

DIELECTRIC STRENGTH OF INSULATING MATERIALS

L. I. Berger

The loss of the dielectric properties by a sample of a gaseous, liquid, or solid insulator as a result of application to the sample of an electric field* greater than a certain critical magnitude is called *dielectric breakdown*. The critical magnitude of electric field at which the breakdown of a material takes place is called the *dielectric strength* of the material (or *breakdown voltage*). The dielectric strength of a material depends on the specimen thickness (as a rule, thin films have greater dielectric strength than that of thicker samples of a material), the electrode shape**, the rate of the applied voltage increase, the shape of the voltage vs. time curve, and the medium surrounding the sample, e.g., air or other gas (or a liquid — for solid materials only).

Breakdown in Gases

The current carriers in gases are free electrons and ions generated by external radiation. The equilibrium concentration of these particles at normal pressure is about 10^3 cm^{-3} , and hence the electrical conductivity is very small, of the order of $10^{-16} - 10^{-15} \text{ S/cm}$. But in a strong electric field, these particles acquire kinetic energy along their free pass, large enough to ionize the gas molecules. The new charged particles ionize more molecules; this avalanche-like process leads to formation between the electrodes of channels of conducting plasma (streamers), and the electrical resistance of the space between the electrodes decreases virtually to zero.

Because the dielectric strength (breakdown voltage) of gases strongly depends on the electrode geometry and surface condition and the gas pressure, it is generally accepted to present the data for a particular gas as a fraction of the dielectric strength of either nitrogen or sulfur hexafluoride measured at the same conditions. In Table 1, the data are presented in comparison with the dielectric strength of nitrogen, which is considered equal to 1.00. For convenience to the reader, a few average magnitudes of the dielectric strength of some gases are expressed in kilovolts per millimeter. The data in the table relate to the standard conditions, unless indicated otherwise.

Breakdown in Liquids

If a liquid is pure, the breakdown mechanism in it is similar to that in gases. If a liquid contains liquid impurities in the form of small drops with greater dielectric constant than that of the main liquid, the breakdown is the result of formation of ellipsoids from these drops by the electric field. In a strong enough electric field, these ellipsoids merge and form a high-conductivity channel between the electrodes. The current increases the temperature in the channel, liquid boils, and the current along the steam canal leads to breakdown. Formation of a conductive channel (bridge) between the electrodes is observed also in liquids with solid impurities. If a liquid contains gas impurities in the form of small bubbles, breakdown is the result of heating of the liquid in strong electric fields. In the locations with the highest current density, the liquid boils, the size of the gas bubbles increases, they merge and form gaseous channels between the electrodes, and the breakdown medium is again the gas plasma.

Breakdown in Solids

It is known that the current in solid insulators does not obey Ohm's law in strong electric fields. The current density increases almost exponentially with the electric field, and at a certain field magnitude it jumps to very high magnitudes at which a specimen of a material is destroyed. The two known kinds of electric breakdown are thermal and electrical breakdowns. The former is the result of material heating by the electric current. Destruction of a sample of a material happens when, at a certain voltage, the amount of heat produced by the current exceeds the heat release through the sample surface; the breakdown voltage in this case is proportional to the square root of the ratio of the thermal conductivity and electrical conductivity of the material. The electrical breakdown results from the tunneling of the charge carriers from electrodes or from the valence band or from the impurity levels into the conduction band, or by the impact ionization. The tunnel effect breakdown happens mainly in thin layers, e.g., in thin p-n junctions. Otherwise, the impact ionization mechanism dominates. For this mechanism, the dielectric strength of an insulator can be estimated using Boltzmann's kinetic equation for electrons in a crystal.

In the following tables, the dielectric strength values are for room temperature and normal atmospheric pressure, unless indicated otherwise.

* The unit of electric field in the SI system is newton per coulomb or volt per meter.

** For example, the U.S. standard ASTM D149 is based on use of symmetrical electrodes, while per U.K. standard BS2918 one electrode is a plane and the other is a rod with the axis normal to the plane.

