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(54) Load bearing means in cryostat systems

(57) The various components, namely the different vessels contained within each other for housing the superconducting magnet, or the liquid comprising a cryostat or storage tank for cryogenic liquids are generally either suspended or supported by each other. Thus, a support/suspension system has various tasks, besides carrying the magnet or shield loads, it also keeps the position of the cold mass during shipping and also fixes the internal clearances between the radiation shields during installation as well as repeated cooldown. The various constraints put onto these suspension systems result in an increased input of heat into the cryostat depending on the overall size of cryostat and superconducting magnet system.

Various parts of the cryogenic components such as radiation shields have to be cooled, either by means of using liquids or by using forced convection cooling, or by other external means such as conventional GM-cryocoolers.

The present invention therefore provides a new type of support or suspension system which combines the two functions mentioned above, namely supporting or suspending and cooling, and applies these to the pulse tube cooler. The pulse tubes (22-38) could be arranged in series or in parallel, could be single or multistaged or feature an additional liquefying stage and suspend or support a superconducting magnet or HTS conductor within a cryostat. The pulse tube being either a suspension or support member could also simultaneously cool the shields 26 connected to it and at the same time carry shield or magnet loads.

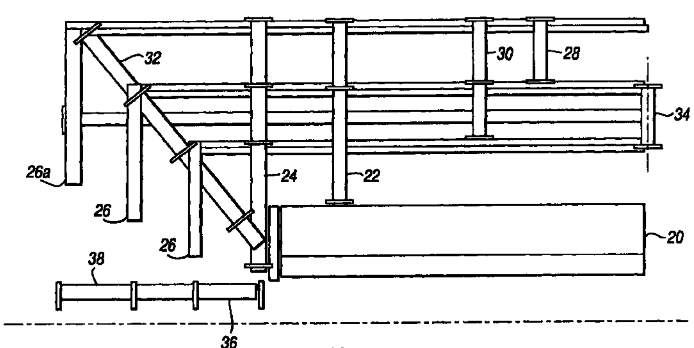

Fig.2

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Description

[0001] The present invention relates to a load bearing means for use in MRI or similar cryostat systems as support or suspension elements.

[0002] In such systems the various radiation shields or vessels in a cryostat are cooled by means of inserting a GM-type or other type of piston-driven cryocooler and by connecting its respective cooling stages by means of thermal links located within the cryostat.

[0003] Furthermore the different stages of the cryocooler in the cryostat are usually contacted to the shields by means of copper braids or other contacting means and by a sleeve system which makes it possible to maintain and replace the cold head.

[0004] Directly connecting a common cooler to the internal shields of a cryostat was not feasible up to now as this would transmit mechanical noise and vibrations, and this would affect the quality of the image. The image distortion might make its clinical interpretation questionable.

[0005] In contrast to piston-driven coolers, a pulse tube refrigerator consists of a regenerator and a pulse tube for each refrigeration stage, and these items may be arranged in many different configurations, e.g. as concentric tubes, or spaced apart with different orientations.

[0006] The freedom in design of the pulse tube refrigerator offers new opportunities by allowing the tubes to be placed at various locations within the cryostat, the dimension of the tubes being adjusted to suit the clearances within the cryostat.

[0007] Because pulse tube refrigerators have no moving parts, their service and maintenance is much reduced compared with the present-day piston-driven coolers. If pulse tube refrigerators were to replace, or be retrofitted instead of piston-drive coolers, the mean time between maintenance could be greatly increased.

[0008] No moving parts, apart from the travelling pressure wave down the tube, means an induced level of vibrations transmitted to the internal cryostat structure which is of several orders of magnitude lower than with piston-driven coolers. Thus it is possible to make use of the whole spectrum of directly contacting or coupling the radiation shields to a cooler, such as soldering, bolting, screwing, clamping, gluing, welding, sliding, pressing, or by means of shrink-fitting or spring-loading or by mechanical means by, for example, using a lever-actuated contacting system.

[0009] An aim of the present invention is to provide a pulse tube or tubes refrigerator which can also be used as a load bearing element.

[0010] With a great degree of freedom in design, the pulse tube or tubes and the various stages as well as the regenerator tube or tubes can act as structural members or can be incorporated in structural members. It is also a well-established fact that small neck tubes of cryostats, usually of stainless steel and with diameters as small as 30 to 50 mm and a wall thickness of 0.25 to 0.8mm, can carry shield and magnet loads of more than 1500 kg. In the same way, both the thin-walled pulse tube and the regenerator tube may be used as a reinforced suspension element to carry higher loads than have been possible before.

[0011] According to the present invention, there is provided load bearing means comprising at least one pulse tube refrigerator including a pulse tube and at least one regenerator tube acting as at least one support or suspension member, in an MRI system.

[0012] The pulse tube refrigerator may be an integral part of the support member.

[0013] The pulse tube refrigerator may be a multi-stage pulse tube refrigerator.

[0014] Single and multi-stage pulse tube refrigerators may be connected in series or in parallel.

[0015] The pulse tube and the regenerator tube may take different geometric shapes.

[0016] When a pulse tube refrigerator is used as a suspension member it may support the thermal shields or the superconducting magnet system.

[0017] When the pulse tube refrigerator is incorporated as part of a support member, the support member may be of the Heim/SSC/Hartwig family or Marsing type.

[0018] Various embodiments of the present invention will now be described with reference to the accompanying drawings, in which:

Figure 1 shows a cooler arrangement according to the present invention,
Figure 2 shows various ways in which pulse tube refrigerators are used as suspension elements,
Figure 2a shows an arrangement of pulse and regenerator tubes in parallel,
Figure 3 shows a pulse tube refrigerator incorporated into a support column,
Figure 4 shows a cut-through section of a support column including a pulse tube refrigerator,
Figure 5 shows a cryogenic stand, including a support element for housing a pulse tube refrigerator,
Figures 6a and 6b show a pulse tube refrigerator attached to a wet or dry open or standard magnet system respectively,
Figure 7 shows a pulse tube refrigerator having first and second stages in parallel,
Figure 8 shows a pulse tube refrigerator acting as a suspension member for a magnet and thermal shield assembly, and,
Figures 9 and 10 show a side and top view of load bearing twin-type pulse tube arrangement for various MRI systems.

[0019] Figure 1 shows a cooler arrangement in accordance with the present invention. There are two radiation shields, 2, 4, at 20K and 80K respectively, and an outer vacuum case 6 at 300K. There are several coolers 8, 10, 12, 16 arranged in parallel and a solenoid valve box 18 being located at a sufficient distance away from the magnet or being magnetically shielded by magnetic shields, so that the solenoid valve system can be serviced without having to reduce the magnetic field. The neck tube opening is designated 19.

[0020] The following Figures 2 to 7 show some arrangements of pulse tube load bearing means as applicable to various standard and open system cryostats for MRI as well as interventional MRI. Each of the systems has different advantages, depending on the application.

[0021] In a two-stage cryocooler system typically four tubes comprising a cooler would be available for carrying shield and magnet or other loads.

