Sensor and Simulation Notes XIV

Design Considerations for a Special Twinaxial Cable

I. Introduction

Twinaxial cable is relatively new in the realm of high frequency cable types and has not as yet reached the level of standardization that has been reached by coaxial cable. There is a definite need for a standard twinaxial cable. This note is an analytical calculation that is suggested as a basis for the design of a special twinaxial cable for high frequency and/or pulse data transmission.

While twinaxial cables (or shielded twisted pairs as they are also known) have existed for some time their application has largely been limited to relatively low frequencies. The special cable suggested here is designed specifically for high frequency and/or pulse data transmission. The prime difference between this special cable and any previous twinaxial cable is its impedance values. A twinaxial cable has associated with it two impedances that are of interest to us. The first is the differential mode impedance which is the impedance normally defined in a twinaxial cable. The second is the common mode impedance which is not usually considered in a twinaxial cable. The common mode impedance is significant when using the twinaxial cable as a coaxial cable (i.e., center conductors in parallel with sheath return). Although a twinaxial cable with both the differential mode impedance and the common mode impedance specified has not to the author's knowledge been produced commercially, the author can see no reason why such a cable could not be produced. The quality control necessary to produce a useful cable would be rigorous due to the tolerances involved, but I believe that the problems involved are not beyond the present state of the art as indicated by the precision coaxial components available from various sources at this time.

II. Differential Mode and Common Mode Impedances

To illustrate the possibility of producing a twinaxial cable with both differential mode and common mode impedance specified, design calculations for a specific type of twinaxial cable considering both impedances were made. These design calculations considered the variation of: dielectrics; cable impedances; and differential to common mode impedance ratios. Thus, from the results of this problem, a cable user could choose his impedances, his dielectric, and one dimension parameter to define his cable.

For the case considered, in which all conductors have a circular cross section and the inner conductors are symmetrically located with respect to the axis of the outer conductor, a close approximation of the characteristic impedance, Z_D, for the differential mode of operation is given by:

$$Z_D = \frac{1}{\pi}\sqrt{\frac{\mu}{\varepsilon}}\left\{ \ln\left[2P\left(\frac{1-Q^2}{1+Q^2}\right)\right] - \left[\frac{1+4P^2}{16P^4}\right]\left[1-4Q^2\right] \right\} \qquad (1)$$

where P is the ratio of the inner conductor spacing to the inner conductor diameter and Q is the ratio of the inner conductor spacing to the diameter of the dielectric. (See figure 1.)

Likewise, a close approximation of the characteristic impedance, Z_c, for the common mode of operation is given by:

$$Z_c = \frac{1}{4\pi}\sqrt{\frac{\mu}{\varepsilon}}\left\{ln\left[\frac{P(1-Q^4)}{2\ Q^2}\right] - \left[\frac{1+4Q^4}{1+4P^4}\right]\left[1+4Q^4\left(\frac{5+4P^2}{1+4P^2}\right)\right]\right\} \qquad (2)$$

If $\mu = \mu_o\mu_r$ *and* $\varepsilon = \varepsilon_o\varepsilon_r$ *and assuming that* $\mu_r = 1$ *the equations become:*

$$Z_D = \frac{120}{\sqrt{\varepsilon_r}}\left\{ln\left[2P\left(\frac{1-Q^2}{1+Q^2}\right)\right] - \left[\frac{1+4P^2}{16P^4}\right]\left[1-4Q^2\right]\right\} \qquad (3)$$

$$Z_c = \frac{120}{4\sqrt{\varepsilon_r}}\left\{ln\left[\frac{P(1-Q^4)}{2Q^2}\right] - \left[\frac{1+4Q^4}{1+4P^4}\right]\left[1+4Q^4\left(\frac{5+4P^2}{1+4P^2}\right)\right]\right\} \qquad (4)$$

In a generalized form the equations become:

$$Z_1 = \frac{Z_D\sqrt{\varepsilon_r}}{120} = ln\left[2P\left(\frac{1-Q^2}{1+Q^2}\right)\right] - \left[\frac{1+4P^2}{16P^4}\right]\left[1-4Q^2\right] \qquad (5)$$

$$Z_2 = \frac{Z_c\sqrt{\varepsilon_r}}{120} = \frac{1}{4}\left\{ln\left[\frac{P(1-Q^4)}{2Q^2}\right] - \left[\frac{1+4Q^4}{1+4P^4}\right]\left[1+4Q^4\left(\frac{5+4P^2}{1+4P^2}\right)\right]\right\} \qquad (6)$$

