III. PROPERTIES OF DIELECTRICS USED IN COAXIAL CABLES

	Polyethylene	Teflon (polytetra-fluoroethylene)	Polystyrene	Styrofoam 22 (foamed poly-styrene)	Air
Dielectric constant at 10^8 cps	2.25	2.0b	2.4 - 2.65a	1.025	1.00059e
Dissipation factor at 10^8 cps	<0.0005	<0.0003b	0.0001-0.0004a @ 10^6 cps		
Temperature variation of dielectric constant per °C (at constant pressure of 1 atmos.)	-0.0007d	-0.0003c	-0.0005d		
Dielectric strength, short-time 1/8" thickness, volts/mil	460a	480a	500-700a		
Volume resistivity, ohm-cm, 50% humidity, 23 °C	$1\text{-}2 \times 10^{13}$a	$>10^{15}$a	$10^{17}\text{-}10^{19}$a		
Refractive index, n_d	1.51a	1.35a	1.59-1.60a		1.00029e
Coefficient of linear thermal expansion, parts per 10^6/°C	160-180a	100	60-80a	70f	
Mechanical distortion temp., °C	41-50a	135g @ 66 psi	70-100a	80f	
Brittleness temperature, °C	-70	-76			
Effect of sunlight	surface crazing-a	none-a	yellows slightly-a	yellows-f	
Effect of dielectric on metal inserts	inert	inert			
Specific gravity	0.92a	2.1-2.3a	1.04-1.065a	0.021-0.027f	
Moisture absorption, 24-hr immersion, 1/8" thick., %	<0.015a	0.005a	0.03-0.05a	0.20 lb H_2O/ft^2 surface area in a week	

References: - a) Modern Plastics Encyclopedia, 1955; b) DuPont specs; c) National Bureau of Standards Journal of Research, vol 51, p. 185; d) Calculated; e) Chem. Rubber Hdbk.; f) Dow Chem. Co. specs.; g) Ethylene Chem. Corp.

IV. Temperature coefficient of length of certain cables.

RG 8, 63, 87A. The temperature coefficient of electrical length is a function of temperature, but near room temperatures, the coefficient is essentially a constant. Measured values are tabulated below.

Cable type	Temp. coeff.	In temp. range
RG 8	$\sim 2 \times 10^{-4}$	+ 20° to + 50°C*
63	$\sim 1 \times 10^{-4}$	- 20° to + 50°C
87A	$\sim 1 \times 10^{-4}$	- 60° to + 50°C

