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AUTHORIZATION

1. The general investigation of transmission lines is authorized by Bureau of Ships Problem B2 as covered by Bureau of Ships letter S67/A62(5-27-480) of 29 May 1941. Additional references which are alluded to in this discussion are listed below:

- References:
- (a) Alford and Pickles, "Radio Frequency High Voltage Phenomena," Electrical Engineering Transactions, pp. 129-136, March, 1940.
 - (b) NRL Report No. R-1603, 27 March 1940.
 - (c) Rohde and Wedemeyer, "Losses and Breakdown at High Voltage and High Frequency," ETZ Vol. 61, No. 51, Dec. 19, 1940, and Vol. 61, No. 52, Dec. 26, 1940.
 - (d) Nonken, "High Pressure Gas as a Dielectric," AIEE Technical Paper 41-159, Sept., 1941.
 - (e) Hudson, Hoisington and Royt, "Dielectric Strength of CCl_2F_2 - Air and SO_2 - Air Mixtures," Physical Review, Vol. 52, No. 6, pp. 664-665, Sept. 15, 1937.
 - (f) Trump, Safford, and Cloud, "D-C Breakdown Strength of Air and of Freon in a Uniform Field at High Pressures," Electrical Engineering Transactions, pp. 132-134, March, 1941.
 - (g) NRL Report No. R-1824, 30 Dec. 1941.

INTRODUCTORY

2. Coaxial transmission lines used in conjunction with high power, high voltage pulsing equipment present problems which hitherto had been of secondary importance in the electrical and mechanical design of the component parts of such lines. Attention is invited to the fact that this report is concerned with transmission lines used in conjunction with pulsing apparatus, wherein the average transmitted power is only a small fraction of the peak power. The data herein cannot be used for transmission lines operating under continuous duty applications, since the current limitations, or heating, of the line have not been considered. The various details of coaxial lines which govern the maximum peak power that can be transmitted may be listed as follows:

- (a) Characteristic impedance of the line (relative size of inner and outer conductors).

- (b) Electrical continuity of the line (number of reflection points and magnitude of reflection coefficients at those points).
- (c) Design of the insulators.
- (d) Dielectric constant of the insulating material used.
- (e) Manner in which the insulators are held in place on the inner conductor (crimping, rolling, spring clips, perforations in conductor or molded plastic on conductor).
- (f) Smoothness of surface of inner conductor and inside surface of outer sheath.
- (g) Concentricity of conductors.
- (h) Amount of contamination and moisture on the insulators.
- (i) Size and design of end seals.
- (j) Gas pressure in line.
- (k) Kind of gas used.
- (l) Degree of impedance mismatch at load end of line.
- (m) Design of line fittings.
- (n) Frequency of transmitted power.

3. An investigation of the above factors on actual transmission lines at the ultra-high frequencies would require either an extremely powerful signal generator or the development of a measuring technique when using pulse generators. Because of the difficulties which would be encountered in either of these methods, the following indirect method was considered.

4. The high voltages necessary for studying the transmission lines can be easily obtained and accurately measured at 175 kc. The factors listed in Par. 2, with the exception of (b), (l) and (n), can be studied and analyzed from the measurements at 175 kc made on a short section of line. The effect of the factors (b) and (l) upon the power rating or the maximum input power to the line can be calculated theoretically. If the relationship between the corona voltage and frequency could be established, then the various design

factors at the ultra-high frequencies could be computed from the measurements at 175 kc and one would have a fairly complete solution to the problem.

5. A review of the literature reveals that considerable work has been done on the corona and breakdown voltages for sphere gaps, concentric cylinders and cylindrical conductors at the commercial power frequencies. The dielectric strengths of several gases at various pressures have also been studied at power frequencies. On the other hand, comparatively little work has been done on the breakdown voltage of various physical configurations at the radio frequencies. Experimental work has been done over a wide range of frequencies on the breakdown voltage of a sphere gap (see reference (c)).

6. The breakdown voltage of two concentric cylinders was measured in the frequency range 175 to 18,000 kc for the purpose of obtaining the relationship between the frequency and the breakdown voltage. Both cylinders were of small diameter in order to permit measurements at comparatively low voltages.

7. As shown in reference (b), the maximum corona-free voltage that can be applied between two concentric cylinders can be expressed in terms of the radii of the two cylinders. It is necessary to use spacing insulators and fittings in the construction of coaxial transmission lines. In general, these insulators and fittings will tend to increase the potential gradient at some points in the line, and thus the safe operating voltage may be lower than for concentric cylinders of the same size. Measurement of the breakdown voltage on lines containing these various insulators and fittings affords a relatively simple means for determining their weak points, from which a process of correction can be initiated.

8. The purpose of this investigation may be summarized as follows:

- (a) To determine the size of the inner conductor for maximum output or load power for a given size of outer conductor.
- (b) To determine the proper design of insulators and fittings for a given line.
- (c) To determine the dielectric strength of various gases at various pressures.
- (d) To determine so far as possible the relationship between the breakdown voltage and the frequency.

THEORY

9. A number of well known transmission line formulas are used in the following discussion. For convenient reference, these formulas are given below.

10. The characteristic impedance of a transmission line is given by

$$Z_0 = \frac{60 \log_e \frac{b}{a}}{k^{1/2}} \quad \text{ohms} \quad (1)$$

Where k is the "effective" dielectric constant of the line,
 b is the inside radius of the outer conductor in inches,
 a is the radius of the inner conductor in inches.

11. If disc insulators are used in the line, then the "effective" dielectric constant k is given approximately by

$$k = \frac{mK + n - m}{n} \quad (2)$$

Where m is the thickness of the insulator in inches,
 n is the spacing between the insulators (center to center) in inches,
 K is the dielectric constant of the insulator.

12. The "effective" dielectric constant k of the line can be computed from measurements of the physical and electrical length of the line

$$k = \left(\frac{L}{L_e} \right)^2 \quad (3)$$

Where L is the length of the line in feet,
 L_e is the electrical length of the line.

13. The attenuation constant of a transmission line at radio frequencies is given by

$$\alpha = \frac{r}{2Z_0} + 4\pi f CZ_0 \psi \quad (4)$$

Where α is the attenuation constant in nepers per foot of line,
 r is the resistance in ohms per foot of line,
 C is the capacity in farads per foot of line,
 f is the frequency in c.p.s.,
 ψ is the power factor of one foot of line.

$$r = 0.504 \times 10^{-6} f^{1/2} \left(\frac{1}{a} + \frac{1}{b} \right) \text{ ohms per foot. (5)}$$

$$C = \frac{16.93 k \times 10^{-12}}{\log_e \frac{b}{a}} \text{ farads per foot. (6)}$$

14. If Eq. (1), (5) and (6) are substituted in Eq. (4), then one obtains

$$2^{\alpha} L = \frac{D \left(\frac{1}{a} + \frac{1}{b} \right)}{\log_e \frac{b}{a}} + G \quad (7)$$

Where

$$D = 0.504 \times 10^{-6} f^{1/2} k^{1/2} L \quad (8)$$

$$G = 1.03 \times 10^{-9} \pi k^{1/2} L f \psi \quad (9)$$

It should be noted that D and G are independent of the ratio of b/a.

15. The efficiency of a matched transmission line is given by

$$\text{Line Efficiency} = 100 e^{-2^{\alpha} L} \% \quad (10)$$

The line efficiency is a maximum or the line loss is a minimum when

$$\log_e \frac{b}{a} = \left(1 + \frac{a}{b} \right) \quad (11)$$

or when the ratio of b/a is 3.59.

16. The input power to a transmission line that is mismatched at the load end of the line is given by

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$$P_i = \frac{V_{\max} V_{\min}}{Z_0} \quad (12)$$

Where $V_{\max}$ is the maximum value of the standing wave voltage at the input end of the line,
 $V_{\min}$ is the minimum value of the standing wave voltage at the input end of the line.

17. The standing wave ratio at the input end of the line is

$$R = \frac{V_{\min}}{V_{\max}} \quad (13)$$

From Eq. (12) and (13), one obtains

$$P_i = \frac{R V_{\max}^2}{Z_0} \quad (14)$$

18. The maximum corona-free voltage of two smooth concentric cylinders can be computed from Eq. (7) of reference (b) and is

$$V' = A (a + Ba^{1/2}) \log_e \frac{b}{a} \quad (15)$$

Where V' is the maximum corona-free voltage in peak kilovolts,
 A is independent of the size of the conductors and varies somewhat with the frequency. $A = 60$ at 175 kc.
 B is a constant. $B = 0.21$.

19. It was found in reference (b) that the initial corona voltage was less than the maximum corona-free voltage. The maximum voltage at which a transmission line can be operated must be less than the initial corona voltage. The maximum voltage at which the transmission can be operated is

$$V = AH (a + Ba^{1/2}) \log_e \frac{b}{a} \quad (16)$$

Where H is the ratio of the initial corona voltage to the maximum corona-free voltage. H is approximately 0.7.

Matched Transmission Line

20. The input power to a matched transmission line is given by

$$P_i = \frac{V^2}{Z_0} \quad (17)$$

21. If it is assumed that insulators can be designed so that the breakdown voltage of the transmission line is the same as for an ideal line, then the input power is obtained by substituting Eq. (16) and (1) in Eq. (17). The input power in peak megawatts is

$$P_i = \frac{A^2 H^2 k^{1/2} a}{60} (a^{1/2} + B)^2 \log_e \frac{b}{a} \quad (18)$$

Where P_i is the input power in peak megawatts.

22. For a given size of outer conductor this power will be a maximum when

$$\log_e \frac{b}{a} = \frac{a^{1/2} + B}{2a^{1/2} + B} \quad (19)$$

23. In Plate 9 the maximum corona-free voltage (Eq. 15), the input power (Eq. 18), and the line efficiency are plotted as a function of the ratio of b/a for a 200-foot section of matched 7/8-inch line. It is of interest to note that only the line efficiency is a function of the length of the line. In the computations for the above curves, the effect of the insulators has been neglected. It will be noted also that the maximums for all three curves in Plate 9 are quite broad. The maximum values of the maximum corona-free voltage and line efficiency occur at approximately the same ratio of b/a or about 3.5. The maximum value of input power occurs at a much lower ratio of b/a , or approximately 1.8.

24. The design of a transmission line with a given size of outer conductor that will deliver maximum power to the load is of greater interest than a line designed for maximum input power when considered for use with high-power pulsing equipment. In other words, the efficiency of the line should be included in the computations.

25. If it is assumed that insulators can be designed so that the potential gradient is no greater at any point in the air in the line than in an ideal line, then Eq. (16) gives

the maximum safe operating voltage for such a line, and the output peak power is given by

$$P_o = \frac{V^2 e^{-2\alpha L}}{Z_o} \quad (20)$$

Where P_o is the load power in peak megawatts.

26. After substituting Eq. (1), (7) and (16) in Eq. (20), one obtains for the load power

$$P_o = \frac{A^2 H^2 k^{1/2} e^{-G} a}{60} (a^{1/2} + B)^2 e^{-X} \log_e \frac{b}{a} \quad (21)$$

where

$$X = \frac{D}{\log_e \frac{b}{a}} \left(\frac{1}{a} + \frac{1}{b} \right) \quad (22)$$

27. The output power is a maximum for a given size of outer conductor when:

$$\log_e \frac{b}{a} = \left\{ \frac{a^{1/2} + B}{2a^{1/2} + B} \right\} \left\{ 1 + \frac{D \left[\frac{1}{a} (1 - \log_e \frac{b}{a}) + \frac{1}{b} \right]}{\log_e \frac{b}{a}} \right\} \quad (23)$$

28. It is evident from Eq. (21) and (22) that the ratio of b/a for the maximum value of output power is a function of the length and resistance of the line but is not a function of the dielectric loss in the insulators. The insulators increase the "effective" dielectric constant of the line and the ratio of b/a is a function of the "effective" dielectric of the line. Thus, in normal lines the effect of the insulators on the ratio of b/a is of secondary importance and can be neglected.

29. A comparison of Eq. (19) and (21) and (22) reveals that the ratios of b/a for maximum input and output or load power are not the same; e.g., if a 200-foot 7/8-inch line is used at 200 mc, then the ratios of b/a for maximum input and load power are 1.8 and 1.88, respectively. Maximum load power occurs for a slightly higher ratio of b/a than for maximum input power. Attention is invited to the fact that the ratio of b/a for maximum load power increases as both the frequency

and length of the line increase. The ratio of b/a for maximum power at the load end of a 200-foot section of 7/8-inch line at 3000 mc is 2.1.

30. In Plate 11 the input and output powers are plotted as a function of the ratio of b/a for a 200-foot 7/8-inch transmission line operating at a frequency of 200 mc. The ratio of b/a is plotted on a logarithmic scale which corresponds to a linear scale for the characteristic impedance of the line. The difference in power between the two curves is equal to the line loss. The maximum value of the load power occurs at a slightly higher ratio of b/a than for maximum input power (see Plate 11). The load power is equal to the product of the line efficiency and the input power. Thus, the maximum value of the load power should occur at a greater value of b/a than for maximum input power, because the line efficiency is a maximum at a greater value of b/a . The line efficiency is a maximum for $b/a = 3.59$.

Mismatched Transmission Line

31. The transmission line antenna system for high-power pulsing apparatus consists of the transmission line, matching network and the antenna. The antenna impedance and the characteristic impedance of the line generally differ in value, and, in addition, the antenna may be a balanced or symmetrical system. Hence, the matching network must change the antenna impedance to the line impedance and in some cases perform the additional operation of changing a symmetrical to a nonsymmetrical system. It is difficult to obtain a unity standing wave ratio in such a complex matching network. The experimental measurements indicate that approximately the same value of standing wave ratio can be obtained for various values of the line impedance or ratio of b/a . This assumes that the range of line impedances is not too great. Thus, the standing wave ratio R in Eq. (14) is independent of the line impedance or of b/a over a limited range of the ratio of b/a .

32. The power input to a transmission line that is mismatched at load end only is given by Eq. (14) and is

$$P_i = \frac{R V_{\max}^2}{Z_0} \quad (24)$$

where $V_{\max}$ is the maximum value of the voltage near the input end of the line. If the line is to operate corona-free, then the voltage $V_{\max}$ must be less than the initial corona voltage V . After substituting the value of V as given by Eq. (16) for $V_{\max}$ in Eq. (24), one obtains for the input power

$$P_i = \frac{R A^2 H^2 k^{1/2} a}{60} (a^{1/2} + B)^2 \log_e \frac{b}{a} \quad (25)$$

where P_i is the input power in peak megawatts. It is assumed in Eq. (25) that the insulators or fittings in the line do not lower the breakdown voltage of the line.

