Nov. 24, 1970 C. DAMMANN ET AL 3,542,937

ELECTRICAL CONDUCTORS FOR CRYOGENIC ENCLOSURES

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FIG.1

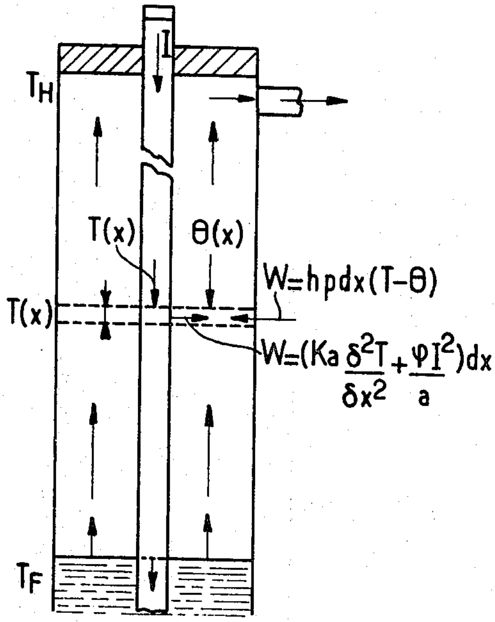


FIG.2

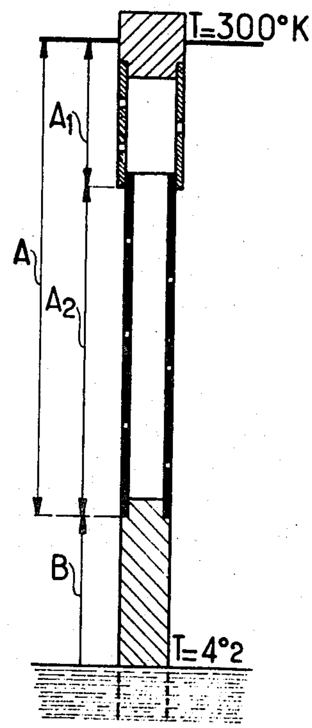


FIG.3

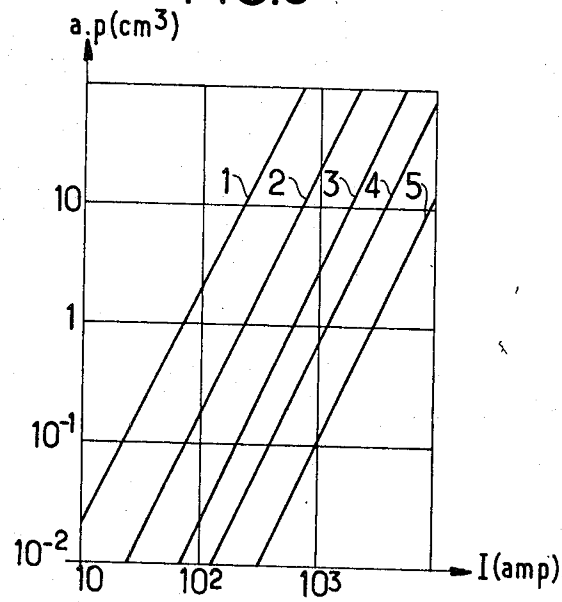


FIG. 4

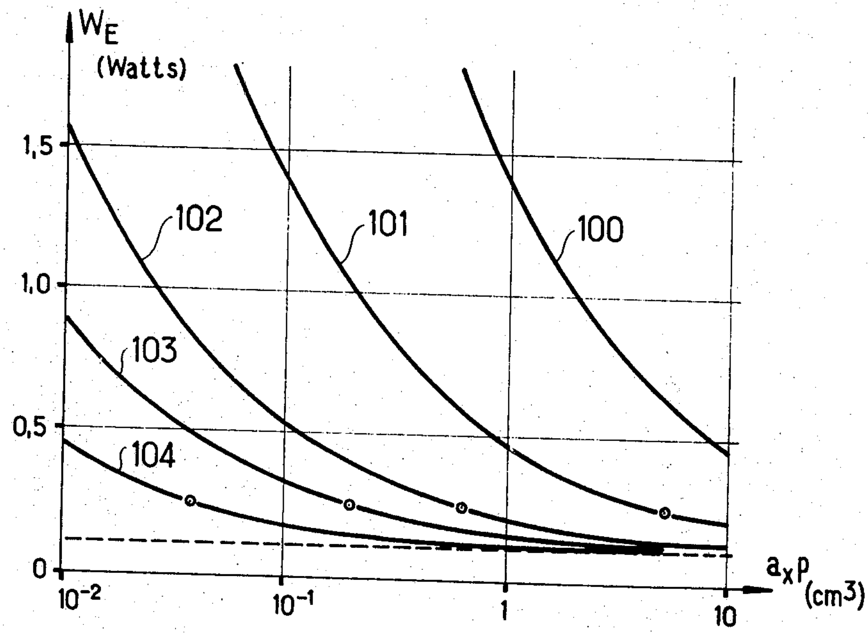
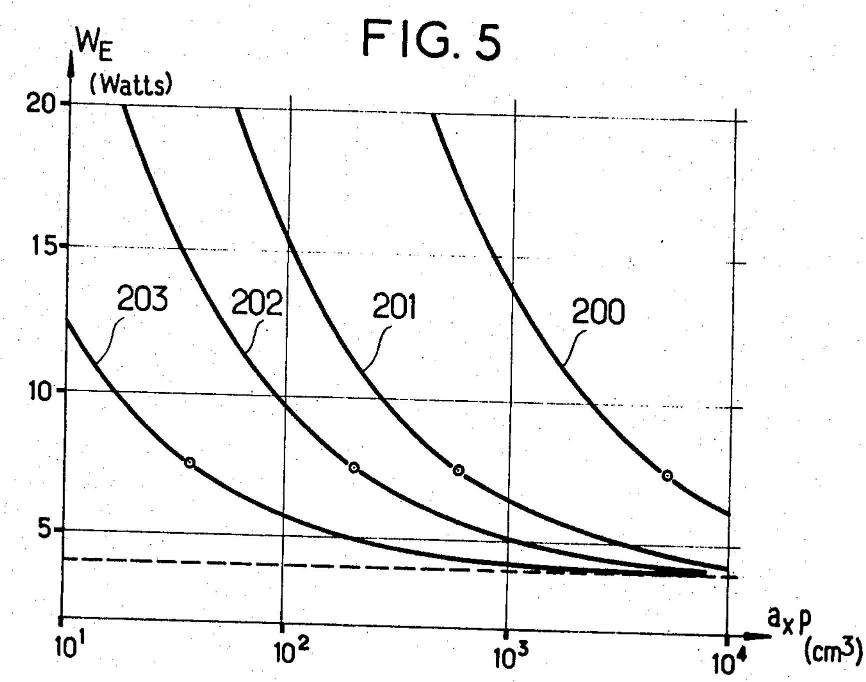

W_E
(Watts)
1,5
1,0
0,5
0
102
101
100
103
104
10^{-2}
10^{-1}
1
10
$a_x p$
(cm³)

FIG. 5


W_E
(Watts)
20
15
10
5
203
202
201
200
10^1
10^2
10^3
10^4
$a_x p$
(cm³)

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3,542,937

ELECTRICAL CONDUCTORS FOR CRYOGENIC ENCLOSURES

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Int. Cl. H01b 7/34

U.S. Cl. 174—15 7 Claims

ABSTRACT OF THE DISCLOSURE

Electrical conductor for cryogenic enclosures arranged to reduce heat loss to a minimum, said conductor having a hot portion with a heat impedance as high as possible and a cold portion dipping in a cryogenic fluid and having an electrical impedance as low as possible, the length of each of the portions and the product of the section by the wet perimeter having optimum value.

The present invention concerns conductors carrying current at normal or moderately low temperature to low temperature which may range up to several degrees Kelvin.

The development of superconductor coils of large dimensions and high-power cryogenic transformer and cable projects give rise to the problem of conductors for current of very high strength. Thus, the large bubble chambers being constructed in Europe at the C.E.R.N. and at Argonne and Brookhaven in the U.S.A. will have superconductor coils operating between 2 and 10 kiloamperes. With regard to the projected superconducting or hyperconducting cryogenic transformers and cables, there may be mentioned currently current strengths between 10 and 100 kiloamperes. The known conductors create heat losses, which it is desirable to minimize.