[0022] The design of the pulse tube refrigerator makes it possible to reinforce any of the tubes by wrapping layers of, for example, epoxy impregnated cloth around the tube circumference. This will give the tube additional strength depending on the amount and type of reinforcement applied. Most conveniently the tube could be heated to cure the resin. The reinforcement could be done on either or both of the pulse tube or regenerator tube.

[0023] The PTR-tube outer surface could be further reinforced by the use of stiffeners or ribs applied both in axial or radial directions, depending on the various design constraints.

[0024] Even existing structural suspension and support members, well known in the aerospace industry could be used as a pulse tube refrigerator housing.

[0025] Different suspension and support geometrics could be more suited to different cryostat designs: circular or conical shapes could have their ends threaded so as to be easily connected to a cryogenic structure or magnet former. Other configurations might be advantageous, e.g. annular, angled coil-shaped, distributing i.e. branching out, bent-shaped, in the form of a tensile testing probe, or being incorporated into a standard fork head design.

[0026] Figure 2 shows various ways in which pulse tube refrigerators can be used as suspension elements.

[0027] Figure 2 shows various configurations of simultaneous support and cooling using one, two, or three stage pulse tube refrigerators as follows:

[0028] Single stage pulse tube refrigerators 28 and 34 respectively cool and support the outer shield 26 from the outer vacuum case 26a, and the inner shield 26 from the outer shield 26

[0029] Two stage pulse tube refrigerators 30, 22, and 38 respectively cool and support the two shields from the outer vacuum case; cool and support the outer shield and the helium vessel from the outer vacuum case; cool and support the two shields and the helium vessel from the outer vacuum case, but in this case the refrigerator is extended by a thermally insulating section 36, e.g. glass reinforced epoxy resin, to support the helium vessel. The three stage pulse tube refrigerators 24, 32 cool and support the two shields and the helium vessel from the outer vacuum case.

[0030] Because of the option of being able to directly cool the shields there is no need to provide a thermal interface sleeve in the event of having to change the cryocooler, as no maintenance of the cooler is required.

[0031] Whilst Figure 2 shows the principle of the pulse tube suspension system, the suspension system could be made of concentric design or in parallel. Figure 2a shows the pulse and regenerator tubes in parallel and elongated with a tube to support the helium vessel and to keep the clearance between the radiation shields.

[0032] A two-stage, two legged pulse tube refrigerator for carrying shield loads is shown in Figure 2a, which is parallel with the horizontal cryostat axis 23. Also shown is a dual stage pulse tube refrigerator 32a which supports the loads of the thermal shields 26 from the outer vacuum case 26a.

[0033] Referring to Figure 3, the type of pulse tube refrigerator shown refers to an application where the pulse tube refrigerator is integrated into a column-like support, the design of which is well-known in cryogenics design e.g. Heim, Marsing, SSC, Hartwig etc. One column in particular, the Heim column, achieved a load of 9000 kg for a diameter of 110 mm. The Heim, Hartwig, SCC, and Marsing column supports are very easily adapted to integration with the cryocooler design.

[0034] In Figure 3, the cryogenic vessel 40 is shown supported by a support stand 42 incorporating a pulse tube refrigerator 44. The refrigerator 44 is connected to the thermal shields 46, 48 for the purpose of supporting and cooling them. Also shown is a pulse tube refrigerator 50 supporting the helium vessel structure 52 and the thermal shields 46, 48, whilst simultaneously cooling the shields.

[0035] The suspension system 51, is a pulse tube cooler used as a

[0036] The cooler tube and regenerator tube could be arranged concentrically or the regenerator tube could be spaced apart from the column support. It is also known that this column arrangement consisting of negative thermal expansion Hartwig type elements can support more than 5000 kilograms of weight even with a diameter as small as 50 mm and an outer wall thickness of 4 mm and thus such a system would completely satisfy the need for supporting a cold superconducting magnet. Principally, the design of the Heim column is such that there is a permanent thermal contact to the structure being attached to e.g. a magnet or vessel surface. Also this support tube material could be tailored to fit particular requirements with regard to contact pressure and force applied.

[0037] Furthermore, incorporating the pulse tube in this way enables good contact to the neighbouring surfaces, and an enhanced thermal conductance value, whereas otherwise the contact resistance has to be overcome usually by applying an external force e.g. screwing together tightly.

[0038] Thus the integrated pulse tube refrigerator-Heim column cooler can be used as a support member for the shields being a single or multistage cooler, and it would be feasible to connect a further epoxy tube to the cold stage of the Heim column. This arrangement is of prime importance when using this type of pulse tube for any open and cryofree system. In that case the Heim pulse tube refrigerator temperature range spans from 300K down to 4.2K (or greater than 4.2K) and is directly fitted to the coil former surface as stated above.

[0039] The great advantage for many applications lies in the fact that these type of columns have a long heat path from room temperature to 4.2K and thus impose only small heat loads to the cold stages of the pulse tube cooler. If the warm end of the pulse tube is to be rigidly fixed at the outer vacuum case the thermal shrinkage of the cooler could be overcome by introducing a flexible part, e.g. by placing a set of Belleville-type or other spring types or bellows beneath the Heim column, where the springs are guided by means of bolts, in accordance with Figure 4. If thermal shrinkage has to be compensated for in case of a rigid connection, this can be done by attaching CFRP (carbon fibre composites) to provide the negative thermal expansion desired.

[0040] Referring to Figure 4, a cut-through section of a Heim/SCC-type column with an integrated pulse tube refrigerator is shown. Figure 4 further shows the temperatures experienced at the various points of contact from the outer vacuum case (OVC) side to the magnet side.

[0041] The pulse tube refrigerator 50 is enclosed within the regenerator tube 52, and may be provided with stiffeners 54. Epoxy tubes 56 provide further reinforcement. An aluminium tube 58 allows for contraction in the direction of arrow Y. Insulation material 60 is provided in the spaces between the epoxy tubes and the aluminium and epoxy tube. The various spring-types or bellows are located at locations 62.

[0042] The pulse tube could be fixed rigidly at the support structures to provide good thermal contacts.

[0043] Rather than introducing the pulse tube into the column, the pulse tube could also be designed so that it takes on the form of a Heim column and becomes an integral part of the support member. The advantage of the configuration shown in Figure 4 lies in the fact that the thermal link to the shields is most easily effected, and at the same time the heat load from the column to the shields is minimised.

[0044] In prior art designs this type of column normally introduces a heat leak due to radiation through 'windows'. This new type of design shows a structural member which cools itself as well as the shields and thus eliminates the window heat losses.

[0045] When rigidly fixed, shrinkage/expansion can be accounted for by using a spring-loaded interface at position 62 or by other compensating means.

[0046] Figure 5 shows an example of a cryogenic stand 70 where a commercially available support element 72 is used to house the pulse tube refrigerator (not shown). The element 72 may have its section reinforced with copper interface plates or rings being integrated in the strut so that simple connection to the shields can be facilitated. A side support system 74 may also be provided.

[0047] The pulse tube load bearing system described is extremely compact, combining various functions e.g. incorporating support of the magnet and the shields as well as thermally linking the shields for cooling. Also, the support mechanism is cooled simultaneously and enables the so-called windows (i.e. areas which cannot normally be closed completely due to assembly clearances which have to be kept) to be closed, which considerably reduces the amount of radiation being transmitted from the outer to the inner shields.

