

## 5d. Properties of Dielectrics

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Dielectrics store electric energy and the intrinsic property of the material which measures this ability is the *dielectric constant* or *permittivity*  $\epsilon'$ . (The term *constant* refers to the  $\epsilon'$  independence of field strength; as shown below,  $\epsilon'$  usually does depend on temperature, frequency, and other parameters.) Part of the electric energy put into a dielectric is not recoverable from storage; i.e., it is "dissipated." The intrinsic property which measures dissipation is the *loss factor* (index),  $\epsilon''$ . Other convenient parameters expressing this information include  $\tan \delta = \epsilon''/\epsilon' = 1/Q$ . Typical values of  $\tan \delta$  are of order  $10^{-2}$ , with low-loss materials being of order  $10^{-4}$  and high loss of order one or higher.

Since  $\epsilon'$  measures motions at all higher frequencies, and  $\epsilon''$  measures motion at a particular frequency, it is not surprising to find a relation between  $\epsilon'$  and the integral of  $\epsilon''$  over frequency. This, the Kramers-Krönig relation, is

$$\begin{aligned}\epsilon'(f) - \epsilon_\infty &= \frac{2}{\pi} \int_0^\infty \epsilon''(F) \frac{F dF}{F^2 - f^2} \\ \epsilon''(f) &= -\frac{2}{\pi} \int_0^\infty (\epsilon'(F) - \epsilon_\infty) \frac{f dF}{F^2 - f^2} \\ \epsilon_\infty &= \epsilon' \text{ at high frequency}\end{aligned}$$

For the special case of  $f = 0$  (i.e., very low frequency) this reduces to

$$\epsilon_0 - \epsilon_\infty = \frac{2}{\pi} \int_{-\infty}^\infty \epsilon'' d \ln F$$

The optical  $\epsilon$  is determined by electronic polarizability and is the square of the (complex) refractive index. Since this polarizability is really a measure of the size of the electron cloud around an atom, and since this size is about constant in most covalent compounds, it is possible to estimate  $\epsilon_\infty$  for such compounds simply by adding individual contributions (provided we know the density and chemical structure of the compound), as illustrated in Table 5d-1. The dependence of  $\epsilon$  on density,  $\rho$ , is given

by the Clausius-Mossotti (Lorentz-Lorenz) equation which is especially useful in estimating  $\epsilon(t)$  when  $\rho(t)$  is known (where  $t^\circ\text{C}$  is the temperature):

$$\frac{\epsilon - 1}{\epsilon + 2} = \frac{4\pi}{3} \frac{\rho}{M} \alpha$$

where  $\rho$  is density,  $M$  is molecular weight, and  $\alpha$  is (electronic) polarizability. [The general validity of the  $\epsilon - 1$  proportional to  $\rho$  relation is illustrated by comparing gas and liquids where typical  $\rho$ 's differ by a factor of  $10^3$  as do the  $(\epsilon - 1)$ 's.] In practice, this relation holds to about 1 percent accuracy. More accurate relations require a third parameter; several are described by Brown in his lucid synopsis of dielectric theory.<sup>1</sup>

The electronic effects just described occur at such high (optical) frequencies because of the small mass of the electrons. These resonant dispersions are inertial, depending only on the electron's ability to rapidly respond to the imposed electric field variations. Any molecule with an asymmetric charge distribution constitutes a permanent dipole which also can respond to an alternating electric field, but because of the mass of the atoms the natural (inertial) period of motion will be much longer and hence dispersions occur at lower frequencies.

In the condensed phase, molecular motion is typically determined by viscous (not inertial) forces, and the corresponding relaxation (not resonant) dispersions occur at microwave, radio, and even lower frequencies. These dispersion processes result from the (slow) motion of the molecule being coupled to the alternating electric field by an attached permanent dipole. (Relaxation processes are characterized by  $\epsilon'$  which monotonically decreases with increasing frequency throughout the entire dispersion range, unlike resonant dispersions.)

In addition to molecular motion in the condensed phase, it is also possible to have ionic motion. The d-c conduction caused by ions will cause  $\epsilon''$  to vary inversely with the frequency while  $\epsilon'$  remains constant. If the ions are constrained, as frequently happens in inhomogeneous materials, the resulting induced "dipole" gives rise to a (usually low frequency) dispersion with appropriate changes in both  $\epsilon'$  and  $\epsilon''$ . (See Figs. 5d-2 and 3.)

The temperature dependence of  $\epsilon'$  can often be estimated a priori. In the gas phase  $\epsilon - 1$  is frequently proportional to the gas density and for nonpolar molecules is independent of frequency. Discernible frequency dispersions occur in polar molecules, e.g., water, in the microwave region.

In the condensed phase  $\epsilon - 1$  is again proportional to density in nonpolar substances so that  $d\epsilon/dt$  is small and negative except in the vicinity of phase transitions. For polar molecules,  $d\epsilon/dt$  is usually negative, although it can be large and positive in that temperature range on the cool side of a dispersion. (In this case the  $e^{-H/kT}$  dependence of dipolar motion dominates the smaller temperature dependence of the density, the large values of  $d\epsilon/dt$  resulting from the high dipole concentration and consequent large values of  $\epsilon_s - \epsilon_\infty$ .) Phase transitions in polar molecules can be accompanied by dramatic drops in  $\epsilon'$  as the dipole motion is frozen out. (These drops tend to be sharper when the molecule is more symmetrical, as illustrated by the nearly spherical camphor and its derivatives as contrasted to asymmetric derivatives of the planar benzene molecule, as illustrated in Figure 5d-1.)

Very high molecular weight materials (polymers) often form supercooled liquids rather than freeze into crystals, and consequently do not have discontinuities in  $\epsilon(t)$ . In those polymers that are partially crystalline, it is usually possible to discern two  $\epsilon''(t)$  or  $\epsilon''(f)$  loss peaks, one corresponding to each phase in which the relative ampli-

<sup>1</sup> W. F. Brown, Jr., "Handbuch der Physik," vol. 17, Springer-Verlag OHG, Berlin, 1956 (in English).

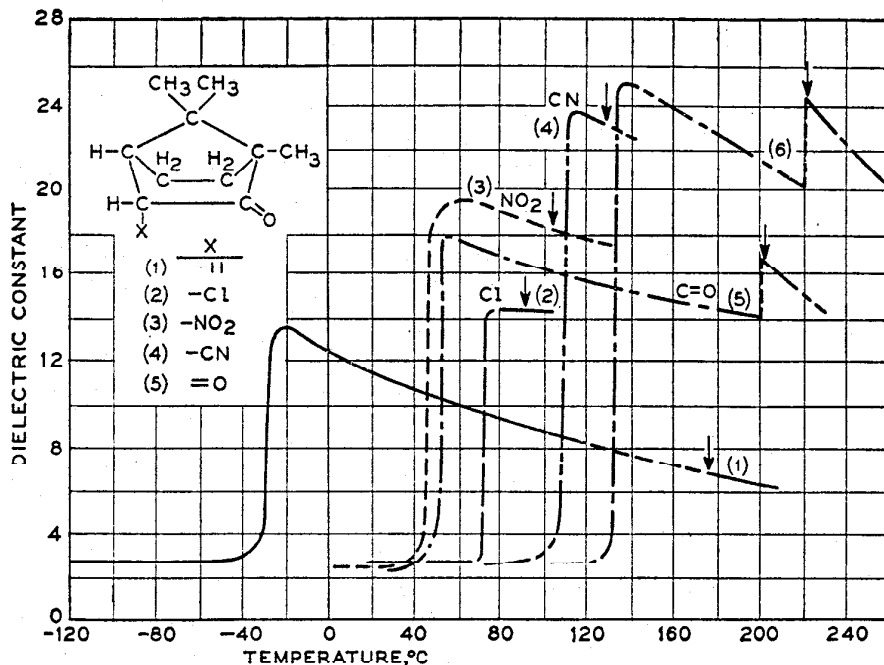


FIG. 5d-1a. Dielectric constant of camphor (1), chlorocamphor (2), nitrocamphor (3), cyanocamphor (4), camphor quinone (5), and camphoric anhydride (6). Heavy arrow indicates the melting point; values are independent of frequency below 100 kHz. [(From Morgan and Lowry, *J. Phys. Chem.* 34, 2385 (1930).]

