

[54] **HIGH VOLTAGE MULTI-LAYER  
CYLINDRICAL DEVICES**

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174/110 PM, 317/258

3,340,446 9/1967 Cox ..... 317/259 X  
3,433,891 3/1969 Zysk ..... 174/120 R

**FOREIGN PATENTS OR APPLICATIONS**

223,198 7/1959 Australia ..... 174/110 PM  
1,568 1901 Great Britain ..... 174/120 R

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[57] **ABSTRACT**

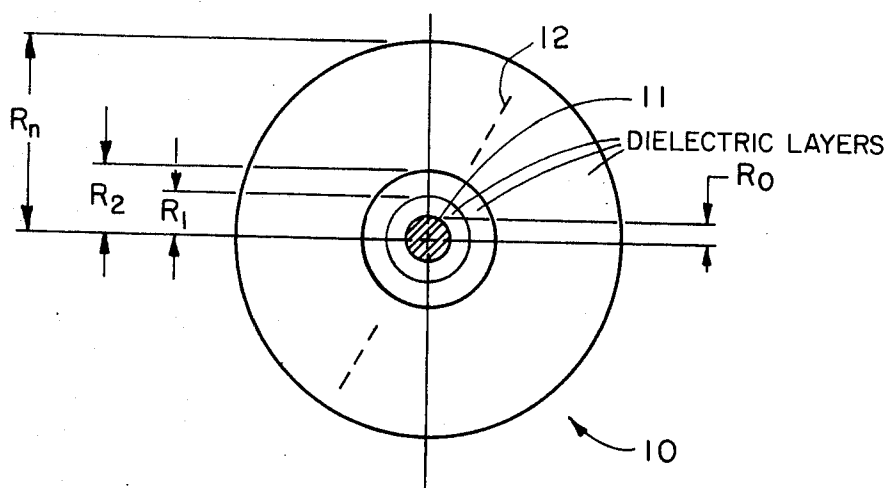
High voltage cylindrical devices having coaxial cylindrical insulation layers of different strength constants, the strength constants and the dimensions of the insulation layers being selected to achieve approximately the minimum obtainable outside diameter of the device or to achieve a device having a smaller outside diameter than a one layer device of equivalent electrical characteristics.

