EXPERIMENTS ON
ELECTROMAGNETIC
SHIELDING

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EXPERIMENTS ON ELECTROMAGNETIC SHIELDING AT
FREQUENCIES BETWEEN ONE AND THIRTY KILOCYCLES

Respectfully submitted as thesis in partial fulfilment of the requirements for the M.Sc. degree

by

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ABSTRACT

This paper describes a method used in measuring the ratio of magnetic field intensities within conducting cylindrical and spherical shells to that outside, values being given for various frequencies between 1000 and 30,000 cycles per second of the exciting field and various length and radii. A theoretical derivation of a shielding formula is given for a thin spherical shell and a cylindrical one of infinite length. Satisfactory agreement between theory and observation is found in the case of the sphere and in cylinders of lengths greater than their diameters.

INTRODUCTION

The following investigations were carried on in the Communications Laboratory of the Engineering Department at McGill University under the direction of Dr. F. S. Howes, of the staff of the Faculty of Engineering, and Professor Louis V. King, of the Physics Department. This work was begun in October, 1930, and completed in April, 1932.

The purpose of this research is to offer experimental evidence in support of shielding formulae derived by Dr. King, and to furnish data on the shielding effect of hollow cylindrical conductors in oscillating magnetic fields, which may serve as a guide in the proper design of shielding apparatus against high-frequency electro-magnetic fields. Recently the use of high-frequency measuring equipment and development of radio circuits have required the shielding of various pieces of apparatus to an almost perfect degree. The usual form that the shielding is required to take is that of a more or less cylindrical shape and as sheets or plates. Since the shielding effect of plates has been rather fully covered by J. H. Morecroft and Alva Turner,⁽¹⁾ the sub-

(1) Proc.I.R.E., 13, p.477,(1925).

ject matter of this paper will confine itself to hollow cylindrical shells.

Experiments of R. H. Barfield⁽¹⁾ in 1923 furnish quantitative data on the screening effect of large iron containers and mesh screens. In this paper methods of shielding either the magnetic or electric intensities alone are discussed.

In 1882 Lord Rayleigh⁽²⁾ found that the induction between two coils was decreased greatly when a copper sheet was placed between them. The experiment was qualitative, no quantitative values of shielding being given. In the paper Lord Rayleigh quotes Maxwell,⁽³⁾ who showed in 1871 that a perfectly conducting sheet acts as a barrier to magnetic force.

A theoretical and quantitative consideration of the shielding effect of spherical shells was given by Sir James Larmor⁽⁴⁾ in 1884. The treatment here is for the case of low-frequency fields.

In 1930 Professor L. V. King⁽⁵⁾ derived formulae for the shielding effect of infinitely long cylinders and hollow spheres of finite wall thickness and diameter, applicable to all frequencies.

(1) Jr. I.E.E., vol.62, p.249, 1924.

(2) Phil.Mag., vol.13, p.344, May, 1882.

(3) Electricity and Magnetism, vol.2, 655.

(4) Phil. Mag., vol.17, p.5, Jan., 1884.

(5) To be published shortly.

An examination of the various scientific periodicals showed a dearth of papers on the experimental treatment of the shielding effect of cylinders, and, therefore, an investigation of this kind seems worth while. This paper does not pretend to be an exhaustive treatment of the subject, but only the beginning of further work in this field.

Fig. I

APPARATUS

The arrangement of apparatus used in the experimental work is shown in Fig. I. On the left is found the oscillator and amplifier which is connected to a pair of Helmholtz coils tuned to the desired frequency by a condenser connected in shunt with them. In the centre of the Helmholtz coil arrangement there are two search coils, one large and one much smaller, each fixed on an arm so that they may rotate freely about the centre shaft. The drum to which they are connected is so fixed that the coil occupying the lower position is connected through two leads shielded by the shaft, to the vacuum valve voltmeter found on the extreme right of the figure.

In Fig. 2 may be seen a close up of the Helmholtz coils. They are 15 inches in diameter and $1\frac{1}{2}$ inches wide wound with 104 turns each of Litz wire having the d-c conductance of #14 copper wire. Their diameter was made large in order to secure as large a field of uniform magnetic flux as possible and adequate for the purpose, bearing in mind the possible distortion of the field due to the shielding cylinder located in it. A great deal of precision is unnecessary here since both search coils occupy

very nearly the same position in the field when connected in circuit.

