United States Patent

[11] **3,613,006**

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[73] Assignee **Avco Corporation**
Cincinnati, Ohio
Continuation-in-part of application Ser. No. 367,814, May 15, 1964, now abandoned.

[54] STABLE SUPERCONDUCTING MAGNET

15 Claims, 7 Drawing Figs.

[52] **U.S. Cl.** **335/216,** 174/126
[51] **Int. Cl.** **H01f 7/22**
[50] **Field of Search** 335/216; 174/126

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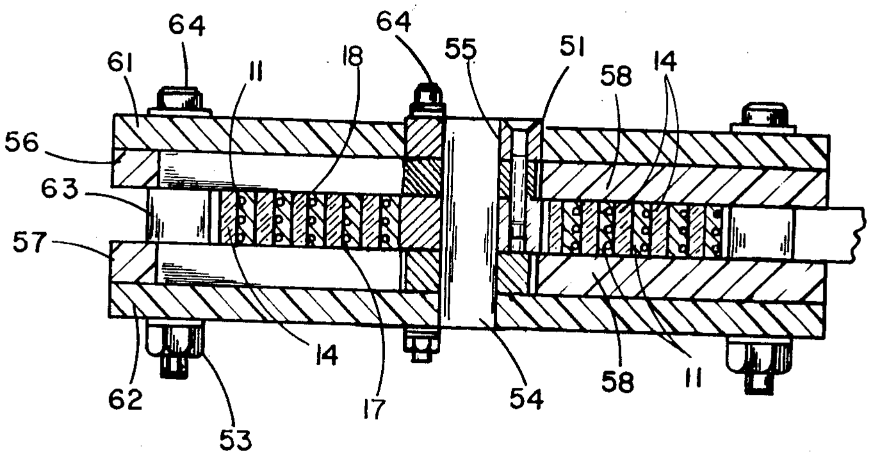
ABSTRACT: Superconductive coils formed from and a superconductive conductor comprised of superconductive material combined with a substantial amount of normal metal in such a manner as to prevent propagation of normal regions in the superconductive material when exposed to a cryogenic environment.



