LBL-CC-2-1A

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COUNTING NOTE

PULSE RESPONSE OF COAXIAL CABLES

I. ABSTRACT

For most cables useful in counting work, attenuation below approximately 1000 mc is due mainly to skin-effect losses and varies as the square root of frequency. For such cables the step-function response has a rise time that varies as the square of the attenuation at a given frequency. Curves are given to aid in the selection of cables for transmitting nanosecond pulses.

II. STEP FUNCTION RESPONSE

Mathematically ideal, lossless coaxial cables can be shown to transmit electrical pulses in the TEM mode without attenuation or distortion. However, all physically realizable cables have losses, the magnitude of which changes with frequency. Pulses transmitted through such cables suffer both attenuation and distortion. By means of the Laplace transform, the nature of the distortion can be calculated if the attenuation and phase-shift are known at all frequencies. In most of the cables presently useful in counting work, skin effect losses in the conductors are the predominate losses below about 1000 mc. Skin-effect losses produce an attenuation whose magnitude in decibels varies as the square-root of frequency. This results in a step function response of:

$$E_{out} = E_{in} \left(1 - \text{erf} \frac{b\ell}{\sqrt{2\,(t-\tau)}}\right)$$

where

E_{out} = voltage at distance ℓ from input end of semi-infinitely long uniform cable,(1) at time t (seconds).

E_{in} = amplitude of step of voltage applied to input of cable at time t = 0.

ℓ = distance from input end in feet.

b = constant for the particular cable in question.
= 1.45×10^{-8} A - feet^{-1} sec$^{\frac{1}{2}}$

A = attenuation of cable at 1000 mc - db/100 feet (attenuation figures for coaxial cables are commonly quoted in these units).

erf = error function(2)

τ = transit time of cable defined as the value of t at which the voltage at ℓ first begins to change (considering only the step function occurring at t = 0, of course).

(1) With negligible error in most cases E_{out} can be taken as the response at the receiving end of a cable of length ℓ, terminated in a resistor equal to its characteristic impedance.

(2) As defined in Reference 1, p 256.

Fig. 1 may clarify the nomenclature involved in this relation.

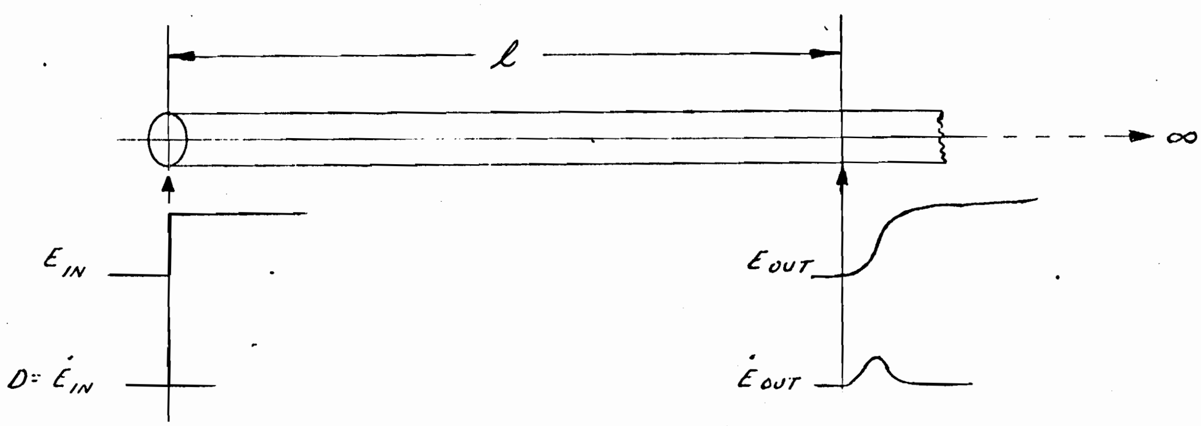

Fig. 1 - This illustrates the space relation between E_{in} and E_{out}.

A normalized curve of E_{out}/E_{in} is shown in Fig. 2. The abscissa is plotted in units of T_o, the 0-50% rise time. In other words, T_o is the value of $(t - \tau)$ at which $E_{out}/E_{in} = 1/2$. For cables whose attenuation varies as the one-half power of frequency, it is convenient to calculate T_o as:

$$T_o = 4.56 \times 10^{-16} A^2 \ell^2 \text{ seconds } \left(= \left[\frac{b\ell}{0.6745}\right]^2\right).$$

It is evident that T_o varies directly as the square of the total attenuation of the length of cables. Cables of different sizes or types may therefore be compared for rise time in terms of A, their attenuation at 1000 mc. Figures of A for most commercially available cables are given in CC 2-2.

In cases where: a) the attenuation is known only at a frequency other than 1000 mc; or b) the frequency dependence of attenuation departs somewhat from the 1/2 power law (say, where $\alpha = \text{constant} \cdot f^n$, in the region $0.4 < n < 0.7$) T_o may be calculated:

$$T_o = \frac{4.56 \times 10^{-7} \alpha_f^2 \ell^2}{f}$$

where

α_f = attenuation of cable at frequency f - db/100 feet.

f = frequency - cycles.

In case a) the nomogram of Sec. VII CC 2-2 may be useful. In case b), it has been empirically determined that reasonably accurate results are obtained where f is the frequency at which the total attenuation (i.e., $\alpha_f \ell/100$) of the cable is 6 decibels. Substituting $\alpha_f \ell/100 = 6$ db into the above gives the useful relation

$$T_o \cong 1/6f_6$$

where

f_6 = frequency at which the total attenuation of the length of cable in question is 6 db.

The times to reach other precentages of the input step amplitude are given in Table I.

TABLE I

RISE TIME CONVERSION FACTORS

X	0 to X % rise time / T_o
10	0.17
20	0.28
50	1.0
70	3.1
80	7.3
90	29.
95	110.

The 10 to 90% rise time is thus $(29 - 0.17)\ T_o = 28.83\ T_o$.

III. IMPULSE RESPONSE

The response to an impulse (delta function), of a cable having decibel attenuation proportional to the square-root of frequency, may be obtained by differentiating E_{out} above. As with the step-function response, the impulse response can be represented by a universal curve, that of Fig. 3. The area under this curve (coulombs) is conserved as the pulse travels along the cable. Thus, the peak amplitude of the response varies as

$$\frac{1}{b^2 \ell^2} \quad \alpha \quad \frac{1}{A^2 \ell^2}$$

and the time between, for example, the half-amplitude points, varies as $b^2 \ell^2$. The peak amplitude occurs at $0.152\ T_o$.

IV. RESPONSE TO OTHER PULSE SHAPES

It will be noted that, since the rise time T_o is proportional to ℓ^2, if two equal lengths of a given type of cable are cascaded, the rise time of the combination is four times the rise time of either length alone. This is in contrast to the well-known case of amplifiers of "Gaussian" frequency response, in which the rise time varies as the square root of the number of identical sections. For this reason, and also because the characteristic step-or impulse-function responses of cables and of "Gaussian" amplifiers are so different, the rule-of-thumb that the over-all rise time = $\sqrt{\text{sum of squares of individual rise times}}$ is not applicable either with cables alone, or where cables are combined with Gaussian elements. Instead, the overall response of a system with cables and other elements may be obtained graphically or with the standard convolution integrals[3] using either the step-or impulse-function response of the cables.

V. RECTANGULAR PULSE RESPONSE, CLIPPING LINES

The response of a cable to a rectangular pulse of a duration T can be found by a simple application of superposition. The rectangular pulse is considered to consist of a positive step-function at $t = 0$, followed by a negative step-function at $t = T$. The amplitude reduction of such a pulse as a function of the distance it has traveled along the selected coaxial cables is shown in Fig.s 5, 6 and 7. Fig. 5 includes a curve showing the time-stretching of the output pulse with respect to the input pulse. By suitably changing the length scale in the way indicated on the figure, the two curves of Fig. 5 can be applied to any pulse duration and any cable for which attenuation varies as the square root of frequency. The amount of time-stretching of any output pulse can therefore be determined from Fig. 5 by knowing the value E_{out}/E_{in} for the pulse, where E_{out} is the peak amplitude of the output pulse, and E_{in} is the amplitude of the input pulse.

The relative merits of various coaxial cables as conductors of pulses from multiplier phototubes or other current generators can be estimated from the curves of Fig. 6 which are replotted from Fig. 5. Use Fig. 6a for pulses of $T = 10^{-8}$ second; 6b for $T = 10^{-9}$; 6c for $T = 10^{-10}$. Note that the input is a rectangular current pulse of 1 ampere amplitude. At the input end of the cable, therefore, the voltage amplitude of the rectangular pulse is Z_o volts, where Z_o is the characteristic impedance of the line. The curves show, for example, that for an input current pulse of $T = 10^{-9}$ second, the peak voltage of the output pulse at the end of a 75 foot run of RG 114 would be the same as that at the output end of a 75 foot run of RG 63, even though the voltage developed at the input end of the RG 114 would be 185/125 times the voltage at the input of the RG63.

[3] Reference 1, pp 112-120

In Fig. 7 are shown some specific output pulse shapes together with the lengths of commonly used cables that give the corresponding output pulse shape for an input pulse of $T = 10^{-9}$ second. These pulse shapes were determined from Fig. 2 in the way mentioned above.

The curves of Fig.s 5, 6 and 7 also apply[4] to clipping lines if the input is a step-function and T = 2 times the electrical length of the clipping line. This is true whether the clipping line is located at the input or output end of the transmission line. The minimum 0-100% rise-time of a clipped pulse is $0.15\ T_o$. Clipping lines of electrical length less than $0.075\ T_o$ will not decrease the rise-time, but will only decrease the amplitude of the output pulse.

The curves and data are intended to present the properties of the coaxial cables, and therefore do not include the effect of quantities that depend on the way in which the cables are used. Examples of such quantities are the rise-time of multiplier phototube output pulses and imperfect cable terminations. The curves and data also do not take into account the inevitable small variations of characteristic impedance along the line. These impedance variations will generally degrade the rise-time of the output pulse by reflecting portions of the faster rising parts of the pulse being transmitted.

VI. EXPERIMENTAL VERIFICATION

Photographs of the responses of several cable types to step-function inputs are shown in Fig. 8. These photographs were all taken from displays on a DuMont K1056 cathode ray tube connected as shown in the block diagram of Fig. 8. Fig. 8a shows the step from the pulse generator delayed only by 25 nanoseconds of cable inserted at A-A in Fig. 9. The rise time of the pulse generator-oscilloscope combination is about 0.45 nanosecond, and therefore obscures the shape of the leading edge of the waveform of some of the better cables. The typical 1 - erf shape is plainly seen in Fig. 8f, for RG 63.

[4] Provided the clipping line is short enough that its attenuation may be neglected.