[0048] Furthermore, the present invention can be most efficiently used for those MRI systems, where a compact design is of utmost importance.

[0049] The outer shell and buffer volume of a pulse tube can be located outside the vacuum vessel with the cylinder being inserted into the circular column and comprising e.g, the first or second stage of a pulse tube refrigerator.

[0050] A further benefit of the Heim column lies in the fact that the bottom part of the tube arrangement of the pulse tube being the cold stage, could be connected to a heat pipe.

[0051] For some applications it is important to attach a heat pipe directly to the cooler. The principle of attaching a heat pipe to a piston-driven cooler is known.

[0052] This technology can be applied to the design described in Figures 6a and 6b.

[0053] Figure 6a shows a pulse tube refrigerator 80 attached to a wet open or standard magnet system having a heat pipe 82 connected between the refrigerator and the helium vessel 84 housing the magnet. The heat pipe provides rapid cooldown of the magnet.

[0054] Figure 6b shows a pulse tube refrigerator 80 attached to a dry open or standard magnet system having a heat pipe 82 connected between the refrigerator and the magnet 85 for rapid cooldown of the magnet. The heat pipe fitted on the first stage facilitates cooldown of the magnet and reduces that time required to a minimum. After cooldown has been effected or the temperature of the magnet has reached its specified temperature the heat pipe takes over the function of the epoxy tube mentioned above, as a support for the magnet only.

[0055] As the heat pipe is made of epoxy or of another low-conductance material or a combination of a thin-walled metal tube with an epoxy or another plastics lining, the parasitic heat travelling down to the magnet is small.

[0056] If the superconducting magnet goes normal the cryogenic heat pipe resumes operation and cools down the magnet again within a short time.

[0057] Furthermore, referring to Figure 7, the pulse tube's first stage 200 could be attached to the heat pipe or compressive column 202 which is directly attached to the magnet 204. The second stage 206 of the pulse tube comprising the regenerators 208 is then designed in parallel with the heat pipe to directly support and cool the magnet, once initial cooling has been effected. This is especially suitable for dry magnet designs.

[0058] Figure 7 also shows an outer vacuum case 210, a radiation shield 212 at, e.g. 50K, a radiation shield 214 at, e.g. 15K, and a further compressive column 216. The external valve box S has a pair of hoses 218 for connection to a compressor. The magnet 204 is housed within a helium vessel 220.

[0059] Referring to Figure 8 there is shown a pulse tube refrigerator 90 acting as a suspension member for a magnet 92 and thermal shields 96. Also shown is a pulse tube refrigerator 94 which is supported from the outer vacuum vessel 104, and which supports the helium vessel and the thermal shields 96. Provision may also be made for liquefaction at location 100.

[0060] In addition, the reinforced pulse tube 102 could also have the additional function of acting as a stopper or bumper for transportation of the cryostat and furthermore could carry the mechanical loads being applied to the system. Its function is to limit the movement of the vessels during transport, there being no contact between vessel and stopper during normal operation.

[0061] Incorporating the cooler-suspension system into a cryostat stand is of particular importance for the next generation MRI systems. In such systems, one cryocooler or a distributed set of pulse tube refrigerator coolers in parallel and/or in series could be inserted in each stand which in turn makes the system compact and cost efficient.

[0062] This is also of particular interest with respect to redundancy, e.g. if one cooler fails to supply the helium exchange gas needed in particular for shield or direct magnet cooling.

[0063] Referring to Figures 9 and 10, there is shown a load bearing twin-type pulse tube arrangement, which may be a single or dual stage arrangement, for an MRI open C-type design of the zero-loss or cyrofree type. A magnet 112 is housed within a helium vessel 110, which is surrounded by a radiation shield 114, e.g. an 80K shield. First and second pulse tubes 124, 126 are connected to the helium vessel 110 via an optional heat pipe or support member 122. A heat exchanger 128 is connected to each of the pulse tubes 124, 126. A common regenerator tube 130 is provided for the pulse tubes 124, 126. A number of columns 116 suspend or support the helium vessel 110 and the radiation shield 114 from the outer vacuum case 120. An external valve box 118 has connections to the columns 116 and to a compressor via line 130. Optional buffer volumes 132 may also be provided.

[0064] The twin arrangement shown in Figure 9 may supply the same temperature at different circumferential locations or preferably at two positions along the vertical or horizontal axis of an open system.

[0065] The present invention is also of particular interest to NMR, MRI systems and related fields such as storage tanks or for HTC applications. In operation, the prior art suspension system normally carries the magnet loads in addition to the shield system, and thus has to be cooled. This is normally achieved by multiple heat-stationing or thermal links, where each suspension element has to be cooled in order to minimise the heat leak to the helium vessel so as to minimise boil off. A further advantage of the present invention is that this suspension system cools itself without producing any additional heat input to the helium vessel.

[0066] It will also be appreciated that the pulse tube could be inserted into a turret of an MRI system to act as a support rod, being rigidly connected to the outer vessel container. The turret is of a design such that the pulse tube can be fitted or retrofitted and rigidly fixed in the neck tube assembly to carry shield and, if possible, magnet loads. It will therefore further be appreciated that the pulse tube refrigerator can be designed to be flexible at the point where the pulse tube connects to the regenerator tube. This is of utmost importance when retrofitting the cooler on installation sites with low ceiling height.

[0067] It will also be appreciated by those skilled in the art that various modification or alternative arrangements are possible within the scope of the following claims.

Claims

1. Load bearing means comprising a single pulse tube refrigerator including a pulse tube and at least one regenerator tube acting as a support or suspension member, in a cryostat system.

2. Load bearing means as claimed in claim 1, wherein a pulse tube refrigerator is an integral part of the support member.

3. Load bearing means as claimed in claim 1 or claim 2, wherein the pulse tube refrigerator is a multi-stage pulse tube refrigerator.

4. Load bearing means as claimed in claim 1, claim 2 or claim 3, wherein an arrangement of single and multi-stage pulse tube refrigerators are connected in parallel or in series.

5. Load bearing means as claimed in any preceding claim, wherein the pulse tube and the regenerator tube are of a particular geometric shape.

6. Load bearing means as claimed in claim 1, claim 3, claim 4 or claim 5, wherein the pulse tube refrigerator is used as the suspension member for connecting to thermal shields or to the superconducting

magnet system.

7. Load bearing means as claimed in claims 3 to 6, wherein a first stage of the pulse tube refrigerator cools a first thermal shield and a second stage of the pulse tube refrigerator cools a second thermal shield.

8. Load bearing means as claimed in claim 7, wherein said first stage of the pulse tube refrigerator cools said first thermal shield whilst pointing to a warmer thermal shield and the second stage of the pulse tube refrigerator points to a colder thermal shield thus enabling a fixation of the clearance between the two thermal shields without accompanying heat loss.

9. Load bearing means as claimed in any of the preceding claims 6 to 8, wherein said pulse tube branches out into one or more tube arrangements for cooling of open vertical or horizontal cryostat system.

