0.9199	0.9282	0.9365	0.9453	0.9545
3,000	0.8959	0.8977	0.9000	0.9015	0.9084	0.9167	0.9248	0.9334	0.9424
3,500	0.8851	0.8871	0.8892	0.8909	0.8984	0.9062	0.9142	0.9225	0.9312
4,000	0.8771	0.8794	0.8812	0.8888	0.8966	0.9044	0.9126	0.9208
5,000	0.8596	0.8622	0.8639	0.8709	0.8796	0.8874	0.8949	0.9028
6,000	0.8489	0.8565	0.8645	0.8721	0.8794	0.8871
7,000	0.8515	0.8586	0.8659	0.8731
8,000	0.8396	0.8564	0.8534	0.8604
9,000	0.8287	0.8354	0.8422	0.8490
10,000	0.8186	0.8252	0.8318	0.8385
11,000	0.8090	0.8157	0.8222	0.8385
12,000	0.8006	0.8070	0.8134	0.8199

TABLE 2I-13. RELATIVE OR DIFFERENTIAL VOLUME OF PURE AIR-FREE H₂O AS A FUNCTION OF PRESSURE AND TEMPERATURE (Continued)Temp. range 25-175°C; † pressure range 5,000-36,560 kg/cm²; Δv in cm³/1,000 g from 5,000 kg/cm²

p, kg/cm ²	25°C	75°C	125°C	175°C
5,000	0.000	0.000	0.000	0.000
9,800	0.057			
10,000		0.063	0.066	0.070
15,000	Ice VI	0.105	0.112	0.120
20,000		0.136	0.146	0.157
21,430		0.144		
25,000			0.173	0.185
28,140		Ice VII	0.186	
30,000				0.207
35,000			Ice VII	0.226
36,560				0.231
				Ice VII

Temp. range 0-360°C; † pressure range 1-350 atm; specific volume in ml/g

p, atm	0°C	20°C	40°C	60°C	80°C	100°C	120°C	140°C
1	1.0002	1.0020	1.0079	1.0170	1.0289	1.0434		
25	0.9991	1.0009	1.0068	1.0159	1.0277	1.0421	1.0590	1.0785
50	0.9980	0.9998	1.0057	1.0147	1.0265	1.0408	1.0576	1.0769
75	0.9968	0.9987	1.0046	1.0136	1.0253	1.0396	1.0562	1.0754
100	0.9957	0.9976	1.0034	1.0124	1.0241	1.0383	1.0548	1.0738
125	0.9946	0.9965	1.0024	1.0113	1.0230	1.0370	1.0535	1.0723
150	0.9935	0.9955	1.0013	1.0102	1.0218	1.0358	1.0521	1.0708
175	0.9935	0.9944	1.0002	1.0091	1.0207	1.0346	1.0508	1.0694
200	0.9914	0.9934	0.9992	1.0080	1.0195	1.0334	1.0495	1.0679
250	0.9893	0.9913	0.9971	1.0059	1.0173	1.0310	1.0469	1.0650
300	0.9873	0.9893	0.9950	1.0038	1.0151	1.0286	1.0444	1.0622
350	0.9853	0.9873	0.9930	1.0017	1.0129	1.0264	1.0419	1.0595

p, atm	160°C	180°C	200°C	220°C	240°C	260°C	280°C	300°C	320°C
1									
25	1.1007	1.1262	1.1555	1.1897					
50	1.0989	1.1241	1.1530	1.1866	1.2264	1.2747	1.3285		
75	1.0972	1.1221	1.1506	1.1836	1.2225	1.2694	1.3213		
100	1.0954	1.1200	1.1482	1.1806	1.2187	1.2644	1.3146	1.3965	
125	1.0937	1.1181	1.1458	1.1778	1.2150	1.2596	1.3082	1.3860	1.4882
150	1.0920	1.1161	1.1435	1.1749	1.2115	1.2549	1.3020	1.3764	1.4712
175	1.0904	1.1142	1.1412	1.1722	1.2080	1.2505	1.2962	1.3675	1.4563
200	1.0887	1.1123	1.1390	1.1694	1.2047	1.2461	1.2962	1.3591	1.4428
250	1.0855	1.1086	1.1346	1.1642	1.1982	1.2379	1.2854	1.3438	1.4192
300	1.0824	1.1050	1.1304	1.1592	1.1921	1.2302	1.2754	1.3303	1.3992
350	1.0793	1.1015	1.1263	1.1544	1.1862	1.2230	1.2662	1.3181	1.3816

TABLE 2I-13. SPECIFIC VOLUME OF PURE AIR-FREE H₂O AS A FUNCTION OF PRESSURE AND TEMPERATURE (Continued)

Temp. range 0-360°C; † pressure range 1-350 atm; specific volume in ml/g

p, atm	340°C	360°C
1		
150	1.0287	
175	1.5943	
200	1.5671	1.8140
250	1.5243	1.6905
300	1.4908	1.6232
350	1.4631	1.5758

For more extensive collected data, see G. C. Kennedy, and W. T. Holser, sec. 16 in "Handbook of Physical Constants," S. P. Clark, Jr., ed., The Geological Society of America, 1966.

