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Components and Materials: Part 6.

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2-24. Dielectric Data:

Collected below are the properties of some common dielectrics. This information is not meant to represent the state-of-the-art in electrical engineering, but is rather a list of materials which might be of interest to amateur experimenters; i.e., it includes the materials which you might come across while rummaging in the shed, along with the materials used in commercially available capacitors and structural components. Vastly more information is available, as may be determined by obtaining references [7], [8], and [40] for example.

In the matter of selecting materials: it should now be obvious that in situations where we specifically do not want to create capacitance, such as when choosing materials for coil-formers and insulators, then non-polar dielectrics are to be preferred. Non-polar materials are also to be preferred for for their low losses and constancy of the dielectric constant over the radio-frequency range, and so find service in transmission-line cables and small value capacitors. There is a particular advantage of polar materials and ferroelectrics however, which is that they permit a relatively large amount of capacitance to be achieved in a small volume. Sometimes therefore, we may be inclined to overcome the technical challenges posed by materials with a large εr' so that we may enjoy the benefits of miniaturisation; one of these benefits being low parasitic inductance. It also transpires that the selection of available non-polar materials is somewhat limited, and it may be necessary to choose a polar material in order to obtain a desired combination of strength, rigidity, and heat-resistance. The art in selecting polar materials therefore, lies in knowing the general form of the spectrum of the dielectric constant, and examining the available data to ensure that there are no significant (unwanted) dispersion regions in the frequency range of interest.

The properties of manufactured dielectric materials are often modified by the use of additives, and so may vary according to manufacturer and sometimes between different batches. This applies particularly to ceramics, plastics, and rubbers, and obviously to composite materials (glass-reinforced plastics etc.). The inclusion of additives in the pre-polymerisation or melt stages of production is known as *compounding*. Compounding ingredients may be present in high concentration; and so the dielectric constant at a particular frequency, normally being the average for the mixture, may deviate substantially from that of a pure material. There may be a greater effect than simple averaging however, particularly when *plasticisers* are added to polar materials. Plasticisers are waxy substances with a plate-like molecular structure, which are added to plastics in order to improve softness and flexibility. They work by facilitating sliding between adjacent polymer chains, but by so doing also alter the relaxation time for orientation polarisation and the extent to which it may occur. The use of plasticisers in PVC (polyvinyl chloride), for example, has the effect of shifting the dispersion for internal rotation to higher frequency and thereby degrading RF performance (not that it was any good in the first place).

In addition to the true dielectric properties of a material; there may also be anomalous behaviour due to so-called 'interfacial effects'. Some possible causes are: discontinuities (cracks and layers) in the material, the trapping of charge carriers at the electrodes, and there may be impurities which give rise to pockets of conductive or resistive material. These usually minor deviations from true dielectric behaviour are classified under the general heading of 'Maxwell-Wagner effects' (ref. [8], section 1.8.5), and normally result in additional loss and low-frequency behaviour indistinguishable from dielectric absorption.

An important property of dielectrics, so far not discussed, is that of dielectric strength. Except for ferroelectrics, dielectric materials behave in a reasonably linear fashion with increasing field strength, up to a certain point; after which there is sufficient force to rip electrons out of the constituent atoms or molecules and the material breaks down. In the case of solid materials based on chains of carbon atoms, such as plastics, rubbers, and many composites, this results in liberation of free carbon (charring); and since carbon is a moderate electrical conductor, a permanent short-circuit is created. This problem is circumvented in capacitors made by vapour deposition of a thin metal film onto a plastic sheet (metallised film capacitors), because the amount of metal in the electrode is so small that it will vaporise and be blasted away from the site of injury. Such capacitors are said to be self-healing; but even so, the capacitance will be reduced slightly if parts of the electrodes are destroyed [29]. In foil capacitors (i.e., capacitors using metal foil electrodes), which are to be preferred in RF applications for their low electrode resistance, self-healing is not possible. Solid materials not based on carbon may also fail by permanent short circuit; in this case the mechanism being physical puncturing of the dielectric, and plating of the resulting channel by conductive decomposition products and metal vaporised from the electrodes.

Only liquids, gases, and vacuum recover fully from over-voltage events; but the electrodes may not fare so well. An arc (conduction process involving ionised gas) will scar the plates of a capacitor, leaving the surface rough on a microscopic scale. Free electric charges in a conductor tend to congregate at the sharpest points, and so initiate discharges by the so called 'field-emission effect'. This means that once an air capacitor (for example) breaks down, its breakdown voltage will be reduced from that time onwards, and will not recover until the capacitor is dismantled and the scarred areas re-polished (vacuum capacitors are more forgiving in this respect, since the gas pressure is very low and the electrode erosion process is consequently less vigorous). It follows also, that an air-variable capacitor will only achieve its maximum possible voltage rating if the plates have a mirror finish and are free from burrs and sharp edges. Smooth surfaces and rounded edges are also required in dielectric test capacitors, to ensure a uniform field, even when measurements are only to be carried out at low voltages.

The breakdown voltage of a solid dielectric is not perfectly proportional to the electrode spacing. The field strength (volts per metre) for dielectric breakdown is usually greater for small electrode spacings than it is for large electrode spacings. Note also that the dielectric strength of a material may vary according to the frequency and waveform of the applied field. It is the *peak* voltage of the applied waveform, not the RMS voltage, which should be used when estimating the electrical stress; i.e., for a sine wave (such as a radio signal):

$V_{pk} = V_{RMS} \times\sqrt{2}$

If a capacitor is used in a DC-blocking application (e.g., valve anode (tube plate) coupling), the constant DC potential must be added to the peak RF potential.