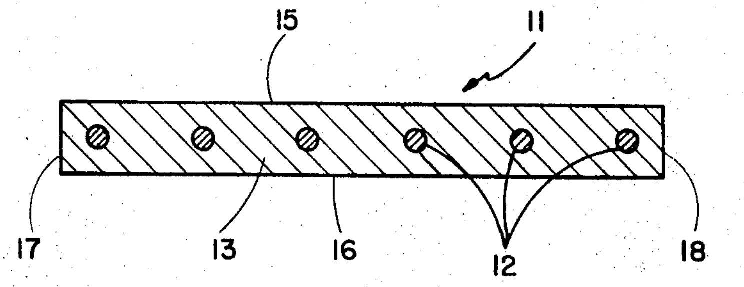


FIG. 1

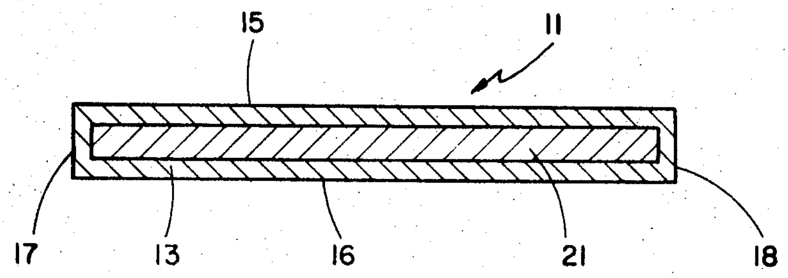


FIG. 2

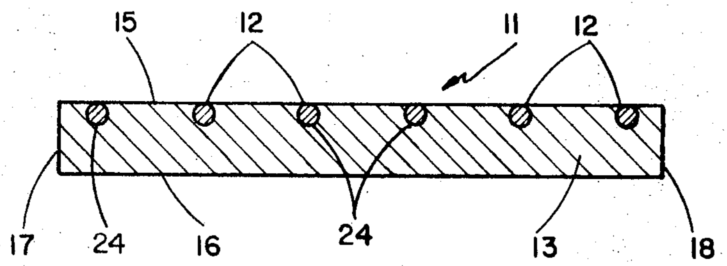


FIG. 3

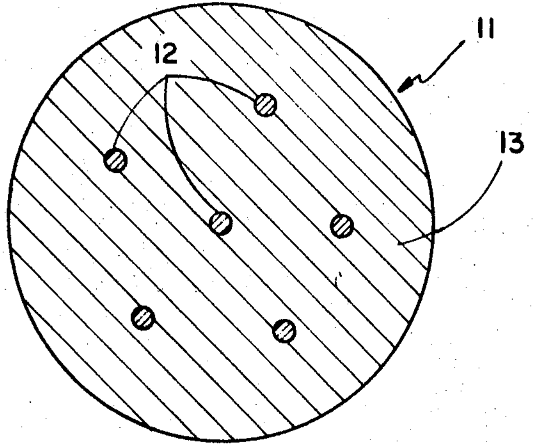


FIG. 4

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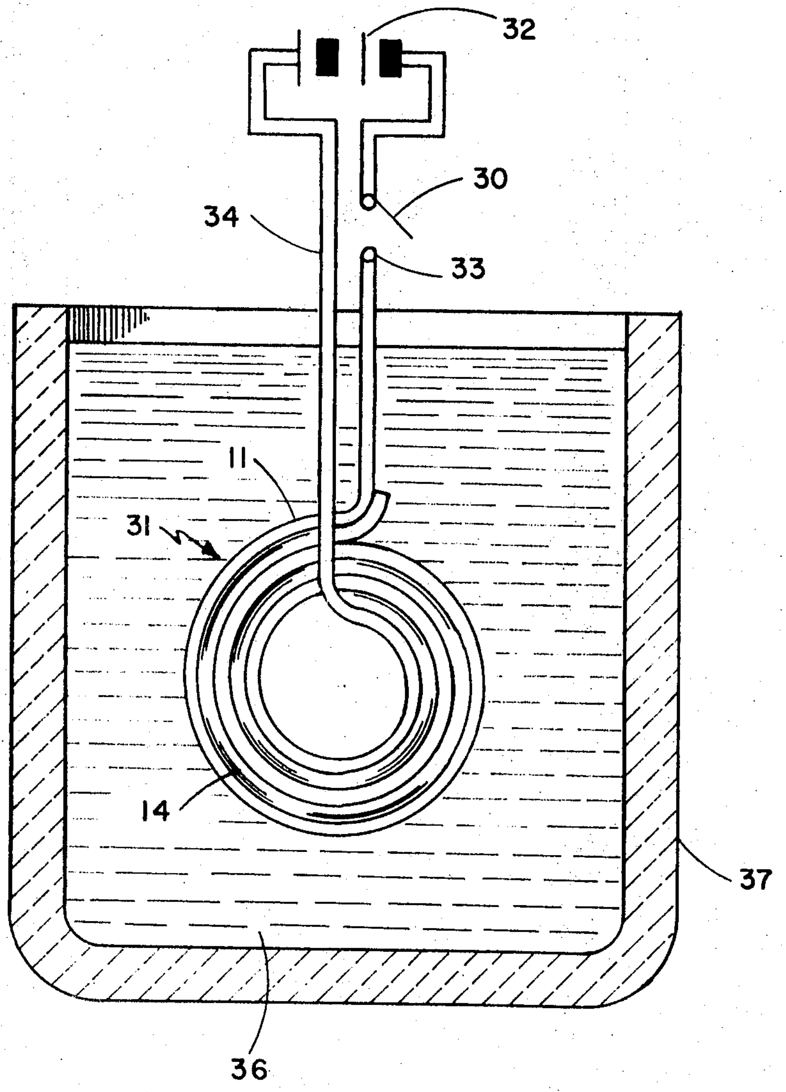

FIG. 5

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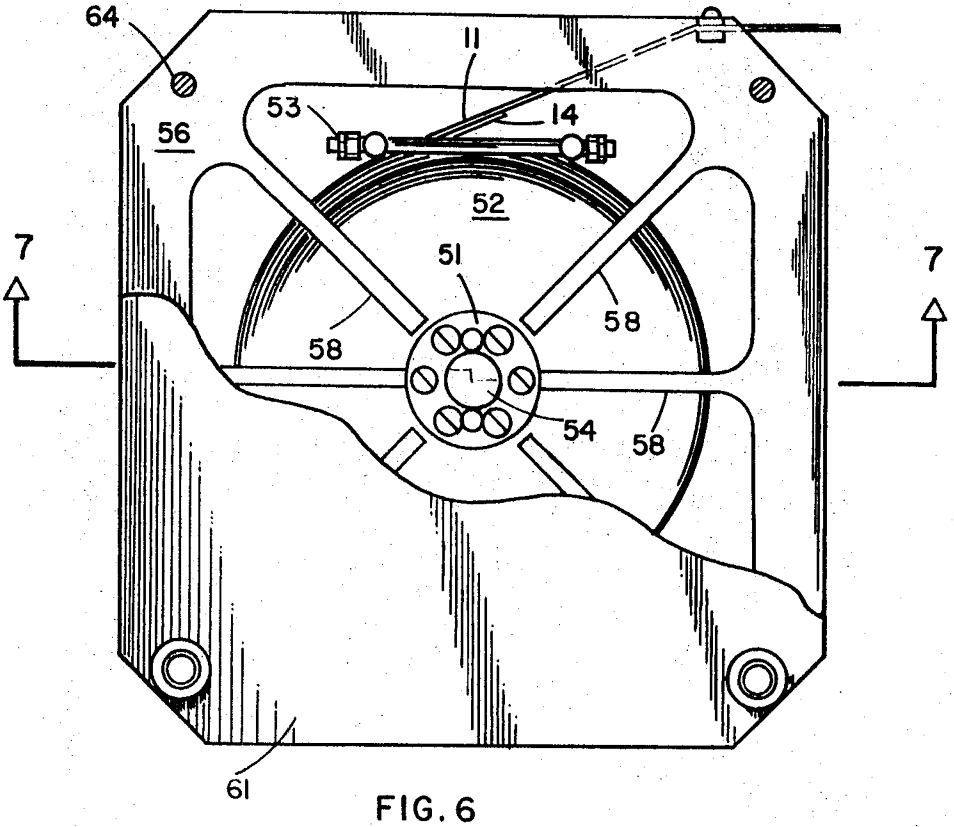

FIG. 6

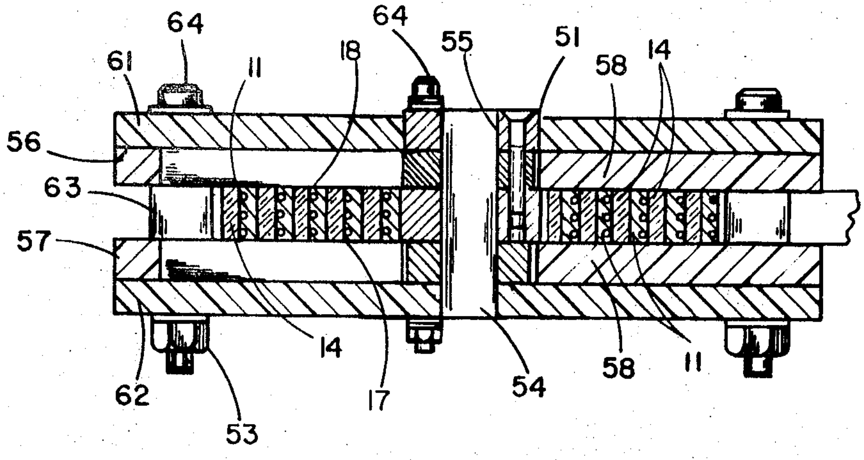

FIG. 7

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STABLE SUPERCONDUCTING MAGNET

This application is a continuation-in-part of application Ser. No. 367,814, filed May 15, 1964, now abandoned.