For data measured by acoustic techniques (Section 2I-8), see R. Vedam, and G. Holton, *loc. cit.*

* N. F. Dorsey, "Properties of Ordinary Water Substance," Reinhold Book Corporation, New York, 1948. Based on data of P. W. Bridgman, *J. Chem. Phys.* 3, 397 (1935). See Dorsey for a further discussion of the factors involved in the interpretation of these data.

† P. W. Bridgman, *Proc. Am. Acad. Arts. Sci.* 74, 419 (1942). These data were taken directly from the original publication.

‡ L. B. Smith and F. G. Keyes, *Proc. Am. Acad. Arts. Sci.* 69, 285 (1934). See Dorsey for a comment on these data.

Temp. range 200-1000°C; * pressure range 100-2,500 bars; specific volume in cm³/g

Temp., °C	Pressure, bars						
	100	200	500	1,000	1,500	2,000	2,500
200	1.14830	1.13899	1.1145	1.0811	1.0533	1.0258	1.0027
300	1.39704	1.35992	1.2869	1.2131	1.1639	1.1257	1.0946
400	26.31	9.96	1.745	1.4443	1.3284	1.2591	1.2092
500	32.35	14.77	3.890	1.8794	1.5653	1.4402	1.3566
600	37.78	18.11	6.114	2.6802	1.9496	1.6630	1.5252
700	42.517	20.973	7.7651	3.5829	2.449	1.980	1.7346
800	46.082	23.391	9.0925	4.4338	2.994	2.350	2.000
900	49.54	25.74	10.28	5.208	3.531	2.738	2.296
1000	52.90	27.84	11.30	5.900	4.035	3.123	2.589

* G. C. Kennedy, *Am. J. Sci.* 243, 540 (1950).

TABLE 21-14. SPECIFIC VOLUME OF 99.9% D₂O AS A FUNCTION OF PRESSURE AND TEMPERATURE*

Temp. range -20 to 100°C; pressure range 1-12,000 kg/cm²; specific volume in ml/g

P , kg/cm ²	-20°C	-15°C	-10°C	-5°C	0°C	20°C	40°C	60°C	80°C	100°C
1	0.9048	0.9049	0.9087	0.9169	0.9272	
500	0.8833	0.8857	0.8905	0.8979	0.9074	0.9187
1,000	0.8642	0.8652	0.8690	0.8744	0.8820	0.8912	0.9011
1,500	0.8475	0.8485	0.8495	0.8543	0.8605	0.8680	0.8769	0.8864
2,000	0.8318	0.8331	0.8344	0.8359	0.8415	0.8479	0.8553	0.8639	0.8731
2,500	0.8178	0.8193	0.8208	0.8222	0.8239	0.8298	0.8365	0.8440	0.8521	0.8613
3,000	0.8066	0.8082	0.8099	0.8116	0.8132	0.8194	0.8260	0.8335	0.8413	0.8502
3,500	0.7982	0.8001	0.8019	0.8036	0.8096	0.8165	0.8240	0.8317	0.8400
4,000	0.7892	0.7910	0.7928	0.7946	0.8009	0.8078	0.8153	0.8227	0.8305
5,000	0.7772	0.7789	0.7854	0.7924	0.7996	0.8064	0.8143
6,000	0.7665	0.7722	0.7787	0.7860	0.7926	0.8000
7,000	0.7597	0.7668	0.7736	0.7801	0.7870
8,000	0.7490	0.7559	0.7625	0.7690	0.7755
9,000	0.7391	0.7461	0.7526	0.7588	0.7653
10,000	0.7373	0.7432	0.7493	0.7558
11,000	0.7293	0.7348	0.7407	0.7470
12,000	0.7216	0.7271	0.7328	0.7393

* P. W. Bridgman, *J. Chem. Phys.* **3**, 597 (1936). These values were calculated from the original data assuming a molecular weight of 20.028 (chemical scale) for D₂O.

TABLE 21-15. SPECIFIC VOLUME OF MERCURY AS A FUNCTION OF PRESSURE AND TEMPERATURE

Temp. range -30 to 20°C; * pressure range 1-12,000 atm; specific volume in ml/g†

p , atm	-30°C	-20°C	-10°C	0°C	10°C	20°C
1	0.073155	0.073288	0.073421	0.073554	0.073687	0.073820
1,000	0.072888	0.073016	0.073143	0.073270	0.073397	0.073524
2,000	0.072626	0.072748	0.072871	0.072993	0.073115	0.073237
3,000		0.072487	0.072605	0.072724	0.072842	0.072961
4,000		0.072233	0.072348	0.072463	0.072579	0.072696
5,000			0.072101	0.072213	0.072372	0.072440
6,000			0.071863	0.071973	0.072085	0.072196
7,000				0.071744	0.071853	0.071962
8,000					0.071632	0.071740
9,000					0.071422	0.071528
10,000					0.071223	0.071328
11,000						0.071140
12,000						0.070962

For critique, see K. E. Bett, K. E. Weale, and D. M. Newitt, *Brit. J. Appl. Phys.* **5**, 243 (1954).
For data measured by acoustic techniques (Sec. 21-8), see L. A. Davis and R. B. Gordon, *J. Chem. Phys.* **46**, 2650 (1967).