Table 1
Dielectric Strength of Gases

Material	Dielectric* Strength	Ref.	Material	Dielectric* Strength	Ref.
Nitrogen, N ₂	1.00		Trichlorofluoromethane, CCl ₃ F	3.50	1
Hydrogen, H ₂	0.50	1,2		4.53	2
Helium, He	0.15	1	Trichloromethane, CHCl ₃	4.2	1
Oxygen, O ₂	0.92	2		4.39	2
Air	0.97	6	Methylamine, CH ₃ NH ₂	0.81	1
Air (flat electrodes), kV/mm	3.0	3	Difluoromethane, CH ₂ F ₂	0.79	2
Air, kV/mm	0.4-0.7	4	Trifluoromethane, CHF ₃	0.71	2
Air, kV/mm	1.40	5	Bromochlorodifluoromethane, CF ₂ ClBr	3.84	2
Neon, Ne	0.25	1	Chlorodifluoromethane, CHClF ₂	1.40	1
	0.16	2		1.11	2
Argon, Ar	0.18	2	Dichlorofluoromethane, CHCl ₂ F	1.33	1
Chlorine, Cl ₂	1.55	1		2.61	2
Carbon monoxide, CO	1.02	1	Chlorofluoromethane, CH ₂ ClF	1.03	1
	1.05	2	Hexafluoroethane, C ₂ F ₆	1.82	1
Carbon dioxide, CO ₂	0.88	1		2.55	2
	0.82	2	Ethyne (Acetylene), C ₂ H ₂	1.10	1
	0.84	6		1.11	2
Nitrous oxide, N ₂ O	1.24	2	Chloropentafluoroethane, C ₂ ClF ₅	2.3	1
Sulfur dioxide, SO ₂	2.63	2		3.0	6
	2.68	6	Dichlorotetrafluoroethane, C ₂ Cl ₂ F ₄	2.52	1
Sulfur monochloride, S ₂ Cl ₂ (at 12.5 Torr)	1.02	1	Chlorotrifluoroethylene, C ₂ ClF ₃	1.82	2
Thionyl fluoride, SOF ₂	2.50	1	1,1,1-Trichloro-2,2,2-trifluoroethane	6.55	2
Sulfur hexafluoride, SF ₆	2.50	1	1,1,2-Trichloro-1,2,2-trifluoroethane	6.05	2
	2.63	2	Chloroethane, C ₂ H ₅ Cl	1.00	1
Sulfur hexafluoride, SF ₆ , kV/mm	8.50	7	1,1-Dichloroethane	2.66	2
	9.8	8	Trifluoroacetonitrile, CF ₃ CN	3.5	1
Perchloryl fluoride, ClO ₃ F	2.73	1	Acetonitrile, CH ₃ CN	2.11	2
Tetrachloromethane, CCl ₄	6.33	1	Dimethylamine, (CH ₃) ₂ NH	1.04	1
	6.21	2	Ethylamine, C ₂ H ₅ NH ₂	1.01	1
Tetrafluoromethane, CF ₄	1.01	1	Ethylene oxide (oxirane), CH ₃ CHO	1.01	1
Methane, CH ₄	1.00	1	Perfluoropropene, C ₃ F ₆	2.55	2
	1.13	2	Octafluoropropane, C ₃ F ₈	2.19	1
Bromotrifluoromethane, CF ₃ Br	1.35	1		2.47	2
	1.97	2	3,3,3-Trifluoro-1-propene, CH ₂ CHCF ₃	2.11	2
Bromomethane, CH ₃ Br	0.71	2	Pentafluoroisocynoethane, C ₂ F ₅ NC	4.5	1
Chloromethane, CH ₃ Cl	1.29	2	1,1,1,4,4,4-Hexafluoro-2-butyne, CF ₃ CCCF ₃	5.84	2
Iodomethane, CH ₃ I	3.02	2	Octafluorocyclobutane, C ₄ F ₈	3.34	2
Iodomethane, CH ₃ I, at 370 Torr	2.20	7	1,1,1,2,3,4,4,4-Octafluoro-2-butene	2.8	1
Dichloromethane, CH ₂ Cl ₂	1.92	2	Decafluorobutane, C ₄ F ₁₀	3.08	1
Dichlorodifluoromethane, CCl ₂ F ₂	2.42	1	Perfluorobutanenitrile, C ₃ F ₇ CN	5.5	1
	2.63	2,6	Perfluoro-2-methyl-1,3-butadiene, C ₅ F ₈	5.5	1
Chlorotrifluoromethane, CClF ₃	1.43	1	Hexafluorobenzene, C ₆ F ₆	2.11	2
	1.53	2	Perfluorocyclohexane, C ₆ F ₁₂ , (saturated vapor)	6.18	2

*Relative to nitrogen, unless units of kV/mm are indicated.