Notice that air, albeit a very low loss dielectric, has a low dielectric strength. Since capacitance is inversely proportional to the plate spacing, the need for large plate spacings (at least 1mm for every 3KV peak) makes it impossible to construct physically small high-voltage air capacitors. Fortunately, the dielectric strength of air *increases* as the humidity increases; the reason being that water vapour acts as an electron-capture agent, and so tends to extinguish arcs.

Dielectric constant, Tanδ, dielectric strength, and resistivity may all vary with temperature. Resistivity in general will reduce (i.e., conductivity will increase) as the temperature increases (either due to high ambient temperature or dielectric losses); most insulators being effectively semiconductors in the broadest sense of the term. Increased conductivity is associated with a reduction in dielectric strength, since it is leakage current which initiates the avalanche process involved in insulation breakdown. Improved cooling of the dielectric is partially responsible for the increase in dielectric strength (but not breakdown voltage) which occurs when the electrode spacing is reduced.

Properties of Dielectrics.

Note 1: Material properties may vary according to manufacturer, age, storage, and condition. Data are selected from diverse sources and are for general guidance only. For critical applications; refer to manufacturer's data or original references.

Note 2: Dielectric strength (field strength for insulation breakdown) varies according to sample thickness, being greatest for thin films. Sample thickness is given in brackets (where known). 1mil = 0.001" = 25.4 µm. 1" = 25.4 mm.

Abbreviations: RH=relative humidity. typ=typical. k=1000, M=10^6, G=10^9, T=10^{12}. < means "less than". > means "greater than". ~ means "approximately".

A. Minerals, Ceramics, Glasses.

Material	Dielectric Type	Freq / Hz	εr'	Tanδ	Dielectric strength / kV/mm	resistivity ρ / Ωm
High Vacuum (< 10^{-3}mmHg)	-	0 - ∞	1	0	∞ (see note *)	∞ (see note *)
Air, Dry 20°C, 1bar	Non-polar	<30G	1.0005361	~0	3.1 *** (1.6-10mm)	-
Air 20°C, 1bar 25%RH			1.00060		>3.1	-
60%RH			1.00066			
100%RH			1.00074			
Barium Titanate** (BaTiO3) ceramics	Ferro-electric	1M	200 - 12000	0.016 (εr'=1200)	2 - 12	-
Glass, Borosilicate (Pyrex), 20°C,	Polar	1k	5.3	0.005	13	10^{12}
		1M	5.3	0.004		
Glass, soda (ordinary), 20°C	Polar	1M	7.5	0.01	8 - 10	10^9 - 10^{11}
		100M	7.5	0.008		
Ruby mica	Polar	1M	5.4	0.0003	150 - 220	10^{11} - 10^{15}
		100M	5.4	0.0002		
Porcelain, 20°C	Polar	1M	7 - 5.5	0.007 - 0.008	1.6- 3.9	-
Porcelain (HV electrical) 20-100°C	Polar	50	5.5	0.03	-	-
		1M	5.5	0.008		

* The dielectric strength of vacuum is practically infinite, but no vacuum is perfect. Typical (un-gettered) vacuum capacitors and relays have an internal pressure of about 10^{-7} Torr (mmHg). This leads to a breakdown field strength of about 40 kV/mm [See Jennings Technology Website, Tech Notes: Vacuum Dielectric]. Vacuum devices also conduct electricity when the field strength between electrodes is high, due to the Schottky effect [41][42], i.e., the reduction of the threshold for thermionic emission in the presence of an electric field. This conduction process is dependent on the work-function (Helmholtz free energy) of the electrode material, i.e., it is a property of the electrodes, not the vacuum.

** The entry above refers to Class 2, 3 and 4 capacitor ceramics. High-stability Class 1 (C0G or NPO) ceramiccs have little or no ferroelectric contribution to εr'.

*** See Paschen's law.

B. Composites.

Material	Dielectric Type	Freq / Hz	εr'	Tanδ	Dielectric strength / kV/mm	resistivity, ρ / Ωm
Fibreglass- epoxy	Polar	60	4.2 - 5.3	0.003 - 0.015	12 - 24 (1/8")	10^{13}
		1M	4.2 - 5.3	0.010 - 0.030		
Fibreglass- polyester	Polar	60	4.0 - 6.0	0.005 - 0.090	8 - 24 (1/8")	10^3 - 10^{10}
		1k	4.2 - 5.0	0.004 - 0.040		
		1M	3.0 - 6.0	0.007 - 0.040		
Fibreglass- PTFE	mainly non-polar	60	2.2 - 2.33	0.004	10.6 - 11.8 (1/8")	$>10^5$
		1k	2.2 - 2.33	0.001		
		1M	2.2 - 2.4	0.00035		
Phenolic resin, fabric filled (SRBF, Tufnol), 20°C	Polar	60	5.0 - 10.0	0.04 - 0.05	4.7 - 17.3 (1/8")	10^8 - 10^{10}
		1k	4.2 - 6.5	0.04 - 0.09		
		1M	5.0 - 7.5	0.05 - 0.10		
Phenolic resin, paper filled (SRBP, Paxolin) 20°C	Polar	60	4.5 - 7.5	0.02 - 0.10	10.2 - 32 (1/8")	10^8 - 10^{11}
		1k	4.2 - 6.0	0.03 - 0.07		
		1M	3.6 - 6.0	0.02 - 0.08		
		100M	5	0.02		
		1G	5	0.08		
Wood, Scots pine 15% water, density 0.61 gm/cm³. 20°C	Polar	1M	8.2	0.059	-	-
		100M	7.3	0.094		