**8 Claims, 2 Drawing Figures**

[56] **References Cited**

**UNITED STATES PATENTS**

2,198,977 4/1940 Rost ..... 174/120 R  
2,221,671 11/1940 Cooper ..... 174/17 GF



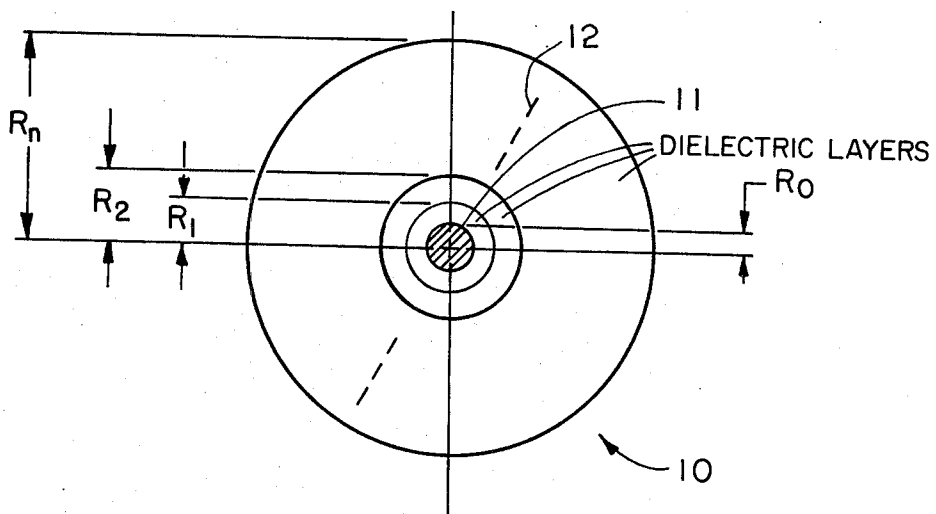


FIG 1

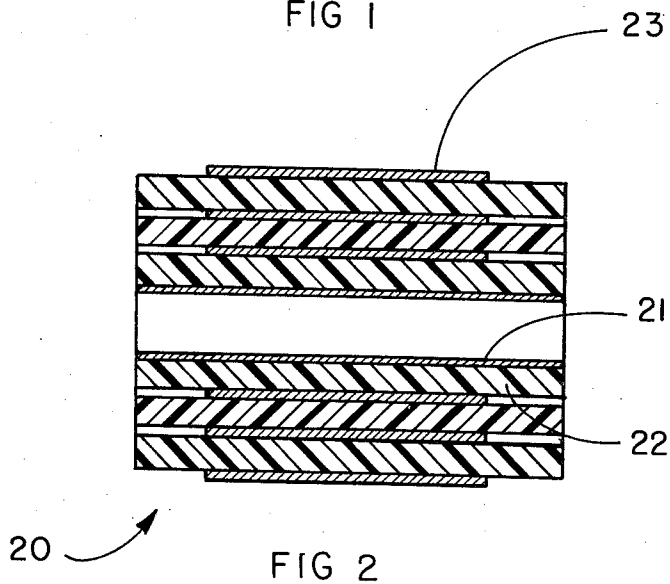


FIG 2

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# HIGH VOLTAGE MULTI-LAYER CYLINDRICAL DEVICES

## BACKGROUND OF THE INVENTION

### 1. Field of the Invention

This invention relates to multi-layer electrical devices and processes for making same, and more particularly to a cylindrical multi-layer device having a smaller outside diameter than single layer devices of equivalent electrical characteristics, the diameter approaching the optimum minimum obtainable, and to a process for making same.

### 2. Description of the Prior Art

In single layer high voltage cylindrical devices, such as high voltage power transmitting cables, tubular capacitors, and the like, the electrical field created in the device has a hyperbolic distribution, with the highest electrical stress appearing on the inside surface. In such devices constructed with insulating materials of presently known substances the outside diameter of a single layer insulation cable is generally impractically large at higher voltages. Thus, as a practical matter, in the past such cylindrical devices have been unusable for power transmission and other such desirable uses.

As an example, in a single insulation layer cable with a working voltage of 670 kv RMS, 60 Hz alternating voltage, the peak voltage on the cable is 950 kv. If the radius of an inner copper conductor, coated with an equipotentializing semi-conductive layer, is  $R_o = 1$  cm, and the insulation of the cable is extruded cross-linked polyethylene having an allowable dielectrical stress of  $E = 200$  kv/cm, the outside radius,  $R_n$ , will be 115 cm, or, an outside diameter of more than 90 inches. This would be not only too expensive, but practically, impossible.

In the past, cables with multi-layer insulation have been proposed for various purposes, and many improvements of mechanical, environmental, and other aspects, not herein pertinent, have been made. The improvements in many multi-layer applications are employed for increasing the mechanical strength, flexibility, humidity resistance, and the like, of the systems, but the use per se of multi-insulation layers in the prior art devices serves no particular electrical purpose.

For example, in one multi-layer system advanced, semi-conducting layers on the conductor and metal shield are used to eliminate corona on the surface of the conductors. Although the electrical characteristics of this device are of interest, and although such arrangements may also be used with cables in accordance with the present invention, they are unrelated to minimizing the outside diameter of the cable, the subject matter of the present invention.

Propositions have also been made for improving voltage carrying cables in which several layers of insulating materials are arranged with the inner insulations having a higher breakdown strength than the outer insulation, taking the hyperbolic stress distribution into consideration. This structure, however, has no particular technical advantages except possibly a cost advantage over a cable with a single insulating layer of highest breakdown voltage material.

In another proposal, disclosed in U.S. Pat. No. 3,433,891, several layers of crosslinked ethylene polymer containing various amounts of titanium dioxide are employed to achieve varying dielectric con-

stants of the layers, increasingly inwardly. Again, although a structure made in accordance with this proposal results in decreased outside cable diameter, the decrease is generally insignificant since the method by which it is achieved fails to recognize the determination of the optimum radii, dielectric, and strength constants of the different layers. In fact, based on equations disclosed below as a part of the present invention using the data of the most effective example of U.S. Pat. No. 3,433,891: three layers having dielectric constants 4.8, 3.2, and 2.4; with the innermost layer comprising 15 percent, the intermediate layer 30 percent, and the outermost layer 55 percent of the total wall thickness; and the allowable dielectric stress being 200 kv/cm, the cable diameter is more than 27 inches. This, of course, is too large and expensive for practical considerations.

