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(6) PRODUCTION AND STANDARDIZATION
OF ELECTROMAGNETIC WAVES
WITHIN SHIELDED ROOMS,

BY

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~~Radio Division - M and D. F. Section~~
~~Report No.~~ R-2536 (14)

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(251 950)

ABSTRACT

Mathematical analyses have been made of the field intensity existing at close proximity to both a terminated transmission line within a shielded room and an injection loop and are presented to permit the determination of such field intensities in terms of distance from the source of excitation and the exciting voltages. Experimental determinations have verified the accuracy and correlation of measurements made by both methods up to a frequency of 10 megacycles. Further investigations of the action of a terminated transmission line operated within a shielded room have indicated that the accuracy of field intensity below the line with respect to the frequency employed is a function of room size, line length and perfection of termination. For a room 22 x 14 x 12 feet in height, using a relatively small diameter transmission line, computed field intensities may be expected to be accurate within experimental limits up to a frequency of 15 megacycles but beyond this frequency, certain not completely determined conditions may introduce errors as high as 70% due to the existence of relatively sharp resonances. It is shown that pure resistive termination of a small diameter transmission line within a shielded room is inadequate to completely eliminate all standing waves at the higher frequencies.

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INTRODUCTION

1. In radio direction finder work, it is necessary to conduct many tests and obtain much experimental data with the equipment operating in an actual radio frequency field rather than, as can be done in receiver work, by the use of standard signal generators feeding the equipment through dummy antennas. Furthermore, in order to conduct such tests and experimentation meaningfully, it is often necessary to produce such fields within a shielded room to eliminate external disturbances and to permit the control of such fields as well as to readily determine their actual intensity in terms of microvolts per meter.

2. In furtherance of this requirement, the practice has been developed of employing a terminated transmission line within a reasonably sized shielded room for the production of the required electromagnetic waves. Such techniques are presumed to simulate pure vertically polarized waves of computable intensity.

3. A second technique that has been employed in the past and is useful for certain specific purposes involves the employment of a so-called injection loop, rather than a terminated line, for producing the electromagnetic waves. This is convenient for certain production testing purposes inasmuch as it can be employed with relatively close spacing between the injection loop and the direction finder collector using relatively high levels of field intensity and accordingly precludes the necessity of monopolizing a shielded room. Because of this it is believed that a more rigorous treatment of shielded room transmission line techniques is of interest and of practical usefulness. The injection loop case is submitted in this report in the interest of completeness of the presentation. However, and particularly in the case of the use of transmission lines, no mathematical treatment can readily take cognizance of other intangibles, such as the effects of imperfect line terminations, wires, furniture, observers, etc., within the room and similar factors. Because of this, it was believed desirable to conduct experimental determinations in these premises in order to obtain as much information as possible about the magnitude of their influences.

STATEMENT OF PROBLEM

4. From time to time it has been necessary to employ both of the above modern measurement techniques, that is, both injection loops and transmission lines and to extend the frequency range at which they are used to points beyond which any previous experimental data have been obtained.

5. For this reason, and inasmuch as the accuracy of the field intensity in which a direction finder collector is placed is of primary importance in direction finder work, it had become desirable, from time to time, to investigate the accuracy of the various methods of producing such field intensities and to attempt to determine the limiting parameters in order to permit control of these factors.

6. Accordingly the problem reported on herein involved the following:

(a) The development of formulas by which the field intensity existing within a shielded room at various distances from both an injection loop and a terminated transmission line could be calculated in terms of the driving voltages.

(b) The determination of the absolute accuracy of such calculated values.

(c) The determination of the limiting frequencies at which transmission line techniques can be employed with acceptable accuracy.

(d) The determination of the limiting conditions in connection with (c) above.

(e) The determination of the best methods of ascertaining the proper values of line terminations.

(f) The determination of the effects of imperfect line terminations on accuracy.

7. Because the work described herein was carried on as opportunity permitted, it does not represent a complete or consecutive series of tests but rather three separate sets of investigations conducted at different times. Consequently the results can not always be directly correlated. However, this fact is of some advantage, inasmuch as the indirect correlation of the results of tests conducted with different equipments under different conditions and at different times is indicative of the accuracy of procedure and results.

DESCRIPTION OF EXPERIMENTAL SETUPS

8. All experiments were conducted in two separate shielded rooms identical in construction, size, and appointments. These rooms were 22 feet long, 14 feet wide and 12 feet high and were single shielded by heavy copper sheet, with the exception of one end. For purposes of ventilation and light, this end was shielded by small copper mesh, the shielding being double and separated by approximately 2 inches.

9. The transmission lines used were of hard drawn copper wire, 0.065 inches in diameter, spanning the length of the rooms, and centered between the side walls. The spacing of the lines between the floors and ceilings of the rooms differed. In the room used for the test of injection loop versus transmission line techniques, the wire was spaced 98.4 inches from the floor while in the one used for all other investigations, this spacing was 84 inches.

10. The transmission line feed was also different in the two rooms used, in the front case the line being fed from the solid shielded end of the room, and in the other from the screened end. In both cases, however, the standard signal generators used for feeding the lines were mounted on the respective walls with their output jacks immediately adjacent to the transmission lines so that the length of lead between the output jacks and the linesdid not exceed two or three inches.

11. Terminations for the lines were applied at the opposite end of the rooms and consisted of conventional composition resistors bridging the small insulators separating the lines from the walls, the grounded side of the resistors being connected to the shielding of the rooms through short, heavy Belden strips to minimize inductance.

12. In investigating injection loop techniques, the injection loop was kept small (approximately 10 square inches in area) and the spacings between it and the collector loops were similarly minimized, the assembly being kept in the approximate center of the room to avoid serious wall reflections. In all cases, the injection loop was fed from a standard signal generator with sufficiently high swamping resistance in series therewith in order that the current in the loop would be independent of frequency, the value of resistance being chosen so that the inductive reactance of the loop was negligible at the highest frequency used.

PROCEDURES

13. In work of this kind, it has been the practice of this Laboratory to simplify the operation of all measurement setups by making them as direct reading as possible thereby minimizing the necessity for computations. In furtherance of this, it has been the practice in the production of standardized field intensities to employ what has been termed a "K" factor for converting the injection voltage from the standard signal generator to terms of field strengths in microvolts per meter at various distances from the injection loops or transmission lines. This is obviously an arbitrary factor inasmuch as it involves both space attenuation, values of swamping resistance, etc., but it is of great practical convenience inasmuch as for any known and precalibrated spacing between the injection loop or transmission line and the d-f collector, it is only necessary to divide the standard signal generator voltage by the "K" factor to obtain the field strength in microvolts per meter.

14. In determining the actual field strength existing at different distances from the transmission line, standard loop field intensity meters were employed. Up to approximately 15 megacycles, an RCA Type 308A instrument was used while above this frequency, recourse was made to a Measurements, Inc., Type 58A meter. In view of the fact that these two instruments overlap in frequency between 15 and 18 megacycles, it was possible to obtain correlation of their relative accuracies and accordingly minimize errors resulting from the change in measuring equipment.

THEORETICAL CONSIDERATIONS

15. Prior to the conduct of any experimental work on the subject problem, a mathematical analysis was made of the factors affecting the field intensity existing at given distances from a transmission line or an injection loop and formulas evolved or verified for these factors. In all cases, the formulas were arranged to yield results in terms of voltages applied to the injection system rather than currents existing in the system. This treatment is of more practical importance although less orthodox.

16. This mathematical treatment is contained in Appendix A.

INJECTION LOOP INVESTIGATIONS

17. The first experimental work on the problem in question was done with injection loops to determine the validity of the mathmatical treatment and the duplication of measurement r esults when transferring from transmission line to injection loop methods. This resulted from a specific requirement, necessitating the development of a production method of testing in a relatively small space a certain line of small direction finders. Unfortunately the specific requirement of this problem did not n ecessitate consideration of the higher frequencies so that work in these particulars was not carried on above 10 megacycles.

18. The injection loop used was a 10 turn rectangular loop having a total area of approximately 10 square inches and the receiving or direction finder loop was a round five turn balanced loop approximately four inches in diameter. The test setup employed is shown by Plate 1. The basic purpose of these particular tests was to ascertain the validity of the computed variation of field intensity with spacing between the injection and collector loops and with the standard signal generator input to the former. At the time these experiments were conducted no field intensity meter was available and recourse was made to a previously calibrated transmission line as a source of known field intensity. The two standard signal generators, one for feeding the transmission line and the second for feeding the injection loop were previously checked for coincidence of ouutput. A five inch cathode rayoscilloscope was employed as an output indicator, primarily for convenience.

19. The receiving loop was placed beneath the transmission line at a measured distance at which the field intensity was kniwn through previous calibrations; by computation, using Equation 4 of Appendix A, the spacing between the injection loop and the receiving loop to produce the same field intensity was determined and the injection loop fixed in this position. Thereafter the receiving loop was excited alternately from the transmission line and from the injection loop and the difference between the inputs of the two sources of voltage for the same reference output was de termined. This was done at various levels, the receiver gain be ing decreased as the field intensity was increased in order to preclude overloading of the receiver and to maintain the oscilloscope image on the screen. The results are shown by Plate 2. It will be noted that the discrepancies between the field intensities obtained by the respective methods of injection are within observational limits and experimental accuracy, the maximum deviation not being in excess of 5%. It is be lieved that these tests demonstrate the validity and usefulness of Equation 4 of Appendix A for computing field intensity versus loop s pacing and injection voltage. It is further believed that such methods may be less susceptible to inaccuracies resulting f rom uncontr ollable conditions such as may result from the employment of transmission line techniques ove r wide frequency ranges. Plate 3 has been prepared as a useful graph for minimizing the caloulations involved in determining field intensity versus loop spacing and permits the direct determination of "K" in terms of spacing for various values of physical loop configuration and swamping resistance.

