

April 15, 1958

S. P. MORGAN, JR
LAMINATED CONDUCTOR

2,831,172

Filed Sept. 11, 1952

2 Sheets-Sheet 1

FIG. 1

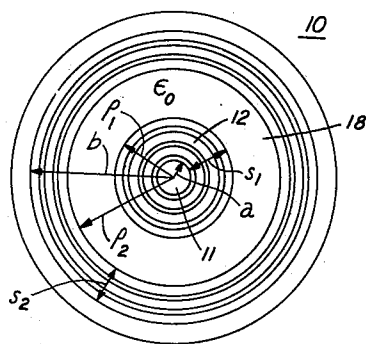
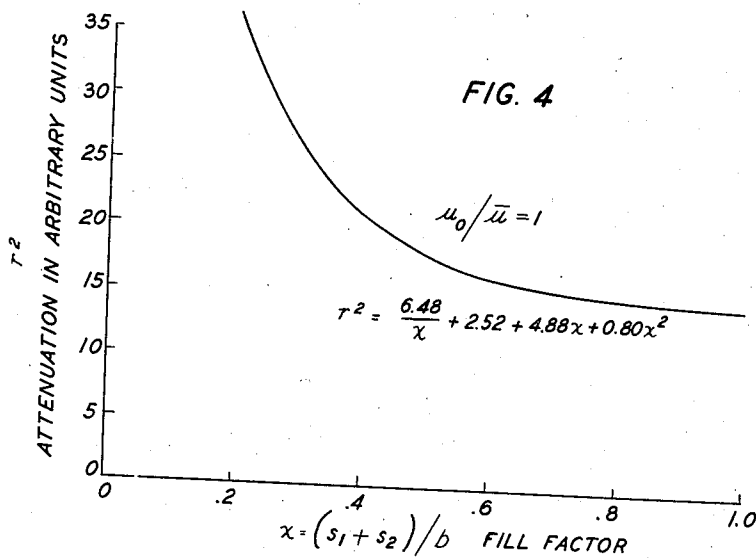
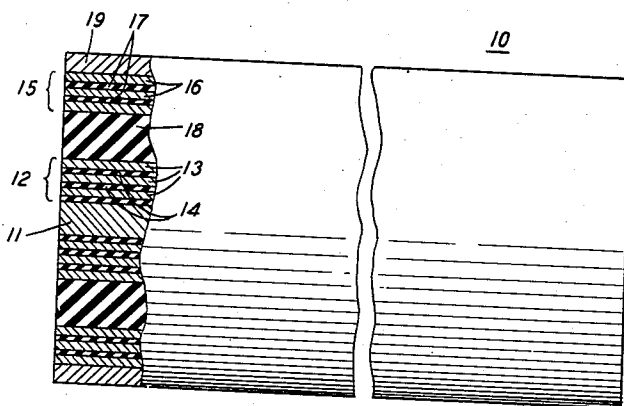