No prior art recognized the decisive importance of determining the approximate correlation between the ratios of dielectric constants, or, more precisely, the ratios of the strength constants of the subsequential insulating layers and the respective dimensions of the insulating layers to obtain the minimum possible outside diameters for such high voltage cylindrical devices, as, for example, in power transmission cables, capacitors, insulators, and the like. (Strength constant is a new characteristic of insulating materials introduced in this disclosure, as described in detail below, and is defined as the product of the dielectric constant and the maximum allowable dielectric stress.) Consequently, because of the difficulty in obtaining practical cable dimensions, for instance, power line transmission cables in use today rarely carry voltages about 345 kv RMS, and, in general, even most lower voltage carrying power transmission lines are the commonly seen aerial lines. Aerial lines have many environmental and ecological disadvantages; among others, they are prone to atmospheric damages, represent dangers to low flying airplanes, and have more power outages than cables. It is to these disadvantages, as well as others discussed below, that the present invention is addressed.

## SUMMARY OF THE INVENTION

In light of the above, therefore, it is an object of the invention to provide a cylindrical multi-layer electrical device having the approximate minimum obtainable outside diameter, and method for constructing such device.

It is another object of the invention to provide a cylindrical multi-layer electrical device having a smaller outside diameter than a single layer electrical device of substantially equivalent electrical characteristics, and method for constructing such device.

It is another object of the invention to provide a cylindrical multi-layer electrical transmission line, and a method for making same, having an approximate minimum obtainable outside diameter.

It is still another object of the invention to provide a cylindrical capacitor, and method for making same, having the approximate minimum obtainable outside diameter.

It is still a further object of the invention to provide a cylindrical multi-layer device, and method for making same, in accordance with the foregoing objects, which has particular high voltage applications.

It is yet another object of the invention to present a practically employable high voltage transmission cable which overcomes many of the disadvantage of heretofore used aerial transmission lines.

These and other objects, features, and advantages will become apparent to those skilled in the art from the accompanying drawing and appended claims, read in conjunction with the following detailed description.

In accordance with the present invention, a first method for fabricating a multi-layered electrical device, and the resulting structure having a smaller outside diameter than a one layer device of equivalent electrical characteristics are presented. In the first method, insulating materials with steadily increasing strength constant values  $M_1, \dots, M_n$  are selected. Then, the insulating materials are formed about an inner conductor, the radius of any one of the insulating layers deviating less than -50 percent downwards and +250 percent upwards from the values of the radii  $R_1, \dots, R_n$  defined by:

$$E_i = \frac{V_i}{R_{i-1} \ln \left( \frac{R_i}{R_{i-1}} \right)} \quad (i=1, \dots, n),$$

$$M_i R_{i-1} = \text{constant} \quad (i=1, \dots, n),$$

and

$$V = \sum_{i=1}^n E_i R_{i-1} \ln \frac{R_i}{R_{i-1}}$$

Additionally presented is a second method for fabricating a cylindrical multi-layer electrical device having approximately the theoretical minimum obtainable outside diameter, and the resulting structure. In accordance with this second method, the device is achieved by selecting the number of layers in which the breakdown strength and strength constants of one insulating material are known, and the approximate values of allowable dielectric stress of the rest of the layers are known. Then, for each of the selected number of layers available and technically employable, insulating materials are selected the strength constants of which are close to the theoretically optimum strength constants defined by the following formulas, in which the asterisk (\*) denotes theoretical values:

$M^*_1 R^*_0 = M^*_2 R^*_1 = \dots = M^*_n R^*_{n-1}$ , in which the radii  $R^*_1, \dots, R^*_n$  are those of the theoretically minimum outside radius  $R^*_n$ , defined by

$$\ln \frac{R^*_i}{R^*_{i-1}} = 1 - \frac{E_{i-1}}{E_i} \frac{R^*_{i-2}}{R^*_{i-1}} \quad (i=2, \dots, n),$$

and

$$V = E_1 R^*_0 \ln \frac{R^*_1}{R^*_0} - E_1 R^*_0 + E_n R^*_{n-1}$$

Then, the selected insulating materials are formed about an inner conductor in accordance with the above described first method for fabricating a device having a smaller outside diameter than a one layer device of equivalent electrical characteristics.