20. As a practical matter, in employing this technique, several precautions are obviously necessary. The loop diameter or the greatest

spacing between sides of a rectangular loop must be kept relatively small with respect to the wave length employed. In no case should it exceed a fortieth of a wave length. Similarly the number of turns, their physical spacing, etc., should be restricted to the point where the resonant frequency of the injection loop is well above the highest frequency at which it is to be used. As a final precaution, the swamping resistor should be so proportioned in size that its value is at least 20 times the inductive reactance of the loop at the highest frequency employed. It is generally of practical use, inasmuch as this value of resistance is not particularly critical, to employ resistors having an even order of resistance, such as 1000, 10,000 ohms, etc.

TRANSMISSION LINE INVESTIGATIONS

21. The tests described above verify the accuracy of data obtained for injection loop methods of producing known field intensities and in view of their correlation with previous field intensity calibrations of a transmission line partially justify the accuracy of results obtained with the latter.

22. Subsequent to their conduct, three questions arose as to the accuracy that might be expected in the use of a transmission line within a shielded room for the creation of determinable field intensities. These involved the effect on accuracy of:

(a) The impedance of the source of driving voltage (i.e., the signal generator output impedance).

(b) The determination and employment of the proper value of line terminating resistance.

(c) The frequency of measurement (i.e., the maximum frequency for any given setup, that can be employed with acceptable accuracy).

EFFECT OF DRIVER OUTPUT IMPEDANCE ON ACCURACY

23. Certain standard signal generators or other drivers are so designed that their output impedance varies with their output level. Practically all calculations of field intensity or "K" factor below a transmission line are based on the assumption that the impedance of the driving source is zero or at least low in comparison with the line impedance. In order to check the magnitude of errors that might result from the practical fact that this is not always true, calculations were made of the errors in "K" factor for lines of various characteristic impedances that would result from the change of impedance of the generators used in the Laboratory when going from low to high output levels. Plate 4 shows the magnitude of these errors and indicates that for a 460 ohm line, the normal ten ohm impedance of the generator introduces an error of only 2.5% with respect to the idealized zero impedance, which is within the limits of accuracy for measurements of this type and hardly warrants the use of a correction factor. However, when going to the 50 ohm impedance, the error increases to 10.8%, which does warrant consideration. This fact is of importance inasmuch as it indicates that once a setup is calibrated for "K" factor with a certain impedance of the driver, this impedance cannot be appreciably changed without correcting the "K" factor for the change. It similarly indicates that,

while a low impedance line might be advantageous for certain other reasons, the use of such a line will make the setup more critical to changes in driver impedance and consequently less flexible in practical use.

EFFECT OF IMPERFECT TERMINATION ON ACCURACY

24. The resistance value for the proper termination of a transmission line can be determined by three methods:

(a) By calculation from the geometric dimensions of the room and the line.

(b) By calculation from a measurement of the open circuited capacitance of the line.

(c) By trial and error based on measurements of the standing waves on the line.

25. Calculation of the line impedance from the geometry of the room and its size and position is rather complicated if accuracy is to be obtained, except for certain special cases.

26. A far more simple method yielding quite accurate results involves merely a measurement of the capacitance of the open circuited line and the calculation of the line impedance from this capacitance by the following formula:

$$Z = \frac{1016}{C/ft}$$

where
Z - Line impedance in ohms
C/ft - Average capacity in uuf per foot of line

The line capacitance may be measured either with a "Q" meter, a "Bridge" or by other methods.

27. The above formula applies only for air dielectric between the wire and the walls of the room.

28. The third method of varying the termination in increments and measuring the standing wave ratio for each value of resistance, obtaining the optimum value by inspection or interpolation of the resulting ratios, while consuming more time, yields the most rigorous results, inasmuch as the measurements are in terms of the desired end results.

29. Measurements that had previously been conducted in the shielded room in question up to frequencies of 30 megacycles, had indicated reasonably accurate termination as judged by measurements made on d. f. equipment and such field intensity checks as were made. However, all such test work had been conducted at certain specific frequencies which conceivably could have straddled frequencies where difficulty could exist. Furthermore, checks made with a field intensity meter under the line had never been carried beyond 18 megacycles.

30. A test was accordingly made to determine any variation in field intensity that might exist at a given distance below the line with respect to variation in frequency. In order to remove as many sources of error as possible, a power measurement technique was employed. A round single turn loop, six inches in diameter was supported under the transmission line at its center and spaced approximately 15 inches from the closest point of its diameter to the line. The terminals of the loop were connected to a sensitive thermocouple, the output terminals of which were connected to an adjacent indicating instrument. The line was driven by a low-power transmitter and the applied voltage measured at the line with a vacuum tube voltmeter. All electrical adjustments including the reading of the loop current were made from behind the screened end of the room so as to preclude any influence from an observer's body. For each observation the voltage in the loop was calculated with due regard to the impedance of the loop circuit, taking cognizance of both the loop reactance at the respective frequencies and the thermocouple resistance.

31. Plate 5 shows the results in terms of percent accuracy of field intensities measured at a fixed distance below the line, for variation in frequency, the ten megacycle value being taken as a reference. While the data taken on two successive runs by this method, as shown by Plate 5 do not produce a smooth plot due probably to reading and indicating inaccuracies of the meter used (which through lack of sufficient power, had to be operated well down on the scale) the trend of the results is unmistakable. It indicates that the errors in presumed field intensity (based on the 10 mc value) begin to increase rapidly above approximately 18 megacycles, reaching a peak at approximately 28 megacycles. These measurements were not carried beyond 30 megacycles, the top range on the transmitter, so that at the time they were taken, the trend beyond 28 megacycles could not be definitely determined.

32. As a result of this test, it was suspected that standing waves might exist on the line due to imperfect termination (490 ohms being employed) and that the existence and the possible movement of the current anti-nodes of such standing waves might account for the errors noted.

33. Accordingly it was decided to check the optimum value of termination and to ascertain the effectiveness of such termination by a measurement of standing waves on the line.

34. In furtherance of this, a two turn loop was constructed on a thin plate of insulating material and arranged with hangers so that the assembly could be run along the line, using it as a messenger. This constituted a magnetically coupled probe. The loop was coupled to a receiver through a shielded concentric transmission line. With this arrangement it was quickly discovered that appreciable standing waves did exist on the line, indicating that the termination of 490 ohms then employed was not optimum.

35. The line was excited at thirty (30) megacycles and the values of terminating resistance changed in increments, from zero to infinity, the standing wave ratio being measured for each value of termination

employed. The results of this experiment are shown by Plate 6. An examination of this plate indicates three interesting facts:

(a) A variation in terminating resistance of plus or minus 10% of the optimum does not appreciably affect the standing wave ratio.

(b) The optimum value of termination appeared to be approximately 464 ohms.

(c) No value of pure resistive termination completely eliminated all standing waves from the line.

36. The line termination was then established at 464 ohms and the check for standing waves repeated by the use of the same setup using frequency as a variable. The results are shown by Plate 7. While it is difficult to draw many specific conclusions from these meager data, they do indicate the possible existence of a reactance even with optimum resistive termination and that the standing wave condition shows an erratic tendency above approximately 20 megacycles.

37. It would appear from the impossibility of completely eliminating all standing waves from the line that the terminations employed were never entirely resistive. While it is sometimes thought that this is due to the resistors used having a certain amount of capacitance associated therewith, it is believed that the difficulty is more likely the result of the inductance of the end walls of the room being in series with the terminating resistance. This is predicated on the analogy that the side walls represent the outer shield of a concentric line, which is terminated by the end walls through the driver impedance and the terminating resistance. Should this diagnosis be correct, the use of a capacitance (proportioned for the frequency involved) in series with the terminating resistance should result in the desired elimination of all standing waves. Unfortunately time did not permit an experimental determination of the correctness of this hypothesis.

EFFECT OF FREQUENCY ON ACCURACY

38. Subsequent to the obtainment of the data shown by Plates 6 and 7, it was decided to determine the maximum frequency at which acceptable accuracy could be obtained with a line by measuring field intensity versus frequency up to 50 megacycles, at a fixed distance below the line.

39. For this purpose the loop of a field intensity meter was fixed at a distance of 25½ inches to its center below the midpoint of the line and field intensities measured for constant line injection over the frequency range of 10 to 50 megacycles. The results are shown by Plate 9. No data were taken below ten megacycles, inasmuch as data taken previously in the shielded room used for the injection loop tests indicated that results below 10 megacycles are consistent. These data are shown by Plate 8, which cannot be directly correlated with data of Plate 9, the line spacings being different for the two cases. Plate 9 indicates that, not only may inaccurate results be expected for the particular line and room employed, for frequencies above 15 megacycles but that, as had previously been determined, resonances appeared to exist in the

system beyond this frequency. One quite pronounced resonance appeared at approximately 26 megacycles, another minor resonance at approximately 43 megacycles and a third was making its appearance at 50. It is of interest to note that the use of this particular line and room would result in an error as high as 70% at 26 megacycles although at other frequencies between 12 and 50 megacycles, the errors might be less.

FIELD INTENSITY GRADIENT BELOW A LINE

40. While the field intensity meters were available, tests were made to determine the variation in the field intensity gradient existing between the line and the floor of the shielded room in order to ascertain the correctness of the equations of Appendix A in these particulars that show the "K" gradient as not following an inverse square law with distance due to floor and ceiling reflections.

41. This was accomplished by placing the pickup loop of the Measurements Type 58A field intensity meter at varying distances below the center of the line, noting the field intensity for constant injection voltage. The results of this test, indicating the K factor versus distance below the line, are shown by Plate 10. It will be noted that not only does the field intensity gradient not follow an inverse square law, but that the measured values of "K" compare reasonably well with the computed values.