REFERENCES

1. S. Goldman, Transformation Calculus and Electrical Transients, (Prentice-Hall Publishing Co., New York, 1945)

2. P. Behrend, "Theory of Pulse Technique for Coaxial Cables", Z. Angew, physik 5, 61 (Feb. 1953)

3. Wingington and Nahman, "Transient Analysis of Coaxial Cables Considering Skin Effect", Proc. IRE 45, 166-174 (Feb. 1957)

4. Ramo and Whinnery, Fields and Waves in Modern Radio, (John Wiley and Sons, New York, 1953, Second Edition)

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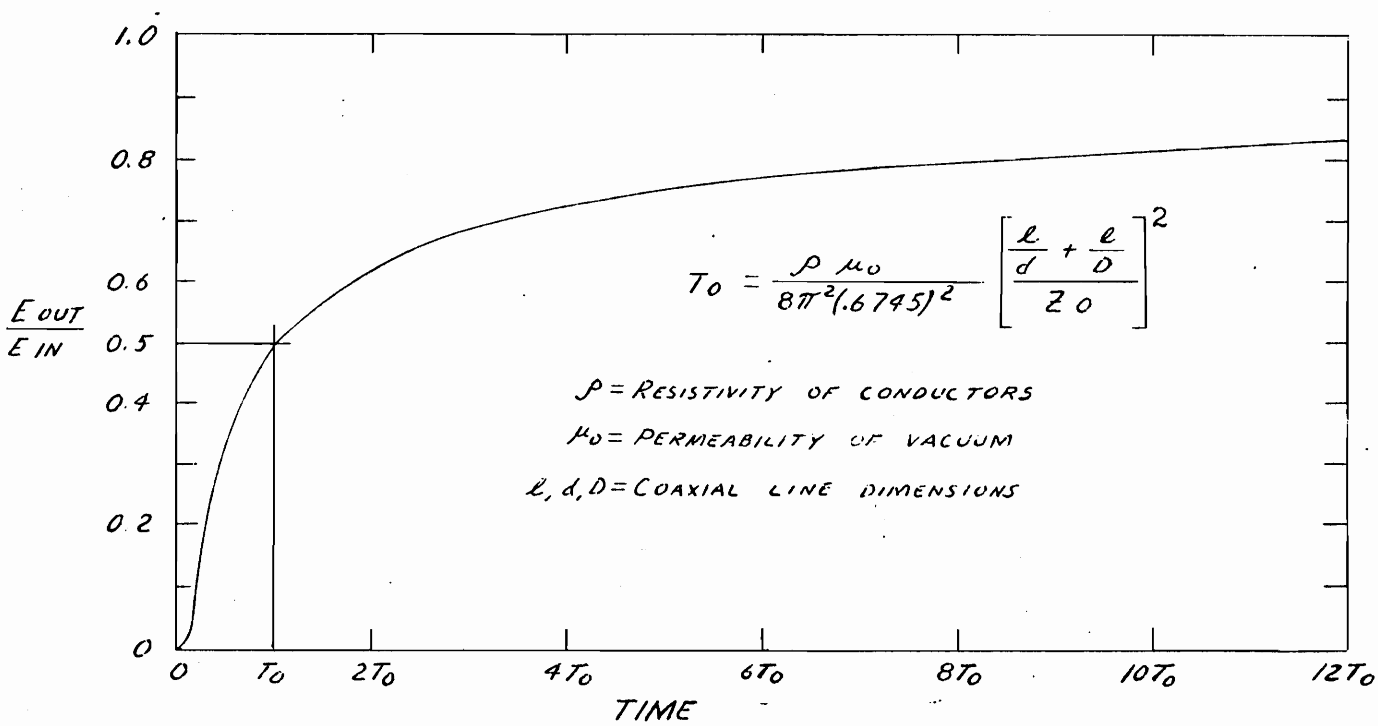


Fig. 2

Step-function response of transmission lines for which decibel attenuation varies as the square root of frequency. The time T_o is defined as the interval measured from the start of the output pulse to the point at which $E_{out} = 0.5 E_{in}$. T_o depends on the transmission line parameters; the relation for coaxial structures with negligible dielectric loss is given in the figure. In Fig. 4, T_o is plotted as a function of cable type and length.

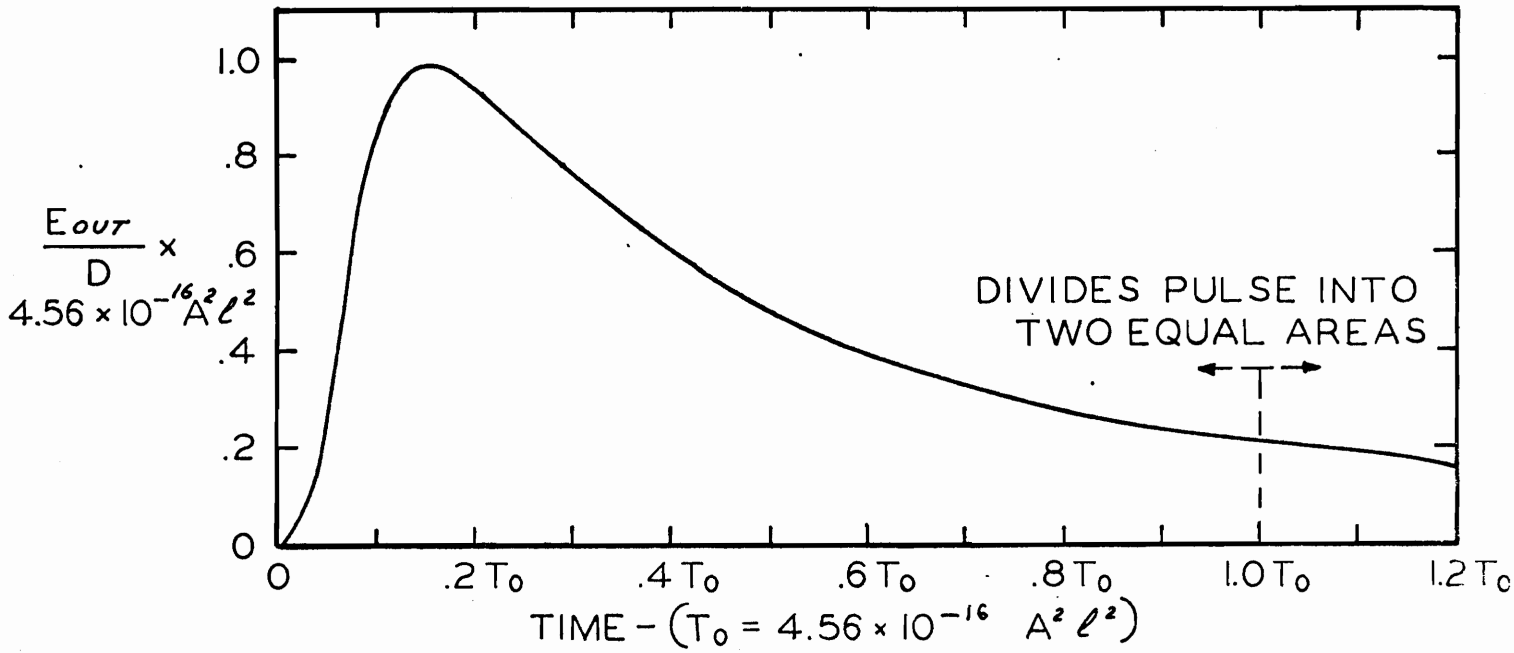


Fig. 3
Delta-function response of transmission lines for which attenuation varies as the square-root of frequency. As given in the text, A is the attenuation in db/100 feet at 1000 mc, ℓ is the cable length in feet, and D is the volt-second product of the input delta function. This curve is the time derivative of the curve of Fig. 2.

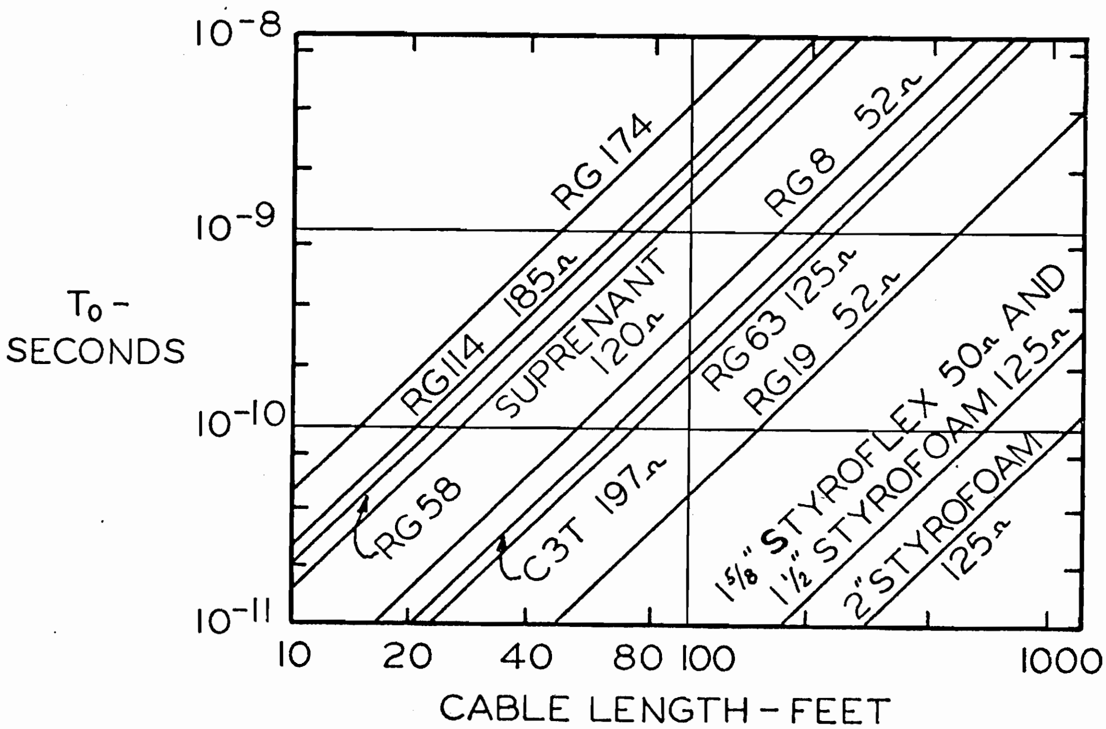


Fig. 4
Calculated variation of T_o with cable length for typical coaxial cables. To obtain the values of T_o for other cable types see CC 2-2B.