These losses are caused both by the thermal conduction due to the temperature difference between their ends and by the Joule effect produced by the passage of the current. The Joule effect may be minimized by increasing the area of the cross-section of the electrical conductors constituting the conductor, but this results in an increase in the losses due to thermal conduction. With ordinary materials, the thermal conductivity varies in the same sense as the electrical conductivity, as is shown by the Wiedeman-Franz law $\rho K=LT$, ρ being the electrical resistivity, K the thermal conductivity, T the temperature and L a constant equal to the Lorentz number. It will readily be appreciated that an optimum solution is reached when a certain balance is produced between these two effects. However, the corresponding heat losses still remain high since, under optimum conditions, they amount to about 0.04 w./a. for conductors operating between 300° and 4.2° K. and still to 0.03 w./a. for those operating between 77° K. and 4.2° K.

A very effective means of reducing the losses is to cool the conductors by the cold gas escaping from the cryogenic liquid bath (helium, hydrogen, argon, nitrogen). Substantially lower losses are then obtained, since they are about 0.002 w./a. for conductors operating between 300° K. and 4.2° K. and extending into a liquid helium bath.

The present invention relates to a conductor having distinctly higher performance than any of the hitherto known bushings.

The present invention concerns a conductor of which one end dips into a cryogenic liquid bath, while the remainder thereof is washed by the gases emanating from the evaporation of the said cryogenic liquid.

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The object of the invention is to minimize the heat losses in order to reduce the evaporation of the cryogenic liquid.

The present invention is based upon research and experiments carried out by the applicants, which have enabled them to establish that the static heat losses of the conductor which are due to the thermal conduction resulting from the temperature differences decrease exponentially with its length, while electrical losses appear to be independent both of the temperature difference between the ends and of the length of the conductor. These losses seem to be due to the Joule effect over a short length of conductor confined to the cold section of the conductor. This characteristic length is limited by the heat exchanges and by the cooling capacity to the extent that one of these factors becomes the more restrictive and depends indirectly upon the resistivity of the conductor and upon the value of the current.

In the case of conductors immersed in a cryogenic liquid bath, the study of the electrical losses shows that there exists a minimum value which is independent of the strength of the current and of the shape and dimensions of the conductors and of its material to the extent to which is obeys the Wiedenmann-Franz law. The minimum value is of the order of 0.00064 w./a. for conductors of which the cold end is immersed in liquid helium (4.2° K.). It is of the order of 0.0044 w./a. in the case of conductors whose cold end is situated in a liquid hydrogen bath.

In accordance with one feature of the present invention, a cryogenic conductor comprises at least two portions, one portion, called the hot portion, having one end at a temperature between 80° and 300° K. and the other end connected to a first end of a portion called the cold portion, the second end of the said cold portion being immersed in a cryogenic liquid bath at a temperature between 0° K. and 80° K., the said hot portion having maximum thermal impedance and the said cold portion having minimum electrical impedance.

For example, in accordance with another feature of the present invention, the cold portion has minimum length which is, however, greater than a characteristic length b_1.

The hot portion may have a length greater than b_1 and preferably greater than $3b_1$ and may consist of strip metal, wires or tubes having maximum "wet" periphery.

The cold portion may have maximum cross-section which preferably does not exceed a characteristic value a_0, and said cold portion may consist of a material having relatively high electrical conductivity.

Further, the cold portion may consist of a superconductor material which has zero resistivity and poor thermal conductivity.

Further features and advantages of the present invention will become apparent in the course of the following description, which is given with reference to the accompanying drawings, in which:

FIG. 1 is a diagrammatic illustration of a conductor which is intended to illustrate the thermal and electrical phenomena which occur during the passage of a current;

FIG. 2 diagrammatically illustrates a conductor according to the invention;

FIG. 3 illustrates in logarithmic co-ordinates, the curves of the optimum values of the product of the cross-section by the wet periphery of the conductors according to the invention; and

FIGS. 4 and 5 are diagrams giving, for two values of the current and various materials, the curves of the electrical losses of the conductor as a function of the product of the cross-section of the conductor by its wet periphery.

Considering a conductor which carries a current I into a cryogenic enclosure, the conductor may be formed of a number of conductors disposed in parallel and the current I corresponds to the total current carried independently of the direction. The upper temperature of the bushing is T_H; the cold temperature T_F is that of the boiling cryogenic liquid. The cold gas which escapes from the bath cools the conductors of the conductor. The schematic diagram of the various thermal processes is given in FIG. 1.