C. Plastics

Material	Dielectric Type	Freq / Hz	εr'	Tanδ	Dielectric strength / kV/mm	resistivity, ρ / Ωm
ABS (acrylonitrile-butadiene-styrene)	Polar	60	2.4 - 5.0	0.003 - 0.008	-	10^{14}
		1k	2.5 - 3.0	-		
		1M	2.4 - 3.8	0.007 - 0.015		
Acrylic (polymethyl-methacrylate, Perspex, Lucite, Plexiglass) 20°C	Polar	60	3.5 - 4.5	0.04 - 0.06	40	$>10^{13}$
		1k	3.5 - 4.0	0.040		
		1M	3.0 - 3.5	0.02 - 0.030		
		100M	2.6	0.006		
		1G	2.58	0.009		
ETFE (ethylene-tetrafluoroethylene copolymer, Tefzel)	slightly polar	1k	2.6	0.0008	200 (1 mil) 100 (5 mil)	10^{14}
		1M	2.6	0.005		
		1G	2.4	0.0005		
Nylon-66 (ordinary, typical) 20°C	Polar	60	4.0 - 4.6	0.014 - 0.04	-	10^{12}-10^{13} dry (10^{10} @ 50%RH)
		1M	3.4 - 3.6	0.04		
		100M	3	0.02		
PET (polyethylene-terephthalate, polyester, Mylar), 20°C	Polar	50	3.2	0.002	300 (1mil) 134 (5mil)	10^{15} - 10^{17}
		1k	3.2	0.005		
		1M	3.0	0.016		
		100M	2.9	0.015		
		1G	2.8	0.003 - 0.008		
PEEK (polyether ether ketone)	Polar	100	3.2	0.001	24 (1 mm)	$>10^{12}$
		1 M	3.2	0.002		
Polycarbonate (PC, Lexan, Merlon, Tuffak) typical 20°C	Polar	60	3.17	0.0009	250 (1 mil) 80 (5 mil)	2×10^{14}
		1k	2.99	0.0015		
		1M	2.93 - 2.96	0.010		
		1G	2.89	0.012		
Polyethylene (Polythene, PE) 20°C	non-polar	50 - 1G	2.2 - 2.35 typ 2.3	≤ 0.0003	200 (1 mil) 120 (5 mil)	10^{14} - 10^{18}
Polypropylene (PP) 20°C	non-polar	50 - 1G	2.2 - 2.6 typ 2.2	≤ 0.0005 typ 0.0003	106 (5 mil)	10^{13} - 10^{15}
Polystyrene (PS, Distrene, Victron, Trolitul) 20°C	non-polar	50 - 1G	2.7 - 2.4	0.0002 - 0.0005	200 (1 mil)	10^{15} - 10^{19}
		1M	2.56	0.00007		
		100M	2.55	0.0001		
		10G	2.54	0.00043		
PTFE (poly-tetrafluoroethylene, Teflon), 20°C	non-polar	50 - 3G	2.0 - 2.1	≤ 0.0002	50-90 (1 mil) 40 (5 mil)	10^{15} - 10^{19}
PVC, plasticised (polyvinylchloride) 20°C	Polar	1k	4.0 - 8.0	0.07 - 0.16	60 (5 mil)	5×10^{6} - 5×10^{12}
		1M	3.3 - 4.5	0.04 - 0.14		
		10M	4	0.06		
PVC-U (unplasticised) 20°C	Polar	50	3.2	0.02	55 (5 mil)	5×10^{12} - 10^{14}
		1k	3.0 - 3.3	0.009 - 0.017		
		1M	2.7 - 3.1	0.006 - 0.017		
		100M	2.8	0.01		
		1G	2.8	0.019		

D. Rubbers

Material	Dielectric Type	Freq / Hz	εr'	Tanδ	Dielectric strength / kV/mm	resistivity, ρ / Ωm
Neoprene (polychloroprene) 20°C (24°C)	Polar	1k	6.5 (6.6)	0.03	4.4 - 28	$10^8 - 10^{11}$
		1M	5.7 (6.26)	0.095		
		100M	3.4 (4.5)	0.16		
Rubber, natural (polyisoprene), soft vulcanised. 20°C	slightly polar	1M	3.2	0.028	10 - 25	10^3
		10M	3.2	0.020		
Silicone rubber unfilled (translucent). 25°C	slightly polar	60	~3.1	0.001	22 (1/8")	$>10^{10}$
		1k	3.12 - 3.30	-		
		1M	3.10 - 3.20	0.001		
		100M	3.06 - 3.18	-		
Silicone rubber 67% TiO2 filled (white) 20°C	Polar	50	8.6	0.005	-	-
		1M	8.5	0.001		
		100M	8.5	0.001		
Silicone rubber Mineral filled (opaque)	slightly polar	60	3.5 - 3.6	0.004	10 - 24	$>10^{12}$
		1M	3.4 - 3.6	0.005 - 0.007		

Sources for tables A - D:

[7] C779-788, E50, E56.
[8] 1.8.3, 1.8.5, 2.11.1.
[8a] p90-95
[9] table 6.04 (p334)
[18] Table II (p111).
[25] Ch IV, p147, table IV.
[36]: tables 6.4 (p6.9) and 10.3 (p10.14).
[40] Section 3.
[43] Dielectric strength of Neoprenes.
[44] Silicone rubbers.

E. Material selection by loss tangent.

Lossy Tanδ ≥ 0.01 (δ ≥ 0.57°)	Good 0.01 > Tanδ ≥ 0.001 (0.57° > δ ≥ 0.057°)	Excellent Tanδ < 0.001 (δ < 0.057°)
Fibreglass (GRP)	ABS*	Vacuum
Nylon	Acrylics (Perspex, Plexiglass)*	Air
PVC	Glass, Porcelain	Mica
Phenolic (SRBF, SRBP)	PET (Mylar, polyester)	Polyethylene (PE)
Rubber	Polycarbonate (Lexan)	Polypropylene (PP)
Neoprene	Silicone rubber	Polystyrene (PS)
Wood	ETFE (Tefzel)	PTFE (Teflon)

* Borderline performance. Tail-end of low-frequency dispersion occurs in HF range.