CC 2-1A (8)

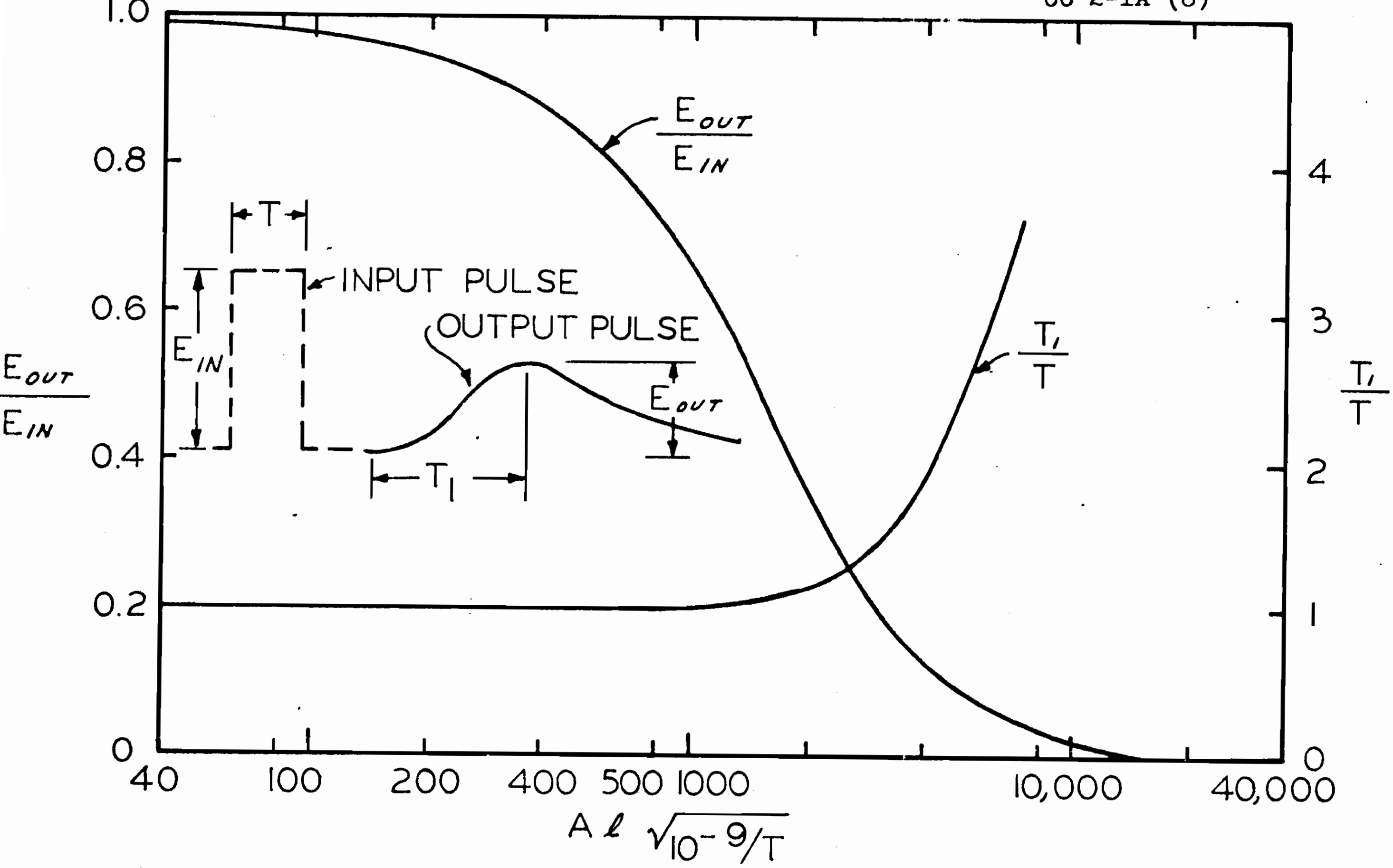
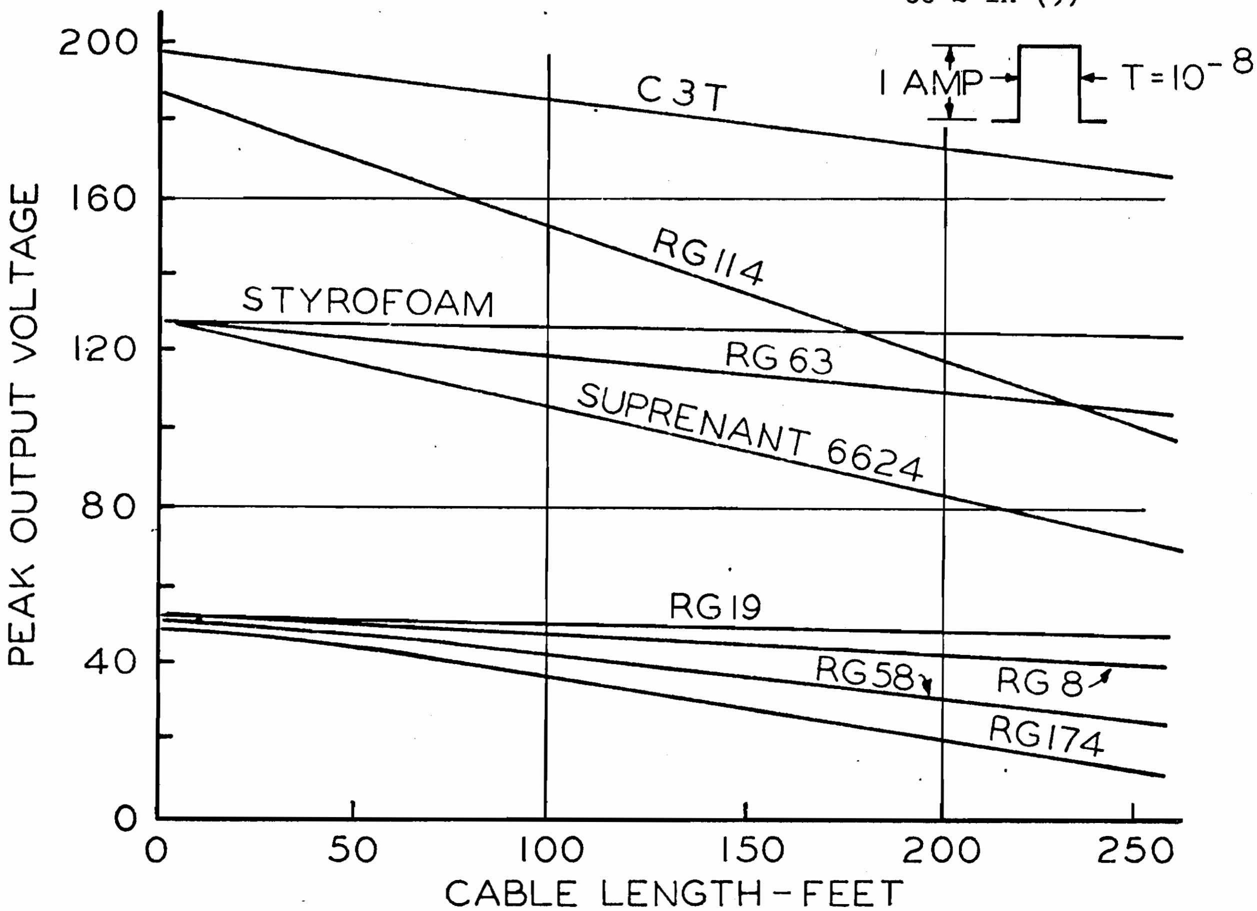


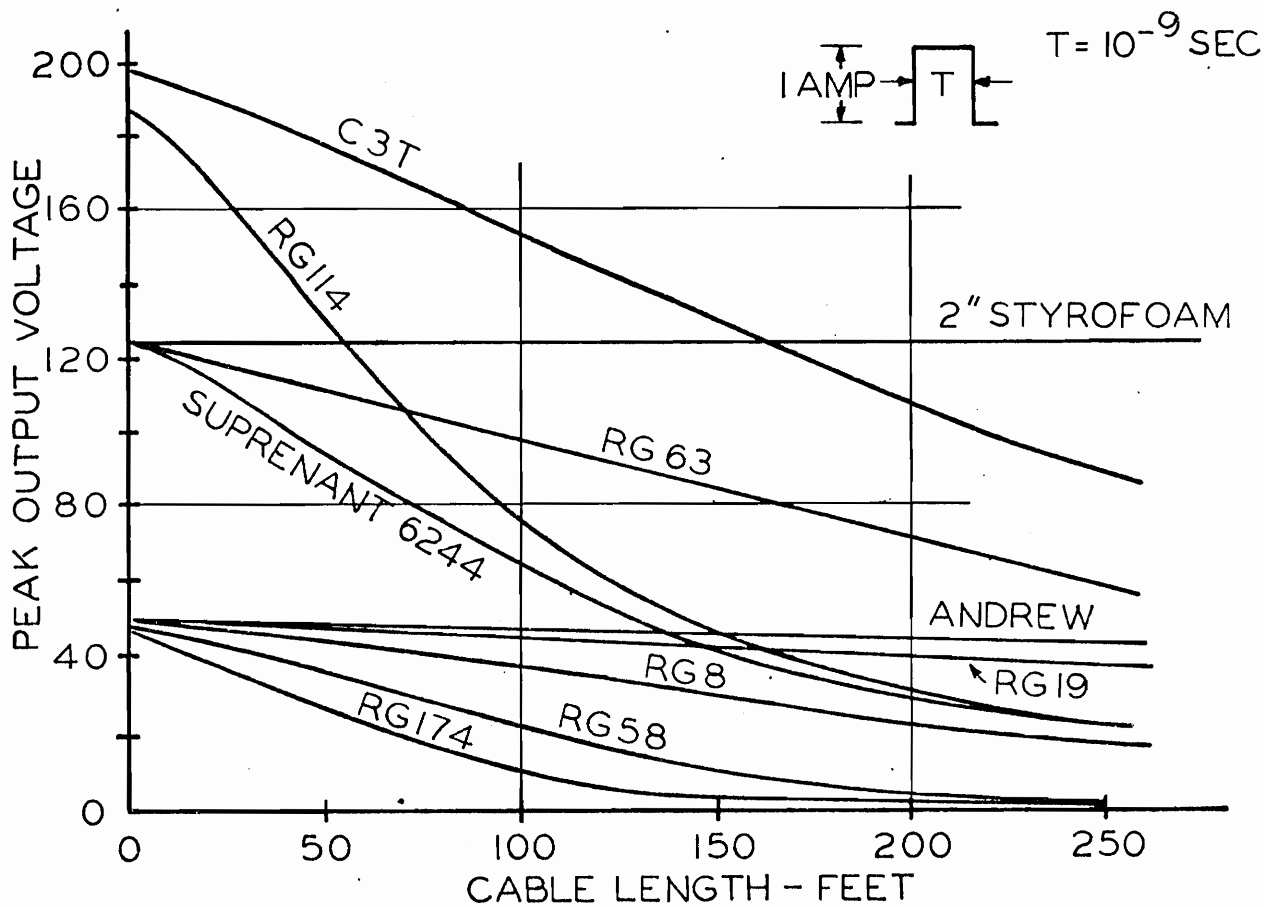
Fig. 5

The time-stretching and amplitude-reduction of an originally rectangular pulse plotted as a function of A, the attenuation of the cable at 1000 mc in db/100 ft.; ℓ, the length in feet; and T, the duration of the input pulse in seconds. Attenuation figures may be obtained from CC 2-2B. As an example, for RG63, A is 7 db/100 ft. Thus if T were 10^{-9} sec, and ℓ were 100 feet, the chart should be entered at an abcissa of 700.