MEASUREMENT OF ROOM RESONANCE

42. An attempt was then made to determine the causes of the apparent resonant conditions existing in either or both the room and the line. In view of the complex nature of the shielded room and the line and the difficulty of coupling to critical voltage or current points of unknown position, an attempt was made to measure the resonances, using the following technique. A relatively high Q inductance was connected to a Q meter bonded to the mid point of one of the side walls of the room with the line in place. A vertical antenna or probe was connected to the high potential side of the loop. The Q of this circuit was then measured at progressively varying frequencies, on the premise that at the resonant points of the room a pronounced reduction in Q would appear. With this arrangement the 43 and 50 megacycle resonance points were located but the more pronounced 26 megacycle resonance failed to appear. Plate 11 shows the results of these measurements.

43. A physically larger inductance or loop was then connected to the "Q" meter which was moved to the center of the room so that the loop was coupled relatively close to the line. Under this condition a pronounced resonance of the line was observed at approximately 22.5 megacycles with it either open or shorted. However, this disappeared when the line was terminated with 464 ohms. Under this condition what might be interpreted as a very broad and ill-defined resonance between 24 and 28 megacycles appeared. The line was then removed from the room and the experiment continued in an attempt to locate any general room resonances. Curve 4 of Plate 12 indicates that under this condition a resonance is apparent at approximately 24.5 megacycles. However, too much credence cannot be placed on this measurement inasmuch as the "Q"

meter was "hot" during the test only being grounded through approximately six feet of power cable and since the addition of three feet of power cable reduced the magnitude of the apparent resonance and at the same time markedly changed the measured "Q" of the loop.

ADDITIONAL WORK TO BE DONE

44. It is unfortunate that the experimental work reported herein had to be conducted at such times as opportunity and the pressure of more important work permitted. For this reason the data obtained are in many cases inconclusive and in any event have not been carried sufficiently far to be useful under many practical conditions. For example, it is believed desirable to make further investigation of the nature and causes of the apparent resonances existing within the shielded room and under the transmission line with a view toward developing methods of eliminating or correcting such conditions and to determine the correlation between room size, line length and frequency of operation with respect to usable accuracy of the transmission line method of producing determinate field intensities.

45. Similarly, it is believed desirable to make further investigations with respect to the difficulty of obtaining perfect line termination with a view toward the complete elimination of all standing waves on the transmission line.

46. It is hoped that it will be possible to obtain more data in those particulars and in the near future prepare an addendum to this report.

CONCLUSIONS

47. While the tests described herein have not been sufficiently exhaustive to permit the determination of all the parameters involved in the employment of transmission line techniques within a shielded room for the production of predetermined field intensities, from the trend of the data obtained, it is concluded:

(a) That the upper frequency limit at which a transmission line within a shielded room may be used with reasonable assurance of accuracy is determined by the size of the room.

(b) That within certain limits, the smaller the room the higher the frequency at which a line may be used with acceptable accuracy.

(c) That the line length, regardless of room size should preferably be less than $\frac{1}{2}$ wave length for the highest frequency at which measurements are to be made.

(d) That the value of line impedance, as determined by capacity measurements of an open line is sufficiently accurate to use for the value of terminating resistance.

(e) That no resistive termination completely eliminates standing waves.

(f) That the use of capacitance in series with the line termination might be advantageous in reducing the standing waves.

(g) That the elimination of all standing waves from a line might possibly require a more critical value of line termination.

(h) That the use of injection loop in lieu of transmission line techniques might be advantageous at the higher frequencies inasmuch as the size of the loop can be suitably proportioned to the frequency involved so as to avoid errors resulting from resonant conditions, whereas with a transmission line, resonances cannot be avoided unless a multiplicity of rooms is available.

(i) That the agreement between the calculated and measured values of field intensity as well as the "K" factors for both injection loops and transmission lines is acceptable, provided that in the calculations consideration is given to all the factors involved.

(j) That, with respect to (i) above, the injection loops lend themselves more readily to accurate calculations because of the absence of intangibles in their design and use.