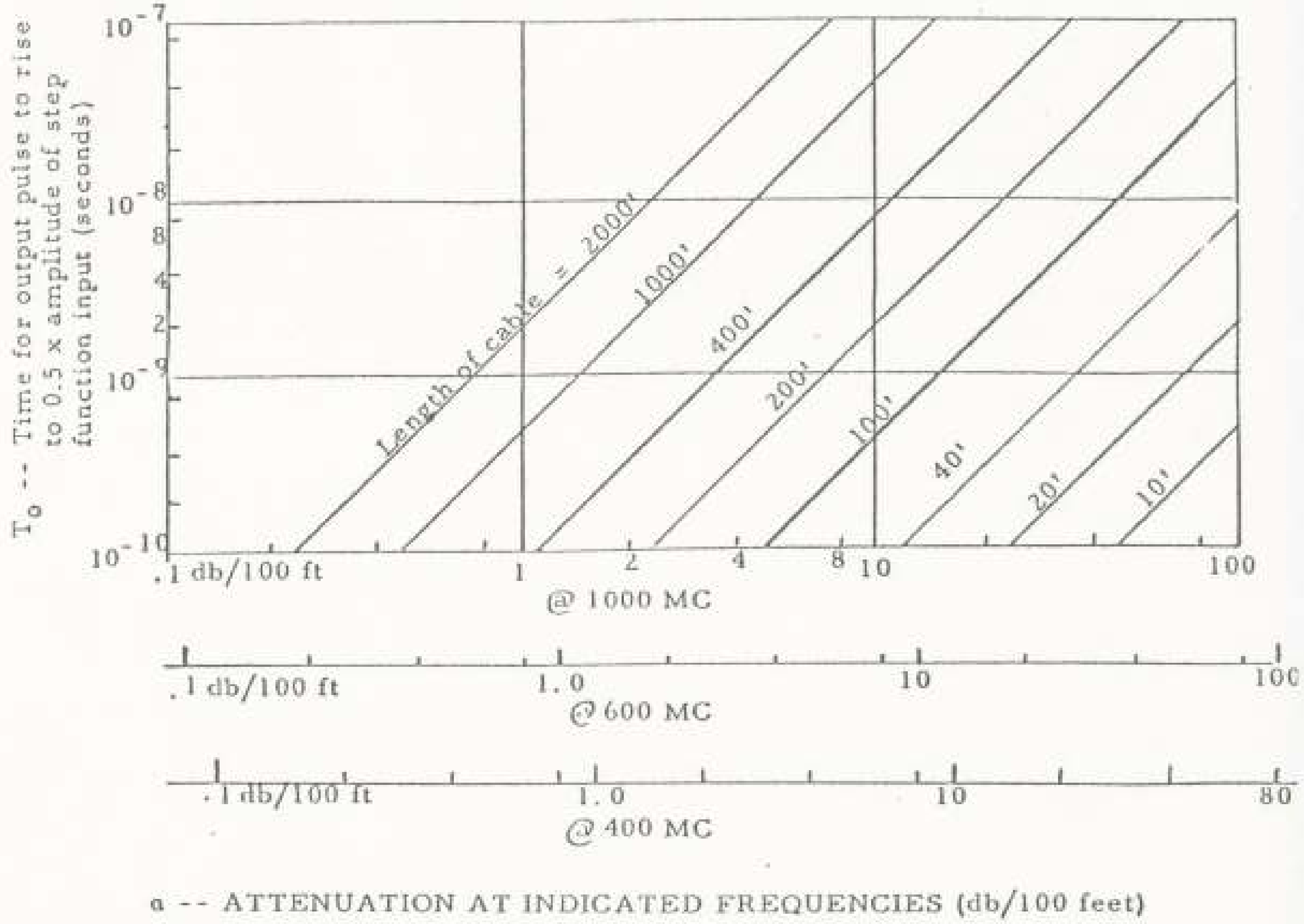
* Not measured below + 20°C.

A 100 foot length of RG 63 will therefore change its electrical length about 0.012 millimicroseconds per degree antigrade.

UCRL Styrofoam: Measurements showed the temperature coefficient to be within $\pm 2 \times 10^{-5}$ parts per °C. (The linear expansion of the copper conductors is $+ 2 \times 10^{-5}$ parts per °C).

V. Noise

"Internal noise" - Owing to manufacturing tolerances the characteristic impedance of a coaxial cable varies along its length. When a pulse travels along the line, reflections are generated by the changing impedance levels. The signal at the output, then, consists of the original pulse followed by a series of smaller, internally generated pulses, the latter referred to as "internal noise." When a pulse from a mercury pulse of risetime $< 5 \times 10^{-10}$ is transmitted along a cable such as RG8 or RG 63, the amplitude of the internal-noise pulses observed is of the order of 1% of the amplitude of the initial pulse, when the observing instrument has a risetime of $\sim 10^{-9}$ seconds (517' scope-direct connections to deflecting plates). Cables having closer mechanical tolerances (e.i. Styroflex) exhibit internal noise of smaller amplitude relative to the signal pulse.