The present invention relates to superconducting magnets and more particularly to superconducting magnets for providing high magnetic field strengths.

The ability to not only provide high-strength magnetic fields but to effectively and safely provide such magnetic fields over an extended period of time is important in connection with solid-state, plasma and particle physics research. In most cases, heretofore, the need for high magnetic fields necessitated the use of pulsed fields or large amounts of power. However, with the advent of new superconducting materials, considerable interest has been aroused in the development of useful magnets of high field strength.

An example of the application of such magnets is the generation of electrical power, magnetic radiation shielding in outer space, plasma propulsion, large-scale physics experiments and the like, providing a continuous magnetic field of high field strength over a large volume is a formidable engineering task.

Broadly speaking, three types of field coils may be used to provide high-strength magnetic fields, namely, room temperature copper, cryogenic, and superconducting field coils. Until recently, the only practical way to produce high-strength magnetic fields was by using water-cooled copper field coils with or without iron cores. This type of field coil has large power requirements.

Since the resistivity of pure metals decreases with temperature, Joule loss in field coils can be reduced by refrigeration. Although this approach requires that power be supplied to the refrigerator, it has been shown that the total power consumed by the refrigerator and a cryogenic field coil can be substantially reduced over that required by a comparable copper magnet operating at room temperature. However, operation of the refrigerator still represents a significant loss because Joule losses still exist in the coil.

Recent developments in high critical-field superconductors have made possible the consideration of high field strength superconducting field coils. The possibility of using superconductor field coils for providing 100 kilogauss or more with only minute refrigeration power requirements and no Joule losses represents obvious advantages for continuously operating powerplants and the like.

The properties and characteristics of superconductors have been treated in such texts as "Superfluids," Vol. 1, by Fritz London, published in 1950 in New York by John Wiley & Son, Inc. and "Superconductivity" by D. Shoenberg, published in 1952 in London by Cambridge University Press.

It has been known for many years that the resistance of metals decreases as a function of decreasing temperature until a given temperature of the order of 18° K. or below is reached, at which temperature electrical resistance very sharply vanishes for those materials which exhibit superconductivity. The temperature at which transition to zero resistance takes place is referred to as the critical temperature and the state of a material upon reaching zero resistance is referred to as the superconductive state. A material that does not or cannot be made to exhibit zero resistance may be referred to as a nonsuperconductor or normal material.

The critical temperature varies with different materials and for each material it is lowered as the intensity of the magnetic field around the material is increased from zero. Once a body of material is rendered superconductive, it may be restored to the resistive or normal state without changing its temperature by the application of a magnetic field of a given intensity to such materials. The magnetic field necessary to destroy superconductivity is called the critical field. Further, at a given magnetic field strength and temperature, a superconductive material may also be driven into its normal state by passing a current of a given magnitude through the material. The current necessary to destroy superconductivity is called the critical current.

Thus, superconductivity in a specific material may be destroyed by the application of energy to it in the form of heat so as to make such material reach its critical temperature, or in the form of a magnetic field so as to make it reach its critical field, or in the form of current so as to make it reach its critical current. It is important that one keep in mind that the critical temperature, field and current, are all interdependent.

Practical examples of superconducting materials to attain high fields are the compounds Nb_3Sn and V_3Ga, alloys of niobium with zirconium, and alloys of niobium and titanium.

As used herein, the term "superconducting temperature of application" means the temperature at which a coil which exhibits superconducting characteristics is maintained during operation, the term "superconducting material" means a material that does or can be made to exhibit zero resistance, i.e., it has a useful and known critical temperature greater than the superconducting temperature of application, and the term "normal material" means a material that does not or cannot be made to exhibit zero resistance at the superconducting temperature of application.

At this point, it will be helpful in understanding the present invention and appreciating its advantages and the new and unobvious results which are achieved, to discuss certain phenomenon associated with superconducting material and coils incorporating such material. Consider now the current-carrying capacity of conductors formed of superconducting material.

It has been found that the ability of a short sample (one measured in terms of inches) of some superconductive materials, such as, for example, niobium-zirconium, to conduct an electric current can be tremendously increased by a controlled heat treatment after the material is drawn. For example, unheat-treated niobium 25 percent zirconium wires having a diameter of 10 mils in a magnetic field of 50 kilogauss can carry about 50 amperes without being driven normal. However, if the same type of wire is heat-treated to a temperature of about 600° C. for approximately one-half hour, it has been found that its current-carrying capacity is increased to about 130 amperes at the same magnetic field. Similar gains can be obtained over the entire range of magnetic fields for which this alloy can be used. It is important to note that these currents, which may be defined as short sample critical currents and which vary somewhat from sample to sample, can be measured only in short samples of material.

In view of the above, it would seem that if the heat-treated wire is used in coils, one need only use 2½times less wire than with ordinary un-heat-treated wire. This result, however, it not achieved in practice. For both un-heat-treated wires and heat-treated wires, the magnetic fields achieved in coils is much less than that suggested from the current-carrying capacity of short samples. This reduction in current-carrying capacity may be referred to as the "coil effect." The coil effect varies with the type of material and the size of the coil. As used herein, the term "heat treated superconductive material" means a superconductive material which has not only the capability to be but has, after it has been drawn to at least substantially its final form, been heat-treated to increase its current-carrying capability over that existing prior to the heat treatment.

For example, in a prior art coil having an internal diameter of 11 inches and wound with un-heat-treated 10-mil niobium-zirconium wire, the maximum current which can be carried is only 11 amperes while producing a field strength between 30 and 40 kilogauss, whereas as previously noted, the short sample current for the same type of wire is approximately 50 amperes in an even higher magnetic field. If heat-treated wires are used, the coil effect is even more pronounced. It has been found that coils wound with heat-treated wire go normal, that is, lose their superconducting properties at currents of the order of 2 amperes. This degradation of current-carrying capacity or coil effect is a consequency of a phenomenon which for convenience is referred to as "flux jumping."