At any point of the conductor, the thermal balancers peculiar to the conductors and to the rising column of gas may be written as follows:

$$ka\frac{d^2T}{dx^2}=hp(T-\theta)-\frac{\rho}{a}I^2 \qquad (1)$$

$$hp(T-\theta)=\beta mc\frac{d\theta}{dx} \qquad (2)$$

in which:

a and p are respectively the sum of the cross-sections and of the wet peripheries of the conductors;

k and ρ are the thermal conductivity and the resistivity of the materials;

h is the coefficient of heat exchange between the conductor and the column of gas;

m is the mass flow of gas;

β is a coefficient expressing the degree of participation of the rising gas column in the thermal exchange and

c is the specific heat of the gas;

T and θ are respectively the temperatures of the conductor and of the gas at the co-ordinate point x.

The total length of the conductors of the conductor is b and the surface of the cryogenic bath is at the level $x=0$.

The heat loss caused by the conductor is by definition the heat flux at the interface of the cryogenic bath:

$$W_T=\left(ka\frac{dT}{dx}\right)_{x=0} \qquad (3)$$

The rate of vaporized gas flow is then:

$$m=(W_c+W_T)/\lambda \qquad (4)$$

where W_c is the characteristic loss of the cryostat and λ is the heat of evaporation of the cryogenic liquid.

The loss is calculated by resolving the system of differential Equations 1 and 2 and obtaining W_T by the Equation 3 subject to the conditions of Equation 4 and to those of the extreme temperatures, which are:

at the cold end

$$\theta(x=0)=T_F$$
$$T(x=0)=T_F \qquad (5)$$

at the upper end

$$T(x=b)=T_H$$

The temperature distributions in the conductor and the gas are given by the following equations:

$$T_{(x)}=\frac{\beta_{mc}}{kab}\left[c_1b_1^2\ \text{Exp.}\left(\frac{x}{b_1}\right)+C_2b_2^2\ \text{Exp.}\left(-\frac{x}{b_2}\right)\right]+\rho\frac{1}{a}I^2\left[\frac{x}{\beta mc}+\frac{1}{hp}\right]+C_3 \qquad (6)$$

$$\theta(x)=C_1\frac{b_1}{b}\ \text{Exp.}\left(\frac{x}{b_1}\right)-C_2\left(\frac{b_2}{b}\right)\text{Exp.}\left(-\frac{x}{b_2}\right)+\rho\frac{1}{a}I^2\frac{x}{\beta mc}+C_3 \qquad (7)$$

It is then possible to calculate the loss, as follows:

$$W_T=\frac{\beta mc}{b}(C_1b_1-C_2b_2+\frac{k}{\beta mc}I^2\cdot\rho \qquad (8)$$

C_1, C_2 and C_3 are the integration constants defined by the conditions at the limits.

b_1 and b_2 are the rots of the equation characteristic of the differential equations; these roots have the dimension of a length and they may therefore be regarded as characteristic lengths. They perform an essential function both in the temperature distributions and in the generation of the losses.

We have:

$$b_1=\sqrt{\frac{ka}{hp}}\qquad(\sqrt{1+A^2}+A) \qquad (9)$$

$$\text{with } A=\frac{\sqrt{ka\ hp}}{2\beta mc}$$

which may be rewritten as:

$$1\ \frac{ka}{2\beta mc}\qquad\left(\sqrt{1+\frac{1}{A^2}}+1\right) \qquad (10)$$

The expression b_2 is identical to the expression b_1 apart from the last sign in the parantheses, which is negative.

A study of these results shows that the characteristic length b_1 (or b_2) does not depend directly upon the electrical parameters of the conductor. Thus, the resistivity of the conductor and the strength of the current have no direct function in the determination of the characteristic lengths.

The resolution of the above equations gives an approximate value of the thermal losses of a conductor of which one end is immersed in a cryogenic liquid bath:

$$W_T=W_S+W_E=\frac{ka}{b_1}f_1\ \text{Exp.}\left(-\frac{b}{b_1}\right)(T_H-T_F)+\frac{\rho}{a}b_1I^2 \qquad (11)$$

It will be seen from this formula that there is an exponential decrease of the static losses W_S with the length of the conductor and that the electrical losses W_E are due essentially to the Joule effect over a conductor length equal to the characteristic length b_1 and that they are independent of the other properties of the conductor, more particularly the total length and the temperature difference.