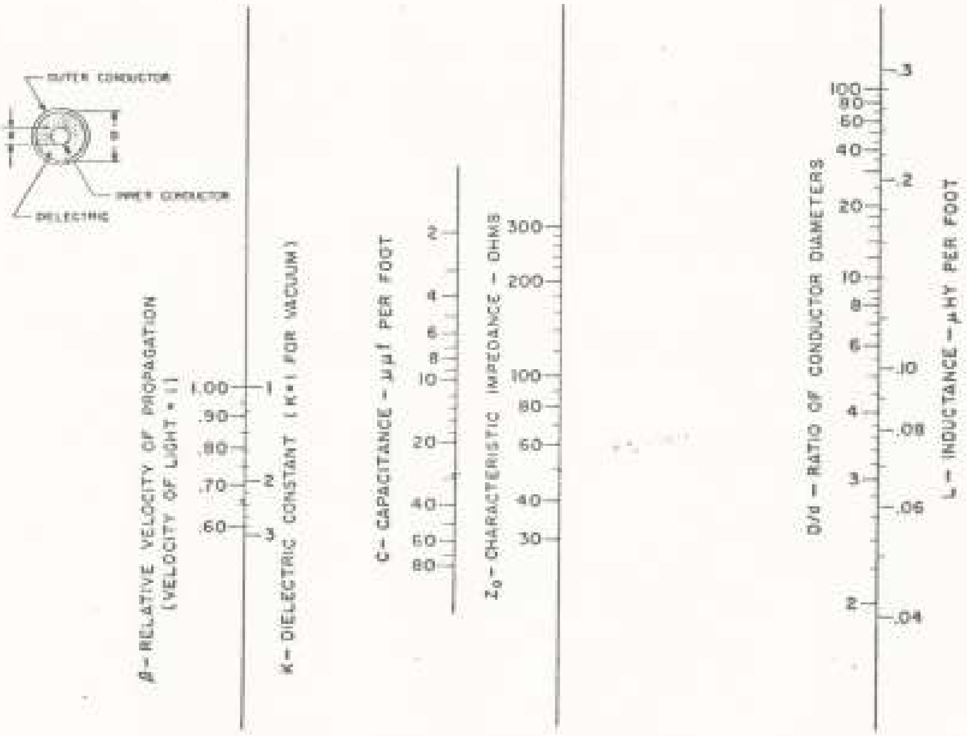


RISE TIME CONVERSION FACTORS

For pulses of the shape shown in Fig. 5 of CC2-1, the rise times from 0 to x% can be expressed as multiples of T_o, where T_o is the 0 to 50% rise time. Pulses of this shape are generated when step-function waveforms are applied to the inputs of transmission lines for which attenuation varies as $(\text{frequency})^{1/2}$. (See CC2-1)

x	0 to x% rise time / T_o
10	0.17
20	0.28
50	1.0
70	3.1
80	7.3
90	63.2
95	238

The 10 to 90% rise time is thus (63.2 - 0.17) T_o ≈ 63 T_o.



COAXIAL TRANSMISSION LINES IMPEDANCE NOMOGRAPH

A single straight line intersecting the four vertical scales represents a possible coaxial transmission line. Known points on any two scales may be used to define the location of the line.

VIII. Transmission line formulas

1. Z_o - characteristic impedance of coaxial lines with perfectly conducting conductors

$$Z_o = \sqrt{\frac{\mu}{\epsilon}}\ \frac{1}{2\pi}\ \ln_{\epsilon} \frac{D}{d} \text{ ohms}$$

For dielectrics for which $\mu = \mu_o$ (this includes the commonly used dielectrics)

$$Z_o = \frac{377}{2\pi\sqrt{K}}\ \ln_{\epsilon}\frac{D}{d} = \frac{60}{\sqrt{K}}\ \ln_{\epsilon}\frac{D}{d}$$

$$= \frac{138}{\sqrt{K}} \log_{10} \frac{D}{d}$$

where

μ = permeability of dielectric - henries/meter

μ_o = permeability of vacuum

$\cong 4\pi \times 10^{-7}$ henry/meter

ϵ = permittivity of dielectric - farads/meter

ϵ_o = permittivity of vacuum

$\cong \frac{1}{36\pi} \times 10^{-9}$ farads/meter

K = dielectric constant

$= \frac{\epsilon}{\epsilon_o}$

D = inside diameter of outer conductor

d = outside diameter of inner conductor

The impedance of a transmission line having distributed inductance (L - henries per unit length) and distributed capacitance (C - farads per unit length) is, neglecting the effects of conductor resistance,

$$Z_o = \sqrt{\frac{L}{C}}$$

2. v - Velocity of propagation of transmission-line waves (TEM mode)

$$v = \frac{1}{\sqrt{\mu\epsilon}} \text{ meters/second}$$

where μ, ϵ are respectively the permeability and permittivity of the dielectric.

