



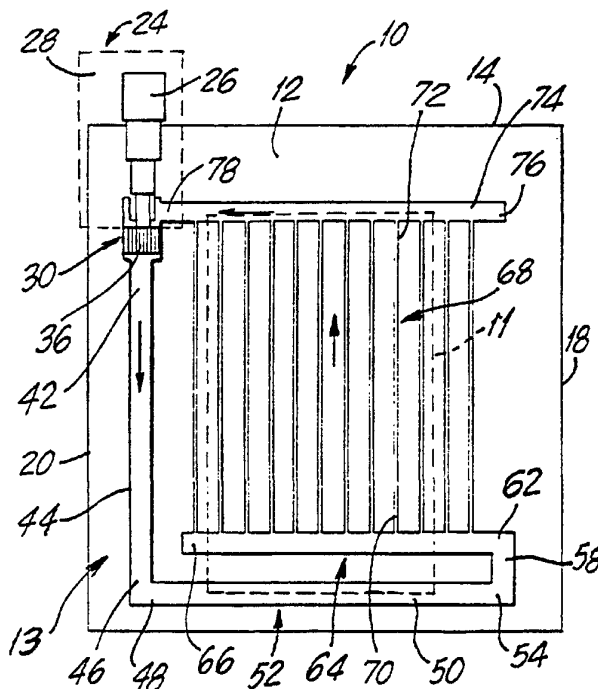
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(54) Title: MEANS AND APPARATUS FOR CONVECTIVELY COOLING A SUPERCONDUCTING MAGNET

(57) Abstract

Apparatus and methods for cooling a superconducting magnet (11) by circulating a pressurized helium gas through a convective cooling loop (13) by natural convection, and for quickly and effectively cooling a warm superconducting magnet (11) down to operating temperature.



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MEANS AND APPARATUS FOR CONVECTIVELY COOLING  
A SUPERCONDUCTING MAGNET

5

FIELD OF THE INVENTION

10 This invention relates to the field of cooling a device  
such as a superconducting magnet. More particularly, the  
invention relates to an apparatus and methods for cooling a  
superconducting magnet with a pressurized helium gas  
circulated through a light weight heat transfer system by  
15 natural convection to maintain a more uniform temperature in  
the superconducting magnet.

BACKGROUND OF THE INVENTION

The use of Niobium Tin ( $Nb_3Sn$ ) wire in a  
20 superconducting magnet enables cooling of the magnet by  
means of a conventional Gifford-McMahon cycle refrigerator,  
which can efficiently produce refrigeration at a temperature  
of between about eight Kelvin (K) to ten Kelvin but is  
capable of cooling to lower temperatures. It has been  
25 demonstrated that a superconducting magnet can be cooled by  
conductively transferring heat generated by the magnet  
through an aluminum shell to a Gifford-McMahon cycle  
refrigerator.

In a paper entitled "Applications of Superconductivity  
30 to Very Shallow Water Mine Sweeping" by E. Michael Golda, et  
al., published in the Naval Engineers Journal, May, 1992, a  
liquid helium cooled Niobium Titanium ( $NbTi$ ) magnet

operating at 4.2 K is described and compared with a  
conductively cooled, Nb<sub>3</sub>Sn magnet operating at 10 K. The  
cooling of the Nb<sub>3</sub>Sn magnet is provided by a two stage,  
Gifford-McMahon, closed cycle refrigerator adapted for a  
5 mine sweeping application. While the weight of the  
conductively cooled, Nb<sub>3</sub>Sn magnet and its insulation is less  
than the weight of the liquid helium cooled, NbTi magnet  
itself, the complete cooling system required for the  
conductively cooled, Nb<sub>3</sub>Sn magnet still weighs more than the  
10 liquid helium cooled, NbTi magnet because of the added  
refrigerator. The refrigerator, however, frees the system  
from the logistical problem of periodically supplying liquid  
helium, often under difficult circumstances. Although the  
Golda, et al. paper is directed to usage in combat  
15 situations, the advantages of using a conductively cooled  
superconducting magnet also apply to other applications,  
such as in hospitals.

A paper by Geoffrey F. Green, et al. entitled  
"Conductively Cooling a Small Nb<sub>3</sub>Sn Coil With a Cryocooler",  
20 presented at the 7th International Cryocooler Conference,  
Nov. 17-19, 1992, describes the construction and testing of  
a conductively cooled Nb<sub>3</sub>Sn magnet. The magnet wire is  
wrapped around an aluminum shell which is cooled by a two  
stage, Gifford-McMahon refrigerator. Heat is transferred  
25 into the aluminum shell from the support structure and the  
cold heat shield. The heat transfer through the aluminum  
results in a temperature difference between the warmest

position on the magnet and the refrigerator of about 2 K. This temperature difference could be reduced by constructing the shell of the magnet from thicker and heavier aluminum material.

5 Another reference paper by Richard Stevenson entitled "50 kG Gas Cooled Superconducting", September, 1973, p. 524, describes a Nb<sub>3</sub>Sn magnet operating at 13 K which is cooled by a forced flow of helium gas through the windings. This is a more complex system than a conductively cooled magnet.

10 While conductive cooling has been demonstrated with a relatively small magnet where the wire is wrapped about an aluminum shell, as discussed above, it has not proven to be effective for a superconducting magnet constructed with a large coil wrapped about aluminum shell because of the  
15 difficulty in designing a suitable light weight shell.

#### OBJECTS AND SUMMARY OF THE INVENTION

It is the object of the present invention to provide a system and method for cooling a superconducting magnet by  
20 circulating pressurized helium gas through a cooling loop which is in heat transfer relationship with the magnet to obviate the problems and limitations of the prior art systems.

It is a further object of the present invention to  
25 provide a system and method of operating the system for cooling a superconducting magnet having at least two modes of operation.

It is still a further object of the present invention to provide a system and method of operating the system for cooling a superconducting magnet by circulating pressurized helium gas through a cooling loop by natural convection.

5 It is yet another object of the present invention to provide a system and method for cooling a superconducting magnet with helium gas which is circulated through a lightweight cooling loop by natural convection so that the magnet is held at a uniform temperature.

10 In accordance with the invention, there is provided a system for convectively cooling a superconducting magnet with helium gas preferentially having a pressure of about 1 Mega Pascals (MPa) to about 3 MPa. The means for convective cooling comprises cooling loop means for circulating the  
15 helium gas by natural convection through the means for supporting the superconducting magnet whereby heat is removed from the superconducting magnet and the superconducting magnet is maintained at a substantially uniform temperature of less than about 15 K.

20 According to the invention, the cooling loop means includes refrigerator means for cooling the helium gas. The cooling loop means also includes a down comer tube below the refrigerator means for directing the helium gas, subsequent to being cooled by the refrigerator means, to a lower header  
25 tube at a location below the superconducting magnet. Further, parallel, spaced, riser tubes connect the lower header tube to an upper header tube at a location above the

superconducting magnet. The riser tubes are in thermal contact with the superconducting magnet. The upper header tube directs the helium gas, subsequent to being in thermal contact with the superconducting magnet, through the  
5 refrigeration means and into the down comer tube.

