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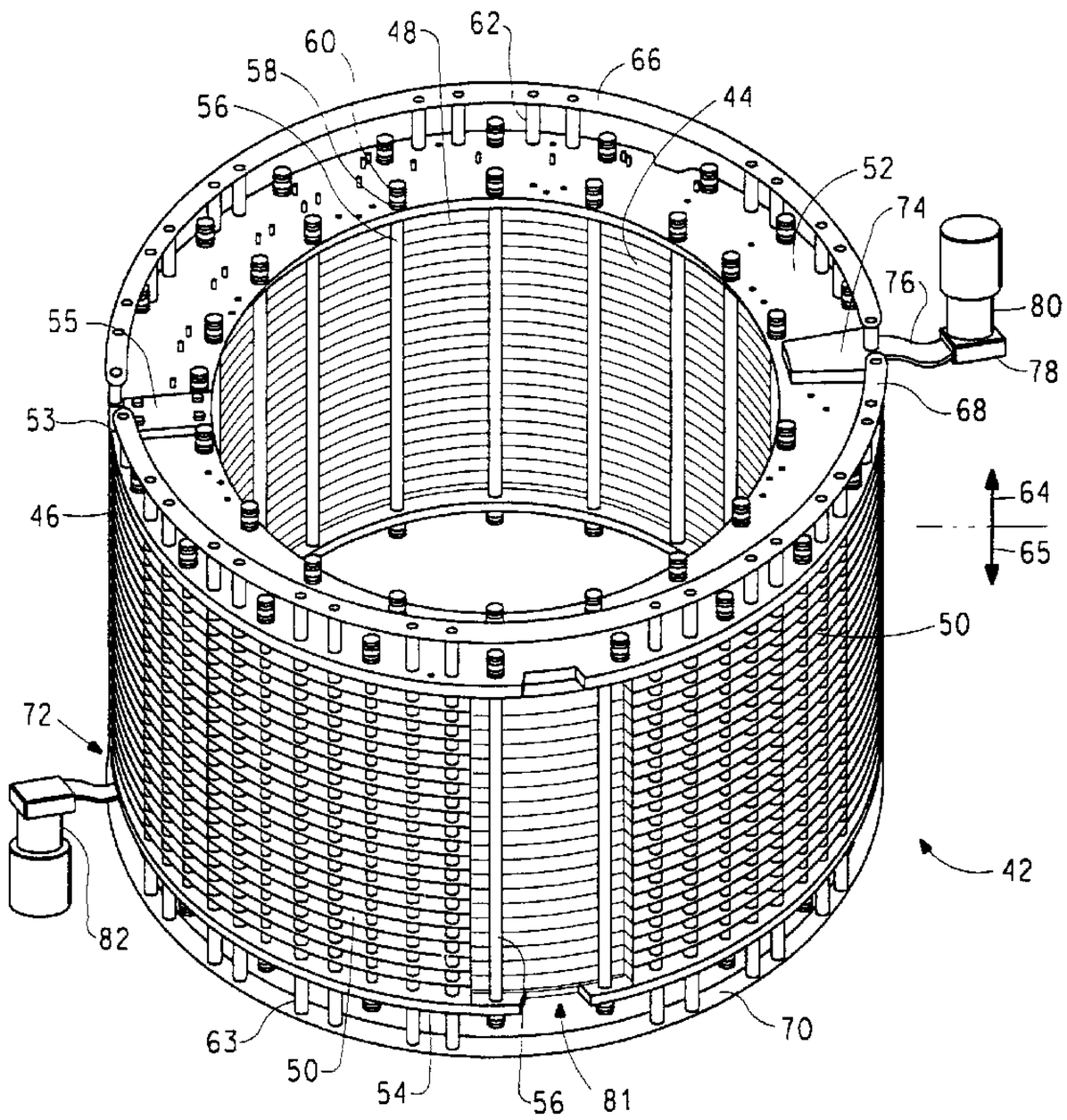

(57) Abrégé/Abstract:
The invention provides a portable, high power superconducting coil assembly for generating a magnetic field with an end piece, at least one pancake assembly adjacent to the end piece, the pancake assembly having superconductive material and a radial heat transfer plate, wherein the superconductive material is disposed between the radial heat transfer element and the end piece. A thermally conductive element having a thermally conductive connection with the end piece and the radial heat transfer element removes heat generated from the magnet during use. The invention also provides for a mandrel and a splice block having recessed channels therein in which the superconducting magnetic material is placed.

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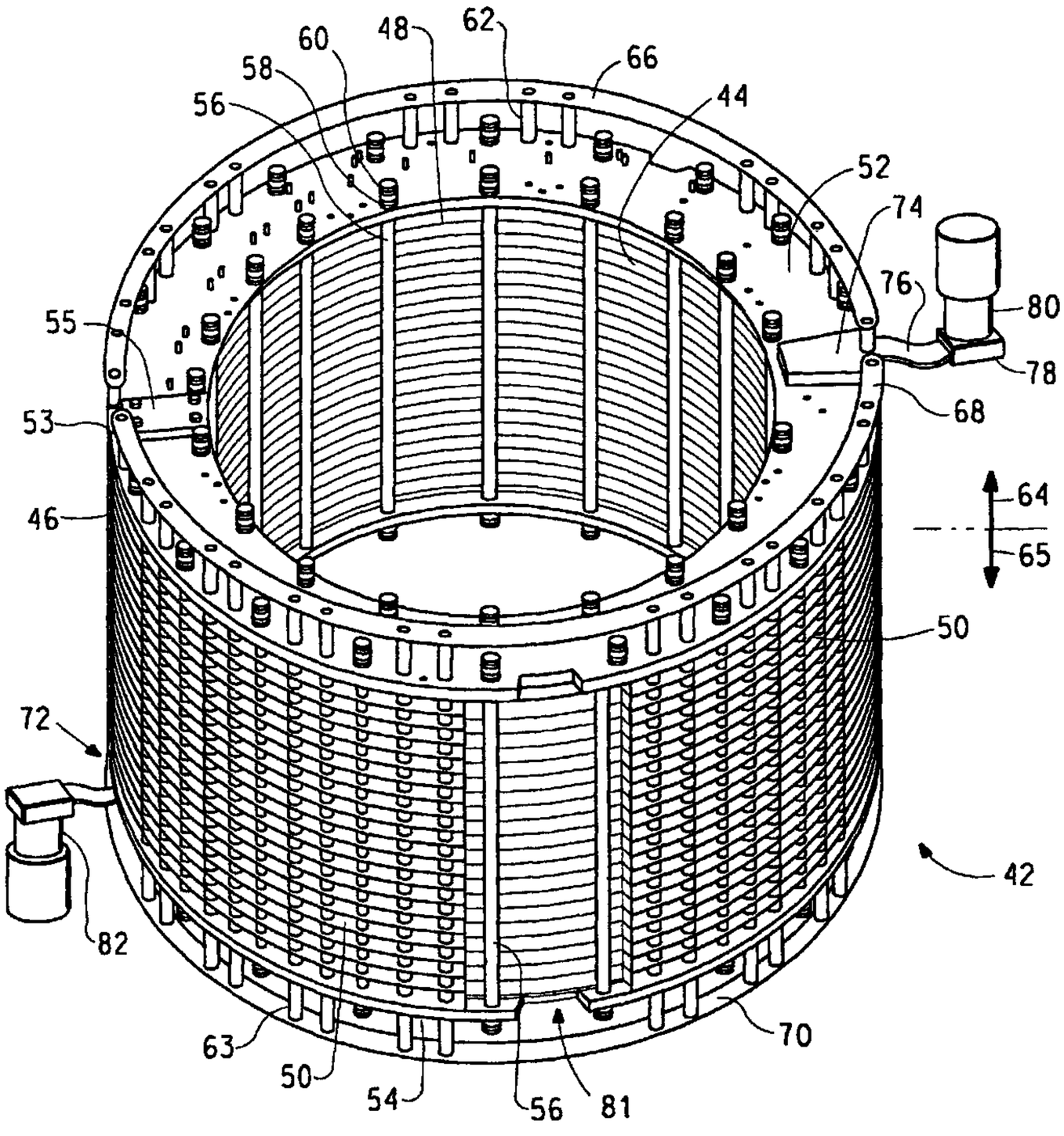

(57) Abstract: The invention provides a portable, high power superconducting coil assembly for generating a magnetic field with an end piece, at least one pancake assembly adjacent to the end piece, the pancake assembly having superconductive material and a radial heat transfer plate, wherein the superconductive material is disposed between the radial heat transfer element and the end piece. A thermally conductive element having a thermally conductive connection with the end piece and the radial heat transfer element removes heat generated from the magnet during use. The invention also provides for a mandrel and a splice block having recessed channels therein in which the superconducting magnetic material is placed.

WO 01/06524 A3

SUPERCONDUCTING COIL ASSEMBLY

CROSS REFERENCE TO RELATED APPLICATION

This application claims the benefit of U.S. Provisional Application No. 60/143,666 filed 14 July 1999.

BACKGROUND OF THE INVENTION

1. Field of The Invention

The present invention is related to the field of superconducting devices energized by an electrical current source and, in particular, superconducting coils and superconducting magnets generating very high magnetic forces. Such magnets have a variety of uses such as separation devices and are useful in the field of refining ores, in particular, titanium dioxide ores in the form of a slurry.

2. Description of the Background Art

Superconductivity is a phenomenon whereby certain metals, when cooled to very low temperatures, become perfect conductors of electricity. In practical application, superconductive materials may be used to construct powerful electromagnets capable of generating very high magnetic fields with relatively little power consumption. Superconductive materials must be kept at temperatures as low as a few degrees Kelvin in order to maintain their superconductive properties.

Superconducting magnets are manufactured by winding turns of superconducting material, in the form of layers of conductor, insulator, and a support material, on a mandrel to form pancake coils that are stacked on one another to form a completed magnet winding. The superconducting material is typically formed into a flat band of material that has limited flexibility and low structural strength. To efficiently wind the flat superconductor and get the end leads located on the outside of the coils for electrical termination, the coils are often wound in pairs from the inside to the outside which requires a winding transition portion at the inside that connects to each coil in the pair. This forms what is called a "double pancake" assembly. One double pancake assembly is electrically connected to an adjacent double pancake assembly with a splice. The splice is often located on the outside of the coils at a splice transition portion. Where the coils cross over the winding transition portion, as well as where the splice transition portion passes over underlying coils, there is a high stress placed on the superconductor that may become a source of electrical failure. During operation, large forces are developed on the structure resulting from the high magnetic field exceeding one tesla. The

superconducting materials in the pancakes must be cooled to a temperature of about -250 to -270°C (23 to 3 °K) to maintain their superconducting properties. The materials are placed in a vacuum container to thermally insulate the materials. In use, heat is developed in the pancakes that also must be removed from the assembly. It is common to achieve the low temperatures in the structure and remove operating heat by submerging the entire assembly in a cryogenic fluid, such as liquid helium, to achieve temperatures of 2-4 °Kelvin for low temperature superconductors (LTS) or of 20-25 °K for high temperature superconductors (HTS). This is referred to as an open refrigerant system since cryogenic fluid connections are required to the structure that are disconnected and reconnected in use. This requires a complex casing design and system for circulating fluid throughout the structure. When the magnet is started up and shut down for maintenance, the cryogenic fluid is removed and replaced, which subjects the assembly, including the transition portions, to thermal stress.

Another cooling system is a closed refrigerant system that is connected to the magnet coil assembly using conductive connections; the fluid is always contained in a separate system terminating in a "cold head" that is never opened when disconnected and reconnected to the magnet assembly. This is referred to as a conductive cooling system and it has been used successfully only on small scale magnet systems where the conductive distances are small (on the order of several inches). A conductive cooling system simplifies the construction, which is desirable, but in a large coil assembly it introduces challenging problems making many high conductivity mechanical connections across many pancake assemblies. U.S. Patent No. 5,861,788 to Ohkura, et al describes problems with heat generation in superconducting magnets using cryogenic refrigerators and cooling heads.

In the field of refining ores, in particular, titanium dioxide ores in the form of a slurry, it would be desirable to provide magnetic separation equipment at remote locations in order to avoid shipping large amounts of ore to a location where suitable magnetic separation equipment exists. The operation of complicated open cryogenic cooling systems at remote locations is problematic and powerful superconductive magnets generating heat loads that can be managed by closed cryogenic cooling systems have not been developed to date. There is a need for a system for removing heat from a large magnet assembly employing many pancakes without requiring submersion of the pancake structure in cryogenic fluids. There is also a need for low stress transition portions in a large double pancake design that produces high magnetic forces.

SUMMARY OF THE INVENTION

The invention provides a portable, high power superconducting coil and magnet having low stress and minimal temperature rise across the device. The superconductive coil assembly for generating a magnetic field according to the invention comprises an end piece, at least one pancake assembly adjacent to the end piece, the pancake assembly comprising superconductive material and a radial heat transfer element, wherein the superconductive material is disposed between the radial heat transfer element and the end piece; and a thermally conductive element having a thermally conductive connection with the end piece and the radial heat transfer element.

The invention also provides a mandrel for a superconductive double pancake coil assembly having a recessed channel provided therein, said recessed channel having a width and depth for placement of a superconductive material.

The invention also relates to a process of removing heat from a stack of pancakes in a superconducting magnet by providing thermal conductive layers between the pancakes with a portion extending beyond the pancakes for radial heat transfer, and providing thermal conductive elements passing through the conductive layer portions extending beyond the pancakes and passing into thermal conductive rings at the ends of the stack of pancakes for providing axial heat transfer. A thermal conductive path is established between the end rings and an external heat transfer device that employs a cryogenic fluid.

The invention is also a low stress transition connector for supporting and guiding the superconducting material in a low stress path between two pancakes in a double pancake structure. The invention is also a splice connector for supporting and guiding the superconducting material in a low stress path between one double pancake structure and another.