* P. W. Bridgman, *Proc. Am. Acad. Arts Sci.* **47**, 345 (1911). These values were calculated from the original data, assuming the density of mercury at 0°C and 760 mm to be 13.5955 g/ml.

† These data have not been corrected in terms of the new definition of the liter (Sec. 21-1). For the conversion factor, see Table 21-1.

TABLE 21-16. RELATIVE OR DIFFERENTIAL VOLUME OF METHYL ALCOHOL (CH₃OH)
 AS A FUNCTION OF PRESSURE AND TEMPERATURE
 The Relative Volumes in Terms of the Volume at 0°C and 760 mm*

 Temp. range 20–80°C; pressure range 1–12,000 atm; v/v_0 ; v = volume at (p, t) ;
 $v_0 = 1.23459$ ml/g at 0°C and 760 mm

p , atm	20°C	40°C	60°C	80°C
1	1.0238	1.0483	1.0737	1.1005
500	0.9811	0.9987	1.0182	1.0400
1,000	0.9494	0.9651	0.9808	0.9993
1,500	0.9256	0.9393	0.9526	0.9672
2,000	0.9064	0.9189	0.9306	0.9429
2,500	0.8906	0.9019	0.9124	0.9231
3,000	0.8763	0.8870	0.8966	0.9065
3,500	0.8636	0.8733	0.8824	0.8915
4,000	0.8523	0.8613	0.8700	0.8782
4,500	0.8420	0.8505	0.8587	0.8663
5,000	0.8325	0.8407	0.8487	0.8559
6,000	0.8163	0.8240	0.8314	0.8381
7,000	0.8023	0.8099	0.8163	0.8231
8,000	0.7907	0.7973	0.8039	0.8102
9,000	0.7797	0.7859	0.7920	0.7981
10,000	0.7696	0.7756	0.7816	0.7875
11,000	0.7605	0.7664	0.7728	0.7785
12,000	0.7527	0.7587	0.7652	0.7709

 The Change in Volume in cm³ per 0.792 g from a Reference Pressure of 5,000 kg/cm²
 along Each Isotherm †

 Temp. range 25–175°C; pressure range 5,000–50,000 kg/cm²; Δv in cm³/0.792 g

p , kg/cm ²	25°C	75°C	125°C	175°C
5,000	0.000	0.000	0.000	0.000
10,000	0.062	0.066	0.073	0.082
15,000	0.099	0.106	0.117	0.128
20,000	0.125	0.135	0.139	0.161
25,000	0.145	0.157	0.174	0.187
30,000	0.161†	0.173	0.194	0.208
35,000	0.173	0.187	0.210	0.226
40,000	0.183	0.198	0.223	0.240
45,000	0.191	0.208	0.234	0.253
50,000	0.199	0.218		

* P. W. Bridgman, "International Critical Tables," vol. 3, p. 41, McGraw-Hill Book Company, New York, 1928.

 † P. W. Bridgman, *Proc. Am. Acad. Arts Sci.* 74, 403 (1942).

‡ Displays subcooling at higher pressures.

TABLE 21-17. RELATIVE OR DIFFERENTIAL VOLUME OF ETHYL ALCOHOL
(C_2H_5OH) AS A FUNCTION OF PRESSURE AND TEMPERATURE
The Relative Volumes in Terms of the Volume at $0^\circ C$ and 760 mm*

Temp. range $20-80^\circ C$; pressure range 1-12,000 atm; v/v_0 ; v = volume at (p,t) ;
 $v_0 = 1.24022$ ml/g at $0^\circ C$ and 760 mm

p , atm	$20^\circ C$	$40^\circ C$	$60^\circ C$	$80^\circ C$
1	1.0212	1.0438	1.0679	1.0934
500	0.9782	0.9943	1.0121	1.0319
1,000	0.9479	0.9608	0.9760	0.9922
1,500	0.9247	0.9358	0.9482	0.9615
2,000	0.9059	0.9159	0.9266	0.9280
2,500	0.8899	0.8991	0.9088	0.9187
3,000	0.8760	0.8848	0.8935	0.9025
3,500	0.8634	0.8718	0.8800	0.8884
4,000	0.8517	0.8599	0.8678	0.8756
4,500	0.8410	0.8491	0.8567	0.8640
5,000	0.8314	0.8394	0.8467	0.8536
6,000	0.8149	0.8225	0.8291	0.8354
7,000	0.8000	0.8080	0.8130	0.8196
8,000	0.7888	0.7953	0.8005	0.8060
9,000	0.7776	0.7836	0.7884	0.7940
10,000	0.7671	0.7726	0.7776	0.7830
11,000	0.7574	0.7626	0.7682	0.7734
12,000	0.7485	0.7535	0.7600	0.7648

The Change in Volume in cm^3 per 0.789 g from a Reference Pressure of 5,000 kg/cm^2
along Each Isotherm †

Temp. range $25-175^\circ C$; pressure range 5,000 kg/cm^2 to 45,000 kg/cm^2 ; Δv in cm^3
per 0.789 g

p , kg/cm^2	$25^\circ C$	$75^\circ C$	$125^\circ C$	$175^\circ C$
5,000	0.000	0.000	0.000	0.000
10,000	0.063	0.069	0.071	0.076
15,000	0.100	0.109	0.113	0.119
20,000	0.128 †	0.137	0.144	0.151
25,000		0.159	0.168	0.175
28,700		0.174 †		
30,000			0.187	0.195
35,000			0.203	0.211
40,000			0.217	0.225
45,000			0.230	0.238

* P. W. Bridgman, "International Critical Tables," vol. 3, p. 41, McGraw-Hill Book Company, New York, 1928.