1 AMP
T=10-8
C3T
RG114
STYROFOAM
RG 63
SUPRENANT 6624
RG19
RG58
RG 8
RG174
PEAK OUTPUT VOLTAGE
200
160
120
80
40
0
0
50
100
150
200
250
CABLE LENGTH-FEET

Fig. 6(a)



1 AMP
T
T= 10-9 SEC
C3T
RG114
2" STYROFOAM
SUPRENANT 6244
RG 63
ANDREW
RG8
RG19
RG174
RG58
PEAK OUTPUT VOLTAGE
200
160
120
80
40
0
0
50
100
150
200
250
CABLE LENGTH - FEET

Fig. 6(b)

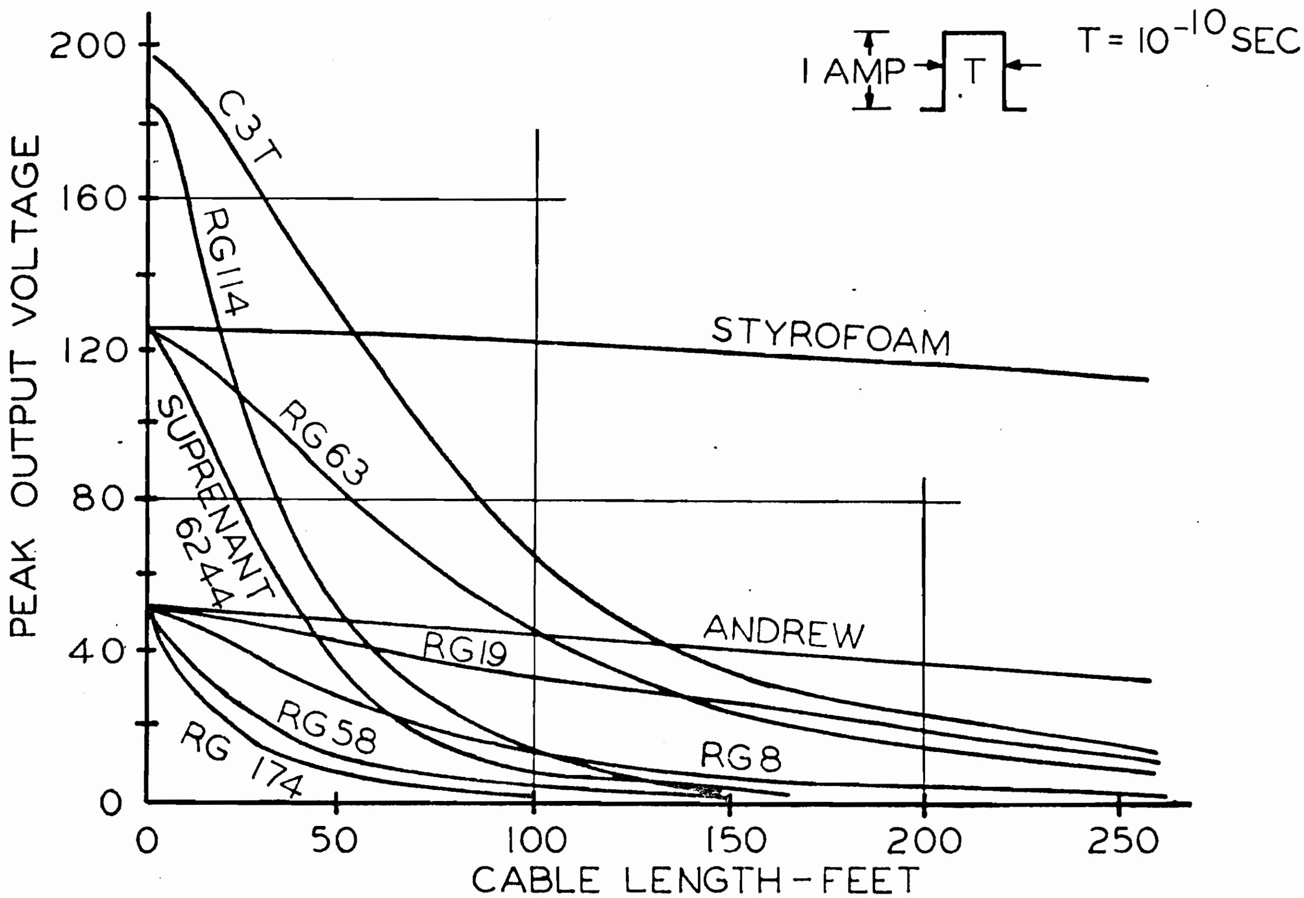
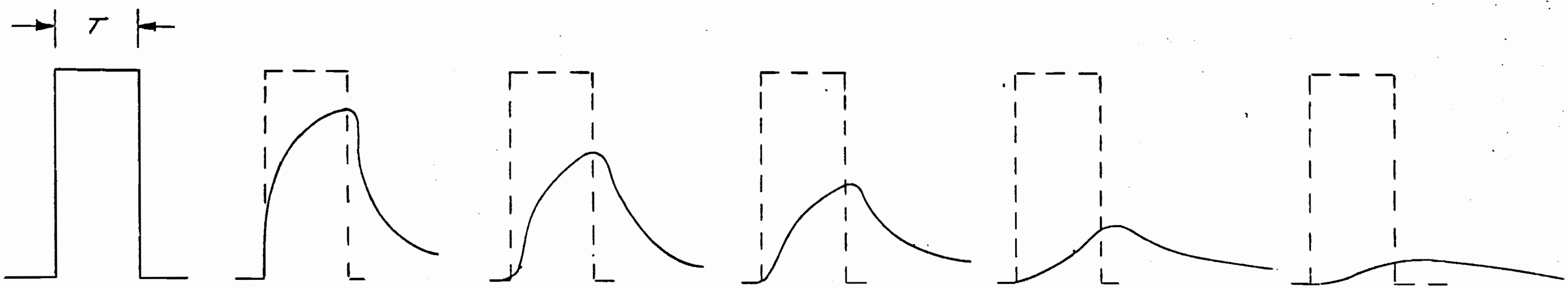


Fig. 6(c)

Peak amplitude of the output voltage pulse from some typical coaxial cables as a function of cable length. The assumed inputs are rectangular current pulses of 1 ampere amplitude and durations of 10^{-8}, 10^{-9} and 10^{-10} seconds. These curves are all replotted from Fig. 5 with suitable scale changes.



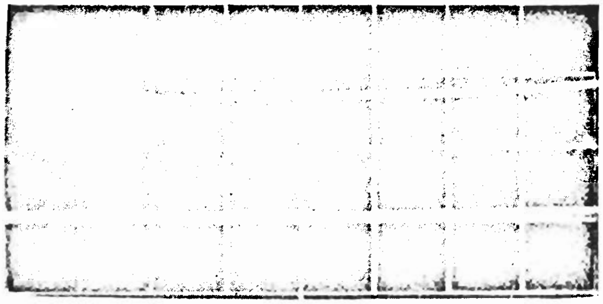
INPUT PULSE (a) (b) (c) (d) (e)

For T = 10^{-9} sec., the output pulse will have the shape and amplitude shown for the following cable lengths.

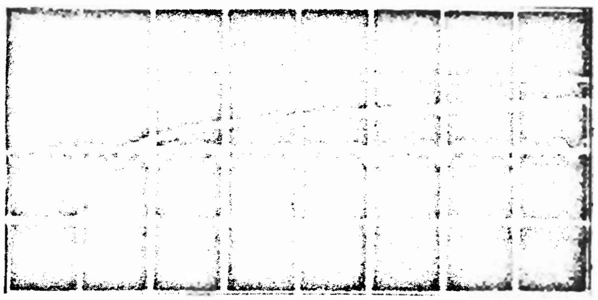
CABLE TYPE	(a)	(b)	(c)	(d)	(e)
RG174	23	41	67	90	110
RG58	30	56	93	136	156
RG8	77	145	240	350	400
RG63	95	180	290	430	500
2" Styrofoam	1200	2300	3700	5500	6400
C3T	90	170	280	400	470
RG114	37	70	110	170	200

Fig. 7

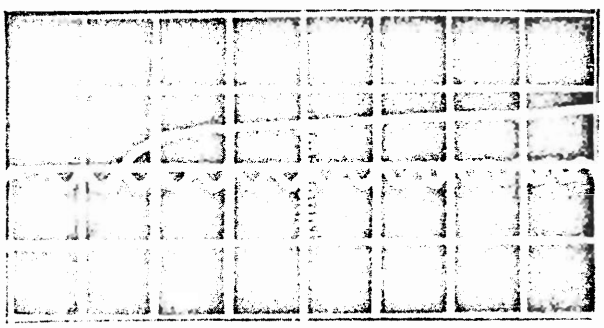
The above waveforms show the deterioration of an originally rectangular pulse as it travels along a transmission line for which the decibel attenuation varies as the square root of frequency. For comparison purposes, the input pulse is also shown with each output waveform. The figures listed above give the cable lengths that will cause the distortion shown when T = 10^{-9} second. To find the cable lengths for which the output pulse will have the same form relative to the input pulse for other input pulse durations, multiply the above lengths by $\sqrt{T}$, where T is the input pulse duration in millimicroseconds.



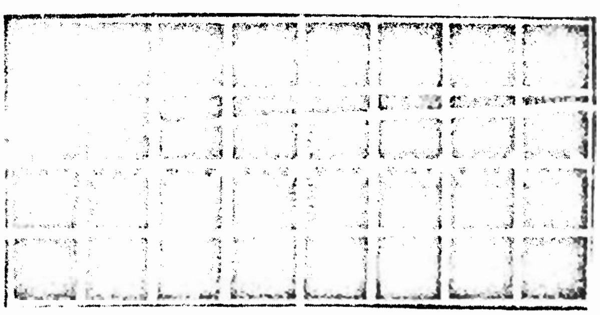
a. Input pulse.



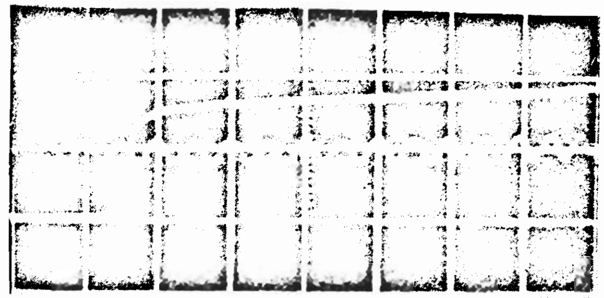
b. RG 9: Z_o = 51 ; d = 300 mus.
(RG 8 gives same response.)