F. Weathering and high-temperature limits of plastics and rubbers.

Material	Water absorption (Saturated)	Melting or softening temp. / °C	UV Resistance
ABS	0.6 - 1%	Softens >77	Fair
Acrylic	0.3 - 0.4%	Softens 180	Good
ETFE	< 0.02%	Melts 270	Fair - Good
Nylon 66	8.5% saturated (2.5% @ 50% RH)	Melts 218	Fair
Polycarbonate	0.35 %	Softens 132	Fair
Polyethylene	< 0.01%	Melts ~133	Poor* - Fair
Polypropylene	< 0.03%	Melts 168	Poor* - Fair
Polystyrene	0.04 - 0.1%	Softens ~98	Poor - Fair
PTFE	0	Melts 327	Very Good
PVC (plasticised)	Negligible		Fair
PVC-U	Negligible	Softens ~80	Fair - Good
Rubber (Natural)		Decomposes	Very poor
Neoprene		Decomposes	Poor
Silicone Rubber	~0	Thermoset	Good

Sources for table F: Refs [40], [8] + practical experience. UV Resistance: Good = no significant change in properties on prolonged exposure. Fair = changes in surface properties or transparency, but maintains structural integrity. Poor = becomes brittle and disintegrates.
* Basic UV resistance may be improved by additives. Addition of carbon black gives UV resistance by preventing light penetration but increases Tanδ.

2-25. Interpretation of Dielectric Data:

The data given in the preceding tables should be sufficient for general selection of materials for RF applications. Note however that there are many excellent engineering materials with rather poor dielectric properties. The point is not to avoid using such materials, but simply to avoid subjecting them to strong RF fields.

PTFE deserves special mention because it manages to combine almost every desirable electrical property in a single material. It has practically no losses, its melting point is higher than that of solder, it can be machined and extruded, it is highly water-repellent, it is almost chemically inert, and it is infinitely resistant to UV light. It is for all of these reasons that PTFE is widely used for wire-coverings, insulators, coil-formers, etc., in professional radio installations. Its main disadvantage is that it is expensive, but since, in general, only small quantities are required, this is not a valid excuse for replacement by inferior materials. One minor disadvantage is that it is a soft plastic, and so cannot be used in situations where high tensile or compression strength is required (e.g., dipole centres and antenna end insulators).

PVC, on the other hand, deserves special mention because it is a thoroughly awful dielectric. The dielectric losses which occur in plasticised PVC, in particular, are similar to those those which occur in untreated wood. This is both unfortunate and pernicious; because PVC is widely used as a cable insulator in power distribution, audio, and telephone applications. The ubiquity of PVC in electrical service appears to lead amateur (and some commercial) designers to believe that it is suitable for RF purposes. The amateur literature abounds with examples of coils wound on PVC formers (drain-pipes etc.), sometimes with PVC coated wire, all of which will exhibit abysmal Q and are likely to melt in medium power (0.4 - 1.5 kW) applications. For an illustration of the effect of PVC formers on coil Q see reference [14a and 14b]. Other failures known to the author include: the use of PVC-covered tinned-copper wire in balun transformers, the use of PVC-covered twin-lead in antenna feeders, the use of PVC sleeving for wire insulation in HF linear-amplifier anode compartments, the use of PVC electrical tape in high-field regions, and so on (ad nauseam). The dielectric constant of PVC is also highly temperature dependent, for which reason PVC components should not be used in the construction of oscillators and other high-stability circuits.

Finally, notice that the circuit-board materials: fibreglass-reinforced epoxy, and phenolic resin bonded paper; are not particularly good dielectrics. This is of no consequence in small-signal applications; but it should explain why antenna tuners and linear-amplifier anode circuits are best built using traditional wire and solder-tag construction techniques. The sometimes-recommended practice of using pieces of double-sided fibreglass copper laminate board to make capacitors should be avoided.

2-26. Properties of water:

Although we would not want to use it as a capacitor dielectric, water is the most important of the polar liquids, and its behaviour is both well-documented and a good illustration of the polarisation theory discussed earlier. Water has a relatively large dipole moment because the molecule is asymmetric (V-shaped), the lowest-energy electronic configuration demanding an angle of 105° between the chemical bonds connecting the oxygen atom to the two hydrogen atoms. This gives rise to a strong orientation effect, and a corresponding εr' of 80 at low frequencies. A wide range of relaxation times for the orientation process results in a very broad peak in εr" at about 17 GHz (at 20°C) corresponding to the rotational spectrum of the water molecule in its liquid state [8]. The broadness of this energy-absorbing region is such that there is still sufficient dielectric loss to impair satellite TV reception at 10GHz during severe rain, and still sufficient loss to heat a cup of coffee in a microwave oven operating at 2450MHz. The data below clearly show the decline in εr' and the corresponding increase in Tanδ as the frequency is increased [8][8a]:

	Frequency / Hz	εr'	Tanδ	εr = εr' -**j**εr' Tanδ
Dielectric data for distilled water at 20°C	1M	80	0.005	80 -**j**0.4
	1G	80	0.065	80 -**j**5.2
	3G	78	0.17	78 -**j**13.3
	10G	64	0.47	64 - **j**30.1

When the orientation process finally drops out of the dielectric constant in the infrared, the residual value of εr' due to atomic and electronic polarisation is 5.0. In the visible part of the spectrum, where the atomic polarisation contribution has dropped out, εr' is reduced to 1.78. The figure of 1.78 is obtained from optical measurements; and is almost exactly equal to the square of the refractive index.

When water is frozen, the rotational process becomes severely restricted, and the absorption peak moves to the 10 kHz to 50 kHz region [8a]. The DC value of εr' however is still about 75, indicating that orientation polarisation remains the dominant effect at low frequencies.