All superconducting coils generate heat during the charging process and this heat comes about by the process of flux jumping. A flux jump may be defined as a sudden change in flux density over a finite volume. During the charging process, a condition arises in the superconducting material similar to the skin effect at high frequencies in a normal material which causes the current to flow mainly on the surface of the superconductor. This results in a high surface current density. Once a critical value of this current density is reached, a redistribution of the current in the superconductor occurs. If this redistribution occurs rapidly, a flux jump is said to have occurred. This redistribution of current in general allows the superconducting material to conduct additional current. This flux jump also generates heat in the region of the superconducting material where the flux jump occurred. While the first flux jump in a conventional coil may not necessarily produce sufficient heating to drive the region of the coil normal, a point is eventually reached wherein a flux jump does in fact produce a normal region. Thus, in conventional superconducting coils, a small region of normal resistance, depending on the severity of the flux jump, may occur at the site of the flux jump. Current flowing through this normal region creates additional heating called Joule heating. If the Joule heating is high enough, the normal region will grow and eventually dissipate the full energy stored in the coil's magnetic field.

The amount of energy stored in some proposed large superconducting coils is measured in tens or hundreds of megajoules. If a coil storing such tremendous energy becomes normal in an uncontrolled manner, complete destruction of the coil, as well as its immediate surroundings, is quite likely to result.

It is therefore of primary importance that superconductive coils storing significant amounts of energy be provided with special fail-safe circuitry that will protect the coil by safely dissipating the energy stored in the coil in the event that a portion of the coil goes normal or that the coil be designed and/or constructed in such a manner as to eliminate the necessity of special fail-safe circuits.

Accordingly, it will now be seen that a conventional superconducting coil constructed, for example, in accordance with the teaching of U.S. Pat. No. 3,109,963 issued Nov. 5, 1963, to T. H. Geballe, is completely incapable of overcoming the coil effect since the copper coating is merely effective to protect the coil from physical destruction by short circuiting the entire coil in the event the coil goes normal. The copper permits dissipation of the energy stored in the magnetic field over a large fraction of the coil volume.

While U.S. Pat. application Ser. No. 220,237 filed Aug. 27, 1962, by Z. J. J. Stekly, now U.S. Pat. No. 3,263,133 is directed to special fail-safe circuits referred to hereinabove, heretofore it has not been possible to eliminate the necessity of providing such special fail-safe circuits to protect superconducting coils storing large amounts of energy and more importantly, to overcome the coil effect, i.e., to operate such coils with a rated current that even approaches the current-carrying capacity of short lengths of the superconducting material used in the coil. As used herein, "rated current" means the maximum current that may be consistently permitted to flow in a superconducting coil over extended periods of time without incurring substantial fluctuations or loss of the magnetic field generated by the aforementioned current flow.

In accordance with the present invention, local normal regions resulting from flux jump, for example, are stabilized by means for controlling the temperature of the superconductive material. In devices incorporating the present invention, current can return to the superconductive material an instant after a flux jump has occurred and the current-carrying capacity of the superconductive material is restored. This occurs without using up more than an insignificant amount of the coil's energy. Thus, the coil effect is substantially, if not completely, eliminated and, accordingly, during charging, the coil can continue to increase its charge and magnetic field until the full current-carrying capacity of the superconducting material, as determined by testing of short samples, is approached. Further, the effects of transients which may occur or be induced during operation at rated current are greatly reduced if not eliminated and the provision of fail-safe features in high-strength superconducting magnets is automatically provided. Still further, the present invention permits superconducting coils to be designed that operate in a stable manner up to a predetermined fraction of the short sample current, which predetermined fraction may approach or possibly equal the short sample current.

All of the above is accomplished in accordance with the present invention by forming the conductor of the coil of a superconducting material in intimate electrically and thermally conductive contact with a normal material having a high electrical conductivity at superconducting temperatures, such as, for example, aluminum, cadmium, copper, gold, silver, sodium, and the like. In accordance with known procedures, the coil, when used, is exposed to a low-temperature environment, such as, for example, liquid helium, to reduce the temperature of the conductor below the critical temperature of the superconducting material when the superconducting material is carrying rated current. The ratio of the total cross-sectional area of the normal material to the total cross-sectional area of the superconductive material and the provision of means for removing heat from the normal material are of particular importance. Other considerations are that the electrical and thermal conductivity of the contacting surfaces of the superconductive and normal material are preferably as high as possible to provide the minimum possible resistance, the maximum possible heat transfer therebetween, and that the thermal conductivity between the conductor and the low-temperature environment is preferably as high as possible. Accordingly, the cross section of the normal material is selected as more fully described hereinafter such that when exposed to a low-temperature environment, such as, for example, 4.2° or 2.0° K., the normal material, when cooled for example in accordance with the present invention, could carry the rated current of the coil without exceeding the critical temperature of the superconducting material assuming constant heat transfer coefficient. Since heat is generated in the normal material when it is carrying current, means constructed and arranged, as more fully disclosed hereinafter, is also provided in combination with the conductor to maintain the low-temperature environment in direct contact with the conductor to prevent the normal material adjacent or surrounding the superconducting material, as the case may be, from reaching a temperature in excess of the critical temperature of the superconducting material when the normal material is carrying, for example, a substantial fraction (about one-half or more) of the rated current of the superconducting material in the rated magnetic field of the coil. Adequate cooling of the conductor is, among other things, facilitated by winding it in such a manner as to place a portion of each turn in communication with the low-temperature environment sufficient to maintain the conductor at a temperature less than the critical temperature of the superconducting material.

It is therefore a principal object of the present invention to provide a stabilized superconducting coil.

It is another object of the present invention to provide a superconducting coil wherein the provision of external fail-safe circuits is rendered unnecessary.

It is a further object of the present invention to provide a large superconducting coil having a rated current greater than that heretofore possible.