## DESCRIPTION OF THE DRAWING

In light of the above, the invention is illustrated in the accompanying drawing, wherein:

FIG. 1 shows a cross-sectional end view of a multi-layer high voltage cylindrical device, in accordance with the invention.

FIG. 2 illustrates a cross-sectional view of a multi-layer, high voltage, cylindrical ceramic capacitor, fabricated in accordance with, and illustrating the principles of, the invention.

## DESCRIPTION OF THE PREFERRED EMBODIMENT

A preferred embodiment of a cylindrical high voltage multi-layer device and method for constructing it, in accordance with the invention, are described with beginning reference to the following derivations of the enabling equations. With specific reference to FIG. 1, an  $n$ -layer cylindrical device, generally denoted by reference numeral 10, is illustrated having a central conductor 11 with radius  $R_0$ , and having  $n$  insulating layers with outside radii of  $R_1, \dots, R_n$ . The dotted lines 12 illustrate that the number  $n$  may be a number greater or equal to 2. The dielectric constants of the respective  $n$  layers are  $\epsilon_1, \dots, \epsilon_n$ , and the maximum allowable dielectric stresses in the  $n$  layers are  $E_1, \dots, E_n$ . The capacitances of the  $n$  insulating layers are

$$C_i = K \frac{\epsilon_i}{\ln \frac{R_i}{R_{i-1}}} \quad (i=1, \dots, n)$$

where  $K$  is a constant, incorporating the length of the device.

The maximum electrical stress of the  $i$ -th insulating tube appears on the equipotential surface of radius  $R_{i-1}$  and its value is

$$E_i = \frac{V_i}{R_{i-1} \ln \frac{R_i}{R_{i-1}}} \quad (i=1, \dots, n) \quad (1)$$

where  $V_i$  is a voltage difference between the equipotential surfaces of radii  $R_i$  and  $R_{i-1}$ .

Since the electrical charge,  $Q$ , is the same throughout each equipotential surface:

$$Q = C_i V_i = \text{constant} \quad (i=1, \dots, n); \quad (2)$$

hence, from the above equations follows:

$$E_i \epsilon_i R_{i-1} = \text{constant} \quad (i=1, \dots, n). \quad (3)$$

In equation (3), the term " $M$ " is introduced to represent the strength constant of the material, and is defined as  $M = E\epsilon$ , with dimensions of volts per cm. (In the calculations below,  $M$  is expressed in kv/cm.)

From equation (3) follows:

$$M_i R_{i-1} = \text{constant} \quad (i=1, \dots, n). \quad (4)$$

As appears more fully below, the strength constant is a particularly important parameter of insulating materials employed in multi-layer cylindrical devices. For convenience, the strength constant of some commonly used insulating materials are listed in Table 1.

TABLE I

|                                | Dielectric constant $\epsilon$ | Allowable diel. stress $E$ , kv/cm | Strength Constant $M$ , kv/cm |
|--------------------------------|--------------------------------|------------------------------------|-------------------------------|
| Sulfur hexafluoride gas, 3 atm | 1                              | 150                                | 150                           |
| Polypropylene                  | 2                              | 200                                | 400                           |

|                                                |     |     |      |
|------------------------------------------------|-----|-----|------|
| Polyethylene                                   | 2.4 | 200 | 480  |
| Polycarbonate                                  | 3   | 150 | 450  |
| Polyethylene terephthalate                     | 3.1 | 300 | 930  |
| Vinylidene Chloride - Vinyl Chloride Copolymer | 4   | 300 | 1200 |
| Polyvinyl Fluoride                             | 8.5 | 250 | 2120 |

The determination of the values of radii  $R_1, \dots, R_{n-1}$  which yield the smallest outside radius,  $R_n$ , is of great importance and is our next step.