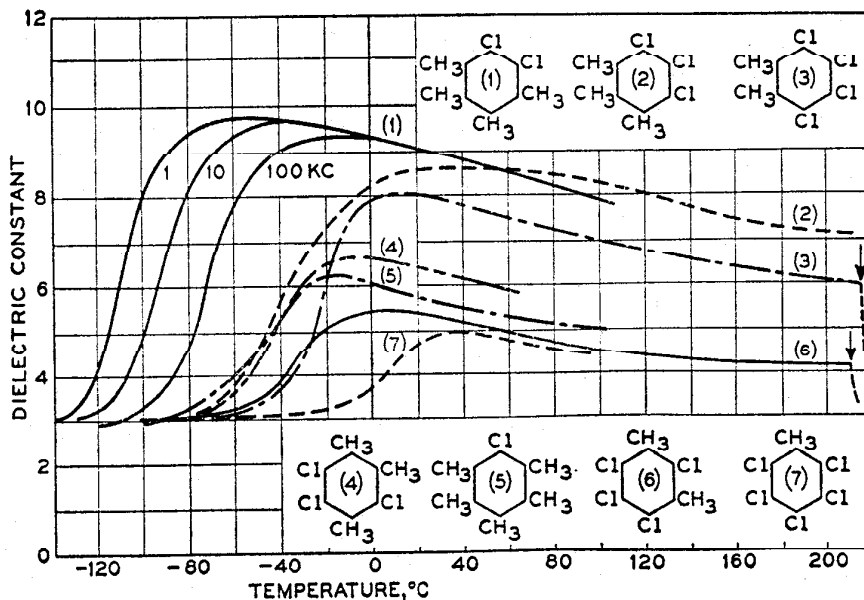


FIG. 5d-1b. Dielectric constant of polar hexasubstituted chloromethylbenzenes at 100 kHz: (1) dichlorophrenitene, (2) trichlorohemimellitene, (3) tetrachloro-*o*-xylene, (4) trichloropseudocumene, (5) pentamethylchlorobenzene, (6) tetrachloro-*m*-xylene, (7) pentachlorotoluene. [From A. H. White and S. O. Morgan: *J. Am. Chem. Soc.* 57, 2078 (1935).]

tudes of  $\epsilon''$  depend on the degree of crystallinity (e.g., in Table 5d-7A,  $r_1$  decreases as the crystallinity is lowered). Below some characteristic temperature for each substance, noncrystalline polymers behave as a glass in which all but the easiest dipole motions are frozen out. Commercial plastics sometimes have "plasticizers" added to

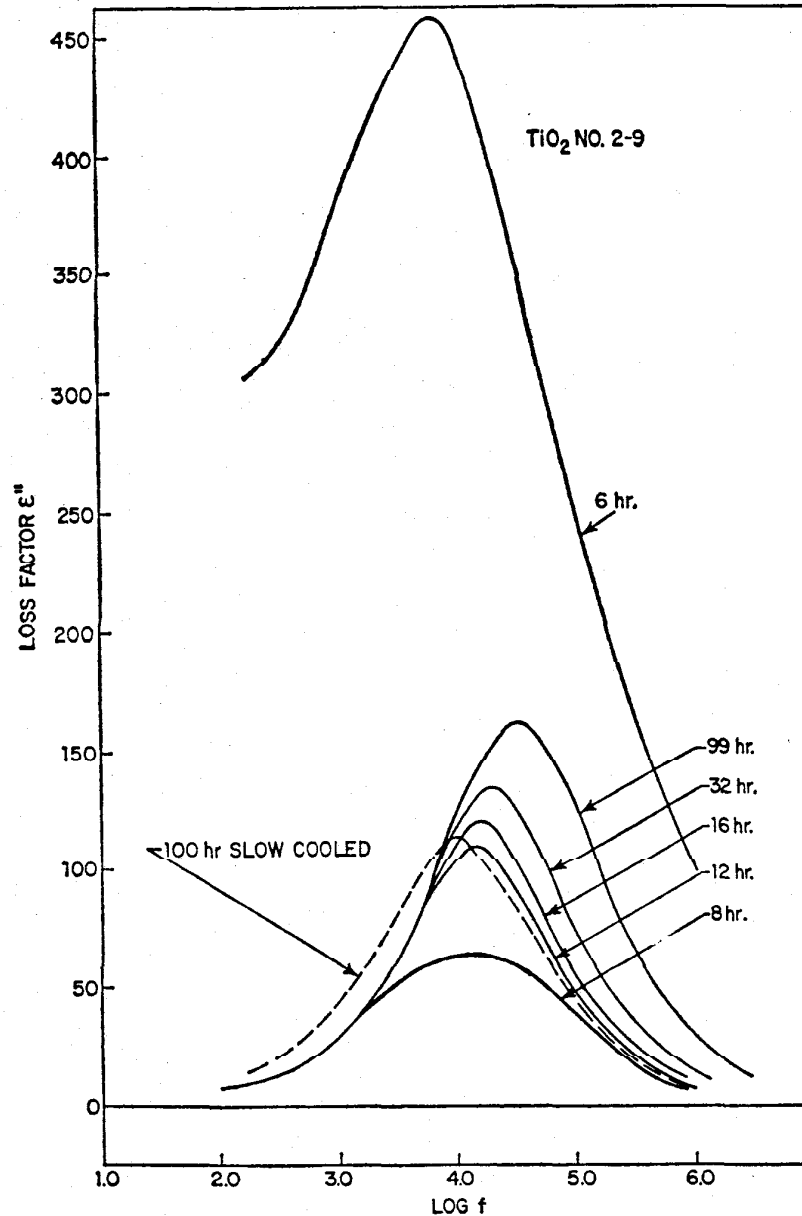


FIG. 5d-2. Dielectric loss for  $\text{TiO}_2$  fired at  $800^\circ\text{C}$  for various times. Different loss characteristics are believed to be caused by oxygen concentration. (Data from L. Egerton, private communication.)

them to keep them less brittle to lower temperatures. Such additions usually raise the frequency for the peak  $\epsilon''(f)$  by an amount dependent on the plasticizer concentration. Plastics also have other additives to stabilize them against chemical degradation and in the case of low-loss polymers these additives raise the value of  $\epsilon''$ , giving considerable (greater than two times) variation in  $\epsilon''$  between different manufacturers of the "same" material. (Other differences result from different topological structures

and impurities.) Polar polymers have varying affinities for water, causing some to have dielectric properties which depend on the humidity of the environment. Polymers that are chemically joined by a (loose) structure of three-dimensional bonds are not able to collapse to the glassy state and so remain "rubbery" even at low temperatures, with corresponding dielectric properties.