Further, in accordance with the invention, the refrigerator means include a refrigerator and a cold heat station. The cold heat station has an upper end abutted against the refrigerator and connected to the upper header  
10 tube and a lower end connected with the down comer tube. The cold heat station includes a plurality of flow channels for cooling the helium gas flowing from the upper header tube, through the flow channels, and into the down comer tube.

15 According to the invention, the system can include a by-pass header to direct a liquid cryogen into the cooling loop means for initially removing heat from the superconducting magnet to thereby lower the temperature of the superconducting magnet to its operating temperature.  
20 The cooling tubes may be arranged so that they carry some of the loop stresses generated by the magnet thereby reducing the weight of the conventional structure.

In accordance with the invention, a method of cooling a superconducting magnet comprises convectively cooling the  
25 superconducting magnet with the helium gas at an elevated pressure of about 1 MPa to about 3 MPa. The step of convectively cooling includes the step of circulating the

helium gas through a cooling loop by natural convection to remove heat from the superconducting magnet whereby the superconducting magnet is maintained at a substantially uniform temperature of less than about 15 K. The step of  
5 circulating the helium gas through the cooling loop includes the following steps. The helium gas flows down through a cold heat station having an upper end abutted against a refrigerator and a lower end connected with a down comer tube. Then, the helium gas flows through the down comer  
10 tube and into a lower header tube. Next, the helium gas flows from the lower header tube into a plurality of riser tubes in close thermal contact with the superconducting magnet where the helium gas is heated by absorbing heat from the superconducting magnet, which causes the helium gas to  
15 rise in the riser tubes by virtue of being at a lower density than the helium gas in the down comer tube. Further, the helium circulates from the riser tubes into an upper header tube and back through the cold heat station.

According to the invention, a method for cooling a  
20 superconducting magnet comprises the following steps. First, the temperature of the superconducting magnet is lowered during a first mode of operation by circulating a liquid cryogen, such as liquid nitrogen, then liquid helium, through the cooling loop to remove heat from the  
25 superconducting magnet until the temperature of the magnet is lowered to its operating temperature less than about 15 K. Then, the delivery of liquid helium is stopped and the

cooling circuit is pressurized to 1 to 3 MPa with gaseous helium. The refrigerator is then turned on and the magnet is cooled to 8 to 10 K by the convective circulation of helium gas.

5

**BRIEF DESCRIPTION OF THE DRAWINGS**

The structure, operation, and advantages of the presently preferred embodiment of the invention will become further apparent upon consideration of the following description taken in conjunction with the accompanying drawings, wherein:

10

Fig. 1 is a schematic end view of a first embodiment of a superconducting magnet structure with the convective cooling loop, in accordance with the invention;

15

Fig. 2 is a schematic side view of the superconducting magnet structure as in Fig. 1;

20

Fig. 3 is a schematic side view of a second embodiment of a superconducting magnet structure with a convective cooling loop, and additional structure for initial start-up cooling of the magnet;

Fig. 4 is a schematic side view of a third embodiment of a superconducting magnet structure with a convective cooling loop and additional cold storage structure provided in the convective cooling loop;

25

Fig. 5 is a schematic side view of a fourth embodiment of a superconducting magnet structure with a convective cooling loop and a cold gas accumulator;

Fig. 6 is a schematic end view of the fourth embodiment in accordance with the invention; and

Fig. 7 is a schematic side view of a fifth embodiment of the present invention wherein a superconducting magnet is oriented vertically and cooled by a single riser tube of a convective cooling loop.

#### DETAILED DESCRIPTION OF THE INVENTION

Referring to Figs. 1 and 2, there is shown a superconducting magnet of a system 10 with a convective cooling loop 13 for cooling a large coiled, superconducting magnet 11, in accordance with the invention. The present invention accomplishes the cooling with a unique structure and method which basically circulates pressurized helium gas through the convective cooling loop 13 using only the natural convection of the cold helium gas.

The system 10 includes a hollow support housing 12 having a cylindrical, outer surface 14, a coaxial throughbore 16, and disk shaped side walls 18 and 20, each having a circular opening therethrough corresponding to the diameter of throughbore 16. The cylindrically shaped, superconducting magnet 11 includes a coil wrapped around a support structure (not explicitly shown) and disposed coaxially about the throughbore 16. An exemplary superconducting magnet 11 is about 760 millimeters (mm) in diameter and has a length of about 500 mm.

A principle feature of this invention is the construction and method by which the magnet 11 is cooled by

the natural convection of a cold helium gas flowing through the convective cooling loop 13. Convective cooling loop 13 includes a conventional, closed cycle refrigerator 24 that is positioned above the magnet 11 and secured to or next to the support housing 12 by any conventional means.

Refrigerator 24 preferably has a capacity, i.e., refrigeration load, of about 0.4 Watts (W) at about 8 K. The refrigerator 24 can be a Gifford-McMahon or a Stirling type refrigerator with a two or three stage expander 26. The space 28 about the upper part of the expander 26 is generally at room temperature. The downstream end of the refrigerator 24 is abutted against a cold heat station 30 having inlet and outlet sections 32 and 34, respectively. Cold heat station 30 includes a plurality of flow channels 36 that are made of a thermally conductive material such as copper, and are open at their upper and lower ends to allow helium gas to flow freely through the flow channels 36 between inlet and outlet sections 32 and 34, as discussed hereinafter.

The outlet section 34 of the cold heat station 30 is connected to an upper end 42 of a down comer tube 44, another part of convective cooling loop 13. Down comer tube 44 is positioned in spaced relationship from one end of the magnet 11 and extends downward from the cold heat station 30 to a location below the magnet 11. Further, down comer tube 44 has a radius of curvature, as shown in Fig. 1, which is substantially the same as that of magnet 11. The lower end

46 of down comer tube 44 is connected to an inlet 48 of a first section 50 of a lower header tube 52, a section of convective cooling loop 13 which extends perpendicularly outward from down comer tube 44 and adjacent the bottom of the magnet 11 to an outlet 54 at the opposite end thereof. Outlet 54 is connected via a second section of tube 58 of lower header tube 52 to an inlet 62 of a third section 64 of the lower header tube 52. Third section 64 extends substantially parallel to first section 52 and projects back along the bottom of magnet 11 to a closed end 66 near the down comer tube 44.

Convective cooling loop 13 further includes a plurality of spaced, cylindrically shaped, riser tubes 68 each having two curved sections 68A and 68B which together surround and are in close thermal contact with the magnet 11. As shown in Fig. 1, each of the curved sections 68A and 68B is connected at its lower end 70A and 70B, respectively, to the third section 64 of lower header tube 52 and projects upward so that the upper ends 72A and 72B, respectively, are connected to an upper header tube 74 having a closed first end 76 and a cylindrically shaped second end 78 which is about an output end of the refrigerator 24 and in flow connection with the inlet section 32 of the cold heat station 20. The plurality of riser tubes 68, typically numbering between eight and twelve, are in close thermal contact with the wire coil of the magnet 11 and at other locations where heat is being removed, and form multiple,

parallel paths for the helium gas to flow about the  
superconducting magnet 11. An advantage of locating curved  
sections 68A and 68B of the riser tube 68 around the outer  
periphery of magnet 11 is that the riser tubes provide an  
5 additional beneficial function of restraining magnet 11  
which has a tendency to expand radially outward under the  
influence of the magnetic field. While curved sections 68A  
and 68B of the riser tubes 68 are shown as located radially  
outward from magnet 11, it is also within the scope of the  
10 invention to locate the curved sections 68A and 68B within  
the inner cylindrical bore of the magnet 11, if desired.

