3e. Acoustic Properties of Liquids[1]

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3e-1. General. The acoustic property of a liquid of most common interest is the propagation constant

$$k = \alpha + i\beta = \alpha + \frac{i\omega}{c}$$

in which α is the attenuation and c the phase speed in a plane progressive wave, $\omega = 2\pi f$ being the angular frequency. The liquid is thus characterized by α and c, both of which are in general functions of temperature, pressure, and frequency.

The total attenuation α consists of two parts, a "classical" part, α_{class}, and an "excess" part, α_{exc}. The classical attenuation is that due to the effects of viscosity and heat conduction (the latter is negligible except for liquid metals), and it varies with the square of the frequency, although presumably this relationship would be "relaxed out" at sufficiently high frequencies, as yet inaccessible experimentally. In the accessible frequency region the phase speed c is independent of frequency; i.e., the dispersion is inappreciable. The excess attenuation is supposed to be connected with a relaxation mechanism induced by slow interchange of energy between various modes. In most cases the relaxation times are so short that at accessible frequencies there is no dispersion and α_{exc} again varies with the square of the frequency; therefore α/f^2 and c completely characterize the liquid at a given temperature and pressure.

3e-2. Mechanism of Relaxation. Herzfeld and Litovitz[1] recognize four mechanisms of relaxation. In the "Kneser" liquids, the main contribution is from slow energy exchange between internal and external degrees of freedom (thermal relaxation), as in a gas. In a few cases the relaxation times are long enough so that dispersion can be observed;[2] these are not considered here. In many associated liquids, a slow change in structure occurs, and in some there are a slow formation and dissociation of chemical complexes. Not considered here are the effects of isomerism in organic liquids and of rigidity in polymeric liquids or of solutions of polymers in ordinary liquids or of associated liquids cooled to the glassy state.

We consider only the normal, Kneser, and associated liquids and only in the nondispersive regime (c and α/f^2 independent of f). The available body of data is very extensive, and much of it represents isolated observations. We present here only such results as illustrate the variation of c and α/f^2 with an important variable. References to other data are given in Sec. 3e-7. For the most part the available data are not critical, and little can be said about the accuracy. Various methods of measurement yield different results, and in many cases the purity of the tested liquids is questionable.

The units used are for the most part those of the original authors. For interconversion of pressure units see Table 2l-12.

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[1] Contribution of the National Bureau of Standards, not subject to copyright.

[2] K. F. Herzfeld and T. A. Litovitz, "Absorption and Dispersion of Ultrasonic Waves," Academic Press, Inc., New York, 1959.

3e-3. Normal Liquids. These are the liquids for which $\alpha/\alpha_{\text{class}}$ is approximately unity. Monatomic liquids (Hg, He I well above the λ-point, A, etc.) and certain liquefied diatomic gases (N_2, O_2, H_2) are the most conspicuous examples. See Tables 3e-1 and 3e-2 for temperature and pressure effects in He I; Table 3e-3 for A, N_2, H_2, and O_2; and Table 3e-4 for Hg.

TABLE 3e-1. SPEED AND ATTENUATION OF SOUND IN LIQUID HE I AT THE VAPOR PRESSURE

T, K	f, MHz	c, m/sec	$10^{15}\alpha/f^2$, sec²/m	Ref.
5.1	15	.....	790	*a*
4.47	15	181	300	*a*
4.22	15	183	260	*a*
4.22	1.3	179.8	...	*b*
4.0	15	211	230	*a*
4.0	1.3	198.2	...	*b*
3.6	1.3	206.5	...	*b*
3.52	15	207	170	*a*

(*a*) J. R. Pellam and C. F. Squire, *Phys. Rev.* **72**, 1245 (1947).
(*b*) J. C. Findlay, A. Pitt, H. Grayson Smith, and J. O. Wilhelm, *Phys. Rev.* **54**, 506 (1938).