The reason for using two search coils, one small, the other larger, the larger coil carrying the shield only, is obvious from the following symbolic consideration:-

I = current in the field coils

Let H_1 = magnetic field small coil in circuit

H_2 = magnetic field large coil in circuit

E_1 = voltage at the terminals of the small search coil

E_2 = voltage at the terminals of the larger search coil

N_1 = number of turns on the small search coil

N_2 = number of turns on the larger search coil

A_1 = cross sectional or turn area of the small search coil

A_2 = cross sectional or turn area of the larger search coil

K = attenuation factor

$K = 1$ with no shield - $K < 1$ inside shield

$E \propto H N A K$

$$\frac{E_2}{E_1} = \frac{H_2 N_2 A_2 K}{H_1 N_1 A_1} = \frac{I_2 N_2 A_2 K}{I_1 N_1 A_1}$$

$$K = \frac{E_2}{E_1} \frac{I_1}{I_2} \frac{N_1 A_1}{N_2 A_2}$$

Thus if the search coils are so arranged that $N_1 A_1 : N_2 A_2 \div K$ and since the current in the field coils does not vary over small intervals of time E_2 will be of the same order as E_1 and can therefore be read on the same voltmeter scale.

The larger search coil was designed after the following consideration in order that the voltage, as measured at the end of the leads, would be very nearly that of the coil terminals.

X = reactance of search coil and capacity of leads and voltmeter

X^1 = reactance of leads and voltmeter

$$X = \omega L - \frac{1}{\omega c}$$

$$X^1 = - \frac{1}{\omega c}$$

$$\frac{e^1}{e} = \frac{- \frac{1}{\omega c}}{\omega L - \frac{1}{\omega c}} = \frac{1}{1 - \omega^2 Lc}$$

Hence if L is made less than 1% of $\frac{1}{\omega^2 c}$, e^1 will equal e within the precision of the experiment.

In fig. 3 is shown the voltmeter used to measure the voltage induced in the search coil. It is of the screen grid valve type with the valve fixed at

the end of a goose neck in order to reduce the input capacity to a minimum. The circuit of the voltmeter is adjusted until the plate current is 3 microamperes in order to obtain rectification on the square law part of the plate current grid voltage curve. This 3 microampere plate current is then balanced out, the a-c voltage applied to the grid and the plate current read on a micro-ammeter. The current reading varies directly as the square of the voltage applied to the grid terminal. Before using, the voltmeter was calibrated, using a Weston Dynamometer type voltmeter at 60 cycles. Since the input capacity of the screen grid valve is only about 4 micro-micro farads practically no current is drawn and the frequency calibration is uniform up to very high frequencies.

The oscillator used, which was not the radio-frequency type shown in the figure, was a General Radio Type - delivering from 25 to 70,000 cycles. This oscillator is guaranteed to 1⁰/o in frequency by the manufacturer, and was used to drive two pentode valves in parallel as amplifiers which were connected directly to the tuned field coils.

The proper design for the large search coil was arrived at after measuring the capacity of the leads and voltmeter, which were found to be 50 ppf, and choosing the frequency to be used. This was very

important since the amount of power available was very small, only about 5 watts, therefore requiring as large a search coil as possible within the limitations allowed.

It was impossible to obtain readings at radio frequencies due, in part, to the small number of turns on the primary and secondary coils. Another limitation, in making radio frequency measurements, arises when King's⁺ asymptotic formula, for the shielding ratio at radio frequencies, is considered. The formula for the cylinder is

$$(1) \quad \frac{1H_1 l}{1H_0 l} = 4 \frac{c}{a} e^{-\frac{d}{c\sqrt{2}}} \quad \text{where } c^2 = \frac{s}{8\pi^2 f}$$

a = radius
 d = thickness
 s = specific resistance
 f = frequency

For one of the aluminium cylinders used

$$\begin{aligned}
 a &= 2.54 \text{ cms.}; d = 2.54 \times 10^{-2} \text{ cms.}; s = 3 \times 10^{-6} \text{ ohms} \\
 &= 3000 \text{ e.m.u.} \quad f = 10^6, c = 6.17 \times 10^{-3} \text{ cms,} \\
 c/a &= 2.43 \times 10^{-3}, \quad \frac{d}{c\sqrt{2}} = 2.91, \quad e^{-\frac{d}{c\sqrt{2}}} = 0.0550
 \end{aligned}$$

$$\text{Formula (1) gives } \frac{1H_1 l}{1H_0 l} \doteq 5 \times 10^{-4}$$

With the coil employed $1H_0 l \doteq 6$ gauss, and in this instance the voltage across the secondary was approximately 18 volts. With the shielding cylinder

⁺ Loc.cit.

this voltage is reduced to 10^{-2} volts, which is beyond the sensitivity of the ionization voltmeter. To study shielding at radio frequencies with the available power a voltage sensitivity of at least 10^{-4} volts is required.