As the sum of  $V_1, \dots, V_n$  equals  $V$ :

$$V = \sum_{i=1}^n E_i R_{i-1} \ln \frac{R_i}{R_{i-1}} \quad (5)$$

the maximum sustainable voltage results for a device if all the following partial differential quotients are equal to 0:  $\delta/\delta R_i V = 0$  ( $i = 1, \dots, n-1$ ), from which we get the following  $n-1$  equations:

$$\ln \frac{R_i}{R_{i-1}} = 1 - \frac{E_{i-1}}{E_i} \frac{R_{i-2}}{R_{i-1}} \quad (i = 2, \dots, n) \quad (6)$$

Substituting the natural logarithm expressions from equation (6) in equation (5), the  $n$ -th equation results as:

$$V = E_1 R_0 \ln(R_1/R_0) - E_1 R_0 + E_n R_{n-1} \quad (7)$$

Equations (6) and (7) define the radii  $R_1, \dots, R_n$  which yield the highest sustainable voltage, or, at the same time, if  $V$  and the stresses  $E_1, \dots, E_n$  are given, the same equations determine the smallest possible radii of the different insulating layers. Substituting these radii values in equation (4), the optimum strength constant of the  $n$  layers can be readily determined.

In the following examples, multi-layer variations of the above described one layer cable are presented, illustrating the principles in accordance with the invention. For the sake of easy comparison the basic parameters:  $V=950$  kv and  $R_0=1$  cm are considered in all examples.

#### EXAMPLE 1

In this example, two insulating layers are employed and the optimum conditions are sought. The allowable stresses of the two layers are approximated as  $E_1=300$  kv/cm and  $E_2=200$  kv/cm.

Equations (6) and (7) result in  $R_1=3.75$  cm and  $R_2=6.8$  cm. If the outside insulating layer is cross-linked polypropylene, the strength constant of which is  $M_2=400$  kv/cm, then from equation (4) results  $M_1=1500$  kv/cm. The smallest cable dimension is, therefore, obtainable with an insulating material having the strength constant.

#### EXAMPLE 2

In the same high voltage cable, three different insulating layers are employed which have the allowable dielectric stresses of  $E_1=300$  kv/cm,  $E_2=250$  kv/cm and  $E_3=200$  kv/cm. The following optimum radii are obtained from equations (6) and (7):  $R_1=2.72$  cm,  $R_2=4.75$  cm and  $R_3=6.3$  cm. If the outside layer is again polypropylene,  $M_3=400$  kv/cm. From equation (4) it follows that  $M_1=1,890$  kv/cm and  $M_2=700$  kv/cm.

Of course, insulating materials with strength constants are obtained from these calculations may not always be available, or, even if available, other param-

ters of the available material may be unacceptable, for example, the power factor, temperature resistance, and so forth. In such cases the insulating materials have to be chosen from those having strength constants approximating the optimum strength constant values.

In most situations, it is advantageous to compare the originally supposed  $E$  values with those of the actually selected materials. If a deviation of more than 50 percent exists, it is recommended that  $R_1, \dots, R_n$  and  $M_1, \dots, M_n$  be redetermined from the corrected equations (6) and (7) to gain the corrected optimum values for  $M_1, \dots, M_n$ . In some cases, in fact, the redetermined values may facilitate the selection of more suitable insulating materials.

In the following two examples, the optimum strength constants obtained in Examples 1 and 2 are substituted with data of actually available materials.

#### EXAMPLE 3

From Table I, the following materials have the closest strength constants to the optimum ones in Example 1:

MATERIAL 1: Vinylidene chloride - vinyl chloride copolymer,  $M_1=1,200$  kv/cm;

MATERIAL 2: Cross-linked polypropylene,  $M_2=400$  kv/cm. From equations (1), (4) and (5), the radii result as  $R_1=3$  cm and  $R_2=8.5$  cm. The diameter of the cable, then, is approximately 7.5 inches.

#### EXAMPLE 4

From Table I, the following materials have the closest strength constants to the optimum ones in Example 2:

MATERIAL 1: Polyvinyl fluoride,  $M_1=2,120$  kv/cm;

MATERIAL 2: Vinylidene chloride - Vinyl chloride copolymer,  $M_2=1,200$  kv/cm;

MATERIAL 3: Cross-linked polypropylene,  $M_3=400$  kv/cm. Equations (1), (4) and (5) result in  $R_1=1.77$  cm,  $R_2=5.3$  cm and  $R_3=6.5$  cm. The outside diameter of the cable, thus, is approximately 6 inches.