It is a still further object of the present invention to provide a superconducting coil wherein the rated current of the coil approaches the current-carrying capacity of short lengths of the superconducting material.

It is another object of the present invention to provide high field strength superconducting coils that may be safely used in applications where high magnetic field strengths over large volumes are required.

It is a further object of the present invention to provide means for using heat-treated superconducting wire in a coil.

It is another object of the present invention to permit the design of superconducting coils that will operate in a stable manner up to a substantial fraction of the short sample current of the superconducting material used in the coil.

The invention, both as to its organization and method of operation, will best be understood from the following description of specific embodiments when read in conjunction with the accompanying drawings, in which:

FIG. 1 is a front cross-sectional view of a conductor in accordance with the present invention;

FIG. 2–4 are front, cross-sectional views of modifications of a conductor in accordance with the present invention;

FIG. 5 is a front view partly in cross section of a superconducting magnet and is illustrative of one embodiment of the invention wherein a conductor depicted in FIG. 3, for example, is utilized;

FIG. 6 is a side view with parts broken away of a superconducting coil in accordance with the present invention; and

FIG. 7 is taken on line 7—7 of FIG. 6.

Referring now to FIG. 1, there is shown a conductor 11 comprising a plurality of superconducting wires 12 spaced one from another and fully imbedded in a normal material 13, such as, for example, copper. The major surfaces 15 and 16 of the conductor 11 may be provided with an electrically nonconducting insulating material (not shown) during fabrication of the conductor, or, alternately, electrically nonconducting material, such as, for example, Mylar, may be interposed between the major surfaces when the conductor is wound to form a pancake-type winding, for example. In this event, the edges or minor side surfaces 17 and 18 are left bare. Although niobium-zirconium is at present preferred, the superconducting wire 12 may be formed of any suitable superconducting material and although substantially pure copper is also at present preferred, the normal material may be of any normal material that has a low-temperature electrical conductivity of, for example, the order of copper at about superconducting temperatures.

FIG. 2 depicts a modification wherein the superconducting material is in the form of a strip 21.

FIG. 3 depicts a further modification wherein the major surface 15 of the normal material 13 is initially provided with grooves 24 to receive the superconducting wires 12. The superconducting wires 12 are placed in the grooves 24 and at least partly imbedded in the normal material 13 as by cold-rolling the normal material to close the grooves over and around the superconducting wire to provide an intimate electrically conductive contact between the superconductive material 12 and the normal material 13. The normal material preferably has as high a purity possible to provide the lowest possible resistivity.

FIG. 4 depicts a still further modification wherein the normal material 13 contains the aforementioned plurality of superconducting wires 12 but is itself in the form of a wire.

FIG. 5 depicts a superconducting magnet utilizing a coil 31 formed from the conductor 11 shown in FIG. 3, for example. Electrically nonconducting material 14 is interposed between the turns to prevent shorting. Coil 31 is connected to an external power source, such as battery 32, by means of switch 30 and the end portions 33 and 34 of the conductor 11. Coil 31 is suspended in a low-temperature environment 36, such as liquid helium, which reduces the temperature of the superconducting material in conductor 11 below its critical temperature. Typically, the liquid helium is contained in a Dewar flask 37.

Referring now to FIGS. 6 and 7, there is shown a superconducting coil constructed in accordance with the present invention. A conductor 11, as shown in FIG. 3, for example, is wound on an annular copper winding core 51 to form a single layer or pancake-type winding designated generally by the numeral 52, comprising a plurality of turns, one on top of the other, a layer of electrically nonconducting insulating material 14 being interposed between each turn to prevent shorting of the winding.

A winding clamp assembly designated generally by the numeral 53 prevents expansion of the winding 52 during operation of the coil.

The working space 54 of the coil is defined by the inner surface 55 of the winding core. Of course if the working space is to be at room temperature, a portion of the Dewar (not shown) must be disposed adjacent the inner surface 55 of the winding core. Disposed adjacent the minor surfaces 17 and 18 on each side of the conductor are spacer plates 56 and 57 formed of a suitable electrically nonconducting material, such as, for example, linen phenolic. The inner and middle portion of each spacer plate is removed to place as much as possible of the minor surfaces or edges 17 and 18 of the conductor in communication with the low-temperature environment. The thickness and radial dimension of the spacer plates are selected to provide the desired volume adjacent the edges of the conductor and substantially all of the inner portion of each spacer plate is removed to provide small supporting fingers 58 which project inwardly to a point adjacent the winding core 51. The volume of the supporting fingers should be as small as possible consonant with providing the necessary support for the winding so that as much as possible of the bare edges or minor surfaces 17 and 18 of the conductor will be exposed to the low-temperature environment.

Cover plates 61 and 62, also composed of linen phenolic, for example, are provided over and in abutting relationship with the spacer plates. Electrically nonconductive spacer members 63 and through bolts 64 at both the inner and outer periphery of the coil complete the assembly of the coil.

It will now be seen that the conductor forms a plurality of turns one on top of the other wherein at least a portion of the surface of the conductor is in communication with the low-temperature environment. While electrically nonconducting insulation is provided between the turns of the winding, the surface of the conductor exposed to the low-temperature environment is bare. Thus, the spacer and cover plates, in addition to providing support for the winding, maintain the low-temperature environment in contact with at least a substantial portion of the exposed surface of the conductor to prevent the superconducting material forming a part of the conductor from reaching a temperature in excess of its critical temperature when the normal material is carrying current.

It has previously been pointed out that Joule heating occurs in the normal material when it is carrying current. Accordingly, where the low-temperature environment is a liquid and is in contact with the conductor, it may be in part converted to a gas when heating occurs in the conductor. The cooling ability of the liquid contact is much greater than that of the gas. If this gas is not exhausted from the area immediately adjacent the conductor where the transfer of heat from the conductor to the low-temperature environment occurs, the temperature of the conductor will rise to a point sufficient to drive the superconducting material normal. Thus, it is important that the spacer plates, cover plates (if used) and the like direct the low-temperature environment as a liquid to the exposed surfaces of the conductor, such as, for example, surfaces 17 and 18, and exhaust the low-temperature environment converted to a gas as a result of contact with these surfaces away at a rate sufficient to maintain the superconducting material at less than its critical temperature at all times, even when the normal material is carrying the rated current. If the flow of low-temperature environment so converted to a gas is restricted (choking occurs) sufficient liquid low-temperature environment will not be in contact with the conductor to maintain its temperature at the required level.