† P. W. Bridgman, *Proc. Am. Acad. Arts. Sci.* 74, 399 (1942).

‡ Solid below this.

TABLE 2I-18. RELATIVE VOLUME OF ACETONE ($\text{CH}_2\text{CO-CH}_3$) AS A FUNCTION OF PRESSURE AND TEMPERATURE*
The Relative Volumes in Terms of the Volume at 0°C and 760 mm

Temp. range $20\text{--}80^\circ\text{C}$; pressure range 1-12,000 atm; v/v_0 ; v = volume at (p,t) ;
 $v_0 = 1.23077$ ml/g at 0°C and 760 mm

p , atm	20°C	40°C	60°C	80°C
1	1.0279	1.0585	1.0925	
500	0.9819	1.0032	1.0282	
1,000	0.9526	0.9706	0.9894	1.0082
1,500	0.9286	0.9441	0.9594	0.9736
2,000	0.9076	0.9217	0.9347	0.9467
2,500	0.8900	0.9028	0.9141	0.9253
3,000	0.8748	0.8868	0.8968	0.9073
3,500	0.8619	0.8729	0.8821	0.8920
4,000	0.8504	0.8607	0.8694	0.8786
4,500	0.8402	0.8498	0.8583	0.8666
5,000	0.8309	0.8398	0.8482	0.8558
6,000	0.8143	0.8225	0.8306	0.8370
7,000	0.7997	0.8072	0.8148	0.8209
8,000	0.7866	0.7935	0.8003	0.8066
9,000	.....	0.7815	0.7876	0.7939
10,000	.....	0.7707	0.7764	0.7821
11,000	Freezes	0.7607	0.7665	0.7715
12,000	.....	0.7515	0.7577	0.7617

* P. W. Bridgman, "International Critical Tables," vol. 3, p. 42, McGraw-Hill Book Company, New York, 1928.

TABLE 2I-19. RELATIVE VOLUME OF BENZENE (C_6H_6) AS A FUNCTION OF PRESSURE AND TEMPERATURE*

Pressure range 1-3,500 kg/cm^2 ; v/v_0 ; v = volume at (p,t) ; $v_0 = 1.11104$ ml/g at 0°C and 760 mm

p , kg/cm^2	50°C	95°C
0	1.0630	1.1295
500	1.0160	
1,000	0.9841	1.0201
1,500	0.9591	0.9916
2,000		0.9684
2,500		0.9494
3,000		0.9325
3,500		0.9177

* P. W. Bridgman, *Proc. Am. Acad. Arts. Sci.* 66, 210 (1931). Phase diagram of benzene given in P. W. Bridgman, *Phys. Rev.* 3, 171 (1914).

TABLE 21-20. RELATIVE OR DIFFERENTIAL VOLUME OF CARBON DISULFIDE (CS₂) AS A FUNCTION OF PRESSURE AND TEMPERATURE
The Relative Volumes in Terms of the Volume at 0°C and 760 mm*

Temp. range 20-80°C; pressure range 1-12 000 atm; v/v_0 ; v = volume at (p,t) ;
 $v_0 = 0.77357$ ml/g at 0°C and 760 mm

p , atm	20°C	40°C	60°C	80°C
1	1.0235	1.0490	1.0774	1.1092
500	0.9854	1.0051	1.0243	1.0458
1,000	0.9567	0.9734	0.9887	1.0061
1,500	0.9338	0.9483	0.9615	0.9762
2,000	0.9151	0.9277	0.9397	0.9592
2,500	0.8994	0.9105	0.9215	0.9327
3,000	0.8852	0.8953	0.9055	0.9154
3,500	0.8730	0.8820	0.8916	0.9003
4,000	0.8620	0.8702	0.8790	0.8870
4,500	0.8521	0.8596	0.8679	0.8754
5,000	0.8429	0.8501	0.8578	0.8649
6,000	0.8265	0.8337	0.8405	0.8468
7,000	0.8119	0.8196	0.8258	0.8316
8,000	0.7990	0.8070	0.8130	0.8188
9,000	0.7875	0.7954	0.8014	0.8071
10,000	0.7774	0.7844	0.7906	0.7962
11,000	0.7686	0.7741	0.7802	0.7857
12,000	0.7609	0.7646	0.7706	0.7758

The Change in Volume in cm³ per 1.261 g from a Reference Pressure of 5,000 kg/cm² along Each Isotherm†

Temp. range 25-175°C; pressure range 5,000-30,000 kg/cm²; Δv in cm³ per 1.261 g

p , kg/cm ²	25°C	75°C	125°C	175°C
5,000	0.000	0.000	0.000	0.000
10,000	0.063	0.068	0.073	0.078
12,600	0.086‡			
15,000		0.110	0.118	0.126
18,300		0.131‡		
20,000			0.148	0.159
24,400			0.170‡	
25,000				0.184
30,000				0.204
30,700				0.206‡

* P. W. Bridgman, "International Critical Tables," vol. 3, p. 41, McGraw-Hill Book Company New York, 1928.

