Chapter 6
Material Notes and Tables

This chapter has been included to place material resistivity, density, and dielectric strength properties in one convenient place for ESD analysts. These lists contain spacecraft materials that might often be considered when doing penetrating electron-charging analyses, charge-accumulation analyses, and breakdown estimates. The lists are generally correct, but the reader should recheck the parameters, especially the resistivity and dielectric strength parameters, for any detail work.

6.1 Dielectric Material List

The partial list of basic dielectric material properties in Table 6-1 is provided for illustration and reader convenience only. Data were taken from references [1,2] and other sources, including manufacturer data sheets. Some of the data may only be specified minimum or maximum limits and not typical values; actual resistivity values may differ by many orders of magnitude, e.g., FR4. Note that dielectric strength is always specified as a function of thickness and may be extrapolated to other thicknesses roughly as the inverse square root of the thickness. Each project must be responsible for compiling its own list based on the most current and relevant data. Reference [3] contains lists of dielectric properties for materials not included here. Other often-significant effects not tabulated here include temperature, radiation-induced conductivity, and electric field-induced conductivity.

Table 6-1. Dielectric material characteristics for internal charging studies[1].

Parameter/ Material (units)	Relative Dielectric Constant[2]	Dielectric Strength[3] (V/mil @ mil)	DC Volume Resistivity (Ω-cm)[4]	Density (g/cm^3)/ density in relation to aluminum	Time Constant[5] (as noted)
Ceramic (Al_2O_3)	8.8	340 @125	$>10^{12}$	2.2/0.81	>0.78 s
Delrin®	3.5	380 @ 125	10^{15}	1.42/0.52	310 s (5.2 min)
FR4	4.7	420 @ 62	$>4 \times 10^{14}$	1.78/0.66	>141 s
Kapton®	3.4	7000 @ 1	$\sim10^{18}$ to 10^{19}	1.4/0.51	3.5 d
Kapton®	--	580 @ 125	$\sim10^{18}$ to 10^{19}	1.4/0.51	3.5 d
Mylar®	3	7000 @ 1	10^{18}	1.4/0.51	3.1 d
Polystyrene	2.5	5000 @ 1	10^{16}	1.05/0.39	37 min
Quartz, fused	3.78	410 @ 250	$>10^{19}$	>2.6	>38 d
Teflon® (generic)[6]	2.1	2-5k @ 1	$\sim10^{18}$ to 10^{19}	2.1/0.78	2.1 d
Teflon® (generic)[6]	--	500 @ 125	$\sim10^{18}$ to 10^{19}	2.1/0.78	2.1 d

(Blank lines below are for reader's notes and additions.)

Notes:
1. If the numbers in the table are "greater than," the actual time constants could be greater than shown (calculated) in this table. The numbers in this table are for room temperature. At low temperatures, the resistivity values may become much greater and the time constants for charge bleed-off can be much greater.
2. Permittivity (dielectric constant) = relative dielectric constant × 8.85 × 10^{-12} F/m.
3. ~508 V/mil is the same as 2 × 10^{7} V/m.
4. Resistivity (Ω-m) = resistivity (Ω-cm)/100.
5. Time constant (s) = permittivity (F/m) × resistivity (Ω-m).
6. Generic numbers for Teflon®. Polytetrafluoroethylene ((PTFE) (Teflon®)) and fluorinated ethylene propylene (Teflon® FEP) are common forms in use for spacecraft.

Figure 6-1 shows how resistivity and dielectric constant together combine to determine material time constants, indicating relative desirability for ESD-sensitive applications. Suggested break points are "safe" (difficult to accumulate charge) with time constants less than 3 hr, "dangerous" (too resistive and likely to cause on-orbit ESD issues in space plasma environments) with time constants greater than 30 hr, and the uncertain/marginal region between. The boxes labeled Kapton® and Teflon® illustrate their possible ranges of resistivity. From this chart, it can be seen that both are undesirable from an ESD standpoint.

6.2 Conductor Material List

Table 6-2 shows resistivity and density information for some conductors. References are the same as Table 6-1 (from mixed sources for illustration only).

The partial list of basic conductor characteristics in Table 6-2 is provided for illustration and reader convenience only.