EQUIPMENT ARRANGEMENT FOR COMPARISON OF INJECTION LOOP VS. TRANSMISSION LINE TECHNIQUES

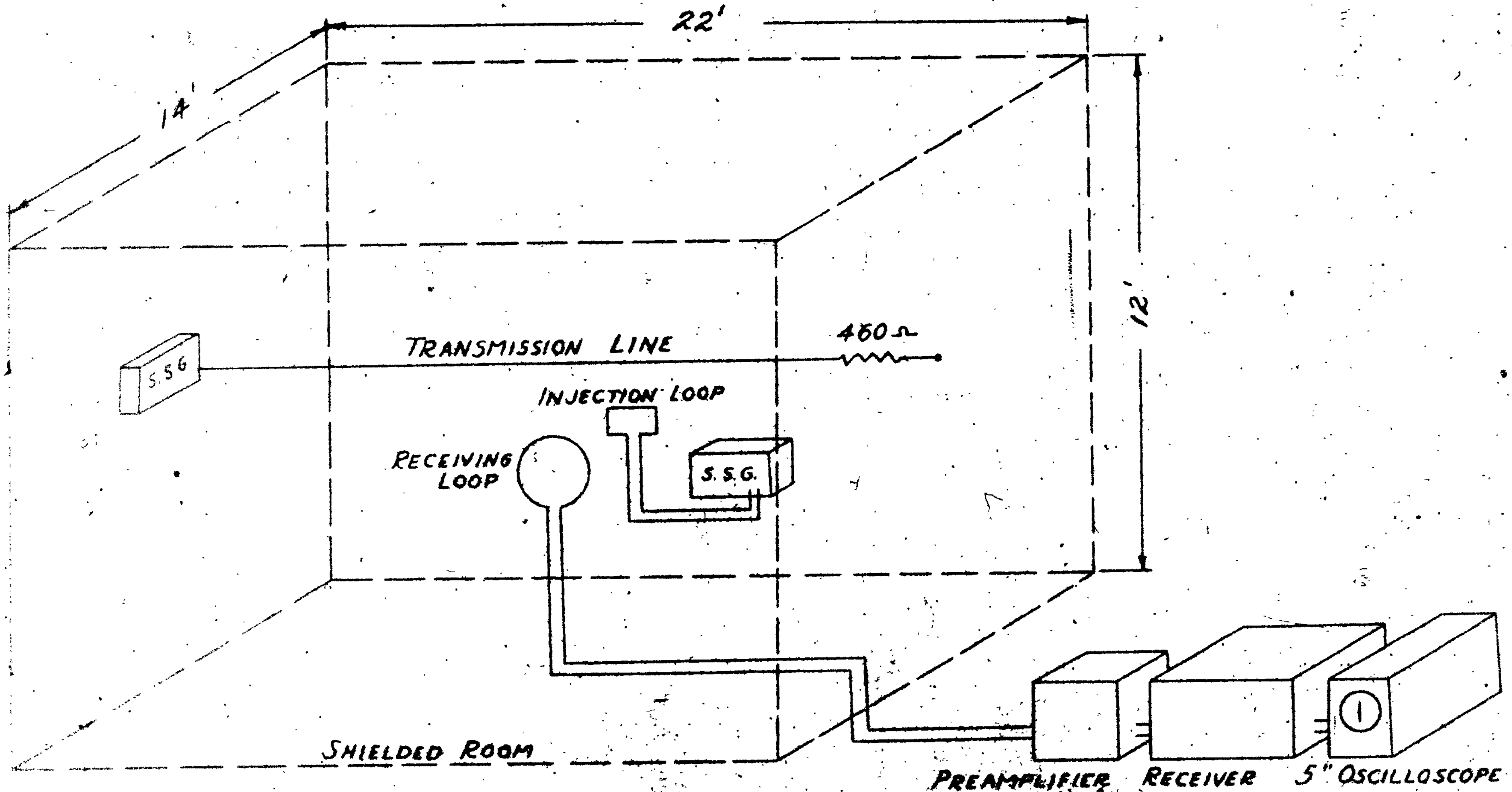


PLATE I

NRL REPORT R-23

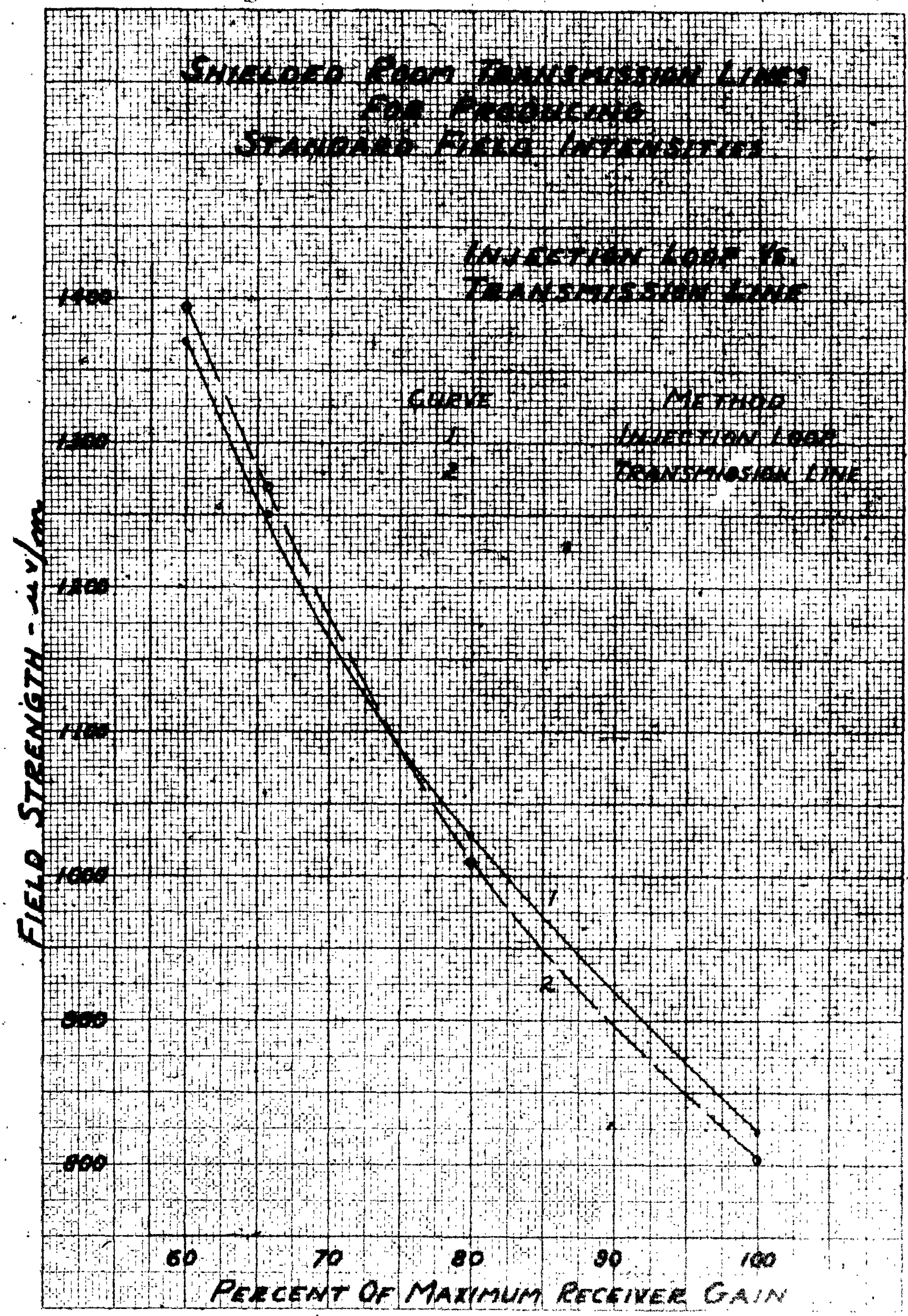