For values of the ratio Z_1/Z_2 from 0.400 to 3.000 and for values of Z_1 from 0.1 to 10, a computer was programmed to find a family of curves for P and Q (figs. 2, 3, & 4). To define the physical parameters of a cable, the designer must choose the values of the two impedances and the desired dielectric constant. These values will give him Z_1 and R where $R = Z_1/Z_2 = Z_D/Z_c$. P and Q are then obtained from the curves. The values of P and Q plus one arbitrarily selected dimension uniquely define the cable.

One of the important factors to consider when designing a cable is versatility. One of the reasons for specifying the common mode impedance of the twinaxial cable is to provide a cable that will function as a high quality coaxial cable for the propagation of common mode signals. Since most of the coaxial cables used for pulse data transmission have an impedance of 50 ohms, (e.g., RG58/U and RG213/U) it follows that a reasonable value for the common mode impedance of the twinaxial cable should also be 50 ohms.

The logical choice for the differential mode impedance is 100 ohms. This impedance value will facilitate the use of the cable as: (1) a transmission line that can be matched to a pair of standard 50 ohm coaxial cables. This matching is accomplished by connecting the outer conductors of the two coaxial cables to the outer conductor of the twinaxial cable and connecting the center conductor of each coaxial cable to one of the center conductors of the twinaxial cable, (2) a standard cable around which the input and output impedances of various devices, which must utilize a twinaxial cable, can be designed. To the author's knowledge, no twinaxial cable with a convenient differential mode impedance exists at this time.

The impedance equations of the twinaxial cable with a 100 ohm differential mode impedance and a 50 ohm common mode impedance become:

$$Z_1 = \frac{100\sqrt{\epsilon_r}}{120} = \ln\left[\frac{2P(1-Q^2)}{1+Q^2}\right] - \left[\frac{1+4P^2}{16P^4}\right]\left[1-4Q^2\right] \qquad (7)$$

$$Z_2 = \frac{50\sqrt{\epsilon_r}}{120} = \frac{1}{4}\left\{\ln\left[\frac{P(1-Q^4)}{2Q^2}\right] - \left[\frac{1+4Q^4}{1+4P^4}\right]\left[1+4Q^4\left(\frac{5+4P^2}{1+4P^2}\right)\right]\right\} \qquad (8)$$

These equations were solved for P and Q for the common dielectrics that are in use today (see table 1).

100/50 Twinaxial Cable Parameters for Common Dielectrics

Dielectric	Dielectric Constant at 10^8 cps	P	Q
Air	1.0006	1.589	0.375
Styrofoam 22	1.025	1.60	0.373
Styrofoam 103.7	1.03	1.602	0.372
Teflon	2.1	2.07	0.301
Polyethylene	2.25	2.14	0.293
Polystyrene	2.55	2.28	0.280

TABLE 1

Using the results obtained a cable was designed for Teflon dielectric ($\epsilon_r = 2.1$). The values for P and Q were 2.07 and 0.301, respectively. Some typical dimensions for other dielectrics are tabulated in table 3 appended to this note.

III. Other Characteristics

With the dimension ratios of the desired cable and its dielectric fixed, one can check to see if the cable meets other requirements levied on a cable for high frequency and/or pulse data transmission. These requirements are:

(1) High voltage capability of greater than 5 KV differential mode and 10 KV common mode.

(2) Attenuation of less than 4 db per 100 feet at 400 mc and less than 2.0 db per 100 feet at 100 mc in either mode of operation. Or equivalently,

(3) A cable tau of less than 0.392 ns for a 100 meter cable length.

<u>High Voltage Breakdown</u>

The dielectric strength of Teflon for a 1/8 inch sample is approximately 480,000 volts per inch. Therefore, for a uniform field distribution, the spacing between center conductors must be greater than 0.0105 inches for a

5 KV differential mode voltage capability and the spacing between center conductors and outer conductor must be greater than 0.021 inches for a 10 KV common mode voltage capability.