It is to be understood that the above description is given merely by way of example and not by way of limitation. For example, where the superconducting material permits, the low-temperature environment may be a gas. Also, conventional means other than that described may be used for maintaining the low-temperature environment in contact with the exposed surface of the conductor, the desiderata being that among other things the coolant passages in communication with the exposed surface of the conductor and the low-temperature environment by selected to result in the removal of heat from the conductor at a rate sufficient to maintain the superconducting material at less than its critical temperature when the normal material is carrying current and in its desired magnetic field. If Helium II (liquid helium cooled below about 2.1° K.) is used as the low-temperature environment, the means for maintaining the low-temperature environment in contact with the exposed surface of the conductor may be simplified because of the increased heat transfer characteristics of Helium II. Still further, one or a plurality of wires may be used depending on the design of the conductor.

A plurality of spaced pancake-type windings concentric about a longitudinal axis may be provided or, alternately, the winding may have a saddle shape configuration or the like. Further, axial passages for receiving the low-temperature environment may be provided between the turns. In this case, for example, an electrically nonconductive annular member having axial grooves in one or both of its major surfaces may be substituted for the insulating material **14**. If the annular member is formed of an electrically conductive material, the necessary insulation to prevent short circuiting need be disposed only on the crests of the grooves which come in contact with the conductor.

From the preceding discussion, it will now be readily seen that the present invention contemplates that the normal material will carry current varying from a minimum of some small value to a maximum of the rated current at various times during operation of the coil. If the temperature rise of the conductor during the time the normal material is carrying rated current, for example, results in a temperature of the conductor which exceeds the critical temperature of the superconducting material, the coil will be driven into the normal state. On the other hand, if the temperature rise does not result in the conductor exceeding the critical temperature of the superconducting material, the superconducting material can remain superconducting and take back the current which is flowing in the normal material.

The relation of the various parameters to achieve the return of current to the superconducting material is given by the equation:

$$\Delta T=\rho I_2 / h P A \qquad (1)$$

where

I is the current in amperes flowing in the conductor;

ΔT is the temperature rise in degrees Kelvin in the conductor when the current I is flowing in the normal material;

ρ is the resistivity of the normal material in ohm centimeters;

h is the effective heat transfer coefficient from the superconducting material to the coolant in watts per square centimeter per degree Kelvin for simplicity assumed constant in the above equation;

A is the cross-sectional area of the conductor in square centimeters; and

P is the cooled portion of the perimeter of the cross section of the conductor in centimeters.

Equation (1) above is an approximate equation which, for purposes of simplicity, neglects the temperature gradients in the conductor.

The cross section of the superconducting material is given by the equation:

$$A_{sc}=I / J_{sc} \qquad (2)$$

where A_{sc} is the total cross section of the superconductive material is square centimeters and J_{sc} is the current density in amperes per square centimeters in the superconducting material.

Solving equation (2) for I and substituting this is in equation (10 gives:

$$\frac{A_{sc}}{A}=\sqrt{\frac{hP\Delta T}{A\rho J_{sc}^2}} \qquad (3)$$

Inspection of the preceding equations will show that for superconductors capable of carrying high current densities, the cross-sectional area of the normal material will be greater than the total cross-sectional area of the superconducting material. Further, inspection of equation (1) also shows that no useful purpose would be served by giving specific values for the various parameters because they are all interdependent and the selection of one necessarily effects the selection of the others. However, although a reasonable amount of latitude is available in selecting values for these parameters, they must all be such that ΔT is not substantially in excess of the difference between the superconducting temperature of operation and the critical temperature of the superconducting material at rated field but at zero current. While it is preferred that ΔT be less than the difference between the superconducting temperature of operation and the critical temperature of the superconducting material, at rated field but zero superconductor current it is to be understood that is some cases ΔT can be greater than this difference without practically unacceptable consequences.

Of course when the normal material is carrying current as a result of a localized normal region in the superconductive material, a constant voltage will be measurable across the conductor. Thus, in accordance with the present invention provision of the minimum necessary cross-sectional area of normal material and electrically and thermally conductive contact between the normal metal and the superconductive material is achieved if, when the conductor is exposed to the low-temperature environment, the normal region does not propagate, i.e., the entire coil is not driven into the normal state. Preferably, both the aforementioned cross-sectional area of the normal metal and the contact between the normal material and the superconductive material are selected to result in disappearance of the normal region which is to say prevent the generation of heat in the conductor at a rate greater than that at which it is removed. If the preceding requirements are not met even with direct exposure of the entire surface of the conductor to the low-temperature medium, then the normal region will not disappear, hence stable operation as described herein will not occur.

The various features and advantages of the invention are thought to be clear from the foregoing description. Various other features and advantages not specifically enumerated will undoubtedly occur to those versed in the art, as likewise will many variations and modifications of the preferred embodiment illustrated, all of which may be achieved without departing from the spirit and scope of the invention as defined by the following claims.