The last class of synthetic materials we consider are non-single-crystal metallic oxides. These inorganic materials are characterized by high  $\epsilon'$  (because of the high

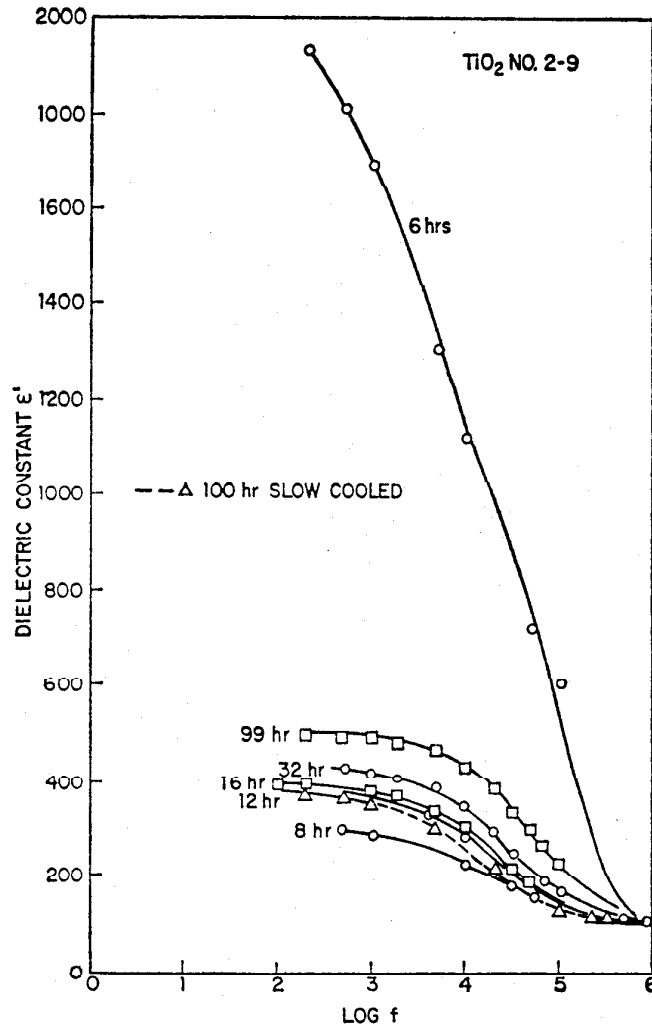


Fig. 5d-3. Dielectric constant corresponding to Fig. 5d-2.

polarizability of oxygen and the high density) and are stable at higher temperatures than organic materials. One class of materials is known as (inorganic) "glasses"; a second class consists of small (about micrometer) crystallites joined together with binders or by sintering and is known as "ceramics." Both are usually considered isotropic but under some conditions of formation are definitely anisotropic. Both also are subject to dielectric dispersions caused by nonstoichiometric compositions (e.g., see Figs. 5d-2 and 5d-3), and at high temperatures the d-c conductivity may become important.

With this introduction it should be clear that the following listings are not intended to be exhaustive; rather, they are intended to be illustrative of the different types of

TABLE 5d-1. MOLAR REFRACTION—ESTIMATION OF OPTICAL FREQUENCY  $\epsilon'$ 

$$R = \frac{M}{\rho} \cdot \frac{\epsilon_{\infty} - 1}{\epsilon_{\infty} + 2} = \text{molar refraction}$$

$$\epsilon_{\infty} = \frac{1 + 2\rho R/M}{1 - \rho R/M} \quad \text{where } R = \sum r \text{ and } M = \sum m$$

Atom (structure)	$r$	$m$	Atom (structure)	$r$	$m$
C.....	2.418	12.01	Br.....	8.865	79.91
H.....	1.100	1.01	I.....	13.900	126.90
O (alcohol).....	1.525	16.00	S.....	7.9	32.06
(carbonyl).....	2.211		N.....	2.5-4.4	14.01
(ether).....	1.643		Structure effects:		
(ester-OR).....	1.04		Double bond....	1.733	
F (one/carbon)....	0.95	19.00	Triple bond....	2.398	
(>one/carbon)..	1.1		3-member ring...	0.71	
Cl.....	5.967	35.45	4-member ring...	0.48	

## Illustration

Heptanol,  $\rho(20^{\circ}\text{C}) = 0.824$ ,  $\text{CH}_3(\text{CH}_2)_5\text{CH}_2\text{OH}$ 

7 C	7(2.418) = 16.926	7(12.01) = 84.07
16 H	16(1.100) = 17.600	16(1.01) = 16.16
1 O <sub>alc.</sub>	1(1.525) = 1.525	1(16.00) = 16.00
	$R = 30.051$	$M = 116.23$

$$\rho R/M = 0.2556 \quad \epsilon_{\infty} = 2.03$$

Cf.  $n^2 = 2.03 \quad \epsilon_{\infty} = 2.35$  (microwave)  
 $n = \text{refractive index (sodium D)}$

TABLE 5d-2. REFERENCE FLUIDS

Gases [1]	$(\epsilon - 1) \times 10^6$ (20°C, 1 atm)*	Nonpolar liquids	$\epsilon'$ (23°C)	$a =$ $-d\epsilon'/dt$	Ref.	Polar liquids [3]	$\epsilon'$ (20°C)	$\alpha = -d$ $\log_{10} \epsilon'/dt$
H <sub>2</sub> .....	253.8 ± 0.3	n-Hexane	1.8829	-0.0015	2	$\phi\text{Cl}$	5.708	0.0013 <sub>3</sub>
He.....	65.0 ± 0.4	Cyclohexane	2.0182	-0.0016	3	EtCl <sub>2</sub> <sup>a</sup>	10.65	0.0024 <sub>0</sub>
O <sub>2</sub> .....	494.7 ± 0.2	CCl <sub>4</sub>	2.2315	-0.0020	4	MeOH <sup>b</sup>	33.62	0.0026 <sub>0</sub>
N <sub>2</sub> .....	548.0 ± 0.5	$\phi\text{H}\dagger$	2.2772	-0.0020	5	$\phi\text{NO}_2$	35.74	0.0022 <sub>4</sub>
Ar.....	517.2 ± 0.4	Silicone (1 cs)‡	2.3000	-0.0028	5			
Air (dry, CO <sub>2</sub> -free)	536.4 ± 0.3	Cryogenic: H <sub>2</sub> § O <sub>2</sub> ¶	1.228 1.507	-0.0034 -0.0024	3 3			

$$*\epsilon(P,t) = \frac{(\epsilon - 1)(t,P)}{(\epsilon - 1)(20^{\circ}\text{C}, 1 \text{ atm})} = \frac{(P)}{1 + 0.003411(t - 20)}$$

 $P = \text{atm}, t = ^{\circ}\text{C}$ 0.02% error for 0 to 30°C, and  $P = 1$  to 0.1 atm.†  $\phi$  represents a benzene ring minus one hydrogen.  $\phi\text{H}$  is benzene.

‡ Centistoke.

§  $\epsilon'$ (20.4 K)¶  $\epsilon'$ (80.0 K)<sup>a</sup> Et = C<sub>2</sub>H<sub>5</sub><sup>b</sup> Me = CH<sub>3</sub>

## References for Table 5d-2

1. NBS Circ. 537, 1953.
2. Mopsik, F. I.: *J. Research NBS* **71A**, 287 (1967).
3. NBS Circ. 514, 1951.
4. Hartmann, H., A. Neumann, and G. Rinck: *Z. phys. Chem.* **44**, 204 (1965).
5. Unpublished results of Bell Telephone Laboratories.

TABLE 5d-3. INORGANIC COMPOUNDS (SMALL MOLECULES)