PLATE 2
OF NRL REPORT R-1536

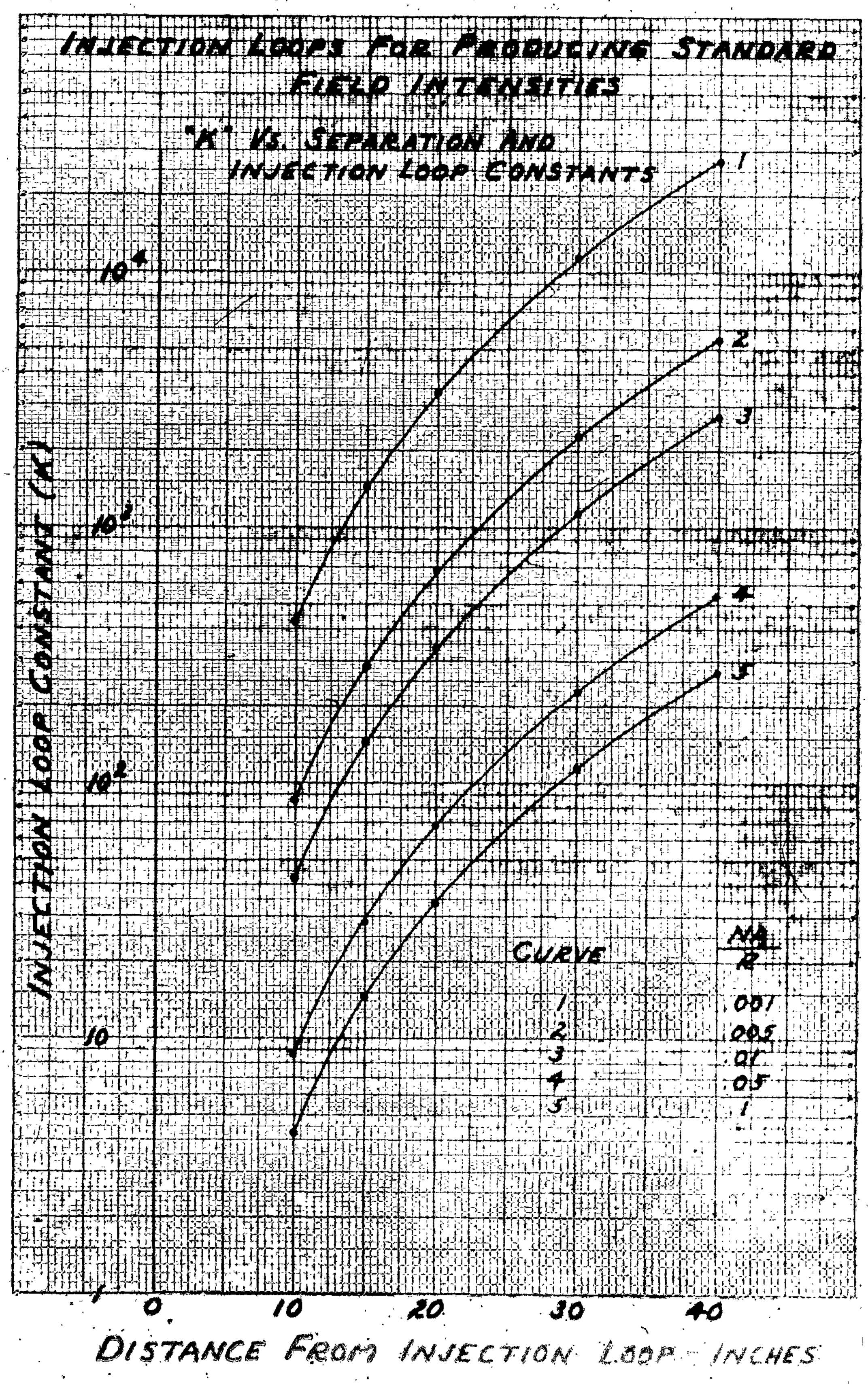


PLATE 3
OF NRL REPORT R 2536

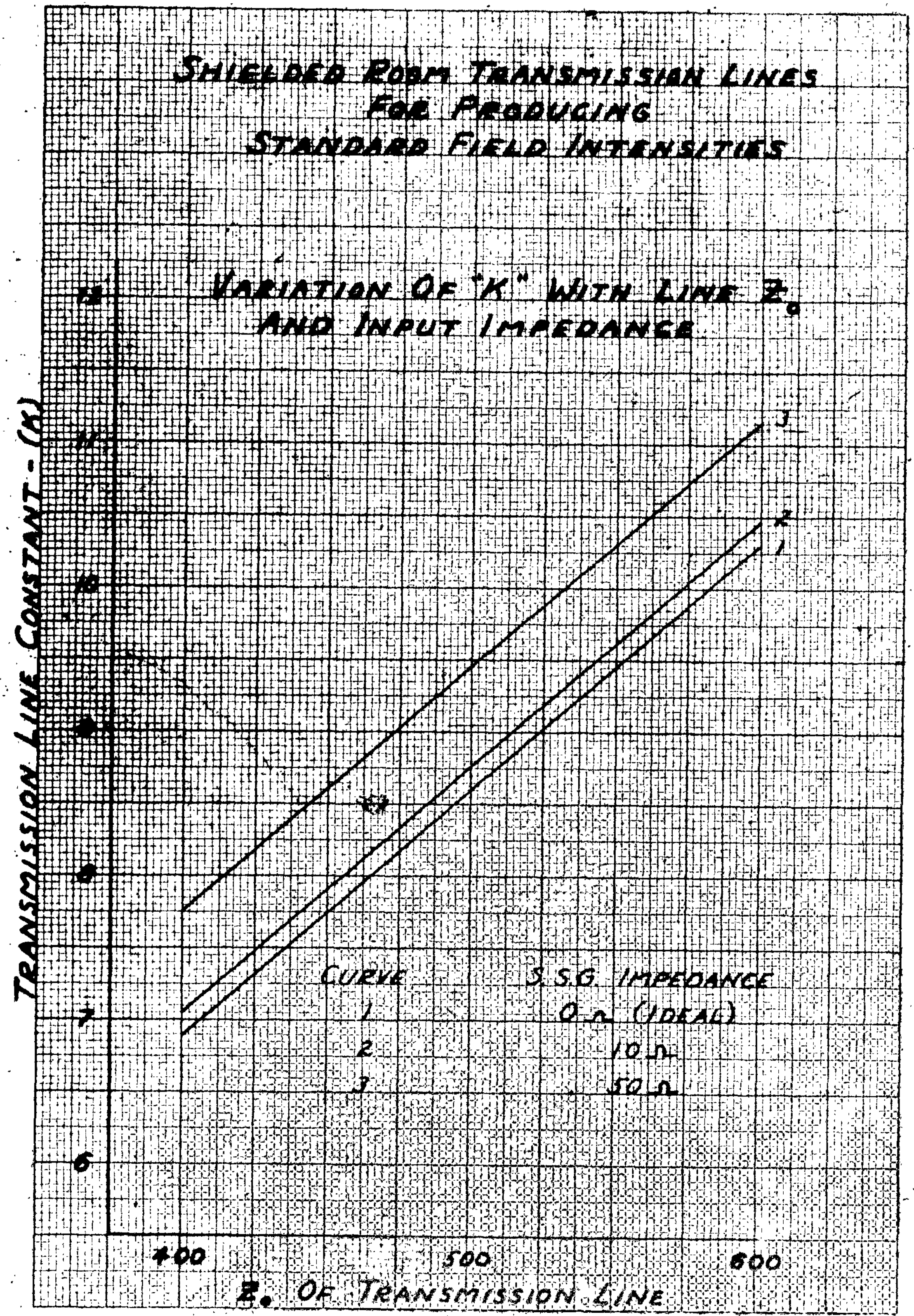
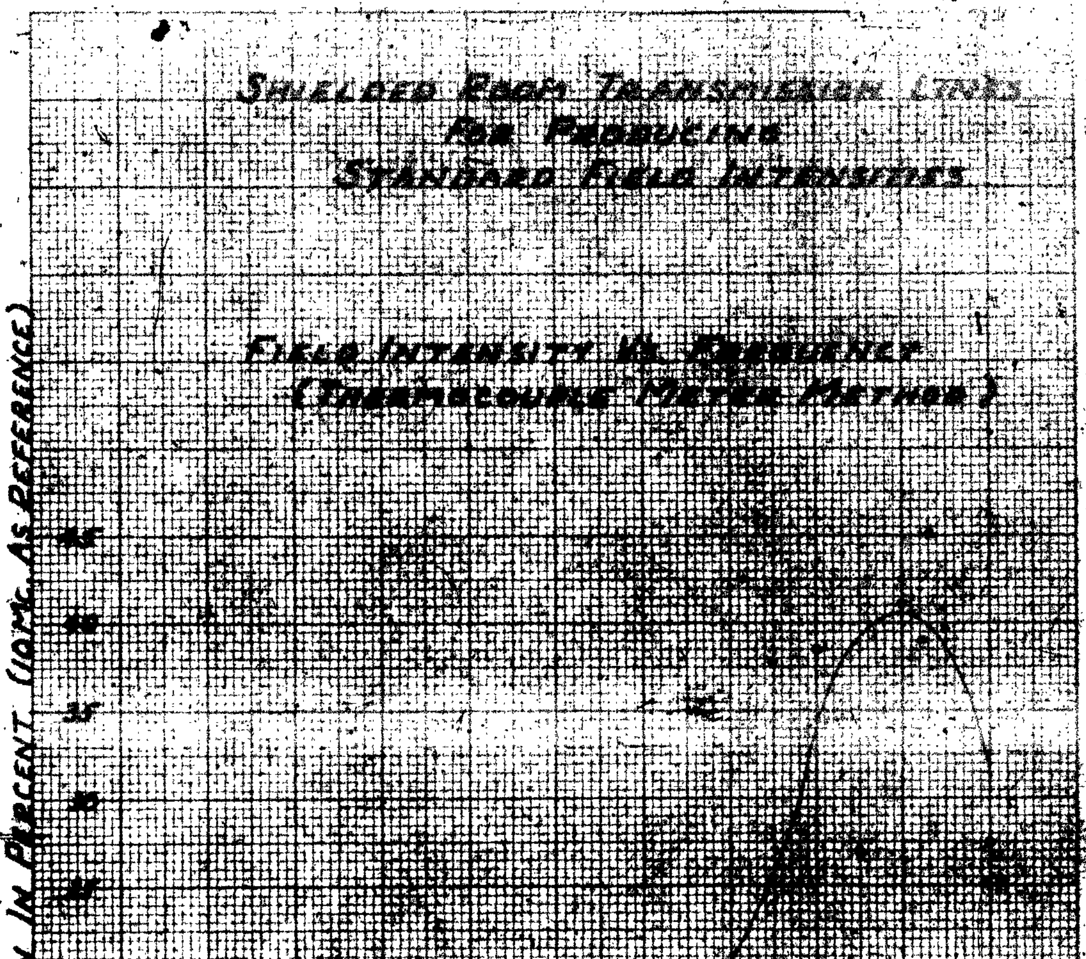