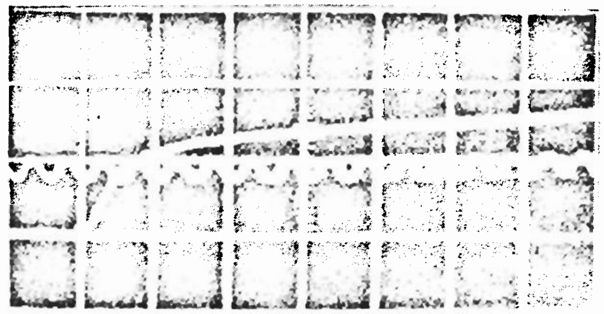
c. RG 19: Z_o = 52 ; d = 300 mus.



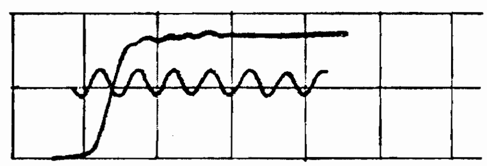
d. [illegible]: Z_o = 52 ; d = 326 mus.



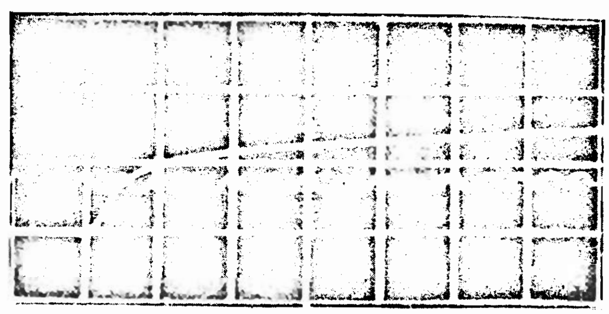
e. Styroflex: Z_o = 50 ; d = 317 mus.



f. RG 63: Z_o = 125 ; d = 300 mus.
(21-342 and 21-406 give same response.)



g. Styrofoam: Z_o = 125 ; d = 258 mus.



h. C3T: Z_o = 197 ; d = 300 mus.

Fig. 8. Photographs of the leading parts of pulses before and after transmission through some coaxial transmission lines used in counting work. All photographs taken with Dumont K1056 cathode-ray tube. a) Pulse applied to input end of transmission lines. b-h) Pulse appearing at output end of transmission line; d = electrical length in millimicroseconds. Frequency of timing wave is 1000 mc. Trace g) replotted from Fig. 4b to about same time scale as other traces of this series. Part of the upward tilt is caused by cathode-ray tube distortion. An estimate of the amount of this distortion can be made by referring to the three traces in a), where the lower trace is a zero reference.

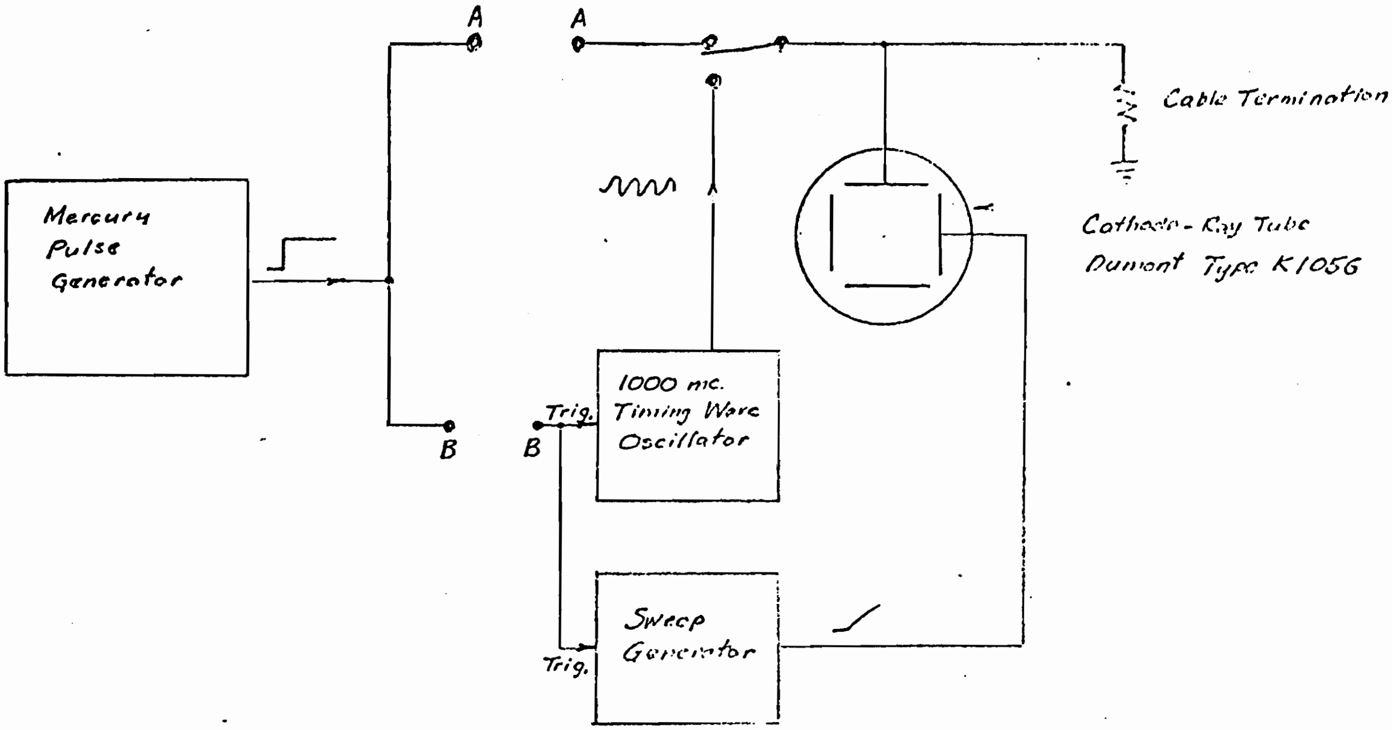


Fig. 9. Block diagram of equipment used to take the cable response photographs of Figure 8. The cable to be tested is placed between points A-A. A time delay of about 25 mus. less than that of A-A is placed between B-B.

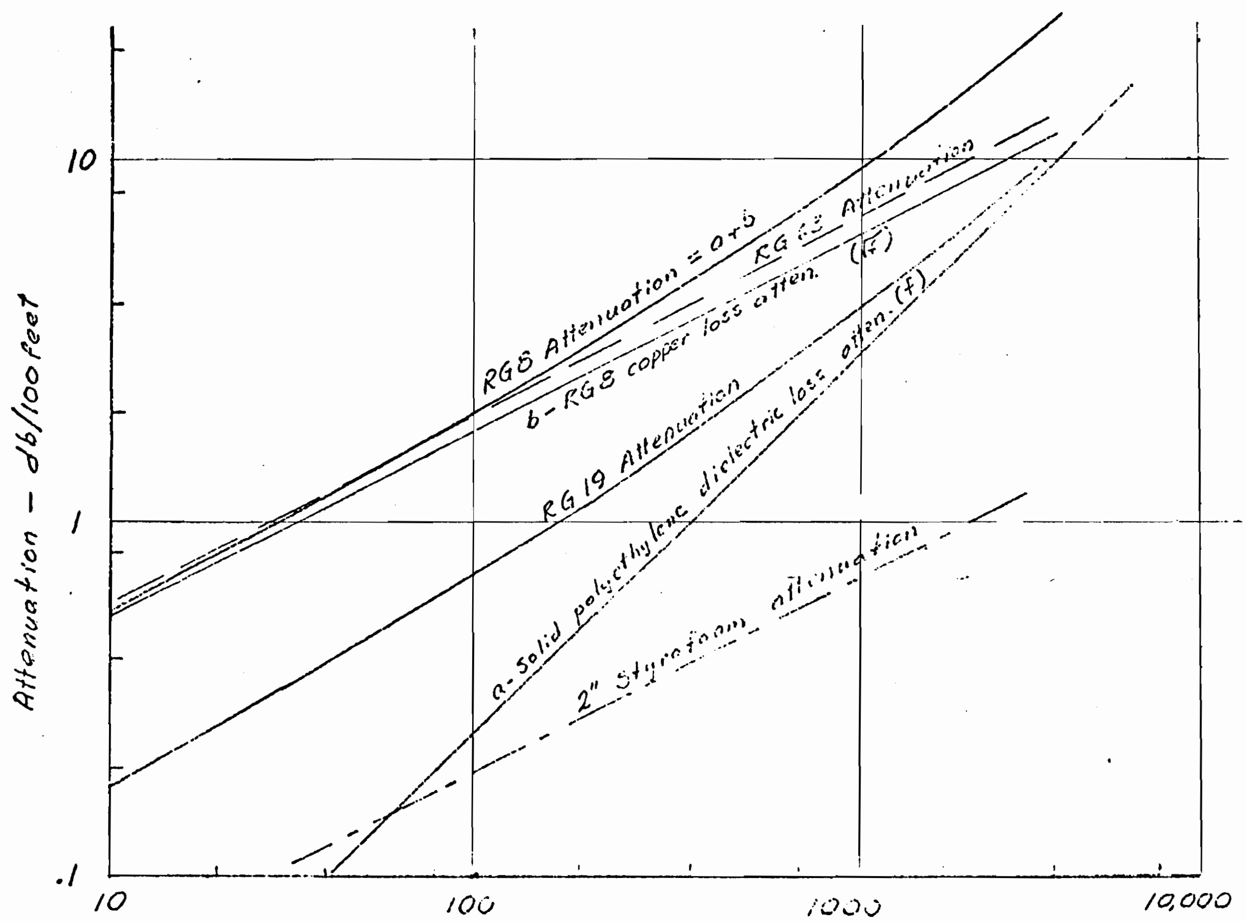


Fig. 10 Attenuation vs frequency. Both RG8 and 19 have solid polyethylene dielectrics, and their attenuation curves are asymptotic to curve a at higher frequencies. RG63 has a semi-solid polyethylene dielectric, and Styrofoam uses Styrofoam dielectric.

File No. CC 2-2B (1)
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COUNTING NOTE

PHYSICAL CHARACTERISTICS OF COAXIAL CABLES

Listings of some of the physical properties of certain commercially available coaxial cables and delay lines are given. The cables listed are those considered to be most probably applicable to counting work. Most of the numbers are taken from manufacturer's literature.

Following the cable listings is a section in which other properties and characteristics of dielectrics and coaxial transmission lines are given.

TABLE OF CONTENTS

I SPECIFICATIONS OF COAXIAL CABLES MOST OFTEN USED FOR COUNTING PURPOSES.

Numerical values are derived from manufacturers literature. In cases where different manufacturers give different numbers either an average value is given or else the range of values is indicated.

