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Losses in Radio Transmission Lines
at High Frequencies

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ABSTRACT

This report pertains to the relative merits of various types of radio frequency transmission lines, used in coupling radio receivers to antenna systems, at frequencies up to 30 megacycles. As would have been expected, it is found that the loss in lines increases with frequency, and in the case of the lines employed in this investigation, it was found that the attenuation in decibels for a given length increased approximately as the three-fourths power of the frequency. A slight modification in wave propagation theory along transmission lines has been introduced herein, and this modified theory is verified by actual measurements in all instances where applicable. It is shown that the dielectric loss is the principal one in cables containing appreciable quantities of higher loss types of plastic insulating material between conductors. Heretofore it has been commonly assumed that the presence of appreciable quantities of dielectric material between line conductors increased the loss to some extent, but had only a slight effect on the other properties of the line; contrary to this common assumption, however, a few references in the pertinent literature are found indicating that certain other properties besides losses are affected considerably, and the statements made in the literature to this effect are verified by this investigation. It is also shown that the velocity of propagation of a wave along a line where dielectric materials lie between the conductors is frequently much less than the velocity of light - sometimes only half that velocity. It follows that the physical and electrical lengths of such lines differ considerably, in some instances the electrical length being nearly twice that of the physical length.

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AUTHORIZATION

1. This problem was authorized by Bureau of Engineering letter, reference (a), and other references pertaining to this problem are listed as references (b) to (j):

- Reference: (a) BuEng let.S67/62/L5(8-4-W8) of 2 Sept.1937.
(b) Hund, Textbook on "Phenomena in High Frequency Systems," 1936.
(c) Sterba and Feldman, "Proceedings of the Institute of Radio Engineers," Vol.20, No.7, July, 1932, pp. 1163-1202.
(d) Green, Liebe, and Curtis, "Bell System Technical Journal, " Vol. XV, April, 1936, pp. 248-283.
(e) Russell, "Philosophical Magazine," Vol. XVII, sixth series, April, 1909, pp. 524-552.
(f) Thomson (Lord Kelvin) Proceedings of the Royal Society of London, Vol.7, May, 1855, pp.382-399.
(g) Fleming, Textbook on "The Principles of Electric Wave Telegraphy and Telephony," Fourth Edition, 1919.
(h) Taylor, Proceedings of the Institute of Radio Engineers, Vol. 24, No. 10, October, 1936, pp. 1342-1366.
(i) NRL Report No. R-1378.
(j) NRL let.S67/46(RAB) of 7 Dec.1936 to BuEng.

STATEMENT OF PROBLEM

2. The object of this investigation was to compare the performance of two types of transmission lines for use in coupling antenna systems to radio receivers, Cabloy and GICA Cable. There are now many more Naval applications for transmission lines than in previous years; this problem therefore presents an excellent opportunity to find out many things about their characteristics, for it is realized that altogether too little information concerning their operation is now available. Also, there has recently been developed at this Laboratory a very useful device for determining the performance of transmission lines, the Cathode Ray Wattmeter, by means of which it is possible for the first time to obtain reliable information regarding their losses. Without this device, it would not have been at all possible to present much of the data shown herein in anything like such a complete and straightforward manner.

KNOWN FACTS BEARING ON THE PROBLEM

3. The classical theory of wave propagation along transmission lines is presented in detail in many scientific textbooks; for example, in Chapter XI of reference (b). As will be discussed later, this theory needs a slight modification for use in conjunction with lines at very high radio frequencies, especially where there are appreciable quantities of dielectric material between the conductors.

In reference (c) it has been shown that the attenuation for several types of line increases in proportion to some power of the frequency; in some cases it is found to be approximately the first power, in others, the half power, and in others, some intermediate power. Also in reference (c), there is one brief mention of the fact that the velocity of wave propagation in some types of transmission lines is considerably lower than the velocity of light. In reference (d), it has been shown that the presence of appreciable quantities of dielectric material between the two conductors causes its characteristic impedance to be lower than were the lines in free space. In references (e) and (f), many useful formulas are derived, which will be introduced into this report at a suitable place hereafter.

THEORETICAL CONSIDERATIONS

4. The classical theory of wave propagation along transmission lines has been developed principally for power lines, telephone lines, submarine cables, etc., in which the leakage between line conductors was considered. At a later time when high radio frequencies were used in conjunction with transmission lines, the leakage idea was extended to embody dielectric loss in the insulation between conductors. However, any transmission line which would be selected for use in actual practice, at the higher radio frequencies would show an inappreciable leakage for steady voltages, and a line which did have appreciable leakage would hardly be employed for radio frequency uses. Hence the idea of direct leakage between conductors will be discarded. Also, the best circuit analogy for a dielectric circuit at high frequencies, provided a simple circuit arrangement is desired, consists of a perfect condenser and a series resistor. The reason that this arrangement seems preferable will not be discussed in detail herein, for the subject is somewhat beyond the scope of this report. By representing the dielectric path between the conductors as a resistor in series with a capacity, instead of as a leaky capacity as in the classical theory, a modified transmission line theory may be developed, which will be presented in the next paragraph.

5. Accordingly, an infinitely long transmission line with uniformly distributed constants may be best represented as a recurrent network as shown in the diagram in Plate 1. Following the reasoning set forth in Chapter XI of reference (b), or Chapter IV of reference (g), the following partial differential equations for this network may be formulated:

$$-\delta e = i(R + j\omega L)\delta l \quad (1)$$

where δe = drop in potential (peak value) along the short length of line δl , expressed in volts.

i = current, in amperes (peak value) flowing through the short length.

R = radio frequency resistance of line per unit length expressed in ohms per centimeter.

L = radio frequency inductance of line per unit length expressed in henries per centimeter.

j = the complex operator, $\sqrt{-1}$

$\omega = 2\pi f$, where f is the frequency in cycles per second.

$$- \delta i = \frac{e}{\left(r - j \frac{1}{\omega C}\right) \frac{1}{\delta l}} \quad (2)$$

where δi = decrease in current (peak value) along the short length of line δl

e = potential difference between conductors of the short length, expressed in volts (peak value).

C = capacity per unit length of line expressed in farads per centimeter.

r = equivalent series resistance of the insulating material forming Capacity C, representing its dielectric loss, per unit length, expressed in ohms per centimeter.

By following the same procedure as outlined in either of the above references, or by recourse to the conventional solution of such a recurrent electrical network, a group of equations may be derived entirely analogous to those shown in classical wave propagation theory, except that instead of a leakage term, the factor representing the equivalent series resistance of the dielectric material is introduced. However, this resistance is only a fictitious one representing the dielectric losses, and in these analogous equations there may be substituted for this resistance term its equivalent in the form of the power factor of the dielectric material. In this manner, various equations may be derived embodying the line inductance, capacity, and conductor resistance per unit length together with the power factor of the dielectric material between the two conductors. By simple a-c theory it may be shown that the equivalent series resistance of the capacitative path formed by the dielectric material in terms of its power factor is given by the following formula:

$$r = \frac{\psi}{\omega C \sqrt{1 - \psi^2}} \quad \text{ohms} \quad (3)$$

where ψ = power factor of the dielectric material forming the insulation of the line expressed in a decimal fraction.

By making this substitution in the analogous equations, it is possible to arrive at the remainder of the equations shown in this paragraph. It should be realized that dielectric loss, when ex-

pressed in the form of its power factor will have considerably more significance to those familiar with the art than when in the form of equivalent series resistance, or in the form of an equivalent leakage as employed in the classical theory. These substitutions result as follows:

$$Z_o = \sqrt{\frac{1}{C} \left[\frac{R \Psi}{\omega \sqrt{1 - \Psi^2}} + L \right]} + j \left[\frac{1}{C} \left(\frac{L \Psi}{\sqrt{1 - \Psi^2}} - \frac{R}{\omega} \right) \right] \text{ ohms} \quad (4)$$

where Z_o = characteristic impedance.

It may be noted that this equation has both a real and an imaginary term which indicates that the characteristic impedance of a transmission line contains reactive components. However, in any line which would be used in practice at radio frequencies, the numerical value of the imaginary term is usually so low that it may be neglected in comparison with the real part. Likewise, the first term of the real part is usually negligible compared with the latter term, and by making this simplification it is apparent that the following expression approximately represents the characteristic impedance of the cable:

$$Z_o \approx \sqrt{\frac{L}{C}} \text{ ohms} \quad (5)$$

The attenuation factor for the cable is as follows:

$$\alpha = \sqrt{\frac{\omega C \sqrt{1 - \Psi^2}}{2} \left[\left(\sqrt{R^2 + (\omega L)^2} \right) - (\omega L \sqrt{1 - \Psi^2}) + R \Psi \right]} \quad (6)$$

where α = attenuation factor.

It is apparent that the following expressions are true

$$\sqrt{R^2 + (\omega L)^2} = \omega L \sqrt{\left(\frac{R}{\omega L} \right)^2 + 1} \quad (7)$$

$$\text{and } \omega L \sqrt{\left(\frac{R}{\omega L} \right)^2 + 1} \approx \omega L \left[1 + \frac{1}{2} \left(\frac{R}{\omega L} \right)^2 \right] \quad (8)$$

for the term $\left(\frac{R}{\omega L} \right)^2$ has a numerical value much less than unity in any type of line which would be used in practice. Likewise

$$\omega L \sqrt{1 - \Psi^2} \approx \omega L \left(1 - \frac{\Psi^2}{2} \right) \quad (9)$$

Substituting these approximations in equation (6) produces the following equation:

$$\alpha \approx \frac{R}{2} \sqrt{\frac{C}{L}} + \frac{\omega \Psi \sqrt{LC}}{2} \quad (10)$$

in which another factor, the fourth root of term $(1 - \Psi^2)$, is eliminated, since its numerical value would approach unity in any type of line used in practice, as Ψ will rarely exceed 0.05 at radio frequencies. The above expression is sufficiently accurate for most practical purposes and has the particular advantage in that the conductor loss and the dielectric loss are separated; that is, the first term of the right hand expression represents the conductor loss, the latter, the dielectric loss. This separation will be advantageous in some analytical work wherein the relationship between conductor and dielectric loss is desired. It may also be shown that the wave length constant is given by the following expressions:

$$\beta = \sqrt{\frac{\omega C \sqrt{1 - \Psi^2}}{2} \left[\sqrt{R^2 + (\omega L)^2} + (\omega L \sqrt{1 - \Psi^2}) - R \Psi \right]} \quad (11)$$

where β = wave length constant.

In the above expression R^2 is usually less in numerical value than 1% of that of $(\omega L)^2$ in any type of transmission line used in practice for high radio frequencies. Consequently, the term R^2 may be eliminated without serious error. Also the square root of the expression $1 - \Psi^2$ approaches unity, for as previously mentioned, Ψ seldom exceeds 0.05 at radio frequencies in commonly used lines, and this term may therefore be ignored. The term $R \Psi$ will likewise seldom exceed 0.1% of the value of the rest of this factor when simplified, $2 \omega L$, and can likewise be eliminated for most practical purposes. From these simplifications, equation (11) becomes:

$$\beta \approx \omega \sqrt{LC} \quad (12)$$

As has been pointed out in classical treatment of the subject, the velocity of propagation along the cable is expressed by the following equation:

$$v = \frac{\omega}{\beta} \quad \text{centimeters per second} \quad (13)$$

where v = velocity of propagation of wave along the line.

Substituting for β in equation (13), its equal in equation (12) produces the following equation:

$$v \approx \frac{1}{\sqrt{LC}} \quad \text{centimeters per second} \quad (14)$$

It may also be shown that the attenuation of the cable is expressed in the following manner:

$$A = 8.686 \alpha C \text{ decibels per centimeter} \quad (15)$$

where A = attenuation of line when properly matched.

Also, the efficiency of a line may be found from the following expression:

$$W = e^{-2\alpha l} \cdot 100\% \quad (16)$$

where W = efficiency of line of length l when properly matched.

$$e = 2.718, \text{ the base of the natural system of logarithms.}$$

In Equation (16), efficiency is defined as the ratio of the power delivered by a transmission line into a load to that applied to the input of the line. Equations (15) and (16) apply either to a line of infinite length or a line of finite length terminated in a resistance equal to its characteristic impedance.