† P. W. Bridgman, *Proc. Am. Acad. Arts. Sci.* **74**, 415 (1941).

‡ Solid below this.

TABLE 21-21. RELATIVE VOLUME OF CARBON TETRACHLORIDE (CCl₄) AS A
 FUNCTION OF PRESSURE AND TEMPERATURE*
 The Relative Volumes in Terms of the Volume at 50°C and 760 mm Pressure

Pressure range 1-3,500 kg/cm²; v/v_0 ; v = volume at (p,t) ; $v_0 = 0.650995$ ml/g, 50°C
 and 760 mm

$p, \text{ kg/cm}^2$	50°C	95°C
0	1.000	
500	0.9519	0.9928
1,000	0.9192	0.9540
1,500	0.8962	0.9362
2,000	.....	0.9049
2,500	.....	0.8872
3,000	.....	0.8762
3,500	.....	0.8603

* P. W. Bridgman, *Proc. Am. Acad. Arts Sci.* **66**, 212 (1931).

TABLE 21-22. DIFFERENTIAL VOLUME OF CHLOROFORM (CHCl₃) AS A FUNCTION
 OF PRESSURE AND TEMPERATURE*
 The Change in Volume in cm³ per 1.489 g from a Reference Pressure of 5,000
 kg/cm² along Each Isotherm

Temp. range 25-175°C; pressure range 5,000-18,400 kg/cm²; Δv in cm³ per
 1.489 g from a reference pressure of 5,000 kg/cm²

$p, \text{ kg/cm}^2$	25°C	75°C	125°C	175°C
5,000	0.000	0.000	0.000	0.000
6,200	0.016†			
10,000	.....	0.067†	0.073	0.079
14,000	.....	.....	0.109†	
15,000	.....	.....	.....	0.124
18,400	.....	.....	.....	0.148†
			

* P. W. Bridgman, *Proc. Am. Acad. Arts Sci.* **74**, 413 (1941).

† Solid below this.

TABLE 21-23. RELATIVE VOLUME OF ETHER ((C₂H₅)₂O) AS A FUNCTION OF PRESSURE AND TEMPERATURE*

The Relative Volumes in Terms of the Volume at 0°C and 760 mm

Temp. range 20-80°C, pressure range 1-12,000 atm; v/v_0 ; v = volume at (p, t);
 $v_0 = 1.3583$ ml/g at 0°C and 760 mm

p , atm	20°C	40°C	60°C	80°C
1	1.0315	1.0669		
500	0.9668	0.9884	1.0123	1.0369
1,000	0.9337	0.9498	0.9683	0.9874
1,500	0.9070	0.9195	0.9336	0.9484
2,000	0.8850	0.8952	0.9069	0.9189
2,500	0.8663	0.8756	0.8860	0.8962
3,000	0.8503	0.8594	0.8688	0.8776
4,000	0.8246	0.8329	0.8407	0.8481
5,000	0.8044	0.8121	0.8189	0.8252
6,000	0.7883	0.7953	0.8017	0.8070
7,000	0.7743	0.7806	0.7865	0.7917
8,000	0.7613	0.7670	0.7725	0.7779
9,000	0.7492	0.7545	0.7597	0.7652
10,000	0.7380	0.7431	0.7482	0.7535
11,000	0.7275	0.7325	0.7377	0.7427
12,000	0.7178	0.7225	0.7280	0.7326

* P. W. Bridgman, "International Critical Tables," vol. 3, p. 41, McGraw-Hill Book Company, New York, 1928. Additional data on ether are reported in the same temperature and pressure range by Bridgman, *Proc. Am. Acad. Arts Sci.* 66, 218 (1931). These data were obtained by a method different from that above.

TABLE 21-24. RELATIVE VOLUME OF GLYCERIN*(CH₂OHCHOHCH₂OH) AS A FUNCTION OF PRESSURE AND TEMPERATURE†

The Relative Volumes in Terms of the Volume at 0°C and 760 mm

Temp. range 0-95°C, pressure range 1-12,000 kg/cm²; v/v_0 ; v = volume at (p, t);
 v_0 = volume at 0°C and 760 mm, $v(1, 50) = 0.80496$ ml/g

p , kg/cm ²	0°C	50°C	95°C
1	1.000	1.0266	
500	0.9900	1.0136	
1,000	0.9806	1.0025	1.0240
1,500	0.9721	0.9930	1.0125
2,000	0.9641	0.9843	1.0024
3,000	0.9501	0.9688	0.9853
4,000	0.9373	0.9548	0.9700
5,000	0.9264	0.9423	0.9565
6,000	0.9157	0.9310	0.9447
7,000	0.9057	0.9211	0.9342
8,000	0.8958	0.9121	0.9244
9,000	0.8867	0.9036	0.9152
10,000	0.8783	0.8955	0.9070
11,000	0.8712	0.8879	0.8994
12,000	0.8648	0.8800	0.8925

* The influence of large viscosities at low temperatures and high pressures (see Sec. 21-6) introduced some complications in obtaining these data.