BRIEF DESCRIPTION OF THE FIGURES

Figure 1 is a diagrammatic view of a magnetic separator for a slurry fluid.

Figure 2A is a perspective view of a superconducting coil assembly.

Figure 2B is an enlarged view of a portion of Fig. 2A showing a connection between a tubular cooling rod and a plurality of cooling plates.

Figure 3 is a plan view of a double pancake coil.

Figure 4A is a section view 4A-4A from Fig. 3 showing a winding transition channel in a double pancake mandrel and a splice transition channel in a splice block connecting the double pancake coils.

Figure 4B is a section view 4B-4B from Fig. 3 showing a detail of a cooling plate engaged in a groove in a double pancake mandrel.

Figure 5A is a perspective view of a mandrel with a connector and Figure 5B is an enlarged plan view of the connector.

Figures 6A and 6B are an elevation view and a plan view, respectively, of a winding transition channel seen in view 6A-6A of the mandrel of Fig. 5A.

Figures 7A and 7B are an elevation view and a plan view, respectively, of a splice transition channel seen in view 7A-7A of the splice block in Fig. 4.

Figure 8 is a diagrammatic side view of a splice between two double pancake assemblies.

Figures 9A, 9B, 9C, and 9D illustrate an assembly procedure for making a double pancake with the mandrel and cooling plate of the invention.

Figure 10 shows the heat flow in a section of the top of a superconducting coil assembly according to the invention.

Figure 11 shows a 2-dimensional analysis of a portion of a magnet.

Figure 12 shows hoop strain in a portion of a magnet assembly.

Figure 13 shows radial strain in a portion of a magnet assembly.

Figure 14 shows hoop strain in a portion of an energized magnet assembly.

Figure 15 shows axial strain in a portion of an energized magnet assembly.

Figure 16 shows a two dimensional analysis thermal fringe plot.

Figure 17 is a three dimensional analysis thermal fringe plot.

Figure 18 shows a portion of a magnet, in partial cross section, with an internal thermal conductive element.

DETAILED DESCRIPTION OF THE INVENTION

The superconducting coil according to the invention may be used in a high temperature superconducting magnet (HTS) operating at from about 5 degrees Kelvin to about 50 degrees Kelvin, preferably from about 15 degrees Kelvin to about 25 degrees Kelvin, more preferably at about 20 degrees Kelvin, depending on the design criteria. The design central field may range from about 0.1 Tesla to about 5

Tesla, more preferably from about 1.0 Tesla to 3.0 Tesla. Stress/strain levels achieved are less than 0.2% mechanical strain, preferably less than 0.12% mechanical strain, more preferably less than 0.1% mechanical strain. Temperature rise or gradients in the superconducting coil assembly are on the order of less than 3 degrees Kelvin, and preferably temperature rise or gradients in the superconducting coil of less than 1 degree Kelvin, or more preferably less than 0.5 degree Kelvin, are obtained by the invention.

A diagram of a magnetic separator 20 is shown in Figure 1 comprising a metal yoke 22, a metal pole piece 24, a filter chamber 26 containing a metal mesh filter 28, a cryogenic coil cavity 30 containing a superconducting coil 32, and an inlet conduit 34 and outlet conduit 36. The inlet conduit 34 contains a shutoff valve 38, and the outlet conduit 36 contains a shutoff valve 40. In operation, a slurry of material, such as titanium dioxide and impurities, passes through the open valve 38 through inlet conduit 34, through filter mesh 28 and through open shutoff valve 40 in outlet conduit 36. The superconducting magnet coil is energized with a DC current to generate a strong magnetic field that acts to attract the impurities in the slurry stream to the filter material. The outlet stream flowing from outlet conduit 36 is purified titanium dioxide slurry. After a period of operation, the filter 28 becomes clogged with impurities and the flow of slurry is stopped and the valves 38 and 40 are closed and the current to the magnet turned off. The filter can be flushed with a cleaning fluid, such as water, by connecting the conduits to a water source and flushing out the filter 28. Alternatively, the pole piece 24 containing the filter 28 can be removed from the yoke and the clogged filter replaced with a clean one. When the magnet is turned off and on, the collapsing and expanding magnet field produces eddy currents and heating in the metal elements in the superconducting coil 32. This heat must be removed to avoid heating the superconducting material.

Figure 2A shows a superconducting coil assembly 42 that is useful in the magnetic separator 20 of Fig. 1. The coil assembly 42 is annular and has an open bore side 44 and an outer side 46. The coil assembly 42 comprises a plurality of pancake coils, which are preferably fabricated in pairs known as double pancake assemblies 48. Between each pancake coil is a cooling plate 50 made of a thermally conductive material, preferably aluminum, that conducts heat primarily in a radial direction between the coils, although it may also conduct heat circumferentially and axially (i.e. through the plate thickness). At the top of the coil assembly 42 is an end ring 52 made of a thermally conductive material, preferably aluminum, and at the bottom of the assembly is an end ring 54 made of a thermally conductive material, preferably aluminum, which conduct heat circumferentially and radially. The end

ring 52 has a gap 53 to interrupt eddy currents in the ring during operation. A bridge plate 55, made of an electrical insulator, bridges the gap 53 to strengthen the ring. End ring 54 has a similar gap and bridge plate. The end rings, plates and coils are held together by tie bolts 56 arranged around the bore side and outer side of the coil. The tie bolts have spring washers 58 and nuts 60 on each end to accommodate thermal expansion and contraction of the coil assembly 42. To avoid completing an electrical circuit for eddy currents between the end rings, plates, and tie bolts, the tie bolts are covered with a tubular insulator and there is an insulator washer (not shown) separating the spring washers from the end rings. Arranged around the outer side of the assembly are a plurality of thermally conductive elements, cooling rods 62 that are shown passing through holes in the end ring 52 and the plates 50 in the top half of the coil assembly. The cooling rods 62 conduct heat in an axial direction indicated by arrow 64 and are preferably copper or copper alloy. Also arranged around the outer side of the assembly are a plurality of thermally conductive elements, cooling rods 63 that are shown passing through holes in the end ring 54 and the plates 50 in the bottom half of the coil assembly. The cooling rods 63 conduct heat in an axial direction indicated by arrow 65 and are preferably copper or copper alloy. The top ends of the rods 62 are connected by thermally conductive straps 66 and 68. The bottom ends of the rods 63 are connected by thermally conductive straps 70 and 72 (not shown). Straps 66, 68, 70 and 72 are preferably copper or copper alloy. It is believed that the copper straps provide better thermal conduction circumferentially around the coil assembly 42 compared to relying solely on the thermally conductive end rings. The end rings also provide structural strength to the assembly.

The cooling rods may comprise solid rods or bars that are attached to the straps, end rings, and plates by soldering, either after passing through holes in the straps, rings, and plates, or attached to the peripheral edge of them. The cooling rods may comprise a plurality of tubular spacers that are placed between the straps, end rings, and plates aligned with holes placed in them. A bolt may be passed through the spacers and holes that may be threaded to a particular one of the plates, or may be provided with a nut on the threaded end. The cooling rods may comprise a threaded rod passing through holes in the straps, rings and plates with nuts on either side of the holes to firmly clamp the straps, rings and plates between the nuts. The cooling rods may comprise tubular members that are placed in holes in the end rings and plates and are then swaged outward by conventional mechanical or hydraulic means to expand and press firmly against the bores of the holes to make a firm connection with low thermal resistance. To further reduce the thermal resistance,

the cooling rod embodiments employing mechanical connections may be plated with gold or other low thermal resistance coatings, or thermal conductive grease may be applied to points of contact between the cooling rods and other heat transfer elements, i.e. straps, end rings and plates.

Figure 2B illustrates a preferred embodiment of a cooling rod 62a that is a tube swaged outward to engage the straps, end rings, and plates. As an illustration, the tubular rods 62a are passed through holes 71 in plates 50 and are then expanded by a conventional hydraulic expansion device placed in the bore 73. The device temporarily closes off one end, such as end 75 of the bore 73 and applies hydraulic pressure to the enclosed bore. This presses the tube firmly against the perimeter of the holes 71 and bulges the tube slightly between plates in an outward direction relative to the central axis of bore 73, such as at 77. If the closing off element of the device prevents expansion at the end 75, this end can be expanded with a conventional mechanical expansion device inserted in the bore 73. The placement and swaging of the tubular cooling rods can be done as a last step in putting together the coil assembly 42.

Figure 18 shows an alternate embodiment of the invention where, in addition to cooling rods, such as 62 (not shown for the top half of the assembly 42) and 63 (at the bottom half of the assembly) around the outer side 46 of the assembly, there are cooling rods, such as cooling rod 63a and 62a, (not shown in the top half) around the inner bore side 44 of the coil assembly 42. Fig. 18 has cooling rod 63 passing through end ring 54 and cooling plates, such as 50a, 50b, and 50d that are arranged within and between double pancake assemblies 48a and 48b as described below. Cooling plate 50a is arranged within double pancake assembly 48a and is connected to cooling rod 63, and cooling plate 50b is arranged within double pancake assembly 48a and is connected to cooling rod 63. Cooling plate 50d is arranged between pancake assemblies 48a and 48b and is connected to cooling rod 63 at the outer side 46 and is connected to cooling rod 63a at the inner bore side 44 spaced from the bore centerline 43 (not to scale). Cooling rod 63a also passes through end ring 54. A similar arrangement may also be present for the top half of the assembly 42.

In embodiments of the invention, cooling rods may be placed at the inner bore side 44, cooling rods may be placed at the outer side 46 or they may be placed both at the inner bore side 44 and the outer side 46, depending on the cooling needs of the superconducting coil assembly 42.

Attached to the end ring 52 is a thermally conductive block 74 that has connected thereto a flexible thermally conductive assembly 76 that is also connected

to another thermally conductive block 78 which is attached in a conventional manner to a cold head 80 of a cryogenic refrigerator for cooling the top half of the coil assembly. The flexible assembly 76 preferably consists of a plurality of braided thermally conductive material, preferably copper strips that are soldered to blocks 74 and 78. The ends of conductive straps 66 and 68 are also physically and thermally connected to thermally conductive block 74. This arrangement of thermal blocks, flexible thermal assembly and conductive strap ends is repeated at end ring 54 for connection to a cold head 82 of another cryogenic refrigerator for cooling the bottom half of the coil assembly. The coil assembly 42 is shown with an axial slot 81 that passes through the top and bottom end rings 52 and 54, respectively, and plates 50, that permits access from the top to the bottom of the coil assembly 42 after it is assembled in the superconducting coil 32 which includes additional conventional elements such as a infra-red radiation shield and a vacuum chamber.

Figure 3 shows a plan view of a double pancake assembly 48a oriented with the cutout for axial slot 81 shown at the top of the figure. The assembly 48a comprises a mandrel 84 around which a superconducting coil 86a is wound on the top side of annular plate 50a; another superconducting coil 86b (not seen in this view) is wound on the bottom side of plate 50a. Coil 86a is separated from plate 50a by an insulating washer 88a. In preferred embodiments, insulating washer 88a is made from G-10CR material, which is a glass fiber reinforced phenolic available from Industrial Laminates/Noplex, Inc. of Postville, Iowa. Plate 50a may be provided with a plurality of radial slots 90 to interrupt any eddy currents that might form in the plate in use and that can be used to aid in removing plate 50a from the assembly. In case the double pancake assembly needs to be repaired and the superconducting material salvaged, cuts can be made from the outer periphery of plate 50a to the slots 90 to separate plate 50a into small segments that can be removed. After placement of double pancake assembly 48a in coil assembly 42, one radial slot is cut through to the periphery to stop the circulation of eddy currents around plate 50a while in use. Large diameter holes 89 in plate 50a are provided for rods 62 (Fig. 2A); small diameter holes 91 are provided for tie bolts 56 (Fig. 2A). At the inner diameter of the coil 86a there is a segment 85 where a winding transition portion is located in the mandrel 84. At the outer diameter of coil 86a is a segment 83 where a splice transition is located between double pancake coils. The two segments 83 and 85 are shown in Figure 3 as overlapping, but they may be displaced from one another so as to be non-overlapping if desired.

In the embodiment shown in Fig. 18, where cooling rods are placed at the inner side of the coil assembly, it may be desireable to allow segments of plate 50a

to pass through the mandrel in the region remote from segment 85 (the segment where the superconductive material is undergoing a winding transition from one side of plate 50a to the other). In the region where plate 50a can pass through the mandrel, it can be engaged by the cooling rods 63a in Fig. 18 as shown by the long and short dashed lines at 248. This technique can be applied to the other plates within each double pancake coil assembly so all plates, such as plates 50a, 50b, and 50c, can be engaged by the cooling rods 63a as shown in Fig. 18, if such measures are required to achieve the desired cooling of the coil assembly.

Figure 4A is a section through three double pancake assemblies 48a, 48b, and 48c taken at the position of section 4A-4A in Fig. 3. The double pancake 48a is shown at the bottom of the coil assembly 42 (Fig. 2A) placed on top of end ring 54 separated from it by two slip sheets 92 and 94 of electrically insulating material, such as G-10CR. During thermal movement of the double pancake coils the slip sheets reduce friction with the end rings to prevent damage to the rings and coils. Similar slip sheets are located at the top end ring as well. Each coil 86a and 86b making up double pancake 48a is made up of a laminate of superconductive material strips and insulating material strips, collectively shown as 95 in coil 86b, and a support material strip shown as 98, the laminate of 95 and 98 collectively shown as 87in coil 86b. The laminate 87 is helically wound around the mandrel 84a of double pancake 48a. Coil 86a is helically wound in a first circumferential direction around mandrel 84a and coil 86b is wound in second circumferential direction around mandrel 84a, the second circumferential direction being opposite the first circumferential direction. For example, if viewed from above (i.e., the perspective of Figure 3), if the first circumferential winding direction would be clockwise, then the second circumferential winding direction would be counter-clockwise. The support material 98 typically comprises a band that is slightly higher than the remaining laminations to take the vertical load in the coil to prevent damage to the superconducting material and preferably is made from stainless steel. The support material 98 also takes the tensile loads during winding, and hoop stresses during operation, to protect the superconducting material. Plate 50a is placed between coils 86a and 86b. Located between plate 50a and coil 86a is insulating washer 88a and located between plate 50a and coil 86b is insulating washer 88b. Plate 50b is similarly arranged in double pancake 48b and plate 50c is similarly arranged in double pancake 48c.