6. As would have been expected, it may be noticed that the various expressions with one exception, when simplified, become the same as those given in classical treatises on the subject, the one exception being in the case of the attenuation factor. However, the attenuation factor is one of the most important characteristics of a line, and it is considered advantageous to present it as shown herein, that is in a more straightforward manner regarding the effect of dielectric loss on the total line loss, and for this reason such means of expression is considered preferable to the equivalent leakage concept which has been used in the classical treatment of the subject.

7. Four of the five lines used in this investigation are of the coaxial or concentric type and it would appear desirable to simplify certain of the formulas shown in paragraph 5 for use with such types of lines. In these simplifications, capacity and inductance terms will be replaced by equivalent factors expressed in terms of the physical dimensions of the lines. Lord Kelvin, in reference (f), has shown the following equation to be true:

$$C' = \frac{0.2416 K}{\log_{10} \frac{d_1}{d_2}} \cdot 10^{-12} \text{ farads per centimeter} \quad (17)$$

where C' = capacity per unit length for a coaxial arrangement of cylinders or for a rod within a cylinder.

d_1 = inner diameter of outer conductor in centimeters.

d_2 = outer diameter of inner conductor (cylinder or rod) in centimeters.

K = dielectric constant of insulation between the two conductors.

In reference (e), Professor Russell has shown the following equation to be true:

$$L' \approx 4.6052 \log_{10} \frac{d_1}{d_2} \times 10^{-9} \text{ henries per centimeter} \quad (18)$$

where L' = inductance per unit length for a coaxial arrangement of cylinders, or for a rod within a cylinder.

By substituting the above values in equations (5), (10), (12), and (14), the relationship shown in the following equations may be derived:

$$Z'_0 = \frac{138 \log_{10} \frac{d_1}{d_2}}{\sqrt{K}} \quad \text{ohms} \quad (19)$$

$$\alpha' \approx \frac{R \sqrt{K}}{276 \log_{10} \frac{d_1}{d_2}} + \frac{\omega \psi \sqrt{K}}{6 \cdot 10^{10}} \quad (20)$$

$$\beta' \approx \frac{\omega \sqrt{K}}{3 \cdot 10^{10}} \quad (21)$$

$$v' \approx \frac{3 \cdot 10^{10}}{\sqrt{K}} \quad \text{centimeters per second} \quad (22)$$

The significance of the prime added to the factors given above is that it indicates the formula applied only to a concentric or coaxial type of line. It may be noted that the factor $3 \cdot 10^{10}$ occurs in two of the formulas above, the velocity of light. The relationship shown in Equation (19) has been indicated in reference (d), and a brief mention of the relationship expressed in Equation (22) has been made in reference (c). As indicated in Equation (22), the velocity of propagation will be somewhat less than velocity of light where a dielectric material is placed between the conductors, and likewise, the electrical and physical lengths of such lines would not be the same. From the general wave motion principle that the product of the frequency and the wave length equals the wave velocity,

the following expression for the ratio of physical to electrical length may be easily derived:

$$\frac{l'}{l'_e} = \frac{1}{\sqrt{K}} \quad (23)$$

where l' = physical length of line.

l'_e = electrical length of line.

Since the conductor resistance is involved in the attenuation factor, Equation (20), means of determining the high frequency resistance of a coaxial arrangement of conductors will be shown. According to Professor Russell, in reference (e), the conductor resistance of a coaxial arrangement is given by the following expression:

$$R' = 2 \left[\frac{1}{d_1} \sqrt{\mu_1 f \rho_1 \cdot 10^9} + \frac{1}{d_2} \sqrt{\mu_2 f \rho_2 \cdot 10^9} \right] 10^{-9}$$

ohms per centimeter. (24)

where R' = radio frequency resistance of a coaxial arrangement of conductors per unit length.

μ_1 and μ_2 = the permeabilities of the outer and inner conductors of the line respectively, which was unity in the case of all lines considered in this report.

ρ_1 and ρ_2 = the resistivity of the outer and inner conductors of the line, respectively, expressed in ohm-centimeters.

Professor Russell derived this expression mathematically, and its suitability and accuracy have been confirmed experimentally, in particular in reference (c). Attention is directed to the fact that Equation (24) is applicable only where solid conductors are used, and may not be used where either conductor is stranded or braided.

8. It may be noted that the value of the dielectric constant of insulation between the conductors is quite an important factor in the various formulas derived for concentric types of lines. In the attenuation factor formula, Equation (20), it may be noted that the value of dielectric constant of insulation affects not only the dielectric loss, but the conductor loss as well.

NARRATIVE OF ORIGINAL WORK DONE AT THIS LABORATORY

9. Due credit has been given to other investigators where their work has been incorporated herein, or if others have pointed out the same relationship derived by the treatment given herein. All other

portions are based on original analysis made at this Laboratory. All data to be shown subsequently are based on original investigation of this Laboratory.

METHODS

10. The attenuation of the lines was measured by means of the Cathode Ray Wattmeter, described in reference (h), and the procedure of such measurements will be described. The power delivered to the line was measured by means of this Wattmeter, and the output of the line was determined by terminating it in a non-inductive type resistance load comprising a Zircon resistor, and a suitably calibrated radio frequency ammeter, the output being determined from the current and resistance of the load. The capacity and power factor of the lines were determined with two pieces of equipment; over the frequency range of 100 cycles to 10 kilocycles, the General Radio Type 714A Capacity Bridge was employed, and the Boonton Type 177 "Q" Meter was used over the frequency range from 50 kilocycles to 15 megacycles. In determining the high frequency capacity and power factor, a short section of line was taken, 30.5 centimeters long, for along such a short section even at the highest test frequencies, only a small fraction of a wave length is represented, and the distribution is substantially uniform along this short section. The electrical length of lines was measured in the following manner. The two conductors at one end of the transmission line were connected together by a small coupling coil which was loosely coupled to a suitable grid dip driver. From wave propagation theory, it is well known that when the other end of the line is open, as the applied frequency is gradually increased, resonances may be obtained first for quarter wave resonance, then three-quarter wave resonance, etc., for various other odd quarter wave resonances. Then if the far end is short-circuited, similar resonance points will be obtained except that they will be at even quarter wave length separations. By noting the frequencies at which various resonances occur, and the increments between them, it is not difficult to ascertain which is $1/4$, $1/2$, $3/4$ or full wave resonance. Then if these data are plotted on linear cross section paper, plotting frequency as the abscissa and fraction of a wave length as the ordinate, and the points are connected by a smooth curve, the length of an electric wave in free space corresponding to the frequency at which the curve intersects the full wave ordinate is obviously the electrical length of the line. From such data it is also possible to determine the velocity of the propagation of the wave along the line. Since a wave front advances the physical distance between the two ends of the line in the time of a period of the oscillation at which full wave resonance is obtained, it is apparent that the velocity may also be computed.

11. A description of various types of lines used in this investigation will be furnished. The subject problem called for the test of two types of lines, Cabloy and GICA Cable. However, during the past few years, this Laboratory has had occasion to test several other types of lines, and for additional information, a certain amount of the data taken from these other types of lines will be included in this report. Descriptions of the lines are as follows:

(1) Cabloy, a transmission line for receiver use, manufactured by RCA, a stranded inner conductor completely enclosed in an impregnated fibrous type of insulation, which is in turn enclosed by a lead sheath containing a copper strap inside the lead, for use as a ground strip. Over the lead covering is placed a layer of thin tape, and surrounding the entire cable is a basket woven steel braid for protective purposes. A view of this cable is shown in Plate 2, Fig. A.

(2) GICA-2 Cable, made primarily for interior communication use, both conductors stranded and enclosed by soft rubber insulation. A hemp or jute-like filler is also placed therein to fill up spaces between the rubber and give a periphery of round cross section, and the entire cable is enclosed in a layer of tape over which is placed basket woven steel braid. A view of this cable is shown in Plate 2, Fig. B.

(3) Circle Wire and Cable Company's Standard 600 volt lead covered power cable, soft rubber insulation covered by fabricated braid, solid inner conductor. A view of this cable is shown in Plate 2, Fig. C. Hereafter in this report this line is referred to as Power Cable.

(4) A concentric type of line with solid inner conductor, a thin wall copper tube for outer conductor, containing distributed Isolantite washer type spacers. A view of this line is shown in Plate 2, Fig. D. For convenience this line is hereafter referred to in this report as Isolantite Insulated Line, which is sometimes abbreviated to Iso. Ins.

(5) Communication Products Type 600 - 1/4", solid inner conductor, outer conductor a thin wall copper tube, insulation provided by means of a paraffin impregnated cotton cord wound about the inner conductor. A view of this line is shown in Plate 2, Fig. E. For convenience, this line is hereafter referred to as Communication Products Line, which is sometimes abbreviated to Com. Prod.

12. From the views of the various types of lines in Plate 2, it may be seen that all but one (GICA) are concentric or coaxial types of lines. It may be noticed that in all concentric types of lines, the low potential terminal is outside. Consequently their sheaths were carefully bonded to a suitable thin copper screen counterpoise in order to prevent radiation. In all tests on GICA Cable, one conductor was used as the high potential, the other as the low, and the sheath was connected to the low potential conductor at both ends, and bonded to the counterpoise. Of these lines, Power Cable was not designed for radio frequency transmission line purposes, but as its name implies, for the distribution of d-c or a-c power at commercial power frequencies. For that matter neither was GICA Cable designed for transmission line service.

DATA OBTAINED

13. The data obtained in this report are shown in Plates 3 to 12 inclusive and in Tables 1 to 4 inclusive.

DISCUSSION OF PROBABLE ERRORS

14. The efficiency measurements of transmission lines are estimated to be accurate within 5% at 1 megacycle and to within 15% at 30 megacycles, the accuracy at intermediate frequencies falling between these two estimated percentages and gradually increasing with frequency between these limits. The accuracy of the capacity measurements in like manner decreases with frequency, and is estimated to be within 1% at 100 cycles and to within about 6% at 15 megacycles. In like manner the accuracy of the power factor measurements is estimated to be within 5% or 0.001, whichever is the greater, at 100 cycles, and to within 15% or 0.0001, whichever is the greater, at 1500 kilocycles.

RESULTS OF TESTS

15. Data pertaining both to the efficiency of the lines and to their characteristic impedance are shown in Plate 3. Herein is shown the effect of various values of terminating resistance on their efficiency. The characteristic impedance of the line is equal to the resistance at which the line shows a maximum efficiency. These tests were made at the highest frequency called for in the subject problem, because at this frequency the lines are electrically longer, and consequently the curves will be more sharply defined in so far as characteristic impedance determination is concerned, at this frequency than at any lower one. It may be noted that Isolantite Insulated Line was tested at 25 megacycles and the others at 30 megacycles. The reason for this is that the data on the Isolantite Insulated Line was obtained sometime ago for laboratory purposes, and it is added herein to make the report as complete as possible. Little would have been gained by repeating these measurements at 30 megacycles for the loss therein is so low in this frequency region that it becomes difficult to measure. It may be noted in Plate 3 that in the case of Isolantite Insulated Line, two sections were used in a balanced arrangement, whereas for all others a single section was used. This procedure was used in the case of the former because all single section concentric lines radiate to a certain extent where it is impossible to obtain a good radio frequency ground on the sheath, as is the case in such measurements. A balanced arrangement will radiate to a much smaller extent, and as the loss in this type of line is quite low, the balanced arrangement was employed in order to prevent radiation losses, thereby allowing the inherent loss to be determined for applications which permit good ground connections, such as ~~where~~ buried in moist earth. The inherent loss in the other types of lines is sufficiently great that little would be gained by recourse to such procedure for their tests. It is apparent that in the case of tests made with a balanced arrangement, the maximum efficiency will occur at a resistance equal to the characteristic impedance of the balanced combination, and since in such a combination the two

sections are effectively in series, the characteristic impedance of a single section will be half of that observed in the case of tests made with a balanced arrangement. For this reason the table at the foot of Plate 3 shows a characteristic impedance of 80 ohms for Isolantite Insulated Line, which is that for a single section, instead of 160 ohms as shown by the upper curve, which is the characteristic impedance of a balanced arrangement. In the case of the various curves in Plate 3, it may be noted that they are extended to pass through the origin, and the reason for this is that the lines would have zero efficiency with the output short circuited. It may be noted that exact impedance matching is unnecessary for these lengths of lines, since the value of terminating resistance may be altered considerably with slight effect upon the line efficiency. It may be noted that the various lines tested were of different length. Consequently the results can not be compared directly by means of the curves, and to reduce them all to the same basis, there has been prepared a table at the bottom of Plate 3 indicating what efficiency the cables would have were they 1,000 centimeters (33 feet) in length, and also there are provided data as to the attenuation of the lines in decibels per centimeter.