† P. W. Bridgman, *Proc. Am. Acad. Arts Sci.* 67, 11 (1931).

TABLE 21-25. RELATIVE VOLUMES OF *n*-OCTANE AND *n*-PENTANE AS FUNCTIONS OF PRESSURE AND TEMPERATURE*
The Relative Volumes in Terms of the Volume at 0°C and 760 mm

Temp. range 0–95°C; pressure range 1–12,000 kg/cm²; v/v_0 ;
 v = volume at (p, t); v_0 = volume at 0°C and 760 mm

p , kg/cm ²	<i>n</i> -Octane $v_0 = 1.39183$ ml/g			<i>n</i> -Pentane $v_0 = 1.54950$ ml/g		
	0°C	50°C	95°C	0°C	50°C	95°C
1	1.0000	1.0595	1.1230	1.0000	(1.0837)	(1.1869)
500	0.9572	1.0005				
1,000	0.9311	0.9654	0.9943	0.9021	0.9395	0.9768
1,500						
2,000	0.8924	0.9200	0.9422	0.8546	0.8820	0.9078
3,000	0.8640	0.8882	0.9068	0.8229	0.8454	0.8671
4,000	.....	0.8639	0.8802	0.7997	0.8193	0.8371
5,000	.....	0.8428	0.8592	0.7811	0.7985	0.8125
6,000	.....	0.8251	0.8416	0.7647	0.7807	0.7933
7,000	.....	0.8103	0.8267	0.7506	0.7657	0.7775
8,000	.....	.....	0.8134	0.7381	0.7520	0.7641
9,000	.....	.....	0.8014	0.7281	0.7409	0.7527
10,000	.....	.....	0.7915	0.7192	0.7316	0.7433

* P. W. Bridgman, *Proc. Am. Acad. Arts Sci.* **66**, 185 (1931).

21-11. References to Compressibility Data for Other Substances

Reference: P. W. Bridgman, *Proc. Am. Acad. Arts Sci.* **67**, 6 (1932)

Pressure range: 0 to 12,000 kg/cm²

Substances:

Ethylene glycol	Methyl oleate
Trimethylene glycol	Tri-caproin
Propylene glycol	<i>n</i> -Butyl phthalate
Diethylene glycol	Eugenol
Tri- <i>o</i> -cresyl phosphate	Isooctane (2,2,4-tri-methyl pentane)
Tri-acetin	Isoprene
Ethyl dibenzyl malonate	

Reference: P. W. Bridgman, *Proc. Am. Acad. Arts Sci.* **66**, 198 (1931)

Pressure range: 0 to 12,000 kg/cm²

Substances:

Isopentane	Chlorobenzene
2-Methyl pentane	Bromobenzene
3-Methyl pentane	Bromoform
2-2-Dimethyl butane	Isopropyl alcohol
2-3-Dimethyl butane	Normal-butyl alcohol
Normal heptane	Normal-hexyl alcohol
Normal decane	

Reference: P. W. Bridgman, *Proc. Am. Acad. Arts Sci.* **68**, 1 (1933)
 Pressure range: 0 to 12,000 kg/cm²
 Substances:

Triethanolamine	Normal-amyl bromide
Normal-propyl chloride	Normal-amyl iodide
Normal-propyl bromide	Octanol-3
Normal-propyl iodide	2-methyl heptanol-3
Normal-butyl chloride	2-methyl heptanol-5
Normal-butyl bromide	2-methyl heptanol-1
Normal-butyl iodide	3 methyl heptanol-4
Normal-amyl chloride	

Reference: P. W. Bridgman, *Proc. Am. Acad. Arts Sci.* **74**, 403 (1942)
 Pressure range: 5,000 kg/cm² to 50,000 kg/cm²
 Substances:

Normal-propyl alcohol	Chloroform
Isopropyl alcohol	Chlorobenzene
Normal-butyl alcohol	Methylene chloride
Normal-amyl alcohol	Ethylene bromide
Ethyl bromide	Cyclohexane
Normal-propyl bromide	Methyl cyclohexane
Normal-butyl bromide	<i>p</i> -Xylene
Ethyl acetate	Benzene
Normal-amyl ether	

Reference: P. W. Bridgman, "International Critical Tables," vol. 3, p. 40, McGraw-Hill Book Company, New York, 1928.
 Pressure range: 1 to 12,000 atm
 Substances:

Phosphorus trichloride
 Ethyl iodide
 Ethyl chloride
 Isobutyl alcohol

Reference: R. S. Jessup, *Bur. Standards J. Research* **5**, 985 (1930), RP 244
 Pressure range: 1 to 50 kg/cm²
 Temperature range: 0° to 300°C
 Substances: 14 petroleum oils

Reference: F. R. Russell and H. C. Hottel, *Ind. Eng. Chem.* **30**, 372 (1938).
 Pressure range: 1 to 400 kg/cm². Max. temperature: 425°C
 Substance: Liquid naphthalene

Reference: R. B. Owens, *J. Chem. Phys.* **44**, 3918 (1966).
 Pressure range: 450 to 9,000 atm
 Temperature range: 300 to 500°C
 Substances: (molten nitrates!)