TABLE 3e-2. INFLUENCE OF PRESSURE ON THE SPEED OF SOUND IN LIQUID HE I AT 3.2 K*
(f = 1.3 MHz)

p, atm.............	Vapor	1	2.47	5.55
c, m/sec............	212	221	238	266

* J. C. Findlay, A. Pitt, H. Grayson Smith, and J. O. Wilhelm, *Phys. Rev.* **56**, 122 (1939).

TABLE 3e-3. SPEED AND ATTENUATION OF SOUND IN SOME LIQUEFIED GASES AT THE VAPOR PRESSURE*
(f = 44.4 MHz)

Liquid	T, K	c, m/sec	$10^{15}\alpha/f^2$, sec²/m
A	85.2	853	10.1
N_2	73.9	962	10.6
H_2	17	1,187	5.6
O_2	87	952	8.6
O_2	70	1,094	8.6
O_2	60	1,119	8.6

* J. K. Galt, *J. Chem. Phys.* **16**, 505 (1948); R. T. Beyer, *J. Chem. Phys.* **19**, 788 (1951).

3e-4. Kneser Liquids. The Kneser liquids are characterized by a value of $\alpha/\alpha_{\text{class}}$ greater than about 3 (in some cases as high as several thousand) and a positive temperature coefficient of attenuation. It follows from the approximately additive and constitutive nature of the molar sound speed[1] that in a homologous series of

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[1] B. B. Kudriavtsev, *Soviet Physics-Acoustics* **2**, 354 (1956).

TABLE 3e-4. SPEED AND ATTENUATION OF SOUND IN Hg AT 1 ATM

T, °C	f, MHz	c, m/sec	$10^{15}\alpha/f^2$, sec^2/m	Ref.
20	0.5	1,451	. . .	*a*
24.3	22	. . . . .	6.3	*b*
24.3	54	. . . . .	6.4	*b*
23.8	152	1,449	5.8	*c*
24.0	291	1,451	5.5	*c*
28.2	390	1,450	5.7	*c*
27.2	774	1,470	4.7	*c*
26.9	996	1,440	6.0	*c*

(*a*) J. C. Hubbard and A. L. Loomis, *Phil. Mag.* **5,** 1177 (1928).
(*b*) P. Rieckmann, *Physik. Z.* **40,** 582 (1939).
(*c*) G. R. Ringo, J. W. Fitzgerald, and B. G. Hurdle, *Phys. Rev.* **72,** 87 (1947).

TABLE 3e-5. SPEED OF SOUND AT 20°C AND ATMOSPHERIC PRESSURE IN SOME STRAIGHT-CHAIN HYDROCARBONS

Alkanes,* C_nH_{2n+2}		Alkenes,† C_nH_{2n}	
Compound	c, m/sec	Compound	c, m/sec
Pentane	1,008	1-Heptene	1,128
Hexane	1,083	1-Octene	1,184
Heptane	1,162	1-Nonene	1,218
Octane	1,197	1-Decene	1,250
Nonane	1,248	1-Undecene	1,275
		1-Tridecene	1,313
		1-Pentadecene	1,351

* W. Schaafs, *Z. Physik. Chem.* **194,** 28 (1944).
† R. T. Lagemann, D. R. McMillan, and M. Woolsey, *J. Chem. Phys.* **16,** 247 (1948).

TABLE 3e-6. SPEED AND ATTENUATION OF SOUND IN CS_2, C_6H_6, AND CCl_4 AT 1 ATM*

f, MHz	2.0		5.0		4.85 and 10.0	
Compound	CS_2		C_6H_6		CCl_4	
T, °C	c, m/sec	$10^{15}\alpha/f^2$, sec^2/m	c, m/sec	$10^{15}\alpha/f^2$, sec^2/m	c, m/sec	$10^{15}\alpha/f^2$, sec^2/m
0	1,220	5,510				
25	1,140	5,680	1,310	873	930	538
40	1,090	5,930				
50	. . . . .	. . . . .	1,190	964	852	590
70	. . . . .	. . . . .	1,100	1,050		

* J. F. Mifsud and A. W. Nolle, *J. Acoust. Soc. Am.* **28,** 469 (1956).

compounds the speed of sound will increase smoothly with molecular weight. Examples are given in Table 3e-5.