Table 2
Dielectric Strength of Liquids

Material	Dielectric strength kV/mm	Ref.	Material	Dielectric strength kV/mm	Ref.
Helium, He, liquid, 4.2 K	10	9	Octane, C ₈ H ₁₈	16.6	14
Static	10	11		20.4	15
Dynamic	5	11		179	17,18
	23	12	Ethylbenzene, C ₈ H ₁₀	226	17,18
Nitrogen, N ₂ , liquid, 77K			Propylbenzene, C ₉ H ₁₂	250	17,18
Coaxial cylinder electrodes	20	10	Isopropylbenzene, C ₉ H ₁₂	238	17,18
Sphere to plane electrodes	60	10	Decane, C ₁₀ H ₂₂	192	17,18
Water, H ₂ O, distilled	65-70	13	Butylbenzene, C ₁₀ H ₁₄	275	17,18
Carbon tetrachloride, CCl ₄	5.5	14	Isobutylbenzene, C ₁₀ H ₁₄	222	17,18
	16.0	15	Silicone oils—polydimethylsiloxanes, (CH ₃) ₃ Si-O-[Si(CH ₃) ₂] _x -O-Si(CH ₃) ₃		
Hexane, C ₆ H ₁₄	42.0	16	Polydimethylsiloxane silicone fluid	15.4	20
Two 2.54 cm diameter spherical electrodes, 50.8 μm space	156	17,18	Dimethyl silicone	24.0	21,22
Cyclohexane, C ₆ H ₁₂	42-48	16	Phenylmethyl silicone	23.2	22
2-Methylpentane, C ₆ H ₁₄	149	17,18	Silicone oil, Basilone M50	10-15	23
2,2-Dimethylbutane, C ₆ H ₁₄	133	17,18	Mineral insulating oils	11.8	6
2,3-Dimethylbutane, C ₆ H ₁₄	138	17,18	Polybutene oil for capacitors	13.8	6
Benzene, C ₆ H ₆	163	17,18	Transformer dielectric liquid	28-30	6
Chlorobenzene, C ₆ H ₅ Cl	7.1	14	Isopropylbiphenyl capacitor oil	23.6	6
	18.8	15	Transformer oil	110.7	24
2,2,4-Trimethylpentane, C ₈ H ₁₈	140	17,18	Transformer oil Agip ITE 360	9-12.6	23
Phenylxylyethane	23.6	19	Perfluorinated hydrocarbons		
Heptane, C ₇ H ₁₆	166	17,18	Fluorinert FC 6001	8.0	23
2,4-Dimethylpentane, C ₇ H ₁₆	133	17,18	Fluorinert FC 77	10.7	23
Toluene, C ₆ H ₅ CH ₃	199	17,18	Perfluorinated polyethers		
	46	16	Galden XAD (Mol. wt. 800)	10.5	23
	12.0	14	Galden D40 (Mol. wt. 2000)	10.2	23
	20.4	15	Castor oil	65	25

Table 3
Dielectric Strength of Solids

Material	Dielectric strength kV/mm	Ref	Material	Dielectric strength kV/mm	Ref
Sodium chloride, NaCl, crystalline	150	26	Phlogopite, amber, natural	118	6
Potassium bromide, KBr, crystalline	80	26	Fluorophlogopite, synthetic	118	6
Ceramics			Glass-bonded mica	14.0-15.7	6
Alumina (99.9% Al ₂ O ₃)	13.4	6,27a	Thermoplastic Polymers		
Aluminum silicate, Al ₂ SiO ₅	5.9	6	Polypropylene	23.6	6
Berillia (99% BeO)	13.8	6,27b	Amide polymer nylon 6/6, dry	23.6	6
Boron nitride, BN	37.4	6	Polyamide-imide copolymer	22.8	6
Cordierite, Mg ₂ Al ₄ Si ₅ O ₁₈	7.9	6,27c	Modified polyphenylene oxide	21.7	6
Forsterite, Mg ₂ SiO ₄	9.8	28	Polystyrene	19.7	6
Porcelain	35-160	26	Polymethyl methacrylate	19.7	6
Steatite, Mg ₃ Si ₄ O ₁₁ •H ₂ O	9.1-15.4	6	Polyetherimide	18.9	6
Titanates of Mg, Ca, Sr, Ba, and Pb	20-120	3	Amide polymer nylon 11(dry)	16.7	6
Barium titanate, glass bonded	>30	36	Polysulfone	16.7	6
Zirconia, ZrO ₂	11.4	29	Styrene-acrylonitrile copolymer	16.7	6
Glasses			Acrylonitrile-butadiene-styrene	16.7	6
Fused silica, SiO ₂	470-670	26	Polyethersulfone	15.7	6
Alkali-silicate glass	200	26	Polybutylene terephthalate	15.7	6
Standard window glass	9.8-13.8	28	Polystyrene-butadiene copolymer	15.7	6
Micas			Acetal homopolymer	15.0	6
Muscovite, ruby, natural	118	6	Acetal copolymer	15.0	6

Table 3
Dielectric Strength of Solids (continued)