Attenuation-Frequency Characteristics

The differential mode attenuation of this type of twinaxial cable is given by the equations:

$$\alpha_{D1} = \frac{1}{2Z_D}\left\{\frac{2R_{s2}}{\pi d}\left[1+\left(\frac{1+2P^2}{4P^4}\right)\left(1-4Q^2\right)\right] + \frac{8R_{s3}Q^2}{\pi D}\left[1+Q^4 - \frac{1+4P^2}{8P^4}\right]\right\} \qquad (9)$$

$$\alpha_{D2} = \frac{\sigma\eta}{2} = \frac{240\pi\sigma}{\sqrt{\epsilon_r}} \qquad (10)$$

$$\alpha = \alpha_{D1}+\alpha_{D2} \qquad (11)$$

where α_{D1} *is the attenuation due to the conductor losses,* α_{D2} *is the attenuation due to the dielectric losses,* R_{s2} *is the skin effect surface resistance of the center conductors,* R_{s3} *is the skin effect surface resistance of the outer conductor,* σ *is the conductivity of the dielectric and* η *is the* $\sqrt{\mu/\epsilon}$ *of the dielectric.*

In the case of Teflon, it can be shown that ahe attenuation due to the dielectric losses is roughly 10 orders of magnitude below the attenuation due to the conductors, and therefore will not be considered.

For the cable under consideration:

$Z_D = 100$

$P = 2.07$

$Q = 0.301$

$R_{s2} = R_{s3} = 2.61X10^{-7}\ \sqrt{f}$ *for copper conductors*

$R_s = \frac{1}{\delta\sigma} = \sqrt{\pi\rho\mu f}$

Inserting these parameters, the equation for the differential mode attenuation becomes:

$$\alpha_D = \left(\frac{8.988}{d} + \frac{2.6611}{D}\right) X\ 10^{-10}\ \sqrt{f} \qquad (12)$$

Since D/d is fixed by the values of P and Q,

$$\alpha_D = \left(\frac{8.988D}{Dd} + \frac{2.6611}{D}\right) X\ 10^{-10}\ \sqrt{f}$$

$$\alpha_D = \left(\frac{64.5757}{D}\right) X\ 10^{-10}\sqrt{f} \qquad (13)$$

Entering the requirement for $\alpha_D \doteq 2$ *db/100 ft at 100 mc, (7.0175X10*$^{-3}$ *nepers/meter at 100 mc) and solving for D, the required diameter of the dielectric is determined to be:*

$D = 9.19 \times 10^{-3}$ meters

or $D = 0.362$ inches

Since the attenuation is inversely proportional to D a larger value for D would result in a smaller attenuation. Therefore, let D = 0.400 inches (1.016×10^{-2} meter). The attenuation then becomes:

$$\alpha_D = 63.56 \times 10^{-8} \sqrt{f} \text{ nepers/meter}$$

or $$\alpha_D = 1.811 \times 10^{-4} \sqrt{f} \text{ db/100 ft}$$

The common mode attenuation of this twinaxial cable is given by the equation:

$$\alpha_c = \frac{1}{2Z_c}\left[U+V\right] \qquad (14)$$

where $$U = \frac{R_{s2}}{4\pi d}\left[1 + \frac{8P^2(1+4Q^4)}{(1+4P^2)^2}\left(1+4Q^4\left(\frac{9+4P^2}{1+4P^2}\right)\right)\right] \qquad (15)$$

and $$V = \frac{R_{s3}}{2\pi D}\left[1 + 2Q^4 + \frac{8Q^4}{1+4P^2}\left(1+8Q^4\left(\frac{5+4P^2}{1+4P^2}\right)\right)\right] \qquad (16)$$

In the case of teflon dielectric and copper conductors:

$P = 2.07$ | $D = 0.400$ inch (10.16×10^{-3} meter)

$Q = 0.301$ | $d = 0.058$ inch (1.47×10^{-3} meter)

$R_s = 2.61 \times 10^{-7} \sqrt{f}$ | $Z_c = 50$ ohms

The common mode attenuaton is then:

$$\alpha_c = 2.03 \times 10^{-7} \sqrt{f} \text{ nepers/meter}$$
$$\alpha_c = 5.78 \times 10^{-5} \sqrt{f} \text{ db/100 ft}$$