16. The effect of frequency on the efficiency of the various lines is shown in Plate 4. In order to compare these lines directly, in Plate 5 the same data are expressed in the form of attenuation in decibels per centimeter. It may be noted that the curves do not pass through the points obtained at 1 and 2 megacycles, but since the losses in the lines at these frequencies are so low that they are difficult to measure, and since by all known physical theory it would be expected that the attenuation of the lines would gradually decrease with frequency, the curves have been extended in a linear manner for frequencies below 5 megacycles. The curves in both Plates 4 and 5 for Isolantite Insulated Line are based on one point only which was obtained at 25 megacycles. Referring to Equation (10), substitution of values therein for this line indicates that at any frequency below 30 megacycles, the second term of the right hand side of this expression is a very small fraction of the other term. In the case of the larger term, only the conductor resistance varies appreciably with frequency. Reference to Equation (24) indicates that the high frequency resistance of a coaxial arrangement of conductors is proportional to the square root of the frequency, and the curves for Isolantite Insulated Line were constructed from the 25 megacycle point, and are based on the assumption that the attenuation factor of this type of line is proportional to the square root of the frequency. In order to allow the data in Plates 4 and 5 to be compared in a more straightforward manner, in Plate 6 the efficiency is expressed in terms of what it would have been had all lines had a length of 1,000 centimeters (33 feet). The comparison in performance of Cabloy and GICA Cable, requested in the subject problem, may be found in either Plate 5 or Plate 6. It may also be noted that the problem called for loss measurements at frequencies as low as 100 kilocycles, but it is seen that the attenuation is so low that it is difficult to measure even at a frequency of less than 5 megacycles, hence no measurements were taken at a frequency below 1 megacycle. From the slope of the curves, Plate 5, it is apparent that the attenuation of Power Cable, Cabloy, Communication Products Line, and GICA Cable is approximately proportional to the three-fourths power of the frequency.

17. The capacities of the 30.5 centimeter lengths of lines are shown in Plate 7. It may be noted that the capacity of some of these lines depend somewhat on the applied frequency. To use the extreme instance, Power Cable shows a decrease in capacity of 20% from audio to radio frequencies. Hence, it is seen to be not the best idea, as is the common practice, to base capacity ratings for transmission lines on audio frequency measurements. The data in Plate 7 will also cause a slight modification of the usual conception of capacity, for it is commonly assumed that capacity is not a function of frequency. In Plate 8, the capacity values shown in Plate 7 have been converted into the form of capacity per unit length, which will be used subsequently in this report in various computations.

18. Power factor data on the lines are shown in Plate 9. It may be noted that the power factor depends considerably on the frequency, and in the case of Communication Products Line, the power factor at 1,000 cycles is more than twice as great as at 1 megacycle. Hence, it is also obvious that the determination of the relative merits of transmission line insulation should be determined at a radio frequency, rather than at an audio frequency which is the common practice.

19. Electrical length data for the transmission lines are shown in Plate 10. It may be noted that a straight line passes approximately through all points and the origin, which indicates that the values of inductance or capacity of the lines are not appreciably affected by variations in frequency at the higher radio frequencies. The points at which the curves intersect the full wave ordinate represent the electrical length of the line; that is, the wave length in free space corresponding to the frequency of intersection is the electrical length. Physical and electrical length data have been shown in Plate 10 for each curve. For the purposes of more readily comparing electrical length data of lines, data are shown in Plate 11 as to what the relationships shown in Plate 10 would have been had the physical length of all lines been 1,000 centimeters. It may be seen that lines of the same physical length vary considerably in electrical length. Therefore, if two points of fixed distance apart were to be joined by a transmission line, the electrical length represented would depend considerably on the particular line selected for the purpose. In Table 1 the electrical length data are recapitulated together with wave propagation velocity data. Some computed values of these quantities and other data are also given in this table, which will be discussed in detail later in this report.

20. A brief study was given to the moisture absorption characteristics of two of these lines. The power factor of Cabloy at 1,000 cycles is noted to be 0.016 as furnished, and after drying 24 hours in an oven at 120° C and cooled 3 days in a desiccator, its power factor was found to be 0.012, a reduction of 25%. However, at radio frequencies, no measurable change in the power factor was noted. Communication Products Line, after drying for 6 days in a desiccator had its power factor reduced from 0.039 to 0.018, but likewise no corresponding reduction was noted in high frequency power factor measurements. These data indicate that some moisture

is present in these lines, and although it was not found to greatly affect the radio frequency power factor of the insulating material, it is realized that the presence of moisture certainly can do no good and may do some harm. These data indicate that improvements in the sealing of Communication Products line would be desirable. Although only a minor issue, Cabloy received one power factor test immediately after removal from the oven at 120° C, and it was noted that its power factor at 1000 cycles had more than doubled. This would indicate that its insulation has considerable temperature coefficient of power factor, which may possibly have some bearing on its suitability for use in the Naval Service, for it is realized that quite high ambient temperatures are frequently encountered.

DISCUSSION

21. The modified theory of wave propagation along transmission lines, advanced heretofore in this report, has no practical importance unless it can be shown to actually have some real significance upon the attenuation characteristics of the lines. Referring to Equation (15) and to Equation (10), which forms a part of the former equation, both of which pertain to the attenuation of transmission lines, it may be noted that all quantities therein are in such form that it is possible to obtain pertinent data regarding line constants, some from results shown herein and others by means of computation. In the data given in this report, not all of the constants, subject to measurement, appearing in these equations have been obtained over the entire frequency band covered by the attenuation measurements, but enough information is available, if reasonably extended, to make substitutions in these equations. It may be noted that the line capacity data given in Plate 8 give no values for frequencies above 15 megacycles, but it does not seem unreasonable to make an assumption that no material change in capacity from the 15 megacycle value would occur in the region between 15 and 30 megacycles and, for that matter, its capacity is probably not greatly different at much higher frequencies, even at 50 or 100 megacycles. Referring to Plate 9, it may be seen that the power factor data are not obtained at any frequency above 1500 kilocycles. However, from a general knowledge of dielectric phenomena at the frequencies above which polarization effects are likely to occur therein (100 kilocycles or lower), usually the power factor of a dielectric material does not depend greatly upon the frequency, and even a change in frequency of 10 to 100 times may not cause its power factor to be altered by more than two to one. As a consequence, it does not seem an unreasonable hypothesis to assume that the power factor of the insulation of these cables at any frequency between 1 and 30 megacycles is the same as its measured value at 1 megacycle. For that matter, possibly the power factor is not radically different even at frequencies of 50 or 100 megacycles, although it must be admitted that this statement may be open to question. The inductance of the concentric types of lines may be computed by Equation (18) and the values thereof are shown in Table 2. The conductor loss in certain of the concentric types of lines may be computed by means of Equation (24). The limitation of Equation (24) to solid conductor lines, however, makes it impossible to compute the resistance of Cabloy, for its inner conductor is stranded. By such means of obtaining

line constants, computations of the attenuation of Isolantite Insulated Line, Power Cable, and Communication Products Line were made, and are shown by the dotted curves in Plate 12. Also on Plate 12 there have been plotted the experimental curves for these lines, taken from Plate 5, and which are shown by the unbroken curves. The agreement between the experimentally determined and computed curves over the range subject to measurements is excellent; in fact, it provides some assurance that the computed values up to 100 megacycles are valid. In the case of Isolantite Insulated Line, the only observed point taken has been plotted, and it may appear that there is a fair amount of discrepancy between computed curve and experimentally determined point. However, it may be noticed that in either case, the attenuation is exceedingly low, in fact, almost too low to measure, and an error of less than 4% in the experimentally determined point would account for the discrepancy. It may appear somewhat optimistic to have extended these curves up to a frequency of 100 megacycles, but when it is considered that very little reliable experimental data are available on the subject, such extrapolations are considered of some value for at least they indicate what order of attenuation at this high frequency may be expected. The excellent agreement between theory and practice lends considerable confidence to the validity of the modified theory of wave propagation along transmission lines which has been presented heretofore.

22. A few more computations will be added to show the agreement between theory and practice in other instances. From the capacity per unit length data in Plate 8, it is possible to determine the dielectric constant of the insulation in the case of the coaxial lines by means of Equation (17). In the case of Isolantite Insulated Line and Communication Products Line, reference to the drawing in Plate 2 will indicate that a good portion of the space between the conductors contains no solid dielectric material, but at any rate it is possible to arrive at an equivalent dielectric constant for the capacity path of such types of lines. Such data are necessary in various computations to follow and are shown in Table 1. In this table there also appears some experimentally determined data, which have already been discussed, pertaining to the ratio of physical to electrical length, and to the propagation velocity of the wave, and also the computed values for the lines are added for comparison. It may be noted that, in general, excellent agreement is obtained, the greatest discrepancy being about 8% in the case of the Power Cable. In Table 3 computed and observed values of characteristic impedance data are furnished. For this computation, Equation (5) or (19) was used, whichever was applicable to the particular line. The measured values are taken from the data in Plate 3. Some discrepancy is noted between the computed and experimental values, but when the broadness of the curves shown in Plate 3 is considered, it is realized that it is quite difficult to experimentally determine with great exactness the characteristic impedance of relatively short lines, (in all instances less than two wavelengths long) and for this reason the computed results possibly have less error than the experimentally determined ones.

23. It may be noted that in nearly all instances, all tests as to the attenuation of various lines have been made where the lines were properly terminated, and the question naturally arises as to how these lines may be used to feed receivers, when it is realized

that the input impedance of the receivers are, in general, much higher than the characteristic impedance of the lines, in some instances approximately 10,000 times as much. The obvious answer to this question would be to employ a suitable impedance matching transformer for the purpose. However, to obtain a relatively flat response in an impedance matching transformer to cover a band of 100 kilocycles to 30 megacycles would be quite difficult. Even were it attempted with two or more transformers, it is realized some difficulty would be encountered. One proposed means of coupling a line to the input of a receiver without recourse to a transformer will be discussed, for theoretical reasons lead one to believe it would not be impractical over a narrow band of frequencies up to 10 megacycles. In the following discussion, it will be assumed that suitable means of properly matching the antenna system to the line input have been attained. Then, in order to illustrate how a line may be used to couple the antenna system and the receiver, the following illustration will be offered. One of the lines, Cabloy, for instance, might be terminated in its characteristic impedance, 32 ohms, and across this resistor placed the input terminals of the receiver. In reference (i), it is noted that the input impedance of a receiver depends considerably upon the frequency, and in the cases of the RAA, RAB, RAG, RAH, and RAL type Receivers, at various frequencies up to 10 megacycles, the input impedance varies from 100 to 250,000 ohms, considerably higher than the terminating resistance used with the line, and therefore would not cause a serious impedance mismatch when connected across the terminating resistor. Accordingly, a 1,000 centimeter section (33 feet) of Cabloy, which is considered to be a fairly inferior type of line, could be used with any of these receivers at 10 megacycles with a power loss of only 21%, or a drop in voltage along the line of approximately half that amount, which could be tolerated in many instances. At frequencies of less than 10 megacycles, the loss would be less; in fact, the voltage loss would be only about 2% at 1 megacycle. If instead of this inferior line, it was desired to use a low loss line, such as Isolantite Insulated Line, for which an 80 ohm terminating resistor should be used, the loss in voltage for the same length of line would be approximately 2% at 10 megacycles, which could be readily tolerated. The question might arise as to why these lines should not be connected directly to the receiver terminals without recourse to a terminating resistors, for at first hand it might appear that the line would deliver more voltage unshunted than when shunted by a resistor. However, reference to the electrical length data in Plate 11 indicates that at 10 megacycles, the Cabloy Line would be over a half wave length long and the Isolantite Insulated Line would be somewhat more than 3/8 wave length. As in both instances, the line itself would be in excess of 1/4 wave length, and considering the added length reflected by the antenna to which it is coupled, it is apparent that due to variations in voltage distribution along the conductors normally encountered in a transmission line, that at some frequency a voltage node would probably appear at the receiver terminals; hence a terminating resistor should be employed to prevent such effects. It may be noted that all of the foregoing discussion has been based on the assumption that suitable means have been employed to obtain an impedance match between the antenna and the line input, and it

is realized that such means would be quite difficult to attain in practice over a wide frequency band. Therefore, the method outlined for coupling an antenna to a receiver by means of a transmission line would be practical only over a narrow frequency band. It should therefore be realized that these suggestions have been provided for use in the few instances where they are applicable, and are by no means intended to be a solution to all problems involving transmission lines. Where operation over a wide band of frequencies is desired, no better means can be offered than the Transmission Line Coupling Unit which has already been described in reference (j).