Plate 50d is placed between double pancake 48a and double pancake 48b. An insulating washer 88c is placed between plate 50d and coil 86a, and insulating washer 88d is placed between plate 50d and coil 86c in double pancake 48b. Plate

50e is similarly arranged with insulating washers between double pancake 48b and double pancake 48c. To improve thermal conductivity between the coils, insulating washers, and plates, it is desirable to apply a conductive grease to the interfaces. An indium grease can be used or a grease of silicon oil solvent containing ceramic grains of ZnO or other conductive greases or oils.

Coil 86b is connected to coil 86a by a connecting portion 100 of superconducting laminate material that fits in a recessed channel 102 in mandrel 84a. At the location of the section 4A-4A, the connecting portion 100 is shown halfway between coil 86a and 86b although it forms a continuous serpentine transition between the two coils. This connecting portion is typical for all the double pancakes. Coil 86a of double pancake 48a is connected to coil 86c of double pancake 48b by a splice portion 104 where a splice is formed between the end of superconducting laminate on coil 86a and the end of superconducting laminate on coil 86c. The splice portion is contained in a recessed channel 106 of a splice block 108. The splice block 108 is arranged to rest on the outer turns of the superconducting material of coils 86a and 86c. The splice block 108 has a groove 110 that engages the plate 50d. At the location of the section 4A-4A, the splice portion 104 is shown halfway between coil 86a and 86c although it forms a continuous serpentine transition between the two coils. This splice portion is typical for connecting all double pancakes in the coil assembly. The end 112 of superconducting material on coil 86b is electrically connected to a source of DC current in operation. The current will pass through the turns of coil 86b, through the connecting portion 100, through the turns of coil 86a, through splice portion 104, through the turns of coil 86c and continue in this fashion through all the pancake coils to the top coil in assembly 42 (Fig. 2A) where the superconducting material terminates and is electrically connected to the opposite end of the DC source.

Figure 4B is a partial view of the cross-section 4B-4B from Fig. 3 that shows the relationship of a mandrel, such as mandrel 84a, and a cooling plate, such as plate 50a, at a location remote from the winding transition segment 85 (Fig. 3). The mandrel 48a has a groove 132 that accepts the inner edge 109 of plate 50a as well as the inner edge 111 of insulating washer 88a and the inner edge 113 of insulating washer 88b. This serves to axially and radially position the washers and plate with the mandrel to facilitate fabrication of the double pancake. In certain embodiments of the invention, such as the embodiment of Fig. 18, the groove 132 may go completely through the mandrel 84a to allow segments of plate 50a to pass through the mandrel to engage cooling tubes on the inner side of the coil assembly.

Figure 5A shows mandrel 84, which is preferably fabricated from stainless steel, and has a gap 114 closed by an electrically insulating connector 116 to interrupt eddy currents in the mandrel during use. As described above, one acceptable insulating material is G-10CR. The connector is shown in greater detail in Figure 5B where the connector 116 has a segment 118 that forms part of the outer surface 120 of the mandrel and a segment 122 that forms part of the inner surface 124 of the mandrel 84. Fasteners, shown in this embodiment as screw 126, hold the connector 116 to the mandrel 84. When the screws are removed, the connector can be removed and the diameter of the mandrel can be reduced by moving free end 128 toward free end 130 which is useful during assembly of the mandrel with the plates 50, such as plates 50a, 50b, and 50c in Fig. 4. The mandrel has groove 132 in a portion of the outer surface 120 that accepts the inner edge of annular plate 50 (50a, 50b, 50c). In embodiments of the invention, a portion 134 of the outer surface 120 of the mandrel contains features associated with the recessed channel 102 (Fig. 4A) where groove 132 is not necessary and it may be missing or is not used. The angular length of portion 134 depends on the flexibility of the superconductive material used, the geometry of the coil assembly, and the thermal cycling the coil assembly is expected to experience in use. Small diameter coils and/or less flexible superconductive materials and/or more frequent thermal cycling may require a large angular length of portion 134, and large diameter coils and/or more flexible superconductive materials and/or infrequent thermal cycling may only need a small angular length of portion 134. In preferred embodiments of the invention portion 134 is about 90 degrees. Although some portion of a groove 132 is useful in alignment and assembly of the associated parts of the double pancake assembly, it may be only a small portion, so the angular length of recessed channel 102 may be from about 60 degrees to about 360 degrees. Preferably it is 60 degrees or more to less than 360 degrees and more preferably it is greater than or equal to 60 degrees and less than or equal to 180 degrees.

Figures 6A and 6B show details of channel 102 in mandrel 84. Figure 6A is an elevation view 6A-6A from Fig. 5A that shows outer surface 120 that has groove 132 interrupted in the vicinity of channel 102. In Fig. 6B, the superconducting laminate 87 is shown placed in channel 102 and a portion of a plate 50 is shown in an alternating long and short dashed line. The bottom surface 133 of recessed channel 102 forms a serpentine path for the superconducting laminate and lies below the surface 120 starting at position 136 where it is at the same level as surface 120 and above a top side 138 of groove 132; and ending at position 140 where it is at the same level as surface 120 and below a bottom side 142 of groove 132. At a point

144 intermediate points 138 and 140, surface 133 is below surface 120 at a distance 139 about equal to the width 141 of the superconducting laminate 87 (Fig. 6B) so the laminate is completely contained within the channel 102. Since groove 132 accepts plate 50 as discussed above, the channel passes from a position on one side of plate 50 at point 136 to a position on the opposite side of plate 50 at point 140. In Fig. 6A, plate 50 has been omitted for drawing clarity. In embodiments of the invention channel 102 is helical, relative to the central axis of the magnet assembly. The height 146 of channel 102 is about equal to the height of the superconducting material laminate 87 (Figs. 4A and 6B).

Referring to Fig. 6B, to the left of point 140, the laminate 87 rests in contact with outer surface 120 of mandrel 84. Moving to the right from point 140, the laminate 87 contacts the bottom surface 133 of channel 102 and gradually moves below surface 120 until at position 144 the laminate is completely below surface 120 or the surface of the laminate 87 and the surface 120 are about coincident. This allows the laminate to move past the plate 50 that is also relieved on its inner edge 109a slightly in the region 148 between the ends of groove 132. The mandrel with a recessed channel having a serpentine-path, bottom surface that continuously supports the superconducting laminate and eliminates abrupt direction changes radially and circumferentially as the turns of superconducting laminate overlap one another, is believed to minimize the chance of damaging the semiconducting material in the laminate. The plate 50 (such as 50a, 50b, and 50c in Fig. 4) is also stabilized in position in the double pancake by engagement of groove 132 with plate 50 which facilitates installation and eliminates shifting in the axial direction of the coil assembly 42 (Fig. 2A).

Figure 7A shows an elevation view 7A-7A from Fig. 4, but showing only the splice block 108 made from an insulating material such as G-10CR. Block 108 has an outer surface 150 that has recessed channel 106. In Fig. 7B, the block 108 is shown placed against the last full turns, 87cd of the superconducting laminate in coils 86a and 86c. Block 108 has slots 152 and 154 aligned with groove 110 on an inner surface 158, which slots and groove are arranged to engage plate 50d shown in long and short dashed lines in Fig. 7B. The bottom surface 160 of recessed channel 106 forms a serpentine path for the superconducting laminate and lies below the surface 150 throughout its length and tapers to a sharp edge at the ends162 and 163 where it is at the same level as inner surface 158. Since groove 110 accepts plate 50d as discussed above and in Fig. 4, the channel passes from a position on one side of plate 50d at position 164 to a position on the opposite side of plate 50d at position 166. Plate 50d has been omitted from Fig. 7A for drawing clarity. The height 168

of channel 106 is more than the height 170 of the superconducting laminate 87 placed against the bottom surface 160 of channel 106 so the spliced superconducting laminate 87 is completely contained within the channel 106. Superconducting laminate end 87a at the right side of Fig. 7B is coming from coil 86a of double pancake 48a in Fig. 4 and end 87b at the left side of Fig. 7B is coming from coil 86c of double pancake 48b in Fig. 4. The two ends meet in channel 106 over region 172 to form a splice, which is slightly higher than height 170 of the superconducting laminate. The splice block, supported by the last turns 87cd of the coils in a double pancake coil assembly, and with a recessed channel having a serpentine-path, bottom surface that continuously supports the superconducting laminate and eliminates abrupt direction changes radially and axially, is believed to minimize the chance of damaging the semiconducting material in the laminate. The splice block is also stabilized in position by engagement of groove 110 with plate 50d which facilitates installation and eliminates shifting in the axial direction of the coil assembly 42 (Fig. 2A). Since the splice block is made from an electrically insulating material it prevents accidental contact of the superconducting material in the splice with other conductive elements in the coil assembly 42. If the splice block is made of an electrically conductive material, then additional insulation provisions will be necessary. In embodiments of the invention channel 106 is helical, relative to the central axis of the magnet assembly.

Figure 8 shows a diagrammatic view of a typical splice between two ends of superconducting laminate, 87a and 87b. An inner end of insulating film 174a from end 87a is overlapped with an inner end of insulating film 174b from end 87b at the top of the figure. Below that in the figure are the ends of six layers of superconducting material, 176a,b,c,d,e,f from end 87a and 176g,h,i,j,k,l from end 87b. The ends are abutted, such as end 176a with end 176g, and all abutted ends are staggered apart from one another as shown. A solder 178 is applied at each pair of abutted ends to laminate all the ends together and to the superconducting material adjacent each pair of abutted ends. An outer end of insulating film 180a from end 87a is overlapped with an outer end of insulating film 180b from end 87b. Finally, a band 98a from end 87a is overlapped with a band 98b from end 87b and a solder 182 is applied therebetween. Bands 98a and 98b are preferably made from stainless steel. Care should be taken that the solder in the splice does not create an electrical path between the superconducting material and the stainless steel band. This type of staggered, abutted splice limits the height buildup in the splice compared to a splice where the superconducting material is overlapped.

Figures 9A, 9B, 9C, and 9D illustrate an assembly procedure for making a double pancake assembly in accordance with the invention using the mandrel and cooling plate of the invention.

Referring to Fig. 9A:

1. Align the insulating washer 88a, cooling plate 50 and washer 88b in the order illustrated and rotationally align circumferential features as at 184.

Referring to Fig. 9B:

2. Pass roll 186 through the inner diameters of assembled parts from step 1. Roll 186 represents the superconducting laminate 87e required for one coil of a double pancake, and roll 188 represents the superconducting laminate 87f required for the other coil of a double pancake. Rolls 186 and 188 are a continuous piece of a typical superconducting laminate comprising one insulating ply, six high temperature superconducting (HTS) plies, one insulating ply and one stainless steel support ply.

3. Wrap four turns of a piece of insulating ply material around the six HTS plies for a length slightly greater than what will be required in the winding transition segment and centered on the laminate at 190 between rolls 186 and 188.

Referring to Fig. 9C:

4. Align and center the winding transition channel 102 of mandrel 84 so it aligns with the wrapped HTS plies (step 3.) at position 190 and rotationally align circumferential features of the mandrel with the assembled parts from step 1.

5. Carefully place the step 2 ply lengths and the step 3 wrapped HTS plies into the winding transition channel 102.

Referring to Fig. 9D:

6. Remove the connector 116 in mandrel 84.

7. Carefully close the mandrel ends together and fit the step 1 insulating washers and cooling plate into the mandrel groove 132 (also in Figs. 5A, 6A & 6B). The plate cutout (148 in Fig. 6B) must be centered on the mandrel winding transition channel at 190.

8. Move the mandrel ends apart and reinstall the connector 116 making sure the insulating washers and cooling plate are fitted into the mandrel groove 132.

9. Begin winding the laminate from roll 186 around the mandrel, contacting washer 88a on top of cooling plate 50 in a clockwise direction. When the first turn

of the laminate approaches the winding transition channel, wind four turns of a piece of insulator ply material around the HTS plies for the length of the channel.

10. Complete winding the first side of the double pancake with roll 186. Additional turns of laminate or addition of filler may be needed to achieve the required pancake outer diameter. The outer turn shall be secured to prevent loss of winding tension. Adequate additional laminate shall be provided for the pancake-to-pancake splicing or for pancake end termination to the current source.

11. Repeat steps 9 and 10 with roll 188 winding in a counterclockwise direction on the opposite side of plate 50 contacting washer 88b to complete the second side of the double pancake.

Figure 10 shows a partial sectional view of the top of superconducting coil assembly 200 (similar to assembly 42 in Fig. 2A) for generating a magnetic field in accordance with the invention and in particular illustrates the heat flow through the superconducting coil assembly 200 when it is in operation. Although single pancake configurations may be used, in preferred embodiments double pancake assemblies (shown in brackets and similar to assemblies 48a,b,c of Fig. 4A) 210a, 210b and 210c (partially shown) are used and have separating plates 50x and 50y located between them. The structure of these double pancake assemblies is described in detail above. Separating plates 50x and 50y are similar in structure and function to plates 50k, 50m, 50n and are, in preferred embodiments, provided with openings 89 to allow for installation of a thermally conductive element, shown here as tube 62. Tube 62 may be hollow and also may be swaged by mechanical or hydraulic means to provide a thermally conductive connection with each plate 50k, 50x, 50m, 50y and 50n. Tube 62 is also thermally connected to end ring 52, high heat flux strap 66, and flexible thermally conductive assembly 76. With selection of proper materials having different coefficients of thermal expansion/reduction for the materials of end ring 52, each plate 50k, 50x, 50m, 50y and 50n, and rod 62, the thermal connections between each improve with a reduction of temperature because the plates shrink to a greater extent than the rod. For example, thermally conductive material, preferably aluminum or aluminum alloy may be used for of end ring 52, each plate 50k, 50x, 50m, 50y and 50n and thermally conductive material, preferably copper or copper alloy may used for rod 62. These principles apply to the construction of the lower half of the superconducting coil assembly of the invention as well.