33. Eq. (25) is the same as Eq. (18), except for the factor R --the standing wave ratio--and R is independent of the ratio of b/a (see Par. 31); thus, the ratio of b/a for maximum input power to a mismatched line is the same as for a matched line and is given by Eq. (19).

34. If one assumes the length of the transmission line to be several wave lengths, then the input and output powers for a mismatched line are

$$P_i = \frac{V_{\max}^2 (1 - r e^{-2\alpha L})}{Z_0 (1 + r e^{-2\alpha L})} \quad (26)$$

and

$$P_o = \frac{V_{\max}^2 (1 - r^2) e^{-2\alpha L}}{Z_0 (1 + r e^{-2\alpha L})^2} \quad (27)$$

where P_o is the output power in peak megawatts,
 P_i is the input power in peak megawatts,
 r is the reflection coefficient at the load end of the line.

35. The standing wave ratio at the load end of the line R' is given by

$$R' = \frac{1 - r}{1 + r} \quad (28)$$

36. The standing wave ratio at the input end of the line can be expressed in terms of the reflection and the attenuation coefficients and is

$$R = \frac{1 - r e^{-2\alpha L}}{1 + r e^{-2\alpha L}} \quad (29)$$

37. The efficiency of the line with standing waves is the ratio of Eq. (27)/Eq. (26 and is

$$\text{Line Eff.} = \frac{100 e^{-2\alpha L} (1 - r^2)}{(1 - r^2 e^{-4\alpha L})} \% \quad (30)$$

38. Since the efficiency of a matched line is $100 e^{-2\alpha L}$, the effect of the standing waves upon the line efficiency is given by the factor

$$\frac{1 - r^2}{(1 - r^2 e^{-4\alpha L})}$$

39. The minimum value of this factor for a standing wave ratio at the load end of the line $R' = 0.5$ is 0.89. Thus, for a standing wave ratio of $R' = 0.5$, the line efficiency of any length of line at any frequency would be at least 89 per cent of the value for a matched line. In other words, the line efficiency is nearly independent of the standing wave ratio providing the standing wave ratio is greater than 0.5 at the load end of the line. Since the standing wave ratio and the line efficiency are practically independent of the ratio of b/a for standing wave ratio greater than 0.5, the ratio of b/a for maximum load power is for all practical purposes the same for a matched and a mismatched line. This assumes the standing wave ratio is greater than 0.5

40. Experimental measurements (reference (b)) have shown that any small irregularity on the inside surface of the outer conductor or on the outside surface of the inner conductor will lower the maximum corona-free voltage or breakdown voltage of the line, and that the magnitude of this reduction increases as the ratio of b/a decreases. It was found that if the ratio of b/a was greater than 10, then the irregularities on the outer conductor had very little effect on the breakdown voltage. On the other hand, if the ratio of b/a were about 2, any irregularities or rough spots on either conductor would lower the breakdown voltage. Hence, a ratio of b/a between 2.3 and 2.8 appears to be about the best compromise value for maximum load power for a practical installation.

Insulator Design

41. In existing transmission lines for high-power pulsing equipment, the insulators (ceramic) used to separate the two conductors fit loosely, not only on the inner conductor, but also inside of the outer sheath (see Plate 1, Fig. 2).

Thus, the dielectric path between the conductors consists of two air gaps and the solid insulator, all in series, and having dielectric constants of unity and K, respectively. In an actual installation, the inner conductor and insulators are usually positioned in the outer sheath as shown in Plate 1, Fig. 1. However, since ceramic insulators are not absolutely smooth, the contact they make with the conductors is only point contact, thereby resulting in a considerable air space being left between the insulators and conductor even under the best conditions. The potential gradient in the air gap between the inner conductor and the insulator will be greater than at any point in an ideal line. Since the surface of the insulator is not smooth, it is impossible to give a general solution for the potential gradient in the air gap. For this reason, the following simplified example is used to illustrate the fact that the potential gradient in this air gap will be abnormally high. It is assumed that a solid dielectric is in series with an air gap between two parallel plates as shown in Plate 2. It can be shown that the potential gradient in the solid dielectric (insulator) and air gap are given by:

$$E_1 = \frac{K_2 V}{K_2 L_1 + K_1 L_2} \quad (31)$$

and,

$$E_2 = \frac{K_1 V}{K_2 L_1 + K_1 L_2} \quad (32)$$

Where E_1 is the electric field in volts per centimeter in the insulator, of length L_1 and dielectric constant K_1 ,
 E_2 is the electric field in volts per centimeter in the air gap, of length L_2 and dielectric K_2 ,
 V is the potential difference in volts between the conducting plates.

If it is assumed that:

$V = 9000$ volts,
 $K_1 = 6$ (Isolantite),
 $K_2 = 1$ (Air),
 $L_1 = 0.65$ cm,
 $L_2 = 0.01$ cm,

then:

$E_1 = 12,700$ volts per cm,
and, $E_2 = 76,000$ volts per cm.

Removing the insulator entirely would produce a uniform field between the plates and would reduce E_2 to about 13,600 volts per cm. Thus, the electric field or potential gradient in the small air gap due to the presence of the insulator can be several times the value for air dielectric alone. The partial contact of insulator with the inner conductor under actual conditions (see Plate 1, Fig. 1) will tend to reduce the potential gradient in the air gap at the insulator; it would be less than the 76,000 volts per cm, but greater than the 13,600 volts given in the examples above.

42. The foregoing analysis emphasizes the following facts:

- (a) If the insulators in a coaxial line produce a potential gradient at any point of greater magnitude than at the surface of the inner conductor of an ideal line, then the breakdown voltage of the normal line will be lower than for an ideal line.
- (b) In order to realize the maximum power handling capabilities of a given size of line, it will be necessary to eliminate this air gap, or in some other way reduce the potential gradient at the insulators.

DEFINITIONS

43. "Breakdown voltage," as used in this report, means the r-f voltage at which arc-over occurred between the inner and outer conductors of the sample coaxial line under investigation. It does not mean "safe operating voltage."

44. "Normal line" or "normal inner conductor" is line as manufactured commercially; i.e., with loose-fitting ceramic insulators anchored in place on the inner conductor by crimping or slightly expanding the inner conductor on both sides of the insulators, or by the use of some other special anchoring device.

45. "Ideal line" is line in which the inner and outer conductors are perfectly straight, smooth, exactly concentric and have no insulation between them other than air. In other words, it is merely two concentric cylinders with air dielectric.

EQUIPMENT USED IN THE INVESTIGATION

46. Plate 3 shows the general arrangement of apparatus used in the measurement of breakdown voltage for 3/8-inch, 7/8-inch and 1-5/8-inch coaxial line at frequencies from 175 kc

to 600 kc. The external loading coil (L) was used to step up the output of a TAQ-4 transmitter in order to obtain voltages across capacitor (C) higher than the safe operating voltage of the transmitter antenna tank circuit. Capacitor (C) consisted of two nitrogen-filled variable capacitors tested up to 30 peak kilovolts each, which could be connected in series, parallel or used separately as the needs of the tests demanded. R-F ammeter (M) connected in the ground lead of capacitor (C) indicated the current flowing through (C).

47. For measurements at frequencies from 2000 kc to 18,000 kc, an XT3K transmitter was used to supply the r-f voltage. Measurements at these frequencies were made only on 1/4-inch line because of limitation in available sources of voltage. The circuit used in this case is shown in Plate 4. Capacitor (C) was a fixed Eimac vacuum capacitor, and (L) was a tapped inductance.

48. Special end seals (see Plate 5) were required when making measurements on 7/8-inch line under gas pressure.

49. A vacuum pump and mercury manometer system were used to evacuate the 7/8-inch line when measuring breakdown voltages at air pressures below one atmosphere. The vacuum pump was also used to evacuate the sample line before charging it with a pure gas under pressure.

METHODS OF MEASUREMENT

50. The samples of line investigated varied in length from 2 inches for the 1/4-inch, to 24 inches for the 1-5/8-inch line. The length of the small diameter sample lines was kept short because it was thus easier to maintain perfect concentricity of the conductors. The sections of line were always made long enough, however, to make it possible to include in the measurements the effects of at least one insulator in the line. In order to reduce to a practical minimum errors in the measurements arising from end effects, the ends of the outer sheath were slightly flared. The following typical example will illustrate how a breakdown-voltage measurement was made: With capacitor (C) (see Plate 3) set at a known value of capacity, and the transmitter operating at, for instance, 175 kc, r-f voltage, suitably controlled in magnitude, was applied across capacitor (C) by closing the transmitter key. The r-f current (I_C) thus caused to flow through capacitor (C) was read by means of r-f ammeter (M). When breakdown occurred, this current dropped to zero. The highest value of current read just before breakdown was used in calculating the breakdown or arc-over voltage. The r-f voltage in peak volts across capacitor (C) is given by

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$$V_c = \frac{I_c \sqrt{2}}{2\pi f C} \quad (33)$$

where I_c = current in amperes,
 f = frequency in c.p.s.,
 C = capacity in farads.

Assuming that:

C = 500 μ pf,
 and, I_c = 10 amps.,
 then, V_c = 25,700 peak volts.

Since the sample line was connected in parallel with capacitor (C) (see Plates 3 and 4), this voltage was also applied between the conductors of the line.

51. In the measurement of breakdown voltage on the various sizes of line and types of fittings under the various conditions as described herein, an average of at least six readings of current (I_c) (paragraph 50) was taken for each point plotted in Plates 12, 14, 15, 16, 17, 18 and 19. Exception was made in the cases where Freon or a mixture of Freon and air was used; in these cases, each point plotted is the average of only three readings of I_c because it was desirable to keep the decomposition of the Freon, caused by the arc-over (to be discussed later), at a minimum.

1/4-Inch Line

52. The breakdown voltage measurements on 1/4-inch line were confined to one sample of "ideal line" (see Definitions, Par. 45) 2 inches in length. The object of the measurements on this size of line was to determine the breakdown voltage as a function of frequency over as wide a range of frequencies as available sources of r-f voltage would permit.

3/8-Inch Line

53. The breakdown voltage of a section of 3/8-inch line 2-1/2 inches in length was measured in air at atmospheric pressure at frequencies from 175 kc to 600 kc under the following conditions: (1) an ideal line; (2) ideal line modified by addition of one ceramic insulator; (3) normal line (see Definitions, Par. 44) with one ceramic insulator.

7/8-Inch Line

54. Measurements of breakdown voltage were made on samples of 7/8-inch line, 12 inches in length, in air at atmospheric pressure, and at a frequency of 175 kc under the following conditions: (1) ideal line; (2) ideal line modified by addition of loose fitting ceramic insulators properly spaced; (3) normal line. The 12-inch samples were then cut in half and the measurements continued as follows: (4) the two 6-inch sections of ideal line were coupled together by means of a solderless coupling shown in Plate 10 of reference (g); (5) the two 6-inch sections of ideal line were coupled together by means of a differential expansion coupling shown in Plate 14 of reference (g) (this measurement included two types of inner conductor sliding member) (see Tests No. 2 and 3, Table 3); (6) the two 6-inch sections of ideal line were coupled together by means of the two-way junction box shown in Plate 12 of reference (g); (7) the two 6-inch sections were made up into an anchor joint as shown in Plate 13 of reference (g) (two different types of insulators were used in this measurement) (see Tests No. 4 and 5, Table 3); (8) this sample joint was then replaced entirely with, first, the end seal shown in Plate 18, and then with the end seal shown in Plate 16 of reference (g).

55. An attempt was then made to fill in the air space between the inner conductor and the ceramic insulator in order to reduce the potential gradient in this region. Using the section of line of Par. 54 (2), the insulators were secured in place by means of: (1) Clear Glyptal; (2) Aqua-dag; (3) Insa-lute. This idea was further extended by metallizing the contact surfaces of the ceramic insulator with: (1) evaporated platinum; (2) liquid silver (painted on as a lacquer and then heated to drive off the bronzing liquid; (3) sprayed aluminum and zinc. The latter method was unsuccessful because the insulators were too smooth to hold the metal.

56. Breakdown voltage measurements were then made on normal 7/8-inch line with various gases under pressure in the line. For this phase of the investigation, air, nitrogen, carbon dioxide, helium, argon, sulphur dioxide and Freon were used under pressures from zero to 30 pounds per square inch above atmospheric pressure. Various percentage (by volume) mixtures of air and Freon were also measured under pressures from zero to 30 pounds per square inch above atmospheric pressure. These mixtures were obtained, for example, by raising the line pressure (air at atmospheric pressure) to approximately 15 pounds per square inch pressure with pure Freon, allowing several minutes for thorough diffusion of the gases, then bleeding off to atmospheric pressure again. This gave a 50 per cent mixture (by volume) of Freon at atmospheric pressure.

The voltages attained under these conditions made it necessary to use special end seals as shown in Plate 5. The breakdown voltage measurements for air were extended to include pressures below one atmosphere down to 0.2 mm. of mercury.

57. Measurements were then made on a sample 7/8-inch line wherein the loose fitting ceramic insulators were replaced with Polystyrene 912-A insulators. These insulators were of the same general shape as the ceramic, but machined so that they fit tightly on the inner conductor, thereby essentially eliminating all air space between insulator and conductor. Breakdown voltage measurements were again made using air and various percentage mixtures of air and Freon as described in Paragraph 56.

1-5/8-Inch Line

58. Breakdown voltage measurements on 1-5/8-inch line were made in air only, at atmospheric pressure under the following conditions: (1) ideal line; (2) inner conductor perforated to receive insulator anchoring buttons, and with round-headed anchoring buttons holding Polystyrene insulators in place (see Plate 6, Fig. 1); (3) inner conductor perforated to receive insulator anchoring buttons, and with flat-headed anchoring buttons holding "Alsimag" (ceramic) insulators in place (see Plate 6, Fig. 2); (4) same as (3) above with contact surfaces of the ceramic insulators metallized with evaporated silver; (5) inner conductor perforated to receive pin type insulators as shown in Plate 7, Fig. 1; (6) inner conductor smooth except for a slight internally rolled boss for anchoring ungrooved ceramic insulators (see Plate 7, Fig. 2); (7) inner conductor smooth with Polystyrene disc type insulators machined to fit tightly on the inner conductor (see Plate 8, Fig. 1 and 2).