In an attempt to measure this small ratio, experiment indicated a value less than 10^{-3} as indicated theoretically by the result given above.

The apparatus was grounded by soldering separate leads to each section of the brass shield tubes and voltmeter ground and tying a lead to the shielding cylinder. All the leads were brought to one common point which was earthed. This is diagrammatically illustrated below -

THEORY

Nomenclature

- ρ = specific resistance in e.m.u.
 d = thickness of shell in cms.
 a = mean radius in cms.
 f = frequency in cycles per second
 ω = $2\pi f$
 i = current density
 I = ixd = current per unit length
 H_i = $lH_i \sin(\omega t - \beta)$ = magnetic intensity inside shell
 H_o = $lH_o \sin \omega t$ = magnetic intensity outside shell
 C = eddy current or induction constant,
 $C^2 = \frac{\rho}{8\pi^2 f}$
 dz = an element of cylinder length
 E = electric field tending to force current around circles perpendicular to the exciting field

Fig. 4.

Fig. 4

I. Shielding Ratio for Thin Cylindrical Shell of Infinite Length.

The method of attacking the following problem was indicated by Dr. L. V. King.

Let us consider a hollow cylindrical shell of wall thickness d , small compared to the mean radius a . The frequency f considered is so low that the induced current density i in the shell is, approximately, uniform.

For simplicity of calculation the exciting magnetic field H_0 is supposed to be parallel to the axis of the cylinder. According to Faraday's Law, an electric field is set up tending to cause current to flow in circles around the cylinder. Owing to a phase difference of 90° the current, thus induced, opposes the external field, giving rise to a certain degree of 'shielding'.

At high frequencies the induced current is not uniform, but tends to concentrate on the outer surface (skin effect) in the well known manner, and, in general, the shielding effect is a combination of these two.

In order to determine the relation between the internal and external fields, we take a unit pole along a closed rectangular circuit of length dz (1) just inside the shell, (2) through the shell, (3) just

outside the shell, and (4) back through the shell. Since the field is parallel to the side dz of the circuit, it is obvious that the work contributed by the parts (2) and (4) is zero. The remainder of the circuit contributes $(H_i - H_o) dz$ and so by Ampere's Law $(H_i - H_o) dz = 4\pi Idz$

$$\text{or } (H_i - H_o) = 4\pi I \quad \text{-----(1)}$$

where $I = \frac{\text{current}}{\text{length}}$, i.e., $I = \frac{id}{l}$.

The induction through the section dz of area πa^2 is

$$\phi = \pi a^2 l H_i \sin(\omega t - \beta) \quad \text{-----(2)}$$

By Faraday's Law

e.m.f. around the section = work done in taking unit charge around the circuit $2\pi a$

$$\text{i.e. } 2\pi a E = - \frac{d\phi}{dt}$$

By Ohm's Law

$$i = \frac{E}{\rho}, \text{ and since } I = i \cdot d \cdot l \text{ cm.}$$

$$\text{Then } I = \frac{-d}{2\pi a \rho} \frac{d\phi}{dt} = - \frac{\omega a d}{2\rho} l H_i \cos(\omega t - \beta)$$

Substituting for I in (1) we have the following relation which must hold for all instants of time.

$$l H_i \sin(\omega t - \beta) - l H_o \sin \omega t = - \frac{2\pi \omega a d}{\rho} l H_i \cos(\omega t - \beta)$$

Equating the coefficients of $\sin \omega t$ and $\cos \omega t$, or more simply, writing successively $\omega t = 0$, and $\omega t = \beta$,

we find at once

$$\tan \beta = \frac{2\pi\omega ad}{\rho} = \frac{1}{2} \frac{a d}{c^2} \text{-----}(3)$$

and $lH_0 \sin \beta = lH_i \tan \beta$

or $\frac{lH_i}{lH_0} = \cos \beta \text{-----}(4)$

2. Shielding Ratio for Thin Spherical Shell.

We now examine the case of a thin spherical shell, radius, a, and wall thickness, d, in a uniform alternating field, H_0 . Inside and outside the shell, the field may be completely specified by the magnetic potentials $\mathcal{N}_i$ and $\mathcal{N}_o$.