24. As previously indicated, transmission line capacity data are usually based on measurements at an audio frequency - 1,000 cycles, for example - and it has been illustrated that, in some instances, line capacities undergo an appreciable capacity change with frequency. Obviously for the most satisfactory capacity ratings, the data should therefore be obtained at some radio frequency, and for this purpose, a test frequency of 1 megacyclo seems satisfactory. This frequency is great enough to furnish some idea as to the radio frequency capacity of the line, and yet not too high to allow fairly accurate capacity measurements. As has been previously shown, dielectric loss properties of the insulation have quite an important bearing on the subject, and suitable data pertaining to this property, its power factor, should be taken on all transmission lines tested for use in the Naval Service. No limits will be suggested herein for the maximum allowable power factor, for it is realized that insufficient data are now at hand on which to base such requirements. If such data be taken on all lines intended for use in the Naval Service, ultimately there will be an accumulation of sufficient data on which to base specifications.

25. It has been shown previously that measured and computed values of transmission line attenuation are in fair agreement, and it may appear that reliable attenuation data could have been obtained merely by computations based on insulation loss measurements and other measured and computed factors, and that they would have been sufficient for most practical purposes. However, the Cathode Ray Wattmeter is still an indispensable instrument for use in such investigations, for the attenuation of all types of lines is not subject to calculation; for example, Cabloy or GICA Cable, for no formulas are available for computing the conductor loss therein. For this reason it is therefore seen that the Cathode Ray Wattmeter is still quite a necessary adjunct to the general investigation of transmission lines.

26. It may be noted that the subject problem requested tests of lines at frequencies as low as 100 kilocycles and with the short length of Cabloy provided (26 feet), the losses were so low that they became difficult to measure even at a frequency of 2 megacycles. Hereafter, where such low frequency data are desired, it is suggested that at least a 100 foot section of line be provided.

27. A discussion pertaining to Communication Products Line will now be provided, for with some few improvements, it appears promising for certain Naval applications. This line, although housed in copper tubing, is highly flexible; in fact, it can be bent on a radius of 2 inches without damage. Data shown previously in this report indicate that its attenuation factor at 25 megacycles is about three times that of Isolantite Insulated Line, and in all other properties it approaches closely the characteristics of that line. In its present form, Communication Products Line is considered by no means a poor one, and provided some means could be found of reducing its attenuation factor, many more uses in the Naval Service might be found for a line of such characteristics. Reference to Plate 2 indicates that its insulation is formed by a paraffin impregnated cotton cord. It is a well known fact that paraffin has very low losses at radio frequencies, and since the power factor of this line, as indicated in Plate 9, is fairly high, it must be inferred that most of the loss is due to the cotton. Provided some other type of flexible insulation could be used to replace the cotton, it might be possible to produce a line in this small size, of highly flexible nature, to replace the more expensive Isolantite Insulated Line in certain future installations in the Naval Service. Just as a matter of suggestion, it is possible that the recently developed, finely woven type of spun glass might be used for this purpose, for it is known that certain types of glass are quite low loss dielectric materials. Also, as has been previously mentioned, the technique of sealing off this line should also be improved, as the insulation in this sample had apparently absorbed a certain quantity of atmospheric moisture. With these two improvements, this line appears promising for certain Naval uses.

28. In order to provide some data as to how the losses in transmission lines are distributed between conductor loss and dielectric loss pertinent data are presented in Table 4. As in the case of the computed attenuation curves, these data have been extended to frequencies up to 100 megacycles which, of course, must be accepted with the same limitations which have been described previously for attenuation data extrapolations. These data are considered of some value, for the attenuation data given heretofore give no indication of the relative distribution between conductor and dielectric loss. Referring to the data on Isolantite Insulated Line, provided the 100 megacycle computation is accepted as valid, it may be seen that only a small fraction of a total loss is caused by the dielectric material, and consequently, were the Isolantite insulators replaced by higher grade material, no great improvement would be effected. Also it is apparent that dielectric losses account for most of the attenuation in the case of the other two lines at the higher frequencies.

29. A discussion will now be provided as to what transmission line properties are desirable in order to minimize attenuation. As indicated in Equation (10), whose validity has been experimentally determined, it may be noted that the lower the line capacity (per unit length), the lower will be both the dielectric and conductor losses, other factors being equal. Also, the lower the line capacity the shorter will be the electrical length for a given physical length, which may be indirectly inferred from Equations (14), (22), and (23), and this property is desirable, for an impedance mismatch in a line of short length does not cause as much loss as in a longer one, al-

though this factor is nothing like the former in importance. For the foregoing reasons, the desirability of selecting a line whose capacity has been reduced to a practical minimum is apparent. Also, as indicated in Equation (10), the use of low loss types of insulation will also reduce the attenuation. Although not directly brought out in this investigation, the use of solid inner conductors instead of stranded types should produce some reduction in losses, for it is a well known fact that the resistance of stranded conductors at the higher frequencies (above 1-1/2 megacycles or thereabouts) is greater than that of solid conductors. Perhaps the attenuation factor of Cabloy would be reduced somewhat by using for the inner conductor a piece of #14 solid wire instead of 40 strands of #30 wire. It has been noted that at times a copper braid is used as the outer conductor in certain types of concentric lines (no lines of this type were employed in this investigation, however) and since the high frequency resistance of braided conductors is greater than in an equivalent tubular conductor, therefore wherever practicable, in various installations in the Naval Service wherein concentric lines are to be used, those types employing tubular conductors are considered preferable to those employing braided outer conductors.

RECOMMENDATIONS

30. It is recommended that all capacity (per unit length) test data on transmission lines be hereafter based on measurements at a frequency of approximately 1 megacycle, instead of on audio frequency measurements, as has been the practice heretofore.

31. It is recommended that the power factor of the transmission line insulation be determined at a frequency of approximately 1 megacycle, in all lines tested for Naval use, in order that enough data be accumulated on which to base specifications in the future.

32. It is recommended that all samples provided for test be of a length of not less than 100 feet where attenuation measurements as low as 1 megacycle are desired.

CONCLUSIONS

33. Cabloy is considered preferable to GICA Cable for coupling antenna systems to radio receivers, the attenuation of the former being approximately 2/3 of that of the latter under similar operating conditions and when the lines are properly matched.

34. Cabloy, although preferable to GICA Cable, is no more suitable for the purpose than a sample of 600 volt lead covered power cable which was primarily made for d-c or commercial a-c power distribution.

35. Radio frequency losses at the higher frequencies in concentric types of lines containing appreciable quantities of rubber or other plastic types of insulation between conductors are principally due to the dielectric material.

36. As would have been expected, the attenuation of transmission lines increases with frequency, and in the case of lines covered by this report, the attenuation increases approximately as the $3/4$ power of the frequency, when the line was properly matched.

37. Where appreciable quantities of dielectric material are placed between the two conductors, nearly all line properties are affected.

38. The physical and electrical length of transmission lines differ considerably where appreciable quantities of insulating material are placed between the conductors, in some cases the electrical length being approximately twice that of the physical length. In like manner it follows that the wave propagation velocity is much less in such a line than in free space, sometimes approximately only half as great.

Table 2

Inductance Data for Transmission Lines

<u>Line</u>	<u>Outer Diameter Inner Conductor</u>	<u>Inner Diameter Outer Conductor</u>	<u>Radio frequency inductance per cm length*</u>
Iso.Ins.	0.206 cm	0.79 cm	$2.69 \cdot 10^{-9}$ henries
Com.Prod.	0.13	0.46	$2.53 \cdot 10^{-9}$
Cabloy	0.17	0.51	$2.2 \cdot 10^{-9}$
Power Cable	0.16	0.46	$2.11 \cdot 10^{-9}$
GICA	**	**	$3.64 \cdot 10^{-9}$ #

* Computed by Equation (18)

** This line not of the concentric type.

This value obtained by substituting measured value of capacity per unit length at 10 megacycles, as shown in Plate 8, and the measured value of wave propagation velocity as indicated in Table 1, into Equation (14), and solving for inductance per unit length.

Table 3

Characteristic Impedance Data on Lines

Line	Characteristic Impedance	
	Measured *	Computed
Iso. Ins.	80 ohms	71 ohms #
Com. Prod.	66	64#
Cabloy	32	39#
Power Cable	32	32#
GICA	60	52##

* Taken from data in Plate 3.

Computed by Equation (19), taking measured values for the dielectric constant of the insulation as shown in Table 1.

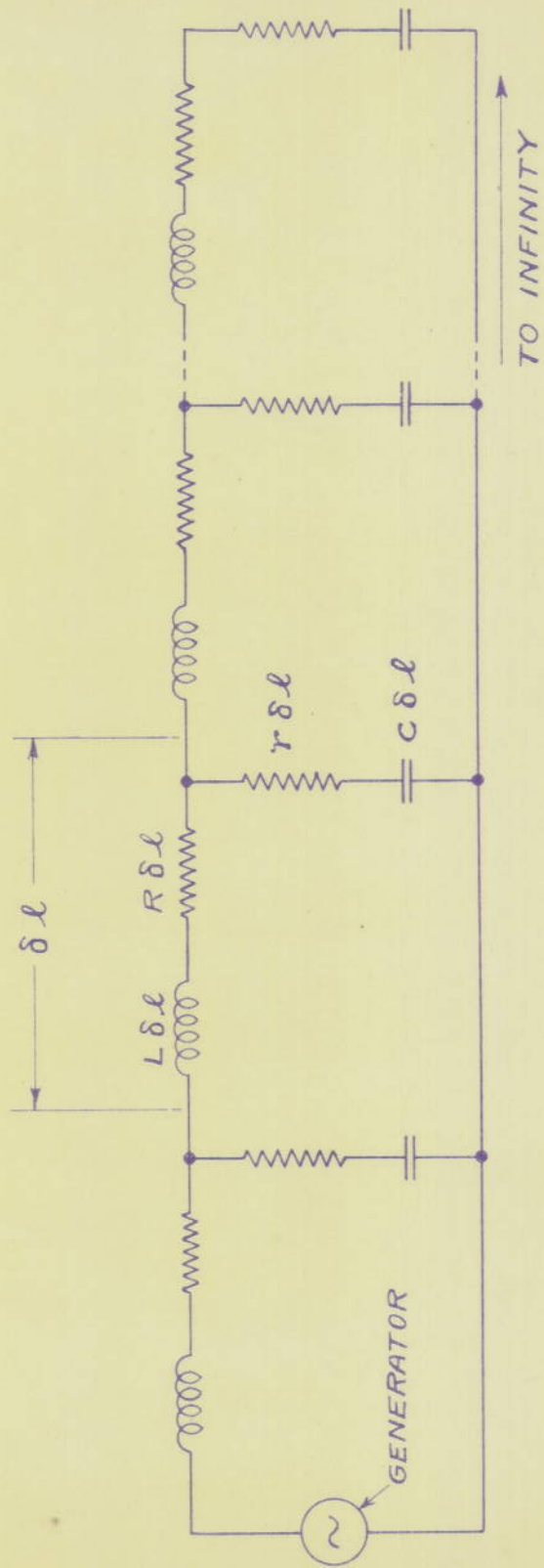
Computed by Equation (5), taking measured values for capacity as shown in Plate 8, and measured value of inductance as shown in Table 2.