PLATE 4
OF NRL REPORT R-2530


SHIELDED ROOM TRANSMISSION LINES
FOR PRODUCING
STANDARD FIELD INTENSITIES
FIELD INTENSITY VS. FREQUENCY
(THERMOCOUPLE METER METHOD)
FIELD INTENSITY VARIATION IN PERCENT (10MC AS REFERENCE)

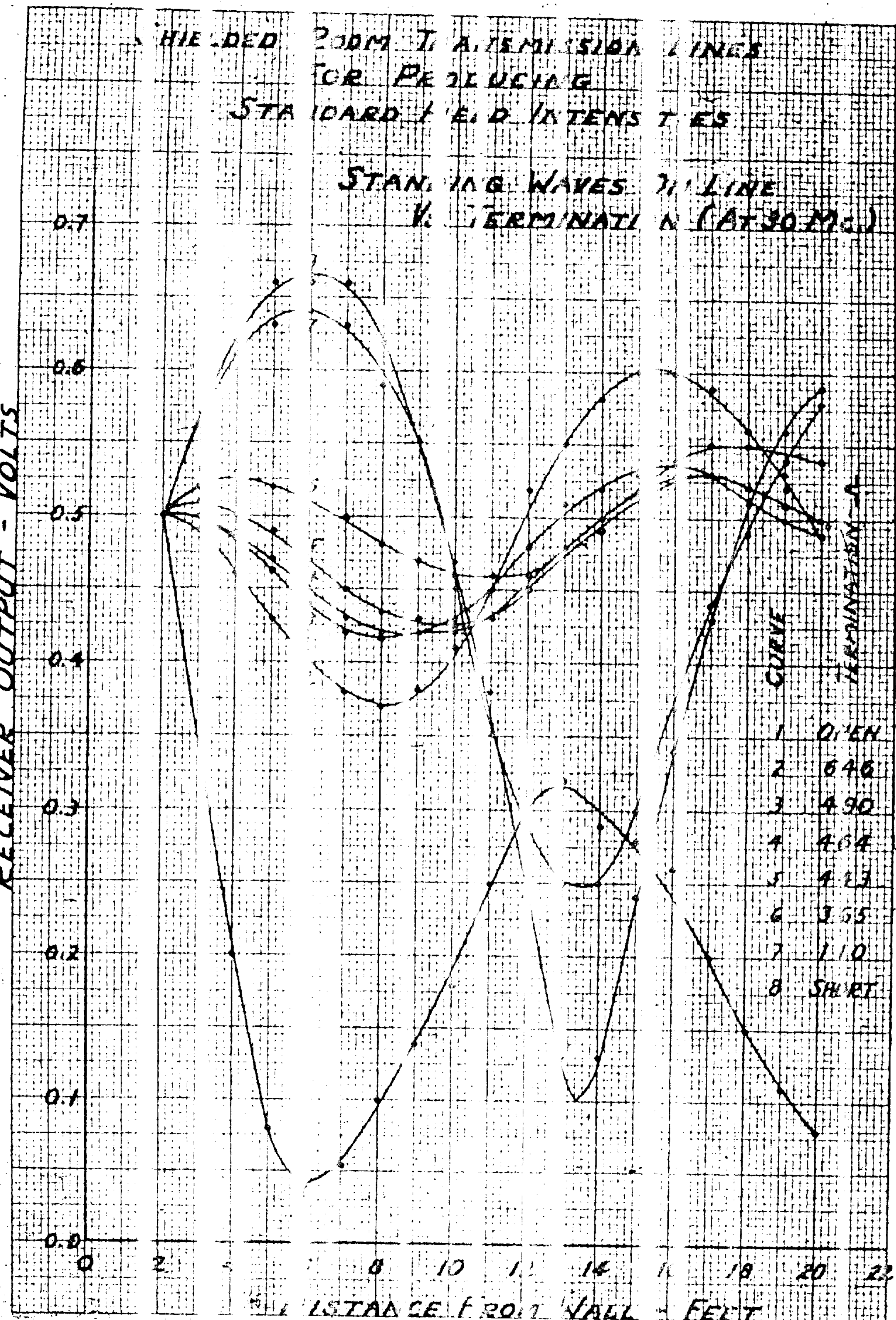


PLATE 6

OF NRL REPORT R-2536

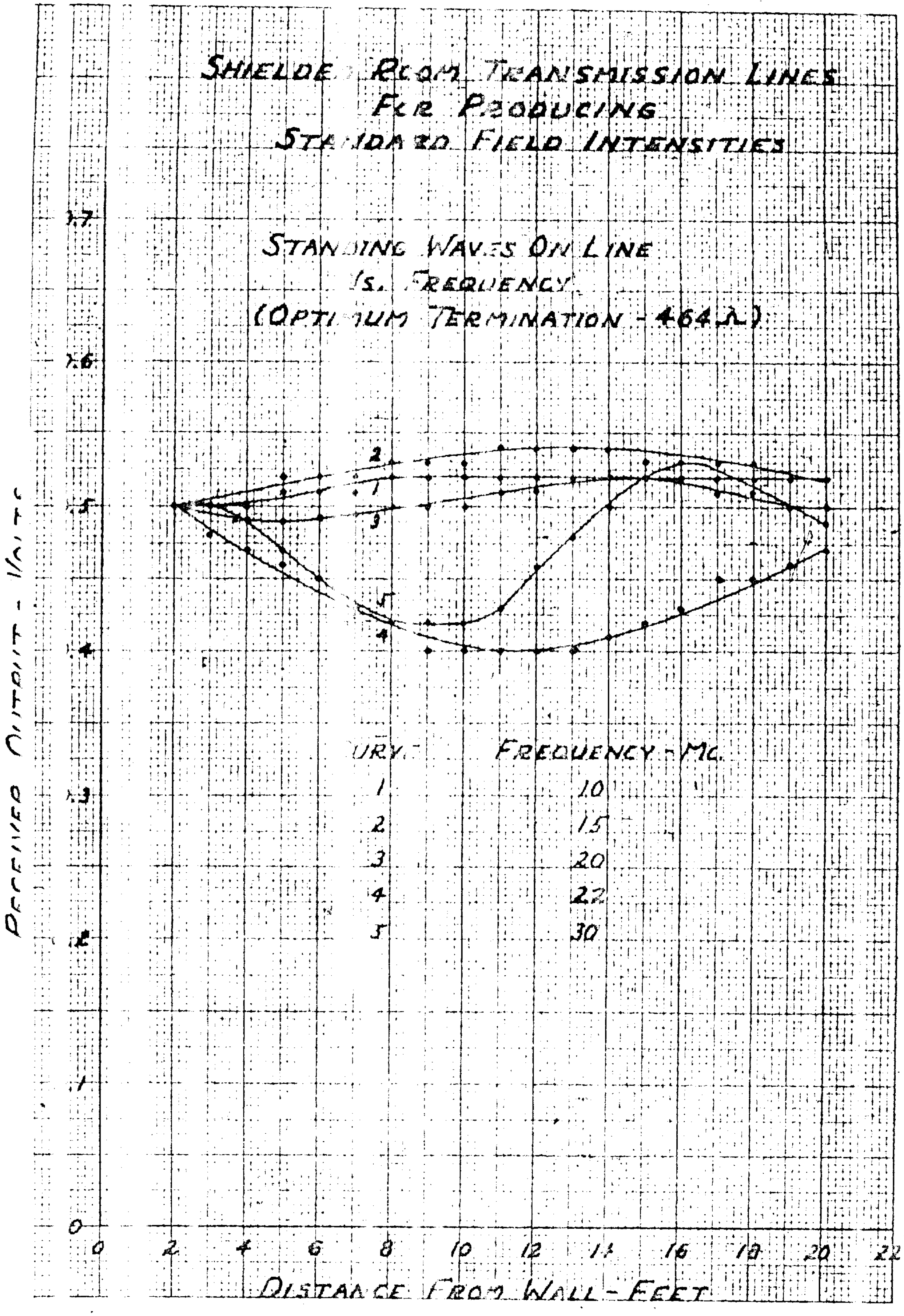
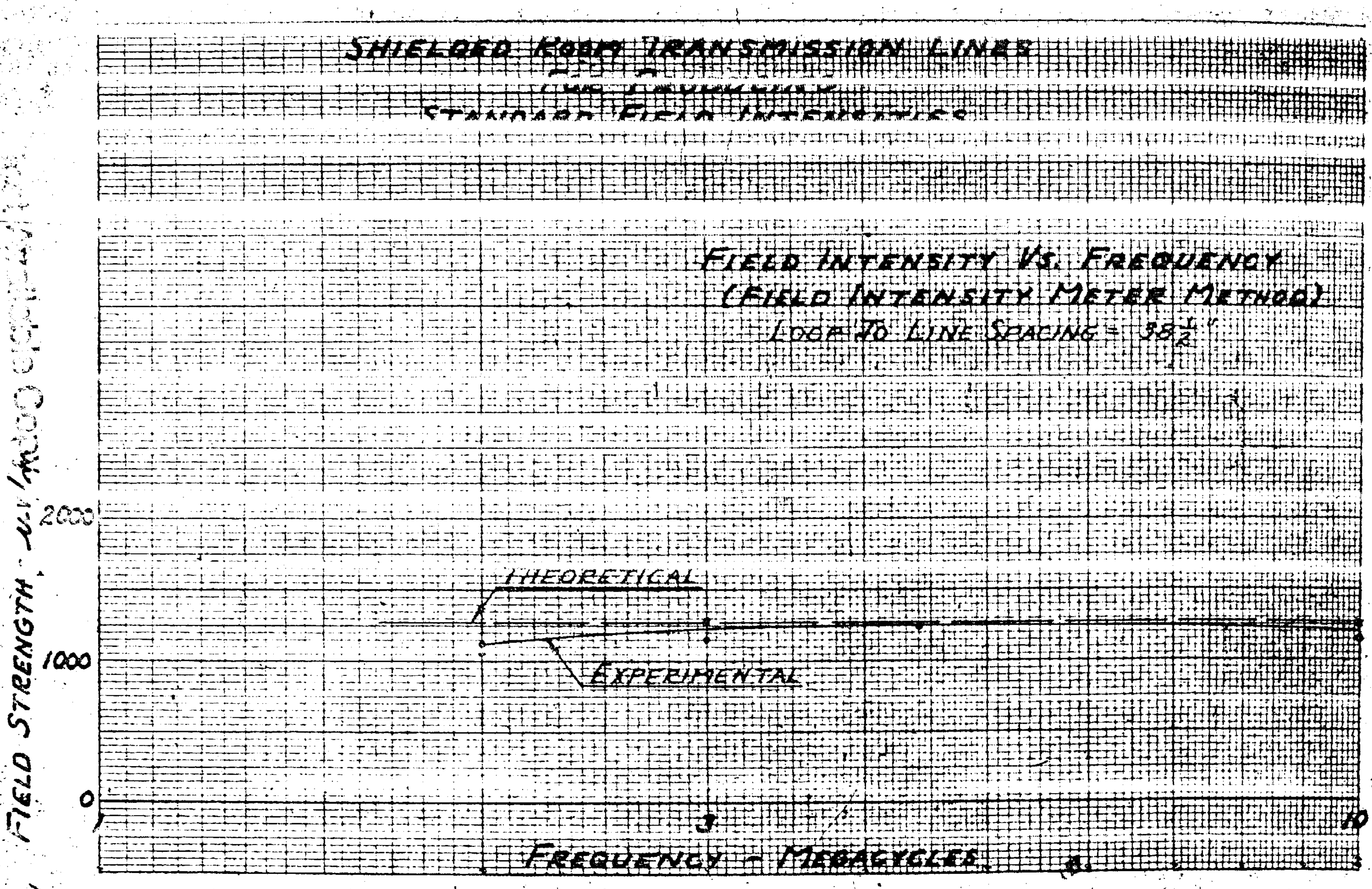


PLATE 7
OF NRL REPORT R-2536



SHIELDED ROOM TRANSMISSION LINES
FIELD INTENSITY VS. FREQUENCY
(FIELD INTENSITY METER METHOD)
LOOP TO LINE SPACING = 38½"
THEORETICAL
EXPERIMENTAL
FIELD STRENGTH
2000
1000
0
1
3
10
FREQUENCY - MEGACYCLES