Clearly, many more insulating materials having high strength constants are available besides those listed in Table I. The dielectric constant of an insulating material can also be regulated by adding other organic materials or inorganic pigments to it. In the latter case care must be exerted that the dielectric constant of the pigment not be much higher than that of the organic polymer because the dielectric stresses at the pigment-polymer interfaces are inversely proportional with the dielectric constants of the two materials, thereby lowering the allowable stress for the system. The loss in the stress may be larger than the gain in the dielectric constant, and the result may be a drop of the strength constant, in spite of the increase of the dielectric constant.

Since the losses of the high voltage transmission cables are considerably important, the selection of the insulating materials should not be governed only by the strength constant values, but the desirability of using materials having low power factors should also be considered. (This may, however, necessitate some sacrifice in the optimum values of strength constants.)

Another consideration in the manufacture of multi-layer high voltage devices in which, in a particular application, the layers need not be any specified critical

radii, is that sometimes it may nevertheless be necessary to deviate from the predetermined optimum dimensions. One important reason for this may be to diminish the voltage difference on a certain insulation section having a relatively higher loss factor. Other less important reasons may be facilitation of production, increase of strength, control of flexibility of a cable, and the like. In this regard, it has been found that a deviation between -50 percent and +250 percent in the inner radii generally does not exceedingly increase the outside diameter of the device, and in most cases is allowable.

In the previous examples, the losses of the cable were not considered. In the following examples, when the different insulating materials are selected, the power factors of the cables are also taken into consideration.

#### EXAMPLE 5

In Example 3, the first insulating layer is changed to polyethylene terephthalate containing 30 percent by weight fine alumina powder. (Alumina was chosen because its dielectric constant is not too high and its power factor is quite low.) The parameters of this material are:  $\epsilon_1=3.5$ ,  $E_1=300$  kv/cm,  $M_1=1,050$  kv/cm,  $P_1=0.0025$ ,  $P$  denoting the power factor. The second layer is cross-linked polypropylene,  $\epsilon_2=2$ ,  $E_2=200$  kv/cm,  $M_2=400$  kv/cm,  $P_2=0.0003$ .

Equations (1), (4) and (5) result in  $R_1=2.6$  cm and  $R_2=9.5$  cm. The diameter of the cable, therefore, is approximately 8 inches.

If the frequency is 60 Hz, the losses of the  $i$ -th section of the cable is in watts per meter cable length:

$$W_1=2 \frac{U_i^2 \epsilon_i P_i}{\ln \frac{R_i}{R_{i-1}}} w/m (i=1, \dots, n), \quad (8)$$

in which  $U_i$  is the potential difference in kv RMS over the  $i$ -th section and  $P_i$  is the power factor of the material of the  $i$ -th section.

In this example,  $U_1=200$  kv RMS and  $U_2=470$  kv RMS. The losses in the two sections are:  $W_1=735$  w/m and  $W_2=205$  w/m. The total loss of the cable, therefore, is 940 w/m.

#### EXAMPLE 6

The losses of the cable described in Example 5 may still be too high for usage in some applications. In this example, the method will be shown by which the losses of the cable are decreased, even if the same materials are employed, by diminishing  $R_1$ , whereby the voltage difference on the lossier layer becomes smaller.

The materials are identical with those of Example 5 but  $R_1=2$  cm is selected (allowable because the decrease from 2.6 cm is less than -50 percent). Equations (1), (4) and (5) give:  $R_2=14.6$  cm. The diameter of the cable is approximately 12 inches.

In this example,  $U_1=110$  kv RMS,  $U_2=560$  kv RMS. The losses are:  $W_1=307$  w/m and  $W_2=186$  w/m. The total losses, 493 w/m, are approximately half of the losses of the cable according to Example 5. However, the diameter of the less lossy structure is 50 percent larger.

#### EXAMPLE 7

The losses can be further diminished by selecting material 1 to have a lower power factor. Cross-linked polyethylene with 60 percent by weight alumina powder filling has the following parameters:  $\epsilon_1=3.8$ ,  $E_1=200$  kv/cm,  $M_1=760$  kv/cm,  $P_1=0.0004$ . Equations (1), (4) and (5) give:  $R_1=1.9$  cm and  $R_2=17.4$  cm. The voltage and loss distributions are:  $U_1=90$  kv RMS,  $U_2=580$  kv RMS,  $W_1=38$  w/m,  $W_2=184$  w/m. The total loss of the cable is only 222 w/m; however, the diameter of the cable is approximately 14 inches.