In Figure 10, the heat flows are indicated by the arrows and when the source of heat is considered as the superconducting material in the pancake, the heat flows both axially and radially, albeit to different extents as it will follow the path of least

resistance. The heat in the superconducting material flows to and through the vertically oriented metal support material 98 in the pancake and then through layers 88e and 88f and into, for example, plates 50k & 50x for superconducting material positioned between them. Plates 50k and 50x transfers the heat energy and the heat flows radially outward to rod 62. Rod 62 transfers the heat energy and heat flows axially to end ring 52 and flexible thermally conductive assembly 76. The heat flows predominantly in the radial directions, such as 212, 214, 216, 217, 218 and 219, and in the axial directions, such as 220, 222, 224, 226, 228, 230 and 232. The heat energy flowing through flexible assembly 76 may then be removed by the cryogenic refrigeration unit 78. The bottom half of the coil assembly 42 operates in much the same manner. Thus, in operation, the superconducting coil in accordance with the present invention may be maintained at nearly constant temperatures throughout, with variations of less than 1 degree Kelvin, preferably less than 0.5 degree Kelvin.

Although the end piece has been depicted in the Figures as a ring, the radial heat transfer element a plate and the thermally conductive element as a rod or tube, different geometries for each piece may be used depending upon the particular application of the magnet.

Experimental Model

The thermal and stress/strain analysis of a 0.8 m diameter cryocooled High Temperature Superconducting (HTS) magnet is provided by computer modeling. The design central field of the magnet is ~ 2 T. The HTS magnet is cryocooled with a target operating temperature of 20 K. A non-linear stress/strain analysis is performed to determine the stress/strain values on the HTS conductor and its corresponding support structure at four critical stages of manufacture and operation: 1) tension winding, 2) axial pre-compression, 3) cool down to 20 K, and 4) magnet energization. Results indicate the HTS conductor and its support structure remain below acceptable stress/strain levels (<0.2 % mechanical conductor strain) during the fabrication and operation of the device. In addition, a steady state thermal analysis is performed in order to demonstrate adequate heat removal within the HTS conductor windings. Results indicate a maximum temperature rise of <3 K for a 12 W input, which represents the worst case operational scenario.

HTS coil performance specifications developed for the magnetic separator are listed below in Table 1 and are based upon existing commercial LTS magnetic separators presently used by the kaolin industry.

Table 1. Major HTS Coil Performance Requirements.

Parameter	Requirements
Magnetic Field	2 T
Coil diameter	0.8 m
Coil height	50 cm
Refrigeration	Cryocooled
Thermal cycles	25
Magnetic cycles	200,000
Cost	equivalent LTS unit
Ramp time	< 2 minutes
Useful life	5 years

A central magnetic field of 2 T is chosen to represent what is commercially available in batch type separators. Dimensional requirements for the HTS coil are determined by those presently used in the kaolin and TiO_2 industries. Other requirements in terms of useful life, magnetic and thermal cycles, ramp time, etc., are representative of those used in commercial LTS magnetic separators, with the exception of the refrigeration system. Presently, the LTS coils used in commercial magnetic separators of this diameter have been limited to using liquid helium as a refrigerant.

Based upon the HTS coil performance requirements, a detailed HTS coil conceptual design is generated. Key elements of the design are summarized in Table 2.

Table 2. HTS Coil Conceptual Design.

Parameter	Design
Operating current	400 A
HTS conductor	Bi-2223 (PIT)
Winding type	Double pancake
No. of pancakes	102
No. of turns per pancake	28
Intercept temperature	60 K
Operating temperature	20 K
Iron yoke	Yes
Refrigerator	Two 2 stage G-M
Current leads	HTS – binary type Ag – 10% Au PIT

The HTS conductor for the coil is several strands of silver sheathed $Bi_2Sr_2Ca_2Cu_3O_x$ (Bi-2223) powder-in-tube multi-filamentary tape. Each Bi-2223 tape is approximately 4 mm wide and 0.25 mm thick and contains over 61 HTS filaments. The HTS tapes have a normal metal to superconductor ratio of ~ 2.5 to 1. The conductor is tension wound into double pancake coils on a pre-formed winding mandrel. A stainless steel support strip is used to support the hoop tension in the coil. Each double pancake coil is stacked and spliced together to form a single continuous HTS coil. The stacked HTS coil assembly is axially pre-compressed via tension rods to minimize conductor movement during cool-down and energization. Kapton® and G-10 is used for the turn-to-turn and pancake-to-pancake insulation, respectively. The current leads are of a binary–type HTS current lead with an intercept temperature of about 60 K. The lower stage (HTS portion) of the current leads are of silver - 10 % gold alloyed Bi-2223 powder-in-tube tape. A 6061-T6 aluminum shield operating at about 60 K is used to intercept the room temperature radiation heat load. The HTS coil assembly is mounted in a donut shaped vacuum cryostat. The cryostat is mounted inside an iron yoke structure. The entire magnet assembly (including the iron yoke) is designed for transportability.

Stress/Strain Analysis

A non-linear finite element analysis (FEA) is used to determine the stress/strain with the HTS conductor and its corresponding support structure at four critical states of HTS coil fabrication through operation: 1) tension winding, 2) axial pre-compression at room temperature, 3) cool-down to 20 K, and 4) magnet excitation. For the magnet excitation stress/strain analysis, two dimensional (2D) and three dimensional (3D) electromagnetic analysis using a commercial Boundary Element Method code determined the magnetic forces.

ABAQUS Version 5.8 FEA code is used to complete the structural analysis. Figure 11 shows the 2D axisymmetric analysis of ½ of a double pancake cross section with the various material parts shaded. The analysis elements include the insulation layers 250 and metallic layers 252 along with half of each pancake coil above and below the layers. By using axisymmetric elements, the analysis approximates the spiral wound coil as a series of concentric rings around the mandrel 254. The first 3 inner diameter (ID) coil plies in the ID region 256 and last 3 outer diameter (OD) coil plies in the OD region 258 included separate HTS plies 260 and stainless steel (SS) support plies 262 to better simulate the actual conditions of

these extremes. The central plies are simulated with average properties to model the basic behavior. Contact surfaces are defined between each part of the analysis.

The lower cut plane through the pancake coil winding is constrained against axial movement. The upper cut plane is constrained to move together axially. These boundary conditions simulate the central portion of the full magnet.

The analysis of the pancake winding process involves defining an initial hoop stress in each HTS and SS ply pair. These stressed ply pairs are released one pair at a time to mimic the actual winding process. The initial stress is adjusted such that the hoop stress in the HTS and SS plies, after release, matches the winding tension. As each new pair is released, the previously released ID plies are compressed and eventually lose their initial tension.

Figure 12 shows the resulting hoop strain in the wound pancake analysis for only the enlarged ID region 256 and OD regions 258 that have separate HTS and SS plies. The mandrel and ID HTS plies are all in compression. The ID SS plies are still in tension although considerably less than the winding tensions. The OD SS plies are all in tension at about the winding tension level. Friction is not included between the contact surfaces during the winding simulation.

Applying an axial load to the analysis simulates the clamped assembly of the stacked pancakes. The resulting axial compression loads to the wound pancake analysis are not large compared to the energized loads.

The next simulation involves cooling the magnet to 20 K. For this state, friction between the contact surfaces is included in the analysis. Due to the difference in coefficient of thermal expansion, the HTS, SS, insulator and metallic materials all shrink differing amounts. This tends to unload the compressive stress holding the HTS/SS plies tightly against the mandrel. The challenge of the modeling task is to determine the level of wind tension necessary to cause the ID HTS plies to maintain contact with the mandrel without overstraining the HTS material. If insufficient winding tension is used, the ID HTS plies will lose contact with adjacent plies and jeopardize heat transfer capability.

Figures 13 shows the radial strain in the ID regions 256 and OD regions 258 for the 20 K cooled condition for the magnet. The intervening plies fall between these bounding strain states. The important result is that the HTS plies are all in radial compression with the adjacent SS support plies. The only tensile radial strains are due to friction between the insulation layers and OD SS plies.

The final state simulates the excitation loads. This is accomplished by applying a radial acceleration to the HTS material in the analysis. The acceleration varied linearly in a 2:1 ratio from ID to OD of the coil. The acceleration magnitude is set to produce the total radial force generated in the energized magnet. In addition, an axial compression load from the magnetic analysis is applied to the top HTS/SS pancake cut plane.

Figure 14 shows the HTS hoop strains in the ID regions 256 and OD regions 258 of the energized coil. As shown, the strain levels are well below the 0.2 % capability of the HTS material.

The HTS axial strains are shown in Figure 15. These strains are compressive due to the large axial energized load. Since the SS support plies carry a large portion of the axial force, the load carried by the HTS is low.

Table 3 details the strains in the HTS and SS support plies for the first and last plies at the three highest load states. Stresses are within the capability of the HTS material.

Table 3. Strains in Pancake Analysis

State	Wound			Cooled to 20 K			Energized		
Direction R - Radial A - Axial H - Hoop	R (%)	A (%)	H (%)	R (%)	A (%)	H (%)	R (%)	A (%)	H (%)
Mandrel	.0049	.0051	-.018	.0087	.0099	-.031	.0014	.0014	-.0049
1st HTS Ply	.0057	.0045	-.015	-.003	-.003	-.0038	.0137	-.051	.022
1st SS Support Ply	-.002	-.005	.007	.006	-.010	-.006	.013	-.049	.019
Last HTS Ply	.0013	-.003	.0003	-.0051	-.005	.015	-.013	-.046	.038
Last SS Support Ply	-.006	-.010	.023	-.0034	-.020	.015	-.006	-.059	.037

Thermal Analysis

A static linear FEA is used to determine the maximum coil temperature under normal operating conditions. The AC loss and DC static heat loads used as inputs to the thermal analysis (~ 12 W at 20 K) are calculated in a separate analysis. A temperature intercept of 60 K is assumed for the radiation shield and the HTS current leads.

Pro/ENGINEER® and Pro/MECHANICA® THERMAL Release 19.0 software running on a HP Visualize C160 Workstation are used to create the models and perform the analyses of the models, respectively. Two types of steady-state thermal

conductive analysis are performed: A 2D Axisymmetric analysis of a ½ cross-section through the magnet and a 3D analysis. Thermal analysis inputs are summarized in Table 4.

For the 2D Axisymmetric model, both the number of coil pancakes and turns per coil (see Table 2) are consolidated ~ 10:1 while maintaining overall physical dimensions of the coil. This consolidation yielded an equivalent 10 pancake structure, in which each pancake is a detailed 3 turn structure (see Figure 16). A thin outer copper shell 264 simulates the actual axial cooling feature. The 12 W heat load is distributed to the HTS elements with a decreasing linear radial gradient. Figure 16 is the 2D analysis thermal fringe plot for the ½ consolidated structure cross section. Line 266 is the centerline of the coil assembly and line 268 is the axial midplane of the assembly. For a starting operating temperature of 20 K, the 2D analysis predicts a maximum temperature of 20.46 K within the HTS material.

For the 3D model, the pancake coil structure is lumped together to give an equivalent single pancake of 3 turns. Orthotropic thermal properties, calculated and verified with the 2D model, are assigned to the lumped structure. The 3D model includes the asymmetric features of eddy current breaks, pancake splices, current lead connections and the discrete mounting of the two cryocoolers (see Table 4).

Table 4. Thermal Model Inputs

Parameter	2D Axisymmetric	3D Solid
Heat Load & Distribution Radial (ID → OD) Axial	12 W Linear Decrease Uniform	12 W Linear Decrease Uniform
Operating Temperature	20 K	20K
Material Properties	Isotropic	Orthotropic & Isotropic
Thermal Contact Resistance	0	0
Eddy Current Breaks	None	Included
Splice features	None	Included (per pancake)
Current Lead features	None	Included
Cryocooler Connection	Distributed at each end	Discrete at each end
Outer Conductive Shell	Uniform	Discrete

Figure 17 is the 3D thermal analysis fringe plot of the lumped coil structure. For a starting operating temperature of 20 K, the 3D analysis predicts a maximum temperature of 22.19 K within the HTS coil. The addition of a 0.50 K calculated

temperature difference across the flexible cryocooler connection (not shown) yields a maximum HTS coil temperature to 22.69 K.

In summary, A 2D axisymmetric stress/strain analysis is performed to simulate the four states of magnet assembly through operation. Results of the analysis indicate that the mechanical stress is less than 10 MPA at room temperature and 32.6 MPA at 20 K and 400 A. These values are well within the operating limits of the HTS material. A 2D axisymmetric and 3D thermal analysis is performed to determine the maximum temperatures of the coil under steady state operating conditions. For a 12 W heat load, the 2D and 3D analysis results show a maximum $\Delta\Delta T$ of ~ 0.5 K and 3K, respectively. These values are well within the safe operating envelope of the HTS magnet system.

What is claimed is:

1. A mandrel for a superconductive double pancake coil assembly having a recessed channel provided therein, said recessed channel having a width and depth for placement of a superconductive material.

2. A mandrel as claimed in claim 1 wherein said recessed channel is a serpentine path.

3. A mandrel as claimed in claim 1 wherein said recessed channel is helical.

4. A mandrel as claimed in claim 1 wherein said recessed channel has a variable depth and a substantially constant width and said superconductive material is completely contained within said channel at a point of maximum depth of said channel.

5. A mandrel as claimed in claim 4 wherein said mandrel is substantially circular and said recessed channel is disposed in an arc of about 60 degrees to 360 degrees of said circular mandrel.