Type/Name	$\epsilon'$	$t, ^\circ\text{C}$	$a$ (or $\alpha$ )	Range	Type/Name	$\epsilon'$	$t, ^\circ\text{C}$	$a$ (or $\alpha$ )	Range
<i>Elements</i>					<i>Hydrides</i>				
A.....	1.53 <sub>s</sub>	-191	0.0034	-191, -184	NH <sub>3</sub> .....	25.	-77.7		
H <sub>2</sub> .....	1.22 <sub>s</sub>	20.4°K	0.0034	14, 21K		22.4	-33.4		
D <sub>2</sub> .....	1.277	20°K	0.004	18.8, 21.2K		18.9	5		
He.....	1.055 <sub>9</sub>	2.06°K				17.8	15		
	1.055 <sub>9</sub>	2.30				16.9	25		
	1.005 <sub>8</sub>	2.63				16.3	35		
	1.053 <sub>9</sub>	3.09			N <sub>2</sub> H <sub>4</sub> .....	52.9	20	0.0021( $\alpha$ )	0, 25
	1.051 <sub>8</sub>	3.58			AsH <sub>3</sub> .....	2.50	-100	0.0043	-116, -72
	1.048	4.19			SbH <sub>3</sub> .....	2.9 <sub>3</sub> <sup>B</sup>	-80		
O <sub>2</sub> .....	1.507	-193	0.0024	-218, -183		2.5 <sub>3</sub> <sup>B</sup>	-50		
N <sub>2</sub> .....	1.454	-203	0.0029	-210, -195	PH <sub>3</sub> .....	2.5 <sub>6</sub> <sup>B</sup>	-60		
F <sub>2</sub> .....	1.54	-202	0.0019	-216, -190		2.7 <sub>1</sub> <sup>B</sup>	-25		
Cl <sub>2</sub> .....	2.10 <sub>1</sub>	-50	0.0031	65, -33	<i>Halides</i>				
	1.9 <sub>1</sub>	14	0.0032	-23, 14	HF.....	17.5	-79		
	1.7 <sub>3</sub>	77				13.4	-42		
	1.5 <sub>1</sub>	142				11.1	-27		
Br <sub>2</sub> .....	3.09	20	0.007	0, 50		8.4	0		
I <sub>2</sub> .....	11.7	118			HCl.....	12	-113		
	11.7	140				6.35	-15	0.00288( $\alpha$ )	-85, -15
	13.0	168				4.6	28		
S.....	3.52	118			HBr.....	7.00	-85	0.0026( $\alpha$ )	-85, -70
	3.48	231				3.8 <sup>B</sup>	+25		
Se.....	5.40	250	0.0025	237, 301	HI.....	3.39	-50	0.008	-51, -37
P.....	4.10	34				2.9 <sup>B</sup>	22		
	4.06	46			SbCl <sub>3</sub> .....	33.8 <sup>B</sup>	75		
	3.86	85			SbCl <sub>5</sub> .....	3.22	20	0.0046	2, 47
<i>Oxides</i>					SbBr <sub>3</sub> .....	20.9 <sup>B</sup>	100		
H <sub>2</sub> O.....	78.54	25	*	0, 100	SbI <sub>3</sub> .....	13.9 <sup>B</sup>	175		
	34.59	200		100, 370	AsCl <sub>3</sub> .....	12.6 <sup>A</sup>	20		
D <sub>2</sub> O.....	78.25	25		0.4, 98	AsBr <sub>3</sub> .....	9.0 <sup>A</sup>	35		
H <sub>2</sub> O <sub>2</sub> .....	84.2	0		-30, 20	GeCl <sub>4</sub> .....	2.43 <sub>0</sub>	25	0.0024 <sub>0</sub>	0, 55
SO <sub>2</sub> .....	17.6	-20	0.00287( $\alpha$ )	-65, -15	SiCl <sub>4</sub> .....	2.4 <sub>0</sub>	16		
	15.0 <sub>s</sub>	0			SrCl <sub>4</sub> .....	2.87	20	0.0030	-30, 20
	14.1	20	0.077	14, 140	TiCl <sub>4</sub> .....	2.80	20	0.0020	-20, 20
	2.1 <sub>0</sub>	154			PbCl <sub>4</sub> .....	2.78	20		
SO <sub>3</sub> .....	3.11	18			<i>Silicones</i>				
CO <sub>2</sub> .....	1.60	20			(CH <sub>3</sub> ) <sub>3</sub> Si[OSi(CH <sub>3</sub> ) <sub>2</sub> ] <sub>n</sub> CH <sub>3</sub>				
		(50 atm)			n = 1.....	2.17	20		
N <sub>2</sub> O.....	1.97	-90			2.....	2.30	20		
	1.61	0	0.006	-6, 11	3.....	2.30	20		
N <sub>2</sub> O <sub>4</sub> .....	2.5 <sub>6</sub>	15			4.....	2.46	20		
<i>Sulfides</i>					5.....	2.50	20		
H <sub>2</sub> S.....	9.26	-85.5			[OSi(CH <sub>3</sub> ) <sub>2</sub> ] <sub>n</sub> (cyclo)				
	9.05	-78.5			n = 4.....	2.39	20		
CS <sub>2</sub> .....	2.63	20	0.0013	0, 40	5.....	2.50	20		
					6.....	2.59	20		
					7.....	2.68	20		
					8.....	2.74	20		

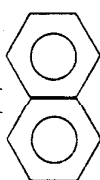
$$* \epsilon = 78.54[1 - 4.579 \times 10^{-3}(t - 25) + 1.19 \times 10^{-5}(t - 25)^2 - 2.8 \times 10^{-8}(t - 25)^3], \pm 0.03\%$$

materials and the different behavior in each type. In the first part we review some small-molecular-weight compounds which are well characterized when pure. In the second part we treat high-molecular-weight materials that are subject to some variation in dielectric properties caused by different conditions of formation (e.g., density variations) and different types and quantities of additives.

Data for Tables 5d-1-4 are taken largely from previous compilations;

"International Critical Tables," Washburn, ed., 1933.  
 Landolt-Börnstein Tabellen, vol. II, part 6, 6th ed., 1959.  
 Maryott and Smith: *NBS Circ.* 514, 1951.  
 Maryott and Buckley: *NBS Circ.* 537, 1953.  
 Buckley and Maryott: *NBS Circ.* 589, 1958.  
 Lange: "Handbook of Chemistry," 10th ed., 1967.

TABLE 5(d)-4. ORGANIC COMPOUNDS (SMALL MOLECULES)

Type/Name	Formula	$t, ^\circ\text{C}$	$\epsilon'$	$n_D^2$	$10^3 a$	Range	Melting point	Boiling point
<i>Hydrocarbons</i>								
<i>Straight chain</i>								
Methane	$\text{H}(\text{CH}_2)_n\text{H}$ ( $n = 1$ )	-173	1.70	.....	0.2	-181, -159	-184	-161.5
Propane	( $n = 3$ )	0	1.61	.....	0.2	-90, 15	-189.9	-42.17
Pentane	( $n = 5$ )	20	1.844	1.841(16°)	0.16	-50, 30	-131.5	36.2
Hexane	( $n = 6$ )	20	1.890	1.89	0.15	-10, 50	-94.3	69.0
Heptane	( $n = 7$ )	20	1.924	1.923(23°)	0.14	-50, 50	-90.5	98.5
Octane	( $n = 8$ )	20	1.948	1.95	0.13	-50, 50	-56.5	125.8
Nonane	( $n = 9$ )	20	1.972	1.97	0.13 <sup>s</sup>	-10, 90	-53.7	150.7
Decane	( $n = 10$ )	20	1.991	1.99	0.13	10, 110	-31	174
Undecane	( $n = 11$ )	20	2.005	2.01	0.12 <sup>s</sup>	10, 130	-26.5	195.8
Dodecane	( $n = 12$ )	20	2.014	.....	0.12	10, 150	-12	214.5
Docosane	( $n = 22$ )	50	2.00	.....	.....	.....	44.4	317.4
Octacosane	( $n = 28$ )	52.2	2.19	.....	.....	.....	.....	.....
<i>Cyclo-</i>								
Pentane	$(\text{C}_5\text{H}_{10})_n$ ( $n = 5$ )	20	1.965	1.97	.....	.....	-93.3	49.5
Hexane	( $n = 6$ )	20	2.023	2.042(15°)	0.16	10, 60	6.5	81.4
<i>Aromatic</i>								
Benzene	$\phi\text{H}$	20	2.284	2.25	0.20	10, 60	5.5	80.1
Toluene	$\phi\text{CH}_3$	25	2.379	2.25	0.24 <sub>3</sub>	0, 90	-95	110.8
Styrene	$\phi\text{CH}=\text{CH}_2$	25	2.43	2.40	.....	.....	.....	146
Diphenyl	$\phi\phi$	75	2.53	2.53(77°)	0.18	75, 155	70	254
Naphthalene		85	2.54	2.51(99°)	.....	.....	80.2	217.9

 $\phi$  represents a benzene ring minus one hydrogen.