Cable type no.	Zo ohms	Cap. pf/ft	β=v/c vel. prop.	Diam. over-all	Outer - i.d. (in.)	Conductor Type	Inner - o.d. (in.)	Conductor Type
RG-8	52	29.5	0.659	0.415	0.285	C	0.085	STR
RG-9	50-51	30	0.659	0.430	0.280	SC-C	0.086	STR
RG-19A	52	29.5	0.659	1.135	0.910	C	0.250	SOL
RG-55B	53.5	~30	0.659	0.206	0.116	TC-TC	0.032	SOL
RG-58 & 58B	53.5	28.5	0.659	0.200	0.116	TC	0.032	SOL
RG-58A& 58C	50	~29.5	0.659	0.199	0.116	TC	~0.036	STR
RG-62 & 62A	93	13.5	0.84	0.249	0.146	C	~0.030	CW
RG-63 & 63B	125	10	0.84	0.415	0.285	C	~0.030	CW
RG-114A	185	6.5	0.84	0.405	0.285	C	0.007	SOL
RG-174	50	~30	0.659	0.105	0.060	TC	0.019	STR
RG-188	50	29.5	0.659	0.110	0.060	SC	0.018	STR
RG-196	50	28.5	0.659	0.084	0.034	SC	0.010	STR
C3T	197	5.4	0.95	0.64	0.472	C	0.015	STR
21-406	125	10	0.84	0.530	0.285	TC-C	0.030	SOL
6244	125	9.3	0.84	0.140		C	0.012	SOL
Foam Heliax								
1/2"	50		0.79	Note #1		CSC	0.158	TUB
7/8"	50		0.79	Note #1		CSC	0.313	TUB
Spir-o-Line	125	~9	0.9	0.875	0.84	AS	0.082	SOL
Styrofoam								
1½"	125	8.2^e	0.99	~1.60	~1.54	Foil	0.188	TUB
2"	125	8.2^e	0.99	~2.10	~2.05	Foil	0.250	TUB

I (continued)

Cable type no.	Diel. Mtr'l	Keff. f.	Attenuation 100 Mc db/100 ft.	1000Mc	Rise-time To ns.	Remarks
RG-8	P	2.3^e	2.1	8.0-9.0	.29 - .37	
RG-9	P	2.3^e	2.0-2.3	7.3-9.0	.24 - .37	Double shielded 8/U
RG-19A	P	2.3^e	0.69	3.6	.59	Limited flexibility
RG-55B	P	2.3^e	4.8	~16.9	1.27 -1.32	Double Shielded.
RG-58 & 58B	P	2.3^e	4.6-5.4	17.8-20	1.5 -1.8	
RG-58AH 58C	P	2.3^e	5.4-6.2	20-24	1.8 -2.6	
RG-62 & 62A	SSP	1.42^e	2.7	8.7-9.0	.35 - .37	
RG-63 & 63B	SSP	1.42^e	2.0	6.5	.19	
RG-114A	SSP	1.35^e	2.9		.39	Amphenol
RG-174	P	2.3^e	9.0	30.0	4.1	
RG-188	T	2.3^e	11.4	31.0	4.4	Amphenol
RG-196	T	2.3^e	13.8	46.0	9.6	Amphenol & Microdot
C3T	PSB	1.1^e	1.9	7.6^k	.44	Transradio
21-406	SSP	~1.5	1.99	6.4		UCRL Specs (5Z9611) similar to 63/U
6244	SSP	~1.4	4.7^e	15^e	1.0	Triaxial. ITT Surprenant
Foam Heliax						
1/2"		1.6	0.81	3.33	0.051	Andrews. Min Rad 5"
7/8"		1.6	0.47	2.00	0.018	Andrews. Min Rad 10"
Spir-o-Line	PT	1.25	~0.6	1.4^e	.0093	Prodelin
Styrofoam						
1½"	STY	~1.03	0.25	0.8	.0016	See(UCRL-3579)
2"	STY	~1.03	0.2	0.6	.0029	See(UCRL-3579)

DIELECTRIC MATERIAL CODING

FP-----Polyethylene foam
P------Polyethylene
PC-----Polyvinyl chloride
PS-----Polystyrene
PSB----Polystyrene beads
PT-----Polyethylene tubes
SP-----Polyethylene spiral
SSP----Semi-solid polyethylene
ST-----Teflon Spiral
STY----Styrofoam
T------Teflon
TPS----Polystyrene tape
TT-----Teflon tape

MANUFACTURERS CODING

Amp----Amphenol-Borg Electronics Corp.
An-----Andrew Corp.
C------Chester Cable Corp.
ITTR---Inter.Tele. & Tele. Royal.
ITTS---Inter.Tele. & Tele. Surprenant.
M------Microdot Inc.
Prod---Prodelin
TR-----Transradio Ltd.

INNER AND OUTER CONDUCTOR CODING

Al-----Aluminum
AS-----Solid aluminum
C------Copper
CSC----Corrugated solid copper
Cu-----Copper
CW-----Copper weld
Foil---Thin Cu foil wrapped & over-lapped
SC-----Silvered copper
SOL----Solid
STR----Stranded
TC-----Tinned copper
TUB----Copper tubing

NOTE CODING

e--------Calculated.
f--------Effective dielectric constant, $1/\beta^2$.
h--------Measured at 400 Mc.
j--------Measured in micromicrofarad per foot.
k--------Measured at 600 Mc.

Note #1.	Without jacket	o.d. = 0.540
	With jacket	o.d. = 0.660
Note #2.	Without jacket	o.d. = 0.980
	With jacket	o.d. = 1.100

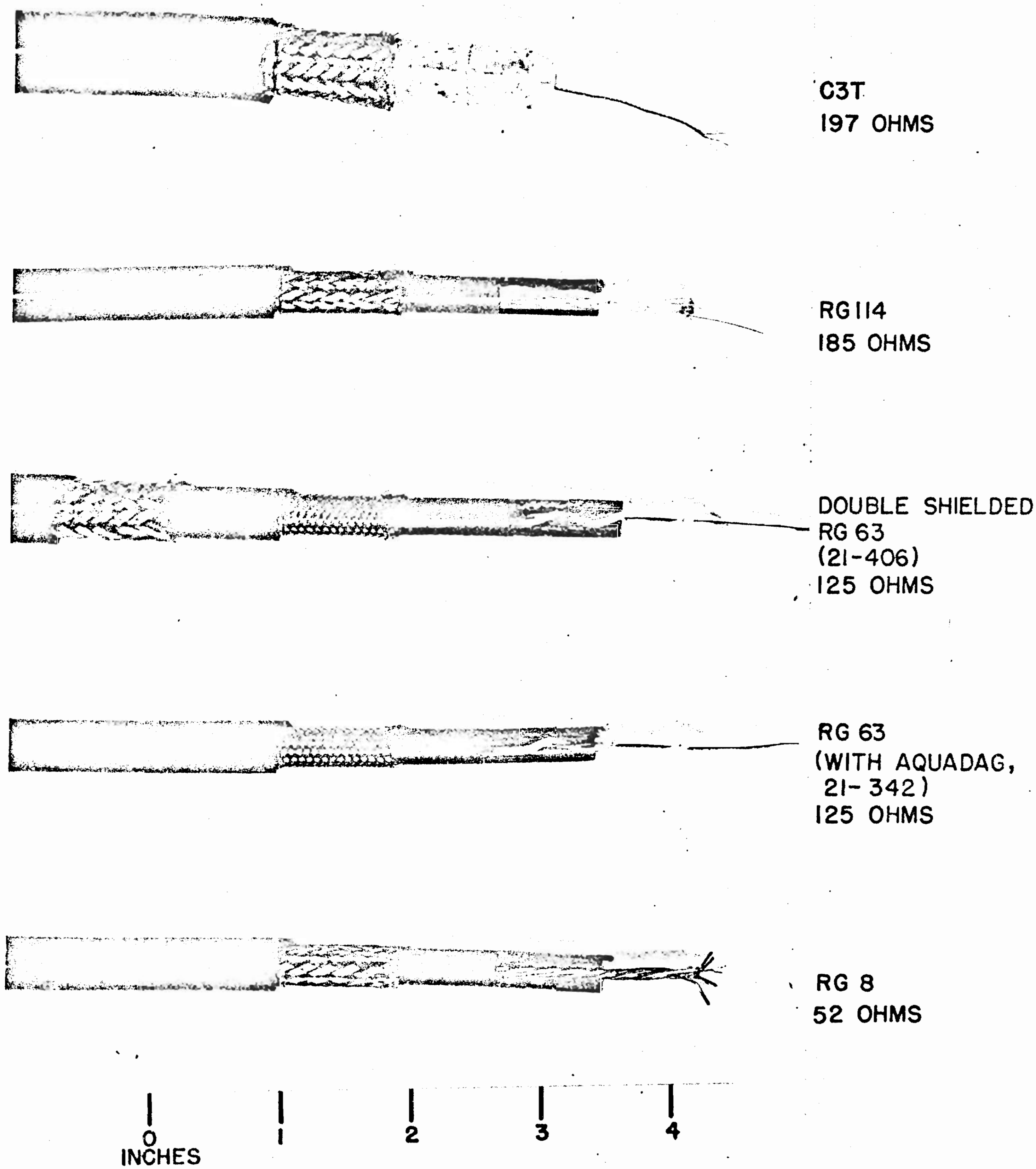


Fig. 1. A photograph of some flexible coaxial cables commonly used for counting applications.