On the other hand, it is possible to calculate the electrical loss, the value of which is:

$$W_E=\frac{\rho kI^2}{2\beta mc}\left(\sqrt{1+\frac{(2mc)^2}{hpka}}+1\right) \qquad (12)$$

with $m=(W_C+W_S+W_E)/\lambda$ expressed in grams per second for a conductor immersed in a cryogenic bath.

It therefore appears that W_E depends upon the nature of the materials (ρ and k), upon the properties of the cryogenic fluid λ and c, upon the heat exchange coefficient h and upon the dimensions of the conductors a and p.

The resolution of the above equations gives:

$$W_E^2-\frac{W_E}{W_E+W_C+W_S}\frac{\rho k\lambda}{\beta c}I^2=\frac{\rho^2kI^4}{hap} \qquad (13)$$

This equation shows that the dissipated electrical power decreases monotonously with the product $a\cdot p$ which represents the geometry of the conductors.

The applicants have discovered that when all the parameters are fixed, and notably the strength of the current of the conductor and the material, the electrical losses are minimum for an optimum value of $a\cdot p$, the optimum value depending essentially upon the nature of the material.

The curves shown in the accompanying FIG. 3 give these optimum values for a number of conventional materials, including brass (curve 1), ordinary copper (curve 2), pure copper (curve 3), annealed OFHC copper (curve 4) and super-refined aluminium (curve 5).

Finally, the applicants have discovered that, for obtaining a minimum value of the electrical losses, the choice of the other parameters is not free and that they must in addition obey the relation:

$$a \cdot p = C \cdot \rho I^2$$

C being a constant;
ρ the resistivity of the metal employed; and
I the value of the current passing through the conductor.

The material and the current strength thus having been chosen, it is deduced from this relation that the cross-section a of the conductor must be close or equal to:

$$a_o = C . \rho \frac{I^2}{p}$$

The calculations and reasonings set out in the foregoing will enable the features and the operation of the conductor according to the invention to be more readily understood. A practical embodiment will now be described with numerical examples given solely by way of illustration and having no limiting character.

In accordance with the present invention as illustrated in FIG. 2, a cryogenic conductor comprises two portions, a portion A called the hot portion and a portion B called the cold portion. The hot portion with one of the ends of which at normal temperature, or not below a value of the order of 80° K., has the highest possible thermal impedance. The thermal impedance may be written in the following simplified form:

$$R_{th} = \frac{l}{K} \frac{l}{a}$$

K being the thermal conductivity,
l the length, and
a the cross-section.

It is thus desirable to increase as far as possible the length l and in any case to adopt a length greater than the characteristic length b_1 defined in the foregoing.

Preferably, one will have $l > 3b_1$.

In order to increase the thermal impedance, the heat exchanges with the gas emanating from the evaporation of the cryogenic liquid are increased as far as possible by increasing the wet periphery. This is obtained, for example, by employing conductors in the form of hollow tubes having holes to permit a heat exchange with the internal surface of the tube.

The increase of the thermal impedance is obtained by appropriate choice of the material and by reduction of the cross-section of the conductor, but this cross-section should not be too small, because the electrical resistance would be too high and for a given value of the current, the tube, which is relatively slightly cooled in its upper part, may melt.

In accordance with a preferred embodiment of the invention, the hot portion A is formed of a first portion A_1 having a relatively large cross-section and of a second portion A_2 having a relatively small cross-section.

The cold portion B of the conductor according to the present invention has a length at least equal to the above-defined characteristic length b_1.

In accordance with the considerations developed in the foregoing, the cold portion B has minimum electrical impedance. This impedance, which may be expressed in the form

$$R_E = \rho \frac{l}{a}$$

will therefore be minimized by a reduction of the length l which is, however, greater than the characteristic length b_1.

In accordance with the material chosen, the other geometrical characteristics will be a function of the optimum value of the product $a \cdot p$ indicated by the curves of FIG. 3, the value of the cross-section preferably being equal to the value:

$$a_o = C \rho I^2 / p$$

C being a constant whose value is in the neighborhood of 200.