RESULTS

59. The major part of the breakdown voltage measurements on the various transmission lines were made at 175 kc. In order to convert these values to the breakdown voltage at 100 mc or higher frequencies, it is necessary to know how the breakdown voltage varies with the frequency. Measurements were made on a short section of 1/4-inch transmission in order to obtain the breakdown voltage as a function of the frequency. Since the breakdown voltage is only a few kilovolts for this line, measurements could be readily made at the higher frequencies.

60. The general purpose of the measurements on the larger size lines was to obtain the actual breakdown voltage, from which the maximum power that these lines can transmit is

computed. In addition, such data may be used in the determination of methods for improving the breakdown voltage and power rating of the line.

Variation of Breakdown Voltage with Frequency

61. The breakdown voltage of the 1/4-inch line is plotted as a function of the frequency in Plate 12. The section of 1/4-inch line was two inches in length with a ratio of $b/a = 4$. The inside diameter of the outer conductor was 0.204 inch and flared at both ends in order to reduce end effects. Both conductors were perfectly smooth. It should be noted in this curve that the breakdown voltage decreases slowly as the frequency increases up to 18 mc, or the maximum frequency of the measurements. It would appear from an extrapolation of the curve in Plate 12 that the breakdown voltage at 100 or 200 mc would not differ greatly from the value at 18 mc.

62. Plate 13 is a reproduction of Fig. 8 in reference (c), wherein the breakdown voltage of two spheres 10 mm in diameter and spaced 2 mm apart is given as a function of the frequency. These data show that the breakdown voltage decreases with the frequency up to about 2.0 mc. The minimum value of the breakdown voltage occurs at 2.0 mc and is about 0.8 of the 60-cycle or d-c value. Above 2.0 mc, the breakdown voltage increases with the frequency and is approximately 1.6 times the 60-cycle value at 100 mc, while at 18 mc it is about 9 per cent greater than the minimum value at 2.0 mc.

63. Referring to Plates 3 and 4, the lead from the capacitor (C) to the 2-inch section of 1/4-inch line, the lead from the capacitor (C) to the r-f ammeter (M), and the lead from the r-f ammeter to ground were all kept short. The capacitor (C) was an Eimac vacuum condenser for frequencies above 2.0 mc and the meter (M) was a shielded Weston ultra-high frequency type r-f ammeter. The error for this meter, as given by the manufacturer, is less than 3.5 per cent at 100 mc. The capacity of (C) was measured with a Q-Meter and corrections were made for the capacity of the connecting leads to the Q-Meter. The breakdown-voltage measurements were made for more than one value of the capacitor (C). The relative error in these breakdown-voltage measurements should not be over about 3 per cent in the frequency range of 2.0 to 18.0 mc.

64. The curves in Plates 12 and 13 are similar for frequencies up to 2.0 mc, but above 2.0 mc the breakdown voltage decreases in Plate 12 and increases in Plate 13 as the frequency increases. The divergence of these curves at 18.0 mc is about 9 per cent. The probable error in the relative values of the breakdown voltage was considerably less than 9 per cent in the frequency range of 2.0 to 18.0 mc; thus, any rise of the break-

down voltage with the frequency should have been observed for the concentric cylinders.

65. The above data indicate that the breakdown voltage at 100 or 200 mc will not differ appreciably from the 18 mc value. Hence, the voltage breakdown measurements at 175 kc can be used for design data and determining the power rating of the line at the ultra-high frequencies.

66. The results of the breakdown-voltage measurements on the 3/8-inch line over the frequency range of 175 to 600 kc are given in Plate 14. The breakdown voltages of the normal and ideal lines are practically independent of the frequency in this narrow frequency band. The breakdown voltage of the ideal 3/8-inch line is in good agreement with the value computed from Eq. (15).

Insulator Design

67. 3/8-Inch Line. It can be seen in Plate 14 that the breakdown voltage is reduced from about 7.1 peak kilovolts for an ideal line to about 4.9 peak kilovolts for a normal line with ceramic insulators. This corresponds to a reduction of 30 per cent for the breakdown voltage and 50 per cent for the power rating of a normal line as compared to an ideal line. The lower breakdown voltage of the normal line is due to the potential gradient in the air gap under the insulators being greater than at any point in an ideal line. These data also show that the breakdown voltage of a normal line with crimped inner conductor and an ideal line with ceramic insulators added are the same. This indicates that the crimping on the inner conductor does not affect the breakdown voltage of a normal line because the potential gradient at the crimped points on the line without insulators is less than the potential gradient in the air gap near the insulators.

68. 7/8-Inch Line. All the measurements on the 7/8-inch and 1-5/8-inch lines were made at 175 kc. The first measurements were made on an ideal 7/8-inch line, for which the breakdown voltage was found to be 14.6 peak kilovolts; this is in good agreement with the maximum corona-free voltage computed from Eq. (15). This breakdown voltage is the optimum value for an ideal 7/8-inch line in dry air at atmospheric pressure and is the criterion for measurements on a normal line and various associated fittings. As will be shown later, the breakdown voltage of any given line can be increased by using a gas of higher dielectric strength than air and by increasing the gas pressure in the line.

69. If a number of ceramic insulators of the type used in normal 7/8-inch lines are placed on the inner conductor of

the ideal line, the breakdown voltage is reduced to 8.8 peak kilovolts at a relative humidity of 53 per cent at 24°C (see Test No. 2 of Table 1). With relative humidity reduced to 30 per cent at 24°C, the breakdown voltage was found to be 9.1 peak kilovolts (see Test No. 3 of Table 1). Breakdown voltage is a function of relative humidity, especially for high values of relative humidity. The higher value of the breakdown voltage for the latter measurement was due primarily to the lower value of the relative humidity.

70. Next, the smooth inner conductor was replaced by the inner conductor used in a normal line, except that the insulators were removed. The breakdown voltage for this condition was 9.6 peak kilovolts (see Test No. 4 of Table 1). On replacing this crimped inner conductor with one with ceramic insulators, a breakdown voltage of 9.1 peak kilovolts was obtained (see Test No. 5 of Table 1). These data clearly indicate that the potential gradient is the greatest in the air gap under the ceramic insulators in a normal line. This value of 9.1 peak kilovolts for the breakdown voltage of a normal line is approximately 60 per cent of the value for an ideal line, and corresponds to about 35 per cent of the power rating of an ideal line.

71. These measurements show that, if the voltage rating of a line is to be increased, the abnormally high potential gradient at the insulators must be reduced. The first attempt to accomplish this was to fill this air gap with a dielectric material such as Glyptal or Insa-lute. The dielectric strength of both of these materials is higher than for air, and should increase the breakdown voltage of the line. The experimental measurements (see Tests 6 and 8 of Table 1), however, showed no increase in breakdown voltage. Apparently, air pockets were formed either while filling the air gap with the dielectric material or during the drying-out process, and thus resulted in a breakdown voltage somewhat less than for a normal line.

72. The potential gradient in the air gap can be reduced by covering the surface of the insulator next to the inner conductor with a conducting material. Measurements were made wherein this contact surface of the insulators was covered with Aqua-dag and with liquid silver. No improvement of the breakdown voltage was obtained, and in one case the breakdown voltage was actually less than for a normal line (see Tests 7 and 9 of Table 1). This conducting layer undoubtedly decreases the potential gradient in the air gap, but sharp edges of conducting material occur at the edges of the insulator. These sharp edges produce a lower corona starting voltage than the normal value for a normal line, thereby actually reducing the breakdown voltage of the line.

73. Since the above methods were not successful in reducing the potential gradient in or near the air gap under the ceramic insulators, it was necessary to investigate other means which would give the desired results. The next logical possibility to eliminate this air gap would be to mold the insulator on the inner conductor. A close approximation to this type of line was obtained by machining Polystyrene insulators to fit tightly on the inner conductor. The breakdown voltage of this line was 14.6 peak kilovolts (see Test No. 10 of Table 1) or the same value as for an ideal line. Thus, the region of the abnormally high potential gradient near the insulator has been eliminated.

74. One method of manufacturing the equivalent of the above line would be to mold either Polystyrene or Mycalex insulators on the inner conductor. The gain in the power rating for a line with tight fitting Polystyrene insulators or its equivalent is illustrated by the fact that the maximum input power for this type of 7/8-inch line is approximately the same as for a normal 1-5/8-inch line. However, it must be realized that there can be no defective insulators in a line containing tight fitting Polystyrene insulators or its equivalent. Attention is invited to the fact that the lower the dielectric constant of the insulating material the easier it is to lower the abnormally high potential gradient near the insulators.

75. 1-5/8" Line. The breakdown voltage of an ideal 1-5/8-inch line was measured at 175 kc and found to be 21.8 peak kilovolts. This value is in good agreement with the maximum corona-free voltage as computed from Eq. (15). This breakdown voltage is the optimum value for a dry 1-5/8-inch line at atmospheric pressure and is the value one strives for in a normal line.

76. Table 2 shows the results of breakdown voltage measurements on 1-5/8-inch lines in air at atmospheric pressure; these lines are shown in Plates 6 to 8, inclusive. These data show a reduction in breakdown voltage from 14.5 kilovolts to 12.1 kilovolts in changing from Polystyrene insulators with round-headed anchor buttons to Alsimag insulators with flat-headed anchor buttons (see Tests No. 3 and 5, Table 2). With a relative humidity in the former case comparable to the 35 per cent in the latter, this reduction in breakdown voltage would be even greater.

77. Although the edges of the flat-headed anchor buttons were slightly rounded, the radius was so sharp that corona discharge readily took place. Silver plating the contact surfaces of the Alsimag insulators decreased the potential

gradient under the insulators sufficiently to increase the breakdown voltage by 13.5 per cent. This small improvement would not justify the increase in manufacturing cost. Another disadvantage in the flat-headed anchor buttons is the fact that it is impossible to remove an insulator, once it is locked in place, without breaking it.

78. Corona discharge also took place in the case of the round-headed anchor buttons, out, as mentioned above, at a considerably higher voltage. The Polystyrene insulators showed a decided disadvantage in their tendency to burn when subjected to corona discharge, thereby greatly reducing their dielectric strength. The arc during breakdown on some occasions burned entirely through the insulator from the tip of the anchor button to the outer sheath (see Plate 6, Fig. 1); the charred substance thus formed effectively short-circuited the line.

79. A sample line was then made up in which the inner conductor was perforated and fitted with Polystyrene pin type insulators spaced spirally around the inner conductor (see Plate 7, Fig. 1). A breakdown voltage of 17.3 peak kilovolts was obtained which was comparable to the line with Polystyrene disc insulators without anchor buttons, i.e., 17.5 peak kilovolts (see Test No. 4, Table 2). Evidence of corona was noted at the edges of the holes in the inner conductor, but careful removal of all burrs from the outer edge of the holes reduced this corona discharge and produced a substantial increase in breakdown voltage. Aside from possible mechanical weakness and the tendency of Polystyrene to "cold flow," this type of insulator has some important advantages. Foremost among these advantages are: (1) reduction of the potential gradient at the insulator; (2) the relatively small mass of the insulator results in minimum dielectric loss; (3) the simple design of the insulator would tend toward ease in manufacture.

Dielectric Strengths of Various Gases

80. In the normal and ideal lines, the breakdown voltage is a function of the dielectric strength of the gas in the line. Thus, it would be advantageous to use a gas with a dielectric strength greater than that of air. Other investigators (references (d) and (e)) have found that the dielectric strength of sulphur dioxide, Freon, and mixtures of air and Freon are greater than air at the power frequencies.

81. An 18-inch section of a normal 7/8-inch line was fitted with special end seals so that the dielectric strengths of the various gases could be measured (see Plate 5). The breakdown voltage of this line is given as a function of the gas pressure for a number of gases in Plate 15. A study of these curves reveals the following facts concerning the

dielectric strengths of the various gases at atmospheric pressure:

- (a) The dielectric strength of the rare gases, helium and argon, is only about 30 per cent of that of air. The ionization potential of both these gases is high.
- (b) The dielectric strength of nitrogen is a few per cent less than that of air.
- (c) The dielectric strength of carbon dioxide is slightly greater than air.
- (d) The dielectric strength of a mixture of air and carbon dioxide is greater than for pure carbon dioxide and about 15 per cent greater than for air.
- (e) The dielectric strength of Freon is nearly twice that of air.
- (f) The dielectric strength of sulphur dioxide is only a few per cent less than that of Freon.

82. The breakdown voltage of a normal 7/8-inch line is plotted as a function of the percentage (by volume) of Freon in air for the line at atmospheric pressure in Plate 17. The breakdown voltage varies from about 9.1 peak kilovolts for 100 per cent air to 18.8 peak kilovolts for 100 per cent Freon.

83. The breakdown voltage of a 7/8-inch line with tight fitting Polystyrene insulators is plotted as a function of the percentage by volume of Freon in air for the line at atmospheric pressure in Plate 18. The breakdown voltage increases from 14.6 peak kilovolts for 100 per cent air to 25 peak kilovolts for 100 per cent Freon. The percentage increase in breakdown voltage is not as great for this line as for the normal line with ceramic insulators.

Gas Pressure in Line Greater Than Atmospheric

84. It is a well known fact that the dielectric strength of a gas increases as the pressure is increased above one atmosphere. Hence, it would be logical to consider operating a high-power transmission line under pressures greater than one atmosphere. In addition, if the line is maintained at a pressure above atmospheric, it prevents "breathing" and with it a gradual process of contamination.

85. The breakdown voltage for a normal 7/8-inch line is plotted as a function of the pressure for various gases in Plate 15. The breakdown voltage increases with the increase in pressure. At a pressure of 30 pounds per square inch above atmospheric pressure, the breakdown voltage has increased from about 30 per cent to 70 per cent, depending upon the type of gas in the line.

86. The breakdown voltage of a 7/8-inch line with tight fitting Polystyrene insulators is plotted as a function of gas pressure in Plate 19 for various mixtures of air and Freon. The breakdown voltage for 100 per cent air in the line increases from 14.6 peak kilovolts at one atmosphere to 25.1 peak kilovolts at 30 pounds per square inch above atmospheric pressure. The peak power rating of this line at 30 pounds per square inch would be 2.7 times the value at atmospheric pressure. It should be noted that the breakdown voltage increased at all pressures as the percentage of Freon increased up to 50 per cent. No increase in the breakdown voltage was observed when the percentage of Freon was increased from 50 to 75 per cent at a pressure of 30 pounds per square inch above one atmosphere. It was observed during the course of these measurements that, at the lower concentrations of Freon at pressures up to 15 pounds per square inch, the Polystyrene insulators were rarely damaged by voltage breakdown. At 30 pounds per square inch pressure and 50 to 75 per cent Freon, the insulators were invariably badly damaged by arc-over.