<u>*Cable Tau*</u>

When a cable is used for pulse data transmission, the cable Tau represents a parameter that is extremely useful for data reduction. This parameter can be used to describe the response of the cable to either a unit impulse or unit step input. The impulse response (or transfer function) of a cable may be expressed as:

$$g(t) = \left(\frac{\tau}{\pi}\right)^{1/2} x^{-3/2} e^{-\tau/x} \qquad x \geq 0$$
$$= 0 \qquad x < 0 \qquad (17)$$

where

$x = t_o - lT,$

t_o is time of application of the impulse and lT is the time delay of the cable.

The step response of the cable can be found from the inverse transform of 1/S times the transfer function. In terms of x and τ :

$$h(t) = \operatorname{cerf}\sqrt{\tau/x} \qquad x \geq 0$$
$$= 0 \qquad x < 0 \tag{18}$$

where cerf $\sqrt{\tau/x}$ is the complimentary error function of $\sqrt{\tau/x}$.

Cable Tau is closely related to the attenuation-frequency characteristic of a cable. The Tau of a cable can be expressed as:

$$\tau = \frac{(l\,\alpha(\omega))^2}{2\omega} \tag{19}$$

where L is the length of the cable, ω is the radian frequency for which Tau is defined, and $\alpha(\omega)$ is the attenuation at ω expressed in nepers per unit length. Tau will be defined for 100 mc in the case of this cable.

The differential mode Tau for 100 meters of this cable is 0.326 ns and the common mode Tau for 100 meters of this cable is 0.0328 ns.

IV. Summary and Conclusions

This note is an analytical approach to the design of a standard twinaxial cable for broad band measurements and pulse data transmission. The author realizes that the realities of engineering and manufacturing will require some compromise and that there will have to be some changes in the design to satisfy unforeseen requirements.

If one looks at the limiting cases where S goes to zero (and the twinax becomes a coax) and where D goes to infinity (open two wire line), it becomes apparent that the equations used are only approximations. However, such approximations are often used in engineering work where their more rigorous counterparts would involve calculations more difficult than the slight increase in accuracy is worth. As a matter of fact, it is common practice to use only the first term of the impedance equations for the manufacture of cables, since this alone is sufficient to be beyond the accuracy limitations of most cable manufacturing machinery. Note that these approximations are only valid when limiting cases are avoided.

It also must be noted that the attenuation equations are based upon solid inner and outer conductors and thus allowance must be made when a braided outer conductor is used. With modern flat wire braid, outer conductor efficiencies approaching 90% can be obtained, so the error introduced by the use of braided outer conductors is not serious.

Finally, under certain conditions Teflon has some undesirable characteristics that eliminate it from consideration. Under these conditions, the material that is, at present, the best choice for a solid dielectric is polyethylene. The use of polyethylene for the dielectric requires that the dimensions of the cable *be recalculated to meet the attenuation requirements set forth. Since this paper is merely an analytical approach to the design of a standard twinaxial cable and is not intended to be a final design these calculations will not be presented.*