By way of numerical example, a conductor intended for a current I of the order of 250 a. comprises:

(a) A portion A_1 formed of a hollow tube consisting of copper CuC_2 of a length of 120 mm., having a cross-section of 22 mm.², a wet periphery of 44 mm. and internal and external diameters equal to 6 and 8 mm., respectively;

(b) A portion A_2 formed of a copper tube having an external diameter of 6 mm., an internal diameter of 5 mm., a cross-section $a = 8.6$ mm.², a wet periphery of 34.5 mm. and a length of 300 mm.;

(c) A portion B formed of a rod consisting of annealed copper CuC_2, having a cross-section $a = 28$ mm.² and a wet periphery $p = 19$ mm., the length emerging from the cryogenic bath being 150 mm. It is to be noted that, in accordance with a variant of the present invention, the portion B may comprise at least a portion consisting of a material which is superconductive at the temperature of the cryogenic liquid end of the vapors of this liquid over a length of the portion B.

The portion consisting of superconductive material may be made in the form of a niobium-tin strip of a thickness of 1/10 millimeter, which has a cross-section of about 1.27 mm.² and a wet periphery of the order of 25.4 mm.

FIG. 4 is a diagram in the form of semi-logarithmic co-ordinates, in which there are plotted along the ordinates, for a current of given value, the electrical losses W_E of a conductor (comprising an outgoing conductor and a return conductor), and along the abscissae the product $a \cdot p$ of the cross-section of the said conductor by its wet periphery. The losses given correspond to an outgoing and return current of 200 a. The static losses W_S due to thermal conduction are 0.41 w., and the coefficient of heat exchange h is equal to 0.0023 w./cm.² ° K.

The curves 100 to 104 relate to conductors consisting of brass, ordinary copper, pure copper, annealed copper of the type OFHC and super-refined aluminium, respectively. The products enclosed in a circle correspond to the optimum value of the product $a \cdot p$.

The horizontal chain line represents the minimum electrical losses which would correspond to a conductor having an infinite product $a \cdot p$.

The curves of FIG. 5, denoted by **200** to **203**, represent the electrical losses of a conductor traversed by 600 a. (outgoing and return), consisting respectively of ordinary copper, pure copper, annealed copper of the type OFHC and super-refined aluminium. The points enclosed in a circle and the chain line have the same meanings as in FIG. 5. The values of h and W_S are values identical to those relating to FIG. 4.

We claim:

1. An electrical conductor for cryogenic enclosures, comprising at least a first hot portion, and a second cold portion, one end of said hot portion being at a temperature between 80° and 300° K and the other end connected to a first end of a second cold portion, the second end of the said cold portion being immersed in a cryogenic liquid bath at a temperature between 0° K and 80° K, and the said cold portion having a length substantially equal to a length defined by:

$$b_1 = \frac{(ka)^{1/2}}{hp} [(1 + A^2)^{1/2} + A]$$

with

$$A = \frac{(kahp)^{1/2}}{2\beta mc}$$

in which:

k is the thermal conductivity of the material of the conductor;
ρ is its electrical resistivity;
h is the coefficient of thermal exchange between the con-

ductor and the column of gas above the cryogenic liquid bath;

c is the specific heat of the said gas;

β is a coefficient expressing the degree of participation of the rising gas column at the thermal exchange between the bushing and the gas;

m is the mass flow of the gas;

a is the cross-section of the conductor;

p is its wet periphery; and wherein said hot portion has a length greater than b_1;

said cold portion is made of a material having an electrical conductivity at least as high as that of aluminium, and said hot portion has a relatively high thermal impedance.

2. The conductor according to claim 1, characterized in that the said hot portion is made of strip metal, having a maximum "wet" periphery.

3. The conductor according to claim 1, characterized in that the said hot portion is made of wires having a maximum "wet" periphery.

4. The conductor according to claim 1, characterized in that the said hot portion is made of tubes having a maximum "wet" periphery.

5. The conductor according to claim 1, wherein the said cold portion has a cross-section approximating:

$$a_0 = c\rho \frac{I^2}{p}$$

where:

I is the current through the bushing;

ρ is the resistivity of the material of the bushing;

p is the wet periphery of the bushing; and

C is a coefficient in the neighborhood of 200.

6. The conductor according to claim 1, wherein said cold portion is a material which is superconductive at the temperature of the cryogenic liquid bath.

7. The conductor according to claim 1, wherein at least a part of the said hot portion is in the form of a metal tube formed with a plurality of apertures to permit the passage of a fluid from the outside of the tube to the inside.

References Cited

UNITED STATES PATENTS

3,263,193	7/1966	Allen et al.	174—126
3,343,035	9/1967	Garwin	174—15 UX

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U.S. Cl. X.R.

174—126; 333—99