The liquids carbon disulfide, dibromomethane, dichloromethane, benzene, and carbon tetrachloride are of special interest because for them the values of $\alpha/\alpha_{\text{class}}$ are among the highest known; at room temperature and atmospheric pressure the values are about 1,150, 354, 183, 100, and 26.6, respectively.[1] See Table 3e-6 for the temperature dependence of c and α/f^2 at 1 atm for CS_2, C_6H_6, and CCl_4 and Table 3e-7 for the pressure dependence at 25°C.

TABLE 3e-7. SPEED AND ATTENUATION OF SOUND IN CS_2, C_6H_6, AND CCl_4 AT 25°C*

(f as in Table 3e-6)

Compound	CS_2		C_6H_6		CCl_4	
p, psi	c, m/sec	$10^{15}\alpha/f^2$, sec²/m	c, m/sec	$10^{15}\alpha/f^2$, sec²/m	c, m/sec	$10^{15}\alpha/f^2$, sec²/m
14.7	1,140	5,700	1,310	870	930	540
5,000	1,270	4,200	1,450	650	1,050	380
10,000	1,350	3,300	1,590	520	1,140	290
15,000	1,440	2,700	.....	...	1,230	220
20,000	1,500	2,400	.....	...	1,300	180

* J. F. Mifsud and A. W. Nolle, *J. Acoust. Soc. Am.* **28**, 469 (1956).

TABLE 3e-8. SPEED OF SOUND IN ETHER* AND ACETONE† AT p = 1 ATM

T, °C	c, m/sec	
	Ether	Acetone
16	1,023	
20	.....	1,203
25	976	
30	945	
30.5	.....	1,158
41	.....	1,097
44	862	

* E. G. Richardson and R. I. Tait, *Phil. Mag.* **2**, 441 (1957).
† H. F. Eden and E. G. Richardson, *Acustica* **10**, 309 (1960).

Tables 3e-8 and 3e-9 give some results for ether and acetone, Tables 3e-10 and 3e-11 for n-pentane and isopentane, Table 3e-12 for n-hexane and cyclohexane, and Tables 3e-13 to 3e-15 for the monohalogenated benzenes.

3e-5. Associated Liquids. The associated liquids are characterized by a value of $\alpha/\alpha_{\text{class}}$ less than about 4 and a negative temperature coefficient of attenuation.

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[1] K. F. Herzfeld and T. A. Litovitz, "Absorption and Dispersion of Ultrasonic Waves," Academic Press, Inc., New York, 1959.

Table 3e-9. Speed and Attenuation of Sound in Ether* and Acetone† as a Function of Pressure

T, °C	Ether		Acetone	
	16	16	30.5	30
p, psi	c, m/sec	$10^{15}\alpha/f^2$, sec^2/m	c, m/sec	$10^{15}\alpha/f^2$, sec^2/m
0	1,023	60	1,158	54.2
2,000	1,117	47.5	1,228	42.8
4,000	1,198	39.8	1,295	33.2
6,000	1,268	33.4	1,353	27.9
8,000	1,328	28.8	1,402	22.7
10,000	.....	25.5	1,450	21.5

* E. G. Richardson and R. I. Tait, *Phil. Mag.* **2,** 441 (1957).
† H. F. Eden and E. G. Richardson, *Acustica* **10,** 309 (1960).