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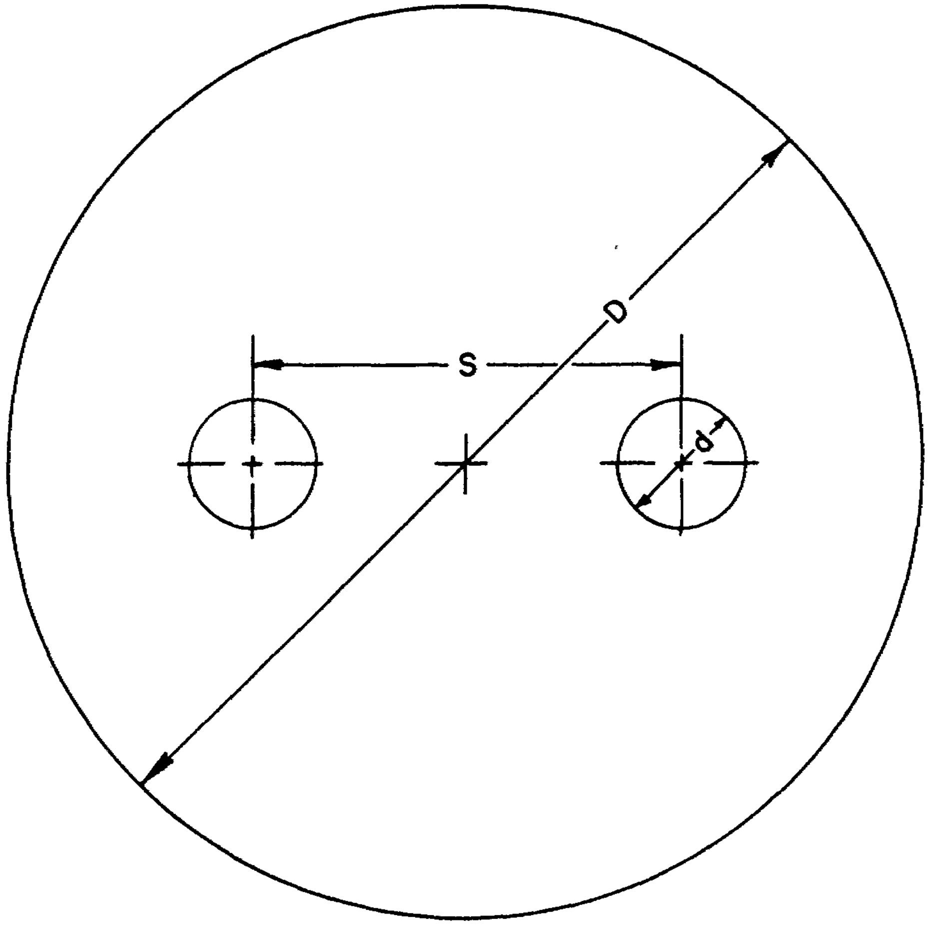
17 March 1965