6. A splice block for a superconductive double pancake coil assembly having a recessed channel provided therein, said recessed channel having a width and depth for placement of a spliced superconductive material.

7. A splice block as claimed in claim 6 wherein said recessed channel is a serpentine path.

8. A splice block as claimed in claim 6 wherein said recessed channel is helical.

9. A splice block as claimed in claim 6 wherein said recessed channel has a variable depth and a substantially constant width and said spliced superconductive material is completely contained within said channel at a point of maximum depth of said channel.

10. A superconductive coil assembly for generating a magnetic field comprising:

an end piece;

at least one pancake assembly adjacent to said end piece, said pancake assembly comprising superconductive material and a radial heat transfer element, wherein said superconductive material is disposed between said radial heat transfer element and said end piece; and

a thermally conductive element having a thermally conductive connection with said end piece and said radial heat transfer element.

11. A superconductive coil assembly as claimed in claim 10 wherein said thermally conductive element is free of contact with said superconductive material.

12. A superconductive coil assembly as claimed in claim 10 wherein said thermally conductive element has greater thermal conductivity than said end piece or said radial heat transfer element.

13. A superconductive coil assembly as claimed in claim 10 wherein said thermally conductive connection is swaged.

14. A superconductive coil assembly as claimed in claim 10 wherein said radial heat transfer element is a plate and said end piece is a ring.

15. A superconductive coil assembly as claimed in claim 10 wherein said thermally conductive element comprises gold-coated copper.

16. A superconductive coil assembly as claimed in claim 11 wherein the central axis of said thermally conductive element is located parallel to the central axis of the superconductive coil assembly and is external to an outermost portion of said superconductive material.

17. A superconductive coil assembly as claimed in claim 11 wherein the central axis of said thermally conductive element is located parallel to the central axis of the superconductive coil assembly and is external to an innermost portion of said superconductive material.

18. A superconductive coil assembly as claimed in claim 16 wherein there is a second thermally conductive element and the central axis of the second thermally conductive element is located parallel to the central axis of the superconductive coil assembly and is external to an innermost portion of said superconductive material.

19. A superconductive coil assembly as claimed in claim 10, wherein said radial heat transfer plate contains a plurality of holes around an outermost portion and said thermally conductive element comprises a plurality of cooling rods, each rod engaging a hole in the heat transfer plate.

20. A superconductive coil assembly as claimed in claim 19, further comprising a thermally conductive strap adjacent the end ring on a side opposite the

pancake assembly, and wherein said plurality of rods each have an end which is thermally connected to the strap.

21. A method of extracting impurities from a stream of material comprising:

passing the stream through a magnetizeable filter located in a magnet coil of a superconductive magnet assembly;

energizing the magnet assembly with a direct current;

cooling the magnet assembly with an closed refrigerant system connected to the magnet coil to thereby magnetically attract impurities to the filter and remove them from the stream.

22. The method of claim 21, further comprising:

stopping the passing of the stream and deenergizing the magnet assembly;

cleaning the impurities from the filter;

repeating the passing and energizing steps.

23. The method of claim 22, wherein passing the stream comprises passing a slurry containing titanium dioxide and impurities.

24. A method of cooling a superconductive coil assembly for generating a magnetic field comprising:

placing a thermally conductive end ring adjacent one side of a first superconductive pancake assembly;

connecting a closed refrigerant system to the end plate;

placing a first radial heat transfer plate adjacent the opposed side of the first superconductive pancake assembly and establishing a thermal connection between the first plate and first pancake assembly; and

connecting a thermally conductive element between the end ring and the first plate to provide a thermal energy flow path between the first plate and the ring, to thereby establish a cooling path between the first pancake assembly and the refrigerant system.

25. The method of claim 24, further comprising

placing a second superconductive pancake assembly adjacent the first radial heat transfer plate;

placing a second radial heat transfer plate adjacent the opposed side of the second pancake assembly and establishing a thermal connection between the second pancake assembly, the first plate, and the second plate; and

connecting the thermally conductive element between the end ring and the second plate to provide a thermal energy flow path between the second plate and the ring, to thereby establish a cooling path between the second pancake assembly and the refrigerant system.

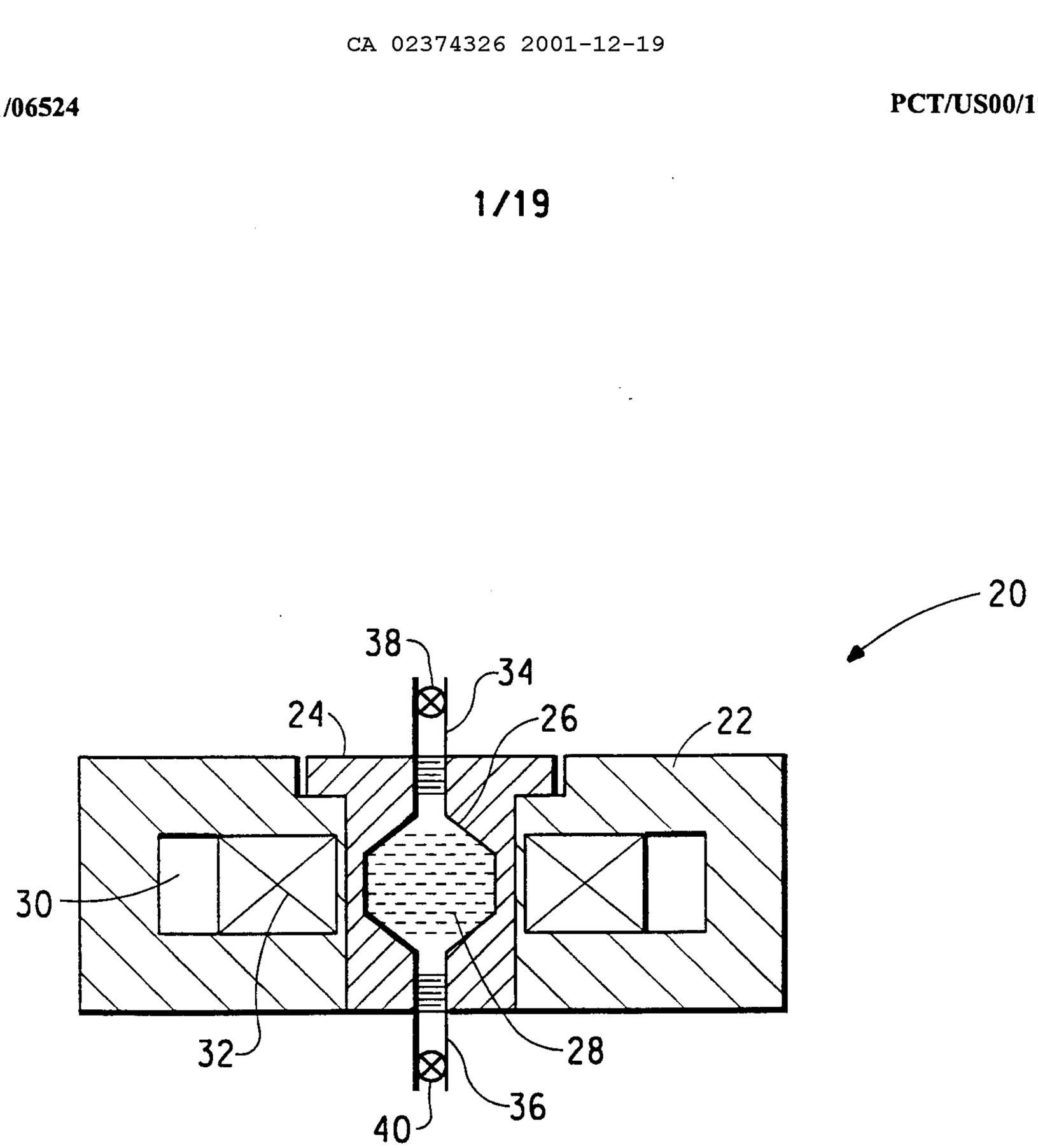

FIG. 1

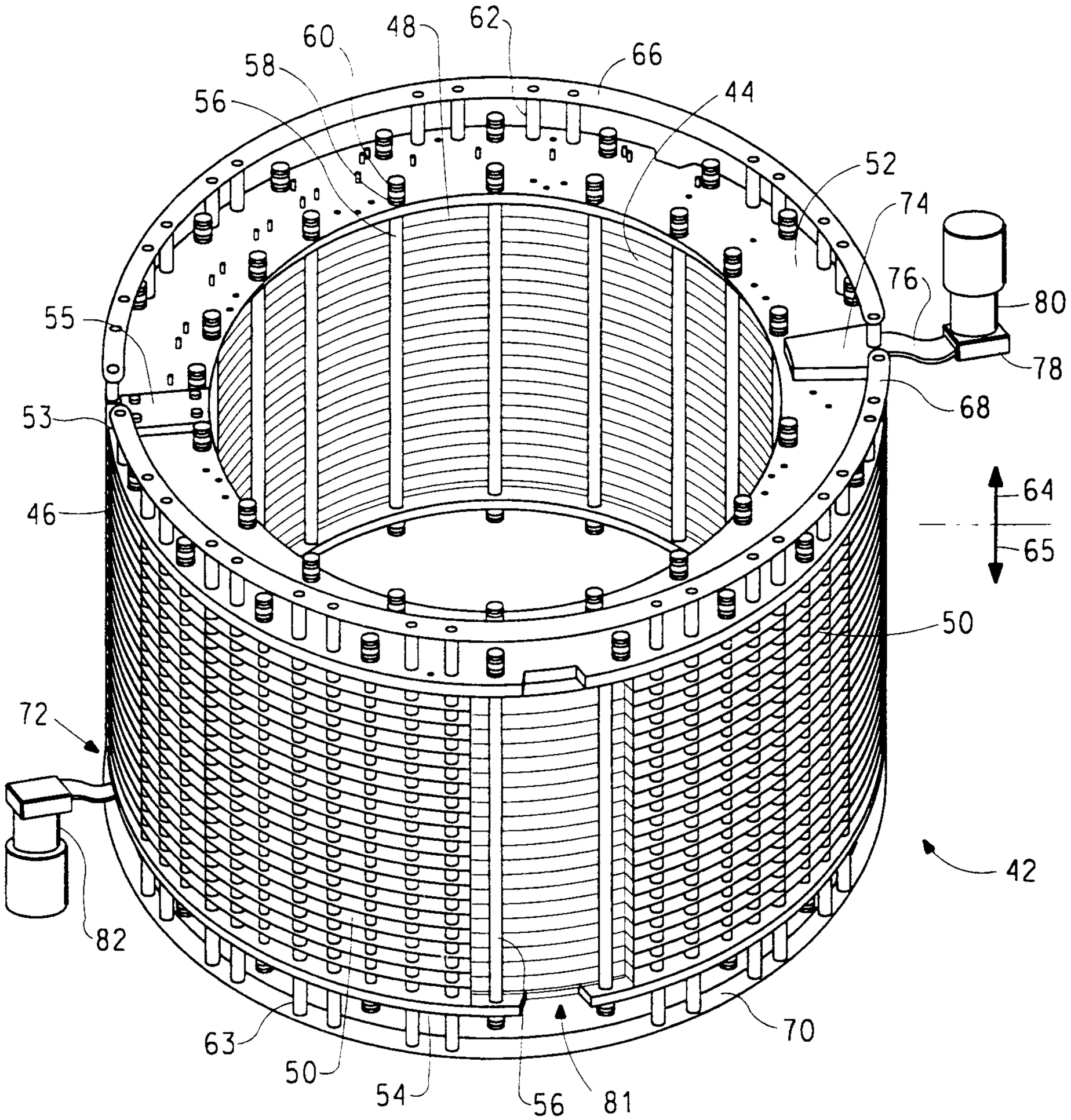
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FIG. 2A

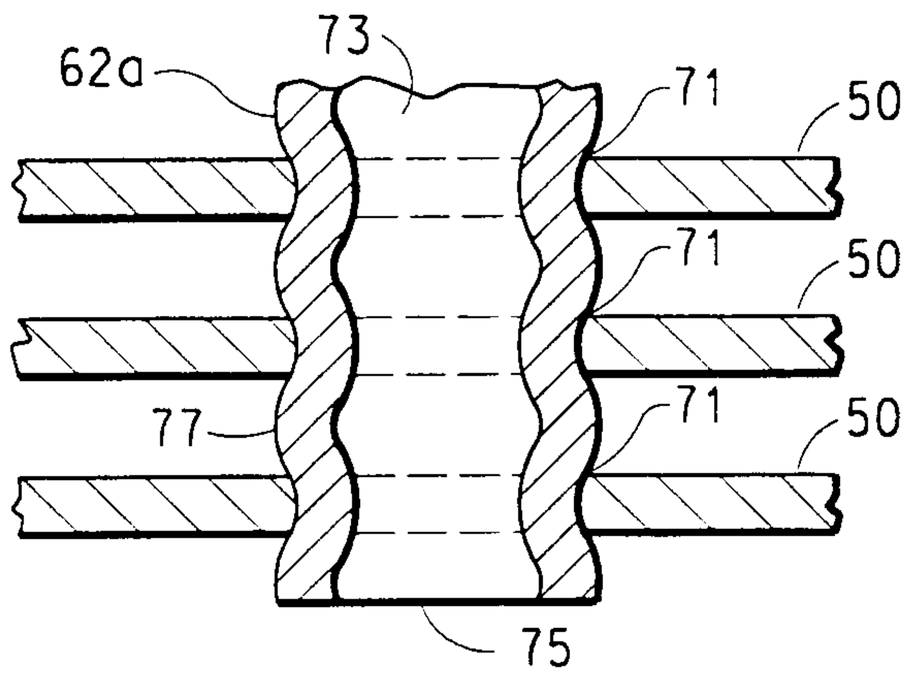
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FIG. 2B