Table 3e-10. Speed of Sound in n-Pentane* and Isopentane† at p = 1 Atm

T, °C	c, m/sec	
	n-Pentane	Isopentane
0	.....	951
3	.....	932
6.5	.....	917
8	.....	900
10.5	.....	883
15	1,027	
25	986	
35	944	
44	908	

* E. G. Richardson and R. I. Tait, *Phil. Mag.* **2,** 441 (1957).
† H. F. Eden and E. G. Richardson, *Acustica* **10,** 309 (1960).

Some Alcohols and the Waters. The speed of sound c (m/sec) is given, for temperature T (°C) and pressure p (psi), by the equation

$$\sum_{i,j} c_{ij}T^i p^j \tag{3e-1}$$

The nonzero coefficients c_{ij} are given in Table 3e-16. The limits of applicability of Eq. (3e-1) are

For the alcohols,	$0 < T < 58$°C	$14.7 < p < 14{,}000$ psi
For heavy water,	$0 < T < 95$°C	$14.7 < p < 14{,}000$ psi
For light water,	$16 < T < 94$°C	$14.7 < p < 14{,}000$ psi

TABLE 3e-11. SPEED OF SOUND IN *n*-PENTANE* AND ISOPENTANE† AND ATTENUATION IN *n*-PENTANE AS A FUNCTION OF PRESSURE

p, psi	*n*-Pentane T = 15°C		Isopentane T = 0°C
	c, m/sec	$10^{15}\alpha/f^2$, sec²/m	c, m/sec
0	1,027	100	951
2,000	1,122	93	1,029
4,000	1,208	86	1,096
6,000	1,282	81	1,153
8,000	1,350	77	1,200
10,000	.....	74	1,242

* E. G. Richardson and R. I. Tait, *Phil. Mag.* **2,** 441 (1957).
† H. F. Eden and E. G. Richardson, *Acustica* **10,** 309 (1960).

TABLE 3e-12. SPEED AND ATTENUATION OF SOUND IN *n*-HEXANE AND CYCLOHEXANE AS A FUNCTION OF PRESSURE*

p, psi	*n*-Hexane		Cyclohexane	
	T = 20°C	T = 30°C	T = 19°C	T = 19°C
	c, m/sec	$10^{15}\alpha/f^2$, sec²/m	c, m/sec	$10^{15}\alpha/f^2$, sec²/m
0	1,103	87	1,280	330
2,000	1,183	79	1,329	299
4,000	1,260	72	1,377	270
6,000	1,327	67		
8,000	1,391	65		
10,000	1,442	63		

* H. F. Eden and E. G. Richardson, *Acustica* **10,** 309 (1960).

TABLE 3e-13. SPEED OF SOUND IN THE MONOHALOGENATED BENZENES AT p = 1 ATM*

T, °C	c, m/sec			
	Fluoro	Chloro	Bromo	Iodo
20	1,183	1,311	1,169	1,114
30	1,144	1,282	1,136	1,085
40	1,105	1,254	1,105	1,058
50	1,066	1,226	1,074	1,030
60	1,028	1,197	1,042	1,003

* H. F. Eden and E. G. Richardson, *Acustica* **10,** 309 (1960).

TABLE 3e-14. SPEED OF SOUND IN THE MONOHALOGENATED BENZENES AT 22°C*

p, psi	c, m/sec			
	Fluoro	Chloro	Bromo	Iodo
0	1,177	1,304	1,167	1,104
2,000	1,228	1,346	1,204	1,135
4,000	1,279	1,382	1,239	1,164
6,000	1,321	1,418	1,270	1,190
8,000	1,357	1,449	1,300	1,210
10,000	1,388	1,479	1,326	

* H. F. Eden and E. G. Richardson, *Acustica* **10,** 309 (1960).

TABLE 3e-15. ATTENUATION OF SOUND IN THE MONOHALOGENATED BENZENES AT 22°C*

p, psi	$10^{15}\alpha/f^2$, sec^2/m			
	Fluoro	Chloro	Bromo	Iodo
0	317	167	163	242
2,000	282	148	136	210
4,000	256	134	119	188
6,000	235	123	104	172
8,000	219	116	96	160

* H. F. Eden and E. G. Richardson, *Acustica* **10,** 309 (1960).