TABLE 5d-4. ORGANIC COMPOUNDS (SMALL MOLECULES) (Continued)

Type/Name	Formula	$t, ^\circ\text{C}$	$\epsilon_s$	$\epsilon_\infty$	$f_c, \text{Hz}$	$n_D^{20}$	$10^2\alpha$	Range	Melting point	Boiling point
<i>Alcohols</i>										
Methanol (wood alcohol)	$\text{CH}_3\text{OH}$	0	37.98	6.1	$1.87 \times 10^9$	1.77	0.264	5, 55	-97.8	64.6
Ethanol (grain alcohol)	$\text{CH}_3\text{-CH}_2\text{OH}$	40	33.64	5.7	$3.00 \times 10^9$	1.85	0.270	-5, 70	-117.3	78.5
Glycol (ethylene glycol)	$\text{CH}_2\text{OH-CH}_2\text{OH}$	20	28.39	4.45	$6.17 \times 10^8$	2.05	0.224	20, 100	-17.4	197.2
1-Propanol	$\text{CH}_3\text{-CH}_2\text{-CH}_2\text{OH}$	40	25.07	4.26	$1.11 \times 10^9$	1.90	0.293	20, 90	-127	97.2
2-Propanol (isopropyl alcohol)	$\text{CH}_3\text{-CHOH-CH}_3$	40	22.14	4.18	$1.8 \times 10^9$	1.96	0.310	20, 70	-89	82.3
1,2-Propanediol	$\text{CH}_3\text{-CHOH-CH}_2\text{OH}$	20	38.7	2.66	$1.5 \times 10^9$	2.08	0.27	20	.....	189
1,3-Propanediol	$\text{CH}_2\text{OH-CH}_2\text{-CH}_2\text{OH}$	20	34.9	3.45	$3.0 \times 10^9$	2.18	0.23	20	.....	214(d)
Glycerol	$\text{CH}_2\text{OH-CHOH-CH}_2\text{OH}$	25	25.0	6.0	$1.56 \times 10^8$	2.00	0.208	0, 100	.....	240
1-Butanol	$\text{CH}_3(\text{CH}_2)_2\text{CH}_2\text{OH}$	20	20.8	2.65	$3.75 \times 10^8$	1.95	0.300	-40, 20	-89.2	117.7
2-Butanol	$\text{CH}_3\text{CH}_2\text{CHOH-CH}_3$	20	24.4	6.7	$3.3 \times 10^8$	1.99	0.23	15, 35	-89	99.5
1-Pentanol	$\text{CH}_3(\text{CH}_2)_3\text{CH}_2\text{OH}$	120	19.0	3.2	$2.14 \times 10^8$	2.00	0.35	15, 35	-78.5	138
1-Hexanol	$\text{CH}_3(\text{CH}_2)_4\text{CH}_2\text{OH}$ ( $n = 4$ )	2	32.0	.....	$1.52 \times 10^8$	2.03	.....	15, 35	-51.6	157.2
1-Heptanol	( $n = 5$ )	120	42.5	.....	$7.5 \times 10^9$	2.07	.....	.....	-34.6	176
1-Octanol	( $n = 6$ )	2	35.0	.....	$1.10 \times 10^8$	2.03	0.410	20, 60	-16.3	195
1-Nonanol	( $n = 7$ )	2	17.1	2.95	$9.1 \times 10^7$	2.03	.....	.....	-5	213
1-Decanol	( $n = 8$ )	120	15.8	3.5	$5.75 \times 10^9$	2.05	.....	.....	-6	231
		2	15.3	3.8	$8.0 \times 10^7$	.....	.....	.....	.....	.....
		2	12.9	3.3	$3.5 \times 10^9$	.....	.....	.....	.....	.....
		.....	3.2	2.34	$9.6 \times 10^7$	.....	.....	.....	.....	.....
		.....	11.7	3.10	$3.0 \times 10^9$	.....	.....	.....	.....	.....
		.....	3.10	2.35	.....	.....	.....	.....	.....	.....
		.....	10.35	3.05	.....	.....	.....	.....	.....	.....
		.....	3.05	2.35	.....	.....	.....	.....	.....	.....
		.....	9.05	3.05	.....	.....	.....	.....	.....	.....
		.....	3.05	.....	.....	.....	.....	.....	.....	.....
		.....	7.75	3.10	.....	.....	.....	.....	.....	.....
		.....	3.10	2.40	.....	.....	.....	.....	.....	.....

(d) = decomposes



Quinone.....		23	2.66	.....	.....	115.7	
<i>Ethers</i> .....							
Methyl ether.....	R-O-R'	25	5.02	.....	.....	-138.5	-23.6
Ethyl ether.....	CH <sub>3</sub> O-CH <sub>3</sub>	20	4.335	.....	25, 100	-116.3	34.6
Propyl ether.....	CH <sub>3</sub> CH <sub>2</sub> CH <sub>2</sub> O-CH <sub>2</sub> CH <sub>3</sub>	26	3.3 <sub>9</sub>	.....	.....	-95.2	142
Vinyl ether.....	CH <sub>2</sub> =CH-O-CH <sub>2</sub> CH <sub>3</sub>	20	3.94	.....	.....	.....	39
Phenyl ether.....	φ-O-φ	30	3.65	.....	30, 50	28	259
<i>Nitrogen Derivatives</i> .....							
Ethylamine.....	CH <sub>3</sub> CH <sub>2</sub> NH <sub>2</sub>	10	6.94	.....	-20, 10	-80.6	16.6
Aniline.....	φ-NH <sub>2</sub>	20	7.07	.....	.....	-6.2	184.4
Pyridine.....		24	12.3	.....	.....	.....	.....
<i>Ethane Derivatives</i> .....							
Chloride.....	CH <sub>3</sub> CH <sub>2</sub> Cl	170	6.29	.....	.....	-138.7	12.2
Bromide.....	CH <sub>3</sub> CH <sub>2</sub> Br	20	9.39	.....	-30, 30	-119	38.0
Iodide.....	CH <sub>3</sub> CH <sub>2</sub> I	20	7.82	.....	-20, 70	-109	72.2
Hydroxide (ethanol).....	CH <sub>3</sub> CH <sub>2</sub> OH	See Alcohols		.....	.....	.....	.....
(acid) (acetic acid).....	CH <sub>3</sub> COOH	See Acids		.....	.....	.....	.....
Amire.....	CH <sub>3</sub> CH <sub>2</sub> NH <sub>2</sub>	10	6.94	.....	-20, 10	-80.6	16.6
Nitrite (nitroethane).....	CH <sub>3</sub> CH <sub>2</sub> NO <sub>2</sub>	30	28.0 <sub>6</sub>	.....	30, 35	.....	17
Nitrate.....	CH <sub>3</sub> CH <sub>2</sub> NO <sub>3</sub>	20	19.4	.....	0, 50	-102	88.7
Zinc.....	CH <sub>3</sub> CH <sub>2</sub> Zn-CH <sub>2</sub> CH <sub>3</sub>	20	2.5 <sub>5</sub>	.....	.....	.....	.....
Thiol (ethanethiol).....	.....	15	6.91	.....	.....	-121	34.7
Thiocyanate.....	CH <sub>3</sub> CH <sub>2</sub> CNS	21	29.3	.....	.....	.....	.....
<i>Benzene Derivatives</i> .....							
Fluorobenzene.....	φF	25	5.42	.....	.....	-41.9	84.8
Chlorobenzene.....	φCl	20	5.71	.....	0, 80	-55	132
Bromobenzene.....	φBr	25	5.40	.....	70	-30.6	155

R represents an aliphatic hydrocarbon minus one hydrogen.  
 φ represents a benzene ring minus one hydrogen.  
 (d) = decomposes

TABLE 5d-4. ORGANIC COMPOUNDS (SMALL MOLECULES) (Continued)