Detrimental Effects of the Various Gases

87. An ideal gas would have a high dielectric strength, would be inert and would not disintegrate or undergo a chemical change in an electric arc. The dielectric strength of the inert, stable, rare gases (helium and argon) was extremely low (see Plate 15), and thus they were not suitable. Nitrogen and carbon dioxide are stable gases, but their dielectric strengths were about the same as air. The dielectric strengths of both Freon and sulphur dioxide are high, but both of these gases have inherent disadvantages. Freon and sulphur dioxide are normally very stable gases, but they are both decomposed by the electric arc during voltage breakdown. This decomposition results in the liberation of their highly active constituents (chlorine, fluorine, sulphur). The fluorine from the Freon reacts with the ceramic insulators, forming compounds which apparently have lower dielectric strength than the original ceramic. This was indicated by the fact that, after an insulator in a test sample had once been subjected to an arc in Freon, the original breakdown voltage could never be reproduced. The pungent odor of chlorine and fluorine was very noticeable when bleeding off the gas from the line after an arc-over had occurred. With sulphur dioxide, the liberated

constituents reacted with the copper of the line, resulting in the formation of a black, sooty substance which fairly covered the surface of the insulators. This was the reason for taking only the two points for this gas as shown in Plate 15. If, however, a reasonable factor of safety were allowed when using either of these gases, a very substantial increase in safe operating voltage over air or nitrogen could be realized in any line.

Gas Pressure Less Than One Atmosphere

88. Measurements of breakdown voltage were made on a normal line for air pressures less than one atmosphere. This breakdown voltage is plotted as a function of absolute pressure in mm of mercury in Plate 16. The breakdown voltage attains its minimum value of about 0.47 peak kilovolt at a pressure of about 1 to 2 mm of mercury. A pressure of 1.5 mm of mercury corresponds to about 1/500 of an atmosphere. The breakdown voltage would increase rapidly as the pressure decreases below 0.2 mm. It is of interest to note that the low absolute pressure required in order to obtain a high breakdown voltage would not be practical in a Naval installation.

Transmission Line Fittings

89. The previous discussion has been limited to a short section of line in which the end effects have been eliminated. In any transmission line installation a number of fittings such as end seals, junction boxes, couplings for inner and outer conductors and differential expansion joints must be used. The electrical design requirements of these various fittings are (a) the change in impedance of the line at the various fittings should be reduced to a practical minimum and (b) the breakdown voltage of the fittings should be at least equal to that of the line.

90. The breakdown voltages of these various fittings were measured in air and these data are tabulated in Table 3. Care was taken in making the measurements in order to obtain the breakdown voltage of each particular fitting. The breakdown voltages of a number of fittings, such as the solderless couplings and soldered butt joints for the outer conductor and the couplings for the inner conductor, were the same as for an ideal line. On the other hand, breakdown voltages of the two-way junction boxes, differential expansion joints, anchor joints and end seals were less than for an ideal line. The breakdown voltage of the end seal manufactured by Isolantite, Inc. was 6.7 peak kilovolts or 46 per cent of the value for an ideal line. The importance of obtaining smooth soldered joints is indicated by the fact that the breakdown voltage of an ideal line with a drop of solder on the inner conductor

is 6.9 peak kilovolts or 47 per cent of the value for an ideal line, and the breakdown voltage of an ideal line with a drop of solder on the inside surface of the outer conductor is 10.0 peak kilovolts or 68 per cent of the value for an ideal line.

SUMMARY

91. The various factors affecting the design of high-power transmission lines for pulsing apparatus have been investigated individually. These factors included:

- (a) The optimum ratio of b/a or the ratio of b/a that will give the maximum power rating for a line with a given size outer conductor. (Note: b and a are the radii of the outer and inner conductors, respectively.)
- (b) The effect of a load mismatch on the power rating of the line.
- (c) The power rating of an ideal line using dry air at atmospheric pressure as the dielectric.
- (d) The factors affecting the design of insulators.
- (e) The dielectric strengths of various gases and mixtures of gases at atmospheric pressure.
- (f) The increase in the dielectric strengths of a number of gases and mixtures of gases with an increase in pressure.
- (g) The dielectric strength of air at pressures less than atmospheric.
- (h) The effect of the various line fittings, such as expansion joints, couplings for inner and outer conductors, two-way junction boxes, end seals, etc. upon the power rating of the line.

92. It was found in the theory that the input power to a matched line with a given size of outer conductor was a maximum for the ratio of $b/a = 1.8$. The efficiency of a line is a maximum for a ratio of $b/a = 3.6$. Thus, the transmission line design for maximum input power is not operating at its maximum efficiency. The ratio of b/a for maximum output or load power is a function of the efficiency of the line or the length and size of the line and the frequency. The ratio of b/a for maximum load power was found to be 1.9 for a 200-foot 7/8-inch line at 200 mc and 2.1 for the same line at 3000 mc. The ratio of b/a for maximum input and load power is the same for very short lines.

93. The ratio of b/a for maximum input and load powers for a mismatched transmission line was also studied. In this case the ratios of b/a for maximum input and load powers were the same as for a matched line, providing the standing wave ratio at the load end of the line was greater than 0.5. This does not mean that the maximum input power ratings of a matched and a mismatched line are the same. In fact, the power rating of a mismatched line is equal to the product of the power rating of a matched line and the standing wave ratio. Since the ratio of b/a for maximum input power is not a function of the standing wave ratio, the optimum value of this ratio is the same for a matched line, a line mismatched at the load end only and a line having reflection points all along its length.

94. In reference (b) it was found more difficult to obtain the theoretical value of the maximum corona-free voltage for lines with a ratio of b/a less than about three or four than above this ratio. In other words, surface irregularities of the inner conductor had a greater detrimental effect for the lower values of the ratio of b/a . In view of these facts, it is recommended that the ratio of b/a for maximum power transmission should be between 2.3 and 2.8. The maximum in the curve for the power rating of a line as a function of the ratio of b/a is very broad so that the power ratings for ratios of b/a between 2.3 and 2.8 are only a few per cent less than the maximum value.

95. The breakdown voltage of a 1/4-inch ideal line was measured over the frequency range of 175 to 18,000 kc, and was found to decrease very gradually as the frequency increased (see Plate 12). The breakdown voltage of the 1/4-inch line was taken to be slightly less than the value at 18 mc on Plate 12. The constants A and B in Eq. (15) at 200 mc are $A = 50$ and $B = 0.21$ if one assumes B to be independent of the frequency.

96. The breakdown voltage was measured as a function of the frequency for two 10 mm spheres that were spaced 2 mm in reference (c). For this condition, the breakdown was found to increase with the frequency for frequencies greater than 2.0 mc. The above data indicate that the breakdown voltage as computed from Eq. (15) may be too low. Thus, if an error exists in the formulas for computing the power ratings of the transmission lines, it will increase the safety factor for the line. The constant B may be somewhat higher at 200 mc than at 175 kc, and thus the ratio of b/a for maximum power input or load power would be a few per cent greater at 200 mc than at 175 kc. This optimum ratio b/a at 200 mc would be less than 2.3 or the minimum design value.

97. Measurements were made of the breakdown voltage of 1/4-inch, 3/8-inch, 7/8-inch and 1-5/8-inch lines at 175 kc. The measured values of breakdown voltage were in good agreement with values computed from Eq. (15).

98. From the breakdown-voltage measurements on 7/8-inch and 1-5/8-inch lines that employed various types of insulators, the following facts were established concerning the design of insulators. The breakdown voltage of an ideal line is used as a standard for comparison purposes.

- (a) The potential gradient is a maximum at the surface of the inner conductor in an ideal line.
- (b) The potential gradient is generally a maximum at some point along the surface of the inner conductor in a normal line (air gap at an insulator or a crimping point).
- (c) Crimping or otherwise distorting the shape of the inner conductors at the insulators lowers the breakdown voltage below the value for an ideal line.
- (d) If an air gap exists between the inner conductor and the insulator, then the potential gradient in this air gap will be greater than at the surface of the inner conductor in an ideal line.
- (e) The potential gradient in a normal 7/8-inch line is greater in the air gap between the inner conductor and the isolantite insulator than at any other point along the inner conductor. The breakdown voltage of a normal 7/8-inch line is about 60 per cent of the value for an ideal line. This means that the potential gradient in the air gap between the insulator and the inner conductor is about 50 per cent greater than the maximum value for an ideal line.
- (f) The potential gradient was a maximum at the metal buttons that are used to hold the insulators in place on the 1-5/8-inch lines (see Fig. 1 and 2 of Plate 6 for details of the insulator design). Note the metal buttons are in the air gap between the insulator and the inner conductor. The breakdown voltage of this line is about 60 per cent of the value for an ideal line. The power rating of a line is proportional to the square of the breakdown voltage. Thus, the power rating of this line would be only about 36 per cent of the value for an ideal line of the same size. Attention is

invited to the fact that the breakdown voltage of this 1-5/8-inch line is slightly less than for an ideal 7/8-inch line; hence, the power rating would also be less.

- (g) The facts pointed out in (e) and (f) above emphasize the importance of eliminating the high potential gradient in the air gap between the insulators and the inner conductor.
- (h) No improvement in the breakdown voltage for the normal 7/8-inch line was obtained by filling the air gap between the inner conductor and the Isolantite insulator with Glyptal or Insa-lute. From this result, it was concluded that air pockets were formed either during the process of filling in the air gap or during the drying-out process.
- (i) The surfaces of the Isolantite insulators next to the inner conductor for the 7/8-inch line were covered with a conducting material such as Aquadag and liquid silver. Again the breakdown voltage was about the same as for a normal line or about 60 per cent of the value for an ideal line (see Par. 72).
- (j) Polystyrene insulators were machined to give a tight fit on the inner conductor of the 7/8-inch line. The breakdown voltage of this line was the same as for an ideal line, thus indicating that the air gap between the inner conductor and the insulators had been eliminated. The power rating of this line would be about 2.5 times the value for a normal line with Isolantite insulators. It may be possible to construct such a line by molding either Polystyrene or possibly Mycalex insulators on the inner conductor.
- (k) The potential gradient in the air gap between the insulator and the inner conductor decreases as the dielectric constant of the insulator decreases providing all other factors remain constant.

99. The breakdown voltage or the power rating of the line can be increased by using a gas with a dielectric strength greater than that of dry air or by increasing the pressure in the line. The following facts were established from these measurements:

- (a) The dielectric strengths of helium and of argon are about one-third of that of dry air.
- (b) The dielectric strengths of dry air, nitrogen and oxygen are about the same.
- (c) For air at room temperature, the dielectric strength decreases as the relative humidity increases. Attention is invited to the fact that it may be difficult to keep the air in a line dry when the line is at a low temperature.
- (d) The dielectric strengths of Freon and of sulphur dioxide are about 1.9 times the value for dry air. The power rating of a line using these gases would be about 3.5 times the value for the same line with dry air. Both of these gases are unstable in an electric arc. Freon decomposes into fluorine and chlorine, each of which is a poison and is very active chemically.
- (e) The dielectric strengths of all the gases at 30 pounds per square inch above atmospheric pressure are about 50 per cent greater than the values at atmospheric pressure.
- (f) It is not practical to operate lines at pressures less than atmospheric (see Par. 88).

100. The breakdown voltages of the various line fittings, such as end seals, couplings for inner and outer conductors, two-way junction boxes, etc., were also measured and the results are tabulated in Table 3. The breakdown voltages of most of these fittings were less than for an ideal line. The breakdown voltages of the fittings should be at least equal to that of the line when the line is used with high-power pulsing apparatus. The importance of maintaining both the inner and outer conductors smooth during the assembly process is indicated by the fact that the breakdown voltage of a 7/8-inch line with a smooth inner conductor and no insulators, but with a lump of solder on the inner conductor, is less than 50 per cent of the value for an ideal line.

Design of High-Power Transmission Lines

101. The maximum safe input power to a transmission line can be computed from the following formula:

$$P_i = \frac{A^2 F^2 H^2 S^2 T^2 R k^{1/2} a (a^{1/2} + B)^2 \log_e \frac{b}{a}}{60} \quad (34)$$

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Where P_i is the maximum safe input power to the line in megawatts (for pulse operation--not continuous duty).
 b is the inside radius of the outer conductor in inches.
 a is the radius of the inner conductor in inches.
 (b/a) ratio should be between 2.3 and 2.8 (see Par. 40).
 k is the effective dielectric constant of the line.
 It can be computed from Eq. (2) or (3).
 $B = 0.21$.
 $A = 50$ at 200 mc. This value of A was estimated from Plate 12. If an error should exist in the above values of A and B , this error would be in such a direction as to increase the safety factor in the value of P_i as computed from Eq. (34) (see Par. 96).
 F is the design factor for the insulators and fittings. If the breakdown voltages of a short section of line with insulators and of all the various fittings are known, then the ratio of the lowest breakdown voltage of the above values to that for an ideal line is the factor F . The breakdown voltage of the ideal line is computed from Eq. (15).
 T is the ratio of the dielectric strength of the gas in the line to that of dry air at atmospheric pressure. T can be read directly from Plate 20 for a number of gases and for pressures up to 30 pounds per square inch above atmospheric.
 S is the safety factor and should be about 0.8 if the gas in the line is kept dry. For the unstable gases, namely, Freon and sulphur dioxide, this factor should be somewhat less.
 R is the standing wave ratio at the input end of the line.
 H is the ratio of the initial corona voltage to the maximum corona-free voltage. H is approximately 0.7.

102. It will be of interest to compute the power rating of a number of transmission lines from Eq. (34). For the first example, let us consider a 7/8-inch transmission line with Isolantite insulators which is to be used at 200 mc. The maximum voltage rating of this line and the various fittings are given in Tables 1 and 3. It is assumed that all of the fittings listed in Table 3 are used in the line. The line is assumed to be filled with dry air at atmospheric pressure. The values of the various constants in Eq. (34) are as follows:

$A = 50$,
 $B = 0.21$,
 $b = 0.392$ inch.
 $a = 0.125$ inch.
 $T = 1$ for dry air at atmospheric pressure (see Plate 20).
 $k = 1.30$ for line with Isolantite insulators spaced three inches.