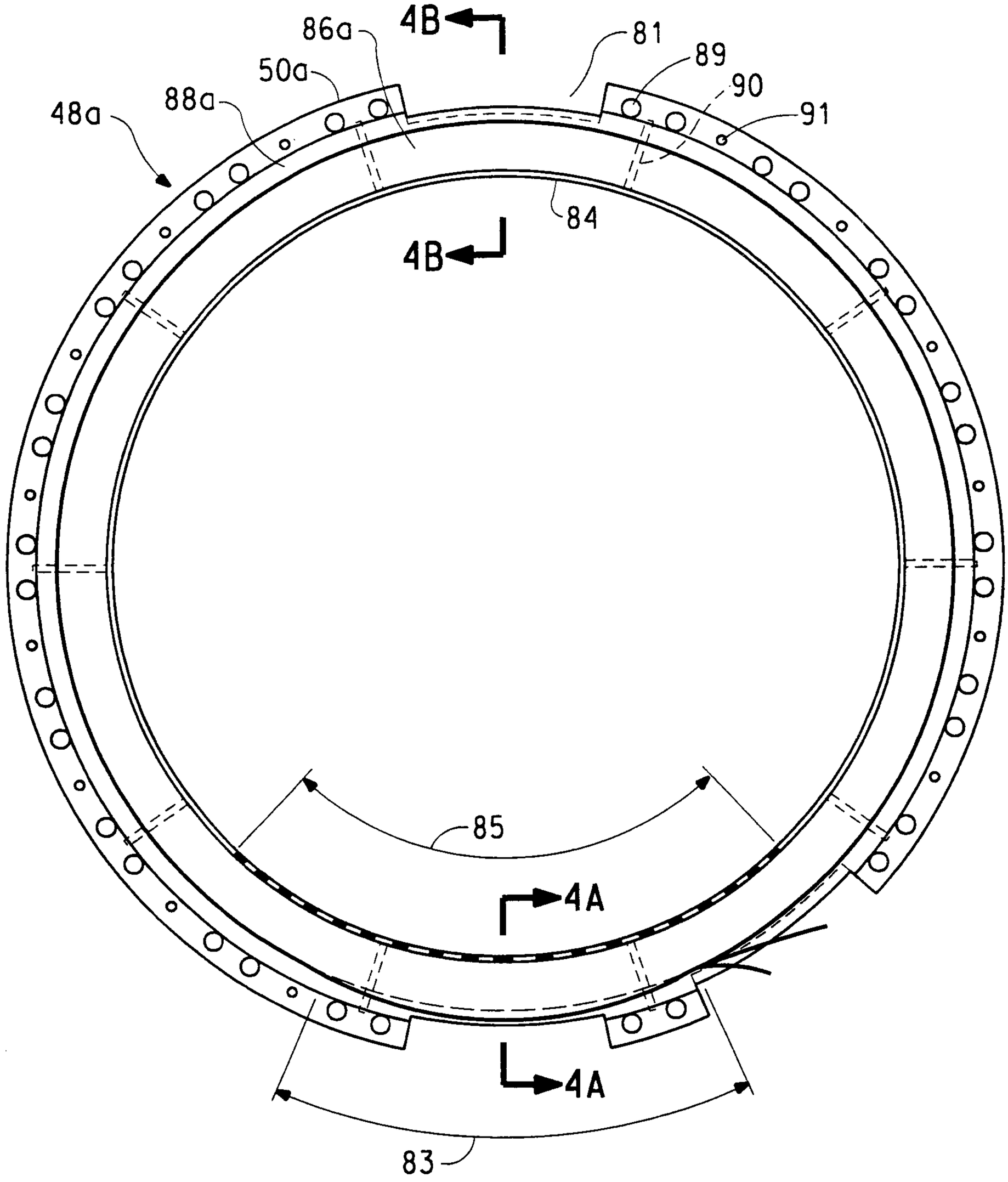
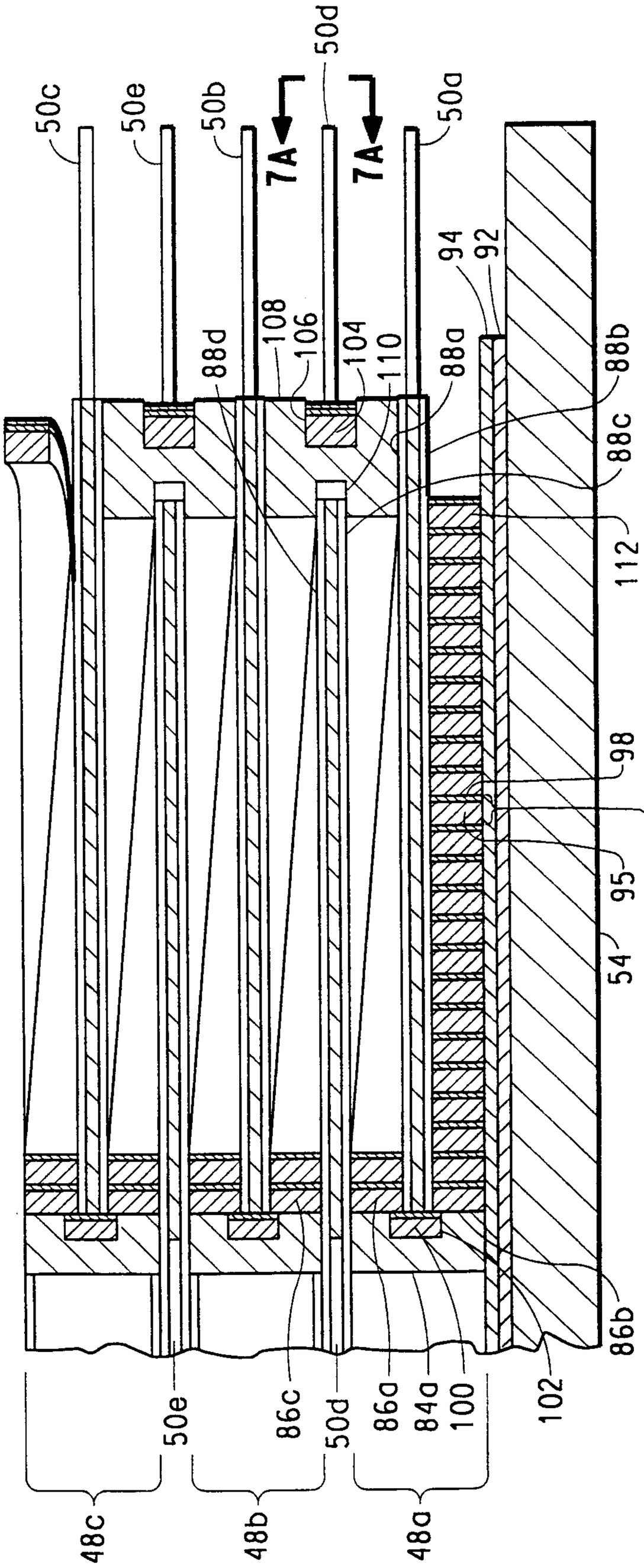


FIG. 3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50b
7A
50d
7A
50a
88d
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106
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110
88a
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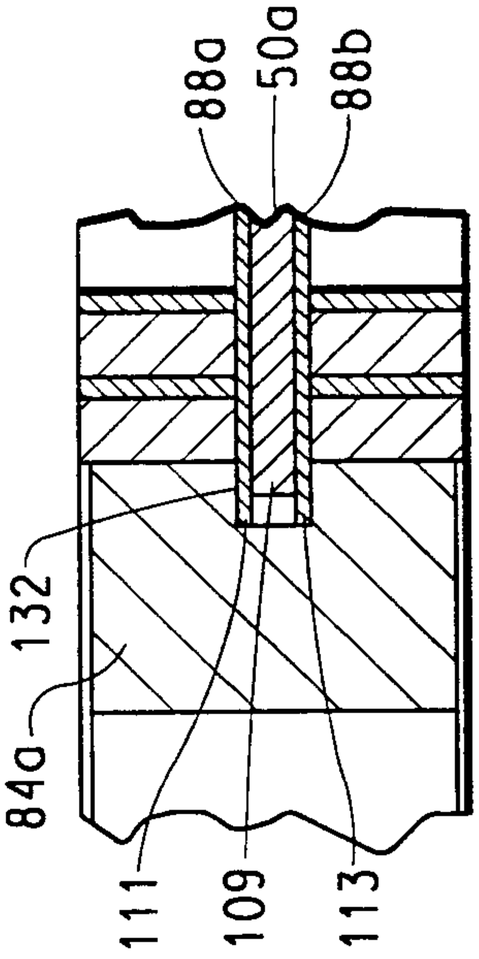
88c
112
98
87
95
54
86b
48c
50e
48b
86c
50d
48a
86a
84a
100
102

FIG. 4A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113

FIG. 4B

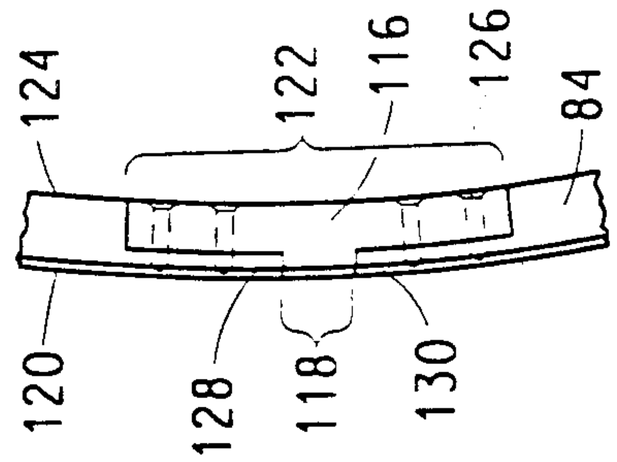

124
122
116
126
84
120
128
118
130

FIG. 5B

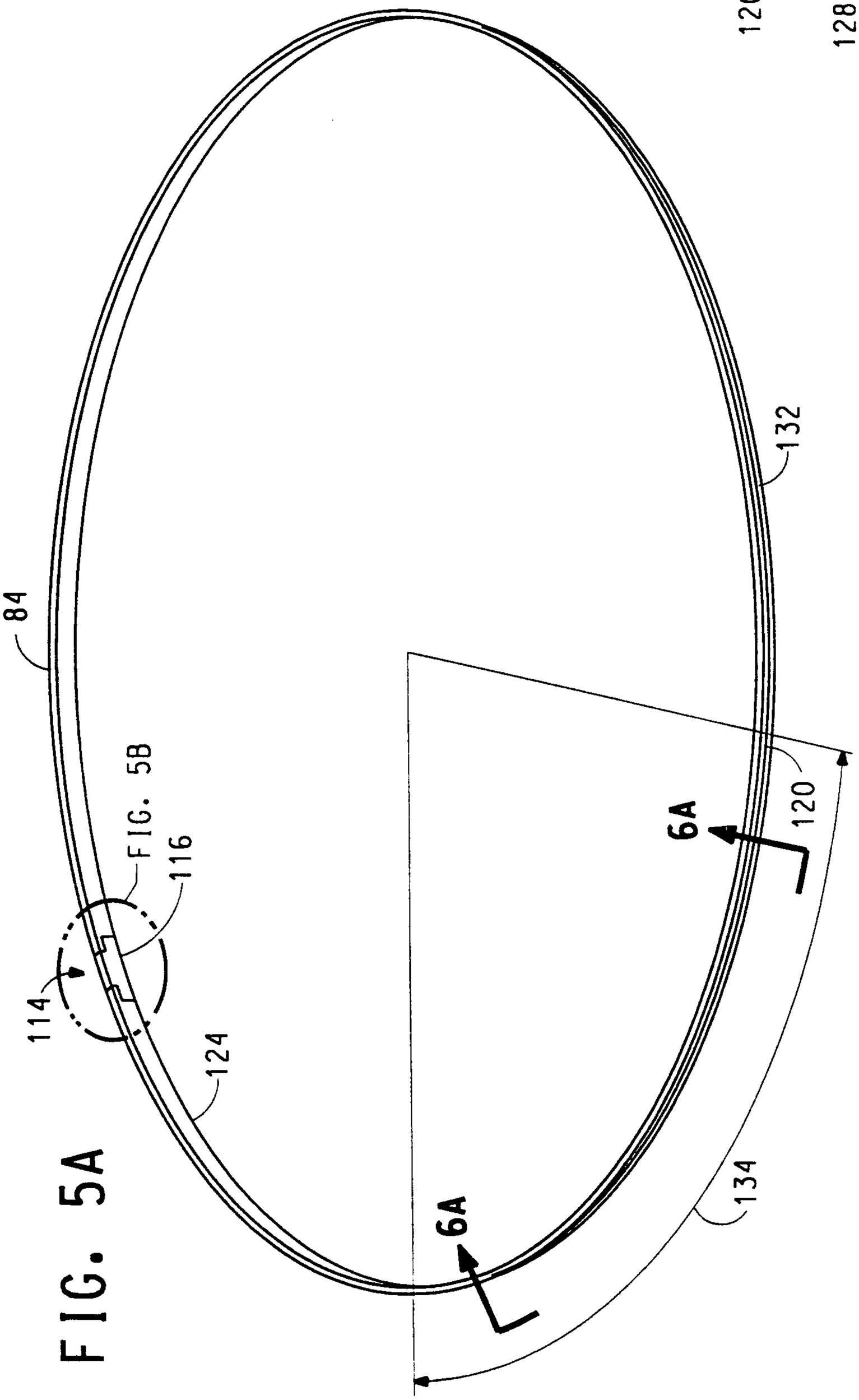
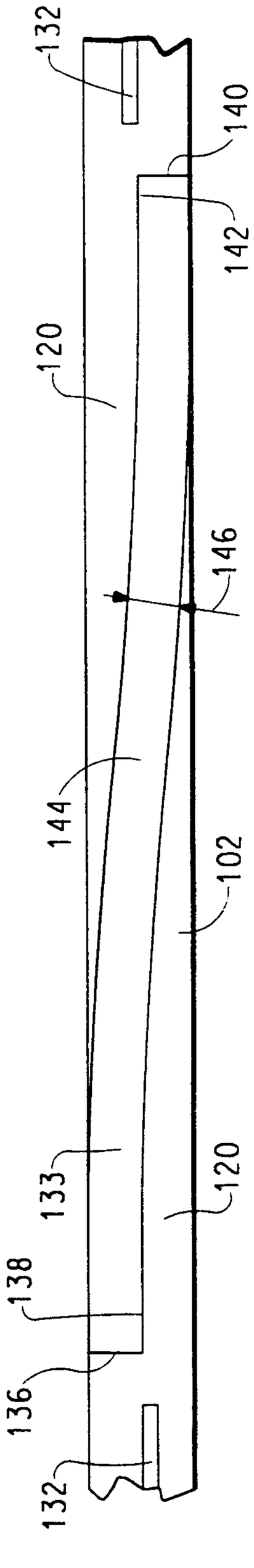