We claim:

1. In a superconducting device having a rated current for providing a given magnetic field when immersed in a low-temperature environment to reduce the temperature of superconducting material below its critical temperature, the combination comprising:

a. a conductor forming a plurality of turns at least a first portion of which turns are in communication with said low-temperature environment, said conductor comprising superconductive material and a normal metal, a short sample of said superconductive material having a predetermined short sample critical current in said given magnetic field, said normal metal having a low-temperature electrical conductivity not substantially greater than that of copper at the temperature at which said superconductive material is superconductive, said normal metal being in intimate electrically and thermally conductive contact with at least a substantial portion of said superconductive material to provide substantially minimum electrical resistance and substantial maximum heat transfer between said normal metal and said superconductive material, said normal metal having a cross-sectional area at least several times greater than the cross-sectional area of said superconductive material so that when said conductor is exposed to a low-temperature environment to reduce the temperature of said superconductive material below its critical temperature and current flowing through the said conductor is increased until a constant voltage is measurable across the ends of said conductor as a result of a localized normal region in said superconductive material, said voltage will disappear upon reduction of said current to a value not substantially less than said rate current;

b. electrically nonconductive means electrically insulating said turns one from another, said first portion of said surface being exposed to said low-temperature environment; and

c. first means maintaining said low-temperature environment in contact with said exposed surfaces for removing heat from said turns at at least a minimum predetermined rate to substantially prevent said superconducting material at substantially any point along its length in said turns from reaching a temperature in excess of its critical temperature when said normal material is carrying a substantial fraction of said critical current.

2. The combination as defined in claim 1 wherein said first means includes coolant passages in communication with both said first portion and said low-temperature environment and said critical current is that resulting from heat-treating to provide the maximum critical current.

3. The combination as defined in claim 2 wherein said first means maintains said low-temperature environment substantially as a fluid in contact with the said first portion of said turns.

4. The combination as defined in claim 1 wherein said first means directs said low-temperature environment as a liquid to the said first portion of said turns and exhausts said low-temperature environment converted to a gas as a result of contact with said first portion of said turns at a rate sufficient to maintain said superconducting material at less than its critical temperature when said normal metal is carrying current.

5. In a superconducting coil having a rated current for providing a magnetic field, the combination comprising:

a. a conductor forming a plurality of turns comprising a superconducting material in intimate electrically and thermally conductive contact with a normal material having a low-temperature electrical conductivity of at least about the order of copper at superconducting temperatures, the total cross section of said normal material being greater than the total cross section of said superconducting material so that when said conductor is exposed to a low-temperature environment to reduce the temperature of said superconductive material below its critical temperature and current flowing through the said conductor is increased until a voltage is measurable across the ends of said conductor, said voltage will disappear upon reduction of said current to a value not substantially less than said critical current;

b. a fluid low-temperature environment for reducing the temperature of said conductor below the critical temperature of said superconducting material; and

c. first means for maintaining said low-temperature environment as a fluid in contact with a portion of the surface of each turn of said conductor, said ratio of cross sections, the amount of said surface of each turn in contact with said low-temperature environment, and said first means being selected, arranged and adapted to conduct heat away from said conductor at a rate sufficient to prevent said superconducting material from reaching a temperature in excess of its critical temperature when said normal material is carrying current.

6. In a superconducting device for providing a given magnetic field when immersed in a low-temperature environment to reduce the temperature of superconducting material below its critical temperature, said device containing superconducting material and having a rated current, the combination comprising:

a. a conductor forming a plurality of turns comprising a superconducting material in intimate electrically and thermally conductive contact with a normal material having a high electrical conductivity at superconducting temperatures, said superconducting material having a predetermined critical current in a magnetic field equal to said given magnetic field, the total cross section of said normal material being greater than the total cross section of said superconducting material so that when conductor is exposed to a low-temperature environment to reduce the temperature of said superconductive material below its critical temperature and current flowing through the said conductor is increased until a voltage is measurable across the ends of said conductor, said voltage will disappear upon reduction of said current to a value not substantially less than said critical current;

b. electrically nonconductive means electrically insulating said turns one from another; and

c. means for maintaining said low-temperature environment in contact with each turn of said conductor and preventing said conductor from increasing in temperature by an amount ΔT less than about the difference between the superconducting temperature of operation and the critical temperature of said superconducting material, said ΔT being substantially equal to $\rho I^2/h\,P\,A$, where

I is the current in amperes flowing in said conductor;

ρ is the resistivity of said normal material in ohm centimeter

h is the effective heat transfer coefficient from said superconducting material to said low-temperature environment in watts per square centimeter per degree Kelvin;

A is the cross-sectional area of said conductor in square centimeters; and

P is the portion of the perimeter of the cross section of said conductor in centimeters in contact with said low-temperature environment.

7. In a superconducting device for providing a magnetic field when immersed in a low-temperature environment to reduce the temperature of superconducting material below its critical temperature, said device containing superconducting material and having a rated current, the combination comprising:

a. a conductor forming a plurality of turns and comprising a superconducting material and a normal material having a high electrical conductivity at superconducting temperatures, at least a major portion of the surface of one of said materials being in electrically and thermally conductive contact with said other material, the electrical conductivity between said contacting surfaces at superconducting temperatures being not substantially in excess of the electrical conductivity of said normal material at superconducting temperatures, said turns being wound to place at least a portion of a surface of said conductor forming each turn in communication with said low-temperature environment, the total cross section of said normal material being substantially greater than the total cross section of said superconducting material whereby at the superconducting temperature of application said normal material will carry said rated current of said device;

b. electrically nonconductive means insulating said turns one from another, said at least a portion of the surface of each said turn being exposed to said low-temperature environment; and

c. means for maintaining said low-temperature environment in contact with said exposed surface of said conductor and preventing said conductor from increasing in temperature by an amount ΔT less than about the difference between the superconducting temperature of operation and the critical temperature of said superconducting material, said ΔT being substantially equal to $\rho I^2/h\,P\,A$, where

I is the current in amperes flowing in said conductor;

ρ is the resistivity of said normal material in ohm centimeters;

h is the effective heat transfer coefficient from said superconducting material to said low-temperature environment in watts per square centimeter per degree Kelvin;

A is the cross-sectional area of said conductor is square centimeters; and

P is the portion of the perimeter of the cross section of said conductor in centimeters in contact with said low-temperature environment.