An aspect of the invention is that the enclosed support  
housing 12 is insulated, with means such as vacuum  
insulation, so that neither heat from the surroundings nor  
15 generated within housing 12 is transferred through the  
housing 12 to the down comer tube 44, or upper and lower  
header tubes 74 and 52.

To better understand the present invention, a  
discussion of the theory and method of operation for cooling  
20 the superconducting magnet 11 with a convective cooling  
cycle and apparatus follows. To initiate the convective  
cooling cycle, helium gas, preferably at an elevated  
pressure of between about 1 MPa and 3 MPa, is cooled by  
thermal contact with a downstream section of the  
25 refrigerator 24 as the helium gas flows in the convective  
cooling loop 13, down through the heat station 30 and into  
the top 42 of the down comer tube 44. Down comer tube 44

depends below refrigerator 24 and is thermally isolated within the enclosed support housing 12 so that the cold helium gas in down comer tube 44 is at essentially the same temperature as at the refrigerator 24. The cold helium gas flows downward through the down comer tube 44 because of its higher density as compared with the gas density downstream in the portion of the cooling circuit where the gas is warmer, i.e., in the riser tubes 68 and in the upper header 74. The cold helium gas then flows into lower header tube 52, which is also thermally isolated, and is distributed to the plurality of small diameter riser tubes 68. Continuing through the convective cooling loop 13 and the convective cycle, the helium gas is heated as it flows upward through the riser tubes 68 by absorbing heat from the superconducting magnet 11 and other heat sources (not shown) so as to maintain superconducting magnet 11 at an operating temperature of less than about 15 K. This heat absorption causes an increase in the temperature of the helium gas and a reduction in its density by expansion. The reduction in density of the helium gas causes it to rise into the upper header tube 74 (chimney effect) because the gas in the risers is now at a lower density than the helium gas in both the down comer tube 44 and lower header tube 52 and is naturally driven upwards by the flow of higher density helium gas through the convective cooling loop 13. To complete the cooling cycle, the warmer, lower density helium gas travels through the upper header tube 74, across the

downstream end of refrigerator 24 across the heat station 30 where it is cooled, and down into the down comer tube 44 to start the cooling cycle again.

An important aspect of the invention relates to the size selection of the tubes forming the closed flow path for the flow of helium gas through the convective cooling loop 13. That is, a uniform flow path is constructed to insure an equal mass flow rate of helium gas through each portion of convective cooling loop 13. That is, an equal mass of pressurized helium gas flows through a first portion of the convective cooling loop 13 including down comer tube 44 and lower header tube 52 where the helium gas is essentially at a constant temperature equal to that of refrigerator 24 and through a second portion of the convective cooling loop 13 including each of the riser tubes 68 and upper header tube 74 where the gas is at a relatively warmer temperature, as compared to the gas in the first portion. Conceptually, the size of the tubes can be changed to compensate for the required path length. For example, by selecting smaller tubes, there is a more restricted flow and less cooling. Conversely, with wider tubes, there is less restricted flow and more cooling.

In an exemplary system of the type illustrated in Figs. 1 and 2, the helium gas flows freely down into a down comer tube 44 having a 8.3 millimeter (mm) internal diameter (ID) and into lower header tube 52 having the same diameter. Note that lower header tube 52 is bent back on itself such

that the length of each flow path is the same so that the flow through each riser tube 68 is the same. Riser tubes 68 have a 2.4 mm ID and the upper header 74 also has an 8.3 mm ID in the present example.

5           An important aspect of the invention is that the coolant medium, preferably cold helium gas, inherently circulates through the convective cooling loop 13 in the hollow support housing 12 of the system 10 by means of natural convection (chimney effect) of the cold helium gas.

10          Natural convection is advantageous because it results in the helium gas being circulated at a more uniform temperature through the convective cooling loop 13 in a relatively lightweight, support housing 12. Also with natural convection, there is no need for additional components such

15          as a pump, which adds cost and weight to the overall cooling system.

          To further increase the effective cooling of the support housing 12, it is desirable for the helium gas in the convective cooling loop 13 to be at an elevated pressure

20          of between about 1 MPa and about 3 MPa. This aspect of the invention can be understood as follows.

          Referring to Fig. 2, helium gas circulates in the convective cooling loop 13 through the housing 12 because of the total pressure difference between upper header tube 74

25          and lower header tube 52. This total pressure difference is equal to the difference between the density of the helium gas in lower header tube 52 and the helium gas in upper

header tube 74 times the height. Since the difference in densities between the helium gas in these two portions of the convective cooling loop 13 increases almost linearly with pressure (based on helium gas being almost an ideal gas where the density is directly proportional to the pressure), at an elevated pressure the increased density of the helium gas leads to an increased pressure differential. The heat, which is transported by the mass flow, equals the mass flow rate times the specific heat of helium gas times the temperature change of the helium gas. That is, with a higher pressure, there is a higher rate of mass circulation. This leads to the change in temperature being approximately equal to one divided by the pressure difference. In effect, by increasing the pressure of the gas in convective cooling loop 13, there is a reduced temperature change. This is important because ideally, the superconducting magnet 11 is kept at a uniform temperature of below about 15 K while heat is being extracted. Therefore, the change in temperature is kept as small as possible with the heat extraction being as large as possible. Thus, the higher pressure leads to extracting the same amount of heat with a lower temperature differential.

In the present example, the helium gas in the down comer tube 44 is at a temperature of 8 K and at a pressure of 2 MPa. This results in a density of 126.2 grams per liter (g/L). The helium gas traveling through riser tubes 68 warms to a temperature of 8.3 K and a reduced density of

121.65 g/L within upper header tube 74. Assuming a constant rate of warming in the riser tubes 68, the pressure difference available to drive helium gas around the convective cooling loop is equal to the difference in density times the height divided by 2, a value of 17.2 Pa for this example. This is equal to the pressure drop in the cooling loop 13. The division by two is because of the assumption of an average temperature change. The mass flow rate of .30 grams per second absorbs .4 W in warming from 8.0 K to 8.3 K. The actual procedure for calculating the temperature rise, circulation rate, and pressure drop is an iterative one in which several values of temperature rise are assumed and the corresponding mass flow rate and driving pressure difference are calculated. The mass flow rate is then used to calculate the pressure drop. The iteration continues until the driving pressure difference equals the pressure drop.