Material	Dielectric strength kV/mm	Ref.	Material	Dielectric strength kV/mm	Ref.
Polyphenylene sulfide	15.0	6	Varnishes		
Polycarbonate	15.0	6	Vacuum-pressure impregnated baking		
Acetal homopolymer resin (molding resin)	15.0	6	type solventless polyester varnish		
Acetal copolymer resin	15.0	6	Rigid, two-part	70.9	6
Thermosetting Molding Compounds			Semiflexible high-bond thixotropic	78.7	6
Glass-filled allyl	15.7	6	Rigid high-bond high-flash	68.9	6
(Type GDI-30 per MIL-M-14G)			freon-resistant		
Glass-filled epoxy, electrical grade	15.4	6	Baking type epoxy varnish		
Glass-filled phenolic	15.0	6	Solventless, rigid, low viscosity,	90.6	6
(Type GPI-100 per MIL-M-14G)			one-part		
Glass-filled alkyd/polyester	14.8	6	Solventless, semiflexible, one-part	82.7	6
(Type MAI-60 per MIL-M-14G)			Solventless, semirigid, chemical	106.3	6
Glass-filled melamine	13.4	6	resistant, low dielectric constant		
(Type MMI-30 per MIL-M-14G)			Solvable, for hermetic electric motors	181.1	6
Extrusion Compounds for High-Temperature Insulation			Polyurethane coating		
Polytetrafluoroethylene	19.7	6	Clear conformal, fast cure		
Perfluoroalkoxy polymer	21.7	6	Standard conditions	78.7	6
Fluorinated ethylene-propylene copolymer	19.7	6	Immersion conditions	47.2	6
Ethylene-tetrafluoroethylene copolymer	15.7	6	Insulating Films and Tapes		
Polyvinylidene fluoride	10.2	6	Low-density polyethylene film	300	31
Ethylene-chlorotrifluoroethylene	19.3	6	(40 µm thick)		
copolymer			Poly- <i>p</i> -xylylene film	410-590	32
Polychlorotrifluoroethylene	19.7	6	Aromatic polymer films		
Extrusion Compounds for Low-Temperature Insulation			Kapton H (Du Pont)	389-430	33
Polyvinyl chloride			Ultem (GE Plastic and Roem AG)	437-565	33
Flexible	11.8-15.7	30	Hostaphan (Hoechst AG)	338-447	33
Rigid	13.8-19.7	30	Amorphous Stabar K2000	404-422	33
Polyethylene	18.9	28	(ICI film)		
Polyethylene, low-density	21.7	6	Stabar S100 (ICI film)	353-452	33
	300	31	Polyetherimide film (26 µm)	486	34
Polyethylene, high-density	19.7	6	Parylene N/D (poly- <i>p</i> -xylylene/poly-		
Polypropylene/polyethylene copolymer	23.6	6	dichloro- <i>p</i> -xylylene) 25 µm film	275	6
Embedding Compounds			Cellulose acetate film	157	6
Basic epoxy resin:	19.7	6	Cellulose triacetate film	157	6
bisphenol-A/epichlorohydrin			Polytetrafluoroethylene film	87-173	6
polycondensate			Perfluoroalkoxy film	157-197	6
Cycloaliphatic epoxy: alicyclic	19.7	6	Fluorinated ethylene-propylene	197	6
diepoxy carboxylate			copolymer film		
Polyetherketone	18.9	30	Ethylene-tetrafluoroethylene film	197	6
Polyurethanes			Ethylene-chlorotrifluoroethylene	197	6
Two-component, polyol-cured	25.4	6	copolymer film		
Two-part solventless,	24.0	6	Polychlorotrifluoroethylene film	118-153.5	6
polybutylene-based			High-voltage rubber insulating tape	28	6
Silicones			Various Insulators		
Clear two-part heat curing electrical	21.7	6	Rubber, natural	100-215	26
grade silicone embedding resin			Butyl rubber	23.6	6
Red insulating enamel (MIL-E-22118)			Neoprene	15.7-27.6	6
Dry	47.2	6	Silicone rubber	26-36	6
Wet	11.8	6	Room-temperature vulcanized	9.2-10.9	35
Enamels			silicone rubber		
Red enamel, fast cure			Ureas (from carbamide	11.8-15.7	28
Standard conditions	78.7	6	to tetraphenylurea)		
Immersion conditions	47.2	6	Dielectric papers		
Black enamel			Aramid paper, calendered	28.7	6
Standard conditions	70.9	6	Aramid paper, uncalendered	12.2	6
Immersion conditions	47.2	6	Aramid with Mica	39.4	6

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