10. Load bearing means as claimed in claim 2, wherein the support member is of the Heim-family, Marsing-type, or Hartwig type.

11. Load bearing means as claimed in claim 7, wherein the first and second stages are arranged in different orientations to support the thermal shields.

12. Load bearing means as claimed in claim 7, wherein the first and second stages are arranged such that only the magnet or the thermal shields or both are supported.

13. Load bearing means as claimed in claim 6, wherein the pulse tube refrigerator is arranged only to suspend and cool the thermal shields.

14. Load bearing means as claimed in claim 6, wherein the pulse tube refrigerator is arranged as a direct cooler to cool a magnet interface and suspend the magnet.

15. Load bearing means as claimed in any of the preceding claims 6 to 10, wherein a pulse tube is reinforced.

16. Load bearing means as claimed in any preceding claim 3 to 15, where one stage of the pulse tube refrigerator is a liquefying stage.

17. Load bearing means as claimed in claim 10, which includes a flexible part beneath the support member.

18. Load bearing means substantially as hereinbefore described with reference to Figures 1 to 7 of the accompanying drawings.

19. An MRI system including load bearing means as claimed in any preceding claim.

20. An NMR system including load bearing means as claimed in any preceding claim.

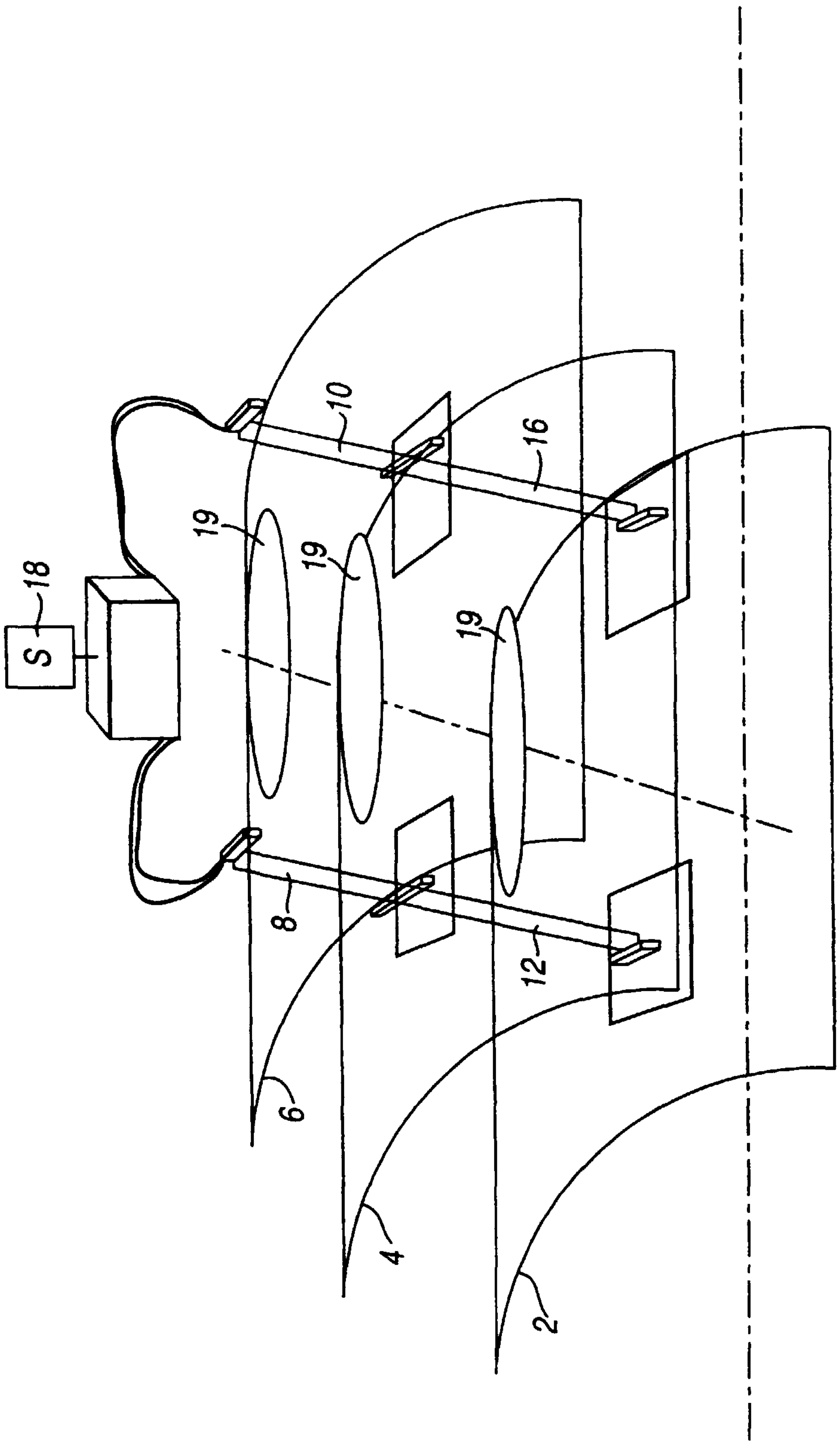


Fig.1

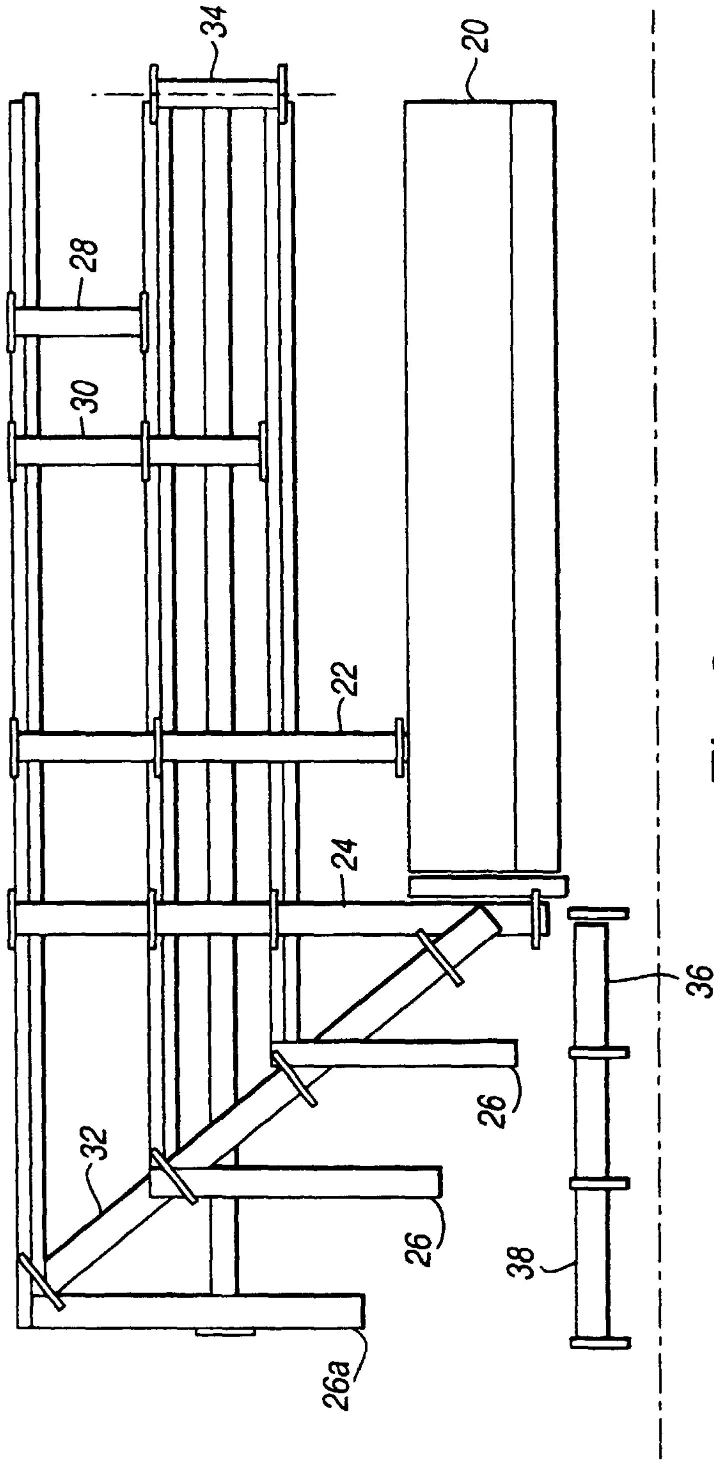


Fig.2

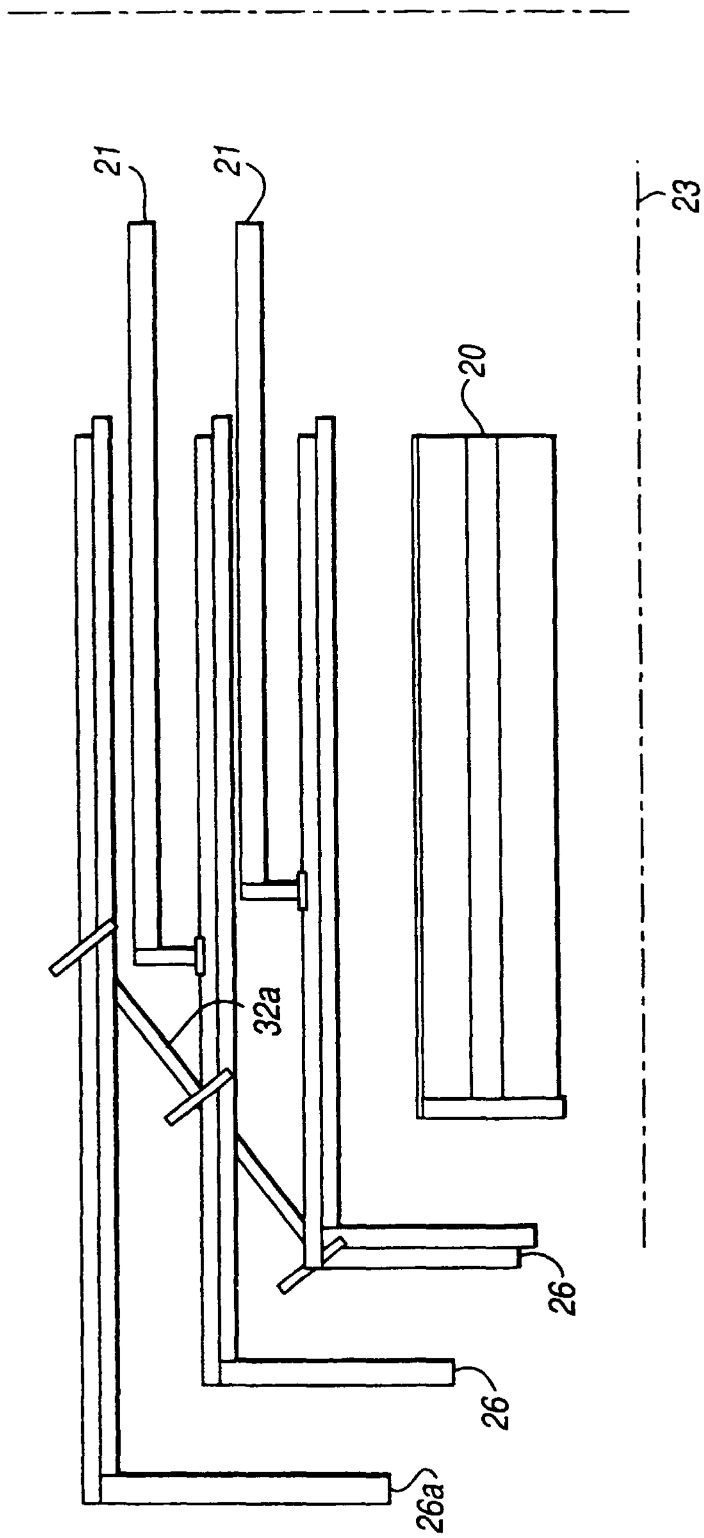


Fig.2a

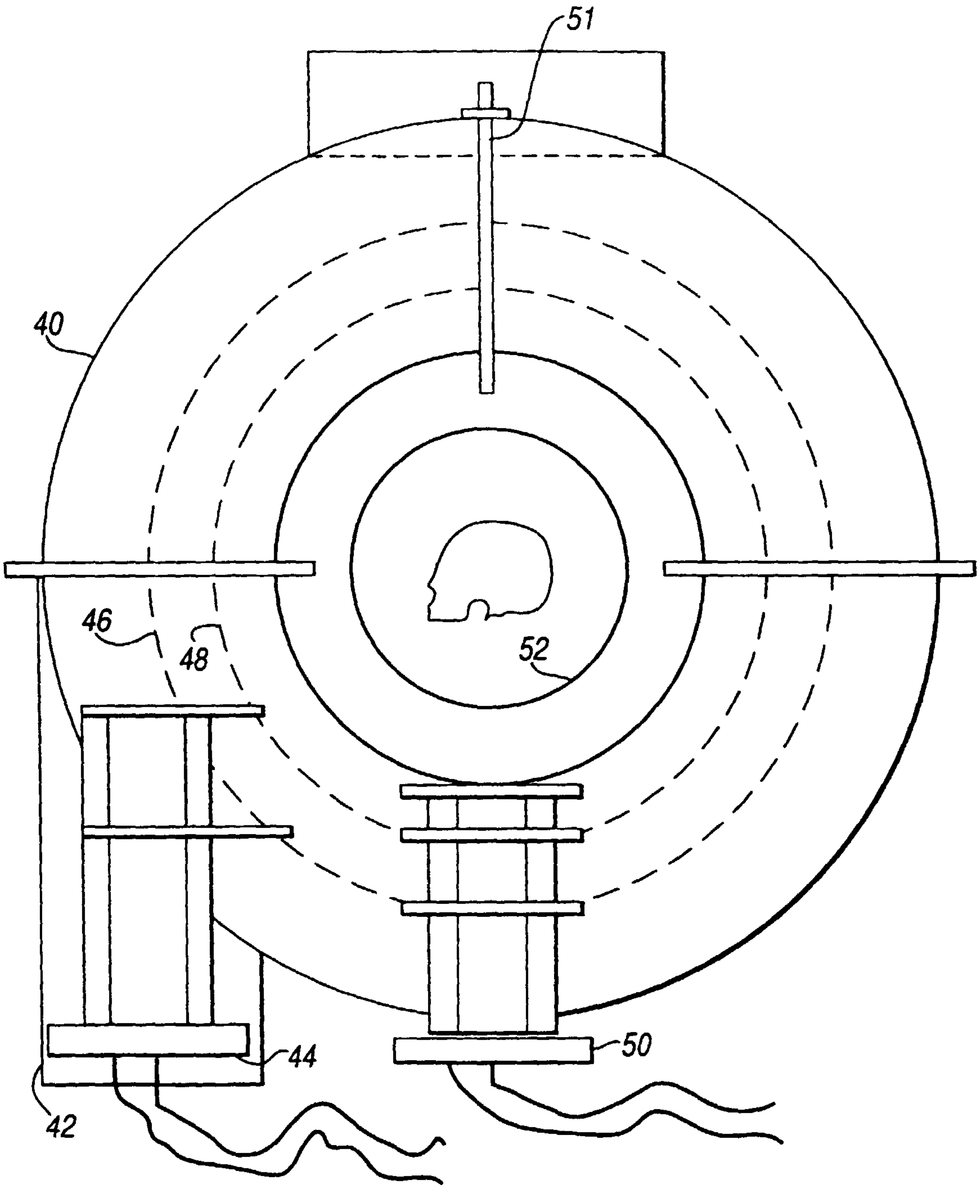
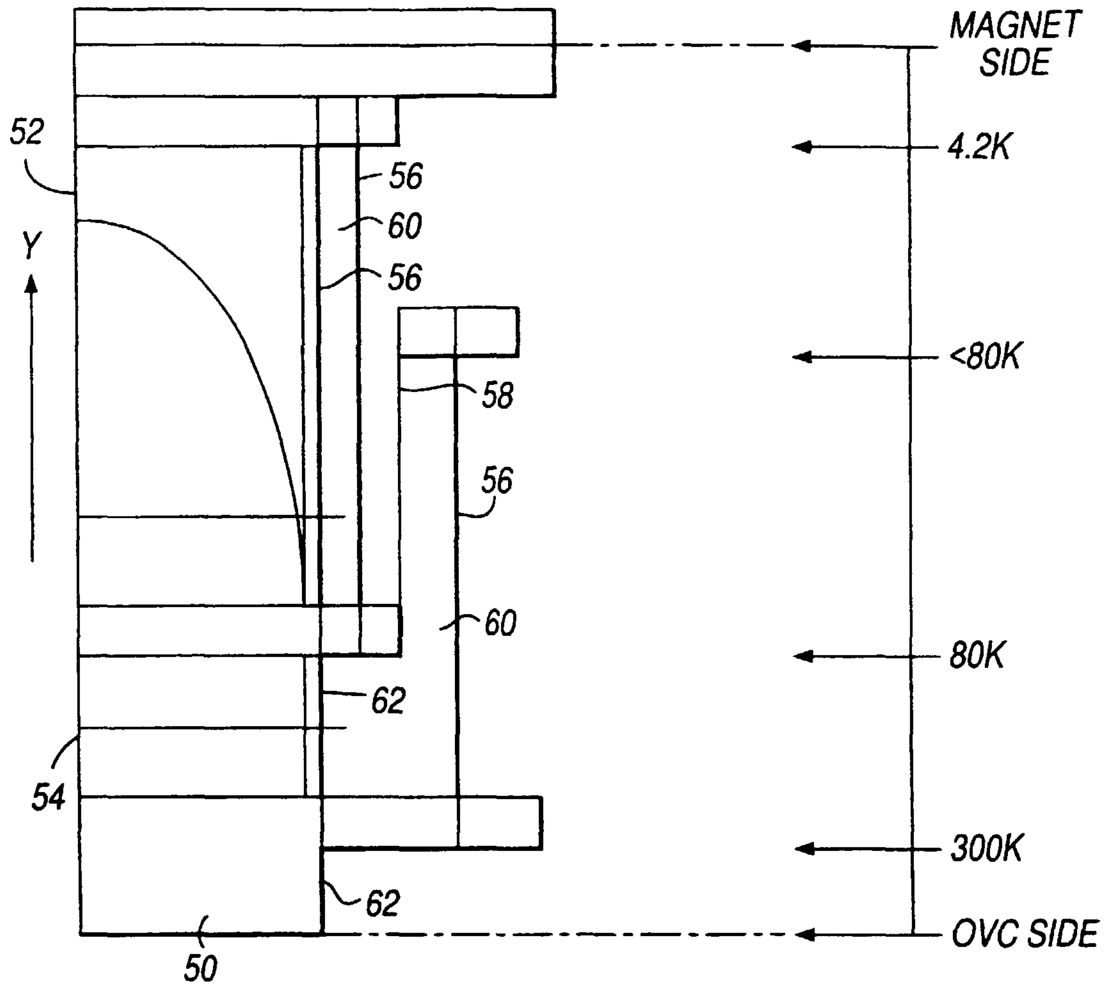


Fig.3


MAGNET SIDE
4.2K
<80K
80K
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OVC SIDE
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56
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Fig.4

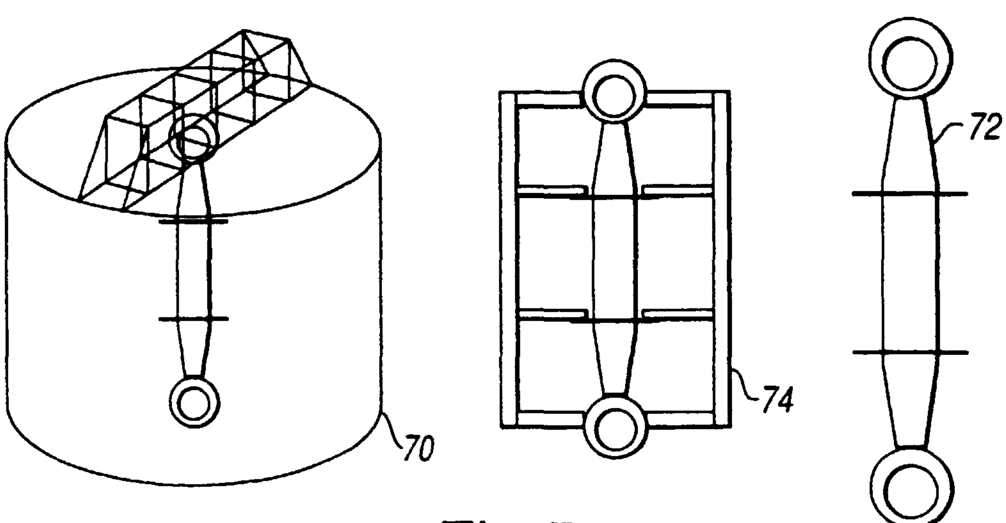
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Fig.5