8. In a superconducting device for providing a magnetic field when immersed in a low-temperature environment to reduce the temperature of superconducting material below its critical temperature, said device containing superconducting material and having a rated current, the combination comprising:

a. a conductor forming a plurality of turns comprising a superconducting material in intimate electrically and thermally conductive contact with a normal material having a high electrical conductivity at superconducting temperatures;

b. electrically nonconductive means electrically insulating said turns one from another; and

c. means for maintaining said low-temperature environment in contact with at least part of each turn of said conductor and preventing said conductor from increasing in temperature by an amount ΔT the ratio of the total cross section of said superconducting material to the total cross section of said conductor being substantially equal to

$$\sqrt{\frac{hP\Delta T}{A\rho J_{sc}^{2}}}$$

where

ρ is the resistivity of said normal material in ohm centimeters;

h is the effective heat transfer coefficient from said superconducting material to said low-temperature environment in watts per square centimeter per degree Kelvin;

A is the total cross-sectional area of said conductor in square centimeters;

P is the portion of the perimeter of the cross section of said conductor in centimeters in contact with said low-temperature environment;

ΔT is the rise in temperature in the conductor with all of the current flowing in the normal material and is less than about the difference between the superconducting temperature of application and the critical temperature of the superconducting material; and

J_{sc} is the current density in amperes per square centimeter in the superconducting material when it is carrying the current flowing in said conductor.

9. In a superconducting device for providing a magnetic field when immersed in a low-temperature environment to reduce the temperature of superconducting material below its critical temperature, said device containing superconducting material and having a rated current, the combination comprising:

a. a conductor forming a plurality of turns comprising a superconducting material imbedded in and in intimate electrically conductive contact with a normal material having a high electrical conductivity at superconducting temperatures, said turns being wound to place at least a portion of the surface of said conductor forming each turn in communication with said low-temperature environment;

b. electrically nonconductive means electrically insulating said turns one from another, said at least a portion of the surface of each said turn being exposed to said low-temperature environment; and

c. means for maintaining said low-temperature environment in contact with said exposed surface of said conductor and preventing said conductor from increasing in temperature by an amount ΔT, the ratio of the total cross section of said superconducting material to the total cross section of said conductor being substantially equal to

$$\sqrt{\frac{hP\Delta T}{A\rho J_{sc}^{2}}},$$

where

ρ is the resistivity of said normal material in ohm centimeters;

h is the effective heat transfer coefficient from said superconducting material to said low-temperature environment in watts per square centimeter per degree Kelvin;

A is the total cross-sectional area of said conductor in square centimeters;

P is the portion of the perimeter of the cross section of said conductor in centimeters in contact with said low-temperature environment;

ΔT is the rise in temperature in the conductor with all of the current flowing in the normal material and is less than about the difference between the superconducting temperature of application and the critical temperature of the superconducting material; and

J_{sc} is the current density in amperes per square centimeter in the superconducting material when it is carrying the current flowing in said conductor.

10. A composite electrical conductor comprising:

a. elongated superconductive material, a relatively short sample of said superconductive material having a predetermined rated current in a given magnetic field; and

b. a normal metal having a low-temperature electrical conductivity of the order of copper at temperature at which said superconductive material is superconductive, said metal being in intimate electrically and thermally conductive contact with at least a substantial portion of said superconductive material to provide substantially minimum electrical resistance and substantially maximum heat transfer between said normal metal and said superconductive material said metal further having a cross-sectional area that in combination with said electrically and thermally conductive contact, in an environment having a temperature less than the critical temperature of said superconductive material, prevents propagation of a localized normal region resulting from increasing current flow through said sample in said given magnetic field until a constant voltage is measurable across said conductor.

11. The combination as defined in claim **10** wherein said cross-sectional area and said thermally and electrically conductive contact causes said normal region to disappear upon reduction of said current to a value not substantially less than said rated current.

12. A composite electrical conductor comprising:

a. elongated superconductive material, a relatively short sample of said superconductive material having a predetermined rated current in a given magnetic field; and

b. a normal metal having a low-temperature electrical conductivity of the order of copper at the temperature at which said superconductive material is superconductive, said metal being in intimate electrically and thermally conductive contact with at least a substantial portion of said superconductive material to provide substantially minimum electrical resistance and substantially maximum heat transfer in said normal material and between said normal metal and said superconductive material, and said normal metal having a cross-sectional area substantially greater than the cross-sectional area of said superconductive material so that when said conductor is exposed to a low-temperature environment to reduce the temperature of said superconductive material below its critical temperature and current flowing through said sample is increased until a constant voltage is measurable across said conductor as a result of a localized normal region is said superconductive material, said voltage will disappear upon reduction of said current to a value not substantially less than said rated current.

13. The combination as defined in claim **10** wherein said normal metal has an essentially rectangular cross section and at least substantially surrounds said superconductive material.

14. The combination as defined in claim **13** wherein said superconductive material comprises a plurality of superconductive wires spaced one from another, said normal metal at least substantially surrounding each said superconductive wire.

15. The combination as defined in claim **10** wherein said superconductive material is heat-treated superconductive material.

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UNITED STATES PATENT OFFICE
CERTIFICATE OF CORRECTION

Patent No. 3,613,006 Dated October 12, 1971

Inventor(s) Arthur R. Kantrowitz and Zdenek J. J. Stekly

It is certified that error appears in the above-identified patent and that said Letters Patent are hereby corrected as shown below:

Column 2, line 49, for "it" read--is--; Column 2, line 74, for "consequency" read--consequence--; Column 5, line 51, after "purity" insert--as--; Column 7, line 14, after "a" insert--common--; Column 7, line 42, for "$\Delta T = \rho I_2 / h P A$" read--$\Delta T = \rho I^2 / h P A$--; Column 7, line 69, for "(10" read--(1)--; Column 9, line 5, for "rate" read --rated--; Column 10, line 5, after "when" insert--said--; and Column 12, line 26, after "at" (first occurrence) insert--the--.

Signed and sealed this 11th day of July 1972.

(SEAL)
Attest:

EDWARD M.FLETCHER,JR.
Attesting Officer

ROBERT GOTTSCHALK
Commissioner of Patents