Another advantage of increasing the pressure of the helium gas is the reduction of both the velocity of the gas flowing in the circulation loop and the pressure drop. These factors permit the use of smaller diameter tubes in cooling loop 13. Assuming the tubes to be aluminum in this example, they weigh about .2 kg. A similar conductive cooling shell operating under the principles of the prior art and constructed of high purity aluminum, would also have a .3 K temperature difference but would weigh about .6 kg.

Moreover, if that same cooling shell were made of the more common 6063 grade of aluminum, it would weigh about 25 kg.

The convective cooling loop 13 of the present invention has two other distinct advantages associated with the effect of a power interruption on the magnet 11, when compared with prior art conductive cooling systems. Assuming that the superconducting magnet 11 is allowed to warm from 8 K to 10 K before it goes normal, then it can continue to operate for 3.5 seconds after cooling is stopped if the conductive shell is .6 kg of Al. The time of operation after cooling has stopped increases to 144 seconds if the aluminum shell weighs 25 kg. When power is interrupted, the refrigerator 24 starts to warm up and the conductive losses that are internal to the expander 26 causes heat to flow toward the cold downstream end of refrigerator 24. As a result, the cold heat station 30 initially warms up when the refrigerator 24 is restarted, and then cools back to its normal operating temperature.

A second advantage which the convectively cooled loop 13 provides is that the heat generated by restarting the refrigerator 24 is not transferred to the superconducting magnet 11 because the convective loop 13 acts as a thermal switch and only transfers heat upward toward the upper header 74 and not downward toward the lower header 52. That is, since the warmer helium gas near the refrigerator 24 has a lower density than the colder helium gas which is in the down comer tube 44 and the lower header tube 52, there is no

pressure difference available to drive the warm helium gas towards the colder part of the cooler loop 13, i.e., down into the down comer tube 44 and lower header tube 52. This thermal disconnect which is an inherent part of system 10 is important because it insures that the hot and cold gases do not mix and thereby reduce the amount of circulation through the coolant loop 13.

While the above described apparatus and method of the invention provides a very effective means of convectively cooling a superconducting magnet 11, it is also within the terms of the invention to provide an alternative embodiment, as illustrated in Fig. 3, wherein the system 10 has a first mode of operation to quickly bring the superconducting magnet 11 to its operating temperature and a second mode of operation to maintain the magnet 11 at an optimum operating temperature.

Referring to Fig. 3, there is shown a schematic of a lightweight, convective cooling loop 13' and system 10', in accordance with the second embodiment, which has a first mode of operation to quickly and effectively bring the magnet 11' down to its operating temperature and a second mode to maintain the magnet 11 at an optimum operating temperature. Throughout the specification, primed, double primed and triple primed reference numerals represent structural elements which are substantially identical to structural elements represented by the same unprimed reference numerals.

The present invention accomplishes these two modes of cooling the superconducting magnet 11' in the system 10' with a unique structure and method by which liquid cryogenics, such as liquid nitrogen at a temperature of about 80 K and then liquid helium at 4.2K, are initially introduced into the down comer tube 100 through a by-pass header 101 which includes an inlet tube 102. The liquid cryogenics flow through the convective cooling loop 13' including the down comer tube 100, a lower header tube 52', riser tubes 68', upper header tube 74', into a closed cycle refrigerator 24', through cold heat station 30', into a connector tube 104 having its downstream end connected to the down comer tube 100. As the liquid cryogenics vaporize and circulate through the convective cooling loop 13', the warmer, returning gas which now has a lower density, cannot mix with the entering higher density, fluid and therefore is forced to flow upward and out of an exhaust tube 106 of the by-pass header 101 which can be concentrically positioned about the inlet tube 102.

After the liquid helium lowers the temperature of the magnet 11' down to within its operating range of less than 15 K, the flow of liquid helium is turned off. A second high pressure, helium gas is then introduced into the convective cooling loop 13' through the tube 106, the refrigerator is turned on and the system operates in accordance with the principles previously discussed with

regard to the first embodiment, as illustrated in Figs. 1 and 2.

While the above described apparatus and method of the invention provides a very effective means of convectively cooling superconducting magnets 11 and 11', it is also within the terms of the invention to provide an alternative embodiment, as illustrated in Fig. 4, wherein there is shown a schematic side view of a third embodiment of a superconducting magnet structure 10" with a convective cooling loop 13" and an additional cold storage structure 120 provided in the convective cooling loop 13" to maintain the cold temperature in loop 13" for a longer period of time in the event the cooling system malfunctions. The cold storage structure 120 can simply be provided by increasing the size of a section of 122 of the down comer tube 44".

While the above described apparatus and method of the invention provide a very effective means of providing additional cooling for a superconducting magnet 11", it is also within the scope of the invention to provide an alternative embodiment, as illustrated in Figs. 5 and 6, wherein a fourth embodiment of a superconducting magnet structure 10''' with a convective cooling loop 130 provides still more additional cooling as compared with the embodiment of Figs. 4 and 5. The down comer tube 132 is now positioned below and includes a horizontal section 134 below the upper header tube 74'''. At the end of the horizontal section 134, a vertical section 136 extends downward away

from the cold heat station 30''' to a location below the magnet 11'''. Further, the vertical section 136 of the down comer tube 132 has a radius of curvature, as shown in Fig. 6, which is substantially the same as that of magnet 11'''.  
5 The lower end 138 of the down comer tube 136 is connected to an inlet 140 of a lower header tube 142 which in turn is adjacent the bottom of the magnet 11'''. Convective cooling loop 130 further includes a plurality of spaced, cylindrically shaped, riser tubes 68''' which surround and  
10 are in close thermal contact with the magnet 11'''. As shown in Figs. 5 and 6, each of the riser tubes 68''' has curved sections 68A''' and 68B''', which are connected at their lower ends to the lower header tube 142 and project upward so that their upper ends are connected to the upper  
15 header tube 74'''. The advantage of the fourth embodiment, is that in the case of a power outage, an inventory of cold gas remains in the horizontal section 134 of the down comer tube 132.

While the above described apparatus and method of the  
20 invention provides a very effective means of convectively cooling a superconducting magnet 11, it is also within the scope of the invention to provide an alternative embodiment, as illustrated in Fig. 7, wherein a fifth embodiment of the present invention provides a superconducting magnet 150,  
25 which is substantially the same as magnet 11 and oriented vertically. Magnet 150 is cooled by a single riser tube 152 of a convective cooling loop 154. Cooling loop 154 includes

a conventional, closed cycle refrigerator 156, substantially identical to the closed cycle refrigerator 24, that is positioned adjacent to the magnet 150. The downstream end of the refrigerator 156 has a cold heat station 30''' having inlet and outlet sections 158 and 160, respectively.

The outlet section 160 of cold heat station 30 is connected to an upper end of a down comer tube 162 of the convective cooling loop 154. Down comer tube 162 is positioned in spaced relationship to one side of the magnet 150 and extends downward from the cold heat station 30 to a location below the magnet 150. The lower end of the down comer tube 162 is connected to a lower header tube 164, a section of convective cooling loop 154, which extends horizontally outward from the down comer tube 162 and below the bottom of the magnet 150. Lower header tube 164 is connected to the riser tube 152 which extends vertically upward and is in close thermal contact with the magnet 150. An upper header 168 connects the upper end of the tube 152 to the inlet section 158 of cold heat station 30'''.