3e. Acoustic Properties of Liquids

TABLE 3e-16. COEFFICIENTS OF EQ. (3e-1) FOR THE SPEED OF SOUND IN METHYL, ETHYL, *n*-PROPYL, AND *n*-BUTYL ALCOHOL* AND HEAVY† AND LIGHT‡ WATER§

Coefficient	CH_3OH	C_2H_5OH	*n*-C_3H_7OH	*n*-C_4H_9OH	99.82 mole % D_2O	H_2O
C_{00}	1,188.68	1,231.54	1,294.40	1.326.42	1.300.96	1,401.97
C_{10}	−3.45382	−3.57641	−3.67732	−3.38784	+5.16714	+5.05172
C_{20}	+1.26504(−3)	+2.38718(−3)	+4.00023(−3)	−9.86829(−3)	−5.50243(−2)	−5.84853(−2)
C_{30}	+7.49187(−5)	+2.65362(−5)	+3.53481(−5)	+3.62362(−4)	+2.23939(−4)	+3.38108(−4)
C_{40}	−8.33143(−7)	−2.44228(−7)	−7.40770(−7)	−3.37830(−6)	−3.95228(−7)	−1.48486(−6)
C_{50}						+3.09107(−9)
C_{01}	+3.80159(−2)	+4.01142(−2)	+3.78515(−2)	+3.68124(−2)	+9.05259(−3)	+8.37365(−3)
C_{11}	+1.58829(−4)	+1.68911(−4)	+1.59730(−4)	+1.32570(−4)	+4.38713(−5)	+4.32593(−4)
C_{21}	+3.95282(−7)	+2.19721(−7)	−6.87332(−8)	−2.42387(−7)	+9.95828(−8)	−2.02013(−5)
C_{31}	−1.14480(−9)	−3.43214(−11)	+3.29403(−9)	+9.83530(−9)	−6.17920(−10)	+4.49332(−7)
C_{41}						−4.49886(−9)
C_{51}						+1.67496(−11)
C_{02}	−1.36252(−6)	−1.57386(−6)	−1.26114(−6)	−1.17082(−6)	+1.90159(−7)	+4.96904(−7)
C_{12}	−1.06463(−8)	−1.03789(−8)	−9.74285(−9)	−6.42786(−9)	−4.94379(−9)	−1.00058(−7)
C_{22}	−1.18491(−11)	−1.21958(−11)	−8.57457(−12)	−2.93630(−11)	+1.99021(−11)	+5.47803(−9)
C_{32}						−1.29087(−10)
C_{42}						+1.35726(−12)
C_{52}						−5.22954(−15)
C_{03}	+6.31651(−11)	+7.87874(−11)	+5.62621(−11)	+4.80566(−11)	−4.93662(−12)	+2.05170(−11)
C_{13}	+3.17911(−13)	+3.01401(−13)	+2.85090(−13)	+2.00600(−13)	+5.21311(−14)	+3.78760(−12)
C_{23}						−3.37361(−13)
C_{33}						+9.46064(−15)
C_{43}						−1.09054(−16)
C_{53}						+4.44147(−19)
C_{04}	−1.53080(−15)	−1.97697(−15)	−1.34003(−15)	−1.04146(−15)	+5.81145(−17)	−3.38357(−15)
C_{14}						+1.45263(−16)
C_{24}						+7.83063(−19)
C_{34}						−1.24589(−19)
C_{44}						−1.98453(−21)
C_{54}						−9.31747(−24)

* W. Wilson and D. Bradley, *J. Acoust. Soc. Am.* **36,** 333 (1964).
† W. D. Wilson, *J. Acoust. Soc. Am.* **33,** 314 (1961).
‡ A. J. Barlow and E. Yazgan, *Brit. J. Appl. Phys.* **18,** 645 (1967).
§ All coefficients to be multiplied by the power of 10 in the parenthesis.