$F = 0.459$. The end seal (see Test No. 8 of Table 3) is the weakest element in the line, with a breakdown voltage of 6.7 peak kilovolts. The breakdown voltage of an ideal line is given in Test No. 1 of Table 1 and is 14.6 peak kilovolts. The maximum corona-free voltage as computed from Eq. (15) is approximately the same as the breakdown voltage. In this case, F is the ratio of 6.7/14.6.
 $H = 0.7$ (see Par. 19).
 $S = 0.8$.

103. After substituting the above values in Eq. (34), one obtains for the input power rating of the line

$$P_i = 0.071 \text{ peak megawatt or } 71 \text{ peak kilowatts.}$$

104. If the fittings and insulators were redesigned so that the breakdown voltage of the line were the same as for an "ideal" line or smooth concentric cylinders of the same size and Freon were used in the line at a pressure of 15 pounds per square inch above atmospheric, then F would be increased from 0.459 to 1.0 and T would be 2.35 instead of 1.0 (see Curve 7 of Plate 20). Since Freon is an unstable gas in an electric arc, it would be desirable to change the safety factor S from 0.8 to 0.7. All of the other terms would be the same as given in the previous example. The input power rating of this 7/8-inch line would be

$$P_i = 1.4 \text{ peak megawatts or } 1400 \text{ peak kilowatts.}$$

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Table 1

Breakdown-Voltage Measurements at
175 Kc on 7/8-Inch Coaxial Transmission
Line in Air at Atmospheric Pressure

Test No.	Line Measured	Rel. Hum. %	Temp. °C	Breakdown Voltage (Peak Kv)
1	Ideal line.	53	26	14.6
2	Ideal line modified by addition of ceramic insulators.	53	27	8.8
3	Ideal line modified by addition of ceramic insulators.	30	24	9.1
4	Inner conductor crimped; ceramic insulators removed.	57	26	9.6
5	Normal line.	40	25	9.1
6	Inner conductor smooth; ceramic insulators anchored in place with Glyptal.	50	23	8.7
7	Inner conductor smooth; ceramic insulators anchored in place with Aqua-dag.	60	23	8.7
8	Inner conductor smooth; ceramic insulators anchored in place with Insa-lute (liquid porcelain).	60	23	5.3
9	Inner conductor smooth; contact surfaces of ceramic insulators metallized with silver.	60	23	7.5
10	Ideal line modified by addition of Polystyrene insulators machined to tight fit on inner conductor.	30	26	14.6

Table 2

Breakdown-Voltage Measurements at
175 Kc on 1-5/8-Inch Coaxial Transmission
Line in Air at Atmospheric Pressure

Test No.	Line Measured	Rel. Hum. %	Temp. °C	Breakdown Voltage (Peak Kv)
1	Ideal line.	80	24	20.0
2	Ideal line.	43	29	21.8
3	Line shown in Plate 6, Fig. 1.	53	30	14.5
4	Line shown in Plate 6, Fig. 1, but with anchor buttons removed.	53	30	17.5
5	Line shown in Plate 6, Fig. 2.	35	28	12.1
6	Line shown in Plate 6, Fig. 2, with contact surfaces of insulators metallized.	38	23	13.7
7	Line shown in Plate 7, Fig. 2.	19	24	14.9
8	Line shown in Plate 7, Fig. 1.	43	30	17.3
9	Line shown in Plate 8, Fig. 1.	19	24	19.5
10	Line shown in Plate 8, Fig. 2.	19	24	19.5

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Table 3

Breakdown-Voltage Measurements at 175 Kc on
Individual Fittings for 7/8-Inch Coaxial Trans-
mission Line in Air at Atmospheric Pressure.
(See Reference (g) for Detail Drawings of Fittings.)

Test No.	Fitting	Mfr.	Cat. No.	Rel. Hum. %	Temp. °C	Breakdown Voltage (Peak Kv)
1	Solderless Coupling.	*C.P.C.	88	40	25	14.6
2	Differential Expansion Coupling.	C.P.C.	485	67	26	8.2
3	Differential Expansion Coupling (No Insulator).	C.P.C.	485	67	26	13.1
4	Anchor Joint.	C.P.C.	483	24	22	7.1
5	Anchor Joint.	C.P.C.	483A	24	22	7.5
6	Two-Way Junction Box.	C.P.C.	480	40	24	11.4
7	End Seal.	C.P.C.	476	61	24	6.7
8	End Seal.	Isolantite Inc.	21967	61	24	10.4
9	Solder Coupling with 0.1" Lump of Solder on Inner Conductor.			24	22	6.9
10	Solder Coupling with 0.1" Lump of Solder on Inside of Outer Conductor.			24	22	13.0

* Communication Products Co.

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$\frac{7}{8}$ " COAXIAL TRANSMISSION LINE

USUAL POSITION OF INSULATORS IN ACTUAL INSTALLATION

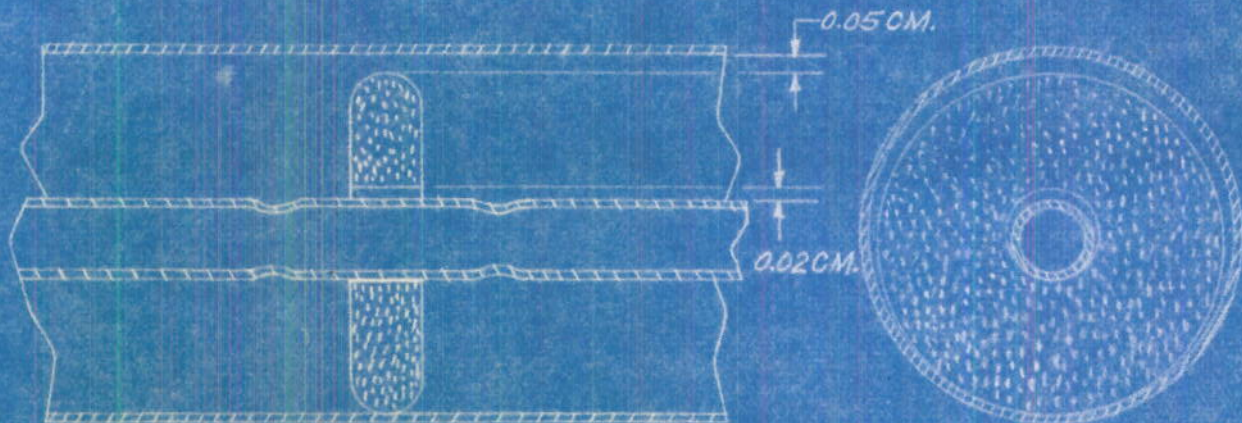


FIG. 1

LINE WITH CONDUCTORS AND INSULATORS EXACTLY CONCENTRIC

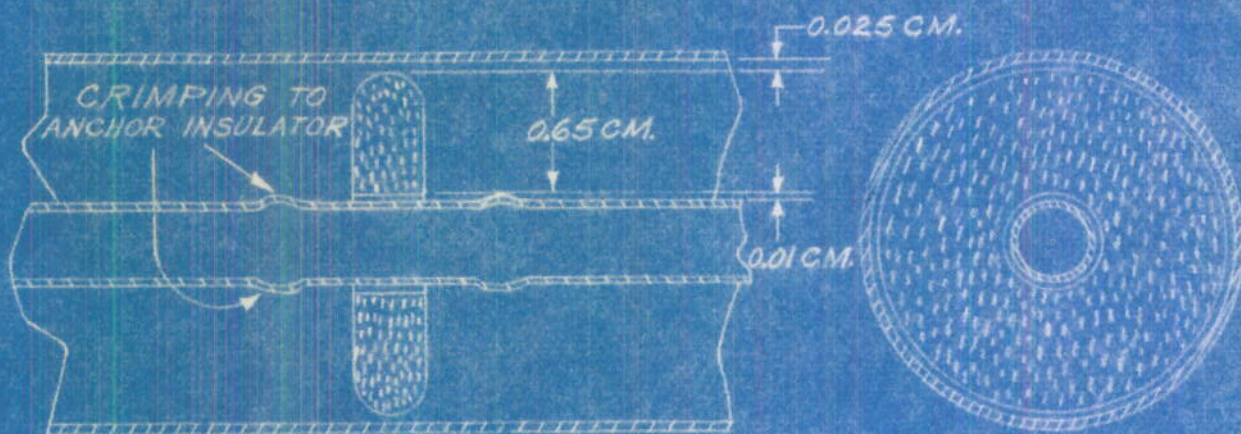
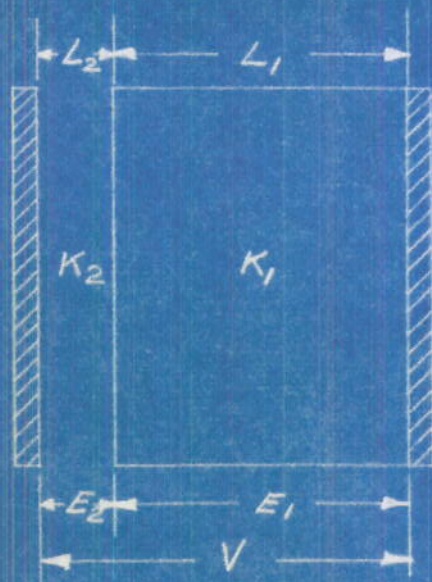


FIG. 2

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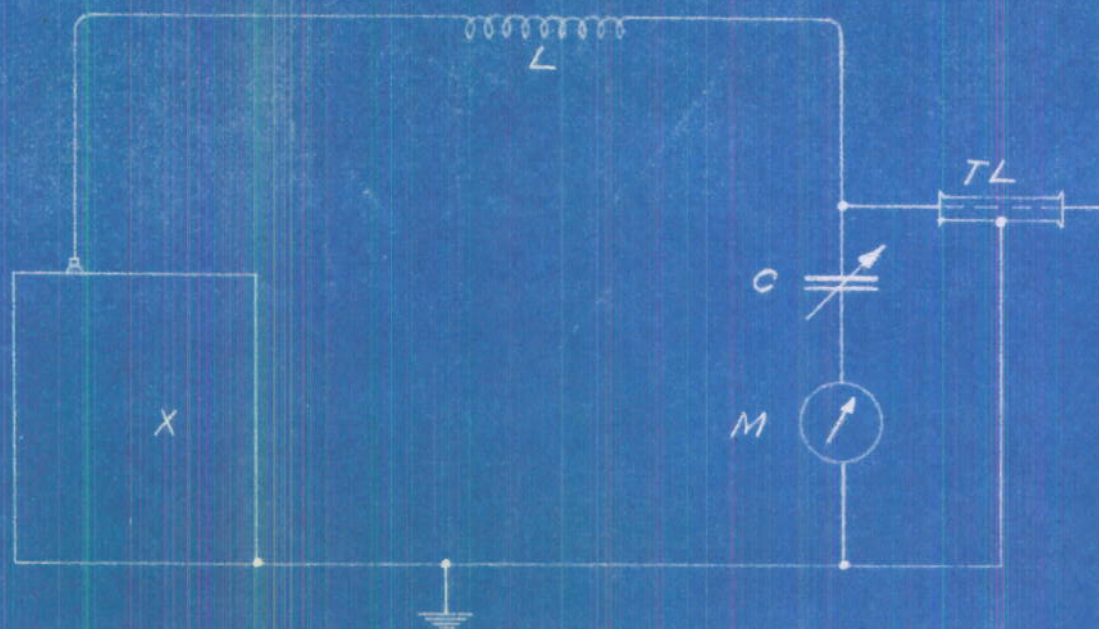
PLATE 1

REFERENCE:- PARAGRAPH 41



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SCHEMATIC DIAGRAM OF CIRCUIT USED FOR
VOLTAGE TESTS - 175 KC. TO 600 KC.



M - R. F. AMMETER.

C - CAPACITOR (DUMMY ANTENNA).

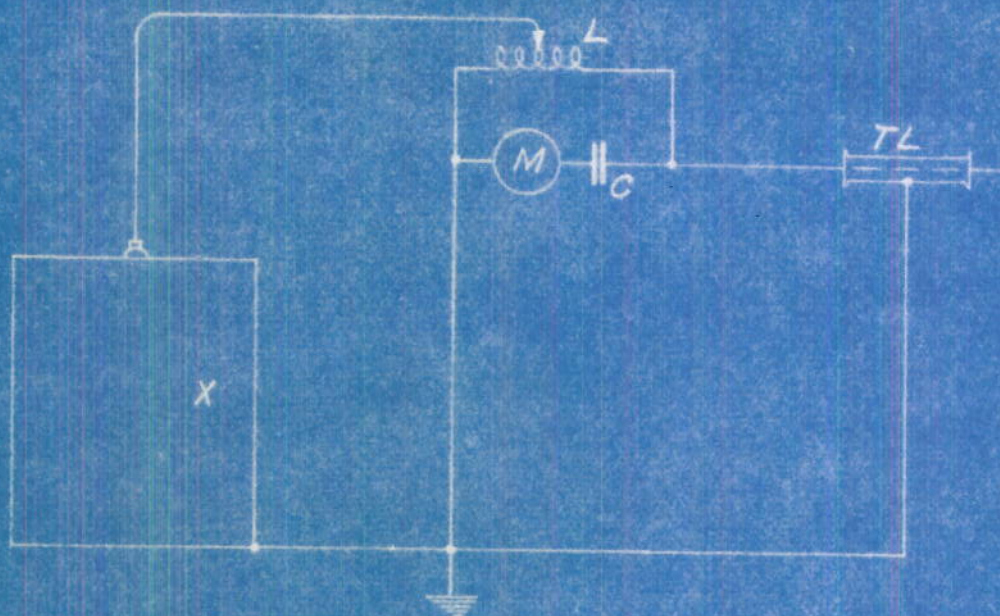
L - EXTERNAL LOADING INDUCTANCE.

TL - SAMPLE OF COAXIAL LINE UNDER TEST.

X - MODEL TAQ-4 TRANSMITTER.

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SCHEMATIC DIAGRAM OF CIRCUIT USED FOR
VOLTAGE TESTS - 2000 KC. TO 18000 KC.



M - R.F. AMMETER.