Table 4

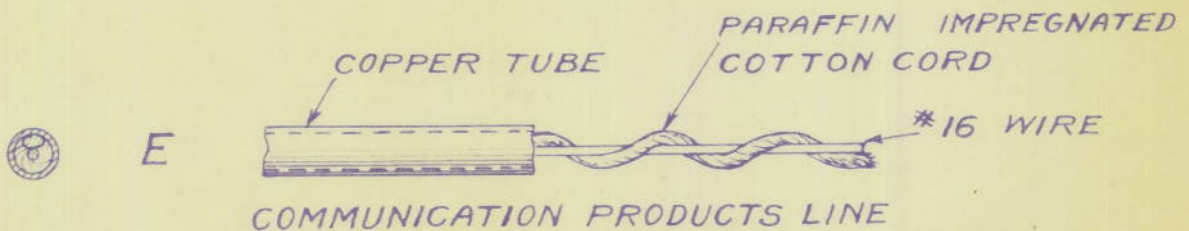
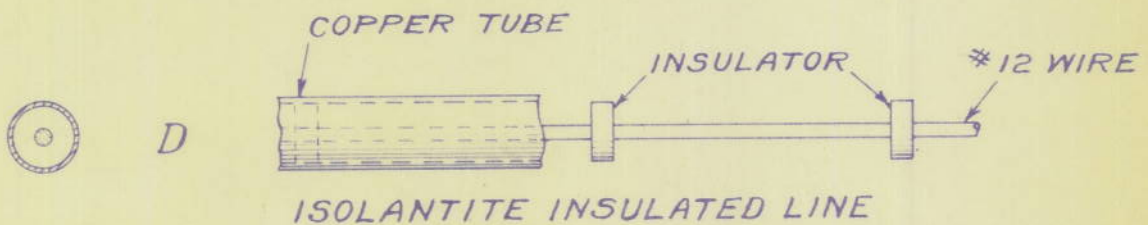
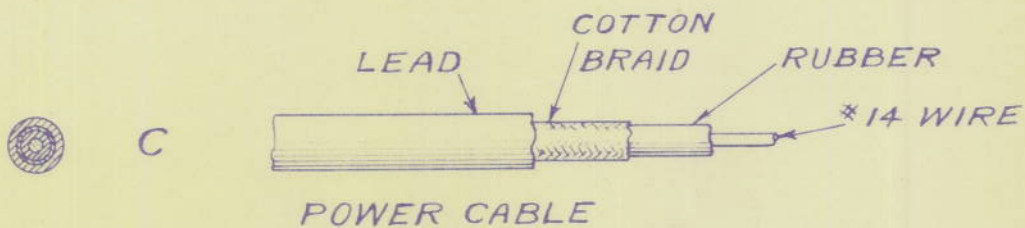
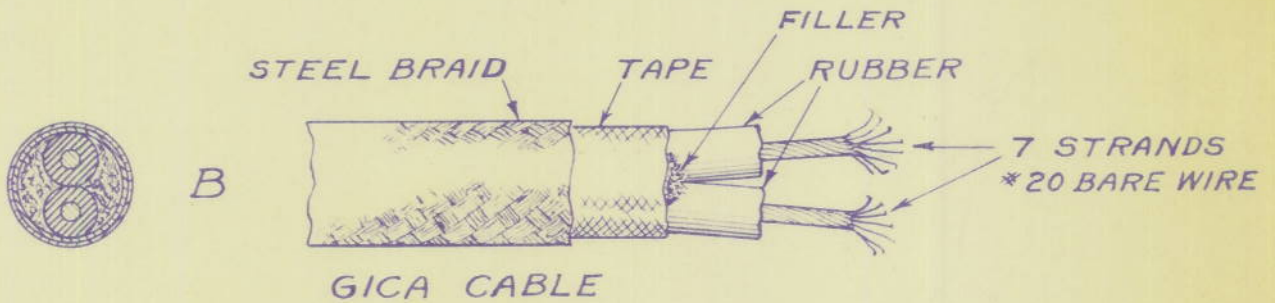
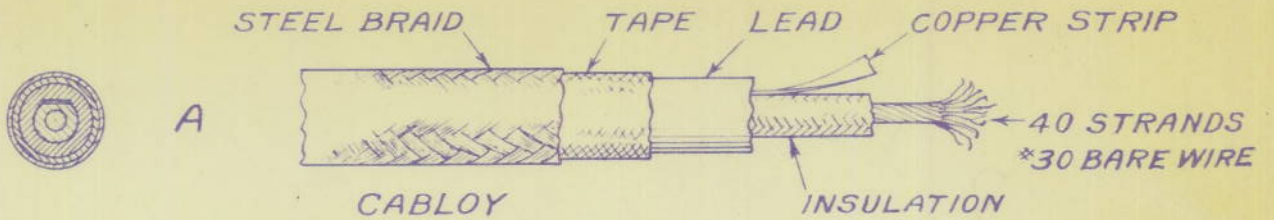
Separation of Losses in Transmission between Conductor Loss and Dielectric Loss

Note: Data below indicates the fraction of the attenuation of line due to conductor loss and that due to dielectric loss, both expressed in percentage of the total. See par. 28 for additional information.

Freq mc	Isolantite Insulated Line		Communication Products Line		Power Cable	
	Conductor Loss	Dielectric Loss	Conductor Loss	Dielectric Loss	Conductor Loss	Dielectric Loss
1	99.6%	0.4%	76%	24%	78%	22%
2	99.4	0.6	66	34	72	28
5	99.1	0.9	59	41	61	39
10	98.8	1.2	51	49	53	47
20	98.2	1.8	42	58	44	56
50	97.3	2.7	31	69	33	67
100	96.2	3.8	24	76	26	74
200	95	5				
250	94	6				
500	92	8				



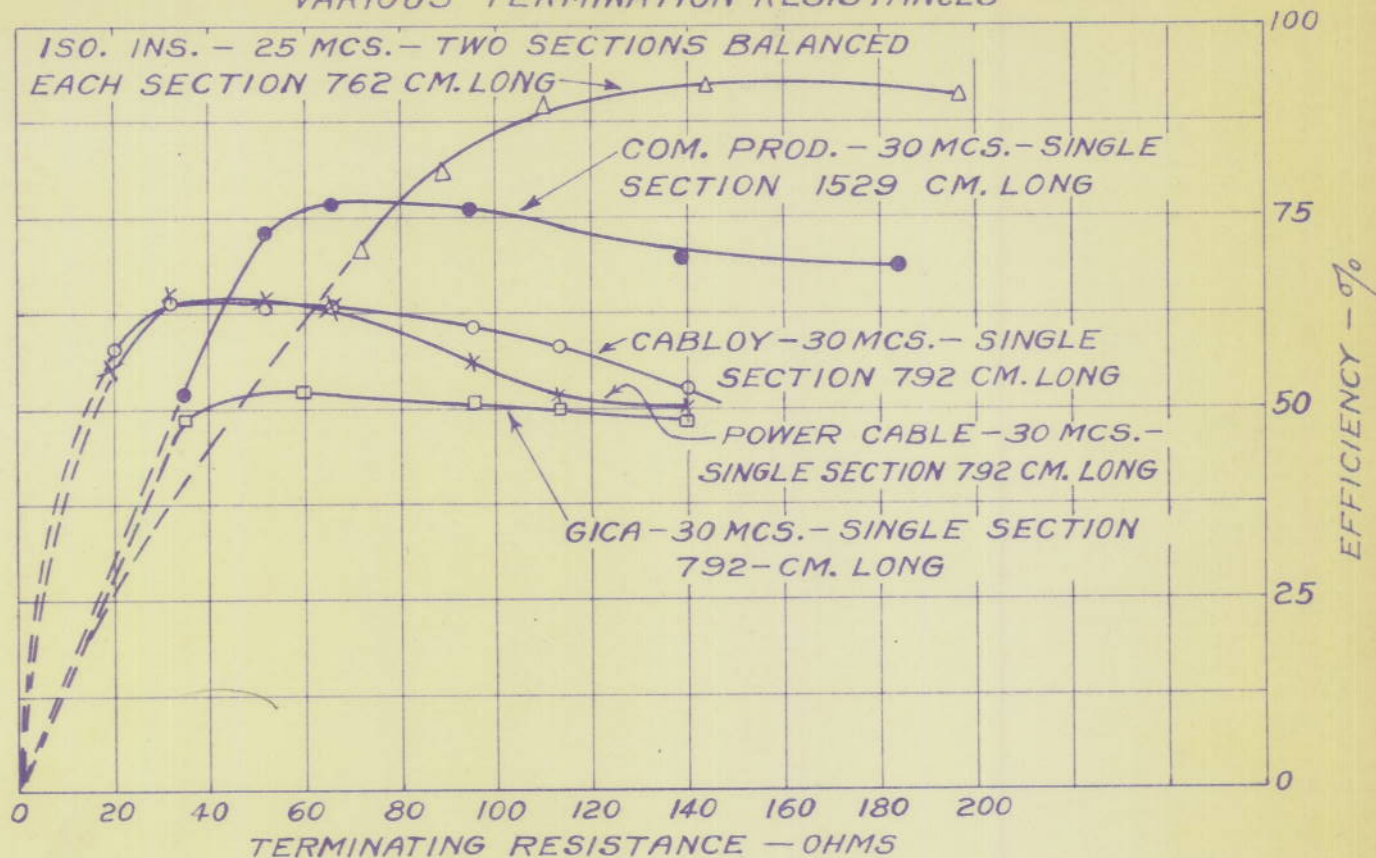
ELECTRICAL NETWORK FORMED BY TRANSMISSION LINE



NOTE:- ALL ILLUSTRATIONS ARE APPROXIMATELY FULL SCALE SIZE.