132
84
FIG. 5B
116
114
124
6A
120
6A
134

FIG. 5A


132
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144
102
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120
138
136
132

FIG. 6A

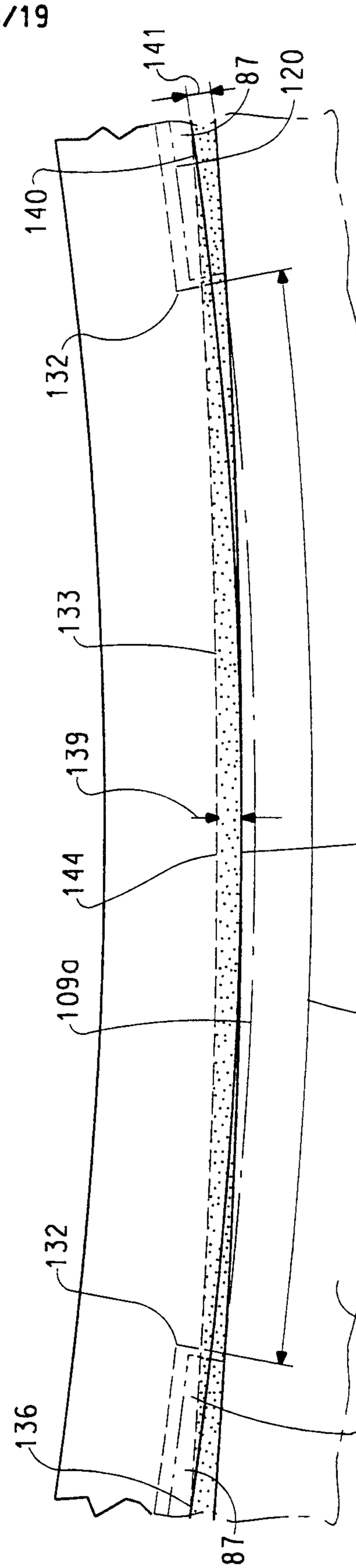
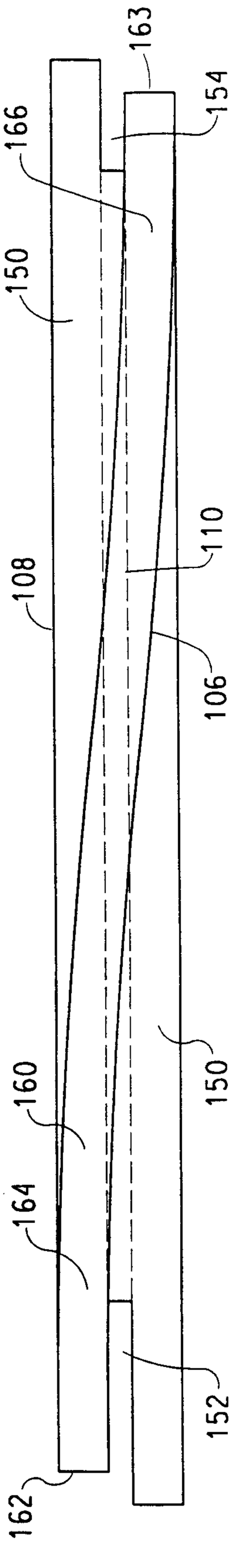

141
87
120
140
132
133
139
144
109a
120
148
132
50
136
120
87

FIG. 6B


163
154
166
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110
106
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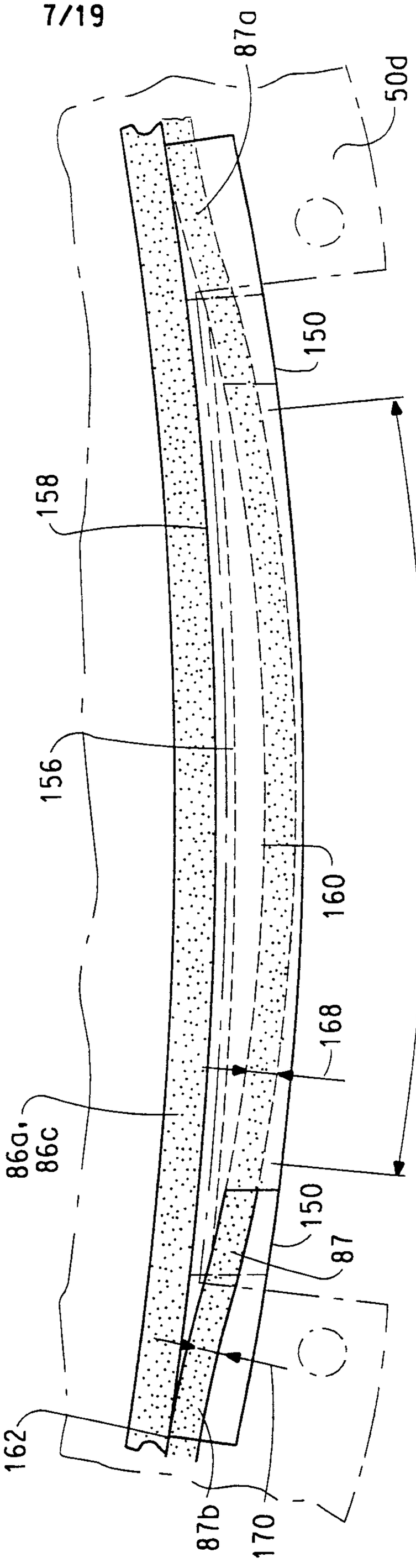
160
164
152
162

FIG. 7A


87a
50d
150
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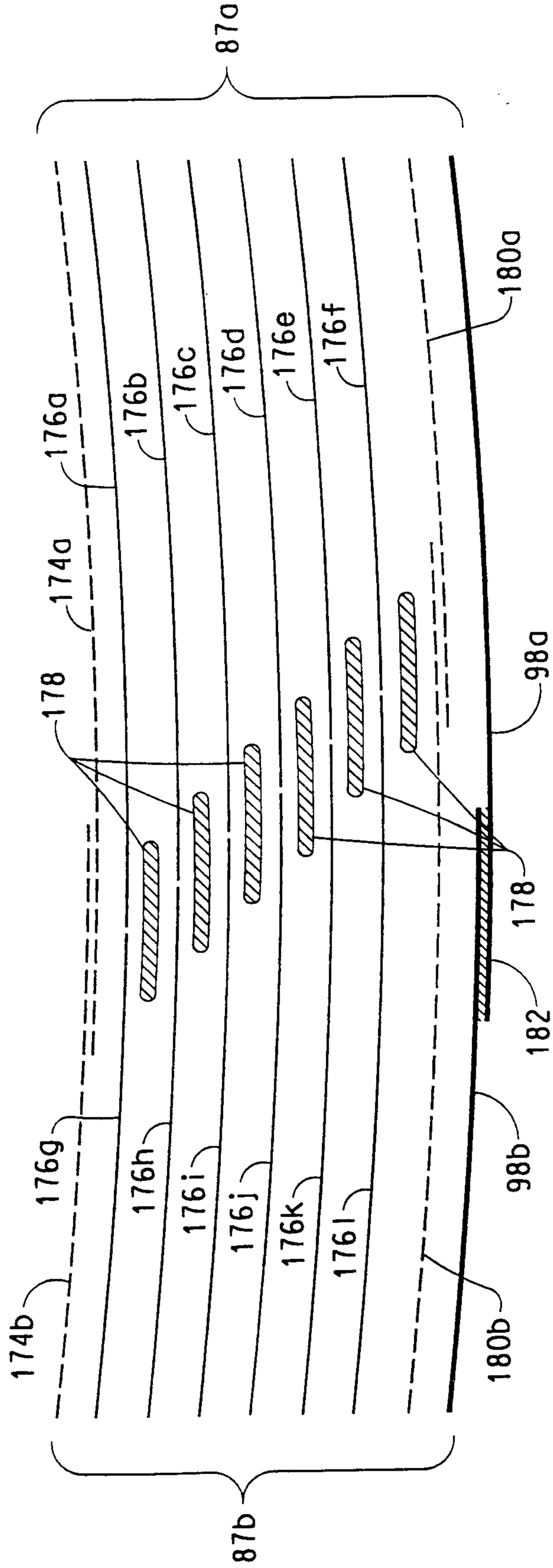
156
160
172
168
86a,
86c
150
87
162
87b
170

FIG. 7B


87a
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176a
178
176b
176c
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176e
176f
180a
98a
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182
98b
180b
176g
176h
176i
176j
176k
176l
174b
87b