Table 3e-17 illustrates the temperature dependence of c in the alcohols at $p = 1$ atm, and Table 3e-18 the pressure dependence at $T = 20°C$.

The pressure dependence of α/f^2 in four alcohols is given in Table 3e-19; the temperature dependence of α/f^2 in n-butyl alcohol is given in Table 3e-20. For other alcohols see references in Sec. 3e-7.

Typical values for ordinary and heavy water are given in Tables 3e-21 to 3e-24. The speeds of sound for H_2O at 1 atm given in Table 3e-21 are more accurate (within 0.1 m/sec) than other such values given in this section. For instance, the values calculated from Eq. (3e-1) and Table 3e-16 may be in error by 0.3 m/sec or more. Lovett[1] has reviewed recent measurements. He recommends that the equation of Greenspan and Tschiegg[2] be modified to read

$$\begin{aligned} c = {} & 1402.336 + 5.033358T - 5.79506 \times 10^{-2}T^2 \\ & + 3.31636 \times 10^{-4}T^3 - 1.45262 \times 10^{-6}T^4 \\ & + 3.0449 \times 10^{-9}T^5 \text{ m/sec} \end{aligned} \tag{3e-2}$$

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[1] J. R. Lovett, *J. Acoust. Soc. Am.* **45,** 1051 (1969).
[2] M. Greenspan and C. E. Tschiegg, *J. Research NBS* **59C,** 249 (1957).

TABLE 3e-17. SPEED OF SOUND IN FOUR ALCOHOLS AT $p = 1$ ATM*

T, °C	c, m/sec			
	Methyl	Ethyl	n-Propyl	n-Butyl
0	1,189.2	1,232.1	1,295.0	1,327.0
10	1,154.9	1,196.7	1,258.6	1,292.5
20	1,121.2	1,161.8	1,223.2	1,257.7
30	1,088.2	1,127.6	1,188.7	1,223.6
40	1,055.9	1,094.1	1,154.7	1,190.3
50	1,024.0	1,061.2	1,121.0	1,157.2

* W. D. Wilson, *J. Acoust. Soc. Am.* **36**, 333 (1964).

TABLE 3e-18. SPEED OF SOUND IN FOUR ALCOHOLS AT $T = 20$°C*

p, psi	c, m/sec			
	Methyl	Ethyl	n-Propyl	n-Butyl
14.7	1,121.2	1,161.8	1,223.2	1,257.7
2,000	1,197.5	1,241.8	1,299.3	1,331.1
4,000	1,264.7	1,311.8	1,367.1	1,397.0
6,000	1,324.8	1,374.1	1,428.0	1,456.5
8,000	1,379.5	1,430.8	1,482.8	1,511.1
10,000	1,430.2	1,483.3	1,535.7	1,562.1
12,000	1,477.5	1,532.4	1,584.3	1,610.0
14,000	1,521.6	1,577.9	1,629.7	1,655.2

* W. D. Wilson, *J. Acoust. Soc. Am.* **36**, 333 (1964).

TABLE 3e-19. ATTENUATION OF SOUND IN FOUR ALCOHOLS AT $T = 30$°C*

p, kg/cm^2	$10^{15}\alpha/f^2$, sec^2/m			
	Methyl $f = 45$ MHz	Ethyl $f = 45$ MHz	n-Propyl $f = 25$ MHz	n-Butyl $f = 25$ MHz
1	30.2	48.5	64.5	74.3
500	18.2	31.2	48.5	60.5
1,000	13.5	24.5	41.5	55.8
1,500	11.2	21.4	39.2	54.0
2,000	9.9	19.9	39.0	53.5

* E. H. Carnevale and T. A. Litovitz, *J. Acoust. Soc. Am.* **27**, 547 (1955).

for T in °C. The values for H_2O in Table 3e-21 were calculated from Eq. (3e-2). Some results at very high pressures, up to 10,000 kg/cm^2, with reduced accuracy, are also available.[1,2]

[1] G. Holton et al., *J. Acoust. Soc. Am.* **43**, 102 (1968).