SECTIONAL VIEWS OF TRANSMISSION LINES

EFFICIENCIES OF TRANSMISSION LINES AT
VARIOUS TERMINATION RESISTANCES



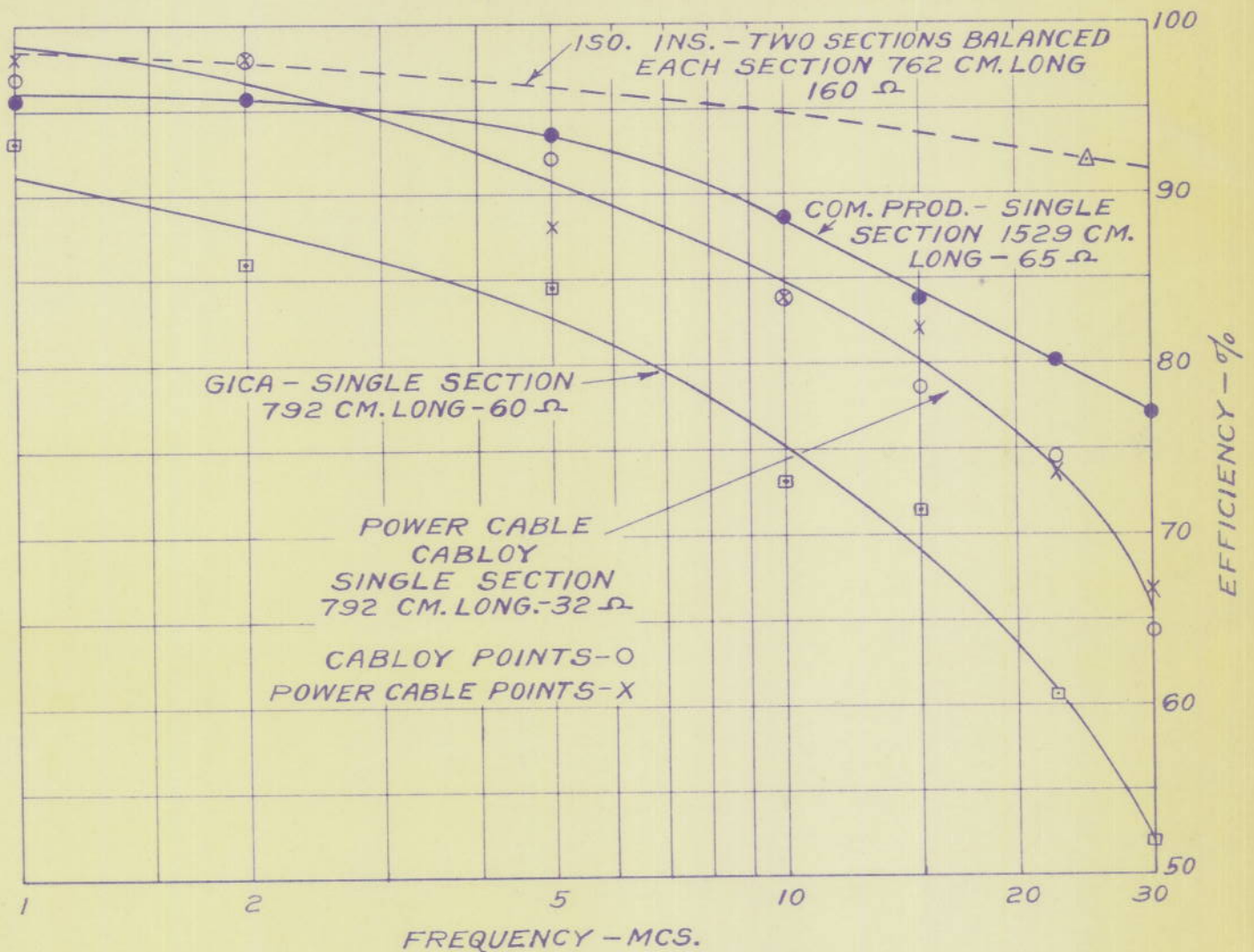
APPLY WHERE LINE IS PROPERLY
TERMINATED

LINE	CHAR. IMP.	EFFICIENCY OF A SINGLE SECTION OF 1000 CM. LENGTE #	ATTENUATION DB/CM.
150. INS.	80 Ω	95 % *	0.000236 *
COM. PROD.	66 Ω	84 %	0.00074
CABLOY	32 Ω	57 %	0.00241
POWER CABLE }	32 Ω	57 %	0.00241
GICA	60 Ω	44 %	0.0036

FOR THE PURPOSE OF MORE READILY COMPARING THE LINES,
ALL EFFICIENCIES WERE REDUCED (BY COMPUTATION) TO THAT
OF A LINE 1000 CM. IN LENGTH.

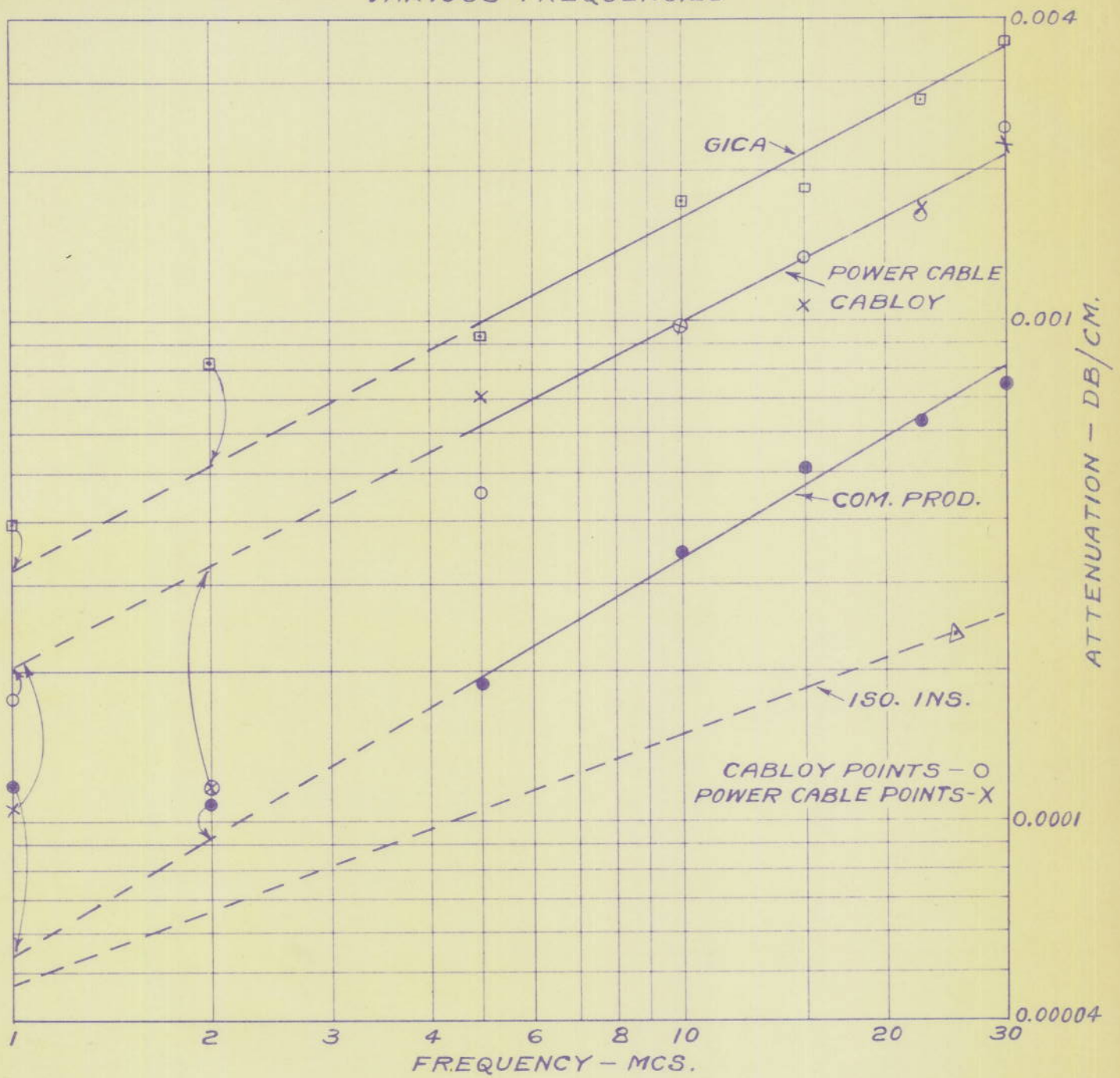
* THESE DATA AT 25 MCS., ALL OTHER AT 30 MCS.

EFFICIENCIES OF TRANSMISSION LINES AT
VARIOUS FREQUENCIES



NOTE:- ALL LINES WERE TERMINATED IN A RESISTANCE EQUAL TO THEIR CHARACTERISTIC IMPEDANCE DURING ABOVE TESTS, WHICH IS INDICATED IN THE DESCRIPTION ON EACH CURVE. A COMMON CURVE IS SHOWN FOR POWER CABLE AND CABLOY, AS SEPARATE CURVES WOULD PRACTICALLY COINCIDE. IN COMPARING THE CURVES, NOTE THAT THEY DO NOT HAVE THE SAME LENGTH, AND REFER TO PLATES 5 AND 6 WHERE RESULTS ARE REDUCED TO THE SAME BASIS.