Lithium nitrate
 Sodium nitrate
 Potassium nitrate
 Rubidium nitrate
 Silver nitrate

¹ For general reference on molten salts, see: G. J. Janz, "Molten Salts Handbook," Academic Press, Inc., New York, 1967.

Reference: J. W. M. Boelhouer, *Physica* 34, 484 (1967).
 Pressure range: 1 to 1,400 atm
 Temperature range: -20° to 200°C
 Substances: (alkanes¹)

Heptane
 Hexane
 Octane
 Nonane
 Hexadecane

21-12. **Compressibility of Liquids.** The instantaneous compressibility is defined by

$$\beta = -\frac{1}{v} \frac{dv}{dp} \quad (21-8)$$

and its reciprocal, the instantaneous bulk modulus, is accordingly defined by

$$K = -v \frac{dp}{dv} \quad (21-9)$$

In some definitions v preceding the derivatives in the above is replaced by v_0 , the value of v at one atmosphere. Bridgman² uses this form which he calls the *compressibility proper*.

As with the specific volume (Sec. 21-6) the compressibility depends upon the temperature and pressure history of the sample. The simplest and most familiar thermodynamic paths are the isothermal and adiabatic (which are reversible when not influenced by viscosity) for which the instantaneous isothermal compressibility is

$$\beta_T = -\frac{1}{v} \left(\frac{\partial v}{\partial p} \right)_T \quad (21-10)$$

and the instantaneous adiabatic compressibility is

$$\beta_S = -\frac{1}{v} \left(\frac{\partial v}{\partial p} \right)_S \quad (21-11)$$

where S is the entropy.³ From reversible thermodynamics⁴ the above may be shown to be related by

$$\beta_T - \beta_S = \frac{T\alpha_p^2}{\rho C_P} \quad (21-12)$$

where T is the absolute temperature, α_p is the isobaric thermal expansivity, and C_P is the isobaric heat capacity. Isothermal compressibilities may be derived from equilibrium PVT isobars. Adiabatic compressibilities are usually obtained directly from acoustic propagation using the relation

$$\beta_S = \frac{1}{\rho_0 c_S^2} \quad (21-13)$$

where c_S is the adiabatic phase velocity, and ρ_0 is the density in the absence of the acoustic field. In order to apply Eq. (21-13), measurements must be made at frequency well removed from the dispersion region of the phase velocity.

The values of β_T in Tables 21-26 through 21-30 were obtained by first determining mean values of β_T from equilibrium PVT data using 1,000 kg/cm² intervals and then interpolating from the smoothed curve on a β_T versus pressure curve.

¹ Adiabatic compressibilities taken from sound velocity data.

² P. W. Bridgman, "The Physics of High Pressure," p. 169, G. Bell & Sons, Ltd., London, 1949.

³ In reversible systems there is no distinction between the adiabatic and isentropic path.

⁴ See, for example, M. W. Zemansky, "Heat and Thermodynamics," p. 260, McGraw-Hill Book Company, New York, 1957.

TABLE 21-26. ISOTHERMAL COMPRESSIBILITY OF WATER
(Calculated from *PVT* data of Table 21-13; all values in units of 10^{-12} cm²/dyne; reliability $\pm 5\%$)

Pressure, kg/cm ²	0°C	20°C	60°C	100°C
1	46	45	47	51
250	43	41	42	46
1,000	37	36	35	36
2,000	30	30	29	30
3,000	25	25	25	25
4,000	22	21	21	22
5,000	19	18	19	19
6,000	...	...	16	17
7,000	...	...	15	15
8,000	...	...	14	14
9,000	...	...	13	13
10,000	...	...	12	12
11,000	...	...	11	12

For adiabatic and isothermal values obtained from velocity of sound data, see R. Vedam and G. Holton, *J. Acoust. Soc. Am.* **43**, 108 (1968).

TABLE 21-27. ISOTHERMAL COMPRESSIBILITY OF 99.9% D₂O
(Calculated from *PVT* data of Table 21-14; all values in units of 10^{-12} cm²/dyne; reliability $\pm 5\%$)

Pressure, kg/cm ²	0°C	20°C	100°C
1	54	47	48
1,000	41	37	36
2,000	32	30	30
3,000	26	25	26
4,000	21	21	22
5,000	18	18	19
6,000	...	16	17
7,000	...	15	15
8,000	...	14	14
9,000	...	...	13
10,000	...	...	12
11,000	...	...	11

TABLE 21-28. ISOTHERMAL COMPRESSIBILITIES OF CERTAIN ORGANIC LIQUIDS
(β_T in units of 10^{-12} cm²/dyne; reliability $\pm 5\%$)

Substance	Pressure, kg/cm ²	t (°C)	β_T	Ref.
Acetic acid.....	1	20	91	1
Acetone.....	1	20	126	2
	5,000	20	21	3
Aniline.....	1	20	45	1
Benzene.....	1	20	95	2
Carbon disulfide.....	1	20	93	2
	5,000	20	21	3
Carbon tetrachloride.....	1	20	106	2
Chlorobenzene.....	1	20	74	1
Chloroform.....	1	20	101	2
Cyclohexane.....	1	25	110	1
Ether.....	1	20	187	2
	5,000	20	22	3
Ethyl acetate.....	1	20	113	1
Ethyl alcohol.....	1	20	111	2
	5,000	20	22	3
Ethylene chloride.....	1	20	80	1
Glycerin.....	1	20	21	3
	5,000	20	12	3
Heptane.....	1	20	144	2
Methyl alcohol.....	1	20	123	2
	5,000	20	21	3
Nitrobenzene.....	1	20	49	1
Toluene.....	1	20	91	2

References for Table 21-28

1. Data from "International Critical Tables," McGraw-Hill Book Company, New York.
2. Data from "Tables annuelles de constantes et données numériques," vol. 9, Gauthier-Villars, Paris, and McGraw-Hill Book Company, New York, 1929.
3. Calculated from PVT data in this section.