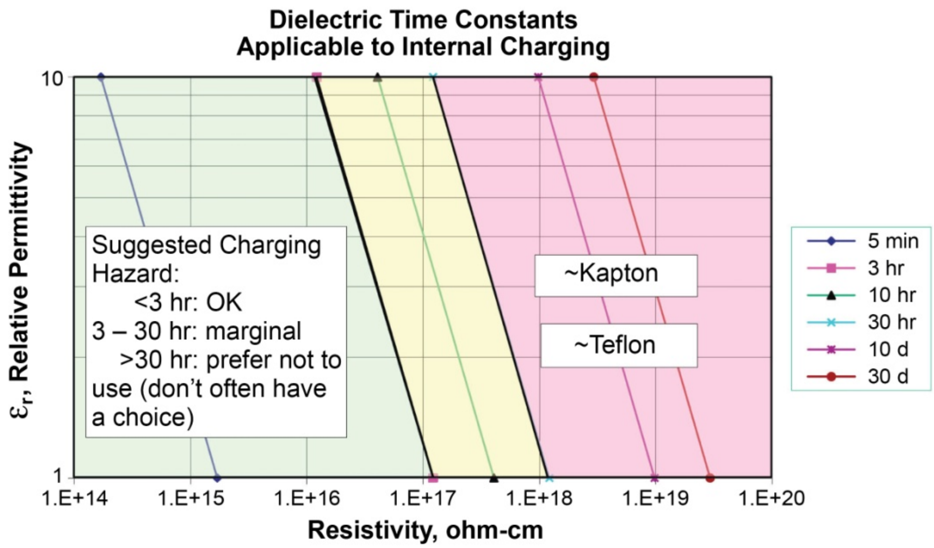

Fig. 6-1. Safe, intermediate, and possibly hazardous dielectric materials based on resistivity and dielectric constant and resultant time constant (Note: Kapton® and Teflon® boxes illustrate uncertainty range for space applications; see text).

Table 6-2. Conductor characteristics for charging studies (approximate).

Parameter/ Material Units	DC Volume Resistivity (Ω-cm (x10^{-6}))	DC Volume Resistivity (relative to Al)	Density (g/cm^3)	Density (relative to Al)
Aluminum	2.62	1	2.7	1
Aluminum Honeycomb	Variable	Variable	~0.049	~0.02
Brass (70-30)	3.9	1.49	8.5	3.15
Carbon graphite	5–30	1.9-11.45	1.3–1.95	0.48–0.72
Copper	1.8	0.69	8.9	3.3
Graphite-epoxy	Variable	Variable	1.5	0.56
Gold	2.44	0.93	19.3	7.15
Invar	81	30.9	8.1	3
Iron-steel	9–90	3.43–34.3	7.87	2.91
Lead	98	37.4	11.34	4.2
Kovar A	284	108.4	~7.8	~2.89
Nickel	7.8	2.98	8.9	3.3
Magnesium	4.46	1.7	1.74	0.64
Silver	1.6	0.61	10.5	3.89
Stainless steel	90	34.35	7.7	2.85
Tantalum	13.9	5.3	16.6	6.15
Titanium	48	18.3	4.51	1.67
Tungsten	5.6	2.14	18.8	6.96

(Blank lines below are for reader's notes and additions.)				

Notes:
1. See text for references and accuracies.
2. Densities from various sources match well; resistivities may vary.
3. Resistivity (Ω-m) = resistivity (Ω-cm)/100.

References

[1] H. P. Westman, ed., *Reference Data for Radio Engineers,* Fifth Edition, Howard Sams & Co., Inc., Indianapolis, Indiana, 1968.

[2] W. T. Shugg, *Handbook of Electrical and Electronic Insulating Materials*, Second Edition, IEEE Press, Piscataway, New Jersey, June 19, 1995.
An excellent general reference for dielectric characteristics written by a leader in the field.

[3] A. R. Frederickson, D. B. Cotts, J. A. Wall, and F. L. Bouquet, *Spacecraft Dielectric Material Properties and Spacecraft Charging*, *AIAA Progress in Astronautics and Aeronautics*, Vol. 107. Washington, D.C.: American Institute of Aeronautics and Astronautics Press, New York, New York, 1986.
Contains dielectric properties data, especially relating to spacecraft charging. Worth obtaining and reading.