PLATE 8

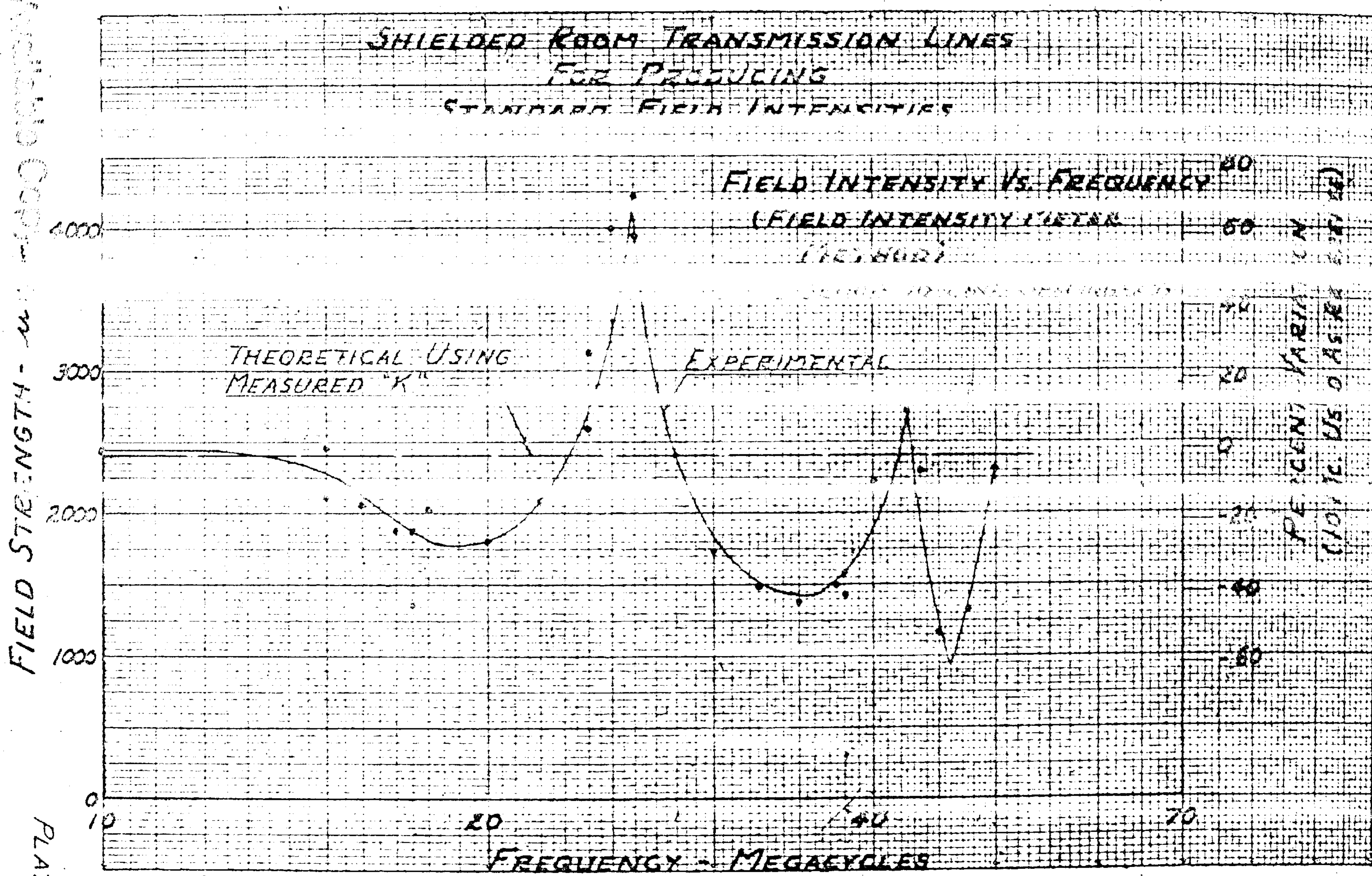


PLATE 9

OF NRL REPORT R-2336

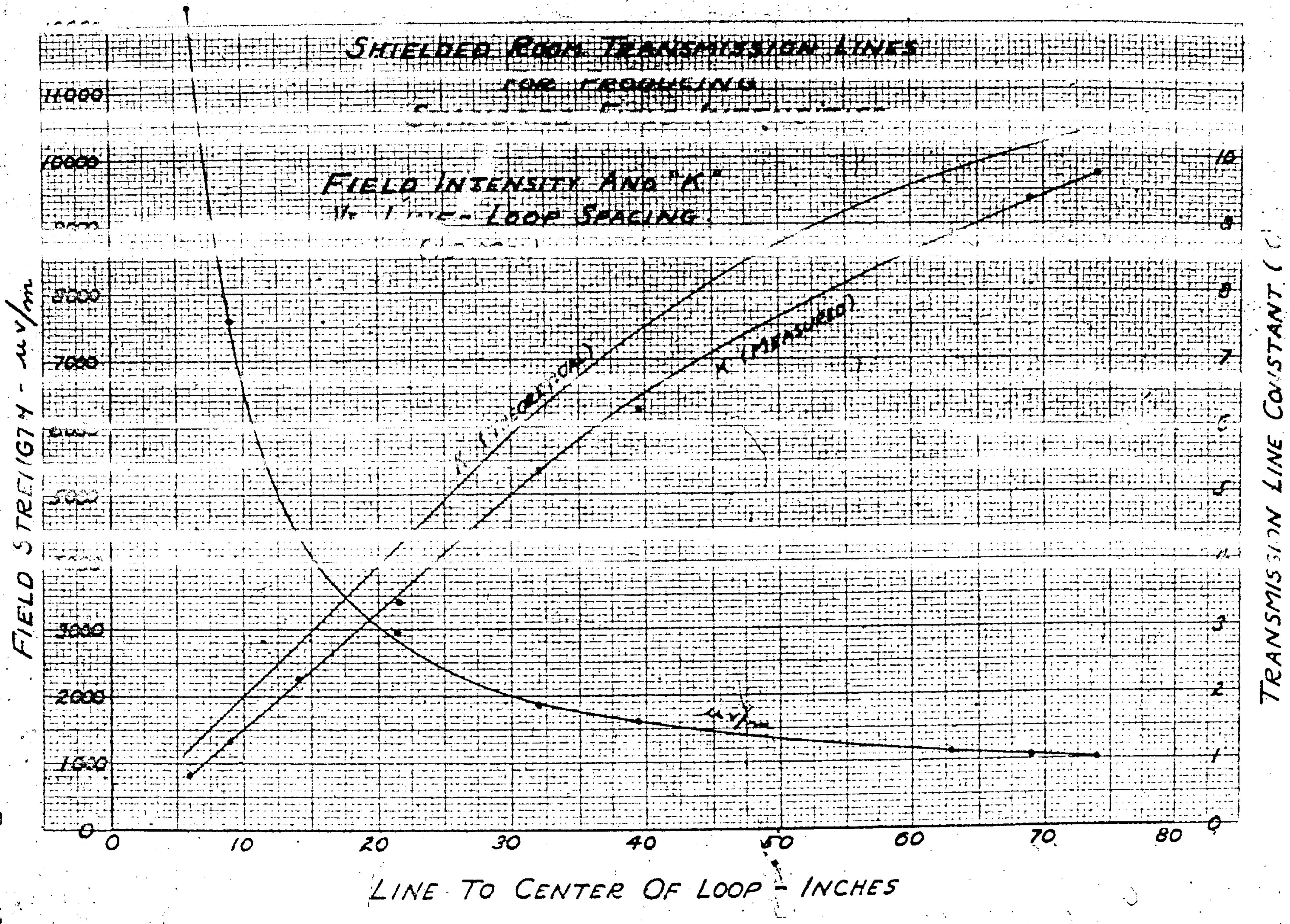


PLATE 10

OF NRL REPORT R-253

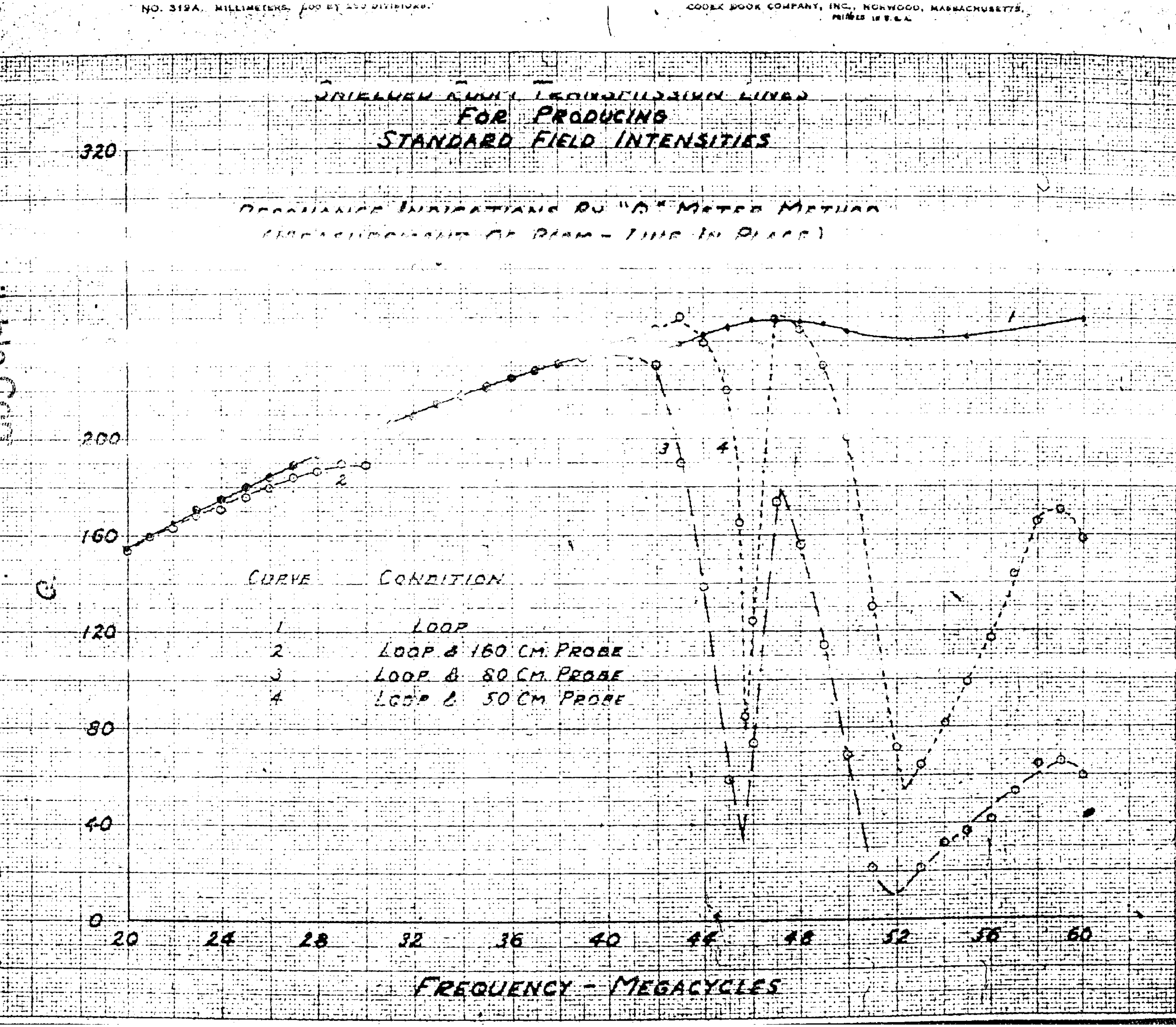


PLATE IV

OF NRL REPORT R-2536

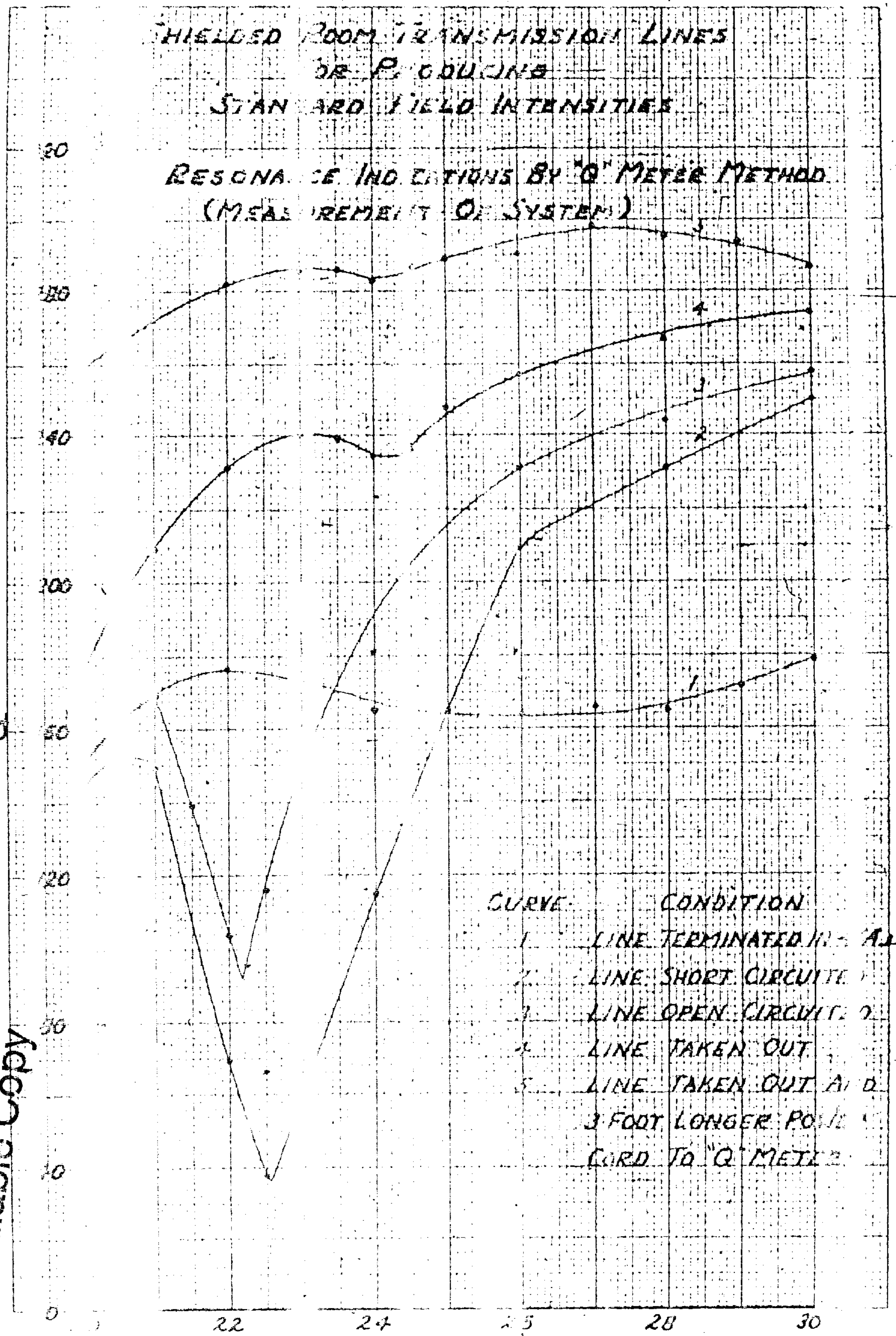
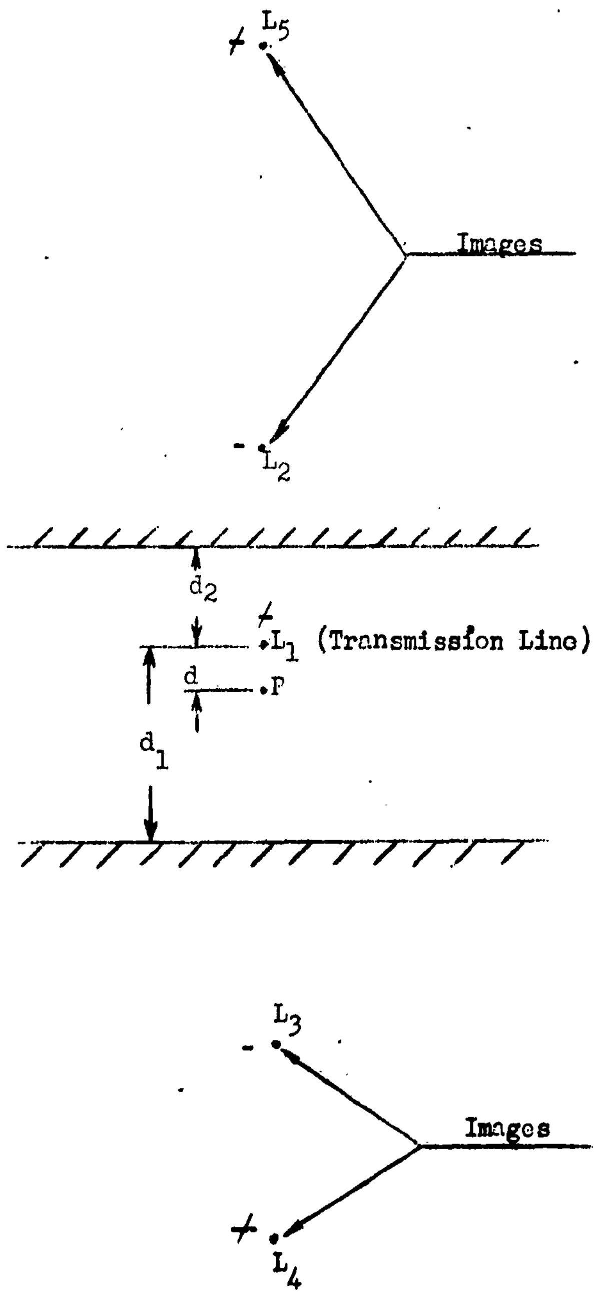


PLATE 12

OF NRL RE ORT R-25 5

Appendix A

DERIVATION
FOR
TRANSMISSION LINE CONSTANT



Assume that the transmission line is infinite in length.

Then by the Biot-Savart law, the magnetic component of the induction field is given by

$$H = \frac{i}{2\pi d}$$

where

H = magnetic field, amperes per meter

d = distance from transmission line to any point, meters

i = current in line, amperes

The field at any point P due to direct induction from the current in the line L_1 is therefore

$$H = \frac{i}{2\pi d}$$

However, the field created by the line also induces currents in the floor and ceiling of the shielded room which in turn produce image fields in space. These in turn react on each other, producing a series of secondary images, which are of minor importance and can be neglected. The fields produced at the point P by the primary images may be defined as:

$$H_2 = \frac{-i}{2\pi(2d_2 + d)}$$

$$H_3 = \frac{-i}{2\pi(2d_1 - d)}$$

The resultant magnetic field at the point P, due to the current in the transmission line and its images, is obtained by the addition of the individual fields, taking cognizance of the signs; thus:

$$H_t = H_1 + H_2 - H_3$$

$$H_t = \frac{i}{2\pi}\left(\frac{1}{d} - \frac{1}{2d_2 + d} + \frac{1}{2d_1 - d}\right)$$

$$i = \frac{E}{Z_o}$$ E = voltage applied to the line; Z_o = impedance of line

substituting and cross multiplying

$$\frac{E}{H_t} = \frac{2\pi Z_o}{\left(\frac{1}{d} - \frac{1}{2d_2 + d} + \frac{1}{2d_1 - d}\right)}$$

changing from meters to inches

$$\frac{E}{H_t} = \frac{2\pi Z_o}{\frac{1}{.0254}\left(\frac{1}{d} - \frac{1}{2d_2 + d} + \frac{1}{2d_1 - d}\right)}$$

ϵ (Field Intensity) = $120\pi H$ Harnwell, Page 535.

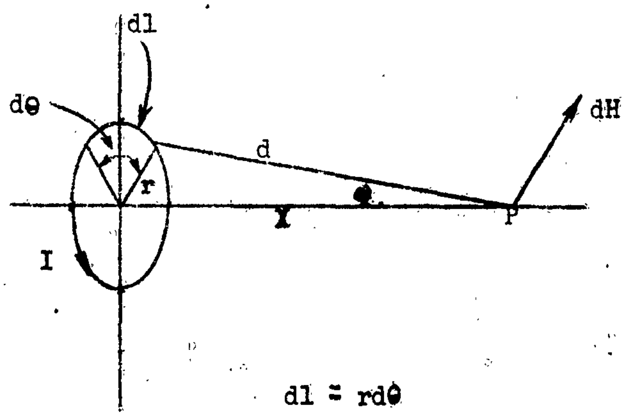
$$K = \frac{E}{\epsilon}$$

$$K = \frac{2\pi Z_o}{\frac{120\pi}{.0254}\left(\frac{1}{d} - \frac{1}{2d_2 + d} + \frac{1}{2d_1 - d}\right)}$$