FIG. 2



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FIG. 3

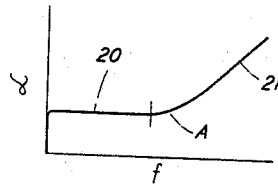


FIG. 5

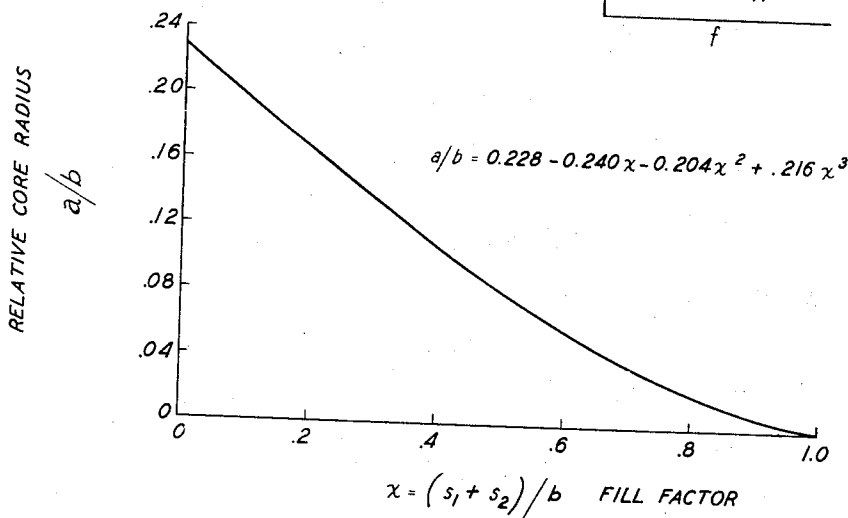
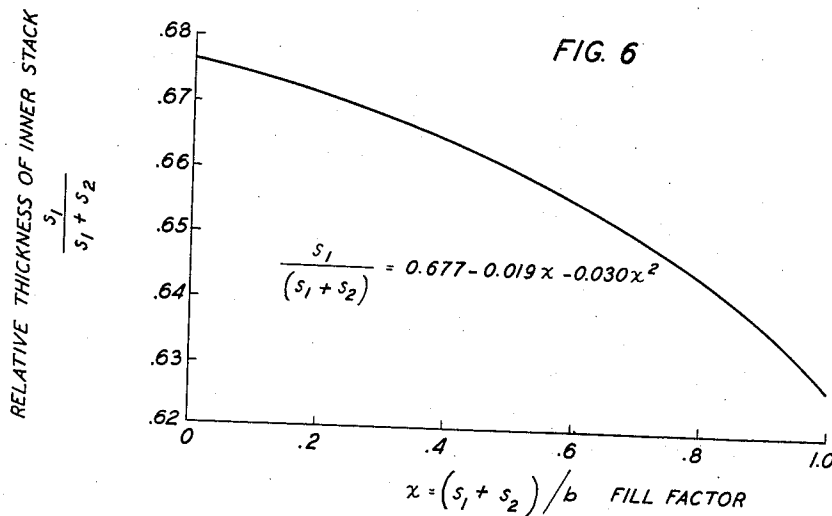


FIG. 6



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2,831,172

LAMINATED CONDUCTOR

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Application September 11, 1952, Serial No. 309,023

2 Claims. (Cl. 333-96)

This invention relates to electrical conductors and more particularly to composite conductors formed of a multiplicity of insulated conducting portions and which have come to be known as "Clogston conductors."

It is an object of this invention to improve the current distribution in composite conductors of the type comprising one or more stacks each including a large number of insulated conducting portions, and particularly to effect such improvement by the proportioning of the stacks.

In a copending application of A. M. Clogston, Serial No. 214,393, filed March 7, 1951, now Pat. No. 2,769,148, October 30, 1956, there are disclosed a number of composite conductors, each of which comprises a multiplicity of insulated conducting elements of such number, dimensions, and disposition relative to each other and to the orientation of the electromagnetic wave being propagated therein as to achieve a more favorable distribution of current and field within the conducting material. In one specific embodiment disclosed in Figs. 7A and 7B of the Clogston application, two coaxially arranged composite conductors (stacks) are separated by dielectric material, each of the composite conductors comprising a multiplicity of thin metal laminations insulated from one another by layers of insulating material, the smallest dimensions of the laminations being in the direction perpendicular to both the direction of wave propagation and the magnetic vector. Each metal lamination is many times (for example 10, 100, or even 1000 times) smaller than the factor δ which is called one skin thickness or one skin depth. The distance δ is given by the expression

$$\delta = \sqrt{\frac{1}{\pi f \mu \sigma}} \quad (1)$$

where δ is expressed in meters, f is the frequency in cycles per second, μ is the permeability of the metal in henries per meter, and σ is the conductivity in mhos per meter. The factor δ measures the distance in which the current and field penetrating into a slab of the material many times δ in thickness will decrease by one neper; i. e. their amplitude will become equal to $1/e = 0.3679 \dots$ times their amplitude at the surface of the slab.