Water is also slightly conductive, even in its pure form, due to spontaneous formation of the ions $H3O^+$ and OH^- (the ion H^+ cannot exist independently in solution and so attaches itself to a water molecule to become $H3O^+$). Water also becomes much more conductive in the presence carbon dioxide, due to the reaction:

$3H2O + CO2 \rightarrow 2H3O^+ + CO3^{2-}$

The conduction processes, being ionic in nature, involve charged particles that are vastly heavier than electrons. Conductivity is therefore limited by the restricted mobility of the current carriers. Absorption losses consequently decline initially as the frequency is increased, reaching a minimum at about 1 MHz with Tanδ=0.005, after which they increase steadily as the frequency moves into the dispersion region for orientation polarisation.

From a radio engineering point of view, water is of interest primarily because we need to exclude it. Notwithstanding its ability to initiate electrochemical corrosion; with its large dielectric constant and its tendency to propagate by capillary action, it can drastically alter the characteristic impedance of semi air-spaced coaxial cables, and it will de-tune resonators and loading coils. Outdoor installations can be protected from water ingress by using O-ring sealed boxes, cable-glands conforming to the European IP68 specification, and by using sealed N-type connectors, not the execrable PL259.

2-27. The microwave oven test?

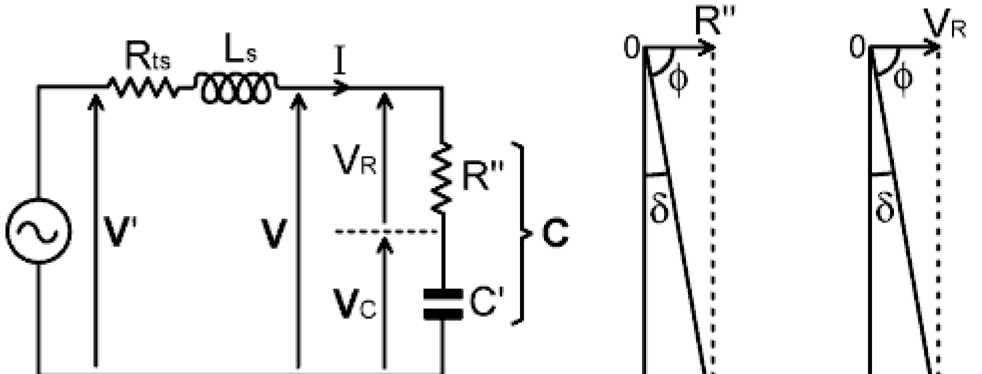
In the Amateur Radio literature, it is often suggested that a dielectric can be tested for suitability at radio frequencies by putting a sample of it into a microwave oven. If such a test is carried out, it is advisable to give the magnetron a load, such as a cup of water; thereby avoiding excessive anode dissipation in the event that the test sample should fail to absorb a significant amount of energy. It should also be noted that the test may be highly misleading.

Microwave ovens operate at approximately 2450 MHz, in a band of frequencies reserved for industrial, scientific, and medical (ISM) use. This fortuitously corresponds to the low-frequency tail of the rotational spectrum of liquid water, and it therefore appropriate for heating food. Solid polar dielectrics, on the other hand, often have dispersion regions at much lower frequencies, and so may have high losses at HF or VHF but show no significant signs of heating at 2450 MHz. Conversely, it is also possible for a polar dielectric to have a strong dispersion region at 2450 MHz, but low losses in the HF range. The point is, that the microwave oven test can only evaluate a material for operation in the 2 - 3 GHz region. For HF and VHF radio purposes, the test is at best, unreliable; and in principle, meaningless.

The only reliable method for determining the suitability of a dielectric for operation in a particular frequency range is to obtain (or measure) its performance in or on either side of that range, and relate the data to the general form of the dielectric constant spectrum as described earlier. Specifically, the implication of the polarisation theory is that; if the dielectric constant is the same below and above a particular range of frequencies, then there cannot be a dispersion region in between.

2-28. Dielectric Power Loss:

Although dielectric data can be used as a qualitative guide for the purpose of material selection, εr' and Tanδ figures can also be translated into actual power-loss in a given application. In an earlier section, we showed how the 'true' (complex) capacitance of a capacitor can be represented as a capacitor C' in series with a resistor R". The resistive component R" represents the losses which occur in the dielectric, and so we can calculate the power dissipated in the dielectric by calculating the power dissipated in R". The situation we must analyse in order to do so is shown below:



The conductor resistance Rts and the circuit inductance Ls are included merely as a reminder that the true capacitance C is not directly accessible from a measurement point of view. In many situations however, the Voltage V will not be significantly different from the voltage V' which can be measured directly across the capacitor terminals; and so for the purpose of this analysis we will assume that the applied voltage is effective at the interface between the capacitor electrodes and the dielectric. Notice, in the diagram above, that the current I has been chosen as a 0° reference vector so that it can be treated as a scalar equal to its own magnitude, i.e., $I=|\mathbf{I}|$; and since VR is in phase with I it can be treated as a scalar $VR=|VR|$ also.