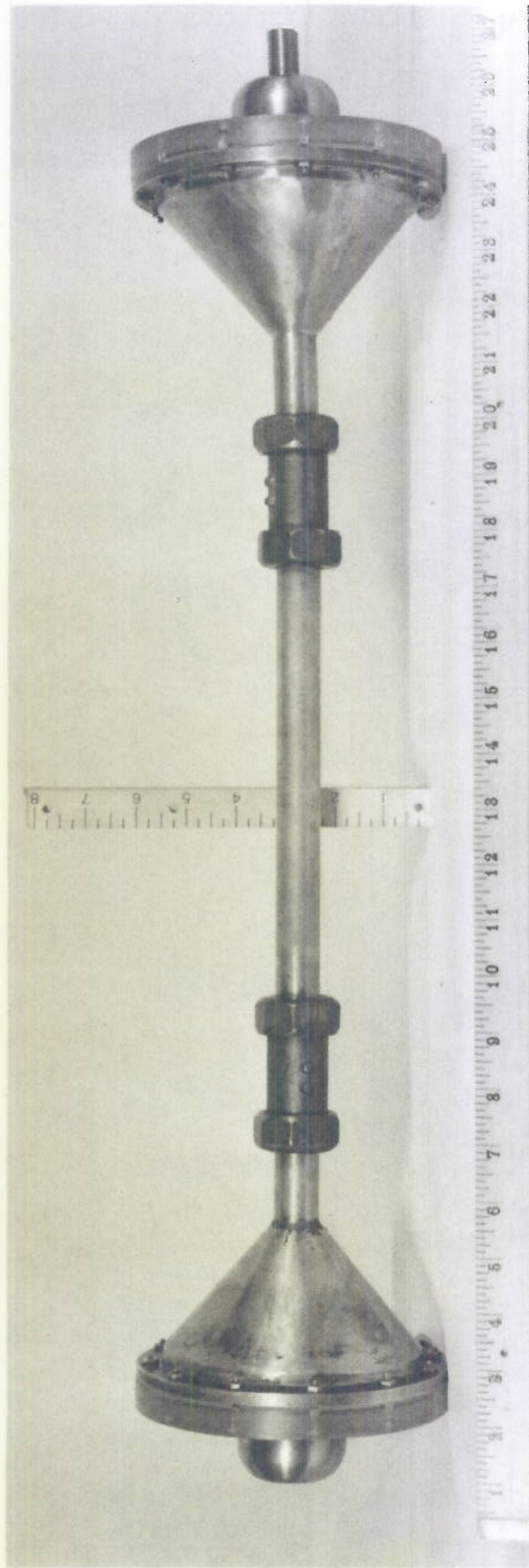
C - 51 $\mu\mu\text{fd.}$ OR 24.6 $\mu\mu\text{fd.}$ EIMAC VACUUM
CAPACITOR DEPENDING ON FREQUENCY.

L - VARIABLE TAPPED INDUCTANCE.

TL - SAMPLE OF COAXIAL LINE UNDER TEST.

X - MODEL XTBK TRANSMITTER.

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TYPES OF INSULATORS TESTED IN $1\frac{5}{8}$ " COAXIAL LINE.



FIG. 1

- a - OUTER SHEATH, $1\frac{5}{8}$ " O.D., 0.049 WALL.
- b - INNER CONDUCTOR, $\frac{5}{8}$ " O.D., 0.042 WALL.
- c - POLYSTYRENE INSULATOR (LOOSE FITTING)
- d - ROUND-HEAD ANCHORING BUTTON.
- e - SEMI-CIRCULAR GROOVE IN INSULATOR.
- f - COIL SPRING.
- g - GAS VENTS.

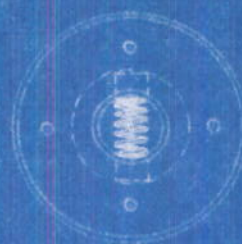
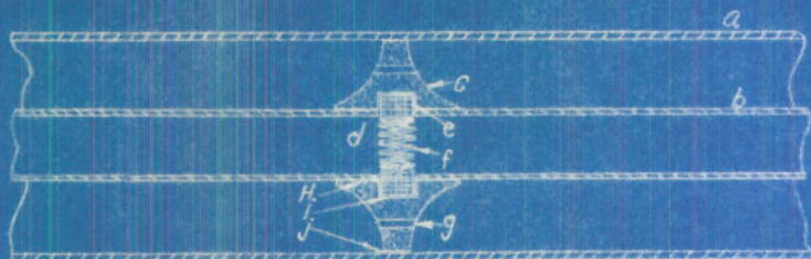


FIG. 2

- a - OUTER SHEATH.
- b - INNER CONDUCTOR.
- c - "ALSIMAG" INSULATOR (LOOSE FITTING).
- d - FLAT-HEADED ANCHORING BUTTON.
- e - SQUARE GROOVE IN INSULATOR.
- f - COIL SPRING.
- g - GAS VENTS.
- h-i-j - CONTACT SURFACES METALIZED (SEE PAR. 60).

NOTE.

SPACING BETWEEN INSULATORS - 6 INCHES

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PLATE 6

TYPES OF INSULATORS TESTED IN $1\frac{5}{8}$ " COAXIAL LINE.

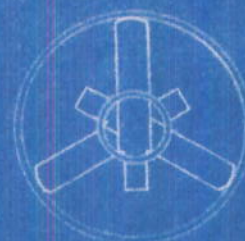


FIG. 1

a - OUTER SHEATH, $1\frac{5}{8}$ " O.D., 0.049 WALL.

b - INNER CONDUCTOR, $\frac{5}{8}$ " O.D., 0.042 WALL.

c - $\frac{1}{4}$ " DIAM. POLYSTYRENE 912A PIN INSULATOR (MACHINED TO TIGHT FIT IN PERFORATIONS.)

d - SHOULDER FOR ANCHORING INSULATOR.

NOTE:

SPACING BETWEEN INSULATORS - 3 INCHES.

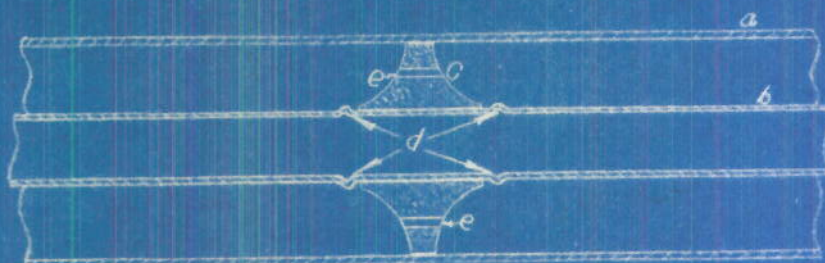


FIG. 2

a - OUTER SHEATH.

b - INNER CONDUCTOR.

c - 'ALSIMAG' INSULATOR (LOOSE FITTING).

d - INTERNALLY ROLLED PROTRUSION FOR ANCHORING INSULATOR.

e - GAS VENTS.

NOTE:

SPACING BETWEEN INSULATORS - 6 INCHES.

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TYPES OF INSULATORS TESTED IN $1\frac{5}{8}$ " COAXIAL LINE.

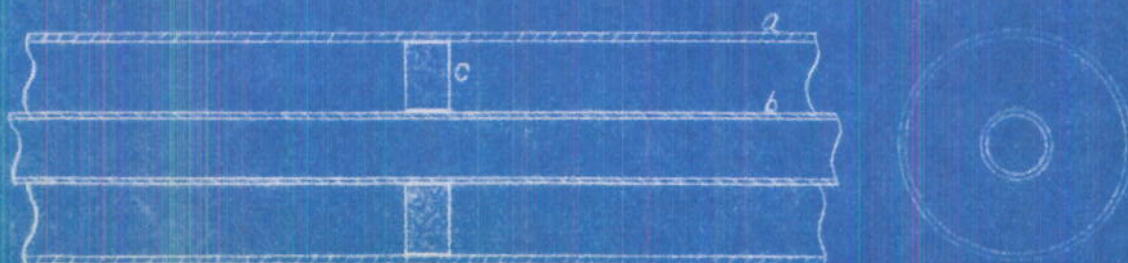


FIG. 1

- a - OUTER SHEATH, $1\frac{5}{8}$ " O.D., 0.049" WALL.
 b - INNER CONDUCTOR, $\frac{5}{8}$ " O.D., 0.042" WALL.
 c - POLYSTYRENE DISC INSULATOR, $\frac{1}{4}$ " THICK, MACHINED TO TIGHT FIT ON INNER CONDUCTOR, AND SLIP FIT INSIDE OF OUTER SHEATH.

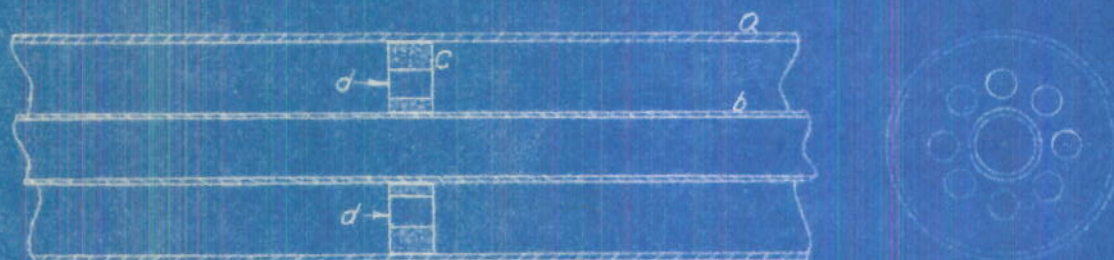


FIG. 2

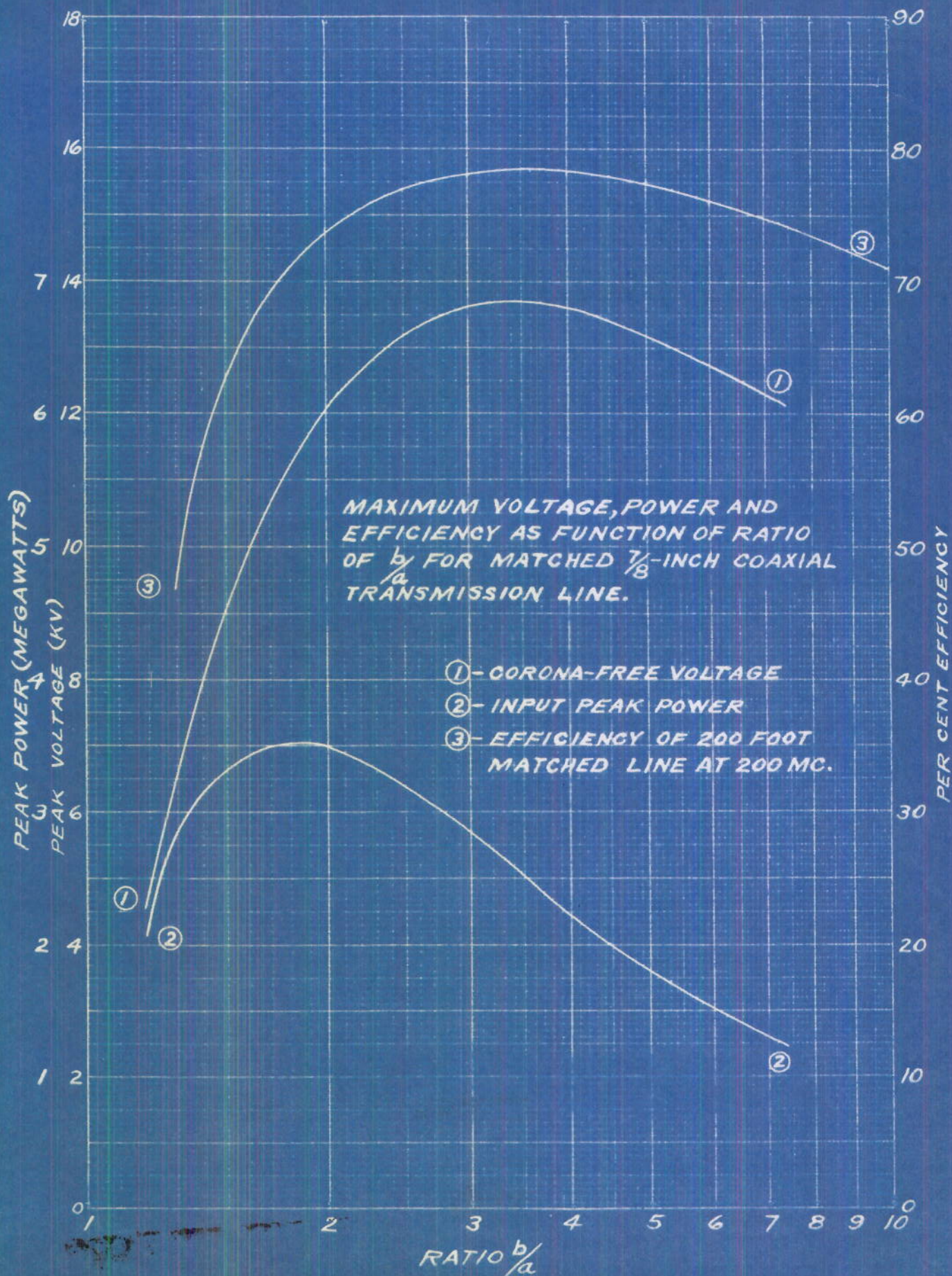
- a - OUTER SHEATH, $1\frac{5}{8}$ " O.D., 0.049" WALL.
 b - INNER CONDUCTOR, $\frac{5}{8}$ " O.D., 0.042" WALL.
 c - POLYSTYRENE DISC INSULATOR, $\frac{1}{4}$ " THICK, MACHINED TO TIGHT FIT ON INNER CONDUCTOR, AND SLIP FIT INSIDE OF OUTER SHEATH.
 d - $\frac{1}{4}$ " HOLES FOR REDUCING VOLUME OF SOLID DIELECTRIC.

NOTE:

INSULATOR SPACING - 6 INCHES.