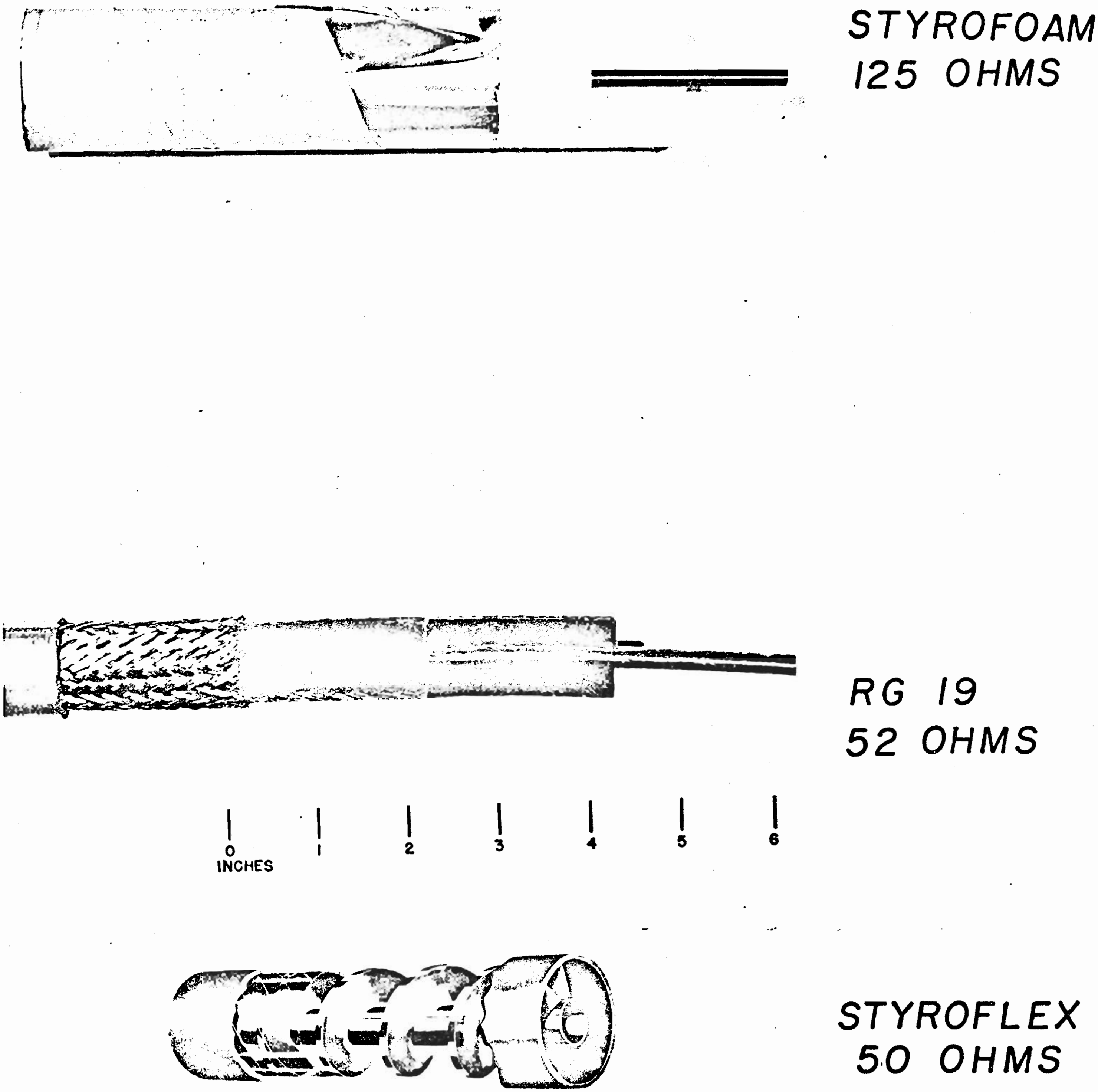


Fig. 2. Photographs showing the construction of some rigid and semi-rigid coaxial transmission lines.

II-A. Cable types of possible use for counting purposes.

ARRANGED BY RG NUMBERS

Cable Type Number	Zo	Diel. Mtr'l.	O.D. of Outer Jacket	Atten. @ 1000 Mc db/100'	Cap. per foot j.	Remarks
RG-5B/U	50	P	0.328	9.1	29.5	Replaced by 212/U
6A	75	P	0.332	11.3	20	
8	52	P	0.405	8.0	29.5	
8A	52	P	0.405	8.0	30.5	Replaced by 213/U
9	50	P	0.420	7.3	30	
9A	50	P	0.420	9.0	30	
9B	50	P	0.420	9.0	30.5	Replaced by 214/U
10A	52	P	0.475	8.0	30.5	Replaced by 215/U
11	75	P	0.405	7.8	20.5	
11A	75	P	0.405	7.8	20.5	
12A	75	P	0.475	7.8	20.5	11A/U with armor.
13	74	P	0.425	7.8	20.5	
13A	74	P	0.420	7.8	20.5	Replaced by 216/U
14A	52	P	0.545	5.5	30.0	Replaced by 217/U
17	52	P	0.870	4.4	29.5	
17A	52	P	0.870	4.4	29.5	Replaced by 218/U
18A	52	P	0.945	4.4	29.5	Replaced by 219/U
19A	52	P	1.120	3.6	29.5	Replaced by 220/U
20A	52	P	1.195	3.6	29.5	Replaced by 221/U
21A	53	P	0.332	43.0	30	
22	95	P	0.405	8.7-h	16	
22B	95	P	0.420	12.0	16	
34B	75	P	0.630	5.85	21.5	
35B	75	P	0.945	3.5	21	Armored.
55B	53.5	P	0.206	16.7	28.5	
57A	95	P	0.625	6.0-h	16	
58	53.5	P	0.195	17.8	28.5	
58A	50	P	0.195	24.0	29.5	
58C	50	P	0.195	24.0	29.5	
59	73	P	0.242	12.0	21	

DIELECTRIC MATERIAL CODING

FP-----Polyethylene foam.
P------Polyethylene
PC-----Polyvinyl Chloride
SSP----Semi-solid Polyethylene
SST----Semi-solid teflon
T------Teflon
TT-----Teflon tape

NOTE CODING

e------Calculated.
h------Measured at 400 Mc.
j------Micromicrofarads per foot
k------Measured at 600 Mc.

II-A. (Continued)

Cable type Number	Zo	Diel. Mtr'l.	O.D. of Outer Jacket	Atten. @ 1000 Mc db/100'	Cap. per foot j.	Remarks
RG-59B/U	75	P	0.242	12	20.5	
62	93	SSP	0.242	8.7	13.5	
62A	93	SSP	0.242	8.7	13.5	
62B	93	SSP	0.242	7.3-h	13.5	
63	125	SSP	0.405	6.4	10	
63B	125	SSP	0.405	6.4	10	
71A	93	SSP	0.245	8.7	13.5	
71B	93	SSP	0.245	8.7	13.5	
74A	52	P	0.615	5.5	29.5	Replaced by 224/U
79B	125	SSP	0.475	6.4	10	63/U with Armor.
87A	50	T	0.425	7.6	29.5	Replaced by 225/U
108A	78	P	0.235	16.8-h	23.5	
111A	95	P	0.490	12	16	22B/U with Armor.
114	185	SSP	0.405	5.4*	6.5	*at 200 Mc.
114A	185	SSP	0.405	5.4*	6.5	*at 200 Mc.
115	50	TT	0.375	7.3	29.5	
115A	50	TT	0.415	7.3	29.5	
116	50	T	0.475	7.6	29.5	Replaced by 227/U
117	50	T	0.730	3.6	29	Replaced by 211/U
119	50	T	0.730	3.6	29	
122	50	P	0.160	29	29.5	
140	75	T	0.233	12.8	21	
141	50	T	0.190	13.8	28.5	
141A	50	T	0.190	13.8	28.5	
142	50	T	0.206	13.8	28.5	
142A	50	T	0.206	13.8	28.5	
143	50	T	0.325	9.6	28.5	
143A	50	T	0.325	9.6	28.5	
144	75	T	0.410	6.9	20.5	
149	75	P	0.405	8.5-h	20.5	Low loss 11/U
164	75	P	0.870	3.5	21	35 B/U less Armor.
178A	50	T	0.075	46	28.5	
149A	75	T	0.105	24	19.5	

DIELECTRIC MATERIAL CODING

FP------Polyethylene foam
P-------Polyethylene
PC------Polyvinyl Chloride
SSP-----Semi-solid Polyethylene
SST-----Semi-solid teflon
T-------Teflon
TT------Teflon tape

NOTE CODING

e-------Calculated.
h------Measured at 400 Mc.
j------Micromicrofarads per foot
k------Measured at 600 Mc.

II-2. (Continued)

Cable type Number	Zo	Diel. Mtr'l.	O.D. of Outer Jacket	Atten. @ 1000 Mc db/100'	Cap. per foot j.	Remarks
RG-180	93	T	0.141	17	15	
180A	95	T	0.145	17	15	
187	75	T	0.110	24	19.5	
188	50	T	0.110	31	29	
195	95	T	0.155	17	15	
196	50	T	0.080	46	28.5	
209	50	SST	0.750	2.5-h	26.5	
210	95	SST	0.242	7.0-h	13.5	Formerly 62C/U
211	50	T	0.730	3.6	29	Formerly 117/U
212	50	P	0.332	9.1	29.5	Formerly 5B/U
213	50	P	0.405	8.0	29.5	Formerly 8A/U
214	50	P	0.425	9.0	29.5	Formerly 9B/U
215	50	P	0.475	8.0	29.5	Formerly 10A/U
216	75	P	0.425	7.8	20.5	Formerly 13A/U
217	50	P	0.545	5.5	29.5	Formerly 14A/U
218	50	P	0.870	4.4	29.5	Formerly 17A/U
219	50	P	0.945	4.4	29.5	Formerly 18A/U
220	50	P	1.120	3.6	29.5	Formerly 19A/U
221	50	P	1.195	3.6	29.5	Formerly 20A/U
222	50	P	0.332	43.0	29	Formerly 21A/U
223	50	P	0.216	16.7	29.5	Formerly 55A/U
225	50	T	0.430	7.6	29.5	Formerly 87A/U
226	50	TT	0.500	3.5-h	29.5	Formerly 94A/U
227	50	T	0.490	7.6	29.5	Formerly 116/U
K-113	35	FP	0.195	12-h	39	
60-3905	30	PC	0.045		65	

DIELECTRIC MATERIAL CODING

FP------Polyethylene foam
P-------Polyethylene
PC------Polyvinyl Chloride
SSP-----Semi-solid Polyethylene
SST-----Semi-solid teflon
T-------Teflon
TT------Teflon tape

NOTE CODING

e-------Calculated.
h-------Measured at 400 Mc.
j-------Micromicrofarads per foot
k-------Measured at 600 Mc.

II-B. Cable types of possible use for counting purposes.

MINIATURE TYPES
(Those with o.d. less than or equal to 0.190 inches.)

CABLE TYPE NUMBER	MFR.	Zo	Diel. Mtr'l.	O.D. of Outer Jacket	Atten. @ 1000 Mc db/100'	Cap. per foot j.	REMARKS
RG-122/U		50	P	0.160	29	29.5	
RG-141/U		50	T	0.190	14	28.5	
RG-141A/U		50	T	0.190	14	28.5	
RG-174/U		50	P	0.100	18-h	29.5	
RG-178A/U		50	T	0.075	46	28.5	
RG-179A/U		75	T	0.105	24	19.5	
RG-180/U		93	T	0.141	17	15.5	
RG-180A/U		95	T	0.145	17	15	
RG-187/U		75	T	0.110	24	19.5	
RG-188/U		50	T	0.110	31	29	
RG-195/U		95	T	0.155	17	15	
RG-196/U		50	T	0.080	46	28.5	
21-597	Amp.	75	P	0.150	12-h	20	
60-3905	M.	30	T	0.045		65	

MANUFACTURER CODING

Amp. -------Amphenol
M.----------Microdot

DIELECTRIC MATERIAL CODING

P-----------Polyethylene
T-----------Teflon

NOTE CODING

h-----------Measured at 400 Mc.
j-----------Capacity is in micromicrofarad per foot.

II-C. Cables types of possible use for counting purposes.