Referring to Fig. 5, calculate the work done in taking a unit pole around the closed circuit (1, 2, 3, 4) of length $d s$ and side $d n$.

At the boundary between the two media we apply Gauss' Theorem to a thin volume whose thickness is $d n$ and area S^1 just inside, and

S just outside the spherical surface. In the limit when S and S^1 are infinitely close, the contribution of the edge to the surface integral

$$\int N \, d s = 0.$$

Since there are no free magnetic poles inside the volume, whose opposite sides are of area S and S^1 we have

$$S H_n - S^1 H_n^1 = 0 \quad \text{where } H_n \text{ and } H_n^1$$

are the normal components of the external and internal magnetic fields.

Ultimately since $S = S^1$ for an infinitely thin shell, we have the usual boundary condition $H_n = H_n^1$, establishing the continuity of the normal component of field through the shell.

In the present problem the normal components

$$H_n = \left(\frac{\partial \mathcal{N}_o}{\partial r} \right)_{r=a} \quad \text{and}$$

$$H_n^1 = \left(\frac{\partial \mathcal{N}_i}{\partial r} \right)_{r=a}$$

$$\text{so that} \quad \left(\frac{\partial \mathcal{N}_o}{\partial r} \right)_{r=a} = \left(\frac{\partial \mathcal{N}_i}{\partial r} \right)_{r=a} \quad \text{-----}(1)$$

The tangential components of the external and internal fields, respectively, are $\frac{1}{r} \frac{\partial \mathcal{N}_o}{\partial \theta}$ and $\frac{1}{r} \frac{\partial \mathcal{N}_i}{\partial \theta}$.

Calculating the work done along the circuit (1, 2, 3, 4) as before, Ampere's Formula gives, after dividing by $\underline{ds}$

$$\left[\frac{1}{r} \frac{\partial \mathcal{N}_i}{\partial \theta} - \frac{1}{r} \frac{\partial \mathcal{N}_o}{\partial \theta} \right] = 4\pi i d \text{ -----(2)}$$

These potentials $\mathcal{N}_o$ and $\mathcal{N}_i$ satisfy Laplace's Equations, $\nabla^2 \mathcal{N} = 0$ The appropriate solutions are

$$\mathcal{N}_o = H_o r \cos \theta + \frac{A \cos \theta}{r^2}$$

$$\text{and } \mathcal{N}_i = H_i r \cos \theta$$

The expression for $\mathcal{N}_o$ when $r \rightarrow \infty$ gives the potential of a uniform field H_o . The solution for $\mathcal{N}_i$ is the only one which enables the boundary conditions to be satisfied for all values of θ .

Inserting the values of $\frac{\partial \mathcal{N}_i}{\partial \theta}$ and $\frac{\partial \mathcal{N}_o}{\partial \theta}$

at $r = a$ in (2) we obtain

$$\left[H_o + \frac{A}{a^3} - H_i \right] \sin \theta = -4\pi i d \text{ -----(3)}$$

From (1) we find

$$H - \frac{2A}{a^3} = H_i$$

$$\text{or } \frac{A}{a^3} = \frac{H_o - H_i}{2} \text{ and by substitution}$$

$$(3) \text{ becomes } \frac{3}{2} [H_o - H_i] \sin \theta = -4\pi i d \text{ -----(4)}$$

$$\text{By Ohm's Law } i = \frac{E}{\rho} \text{ -----(5)}$$

By Faraday's Law

e.m.f. around circuit = work done in taking
unit charge around
circuit $2\pi a \sin \theta$

$$\text{i.e. } (2\pi a \sin \theta)E = - \frac{d\phi}{dt} \quad \text{-----}(6)$$

We at once see that $\phi = H_i \times$ (area of section of
radius $2\pi a \sin \theta$)

$$\text{or } \phi = \pi a^2 \sin^2 \theta |H_i| \sin (\omega t - \alpha)$$

Thus differentiating,

$$\frac{d\phi}{dt} = \omega \pi a^2 \sin^2 \theta |H_i| \cos (\omega t - \alpha)$$

thus according to (6)

$$E = - \frac{\omega a \sin \theta}{2} |H_i| \cos (\omega t - \alpha)$$

and (5) gives

$$i = - \frac{\omega a \sin \theta}{2} |H_i| \cos (\omega t - \alpha)$$

The occurrence of the factor $\sin \theta$, in the above expression enables us to satisfy condition (4) for all values of θ , and thus obtain the required relation between H_i and H_o in the form

$$|H_o| \sin \omega t - |H_i| \sin (\omega t - \alpha) = \frac{4\pi \omega a d}{3\rho} |H_i| \cos (\omega t - \alpha)$$