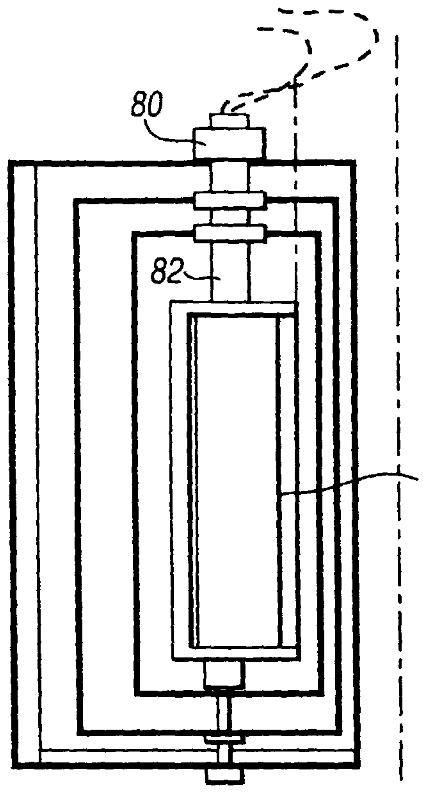

Fig.6a

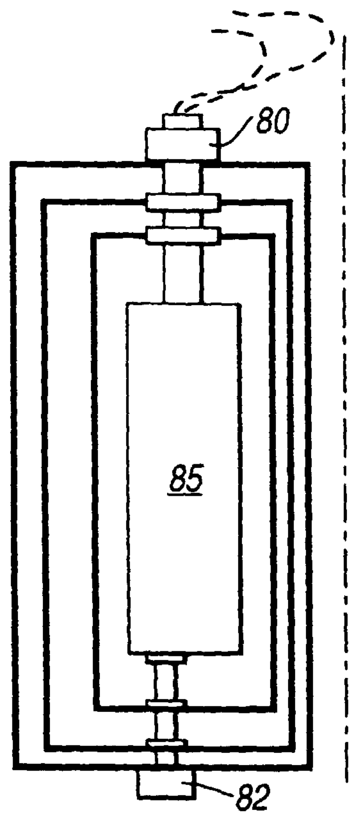

Fig.6b

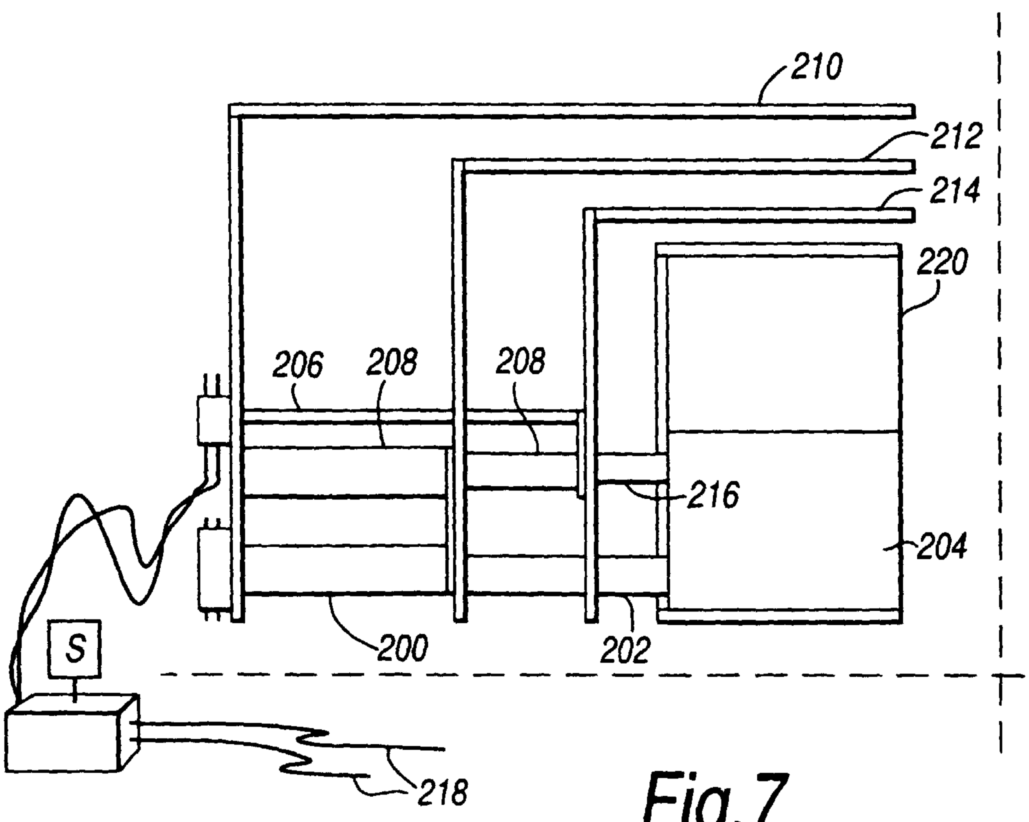

Fig.7

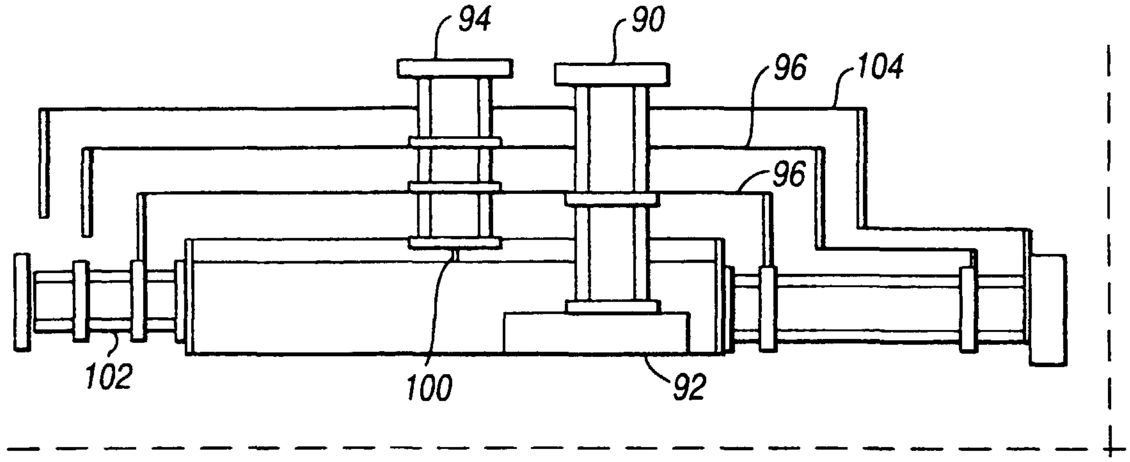
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Fig.8