It is pointed out in the above-mentioned Clogston application that when a conductor has such a laminated structure, a wave propagated along the conductor at a velocity in the neighborhood of a certain critical value will penetrate further into the conductor (or completely through it) than it would penetrate into a solid conductor of the same material, resulting in a more uniform current distribution in the laminated conductor and consequently lower losses. In the case where the cable is not magnetically loaded, the critical velocity for the type of structure just described is determined by the thicknesses of the metal and insulating laminae and the dielectric constant of the insulation between the laminae

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in the composite conductors. The critical velocity can be maintained by making the dielectric constant of the main dielectric, that is the dielectric material between the two composite conductors, or stacks satisfy the following relationship:

$$\epsilon_0 = \epsilon_2 \left(1 + \frac{t_1}{t_2} \right) \quad (2)$$

where ϵ_0 is the dielectric constant of the main dielectric element between the two conductors in farads per meter, ϵ_2 is the dielectric constant of the insulating material between the laminae of the conductors in farads per meter, t_1 is the thickness of one of the metal laminae in meters and t_2 is the thickness of the insulating lamina in meters. The insulating laminae are also made very thin and an optimum thickness for certain structures of this general type is that in which each insulating lamina is one-half the thickness of a metal lamina. This condition does not exist, however, in all cases.

It has been discovered that in unloaded Clogston conductors of the type just described, the attenuation constant is substantially uniform from a very low frequency, in practice a few kilocycles, up to a certain frequency, which may in practice be many megacycles, the value of which is dependent on various factors among which are the composition, thickness and proportioning of the various laminae in the composite conductors. Above this certain frequency the attenuation constant rises. In the description which follows, the attenuation constant in this uniform or flat portion of the curve of attenuation constant vs. frequency will be known as the low frequency attenuation constant although, as mentioned above, in practice this region may extend up to many megacycles.

The present invention is based on the discovery that this low frequency attenuation constant can be minimized for various optimum conditions. Assuming a fixed outer radius and that the electrical constants of the main dielectric and of the inner and outer stacks are fixed, for each value of fill factor x , that is, the ratio of the total stack thickness to the outer radius of the composite conductor, there is a definite radius of core a and distribution of the laminated material between inner and outer stacks for minimum low frequency attenuation.

The invention will be more readily understood by referring to the following description taken in connection with the accompanying drawings forming a part thereof, in which:

Fig. 1 is an end view of a coaxial composite conductor in accordance with the invention, the outer conductor or stack comprising a multiplicity of metal laminations separated by insulating material and the inner conductor or stack being similar in this respect to the outer conductor, the two stacks being separated by an intermediate or main dielectric member;

Fig. 2 is a longitudinal view, with portions broken away, of the composite conductor of Fig. 1;

Fig. 3 is a graph of attenuation constant vs. frequency for a composite conductor of the type shown in Figs. 1 and 2;

Fig. 4 is a graph of r^2 (a constant proportional to attenuation) in arbitrary units vs. fill factor x , that is, the fraction of the total radius of the cable filled with laminations;

Fig. 5 is a graph of relative core radius vs. fill factor in a cable of the type shown in Figs. 1 and 2; and

Fig. 6 is a graph of relative thickness of the inner stack vs. fill factor in a cable of the type shown in Figs. 1 and 2.

Referring more particularly to the drawings, Figs. 1

and 2 show, by way of example, a conductor 10 in accordance with the invention, Fig. 1 being an end view and Fig. 2 being a longitudinal view. The conductor 10 comprises a central core 11 (which may be either of metal or dielectric material), an inner composite conductor or stack 12 formed of many laminations of metal 13 spaced by insulating material 14, an outer composite conductor or stack 15 formed of a multiplicity of layers of metal 16 spaced by insulating material 17 and separated from the inner conductor 12 by an intermediate or main dielectric member 18, and an outer sheath 19 of metal or other suitable shielding material. As disclosed in the above-mentioned Clogston application, each of the metal layers 13 and 16 is made very thin compared to the skin depth of the conductor being used, which, for example, can be copper, silver, or aluminum. The insulating layers 14 and 17 are also made very thin and may be of any suitable material. Examples of satisfactory materials are: polyethylene, polystyrene, quartz and polyfoam. Preferably, the insulating layers are of the order of one-half the thickness of each metal layer, although this is not necessarily true in all cases. The inner conductor or stack 12 has 10 or 100 or more metal layers 13 and the outer conductor or stack 15 has a number of metallic layers 16 of the same order of magnitude as the number of metal layers 13 but, as will be pointed out below, there are not necessarily the same number of conductors in the two stacks. Since there are a large number of insulating and metallic layers, it makes no difference whether the first or the last layer in each stack (12 or 15) is of metal or of insulation.