Since this equation holds for all instants of time we may equate the coefficients of $\sin \omega t$ and $\cos \omega t$, or, more simply, write successively $\omega t = 0$ and $\omega t = \alpha$ and

$$\text{obtain at once } \tan \alpha = \frac{4\pi \omega a d}{3\rho} = \frac{1}{2} \frac{a d}{c^2} \quad \text{-----}(7)$$

$$\text{and } \frac{l_{H_i} l}{l_{H_0} l} = \cos \alpha \quad \text{-----}(8)$$

The results found above, for the theoretical attenuation factor agree exactly with the low frequency approximation of the King formula. It is, therefore, reasonable to expect the above method correct for the assumption made.

PROCEDURE

At the first an attempt was made to measure the shielding effect at a frequency of 1,000 Kc. Since the effect of shielding was of the order of 99.9⁰/o and higher, no reading of voltage generated in the shielded coil could be made with the apparatus used, the lowest measurable voltage being 0.1 of a volt.⁺ The limitations due to the apparatus used, were a maximum power of only 5 watts, field coils of only 13 turns each and a shielded search coil of only 6 turns on a 1¹/₄" form. The size of the field coils was limited in that the tuned circuit impedance $\frac{L}{rC}$ had to be so adjusted that the maximum power output could be obtained from the oscillator amplifier. The number of turns on the search coil was limited by the consideration mentioned under 'Apparatus'.

Since no higher power was obtainable the only solutions to the problem lay in either introducing amplification between the search coils and voltmeter, or the lowering of the frequency to be used. Amplification was tried but found to be unsatisfactory due to extraneous pick up, microphonic effects in the amplifier valves and unsteady amplification. This lead to the necessity of decreasing

⁺ Refer to page 12.

the frequency, first to 100 Kc. and finally to 10 Kc.

The two search coils were so constructed that their turns area was made equal to 0.0790. The larger coil was fixed with a mounting to support the cylinders.

An examination of the voltmeter calibration curve will reveal that the current, measured in microamperes, is directly proportional to the square of the voltage applied. Therefore it was unnecessary to convert the microamperes read into volts and the results of field intensity ratio were arrived at in the following manner.

$$\frac{H_i}{H_o} = K = .0790 \sqrt{\frac{\mu I_i}{\mu I_o}}$$

where H_i = field intensity inside the shield

H_o = field intensity outside the shield

μI_o = scale reading for voltage across unshielded coil

μI_i = scale reading for voltage across shielded coil.

Measurements of field intensity ratios were taken using aluminium cylinders of various lengths, diameters and thicknesses, at a frequency of 10,000 cycles per second, and, in some cases, the frequency was

allowed to vary between 1000 and 30,000 cycles per second. Curves were then plotted for the field intensity ratio against each of the above as variables separately, keeping everything else a constant.

The theoretical values were calculated by using both low-frequency and high-frequency approximations of Dr. King's formula, the low-frequency approximations being plotted since it was found to fit the experimental results more accurately than the high-frequency approximation.

The specific resistance of the cylinders in the direction of the induced currents was measured on a Kelvin double bridge. This was done by first slitting the cylinders lengthwise, the edges thus formed being inserted into mercury filled troughs to be used as the current electrodes. The potential electrodes were made up in the form of a pair of sharp pointed dividers. A cross-section of the apparatus used is shown below.

Resistance readings were taken for various positions of the potential electrodes along the cylinders and an average found, from which the specific resistance was calculated. Approximately thirty readings were made on each cylinder.

Attempts were made to measure the resistance of the cylinders without destroying them, but this was impossible since consistent readings were never obtained, due, for the most part, to inability to secure a definite current electrode contact on the sides of the cylinders, and also so to distribute the current that exactly half would traverse each current path. The arrangement shown below was tried.

The thickness of the cylinder walls was determined by using a pair of micrometer calipers with a ball anvil. The measurement used was the

mean of twenty readings, this value being checked by weighing, and, knowing the density, calculating the thickness.