Type/Name	Formula	$t$ , °C	$\epsilon'$	$10^2\alpha$ (or $a$ )	Range	Melting point	Boiling point
Iodobenzene.....	$\phi I$	20	4.62	.....	.....	-31.4	188.6
Phenol.....	$\phi OH$	60	9.78	0.32	40, 70	+41	182
Benzoic acid.....	$\phi COOH$	See Acids					
Aniline.....	$\phi NH_2$	20	6.89	0.148	0, 50	-6.2	184.4
Nitrobenzene.....	$\phi NO_2$	25	34.82	0.225	10, 80	5.7	210.9
Toluene.....	$\phi CH_3$	25	2.379	0.243(a)	0, 90	-95	110.8
<i>Structural Variations</i>							
Orthodichlorobenzene.....	.....	25	9.93	0.194	0, 50	-17.5	180
Metadichlorobenzene.....	.....	25	5.04	0.120	0, 50	-24.8	172
Paradichlorobenzene.....	.....	50	2.41	0.18	50, 80	+53	173.4
1-Octanol.....	$CH_2OH \cdot (CH_2)_6 \cdot CH_3$	20	10.34	0.410	20, 60	-16.3	195
2-Octanol.....	$CH_3 \cdot CHOH \cdot (CH_2)_5 \cdot CH_3$	20	8.20	.....	.....	-38.6	179
3-Octanol.....	$CH_3 \cdot CH_2 \cdot CHOH \cdot (CH_2)_4 \cdot CH_3$	20	7.03	.....	.....	.....	.....
4-Octanol.....	$CH_3 \cdot (CH_2)_2 \cdot CHOH \cdot (CH_2)_3 \cdot CH_3$	20	5.12	.....	.....	.....	.....
<i>d</i> -Pinene.....	$C_{10}H_{16}$ (camphorlike structure)	25	2.64	.....	.....	-55	161
<i>l</i> -Pinene.....	.....	20	2.76	.....	.....	.....	.....
<i>cis</i> -1,2-Dichloroethylene.....	$\begin{array}{c} Cl \quad Cl \\   \quad   \\ CH=CH \end{array}$	25	9.20	.....	.....	-80.5	60.1
<i>trans</i> -1,2-Dichloroethylene.....	$\begin{array}{c} Cl \quad \quad \quad \\   \quad \quad \quad \\ CH=CH \\   \quad \quad \quad \\ \quad \quad \quad Cl \end{array}$	25	2.14	.....	.....	-50	48.4

 $\phi$  represents a benzene ring minus one hydrogen.

TABLE 5d-5. LOW-LOSS POLYMERS

Name	$\epsilon'$	$\rho, \theta/cc$	$d\epsilon/dt$	$t, ^\circ C$	$10^6 \tan \delta(f)$								References		
					$10^2$	$10^3$	$10^4$	$10^5$	$10^6$	$10^7$	$10^8$	$10^9$		$10^{10}$	
Polyethylene.....	.....	.....	.....	-80	30	40	60	80	...	...	...	...	...	...	1
	2.286 <sub>0</sub>	0.920 <sub>5</sub>	-0.0012	-20	50	50	50	55	55	...	...	...	...	...	1
	2.355	0.966	.....	23	25	30	45	55	80	...	...	...	...	...	2
Polypropylene.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	2
	.....	.....	.....	-110	10	10	10	...	...	...	120	...	...	...	3
	.....	.....	.....	-20	50	45	40	...	...	...	...	...	...	...	3
Polyisobutylene.....	2.25	.....	.....	23	100	125	155	140	100	100	70	60	...	...	4
	2.23	.....	.....	25	400	100	100	<200	100	100	100	300	470	...	4, 5
	2.56	.....	.....	25	<50	<50	<50	50	70	<200	<100	330	430	...	4, 5
	2.55	.....	.....	25	210	110	100	110	130	200	380	460	470	...	4
	.....	.....	.....	23	<20	<20	20	30	60	130	240	240	140	...	2
.....		2.100 <sub>0</sub>	-0.0004 <sub>4</sub>	.....	<20	<20	20	30	60	130	240	240	140	...	2
.....		$d\epsilon/d\rho = 0.61$	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....

References for Table 5d-5

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TABLE 5d-6. POLAR POLYMERS

Name	t, °C	$\epsilon'$ (f/Hz)										$10^6 \epsilon''$ (f/Hz)										References	
		10 <sup>2</sup>	10 <sup>3</sup>	10 <sup>4</sup>	10 <sup>5</sup>	10 <sup>6</sup>	10 <sup>7</sup>	10	10 <sup>9</sup>	10 <sup>10</sup>	10 <sup>11</sup>	10 <sup>12</sup>	10 <sup>13</sup>	10 <sup>14</sup>	10 <sup>15</sup>	10 <sup>16</sup>	10 <sup>17</sup>	10 <sup>18</sup>	10 <sup>19</sup>	10 <sup>20</sup>			
Polychlorotrifluoroethylene: 80% crystalline.....	+23	2.714	2.640	2.555	2.498	2.404	2.440	—	2.388	2.360	31.5	54.9	47.7	29.2	22.9	19.0	—	15.5	18.0	—	—	—	1
	22.7	2.595	2.492	2.398	2.342	—	—	—	—	—	62.2	69.9	52.5	31.0	—	—	—	—	—	—	—	—	—
12% crystalline.....	20	3.1s	3.1o	3.0z	2.9e	2.8s	2.8r	2.8s	2.84	—	41	56	68	62	46	33	23	16	—	—	—	—	2,3
	47	3.6o	3.5z	3.4i	3.2s	3.1a	3.0z	2.9z	2.81	—	36	65	82	86	72	49	32	22	—	—	—	—	—
Polyvinyl chloride.....	75	3.9z	3.8s	3.6s	3.3	3.0	2.8r	2.8	2.81	—	71	84	117	132	105	78	53	49	—	—	—	—	—
	96	6.6o	5.3o	4.4o	3.7	3.3	2.8	2.7	2.6	—	990	740	530	360	240	140	86	75	—	—	—	—	—
Polyvinylidene chloride.....	110	9.9	8.6	6.8	5.6	3.1s	2.9r	2.8z	2.7o	1.020	1.140	1.210	1.060	181	92	51	14	—	—	—	—	—	2
	23	4.8s	4.6s	4.1r	3.6o	3.1s	2.9r	2.8z	2.71	2.7o	220	293	368	304	181	92	51	19	—	—	—	—	—
Polyvinylidene fluoride.....	84	5.1s	4.9s	4.8s	4.7i	4.4o	3.7e	3.2	2.7e	—	400	104	63	154	343	487	288	67	—	—	—	—	—
	23	12.8	12.2	11.6	10.5	8.9	6.8	4.7	4.7	—	461	415	615	1,080	1,897	1,900	1,160	—	—	—	—	—	4,5
Polymethyl methacrylate.....	27	3.4o	3.1z	2.9e	2.8z	2.7e	2.7i	2.6e	2.6o	2.59	260	145	88	57	39	27	16	17	—	—	—	—	2
	80	4.3o	3.8o	3.3i	3.0o	2.8o	2.7o	—	2.5e	—	300	340	267	156	90	57	20	20	—	—	—	—	—
Polycarbonate.....	23	—	2.9z	2.9i	2.8o	2.8o	2.7r	—	—	—	—	1.5	4.5	15	30	35	27	15	—	—	—	—	4,6
	23	—	2.59	2.59	2.59	2.59	2.59	—	—	—	—	0.9	—	—	1.8	—	—	—	—	—	—	—	4
Polyphenylene oxid.....	25	3.13	3.13	3.10	3.10	3.10	3.0e	—	—	2.95	—	3.4	70	68	62	60	20	20	—	—	—	—	7
	25	3.6o	3.5o	3.3s	3.2z	3.1i	3.0e	3.0	2.84	2.73	56	65	70	71	68	60	20	20	—	—	—	—	2,8
Polyamide.....	84	13.6	11.2	9.0	6.3	4.4	3.7	3.4	2.94	3,170	1,570	1,420	1,280	756	426	228	105	20	—	—	—	—	—
	25	3.9e	3.9o	3.8z	3.6r	3.5z	3.4z	3.2e	3.01	2.94	27	44	79	95	96	91	98	88	—	—	—	—	2
Epoxy.....	25	3.9e	3.9o	3.8z	3.6r	3.5z	3.4z	3.2e	3.01	2.94	27	44	79	95	96	91	98	88	—	—	—	—	2
	25	3.9e	3.9o	3.8z	3.6r	3.5z	3.4z	3.2e	3.01	2.94	27	44	79	95	96	91	98	88	—	—	—	—	2
Rubbers: Hevea (vulcanized).....	27	2.9z	2.9z	2.9z	2.8s	2.7z	2.5z	2.4z	2.36	—	14	7	18	63	122	103	43	11	—	—	—	—	2
	25	2.6i	2.6o	2.5s	2.5e	2.5z	2.5o	2.4r	2.36	—	1.3	1.0z	2.3z	5.3e	10.6	20.0	29.6	11.1	—	—	—	—	—
Gutta-percha.....	24	6.7o	6.6o	6.5z	6.4r	6.2e	5.5z	4.5	4.0	107	73	75	97	238	660	405	270	135	104	—	—	—	—
	25	3.3e	3.3o	3.2e	3.2z	3.2o	3.1e	3.1e	3.0e	21	22	21	19	12	9	9	9	11	31	54	—	—	—

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Additional topics covered by these references are: ferroelectrics, liquid crystals, solutions, and pressure dependence of  $\epsilon$ . More recent data on pressure dependence can be found in:

Skinner, Cussler, and Fuoss: *J. Phys. Chem.* **72**, 1057 (1968).