In operation, the heat generated by the magnet 150 flows radially outward through a light aluminum shell disposed about the magnet 150. Since the magnet is oriented vertically, it can be cooled by a single riser tube 152.

It is apparent that there has been provided in accordance with this invention apparatus and methods for cooling a superconducting magnet, by circulating a pressurized helium gas through a cooling loop by natural

convection, that satisfy the objects, means and advantages set forth hereinbefore. In addition, apparatus and methods have been provided for quickly and effectively cooling the superconducting magnet down to operating temperature and to  
5 maintain the low operating temperature after malfunction of the system.

While the invention has been described in combination with embodiments thereof, it is evident that many alternatives, modifications, and variations will be apparent  
10 to those skilled in the art in light of the foregoing teachings. Accordingly, the invention is intended to embrace all such alternatives, modifications and variations as fall within the spirit and scope of the appended claims.

**We claim:**

1. A method of cooling a superconducting magnet,  
5 using a cooling loop including a refrigerator, down comer  
tube, at least one riser tube, a cold heat station, an upper  
header tube and a lower header tube, comprising the steps:

(a) circulating cryogenic gas through a cold heat  
station having an upper end thermally connected to said  
10 refrigerator for cooling said gas, said refrigerator having  
a lower end connected with said down comer tube;

(b) circulating said helium gas from said down  
comer tube through said lower header tube at a level below  
said superconducting magnet and into said at least one riser  
15 tube that is in close thermal contact with said  
superconductor magnet, said helium gas in said at least one  
riser tube absorbing heat from said superconducting magnet  
and rising by natural convection; and

(c) circulating said cryogenic gas from said at  
20 least one riser tube into said upper header tube that leads  
back to said upper end of said cold heat station,

said circulating in steps (a)-(c) being the result  
of natural convection induced by heat exchange in said at  
least one riser tube.

25 2. A method of cooling a superconducting magnet, as  
in claim 1, further comprising steps preceding step (a):

lowering the temperature of said superconducting  
magnet to an operating temperature during a first mode of

cooling operation, said first mode of cooling operation including circulation of at least one liquid cryogen through said cooling loop to remove heat from said superconducting magnet until the temperature of said magnet is lowered to  
5 said operating temperature;

stopping circulation of said at least one liquid cryogen and circulating said cryogenic gas, having a temperature less than said operating temperature, through said cooling loop to maintain said superconducting magnet  
10 substantially uniformly at said operating temperature.

3. A method as in claim 1, wherein said cryogenic gas is helium.

4. A system for cooling a superconducting magnet, comprising:

15 refrigerator means for cooling a cryogenic gas to a temperature below an operating temperature of said magnet;

a down comer tube connected to said refrigerator means for directing said cryogenic gas, after being cooled by said refrigerator means, to a lower header tube at a  
20 location below said superconducting magnet;

at least one riser tube for flow of said cryogenic gas therein connecting said lower header tube to an upper header tube positioned at a location generally above said superconducting magnet, said riser tube being in thermal  
25 contact with said superconducting magnet to cool said magnet by warming and expanding said cryogenic gas; and

said upper header tube being connected to an inlet of said refrigerator means and directing said warmed cryogenic gas to said refrigerator means for cooling, and again into said down comer tube,

5 movement of said cryogenic gas being effected by natural convection.

5. A system as in claim 4, wherein said refrigerator means includes a refrigerator and a cold heat station, said cold heat station having an upper end against said refrigerator and connected to said upper header tube, and a lower end of said cold heat station being connected with said down comer tube, and a plurality of flow channels in said cold heat station cooled by said refrigerator for cooling said cryogenic gas flowing from said upper header tube through said flow channels, and then into said down comer tube.

15 6. A system as in claim 5, wherein said refrigerator is a Gifford-McMahon or Stirling type refrigerator, and said cryogenic gas is helium.

20 7. A system as in claim 4, wherein said cooling loop means is constructed of more than one tube, said tubes being sized so that mass flow rates of said cryogenic gas in said riser tubes are approximately uniform.

25 8. A system as in claim 4, wherein there are a plurality of said riser tubes, said tubes providing multiple, parallel paths for said cryogenic gas to flow through said superconducting magnet.

9. A system as in claim 4, further including a by-pass header for directing a liquid cryogen into said cooling loop means for initially removing heat from said superconducting magnet to lower the temperature of said superconducting magnet from an elevated level to said  
5 operating temperature of said magnet.

10. A system as in claim 4, wherein said superconducting magnet is vertically oriented, said down comer tube being disposed adjacent said magnet and a single  
10 riser tube extending vertically through said superconducting magnet to maintain a substantially uniform temperature within said superconducting magnet.