[2] W. H. Johnson, Jr., and G. Holton, *Rev. Sci. Instr.* **39**, 1247 (1968).

TABLE 3e-20. ATTENUATION OF SOUND IN n-BUTYL ALCOHOL AT $p = 2{,}000$ KG/CM²*
($f = 25$ MHz)

T, °C	0	15	30	45
$10^{15}\alpha/f^2$, sec²/m	124.0	79.6	53.5	39.0

* E. H. Carnevale and T. A. Litovitz, *J. Acoust. Soc. Am.*, **27**, 547 (1955).

TABLE 3e-21. SPEED OF SOUND IN H_2O* AND 99.82 MOLE % D_2O† AT $p = 1$ ATM

T, °C	c, m/sec	
	H_2O	D_2O
0	1,402.3	
4	1,421.6	1,320.9
10	1,447.2	1,347.5
20	1,482.3	1,384.2
30	1,509.0	1,412.3
40	1,528.8	1,433.1
50	1,542.5	1,447.4
60	1,550.9	1,456.3
70	1,554.7	1,460.5
74	1,555.1	
80	1,554.4	1,460.8
90	1,550.4	1,457.8
100	1,543.0	1,452.0

* J. R. Lovett, *J. Acoust. Soc. Am.* **45,** 1052 (1969). M. Greenspan and C. E. Tschiegg, *J. Research NBS* **59C,** 249 (1957).

† W. D. Wilson, *J. Acoust. Soc. Am.* **33,** 374 (1961).

TABLE 3e-22. SPEED OF SOUND IN H_2O* AND 99.82 MOLE % D_2O† NEAR ROOM TEMPERATURE

p, psi	c, m/sec	
	H_2O at 30.68° C	D_2O at 30°C
14.7	1,510.6	1,412.3
1,450	1,527.8	
2,000		1,433.3
2,901	1,544.5	
4,000		1,454.7
4,351	1,561.6	
5,802	1,578.4	
6,000		1,476.3
7,252	1,595.3	
8,000		1,498.0
8,702	1,611.8	
10,000		1,519.8
10,150	1,628.8	
11,600	1,645.4	
12,000		1,541.5
14,000		1,563.0

* A. J. Barlow and E. Yazgan, *Brit. J. App. Phys.* **18,** 645 (1967).

† W. D. Wilson, *J. Acoust. Soc. Am.* **33,** 374 (1961).

Sea Water. Wilson[1] has measured the speed of sound in sea water from the Bermuda–Key West area of the Atlantic over the following range: temperature $-3 < T < 30°C$, pressure $1.033 < p < 1{,}000$ kg/cm^2, and salinity $3.3 < S < 3.7$ percent. Typical results are given in Tables 3e-25 and 3e-26. There is some reason to believe that these values are high. Lovett[2] recommends that they be reduced by 0.65 m/sec.

TABLE 3e-23. ATTENUATION OF SOUND IN H_2O AT $p = 1$ ATM*
(f varied from 8 to 67 MHz)

T, °C	$10^{15}\alpha/f^2$, sec^2/m
0	56.9
5	44.1
10	36.1
15	29.6
20	25.3
30	19.1
40	14.6
50	12.0
60	10.2
70	8.7
80	7.9
90	7.2

* J. M. M. Pinkerton, *Nature* **160**, 128 (1947).

TABLE 3e-24. ATTENUATION OF SOUND IN H_2O AT $T = 30°C$*

p, atm.	0	500	1,000	1,500	2,000
$10^{15}\alpha/f^2$, sec^2/m.	18.5	15.4	12.7	11.1	9.9

* T. A. Litovitz and E. H. Carnevale, *J. Appl. Phys.* **26**, 816 (1955).