Mopsik: *J. Research NBS* **71A**, 287 (1967).

Hartman, Neumann, and Rinck: *Z. Phys. Chem.* **44**, 204 (1965).

Data on dielectric breakdown are omitted. Scatter in reported values is about 10 percent in gases and several-fold in the condensed phases. Some trends are well established, however: Gases which can capture electrons and which have vibrational modes available to store and dissipate energy (e.g., SF<sub>6</sub>) have higher breakdown strengths than air (by two or three times), and gases with no vibrational modes (e.g., He) have lower strengths than air. Condensed phases can have *intrinsic* breakdown strengths around 10<sup>7</sup> volts/cm, but practical values are 10 to 100 times lower than this. Discernible trends in breakdown field strength are: D-c values are 10 to 100 times higher than MHz values; values decrease with increasing thickness; and some polymers show a drop at elevated temperature.

TABLE 5d-7. DETAILED DESCRIPTION OF A PARTICULAR POLYMER  
 A. Loss Index "Map" for Polychlorotrifluoroethylene  
 Smoothed  $10^4\epsilon''$ , 80% Crystalline\*

f, Hz	t, °C										
	-50	-25	0	23	50	75	100	125	150	175	200
$10^{-1}$	360	187	100	53	26	61	58	58	80	102	532
$2 \times 10^{-1}$	382	221	113	60	26	56	58	57	78	66	380
$5 \times 10^{-1}$	389	279	139	75	30	50	58	55	78	42	175
$10^0$	378	326	160	83	34	45	58	54	80	35	121
$2 \times 10^0$	355	370	189	105	38	40	59	53	83	30	79
$5 \times 10^0$	312	421	239	133	49	35	60	53	85	29	38
$10^1$	279	449	298	162	59	33	61	52	85	33	23
$2 \times 10^1$	243	457	364	197	72	35	63	54	83	42	15
$5 \times 10^1$	198	426	445	257	100	44	65	58	79	58	11
$10^2$	167	382	488	315	130	54	66	61	76	70	11
$2 \times 10^2$	145	335	511	387	175	67	68	65	74	83	13
$5 \times 10^2$	126	269	487	490	267	95	70	71	73	99	20
$10^3$	113	224	444	549	348	131	76	77	72	111	28
$2 \times 10^3$	104	192	391	572	445	188	90	82	74	117+	40
$5 \times 10^3$	95	165	320	536	581	294	117	92	82	119	58
$10^4$	91	151	275	477	640	413	166	104	92	116	73
$2 \times 10^4$	87	139	238	413	650	544	244	127	107	113	89
$5 \times 10^4$	82	126	200	335	595	683	404	187	131	123	111
$10^5$	78	120	183	292	535	745	561	277	175	142	127
$2 \times 10^5$	74	115	170	263	479	754	744	432	243	171	146
$5 \times 10^5$	70	112	165	248	442	716	803	552	314	214	158
$10^6$	64	104	155	229	363	586	830	826	608	421	246
$3.2 \times 10^6$	557	96	149	208	306	485	737	720	821	793	518
$10^7$	51	92	144	190	275	425	637	873	1,018	1,090	1,013
$2.92 \times 10^7$	.....	.....	.....	155	.....	.....	403	.....	852	.....	.....



B. Permittivity "Map" for Polchlorotrifluoroethylene†  
Smoothed  $\epsilon'$ , 80% Crystalline

$10^{-1}$	2.597	2.684	2.740	2.772	2.798	2.832	2.862	2.887	2.926	2.958	2.955
$2 \times 10^{-1}$	2.582	674	735	770	797	831	860	886	923	956	2.946
$5 \times 10^{-1}$	2.559	661	727	765	796	827	858	883	918	955	2.942
$10^0$	2.540	647	721	762	794	824	856	881	915	955	2.941
$2 \times 10^0$	2.522	631	713	758	793	821	854	879	913	954	2.940
$5 \times 10^0$	2.500	605	702	751	791	818	849	877	910	953	2.940
$10^1$	2.486	686	690	746	788	816	846	874	908	952	2.939
$2 \times 10^1$	2.474	565	675	737	785	815	842	871	905	950	2.939
$5 \times 10^1$	2.461	538	651	725	781	812	838	868	900	948	2.939
$10^2$	2.454	520	629	714	777	810	835	863	896	945	2.938
$2 \times 10^2$	2.447	503	604	700	772	808	832	861	892	942	2.938
$5 \times 10^2$	2.438	485	571	672	760	804	828	858	888	937	2.937
$10^3$	2.433	474	548	646	748	800	825	854	885	932	2.937
$2 \times 10^3$	2.428	464	529	618	733	796	822	852	882	927	2.935
$5 \times 10^3$	2.423	455	507	578	700	781	818	846	878	919	2.933
$10^4$	2.418	448	495	555	672	771	812	842	875	913	2.930
$2 \times 10^4$	2.415	441	485	534	641	751	807	839	871	908	2.927
$5 \times 10^4$	2.410	434	472	510	596	706	792	832	865	902	2.920
$10^5$	2.407	428	464	498	571	671	771	825	860	898	2.916
$2 \times 10^5$	2.404	424	456	488	552	641	744	814	854	892	2.913
$5 \times 10^5$	2.402	420	451	483	541	623	725	808	848	887	2.909
$10^6$	2.397	412	441	468	516	581	665	757	823	867	2.900
$3.2 \times 10^6$	2.393	405	431	454	493	547	602	688	768	825	2.882
$10^7$	2.390	2.397	2.421	2.440	2.475	2.515	2.552	2.610	2.700	2.762	2.849
$2.92 \times 10^7$	.....	.....	.....	2.432	.....	.....	2.470	.....	2.560	.....	.....

\* Note ridges (r) and valleys (v) in  $\epsilon''$ :

$r_1$  ( $-50^\circ$ ,  $5 \times 10^{-1}$  Hz;  $23^\circ$ ,  $2 \times 10^3$  Hz;  $150^\circ$ ,  $10^7$  Hz)

$r_2$  ( $75^\circ$ ,  $10^{-1}$  Hz;  $100^\circ$ ,  $2 \times 10^2$  Hz),  $r_3$  ( $110^\circ$

$2 \times 10^{-1}$  Hz;  $175^\circ$ ,  $5 \times 10^2$  Hz),

$v_1$  ( $50^\circ$ ,  $10^{-1}$  Hz;  $75^\circ$ ,  $2 \times 10^2$  Hz)

$v_2$  ( $100^\circ$ ,  $10^{-1}$  Hz,  $125^\circ$ ,  $2 \times 10^1$  Hz)

$v_3$  ( $175^\circ$ ,  $2$  Hz;  $200^\circ$ ,  $10^2$  Hz)

† Adjusted value.

‡ Skett, Scheiber, Curtis, Lauritzen, and Hoffman, *J. Research NBS 66A* 269 (1962). There is a typographical error in the data for specimen 0.80 at  $1.75^\circ\text{C}$  and  $2 \times 10^3$  Hz. The listed value of  $137 \times 10^{-4}$  for  $f = 2.10^3$  Hz,  $t = 175^\circ\text{C}$  should be  $117 \times 10^{-4}$ .