As pointed out above, certain optimum relationships exist in unloaded Clogston conductors or cables of the general type just described. These optimum relationships make it possible to select various ratios and proportions of elements within the stack which will give the minimum low frequency attenuation constant. These relationships are optimum only in the low frequency portion of the graph of attenuation constant α vs. frequency f . As shown in Fig. 3, which presents a typical curve of attenuation constant α vs. frequency f , there is a low frequency portion 20 (which extends in practice from a frequency of a few kilocycles to many megacycles) which is substantially flat and parallel to the horizontal axis and a high frequency portion 21 which curves upward. It should be understood that for each particular configuration of cable 10 there is a different curve of low frequency attenuation constant vs. frequency, the curve designated A in Fig. 3 being only one of a family of curves each one of which has the same general shape but which vary in the height of the low frequency portion 20 above the horizontal axis and the extent of this horizontal portion. This invention is based on the discovery that in unloaded Clogston cables, such as, for example, of the general type shown in Figs. 1 and 2, there are optimum conditions which give a minimum height for the portion 20 of the curve A above the horizontal axis, or, in other words, which give a minimum low frequency attenuation constant.

Before pointing out these optimum conditions a general relationship will be set forth. In this relationship the notation is as follows:

- a =radius of inner core 11.
- b =inner radius of outer shield 19.
- ρ_1 =inner radius of main dielectric 18.
- ρ_2 =outer radius of main dielectric 18.
- $s_1=\rho_1-a$ =thickness of inner stack 12.
- $s_2=b-\rho_2$ =thickness of outer stack 15.
- t_1 =thickness of each conducting lamina 13 or 16 (called W by Clogston in the above-mentioned Clogston application Serial No. 214,393).
- t_2 =thickness of each insulating lamina 14 or 17 (called r by Clogston in his application Serial No. 214,393).
- $\theta=t_1/(t_1+t_2)$ =fraction of stacks 12 and 15 filled with conducting material 13 or 16.

- ϵ_0 =dielectric constant of main dielectric member 18.
- ϵ_2 =dielectric constant of insulating laminae 14 and 17.
- $\bar{\epsilon}=\epsilon_2/(1-\theta)$ =average of dielectric constant of stacks 12 and 15.
- μ =the permeability of free space ($4\pi \times 10^{-7}$ henries per meter).
- σ_1 =conductivity of the conducting laminae 13 and 16.
- $\bar{\sigma}=\theta\sigma_1$ average conductivity of stacks 12 and 15.

For all configurations of the cables shown in Figs. 1 and 2 it is assumed that the relationship which has come to be known as "Clogston's condition" that is, the relationship of Equation 2, above, is exactly satisfied. The conducting laminae are considered as being infinitesimally thin compared to the skin depth; the thinner the laminae, the greater the frequency range over which this assumption is valid. Furthermore, the impedances of both the inner core 11 and the outer shield 19 are made so high that the currents, if any, flowing in the core and shield are negligible compared to the currents in the stacks. No restrictions, however, are placed on the values of a , ρ_1 , ρ_2 , and b .

The low frequency attenuation constant of the principle mode in cables of the type shown in Figs. 1 and 2 is given by

$$\alpha = \frac{r^2 \sqrt{\bar{\epsilon}/\mu}}{2\bar{\sigma}b^2} \quad (3)$$

where r is the lowest positive root of the equation:

$$\frac{b}{\tau\rho_2} \frac{J_1(r)N_0(\tau\rho_2/b) - N_1(r)J_0(\tau\rho_2/b)}{J_1(\tau\rho_2/b)N_1(r) - N_1(\tau\rho_2/b)J_1(r)} = \log \frac{\rho_2}{\rho_1} \quad (4)$$

In Equation 4, J and N are Bessel and Neumann functions of orders 0 and 1 as indicated. Given the dimensions of the cable a , b , ρ_1 and ρ_2 , the lowest value of r which satisfies Equation 4 can be obtained by graphical or numerical means. By varying the ratios a/b , ρ_1/b , and ρ_2/b and solving for r in a number of different cases, it is possible to determine how r depends on the geometric proportions of the cable. If, for example, a given fill factor

$$x \left(= \frac{s_1 + s_2}{b} \right)$$

is specified, then the proportions of the cable can be completely determined by giving the relative radius a/b of the inner core and the fraction $s_1/(s_1+s_2)$ of the total laminated material which is in the inner stack. By varying a/b and $s_1/(s_1+s_2)$ and calculating the corresponding values of r , one can find the values of a/b and $s_1/(s_1+s_2)$ which make r as small as possible, consistent with the given fill factor.