TABLE 21-29. ISOTHERMAL COMPRESSIBILITY OF SULFURIC AND NITRIC ACIDS*
Mean compressibility coefficient

$$\bar{\beta}_T = \frac{10^8}{v_1} \left(\frac{v_1 - v_2}{p_2 - p_1} \right) \text{atm}^{-1}$$

Substance	t , °C	p_1, p_2 , atm	$\bar{\beta}_T$
Sulfuric acid.....	12.6	1, 161	~33
Nitric acid.....	0	1, 32	~35

* L. Decombe and J. Decombe, p. 35 in "International Critical Tables," vol. 3, McGraw-Hill Book Company, New York, 1928.

21-13. Complex Compressibility. If a liquid is subjected to a sinusoidally time-

dependent excitation, the oscillating pressure may not be in phase with the corresponding oscillating volume. If the amplitude of the pressure is sufficiently small to obtain linear response, the amplitude and phase relationships between pressure and dilatation may be given by a complex (frequency-dependent) compressibility,

$$B^* = B' - iB'' \quad (21-14)$$

where B' is the ratio of the amplitude of the component of negative dilatation in phase with the pressure to pressure, and B'' is the corresponding ratio of negative

TABLE 21-30. ISOTHERMAL COMPRESSIBILITY β_T AND ADIABATIC COMPRESSIBILITY β_S OF MERCURY*
(Units of bars⁻¹)

Pressure, kbars	$t = 21.9^\circ\text{C}$		$t = 40.5^\circ\text{C}$		$t = 52.9^\circ\text{C}$	
	$\beta_T \times 10^6$	$\beta_S \times 10^6$	$\beta_T \times 10^6$	$\beta_S \times 10^6$	$\beta_T \times 10^6$	$\beta_S \times 10^6$
1	3.881	3.395	3.963	3.444	4.018	3.477
2	3.751	3.289	3.827	3.334	3.878	3.365
3	3.632	3.192	3.702	3.234	3.749	3.262
4	3.522	3.102	3.587	3.141	3.632	3.167
5	3.419	3.018	3.481	3.055	3.523	3.080
6	3.324	2.941	3.383	2.975	3.422	2.998
7	3.235	2.868	3.290	2.900	3.327	2.921
8	3.15	2.799	3.20	2.829	3.24	2.850
9	3.07	2.735	3.12	2.763	3.16	2.782
10	3.00	2.674	3.05	2.701	3.08	2.719
11	2.93	2.616	2.98	2.641	3.01	2.659
12	2.87	2.562	2.91	2.585	2.94	2.602
13	2.80	2.510	2.84	2.532	2.87	2.548

Adiabatic values were obtained from acoustic propagation, using Eq. (21-13). These were converted to isothermal values, using Eq. (21-12).

For isothermal values over a wider temperature range, see: L. B. Smith and F. G. Keyes, *Proc. Am. Acad. Arts Sci.* **69**, 313 (1934).

* L. A. Davis and R. E. Gordon, *J. Chem. Phys.* **15**, 2650 (1907).

dilatation lagging the pressure by $\pi/2$. The reciprocal of the complex compressibility is the complex bulk modulus,

$$K^* = K' + iK'' \quad (21-15)$$

All the components must be nonnegative quantities in both the above definitions.

The complex functions are usually used to study viscoelastic response.¹ Accordingly, it is necessary to separate the contributions from viscosity and heat of compression. The most convenient manner to obtain this resolution is by a selection of frequencies or boundary conditions to achieve (essentially) either adiabatic or isothermal conditions over a cycle. However, in obtaining extensive data over a wide

¹ See, for example: J. D. Ferry, "Viscoelastic Properties of Polymers," John Wiley & Sons, Inc., New York, 1961.

range of frequencies, achieving the above conditions is not always possible, and resolution may be extremely difficult.

Complex compressibility data may be obtained by acoustic propagation (using both bulk and shear waves) by means of the relations given by Herzfeld and Litovitz.¹ These relations reduce to Eq. (21-13) at the low-frequency limit. Except for the molten metals, the conditions are approximately adiabatic for most liquids below 10 MHz. Marvin and McKinney² review other, more novel methods used in polymer and glass-forming liquids to obtain complex compressibilities and time-dependent response functions which are equivalent.

Table 21-30 gives the compressibilities for mercury obtained from velocity of sound data at frequencies well below the dispersion region. The adiabatic compressibilities were obtained using Eq. (21-13). These were converted to isothermal values by means of Eq. (21-12).