$P = \frac{S}{d}$ $Q = \frac{S}{D}$

Figure 1

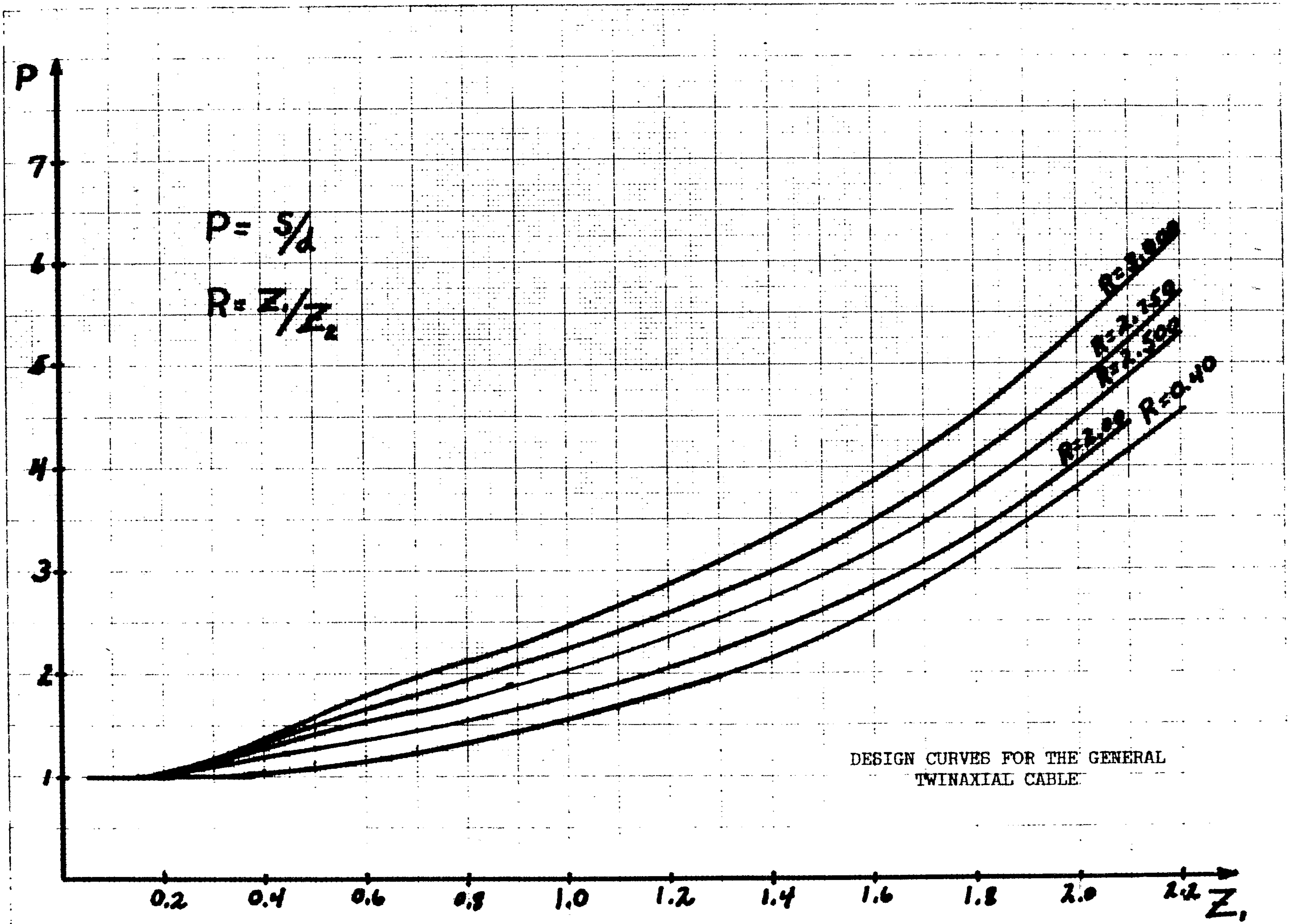
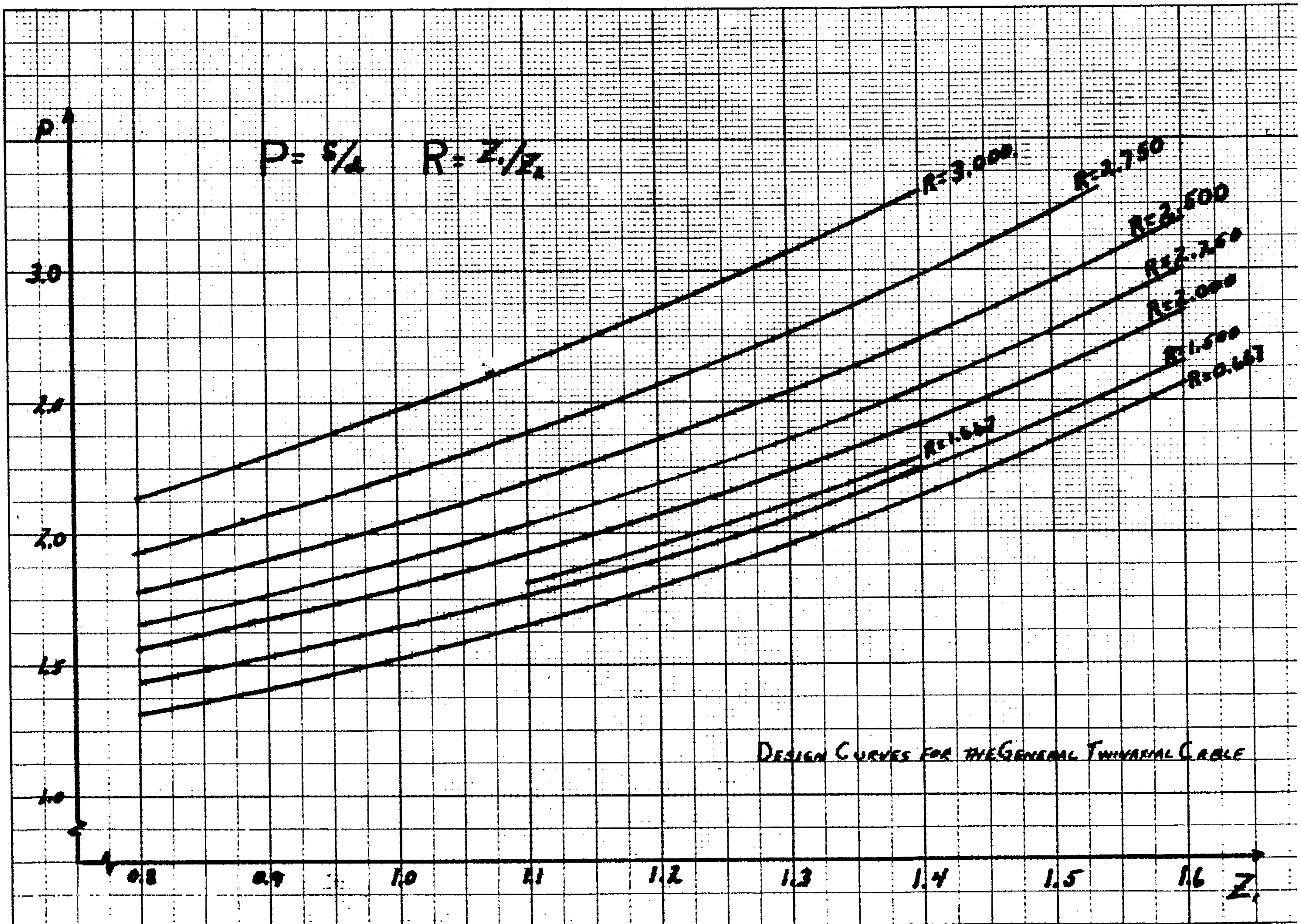