The power dissipated in the dielectric is:

$P = VR^2 / R''$ . . . (2-28.1)

where the RMS voltage VR is the hypothetical fraction of the applied voltage which appears across the dielectric loss resistance R''. We can relate VR to the applied voltage **V** by observing (in accordance with Ohm's law) that $VR=IR''$ and $\mathbf{V}=I\mathbf{Z}C$ (where **Z**C is the impedance of the complex capacitance as a whole), and that by using the magnitude product rule (**1-21.3**) the second relationship may be expressed in terms of magnitudes, i.e., $|\mathbf{V}|=|\mathbf{I}||\mathbf{Z}C|=I|\mathbf{Z}C|$. Thus:

$|\mathbf{V}| / |\mathbf{Z}C| = VR / R''$

hence:

$VR = |\mathbf{V}|\, R'' / |\mathbf{Z}C|$

Substituting this result into (**2-28.1**) gives:

$P = |\mathbf{V}|^2 (R'')^{\color{gray}2} / |\mathbf{Z}C|^2 \,{\color{gray}R''}$

i.e.,

$P = |\mathbf{V}|^2 R'' / |\mathbf{Z}C|^2$ . . . (**2-28.2**)

Now, $|\mathbf{Z}C| = \sqrt{[(R'')^2 + (XC')^2]}$

hence:

$|\mathbf{Z}C|^2 = (R'')^2 + (XC')^2$

and we may substitute for R'' and XC' using equations (**2-14.1**) given earlier, thus:

$|\mathbf{Z}C|^2 = (-XC0\, \varepsilon r'' / |\varepsilon r|^2)^2 + (XC0\, \varepsilon r' / |\varepsilon r|^2)^2$

where C0 is the capacitance in the absence of a dielectric. Thus:

$|\mathbf{Z}C|^2 = XC0^2 [(\varepsilon r'')^2 + (\varepsilon r')^2] / |\varepsilon r|^4$

but $(\varepsilon r'')^2+(\varepsilon r')^2=|\varepsilon r|^2$, hence:

$|\mathbf{Z}C|^2 = XC0^2 / |\varepsilon r|^2$

Substituting this result into (**2-28.2**) gives:

$P = |\mathbf{V}|^2 R'' |\varepsilon r|^2 / XC0^2$

and substituting for R'' using equations (**2-14.1**) gives:

$P = -|\mathbf{V}|^2 {\color{gray}XC0}\, \varepsilon r'' {\color{gray}|\varepsilon r|^2} / ({\color{gray}|\varepsilon r|^2}\, XC0^{\color{gray}2})$

i.e.:

$P = -|\mathbf{V}|^2 \varepsilon r'' / XC0$

but $XC0=-1/2\pi fC0$, thus:

$P = |\mathbf{V}|^2\, 2\pi f\, C0\, \varepsilon r''$

and $C0=\varepsilon 0A/h$, where A is the electrode area, and h is the electrode spacing; hence:

$P = |\mathbf{V}|^2\, 2\pi f\, \varepsilon 0\, \varepsilon r''\, A / h$ . . . (**2-28.3**)

The electric field strength in the dielectric is given by the expression:

$E = |\mathbf{V}| / h$ Volts / metre

where, since |**V**| is an RMS voltage, E is an RMS field strength. Hence:

$|\mathbf{V}| = E\, h$

Substituting this into (**2-28.3**) gives:

$P = E^2 h^{\color{gray}2}\, 2\pi f\, \varepsilon 0\, \varepsilon r''\, A / {\color{gray}h}$

i.e.:

$P = E^2\, 2\pi f\, \varepsilon 0\, \varepsilon r''\, A\, h$

but A×h is a volume; it is the volume of the dielectric in the electric field. Let us therefore define the power per unit volume as:

$W = P / A\, h$ Watts / cubic metre

hence

$W = E^2\, 2\pi f\, \varepsilon 0\, \varepsilon r''$ Watts / metre³	**2-28.4**

or, using equation (**2-15.1**)

$$W = E^2\, 2\pi f\, \varepsilon 0\, \varepsilon r'\, \mathrm{Tan}\delta \qquad \text{Watts / metre}^3 \qquad \textbf{2-28.5}$$

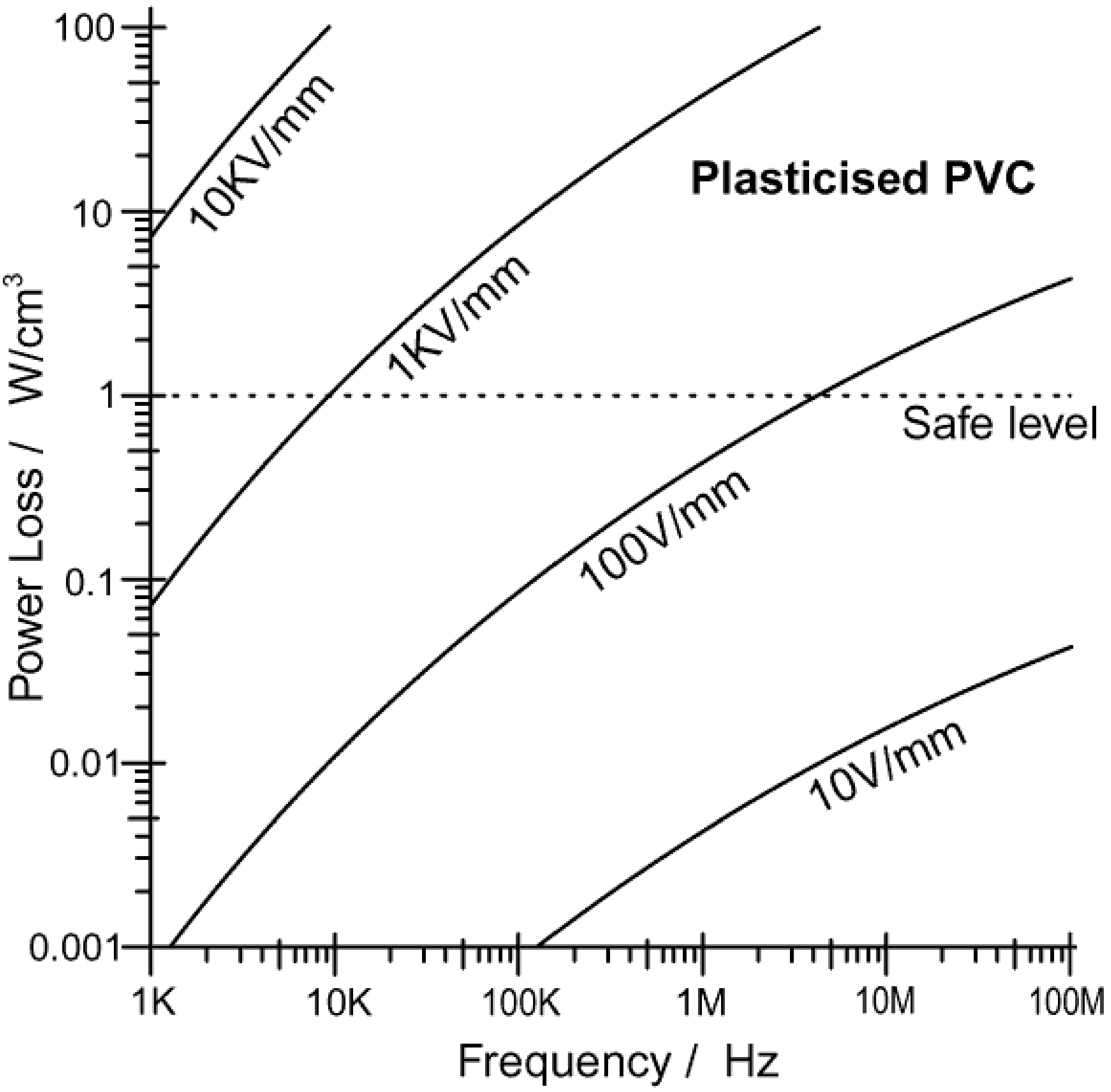
These equations tell us that the power loss in a dielectric is proportional to the frequency of the applied field, and proportional to the *square* of the electric field strength.