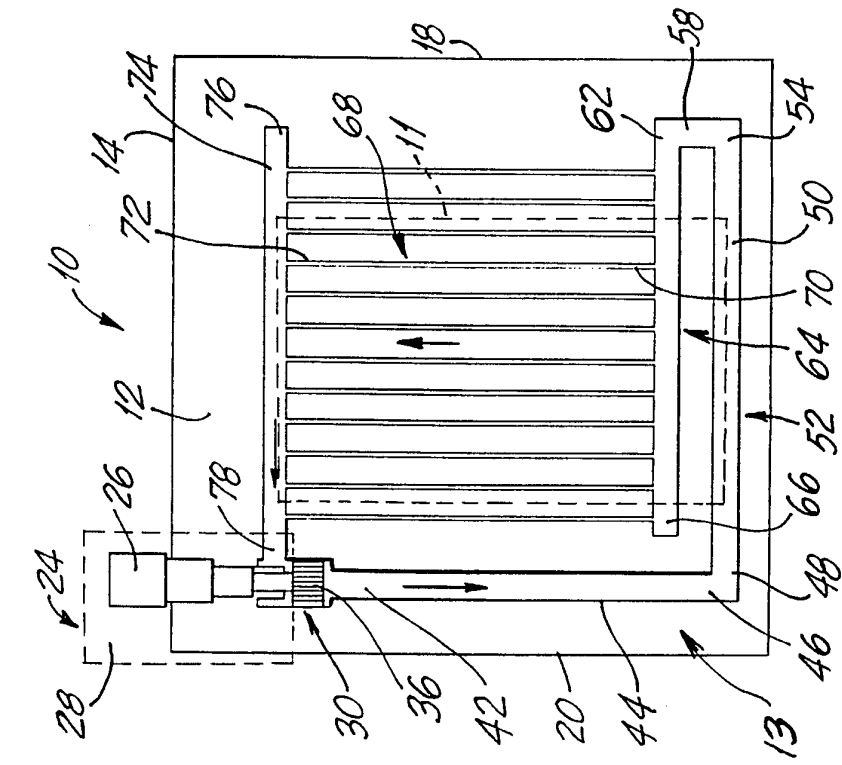


FIG. 1

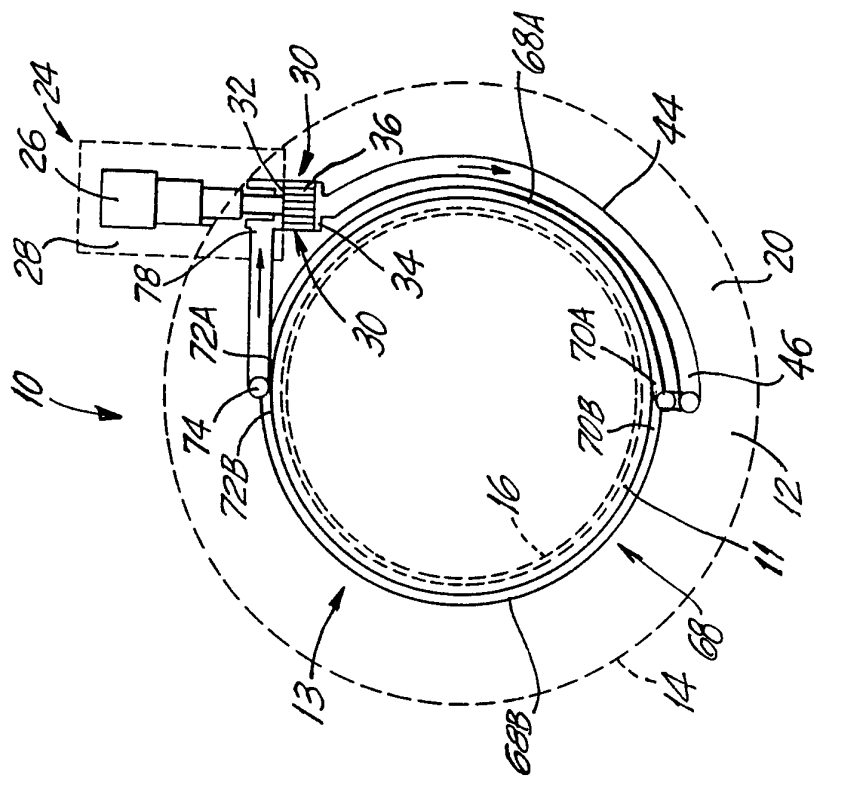


FIG. 2

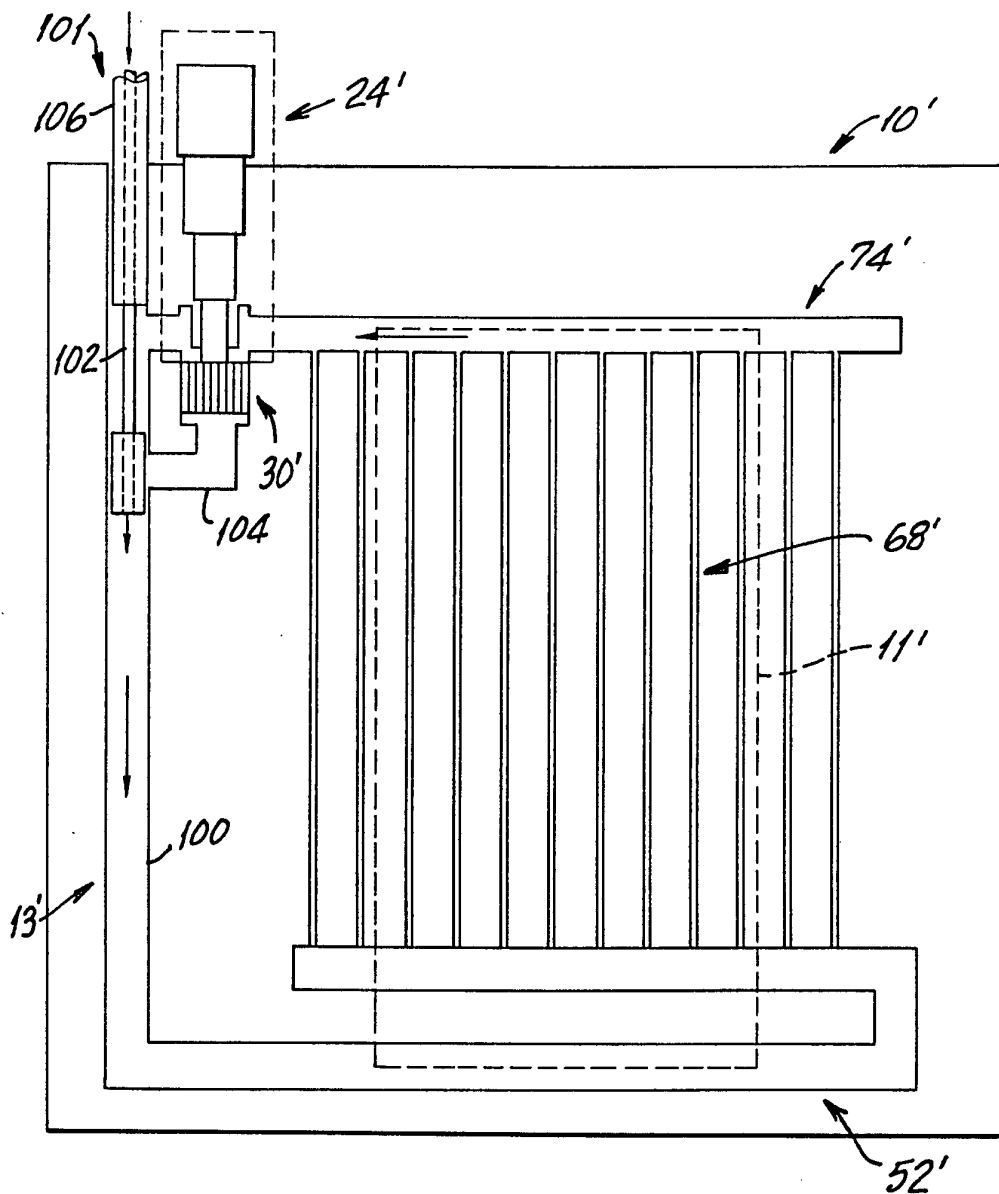


FIG. 3

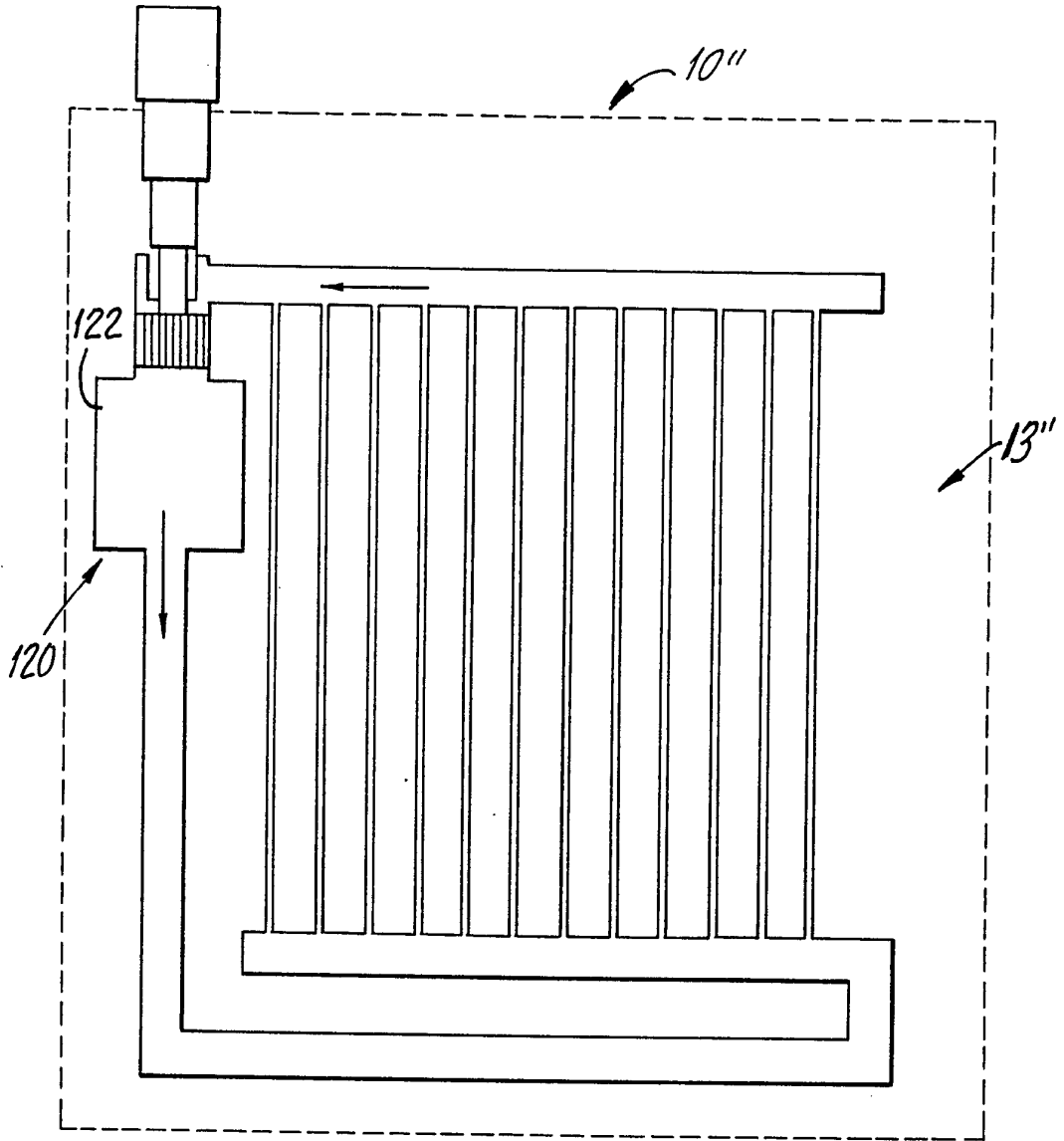


FIG. 4

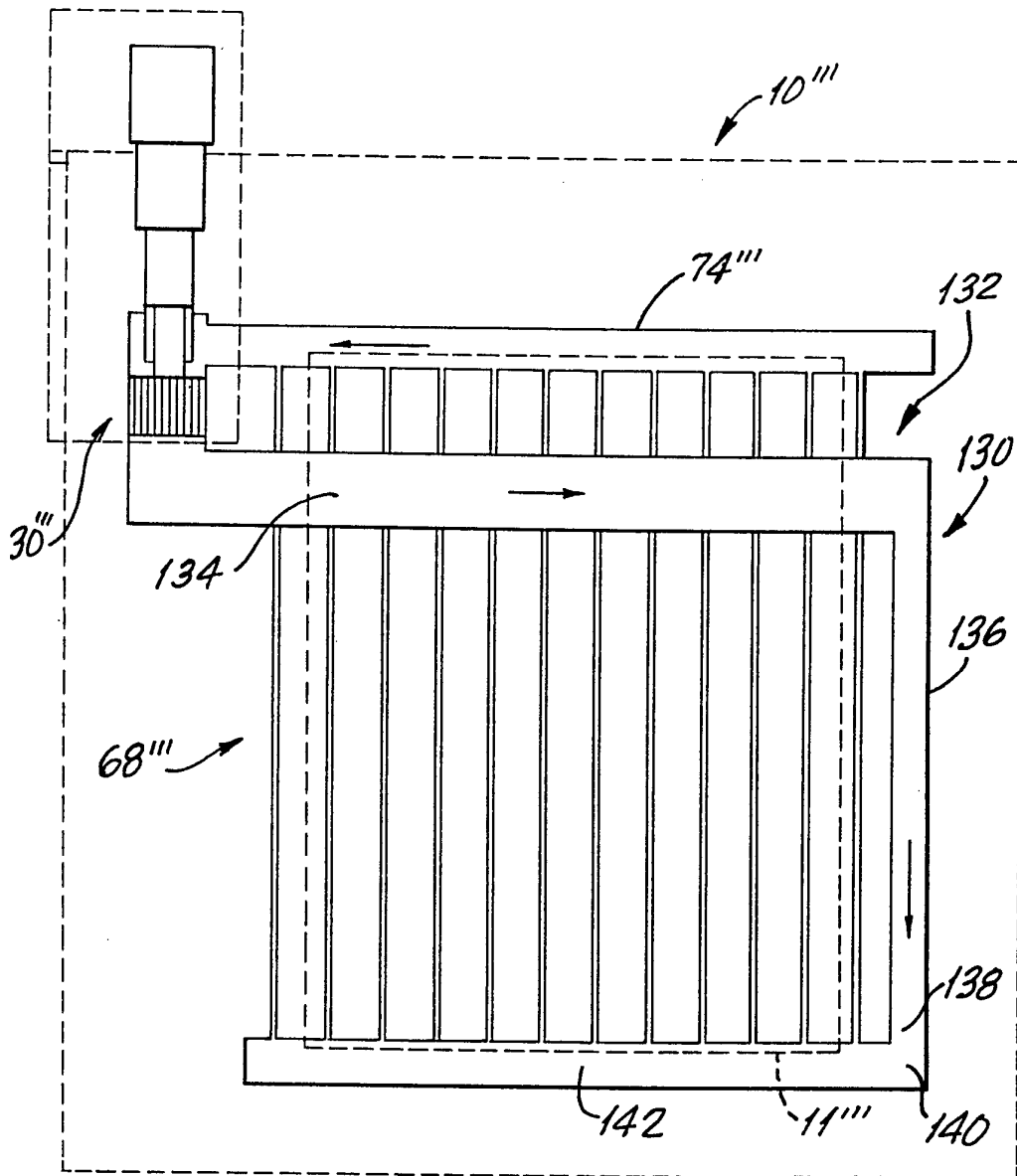


FIG. 5

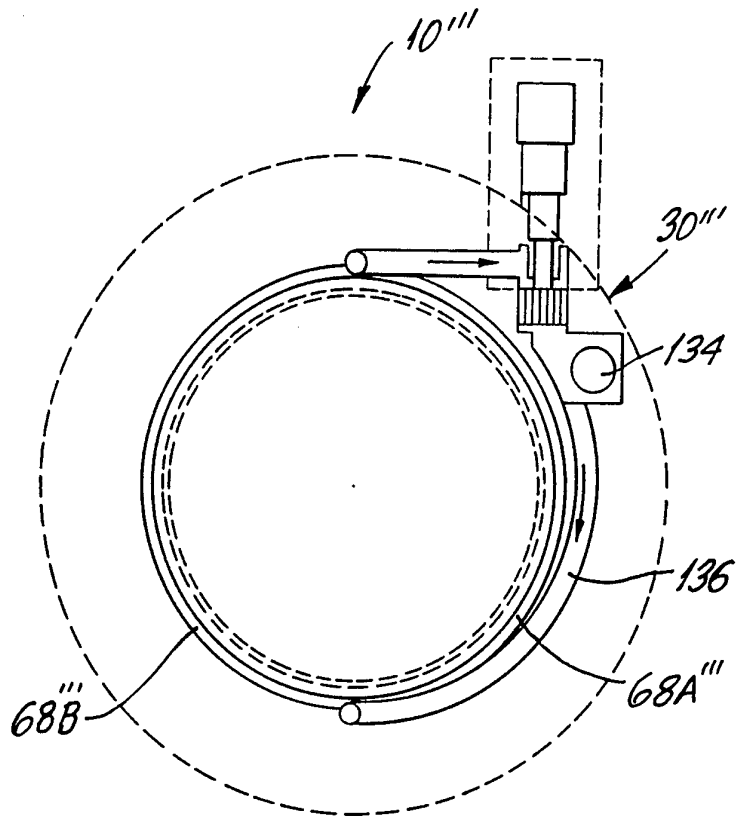


FIG. 6

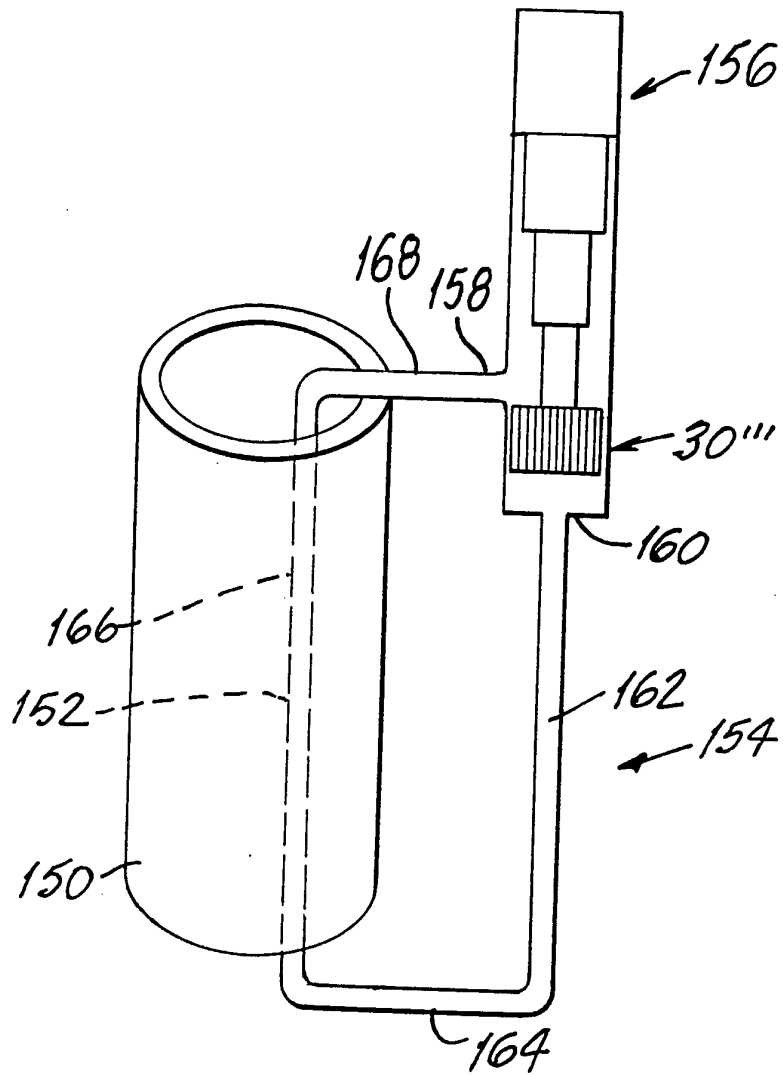
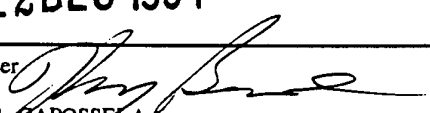


FIG. 7

INTERNATIONAL SEARCH REPORT

International application No.  
PCT/US94/10808

<b>A. CLASSIFICATION OF SUBJECT MATTER</b> IPC(5) :F25B 19/00; F25D 17/02 US CL :62/51.1, 434 According to International Patent Classification (IPC) or to both national classification and IPC		
<b>B. FIELDS SEARCHED</b> Minimum documentation searched (classification system followed by classification symbols) U.S. : 62/51.1, 434 Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)		