TABLE 3e-25. SPEED OF SOUND IN SEA WATER AT $p = 1$ ATM*

T, °C	c, m/sec		
	$S = 3.3\%$	$S = 3.5\%$	$S = 3.7\%$
−3	1,431.9	1,435.0	1,437.6
0	1,446.3	1,449.4	1,451.9
5	1,468.2	1,471.2	1,473.5
10	1,487.6	1,490.4	1,492.7
15	1,504.6	1,507.4	1,509.5
20	1,519.6	1,522.2	1,524.2
25	1,531.9	1,535.1	1,536.9
30	1,443.8	1,546.2	1,547.9

* W. D. Wilson, *J. Acoust. Soc. Am.* **32**, 641 (1960).

Electrolytes. Monovalent ions in most cases affect the attenuation only slightly and increase the speed of sound to an extent depending on the concentration. Polyvalent ions introduce dispersion. References are given in Sec. 3e-7.

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[1] W. D. Wilson, *J. Acoust. Soc. Am.* **32**, 641 (1960).
[2] J. R. Lovett, *J. Acoust. Soc. Am.* **45**, 1051 (1969).

3e-6. Mixtures. The behavior of liquid mixtures is varied. If the two constituents are both Kneser liquids, then c and α are in most cases intermediate to those of the constituents themselves. A mixture of two associated liquids will generally have a maximum in α at some composition and also, especially if one component is water, a maximum in c at some other composition. A mixture of one Kneser and one associated liquid may behave like a mixture of two Kneser liquids or in even a more complex fashion than a mixture of two associated liquids. The literature is extensive; references are given in Sec. 3e-7.

3e-7. Sources of Other Data. By far the best single source of data is Schaafs' book [1]. The coverage is through 1963. Data are given on inorganic, organic, and silico-organic liquids; on supercooled liquids; crystalline liquids; fatty acids; and molten metals and salts. Also treated are binary (and some ternary) mixtures, and aqueous and some nonaqueous solutions of electrolytes. Bergmann's book [2] is a good source for miscellaneous substances, as is a recent report by Turk and Hunter [16]. Sette has published four compilations, treating absorption [3, 6] and velocity [5, 7] in pure liquids [3, 7] and in mixtures [5, 6]. Velocity as related to molecular constitution is treated by Markham et al. [4], Herzfeld and Litovitz [15], Schaafs [17], and Nozdrev [18]. Del Grosso and Smura [8] give the speed of sound in and impedances of liquids suitable for certain applications; liquids simulating sea water and liquids having unusually low or high speeds of sound are included. Weissler and coworkers present considerable data in connection with their work on molecular structure, especially for alcohols [9], linear polymethyl siloxanes [10], cyclic compounds [11], inorganic halides [12], acetylene derivatives [13], and polyethylene glycols [14]. The acoustic and some other properties of many alcohols are given by Marks [19].

TABLE 3e-26. SPEED OF SOUND IN SEA WATER AT $T = 20°\text{C}$*

p, kg/cm^2	c, m/sec		
	$S = 3.3\%$	$S = 3.5\%$	$S = 3.7\%$
1.033	1,519.6	1,522.2	1,524.1
100	1,535.4	1,537.1	1,540.1
200	1,551.5	1,554.2	1,556.3
300	1,567.7	1,571.5	1,572.5
400	1,584.0	1,586.8	1,588.9
500	1,602.0	1,603.1	1,605.2
600	1,616.8	1,619.5	1,621.6
700	1,633.1	1,635.8	1,637.9
800	1,649.4	1,652.1	1,654.2
900	1,665.5	1,668.2	1,670.3

* W. D. Wilson, *J. Acoust. Soc. Am.* **32**, 641 (1960).

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