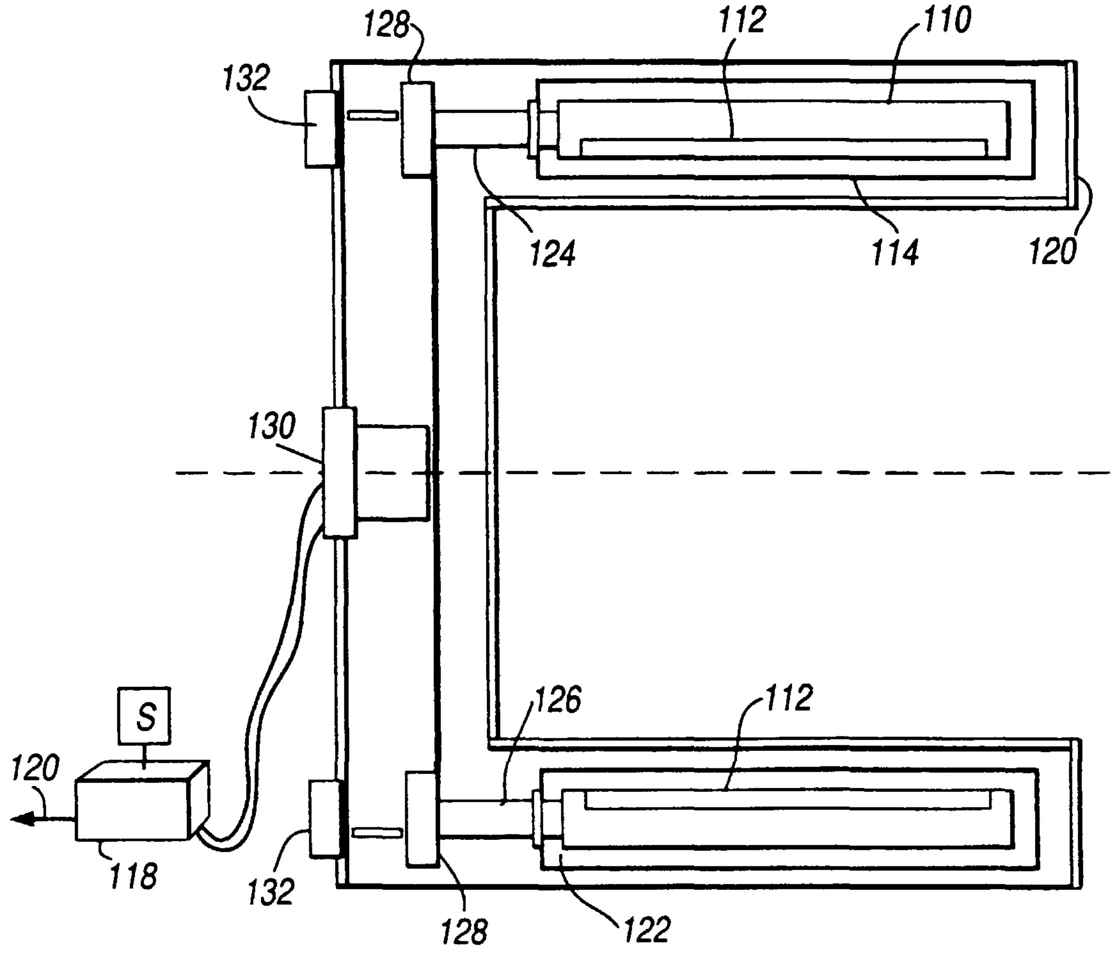
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Fig.9

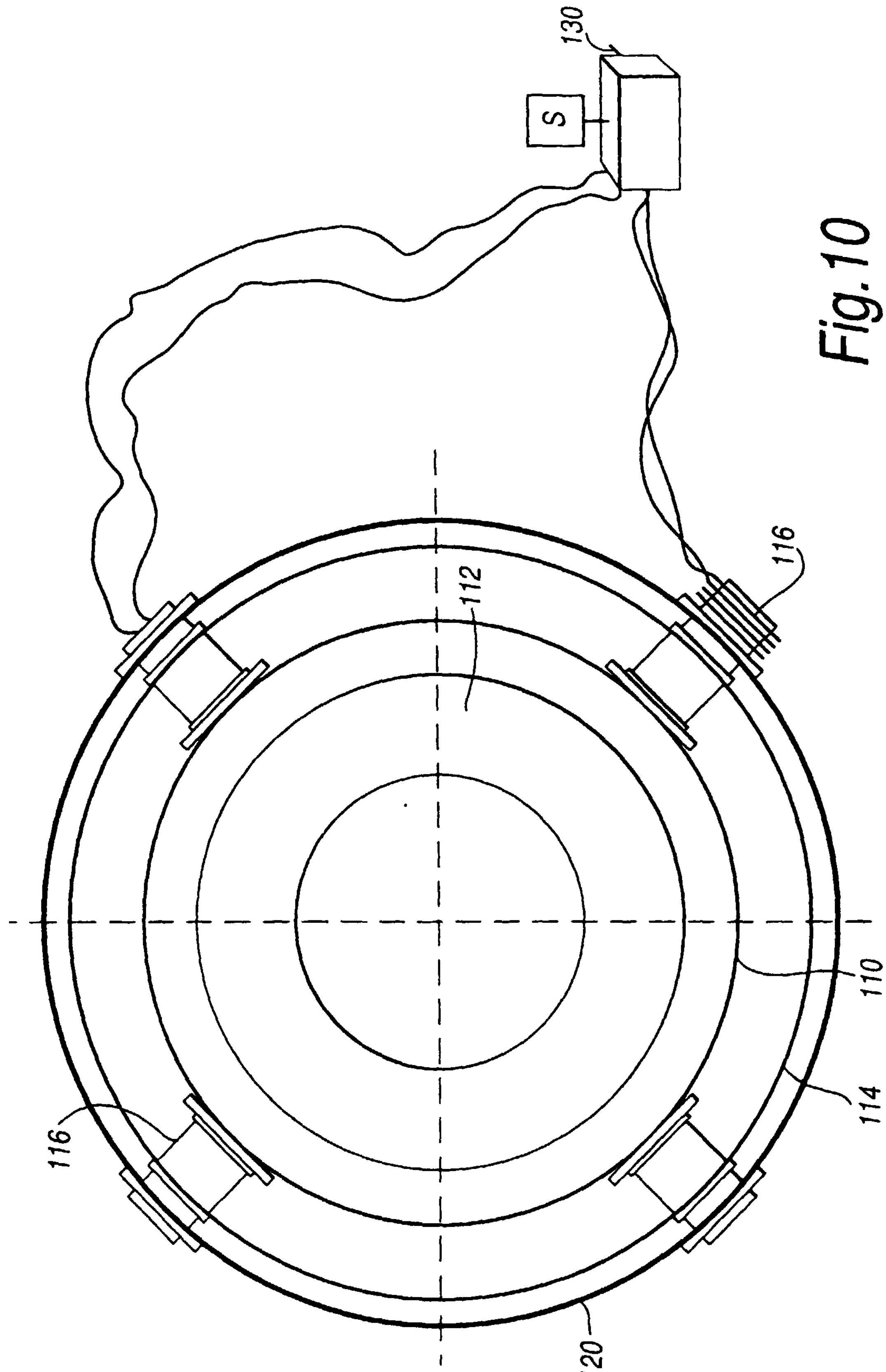

Fig.10