Fig. 4 shows a curve obtained by assigning specific values to the fill factor x and which represents the lowest attenuation that can be obtained for a given fill factor. In this curve the attenuation in arbitrary units (r^2) is plotted against x . The curve of Fig. 4 may be represented approximately by the following equation:

$$r^2 = 6.48/x + 2.52 + 4.88x + 0.80x^2 \quad (5)$$

As shown in this figure, the higher values of fill factor produce lower values of attenuation and the lowest value exists for a fill factor of unity, or, in other words, when the conductor 10 is completely filled with laminations.

Fig. 5 shows the optimum value of the relative core radius for various fill factors. In this figure, the relative

$$\frac{a}{b}$$

that is, the ratio of the inner diameter of the inner stack 12 (s_1) to the outer radius b of the outer stack 15 (s_2),

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is plotted against the fill factor x . As in Fig. 4 this relation exists throughout the region represented by the portion 20 of the curve in Fig. 3. The curve in Fig. 5 obeys substantially the equation:

$$\frac{a}{b} = 0.228 - 0.240x - 0.204x^2 + 0.216x^3 \quad (6)$$

Fig. 6 shows the optimum relative thickness of the inner stack, $s_1/(s_1+s_2)$, plotted against the fill factor x in the low frequency attenuation region 20 of the curve of Fig. 3. The curve shown in Fig. 6 obeys approximately the equation

$$s_1/(s_1+s_2) = 0.677 - 0.019x - 0.030x^2 \quad (7)$$

The optimum relationships shown in Figs. 5 and 6 make it possible to design a cable for minimum low frequency attenuation. Fig. 4 shows that in the absence of magnetic loading, if the fill factor is at one's disposal, the minimum attenuation is to be obtained with a fill factor of unity, that is, with the cable completely filled with laminations. However, there are some disadvantages of having the fill factor unity and given some other fill factor, it is possible to obtain from the curves shown in Figs. 5 and 6 the relative core radius and the relative thickness of the inner stack to produce minimum low frequency attenuation.

What is claimed is:

1. A composite elongated electromagnetic wave conductor adapted for use with high frequency electromagnetic waves comprising an inner stack of insulated elongated conducting members and an outer stack of insulated elongated conducting members surrounding the inner stack and separated therefrom by non-magnetic dielectric material having a thickness greater than that of the insulation between said conducting members, the relationship of relative core radius

$$\frac{a}{b}$$

and fill factor x being given substantially by the equation:

$$\frac{a}{b} = 0.228 - 0.240x - 0.204x^2 + 0.216x^3$$

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in which a is the inner radius of the inner stack, b is the outer radius of the outer stack and the fill factor x is equal to

$$\frac{S_1+S_2}{b}$$

where s_1 is the thickness of the inner stack and s_2 is the thickness of the outer stack, each of the insulated conducting members in said inner and outer stacks being thinner than the skin depth of penetration of waves into the material of said conducting members at the highest frequency of operation of said conductor.

2. A composite elongated electromagnetic wave conductor adapted for use with high frequency electromagnetic waves comprising an inner stack of insulated elongated conducting members and an outer stack of insulated elongated conducting members surrounding the inner stack and separated therefrom by non-magnetic dielectric material having a thickness greater than that of the insulation between said conducting members, the relative thickness $s_1/(s_1+s_2)$ of the inner stack and the fill factor x having substantially the relationship

$$s_1/(s_1+s_2) = 0.677 - 0.019x - 0.030x^2$$

where x is equal to

$$\frac{S_1+S_2}{b}$$

s_1 being the thickness of the inner stack, s_2 being the thickness of the outer stack and b being the outside diameter of the outer stack, each of the insulated conducting members in said inner and outer stacks being thinner than the skin depth of penetration of waves into the material of said conducting members at the highest frequency of operation of said conductor.

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