The diameters of the cylinders were measured with a pair of vernier calipers.

All the above measurements could certainly be relied upon to be within an error of 1⁰/o.

A few sample observations are tabulated below in order to acquaint the reader with the method used in making observations of the shielding effect.

Variation of Frequency

Aluminium Cylinder 8.89 cms. long, 0.0274 cms. thick, 2.64 cms. radius. Specific resistance = 3260 e.m.u.

f	μI_i	μI_o	$\frac{H_i}{H_o} = 0.790 \sqrt{\frac{\mu I_i}{\mu I_o}}$	$\frac{H_i}{H_o} = \cos \alpha$
30,000	1.10	3.47	4.46 ⁰ /o	3.81 ⁰ /o
25,000	1.80	4.30	5.11	4.57
20,000	2.89	4.60	6.26	5.70
18,000	3.13	4.20	6.82	6.34
14,000	5.85	4.75	8.95	8.14
10,000	10.15	4.40	12.0	11.35
9,000	6.08	2.10	13.5	12.6
8,000	6.50	1.76	15.0	14.2
7,000	5.47	1.10	17.6	16.1
6,000	8.83	1.35	20.2	18.7
5,000	7.73	0.82	23.9	22.3
4,000	7.10	0.53	28.9	27.5
3,000	34.0	1.59	36.6	35.5
2,500	74.2	2.70	41.5	41.5
2,000	63.0	1.50	51.4	49.6
1,000	19.8	0.20	78.0	75.1

Curve #1

Curve #2

Curve #3

frequency = 10,000 cycles

Curve #4

frequency = 10,000 cycles

DISCUSSION OF RESULTS

On examination of the curves plotted, showing the effect of variation of frequency upon shielding effect, we notice an extraordinary agreement between the theoretical and observed results. In the cases of the cylinders the discrepancy which exists is due probably to the lengths being too small for the theory to apply exactly, in addition to experimental errors which may be as much as 50/o. The probable error of 50/o is due to the limitation in the determination of the physical constants of the cylinders plus the observational error. The fact that the theoretical curves all lie below the observed bears out the theory for the discrepancy being due to short cylinders. The curves for the variation of length illustrate the effect even more clearly.

The opposite effect is shown in the curves for the sphere, the theoretical lying above the observed. This effect may be due to two things, the distortion of the exciting field and the resulting distortion of the inner field, due to the size of the sphere being comparable to the diameter of the Helmholtz coils and to the presence of a rim used to join the two halves of the sphere in a plane perpendicular to the direction of the exciting field.

In curve # 2 the effect of the variation of thickness is shown. The difference here, between the theory and observation, is due to the length of the cylinder being too small to be considered adaptable exactly to theory.

For the variation of radius we see that the observed values run parallel to the theoretical until the diameter of the cylinder is of the same order as its length. At this point and for larger diameters the shielding ^{ratio} departs from the predicted values, the shielding effect decreasing with increasing radius, which is the reverse of what the theory for a cylinder gives. This phenomenon is also shown in the curves for variation of length, the cylinders departing only slightly from the theoretical values until the length is about equal to the diameter, where a sharp change in the slope occurs and the formula no longer applies. The non-uniformity of the theoretical curve for variation of radius is due to the thicknesses of the several cylinders used not being the same. This is rather unfortunate, but does not prevent a reasonable deduction being made.

The final set of curves illustrates the effect of discs placed over the cylinder ends and the change in shielding due to variation of the length.

Thus we see that placing ends on the cylinders serves to increase the shielding only when the length of the open ended cylinders is decreased below the value which is of the same order as the diameter. This observation is quite reasonable since one would not expect to notice the effect of a thin disc at the end of a long cylinder if we consider as an analogous case the field due to a long solenoid.

The foregoing results taken together illustrate the extraordinary power and simplicity of the theoretical treatment of the subject and the excellent agreement, with the reservations made, of observation and theory.

CONCLUSION

Since the derivations of the formulae by Dr. L. V. King are rigorous and have been tested in the frequency range of 1000 to 30,000 cycles, we may conclude that the formula will hold for all thicknesses of shell and all frequencies from zero to the low frequency radio oscillations. The results lead us also to the conclusion that the theory is not applicable to cylinders having diameters of the same order or greater than the length. Furthermore, that within this same range of dimensions only, ends placed on cylinders will increase the shielding effect and render the combination effect applicable to the theoretical investigation of cylinders of greater diameter.

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