As an illustration of how to use this result, we will now calculate the power loss per unit volume at various frequencies and field strengths for plasticised PVC. Here, using the data given earlier, we may observe that the dielectric strength of PVC is somewhat in excess of 50 kV/mm peak (35 kV/mm RMS), and so we will perform calculations for field strengths of up to 10 kV/mm. εr' and Tanδ are estimated from the data for a worst-case sample; but note that the power dissipation is linear with respect to εr", and so even an average sample will not improve the situation by as much as a factor of two.

Dielectric power loss per unit volume. $W = E^2\, 2\pi f\, \varepsilon 0\, \varepsilon r''$

Plasticised PVC				RMS Field strength			
Freq	εr'	Tanδ	εr"=εr' Tanδ	10 V/mm	100 V/mm	1 kV/mm	10 kV/mm
1 kHz	8.0	0.16	1.28	7.1µW/cm³	0.71mW/cm³	71 mW/cm³	7.1 W/cm³
2 MHz	4.4	0.13	0.572	6.4mW/cm³	0.64 W/cm³	64 W/cm³	6.4 kW/cm³
14 MHz	4.0	0.06	0.24	19mW/cm³	1.9 W/cm³	187 W/cm³	19 kW/cm³
29 MHz	3.9	0.04	0.156	25mW/cm³	2.5 W/cm³	252 W/cm³	25 kW/cm³

Note that equation (**2-28.4**) requires the field strength *E* to be expressed in Volts/metre, and the result W is in Watts/metre³. The conversion factors are: 1 V/mm = 1 kV/m, and
1 MW/m³ = 1 W/cm³. The calculated results are shown below plotted as a family of graphs:

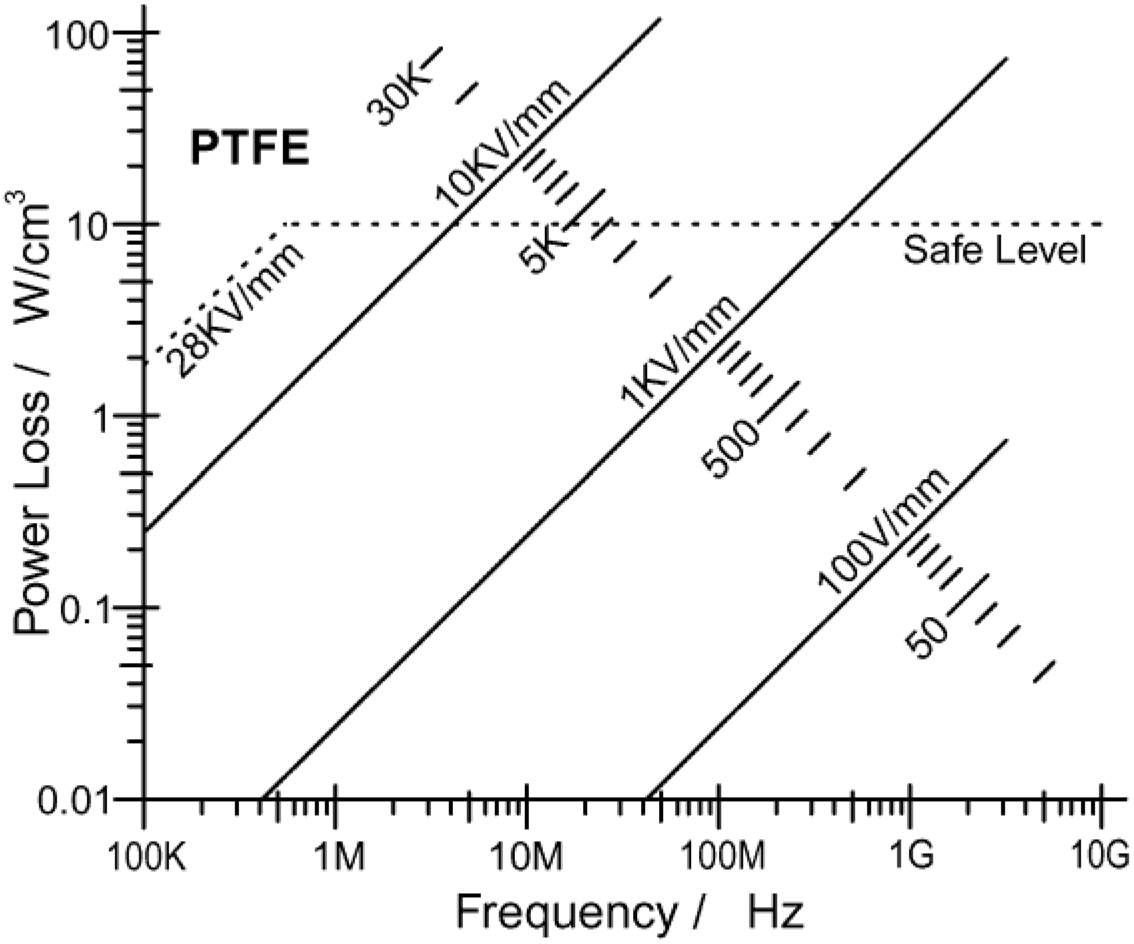


It is not possible to make full use of these calculations without considering the manner in which heat may be removed from the material (see, for example, ref [36], page 10.16], but we can develop a simple rule of thumb for the safe working area for the dielectric by considering the thermal behaviour of light bulbs. Torch bulbs and projector lamps have a volumes of around 1-10 cm³, and anyone familiar with these devices will know that a 1 W bulb becomes gently warm in operation, a 10 W bulb becomes too hot to touch (~100°C), and a the silica-glass of a 100 W projector lamp can be seen to be glowing red-hot (>600°C) immediately after the lamp has been switched off. We may therefore conclude that power dissipation of less than about 1 W/cm³ is safe, provided that the heat does not need to travel more than a few millimetres to reach the surface (plastics are good thermal insulators); but we can expect ordinary plastics to soften or melt at around the 10 W/cm³ level, and a real fire hazard to exist at 100 W/cm³. A quick glance at the graphs will then show why PVC is a perfectly good insulator for use at audio and power-line frequencies; but its use in radio-frequency applications involving field strengths of greater than about 100 V/mm is a decidedly risky business.

A calculation for PTFE, on the other hand, tells a different story: In this case we have εr'=2.1 and Tanδ ≤ 0.0002 from 50 Hz to 3 GHz, giving εr" ≤ 0.00042 throughout the radio spectrum.

PTFE	RMS Field strength			
Freq	10 V/mm	100 V/mm	1 kV/mm	10 kV/mm
2 MHz	≤ 4.7µW/cm^3	≤ 0.47mW/cm^3	≤ 47mW/cm^3	≤ 4.7W/cm^3
14 MHz	≤ 33µW/cm^3	≤ 3.3mW/cm^3	≤ 0.33W/cm^3	≤ 33W/cm^3
29 MHz	≤ 68µW/cm^3	≤ 6.8mW/cm^3	≤ 0.68W/cm^3	≤ 68W/cm^3
145 MHz	≤ 0.34mW/cm^3	≤ 34mW/cm^3	≤ 3.4W/cm^3	≤ 336W/cm^3
1 GHz	≤ 2.3mW/cm^3	≤ 0.23W/cm^3	≤ 23W/cm^3	≤ 2.3KW/cm^3

What we see in this case is that the power dissipation anywhere in the HF spectrum is very small except when the field strength is very large. Each of the entries in the table also corresponds to an upper limit rather than a realistic power loss, and the performance of PTFE is actually much better than the figures suggest. The melting point of PTFE moreover is 327°C, and so we probably do not need to worry about overheating until the power per unit volume exceeds about 10 W/cm^3.



Notice, in this case, that the constant-field lines are straight rather than curved; the reason being that we do not have any data for the decline in εr" with frequency and so must assume it to be constant. This is almost certainly not the case, and so the graph is extremely conservative. Observe also, that in determining the safe-working area for a dielectric, it is necessary for the field strength always to remain below the dielectric strength. In the graph above, the dielectric strength of PTFE has been taken to be about 40 kV/mm peak, i.e., 28 kV/mm RMS, and the safe-working area has been truncated accordingly.

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where ρ is the *density* in g/cm³, and WM is the molar mass in grams, (i.e., the atomic or molecular weight)]

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[12d] "Housekeepers will, without doubt, thank us for informing them that the black sulphide of silver, which forms on plated and silver wares, door plates and knobs, may at once be removed by wiping the surface with a rag wet with aqua ammonia (the ammonia should be very weak). This black film is no evidence that the silver is impure, for it forms as quickly on fine silver as on that which is alloyed with copper. After rain, much sulphide of hydrogen is disengaged from the soil of our streets."
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[50] Information on the design of AC susceptometers is given in the references below. Note that eddy-current effects will dominate AC measurements made on conducting materials; and so the method is primarily of interest for the characterisation of high-resistivity materials, or for finding the transition temperatures of superconducting materials without the need to measure resistance directly. AC relative permeability (and hence susceptibility) is strictly complex; the existence of an imaginary component reflecting the fact that some energy is lost in the process of magnetising and demagnetising materials. In this chapter however, since we are interested in the properties of conductors, we ignore magnetic losses and treat permeability as a purely real quantity.

[50a] "**Superconductivity: A guide to ac susceptibility measurements and ac susceptometer design**". Martin Nikolo. American Journal of Physics. 63 (1) Jan. 1995. p57-65.

[50b] " **A moving coil ac magnetic susceptometer**" R R de Souza, C J Magon. Review of Scientific Instruments, 69 (2) Feb. 1998 p431-436.

[51] "**Coppers for Electrical Purposes**", V A Callcut, IEE Proc. Vol. 133, Pt. A, No. 4, June 1986.