#### EXAMPLE 8

In this example, sulfur hexafluoride gas is employed under a pressure of 3 atm as the second insulating layer:  $\epsilon_2=1$ ,  $E_2=150$  kv/cm. Supposing  $E_1=200$  kv/cm, equations (6) and (7) give  $R_1=5.4$  cm and  $R_2=11.5$  cm, and equation (4) gives  $\epsilon_1=4.05$ .

In the actual realization of the cable, the inside insulating layer is cross-linked polypropylene with 60 percent by weight alumina powder filling which has the following parameters:  $\epsilon_1=3.6$ ,  $E_1=200$  kv/cm,  $M_1=720$  kv/cm and  $P_1=0.0004$ . Equations (1), (4) and (5) result in  $R_1=4.8$  cm and  $R_2=11.6$  cm. The voltage across the first layer is  $U_1=224$  kv RMS and its loss is  $W_1=115$  w/m. This is approximately the total loss of the cable, because losses in the gas layer are negligible. The diameter of the cable is approximately 11 inches, including the gas-tight shield-tubing.

In Table II, the dimensions of the various discussed cables are compared. Comparing the volumes, the minimum volume of Example 4 is set as the unit volume.

TABLE II

| Cable System                                         | Outside diameter<br>in inches | Volume<br>Ratio |
|------------------------------------------------------|-------------------------------|-----------------|
| One-layer cable                                      | 90                            | 225             |
| Three layers according to<br>U.S. Pat. No. 3,433,891 | 27                            | 20              |
| Example 3                                            | 7.5                           | 1.6             |
| Example 4                                            | 6                             | 1               |
| Example 5                                            | 8                             | 1.8             |
| Example 6                                            | 12                            | 4               |
| Example 7                                            | 14                            | 5.4             |
| Example 8                                            | 11                            | 3.4             |

Table II shows the great volume gains with cables made according to this invention, even if the losses are kept to very low values.

Multi-layer cables can be produced by many methods known in the art; for example, by a multiple extrusion, or by wrapping the different layers using ribbon type insulators. Whatever method is employed, it is important that no air enclosures be in any of the layers or between adjacent layers.

In the previous examples, high voltage cables were mainly considered. Another important high voltage cylindrical device is a high voltage tubular ceramic capacitor. An example of a three layer ceramic capacitor will be disclosed, compared to a one layer capacitor, because ceramic materials differ from organic polymers in some respects; for instance, the allowable dielectric stress in ceramic materials is generally much lower, averaging  $E=20$  kv/cm. The dielectric constants of ceramics vary within much broader limits, for exam-

ple, from 2 to 20,000. Practically, almost any dielectric constant can be created between these limits. For high voltage applications, the limits of dielectric constants of useful ceramic compositions are between 3 and 3,000, today.

The following comparative examples discuss ceramic capacitors, and, for ease of description, the following specifications are assumed throughout the examples: inside radius,  $R_0=0.2$  cm; the length of the electrodes 1 cm; the capacitance, 200 pf; and the peak working voltage, 20 kv. All the employed ceramic layers have an allowable dielectric stress of  $E=20$  kv/cm.

If only one dielectric layer is employed, the outside radius, in accordance with the above formulas, is 29.4 cm, again an impossible dimension. The dielectric constant of the ceramic composition should be 1,800 to yield the required capacitance.

#### EXAMPLE 9

In the ceramic capacitor of this example three different ceramic layers are used. Equations (6) and (7) give an outside radius of only 1.056 cm, which is approximately 3 percent of the radius needed in the one-layer capacitor. The volume of the ceramic capacitor made according to the invention has a volume of less than one tenth of a percent of the volume of the one-layer capacitor.