$$K = \frac{Z_o}{2360\left(\frac{1}{d} - \frac{1}{2d_2 + d} + \frac{1}{2d_1 - d}\right)} \qquad (1)$$

d, d_1, d_2 are in inches

FIELD STRENGTH DERIVATION
FOR
INJECTION LOOP



dl = rdθ

The magnetic field produced by a single closed circuit is given by

$$H = \frac{I}{4\pi} \int_{\text{closed circuit}} \frac{dl}{d^2} = \frac{I}{4\pi} \int_{\text{closed circuit}} \frac{r d\theta}{d^2}$$

$$dH = \frac{I\,dl}{4\pi d^2} = \frac{I r d\theta}{4\pi d^2}$$

By symmetry the normal component of H (magnetic field) vanishes, the resultant being along the axis, or H_{axial}; thus:

$$dH_{axial} = \sin\varphi \, dH = \frac{r}{d}\, dH$$

$$= \frac{I r^2 d\theta}{4\pi d^3}$$

Integrating

$$H_{axial} = \frac{I r^2}{4\pi d^3} \int_0^{2\pi N} d\theta$$

where N = number of turns

$$H_{axial} = \frac{Ir^2}{4\pi d^3} \theta \Big|_{o}^{2\pi N}$$

$$= \frac{2\pi r^2 NI}{4\pi d^3} = \frac{Ir^2 N}{2d^3}$$

$$\text{but } d = (r^2 + X^2)^{\frac{1}{2}}$$

therefore

$$H_{axial} = \frac{Ir^2 N}{2(r^2 + X^2)^{3/2}}$$

$\epsilon = 120\pi H$ Harnwell, Page 535.

then

$$\epsilon = \frac{120\pi Nr^2 I}{2(r^2 + X^2)^{3/2}} = \frac{188.5\ Nr^2 I}{(r^2 + X^2)^{3/2}}$$

if $X \gg r$

$$\epsilon = \frac{188.5\ Nr^2 I}{X^3}$$

Reducing the above equation to r in cm., and I in m.a., the field intensity ϵ will be in μv/m.

$$\epsilon = \frac{18.85\ Nr^2 I}{X^3}$$

Reducing this to distance in inches

$$\epsilon = \frac{7420\ Nr^2 I}{X^3}$$

It is more convenient to express I in voltage and impedance; therefore,

$$\epsilon = \frac{7420\ Nr^2 E}{X^3\left((2\pi fL)^2 + R^2\right)^{\frac{1}{2}}} \qquad (2)$$

where R is a series resistor in loop circuit

Let $R \gg 2\pi fL$ so that the current in the loop is independent of the frequency of operation.

Then equation (2) becomes

$$\epsilon = \frac{7420\ Nr^2E}{X^3R} \qquad (3)$$

Equation (3) can be further simplified for practical convenience to

$$\epsilon = \frac{2360\ NAE}{X^3R} \qquad (4)$$

where

ϵ = field intensity in microvolts per meter.

E = signal generator voltage in microvolts applied to the injection loop.

A = area of injection loop in square inches.

N = number of turns of injection loop.

X = distance from injection loop in inches.

R = series swamping resistance in ohms in loop circuit.