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PLATE 8



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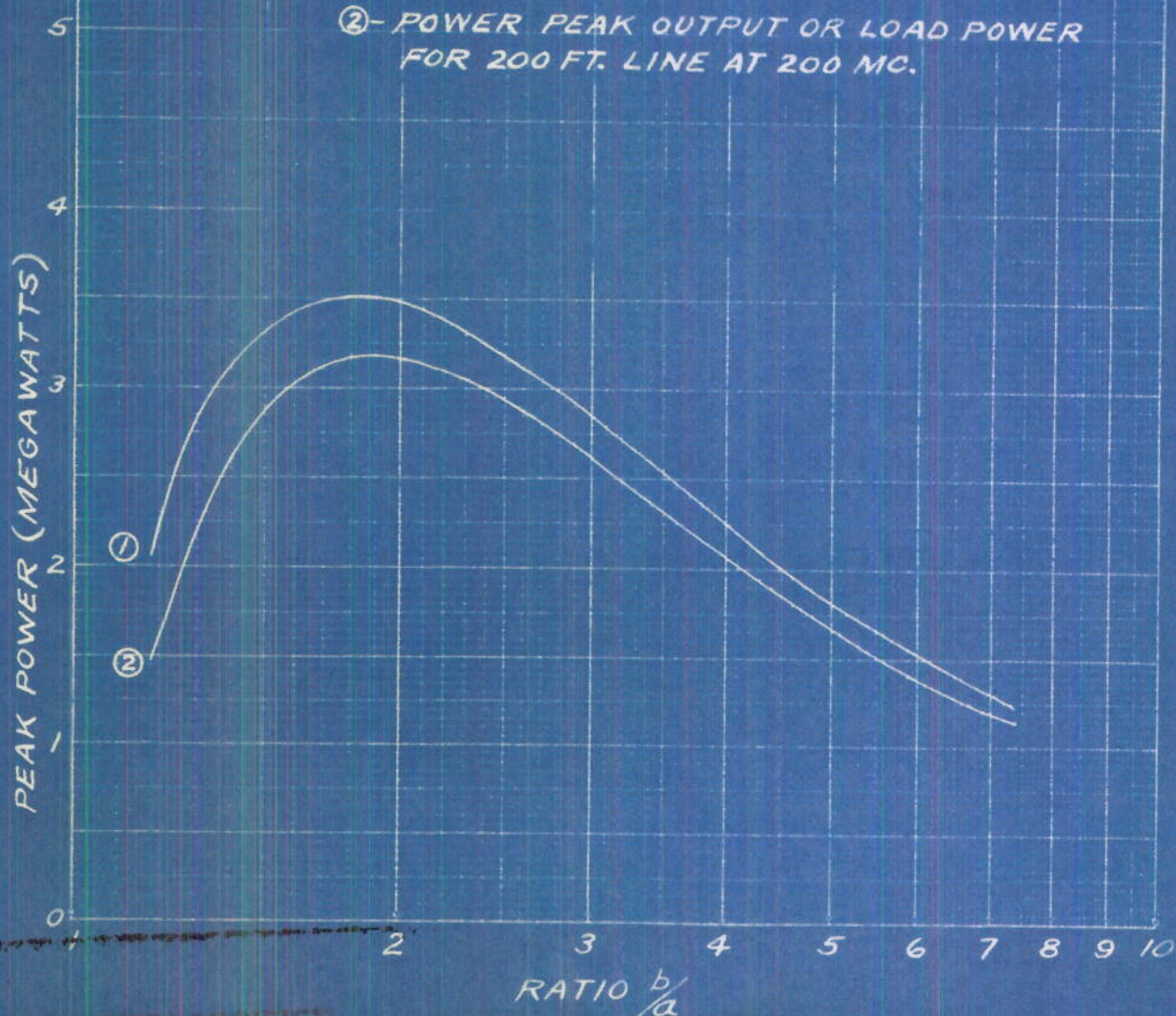
PLATE 9



PEAK POWER AS FUNCTION OF RATIO OF
 $\frac{b}{a}$ FOR $\frac{7}{8}$ " COAXIAL TRANSMISSION LINE.

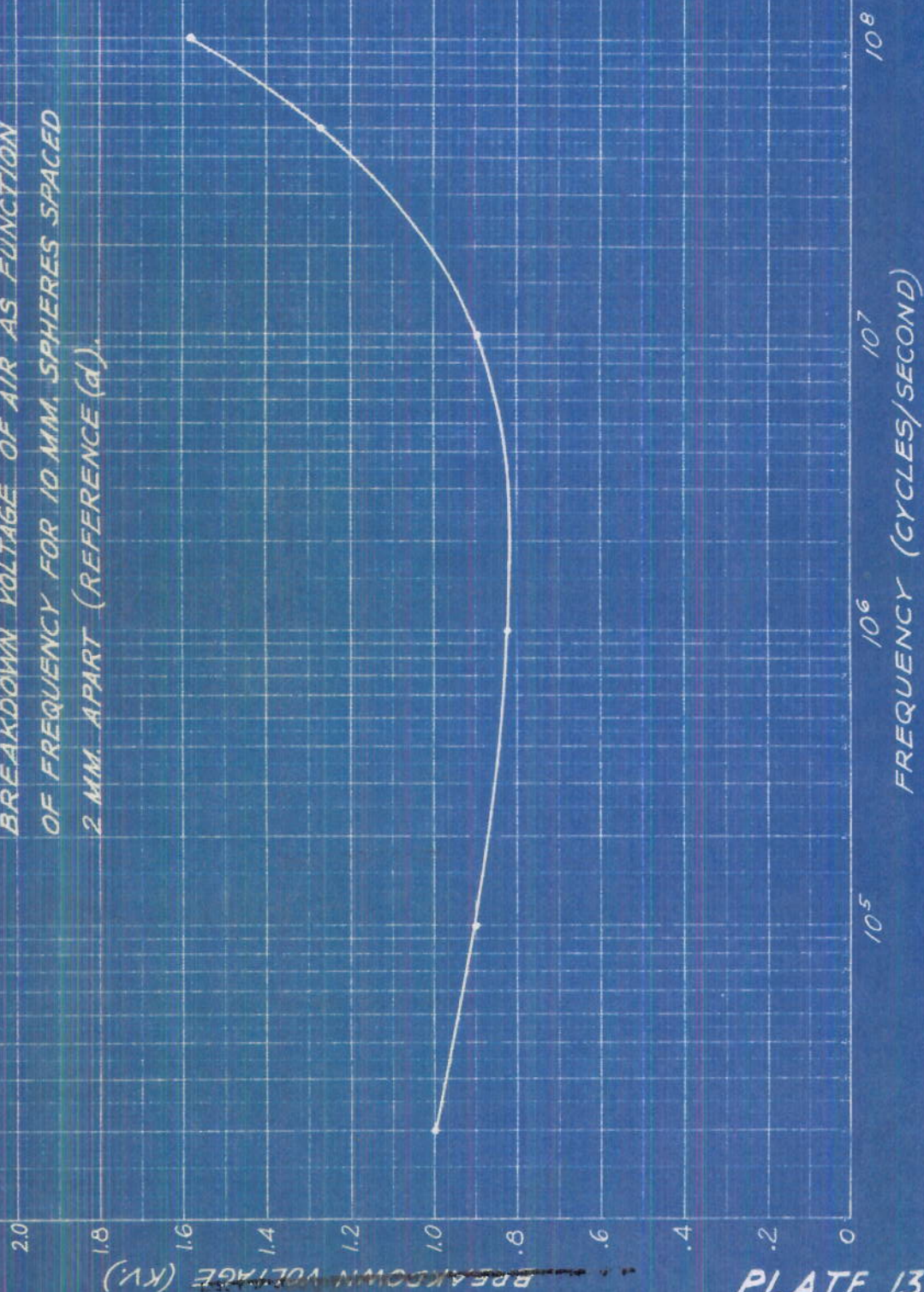
①- INPUT PEAK POWER

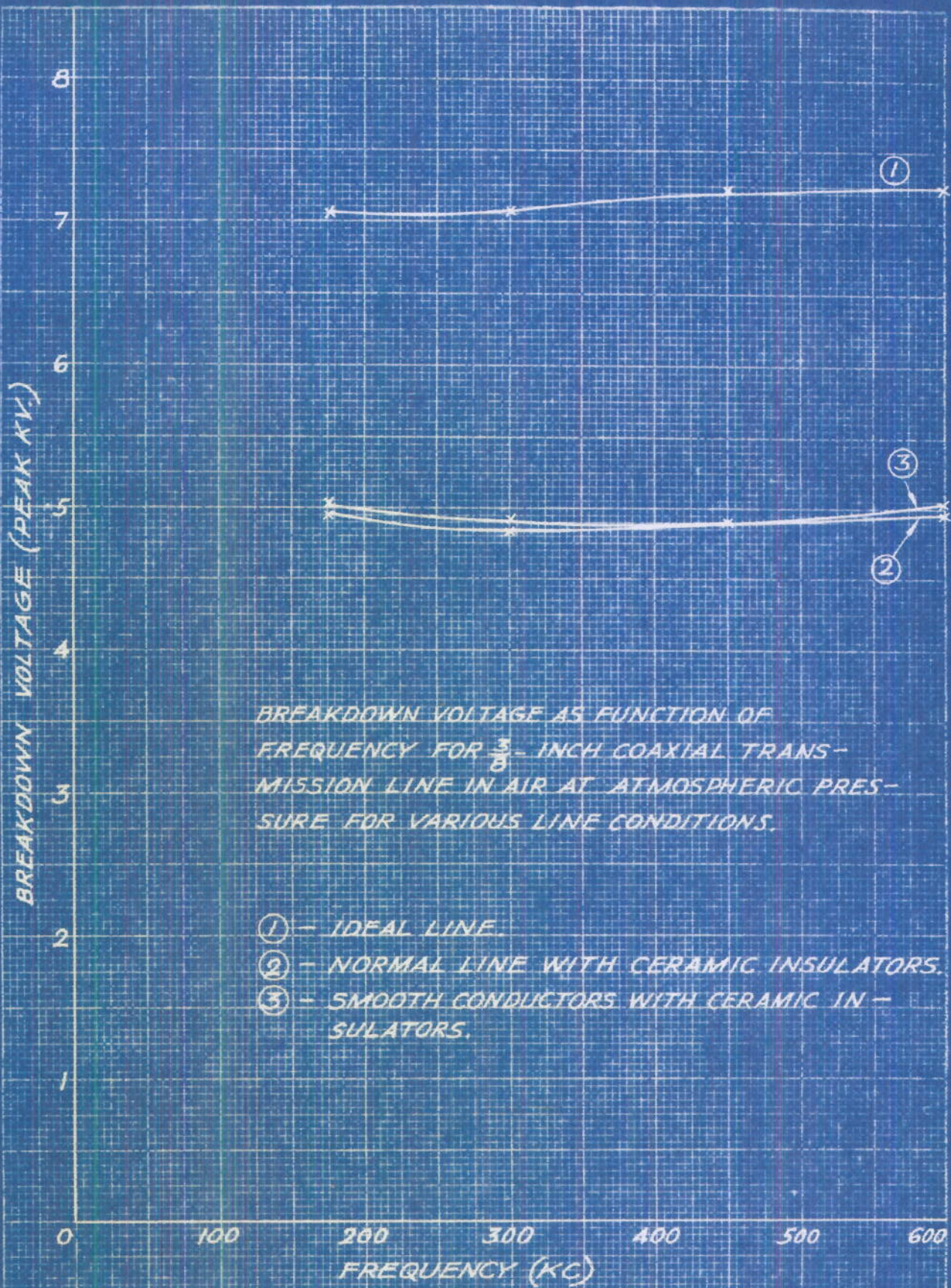
②- POWER PEAK OUTPUT OR LOAD POWER
FOR 200 FT. LINE AT 200 MC.