P
7
6
5
4
3
2
1
P = S/d
R = Z1/Z2
R=2.250
R=2.500
R=0.40
DESIGN CURVES FOR THE GENERAL
TWINAXIAL CABLE
0.2
0.4
0.6
0.8
1.0
1.2
1.4
1.6
1.8
2.0
2.2
Z1

FIGURE 2

FIGURE 3



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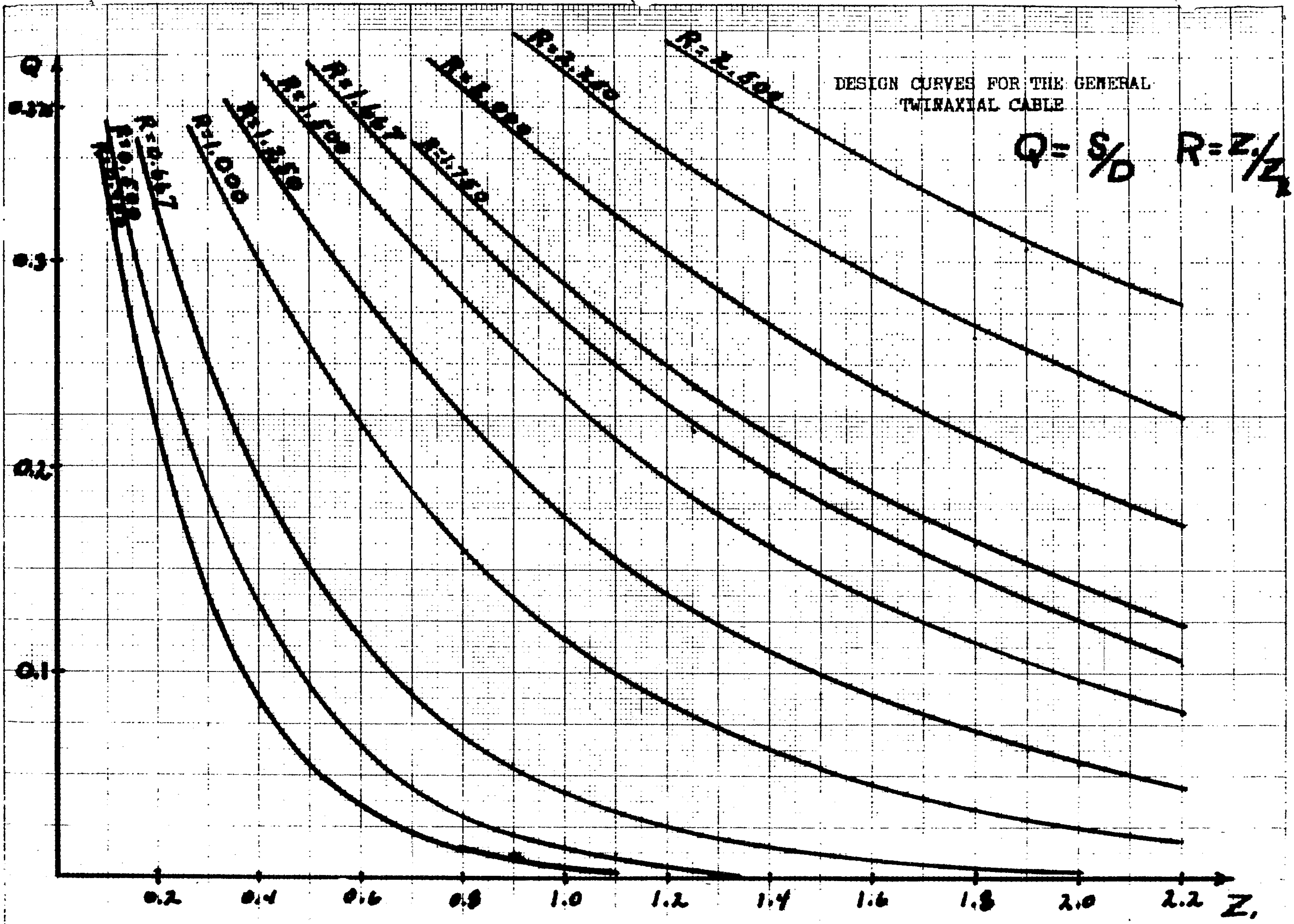
DESIGN CURVES FOR THE GENERAL
TWINAXIAL CABLE
Q= S/D
R=Z1/Z2
R=2.500
R=2.250
R=2.000
R=1.750
R=1.667
R=1.500
R=1.250
R=1.000
R=0.667
Q
0.3
0.2
0.1
0.2
0.4
0.6
0.8
1.0
1.2
1.4
1.6
1.8
2.0
2.2
Z1