TABLE 5d-8. CERAMICS AND GLASSES

Name and Ref. No.	t, °C	$\epsilon'$ (f, Hz)										$10^4 \tan \delta$ (f, Hz)									
		10 <sup>2</sup>	10 <sup>3</sup>	10 <sup>4</sup>	10 <sup>5</sup>	10 <sup>6</sup>	10 <sup>7</sup>	10 <sup>8</sup>	10 <sup>9</sup>	10 <sup>10</sup>	10 <sup>11</sup>	10 <sup>12</sup>	10 <sup>13</sup>	10 <sup>14</sup>	10 <sup>15</sup>	10 <sup>16</sup>	10 <sup>17</sup>	10 <sup>18</sup>	10 <sup>19</sup>	10 <sup>20</sup>	
<i>Glass (Corning no.)</i>																					
Soda lime (0080)—high loss [1]	23	8.30	7.70	7.35	7.03	6.90	6.82	6.75	6.71	6.71	780	400	230	140	100	85	50	170			
(7570)—high $\epsilon'$	25	14.58	14.56	11.54	14.53	14.52	14.50	14.42	14.2	14.2	11.5	13.5	15.9	16.5	19.0	23.5	33	98			
Soda, Pb, borosilicate (7720) Pyrex	24	4.74	4.70	4.67	4.64	4.62	4.61	—	4.59	4.59	78	42	39	22	20	23	—	43			
Soda, borosilicate (7740) Pyrex	25	4.80	4.73	4.70	4.60	4.55	4.52	4.52	4.52	4.52	128	86	65	54	49	45	45	—	85		
96% silica (7900) Vycor [1]	20	3.85	—	—	—	—	—	3.85	3.82	3.82	6	6	6	6	6	6	—	—	9.4		
100		3.85	—	—	—	—	—	3.85	3.82	3.82	6	6	6	6	6	6	—	—	13		
<i>Fused silica</i>																					
915c [1]	25	3.78	—	—	—	—	—	—	3.78	3.78	6.6	2.6	1.1	0.4	0.1	0.1	0.3	—	1.7		
(7040) NBS [2]	RT	—	—	—	—	—	—	—	(3.83)	(3.83)	—	—	—	0.4	0.4	0.3	—	—	1.2		
(7040) NRC [2]	RT	—	—	—	—	—	—	—	(3.83)	(3.83)	—	—	—	0.2	0.1	0.1	—	—	4		
(7040) NPL [2]	RT	—	—	—	—	—	—	—	(3.83)	(3.83)	—	—	—	0.4	0.5	0.2	—	—	0.8		
(7940) NBS [2]	RT	—	—	—	—	—	—	—	6.20	6.20	—	—	—	11.2	12.7	14.0	—	—	77		
<i>Ceramic</i>																					
Stearite* AISiMag A-196* [1]	25	5.90	5.88	84	5.80	5.70	5.65	5.60	5.24	5.24	30	59	79.6	55	30.5	19	16	26			
81		5.90	5.88	84	5.80	5.70	5.65	5.60	—	—	58	40	46.5	70.5	66	40.5	24	38			
Forsterite* AISiMag 243 [1]	85	6.37	6.37	6.37	6.36	6.32	6.28	—	—	—	21	13.7	8.0	<9	3.7	3.5	—	—	20		
<i>Titania ceramic*</i>																					
NPOT 93 [1]	25	29.5	—	—	—	—	—	29.5	28.9	28.9	12	4.9	3.3	2.5	1.6	1.7	2	20			
N 750 T 96	25	83.4	—	—	—	—	—	83.4	83.4	83.4	5.7	4.5	3.5	2.5	2.2	2.3	4.6	14.6			
N 1400 T 110	25	131	130.8	130.7	130.5	130.2	130.2	130.0	—	—	6.7	5.5	3.3	1.4	3.0	5.5	7.0	—			
<i>High alumina</i>																					
85% [1]	35	8.22	8.18	8.17	8.17	8.16	8.16	8.16	8.08	8.08	20	13.4	11.4	10.5	9.0	7.5	9.0	27			
96% [1]	25	8.83	8.83	8.82	8.80	8.80	8.80	8.80	8.79	8.79	14	5.7	4.8	3.8	3.3	3.2	3.0	14			
99.5% [2]	23	—	9.43	(9.41)	9.43	—	—	9.43	9.4	9.4	—	14	7	4	1.6	2.0	0.4	1			
99.5% [3]	23	—	9.55	( $\rho = 3.83 \text{ g/cm}^3$ )	—	—	—	9.55	—	—	—	—	—	—	—	—	—	—			
BeO ( $\rho = 2.88 \text{ g/cc}$ ) [8]	23	—	—	6.60	—	—	—	6.6	—	—	—	—	—	—	—	—	—	—			
TiO <sub>2</sub> —see Figs. 5d-2 and 3		—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—		

$d\epsilon'/d\rho = 3.34 \text{ cm}^3/\text{g}$

$d\epsilon'/d\rho = 3.82 \text{ cm}^3/\text{g}$

$<1$

\* American Lava Corporation.  
**References for Table 5d-8**  
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 3. Unpublished data of Bell Telephone Laboratories.

Name	$\log_{10} \rho(t, ^\circ\text{C}), \Omega \cdot \text{cm}$					
	25	100	250	350	500	900
Soda lime 0080.....	12.4	.....	6.4	5.1		
Soda, Pb, borosilicate 7720 Pyrex.....	16	.....	8.8	7.2		
Soda, borosilicate 7740 Pyrex.....	15	.....	8.1	6.6		
96% silica 7900 Vycor.....	17	.....	9.7	8.1		
Steatite AlSiMag A-196.....	>14	13	...	...	7.6	5.5
Forsterite AlSiMag 243.....	>14	13.7	...	...	10.1	6.5
High alumina 85%.....	>14					

TABLE 5d-9. NATURAL PRODUCTS

Type/Name	$t, ^\circ\text{C}$	$f, \text{Hz}$	$\epsilon'$	$10^4 \tan \delta$	References
<i>Waxes</i>					
Bayberry.....	24	$10^3$	3.22-3.27	50-58	1
Beeswax, crude.....	24	$10^3$	2.87-2.88	28-30	1
yellow.....	23	$10^3$	2.66	14	2
white.....	23	$10^3$	2.63	118	2
		$10^6$	2.43	84	2
		$3 \times 10^9$	2.35	50	2
Spermaceti.....	24	$10^3$	3.60-3.75	30-32	1
Microcrystalline.....	25	$10^3$	2.5	4	4
Candelilla.....	24	$10^3$	2.38-2.49	46	1
Carnauba.....	24	$10^3$	2.66-2.83	34	1
Ozokerite.....	24	$10^3$	2.37-2.43	76-88	1
<i>Resins and Pitches</i>					
Canada balsam.....	22	$2 \times 10^3$	3.22	130	4
Rosin.....	24	$10^3$	2.69-2.76	16-40	1
Manila copal.....	24	$10^3$	3.05-3.09	44-87	1
Asphalt.....	25	$10^3$	2.6	1,200	4
Amber.....	25	$10^3$	2.7	18	2
Shellac.....	24	$10^3$	3.5-3.7	65-80	1, 2
<i>Oils</i>					
Castor.....	23	$3 \times 10^9$	2.68	870	3
Tung.....	23	$2 \times 10^3$	3.32	10	4
<i>Miscellaneous</i>					
Basalt.....	RT	Low	12.		8
Granite.....	RT	Low	7.-9.		8
Sandstone.....	RT	Low	9.-11.		8
Diamond.....	26	$1.6 \times 10^6$	5.7		5
Marble.....	RT	90-650	8.3	30-500	8
Plywood.....	23	$2.4 \times 10^{10}$	1.7	200-700	7
Slate.....	RT	950	6.0-7.5	860	8
Mica (muscovite)...	25	$10^6$	6.6	2	6

References to Table 5d-9

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