The dielectric constants of the three layers which give a capacitance of 200 pf are:  $\epsilon_1=1,160$ ,  $\epsilon_2=570$  and  $\epsilon_3=335$ . These point out a further advantage of the capacitor made in accordance with this invention, namely, that ceramic compositions of lower dielectric constants are only needed. Generally, ceramic compositions of lower dielectric constants can be selected to have higher breakdown voltage, lower temperature dependence of the dielectric constant, higher volume resistivity, and lower ageing, compared to the very high dielectric constant ceramic compositions.

Multi-tubular high voltage ceramic capacitors according to the invention can be made by several methods. They can be, for example, subsequently dipped, employing the methods of U.S. Pat. No. 3,016,597, and then cofired. During firing, a limited codiffusion takes place between the layers of different compositions which, if similar compositions are used, does not unacceptably alter capacitance value. The codiffusion can be further limited by inhibiting layers at the separation surfaces.

In another version, the ceramic tubes of the high voltage capacitor can be formed and fired individually. FIG. 2 shows a multi-layer ceramic capacitor which is assembled of separate tubes. To avoid air layers between the ceramic tubes, all tubes have an inside and outside electrode. In a feed-through type capacitor, as denoted by reference numeral 20 in FIG. 2, the inside electrode 21 of the innermost ceramic tube 22 goes through the full length of the tube. All other electrodes occupy only the center part of the tubes, leaving sufficient insulating areas to carry the high voltage imposed between the inside electrode 21 and outside electrode 23.

The inner electrodes are floating. All the electrodes are coated with a soldering or brazing material, to unite the inner electrodes mechanically and electrically.

The disclosure showed in a few examples the great reduction of dimensions of high voltage cylindrical devices made employing the principles of the invention. The applicability of the principles of the invention is not limited to the examples and many other types of high voltage cylindrical devices, such as, for example, high voltage insulators, and so forth, can be created using the new recognitions of this invention. The selection of the insulating materials is not limited to the used examples either; many other types of solid, liquid, gaseous or complex insulating materials can be employed the parameters of which satisfy the conditions of this invention.

Although the invention has been described and illustrated with a certain degree of particularity, it is to be understood that the present disclosure is made by way of example only, and that numerous changes and modifications will appear to those skilled in the art which fall within the scope of the invention, as hereinafter claimed.

What is claimed is:

1. A cylindrical electrical device, comprising: a cylindrical inner conductor having a radius  $R_0$ , a plurality  $n$  of cylindrical layers of insulating material formed about said inner conductor and each having an outside radius  $R_i$ , a maximum allowable dielectric stress  $E_i$  and a strength constant  $M_i$  equal to the product of the dielectric stress  $E_i$  thereof and the maximum allowable dielectric stress  $E_i$  thereof,  $i$  being the identification number of the layer and being unity for the innermost layer and  $n$  for the outermost layer, said device being operable with a peak voltage difference  $V$  between said inner conductor and the outer surface of the outermost layer of insulating material, the product of the strength constant  $M_i$  and the inside radius of the first layer being approximately the same as the product of the strength constant and inside radius of each of the other layers, and the respective radii of said layers being approximately equal to the radii required to satisfy the following equations:

$$\ln \frac{R_i}{R_{i-1}} = 1 - \frac{E_{i-1}}{E_i} \cdot \frac{R_{i-2}}{R_{i-1}} \quad (i=2, \dots, n)$$

$$V = E_1 R_0 \ln \frac{R_1}{R_0} - E_1 R_0 + E_n R_{n-1}$$

application of said peak voltage  $V$  to said device being effective to simultaneously create said maximum allowable stresses  $E_i$  in the respective layers.

2. The device of claim 1 wherein said device is a capacitor.

3. The device of claim 1 wherein said device is an insulator.

4. The device of claim 1 wherein said device is a cable.

5. The device of claim 4 wherein the outermost insulating layer is a gas.

6. The device of claim 4 wherein the material of one insulating layer is selected from the group consisting of aluminum oxide powder filled polypropylene and aluminum oxide powder filled polyethylene.

7. The device in accordance with claim 1 wherein the first insulating layer is of cross-linked polypropylene mixed with alumina powder and the second insulating

layer is of sulfur hexafluoride gas under pressure greater than 1 atm.

8. The device in accordance with claim 1 wherein the first insulating layer is of cross-linked polyethylene mixed with alumina powder and the second insulating layer is of sulfur hexafluoride gas under pressure greater than 1 atm.

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