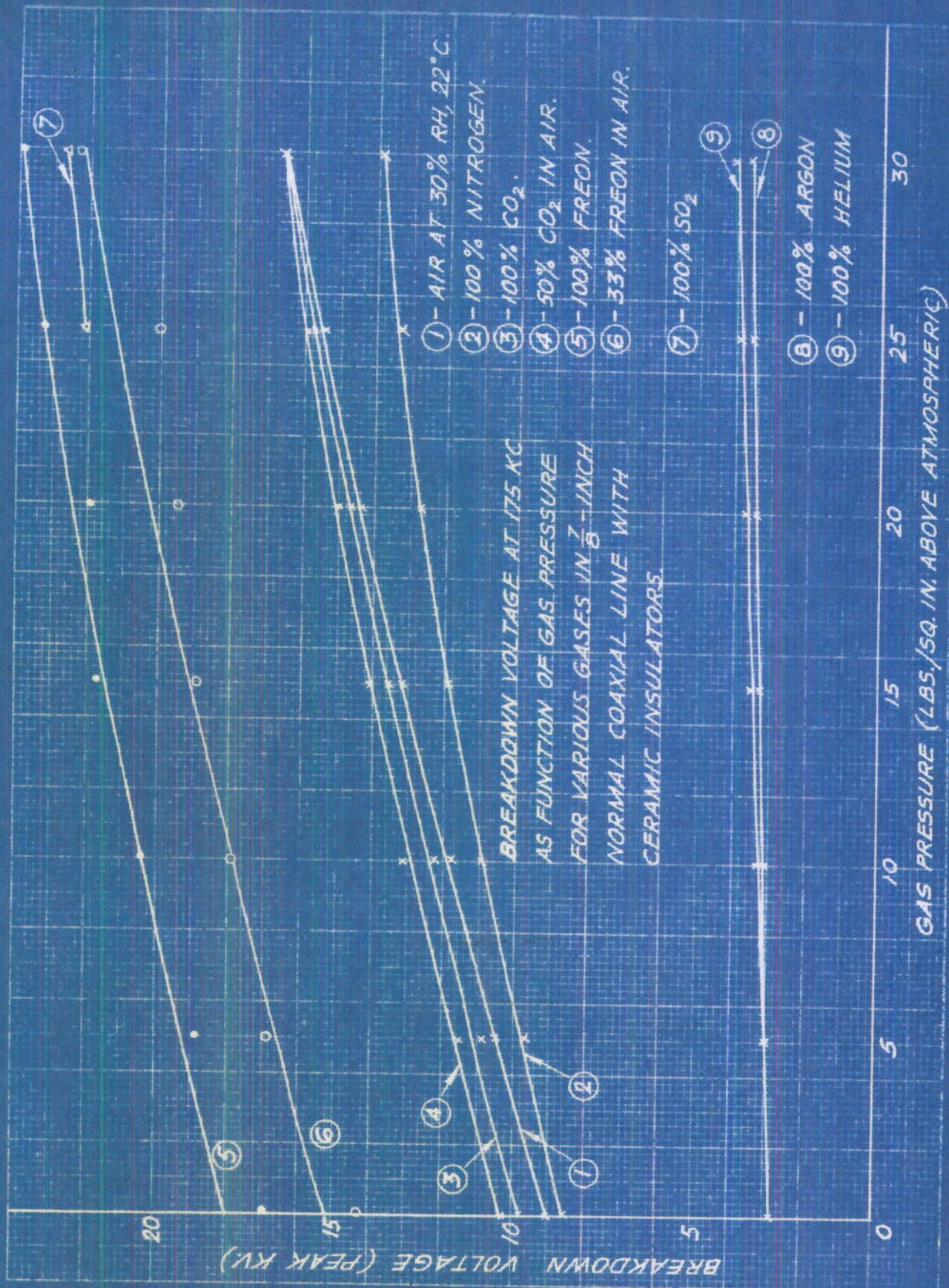




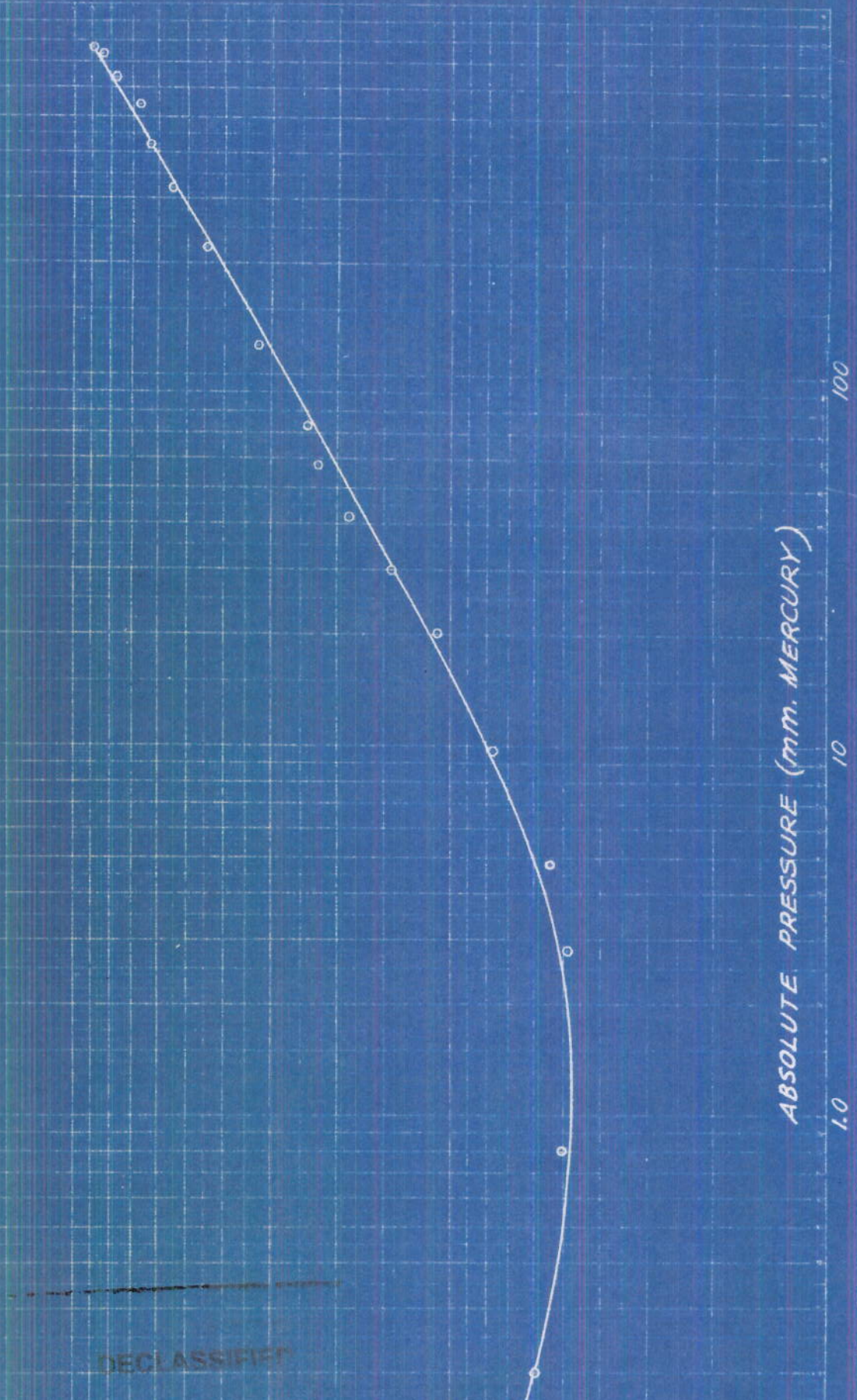
BREAKDOWN VOLTAGE OF AIR AS FUNCTION
OF FREQUENCY FOR 10 MM. SPHERES SPACED
2 MM. APART (REFERENCE (a)).







BREAKDOWN VOLTAGE AS FUNCTION OF ABSOLUTE
PRESSURE FOR AIR IN $\frac{7}{8}$ INCH
NORMAL COAXIAL TRANSMISSION LINE



BREAKDOWN VOLTAGE (PEAK KV)

PER CENT FREON IN AIR (BY VOLUME)

BREAKDOWN VOLTAGE AT 175 KC AS FUNCTION OF
 PER CENT FREON IN AIR (BY VOLUME) AT ATMOS-
 PHERIC PRESSURE IN $\frac{7}{8}$ -INCH NORMAL COAXIAL
 LINE WITH CERAMIC INSULATORS

NOTE: RELATIVE HUMIDITY OF AIR IN LINE
 APPROXIMATELY 30% AT 24°C

x

x

x

x

x

x

x

x

x

x

x

x

x

x

x

x

x

x

x

x

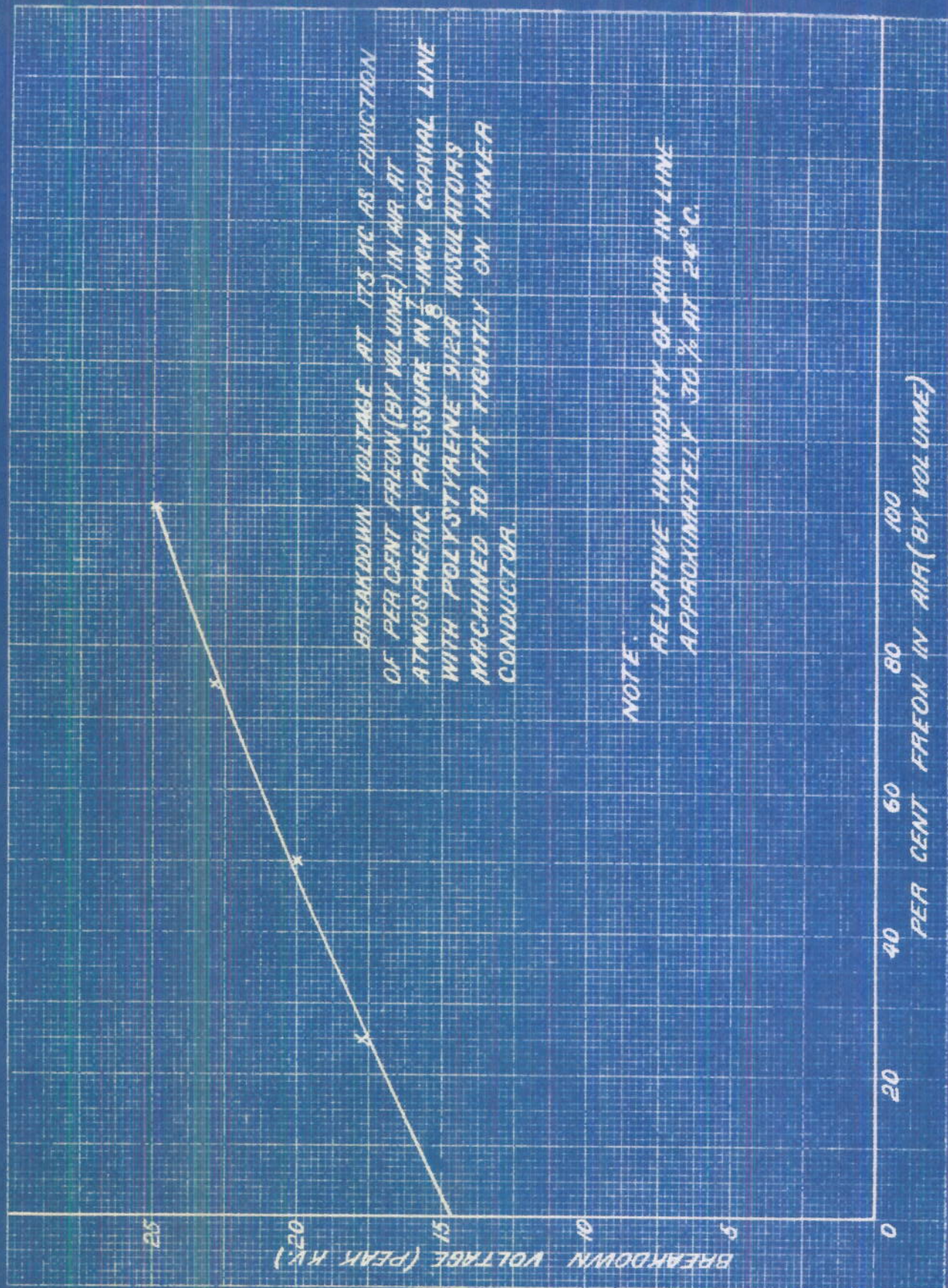
x

x

x

x

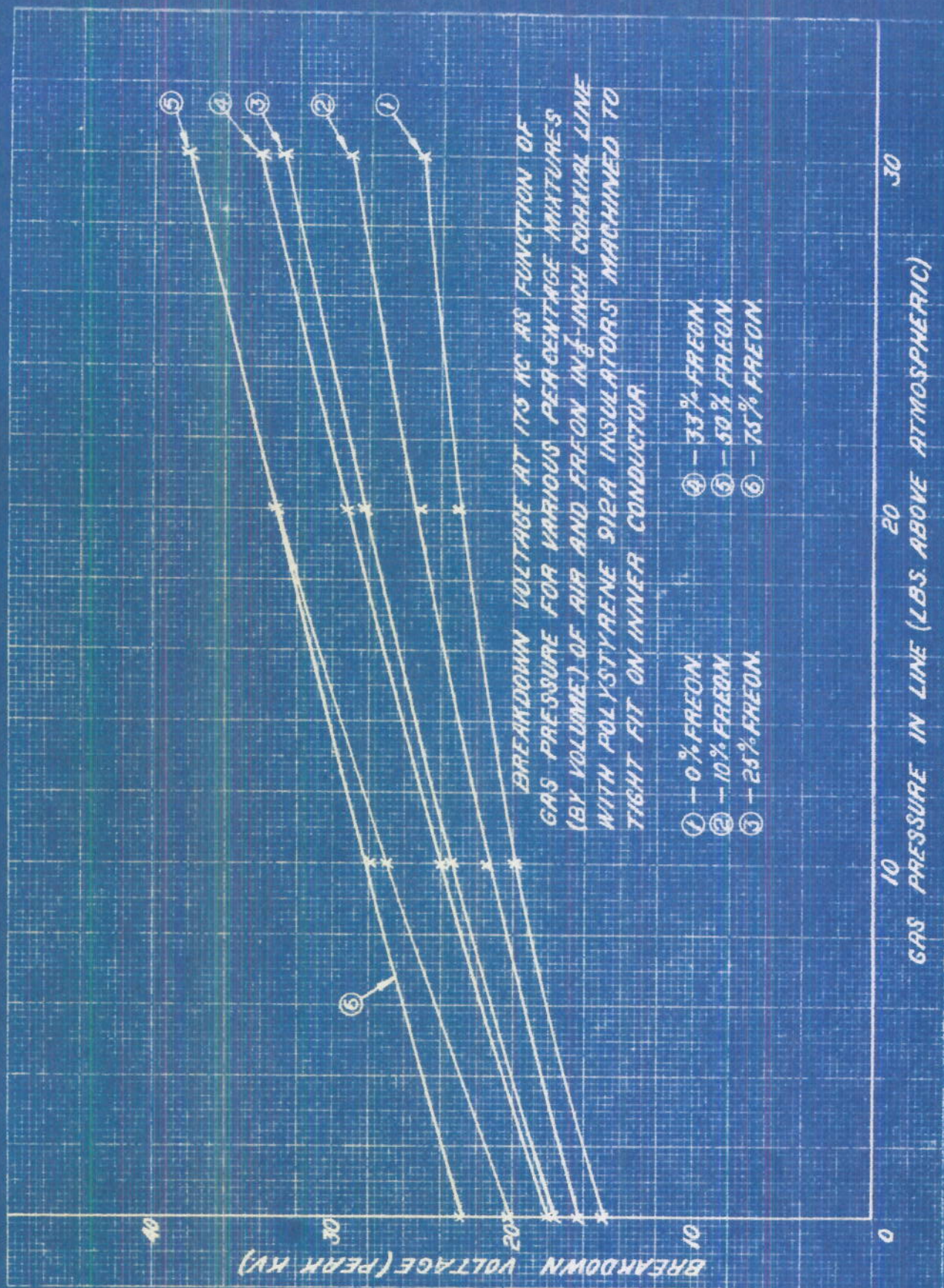
x



BREAKDOWN VOLTAGE AT 175 KC. AS FUNCTION
 OF PER CENT FREON (BY VOLUME) IN AIR AT
 ATMOSPHERIC PRESSURE IN $\frac{1}{8}$ -INCH COAXIAL LINE
 WITH POLYSTYRENE GREA INSULATORS
 MACHINED TO FIT TIGHTLY ON INNER
 CONDUCTOR.

NOTE:

RELATIVE HUMIDITY OF AIR IN LINE
 APPROXIMATELY 30% AT 24°C.



RELATIVE DIELECTRIC STRENGTH
OF VARIOUS GASES AS FUNCTION OF
PRESSURE ABOVE ONE ATMOSPHERE

RELATIVE DIELECTRIC STRENGTH

- | | |
|---------------------|---------------------|
| ①- AIR | ⑥- 50% FREON IN AIR |
| ②- NITROGEN | ⑦- 100% FREON |
| ③- CARBON DIOXIDE | ⑧- SULPHUR DIOXIDE |
| ④- 10% FREON IN AIR | ⑨- HELIUM OR ARGON |
| ⑤- 33% FREON IN AIR | |