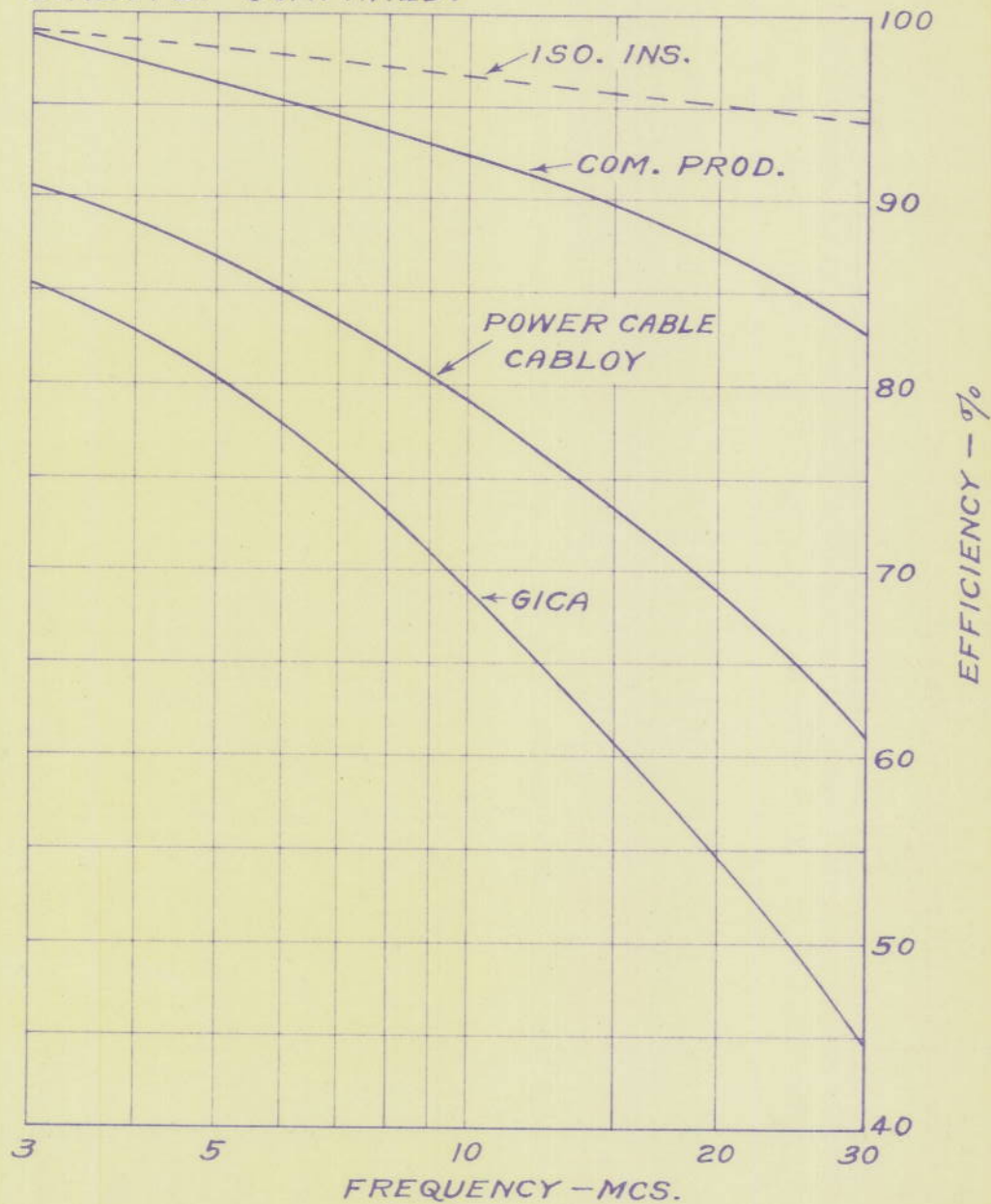
ATTENUATION OF TRANSMISSION LINES AT
VARIOUS FREQUENCIES



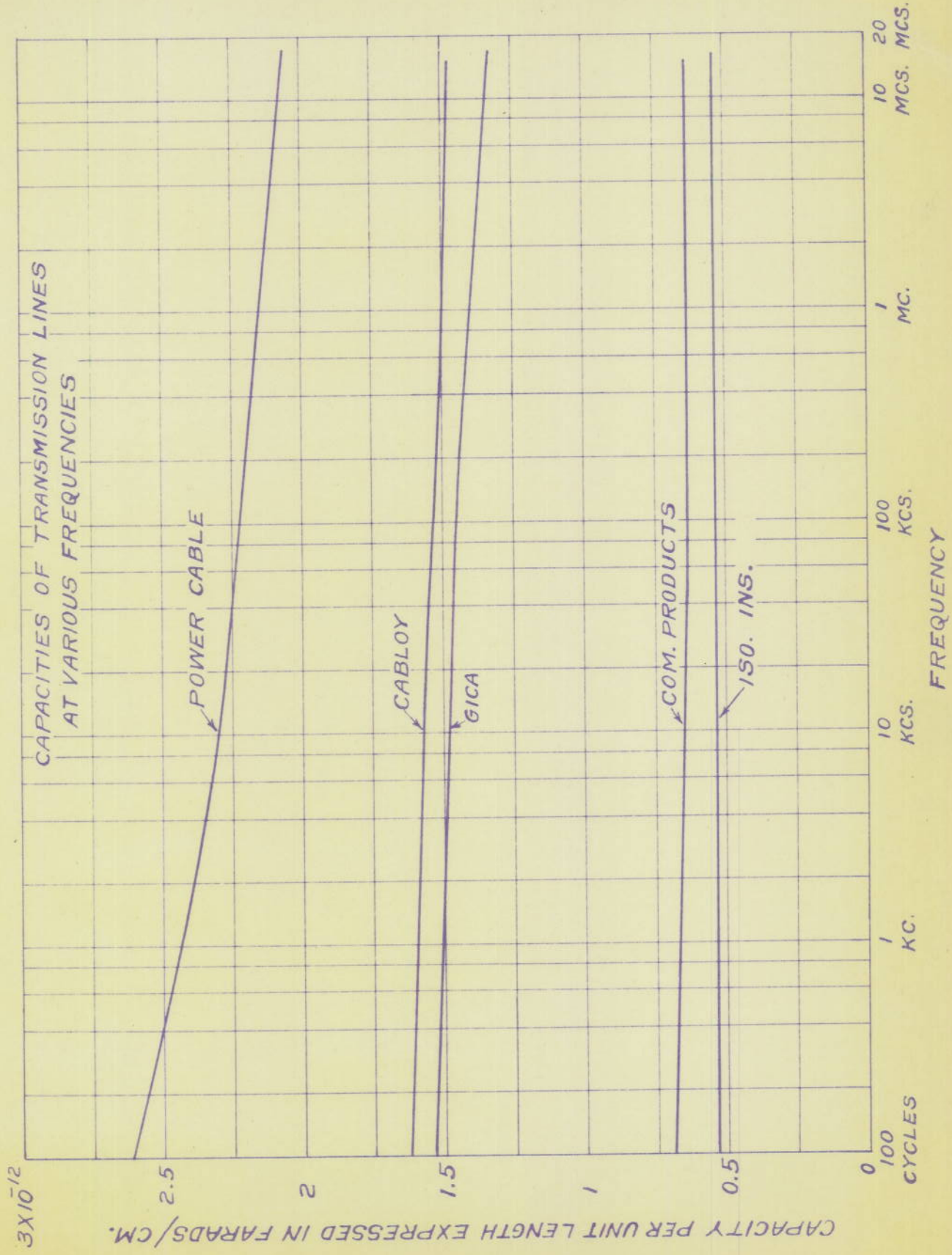
NOTE:- THE LINES MUST BE PROPERLY MATCHED FOR THE ABOVE DATA TO APPLY. POWER CABLE AND CABLOY ARE SHOWN BY A COMMON CURVE. SEE PAR.16 FOR DISCUSSION OF CURVES.

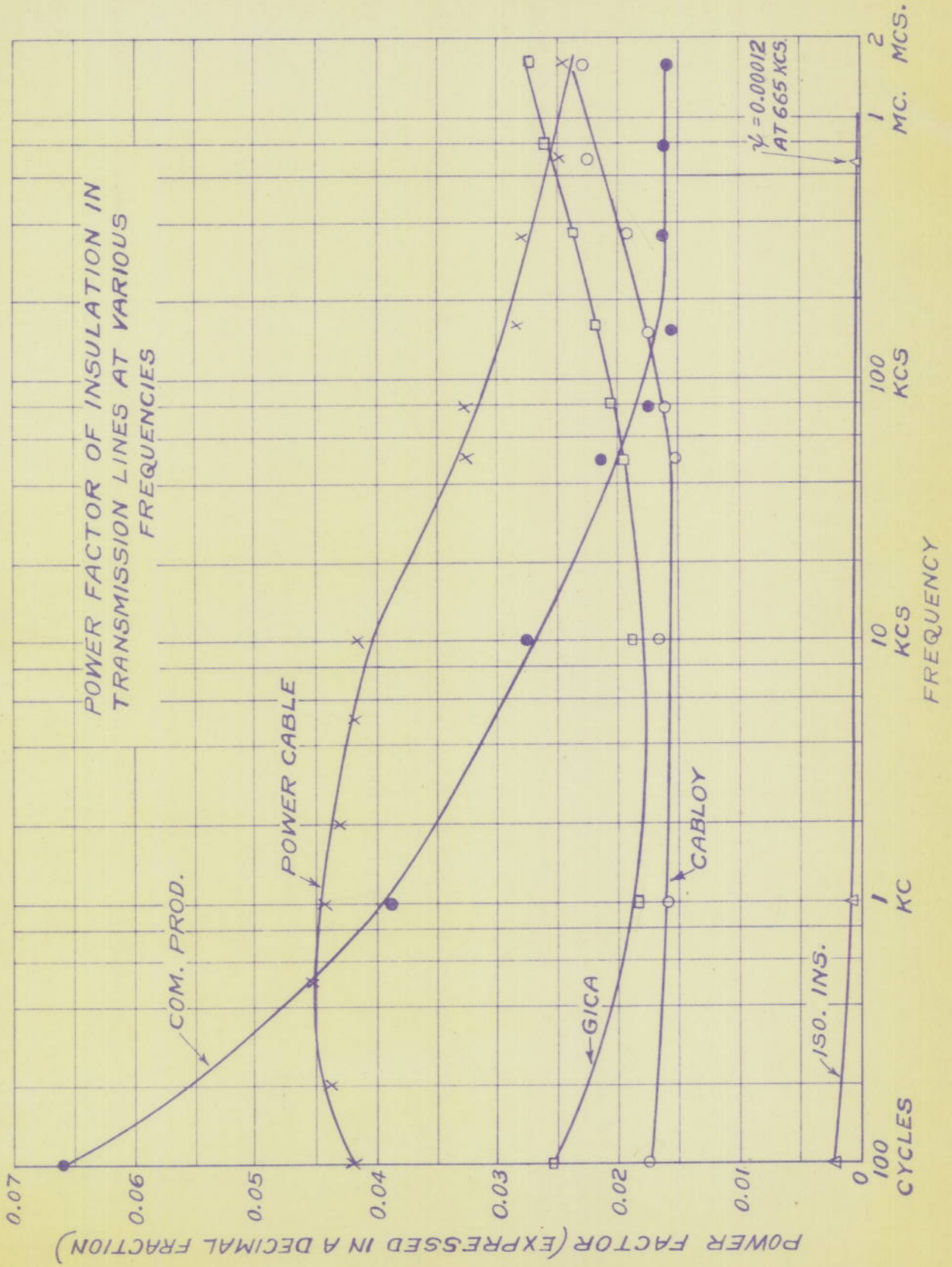
EFFICIENCIES OF TRANSMISSION LINES AT
VARIOUS FREQUENCIES

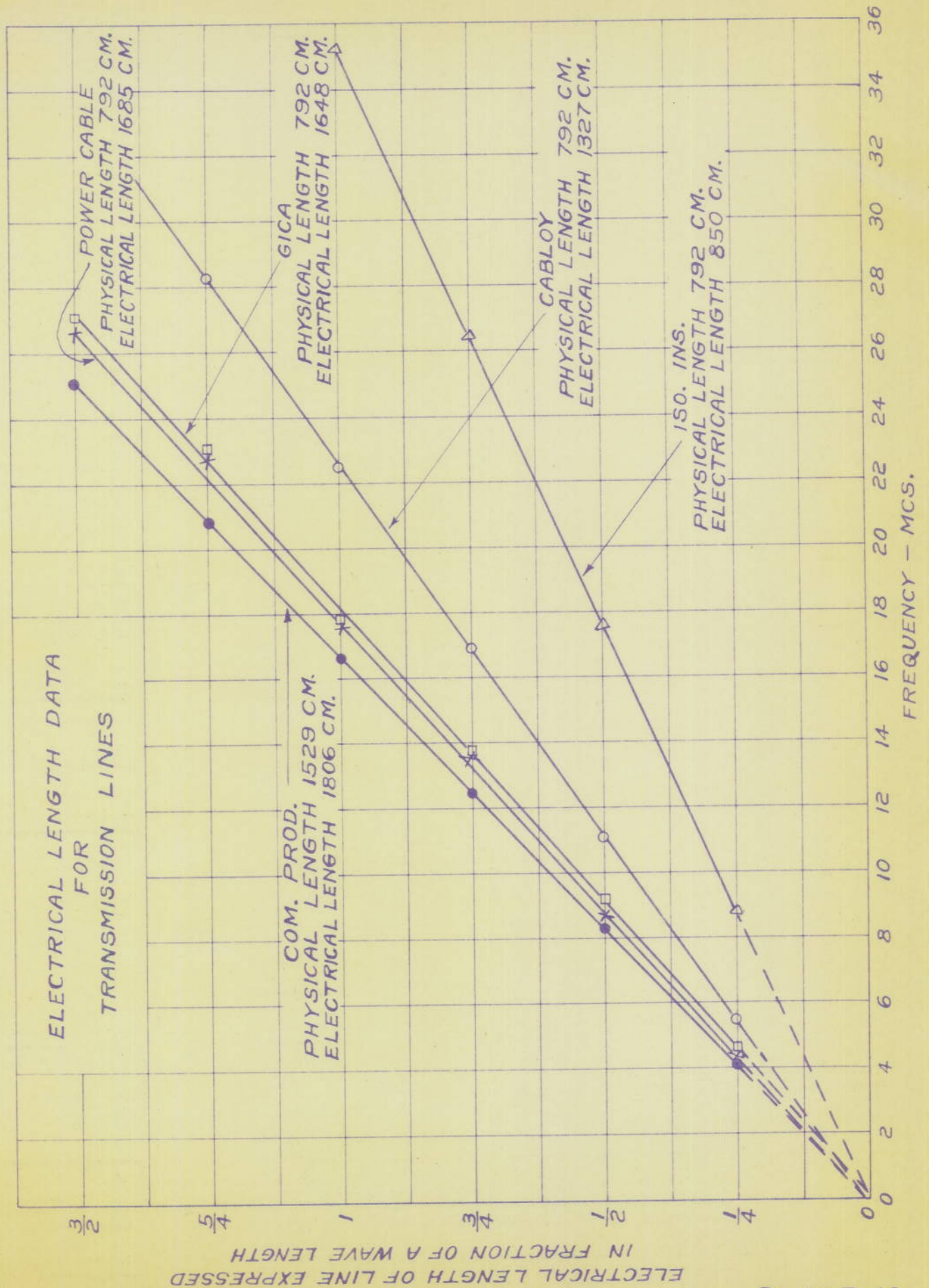
ALL LINES REDUCED TO SAME BASIS, THAT IS
TO A SINGLE SECTION OF 1000 CM. LENGTH,
IN ORDER TO ALLOW THE RESULTS TO BE
DIRECTLY COMPARED.