RIGID AND SEMI-RIGID CABLE TYPES

Cable Type Number		Mfr.	Zo	Diel. Mtr'l.	O.D. of Outer Jacket	Atten. @ 1000 Mc db/100'	Cap. per foot j.	Remarks
	21-592	Amp.	50	P	0.325	7.6	29.5	8/U with solid Cu Shield.
	21-606	Amp.	50	P	0.325	7.6	29.5	8/U with solid Al shield.
	21-607	Amp.	75	P	0.325	7.5		11/U with solid Al shield.
	421-608	Amp.	50	T	0.325	6.2		87A/U with solid Al shield.
	421-609	Amp.	75	T	0.325	6.0		144/U with solid Al shield.
	FH4	An.	50	FP	0.540	3.33		Corrugated solid Cu shield. Minimum radius 5".
	FHJ4	An.	50	FP	0.660	3.33		Corrugated solid Cu shield. Minimum radius 5".
	FH5	An.	50	FP	0.980	2.00		Corrugated solid Cu shield. Minimum radius 10".
	FHJ5	An.	50	FP	1.100	2.00		Corrugated solid Cu shield. Minimum radius 10".
RG-268/U	H3-50	An.	50	SP	0.500	5.00		Corrugated solid Cu shield. Minimum radius 5".
RG-269/U	H5-50	An.	50	SP	1.005	1.07		Corrugated solid Cu shield. Minimum radius 10".
RG-285/U	H5-100	An.	100	ST	1.005	1.07		Corrugated solid Cu shield. Minimum radius 10".
RG-270/U	H7-50	An.	50	SP	1.830	0.79		Corrugated solid Cu shield. Minimum radius 20".
	H7-100	An.	100	SP	1.830	0.79		Corrugated solid Cu shield. Minimum radius 20".
--		Prod	125	PT	0.875	1.4-e	9	Solid Al shield.
Styroflex		P-D	50	TPS	0.875	1.6	22	Minimum radius 10".
Styroflex		P-D	50	TPS	3.125	0.5	22	Minimum radius 50".
Styrofoam		UCRL	125	SF	1.500	0.8		UCRL Spec. (3597).
Styrofoam		UCRL	125	SF	2.000	0.6		UCRL Spec. (3597).

DIELECTRIC MATERIAL CODING

FP------Polyethylene foam.
P-------Polyethylene.
PT------Polyethylene tubes.
SF------Styrofoam
SP------Polyethylene spiral.
ST------Teflon spiral
T-------Teflon
TPS-----Polystyrene

MANUFACTURERS CODING

Amp-----Amphenol-Borg Electronics Corp.
An------Andrew Corp.
P-D-----Phelps-Dodge Electronics Products Corp.
PROD---Prodelin Inc.
UCRL---U.C. Radiation Laboratory Specs.

NOTE CODING

e-------Calculated
j-------Micromicrofarads per foot

INNER & OUTER CONDUCTOR CODING

Al------Aluminum
Cu------Copper

II-D. Cable types of possible use for counting purposes.

1. DELAY CABLES

Cable Type	Number	Mfr.	Zo ± 10%	Delay a.	Band-width b.	D.C. ohms ft.	O.D. inch	Inner Cond. AWG	Loss Insert. c.	Max. volts	Min. Radius inches
RG-266/U	HH1500A	CTC	1500	0.08	15	30	0.40	29	0.20	5000	2
	HH1600	CTC	1700	1.0	6	80	0.28	38	0.40	300	3
RG-176/U	HH2000	CTC	2400	0.11	15	70	0.40	32	0.25	5000	2
	HH2500	CTC	3000	0.60	8	125	0.28	38	0.30	500	3
	HH4000	CTC	3900	1.0	6	85	0.32	38	0.20	1000	4
	65A	Royal	950	0.043			0.415	32		3000	

NOTES:

a) Microsecond per foot, plus or minus 10%.
b) Band-width at one microsecond delay.
c) db loss per microsecond delay.

MANUFACTURER CODING

CTC) Columbia Technical Corporation.
Royal) Inter. Tele. & Tele. Royal

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 ^oC (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 ^oC	$1\text{-}2\times10^{13}$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 $10^6/^oC$	160-180a	100	60-80a	70f	
Mechanical distortion temp., ^oC	41-50a	135g @ 66 psi	70-100a	80f	
Brittleness temperature, ^oC	-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	$\sim 2 \times 10^{-4}$	$+20^\circ$ to $+50^\circ$C*
63	$\sim 1 \times 10^{-4}$	-20° to $+50^\circ$C
87A	$\sim 1 \times 10^{-4}$	-60° to $+50^\circ$C

* Not measured below $+20^\circ$C.

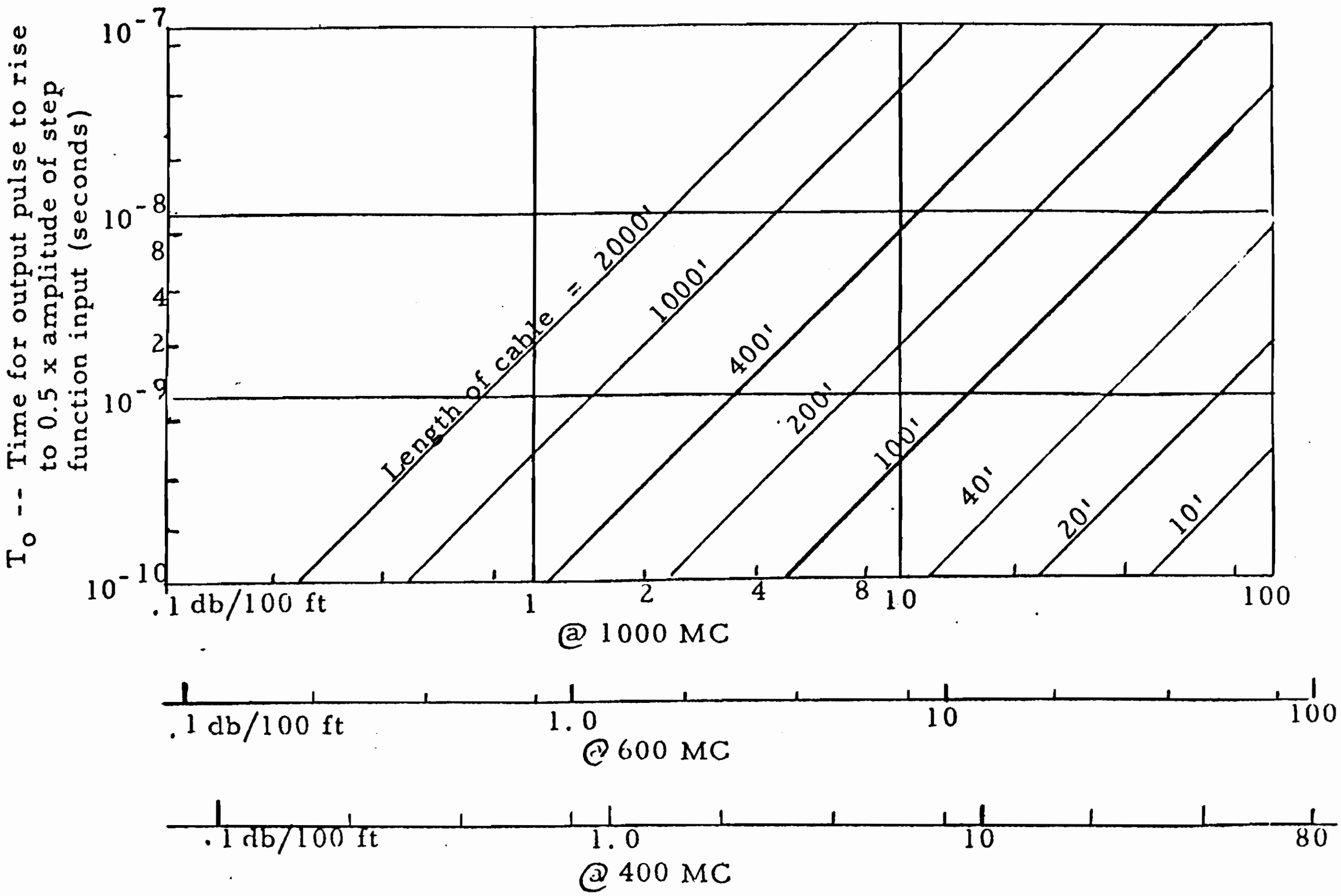
A 100 foot length of RG 63 will therefore change its electrical length about 0.012 millimicroseconds per degree antigrade.

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

VI.



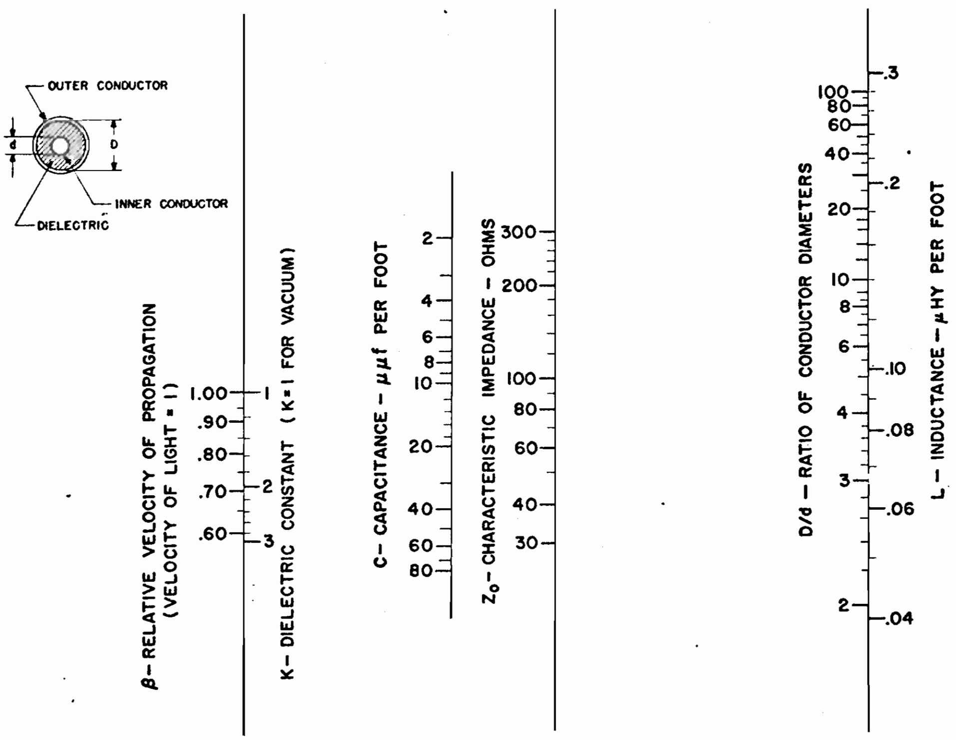
a -- ATTENUATION AT INDICATED FREQUENCIES (db/100 feet)

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	29
95	110

The 10 to 90% rise time is thus (29 - 0.17) T_o = 28.83 T_o.



COAXIAL TRANSMISSION LINES IMPEDANCE NOMOGRAPH

MC-12192

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 velocity of propagation is

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

3. L, C - Distributed inductance and capacitance.

$$L = \frac{Z_o}{v} \text{ henries per meter}$$

$$= 1.01 \frac{Z_o}{\beta} \times 10^{-3} \text{ microhenries per foot}$$

$$C = \frac{1}{Z_o v} \text{ farads per meter}$$

$$= \frac{1.01 \times 10^3}{\beta Z_o} \text{ micro microfarads per foot}$$

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

---

* 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

= 1.45×10^{-8} A - feet^{-1} sec$^{\frac{1}{2}}$

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

f = frequency - cycles per second.

* 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.