For dielectrics for which $\mu = \mu_o$,

$$v = \frac{3 \times 10^{8*}}{K} \text{ meters/second}$$

$$\beta = \frac{v}{c} = \frac{1}{\sqrt{K}}$$

c = velocity of propagation in vacuum.

Along a transmission line having distributed inductance (L - henries per unit length) and distributed capacitance (C - farads per unit length) the relative velocity of propagation is

$$\beta = \frac{1}{\sqrt{LC}}$$

3. L, C - Distributed inductance and capacitance.

$$\begin{aligned} L &= \frac{Z_o}{v} \text{ henries per meter} \\ &= 1.01 \frac{Z_o}{\beta} \times 10^{-3} \text{ microhenries per foot} \\ C &= \frac{1}{Z_o v} \text{ farads per meter} \\ &= \frac{1.01 \times 10^3}{\beta Z_o} \text{ micro microfarads per foot} \end{aligned}$$

For coaxial lines:

$$C = \frac{7.354\,K}{\log_{10} D/d} \text{ micro microfarads per foot}$$

$$L = 0.14 \left(\frac{\mu}{\mu_o}\right) \log_{10} \frac{D}{d} \text{ microhenries per foot}$$

4. α - Attenuation. Two important causes of attenuation are losses in the conductors and losses in the dielectrics.

A. α_c - Attenuation due to conductor losses

$$\alpha_c = 0.43 \times 10^{-3} \sqrt{f} \left(\frac{1/D + 1/d}{Z_o}\right) \sqrt{\frac{\sigma_c}{\sigma}} \text{ db/100 feet}$$

D, d = outer, inner diameters-inches

f = frequency - cycles per second

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* The effective figure 3×10^8 meters/sec for the velocity of electromagnetic waves in free space is a commonly used approximation. A more accurate figure is 2.9977×10^8 meters/sec.

σ_c = conductivity of copper

= 1.724×10^{-8} ohm meters (annealed copper @ 20°C)

σ = effective* conductivity of metal used for conductors - ohm meters

For solid metals -	Silver	Copper	Aluminum	Brass	Solder
$\sqrt{\sigma_c/\sigma}$	0.97	1.00	1.25	1.93	2.86

B. a_D Attenuation due to dielectric losses

For cables with solid dielectric,

$$a_D = 2.8 \times 10^{-7} \frac{f\tau}{\sqrt{K}} \text{ db/100 feet}$$

(independent of Z_o)

where

τ = Dissipation factor of dielectric

= K x power factor of dielectric

5. T_o - Rise time of cable. T_o is the time for the output pulse to rise from 0 to 50% of the amplitude of step-function applied to input. See the table on p. 23 to find values of rise times defined in different ways. The equation given below is valid for output pulses having frequency components predominately in the frequency range where the attenuation a is due mainly to losses in the conductors (i.e. $a_c >> a_D$) and therefore varies as $(\text{frequency})^{1/2}$.

$$T_o = \left[\frac{b\,\ell}{0.6745}\right]^2 \text{ seconds}$$

ℓ = length of cable in feet

b = cable loss factor

= $1.5 \times 10^{-3}\, a/\sqrt{f}\ (\text{seconds})^{1/2}\ (\text{feet})^{-1}$

a = cable attenuation feet at frequency f - db/100 feet

f = frequency - cycles per second.

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* The effective conductivity of an actual conductor may differ from that of the solid metal owing to surface imperfections and discontinuities in braids, etc., and impurities.