FIGURE#4

CALCULATED CHARACTERISTICS OF A 100/50 OHM TWINAXIAL CABLE

DIFFERENTIAL MODE IMPEDANCE:	100 OHMS
COMMON MODE IMPEDANCE:	50 OHMS
DIFFERENTIAL MODE ATTENUATION:	1.825 db/100 feet @ 100 mc 3.65 db/100 feet @ 400 mc
COMMON MODE ATTENUATION:	0.578 db/100 feet @ 100 mc 1.16 db/100 feet @ 400 mc
DIFFERENTIAL MODE TAU:	0.326 ns for 100 meters
COMMON MODE TAU:	0.0328 ns for 100 meters
DIELECTRIC:	Teflon ($\varepsilon_r = 2.1$)
DIAMETER OF THE DIELECTRIC:	0.400 inch
DIAMETER OF INNER CONDUCTORS:	0.058 inch
SPACING (CENTER TO CENTER) OF INNER CONDUCTORS:	0.120 inch

TABLE 2

100/50 TWINAXIAL CABLE PARAMETERS FOR COMMON DIELECTRICS

DIELECTRIC	DIELECTRIC CONSTANT AT 10^8 CPS	P	Q	D IN INCHES	S IN INCHES	d IN INCHES	DISSAPATION FACTOR AT 10^8 CPS	DIELECTRIC STRENGTH 1/8th IN. SAMPLE IN VOLTS/MIL
AIR	1.0006	1.5887	0.3749	0.300	0.1125	0.0707	-	-
STYROFOAM-22	1.025	1.5998	0.3727	0.257	0.096	0.060	-	-
STYROFOAM 103.7	1.03	1.602	0.3722	0.300	0.1117	0.0697	-	-
TEFLON	2.1	2.0725	0.3009	0.400	0.1203	0.058	0.0003	480
POLYETHYLENE	2.25	2.1403	0.2934	0.425	0.125	0.0584	0.0005	460
POLYSTYRENE	2.55	2.2783	0.2798	0.4886	0.1367	0.060	0-0001	500

TABLE 2

REFERENCES:

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2. UCRL Counting Handbook, UCRL-3307 (Rev. 2), Physical Characteristic of Coaxial Cables (CC2-2B)

3. Reference Data for Radio Engineers, 4th Edition, PP 62-71, International Telephone and Telegraph 1956