<b>C. DOCUMENTS CONSIDERED TO BE RELEVANT</b>		
Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
Y	US, A, 4,578,962 (DUSTMANN) 1 APRIL 1986 SEE THE ENTIRE DOCUMENT	1 - 10
A	NAVAL ENGINEERS JOURNAL, MAY 1992, MICHAEL GOLDA ET AL, "APPLICATIONS OF SUPERCONDUCTIVITY TO VERY SHALLOW WATER MINE SWEEPING", PAGES 53 - 64	1 - 10
A	7TH INTERNATIONAL CRYOCOOLER CONFERENCE, NOV., 1992, GEOFFREY GREEN ET AL, "CONDUCTIVELY COOLING A SMALL Nb <sub>3</sub> Sn COIL WITH A CRYOCOOLER" SEE ENTIRE DOCUMENT.	1 - 10
Y	CRYOGENICS, SEPT 1973, R. STEVENSON, "KG GAS COOLED SUPERCONDUCTING SOLENOID OPERATED AT 13K", PP 524- 525	1 - 10
<input type="checkbox"/> Further documents are listed in the continuation of Box C. <input type="checkbox"/> See patent family annex.		
* "A"	Special categories of cited documents: document defining the general state of the art which is not considered to be of particular relevance	"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention
"E"	earlier document published on or after the international filing date	"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone
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"O"	document referring to an oral disclosure, use, exhibition or other means	"&" document member of the same patent family
"P"	document published prior to the international filing date but later than the priority date claimed	
Date of the actual completion of the international search 28 NOVEMBER 1994		Date of mailing of the international search report <b>12 DEC 1994</b>
Name and mailing address of the ISA/US Commissioner of Patents and Trademarks Box PCT Washington, D.C. 20231 Facsimile No. (703) 305-3230		Authorized officer  RONALD C. CAPOSSELA Telephone No. (703)-308-0688