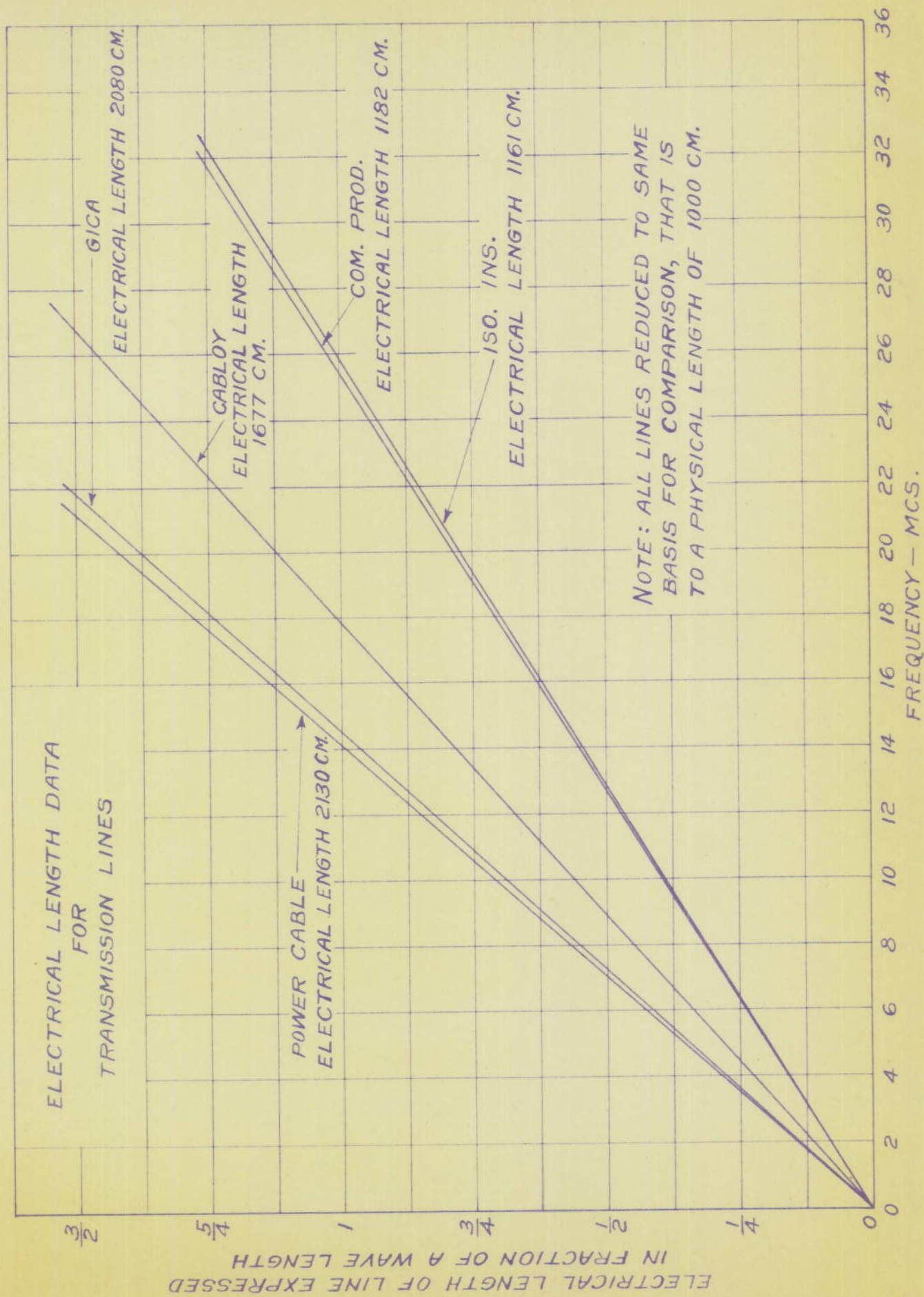


NOTE:- THE LINES MUST BE PROPERLY MATCHED
FOR THESE DATA TO APPLY. AS IN PLATES 4 AND 5,
CABLOY AND POWER CABLE ARE SHOWN BY
A COMMON CURVE.









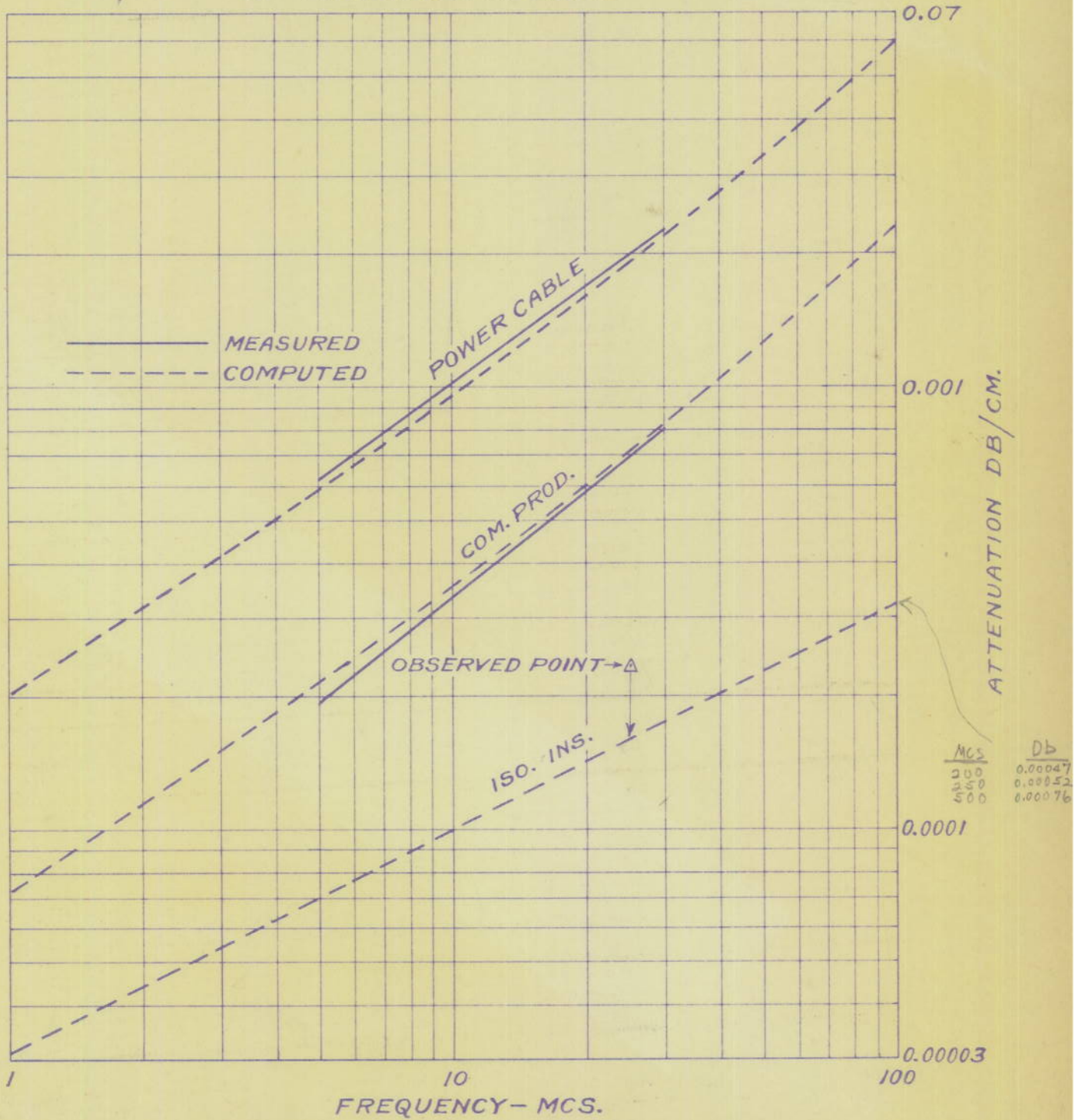
ELECTRICAL LENGTH OF LINE EXPRESSED IN FRACTION OF A WAVE LENGTH

ELECTRICAL LENGTH DATA FOR TRANSMISSION LINES

POWER CABLE ELECTRICAL LENGTH 2130 CM.

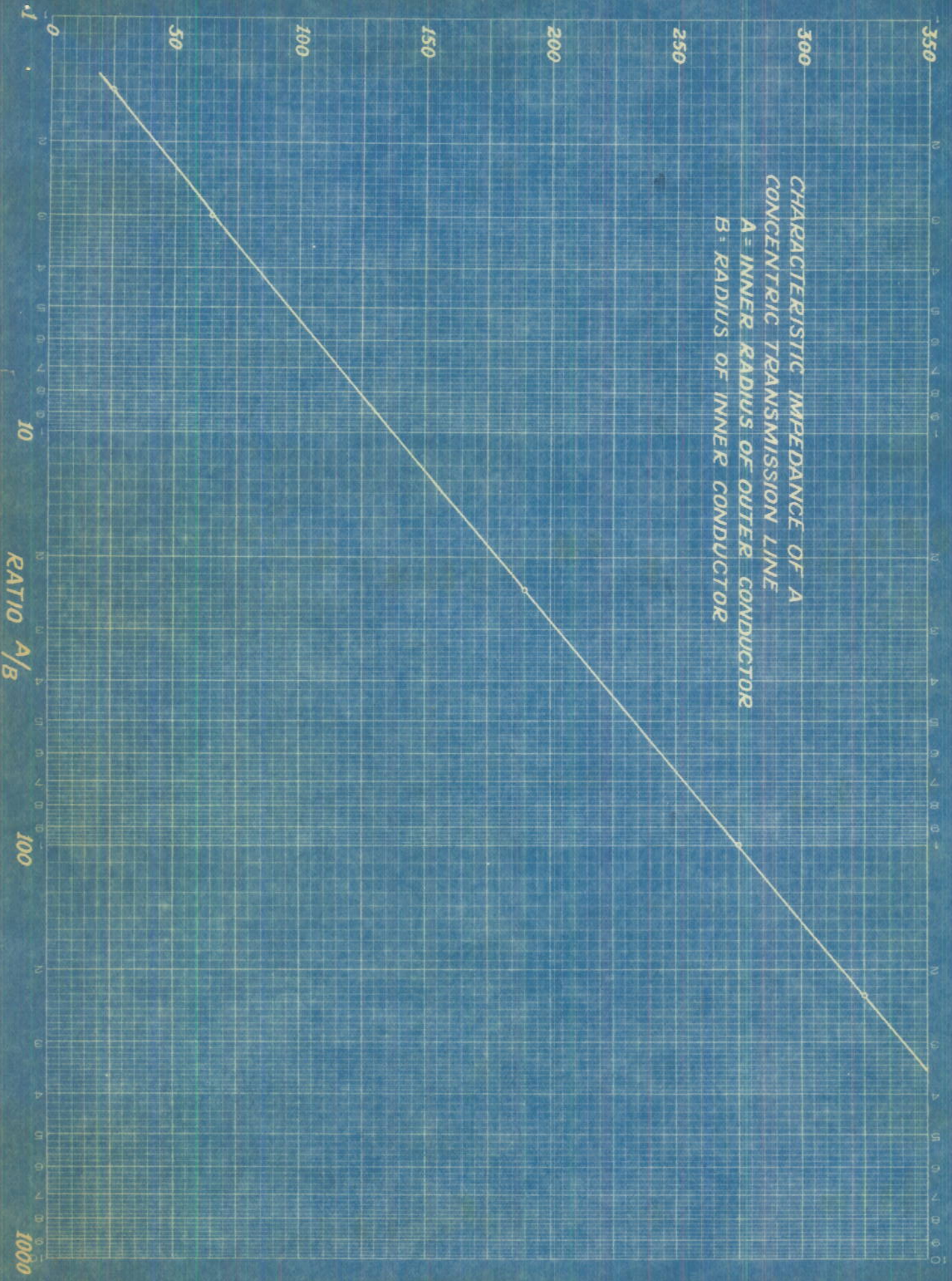
NOTE: ALL LINES REDUCED TO SAME BASIS FOR COMPARISON, THAT IS TO A PHYSICAL LENGTH OF 1000 CM.

COMPUTED AND OBSERVED VALUES OF ATTENUATION
OF TRANSMISSION LINES



NOTE:— THE LINES MUST BE PROPERLY MATCHED FOR THE ABOVE DATA TO APPLY. SEE PAR. 21 FOR DISCUSSION OF CURVES

CHARACTERISTIC IMPEDANCE - OHMS



CHARACTERISTIC IMPEDANCE OF A
CONCENTRIC TRANSMISSION LINE

A = INNER RADIUS OF OUTER CONDUCTOR

B = RADIUS OF INNER CONDUCTOR



Characteristic Impedance of Coaxial line