FIG. 8

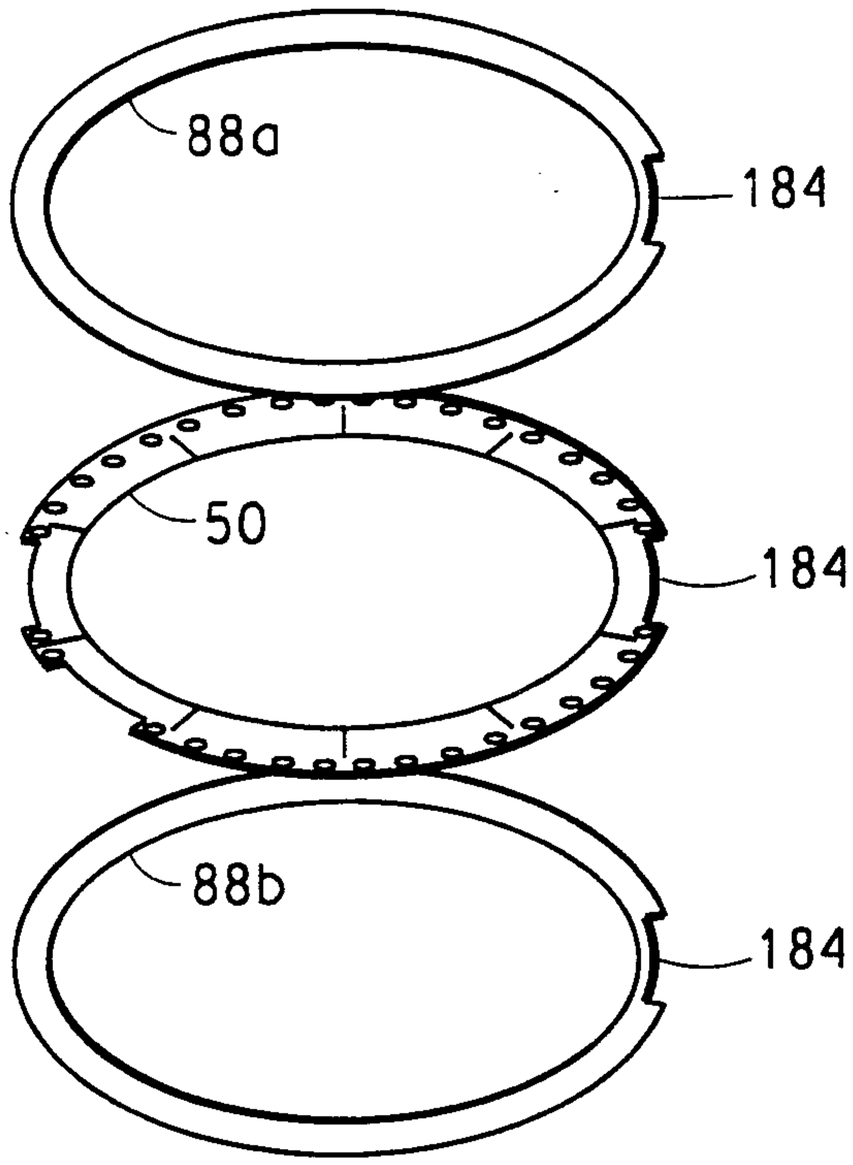


FIG. 9A

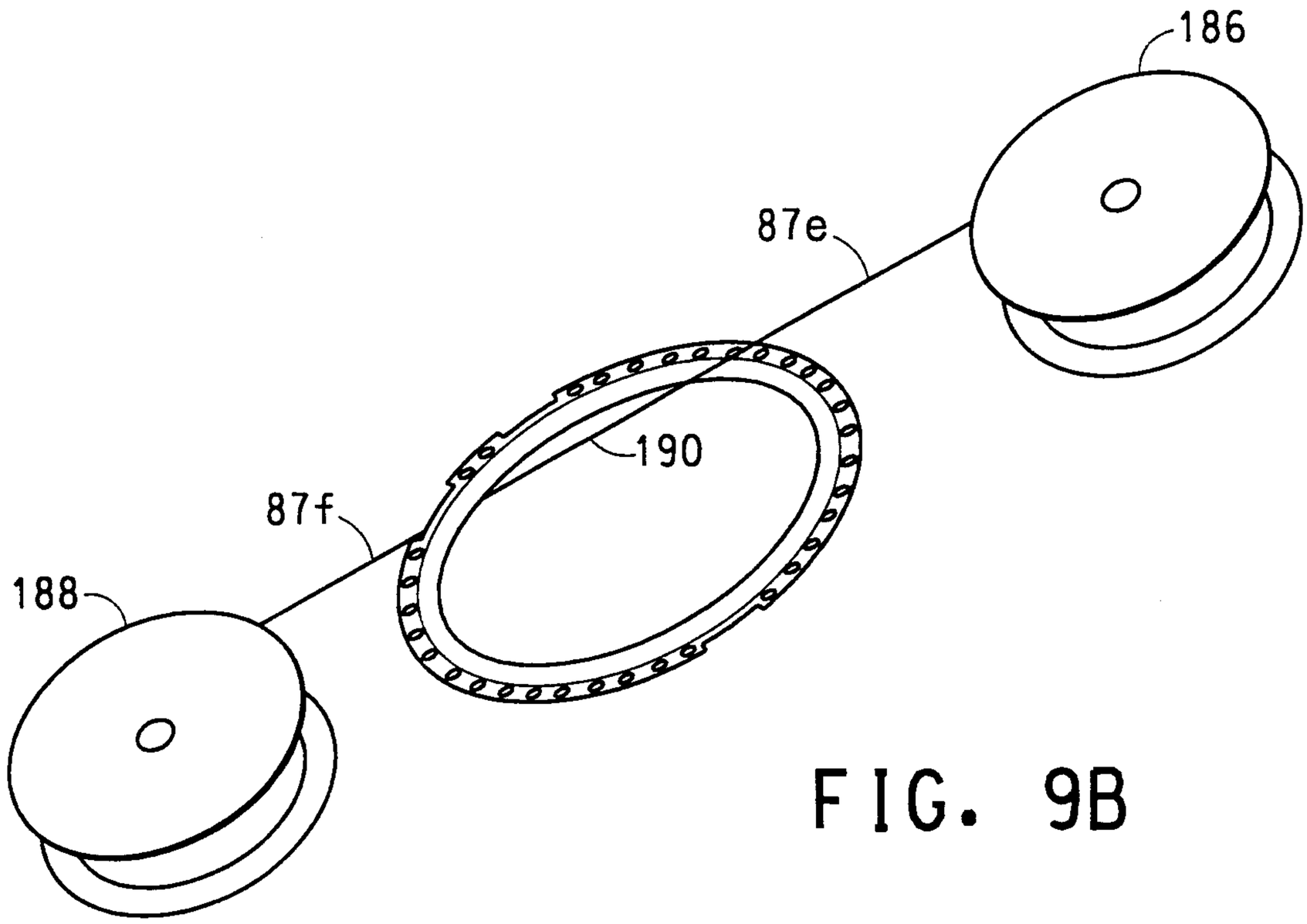


FIG. 9B

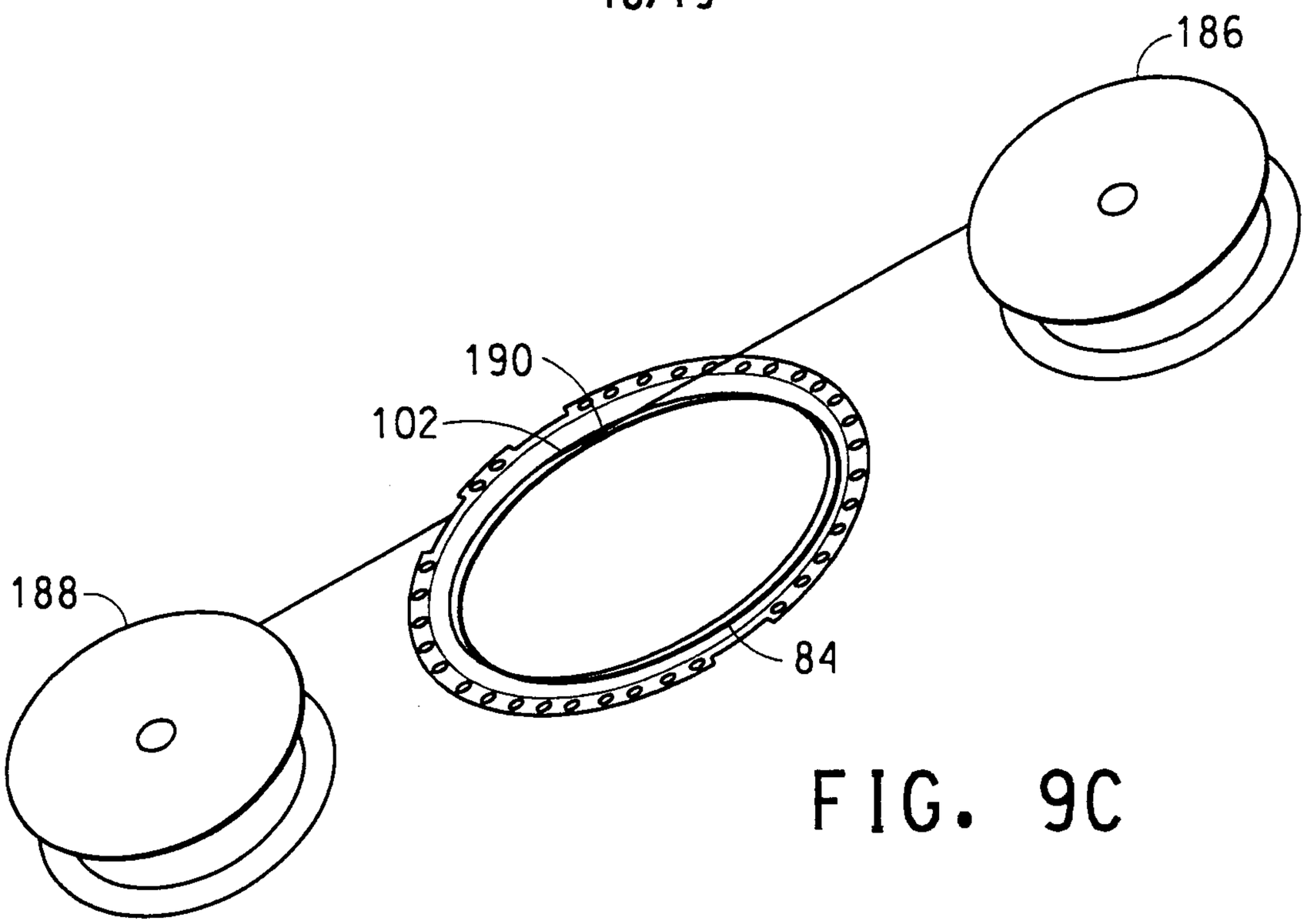


FIG. 9C

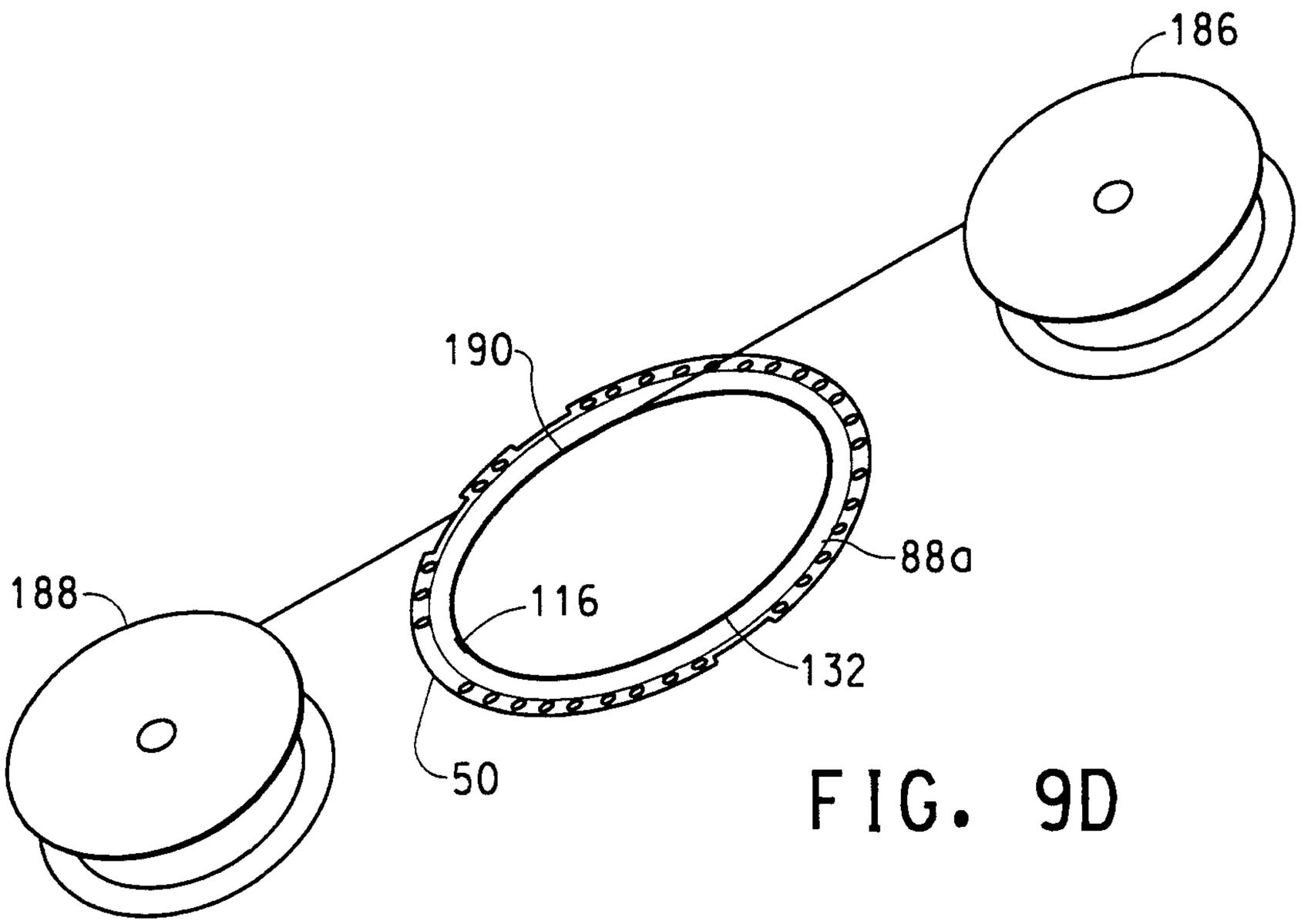
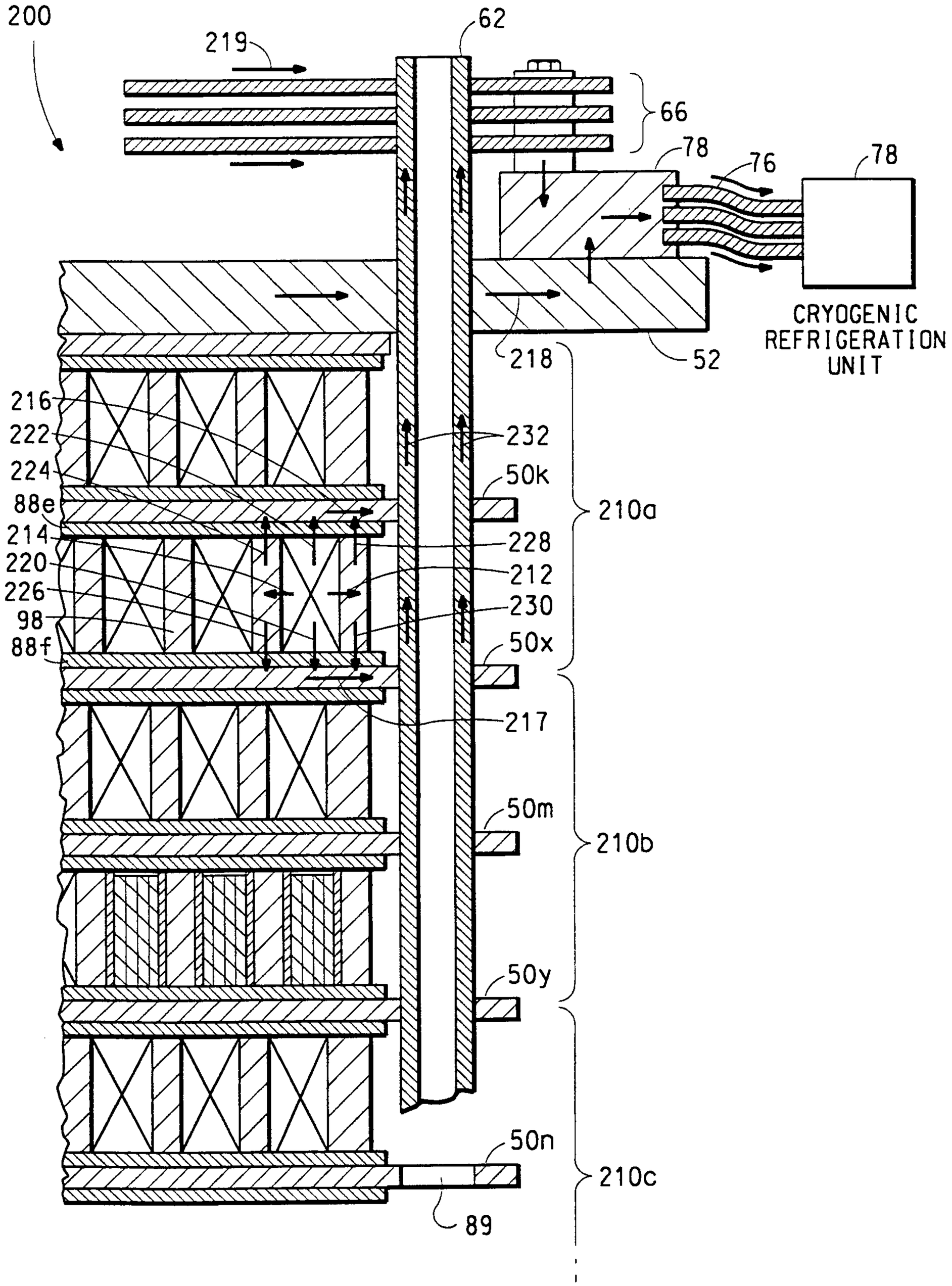


FIG. 9D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76
78
CRYOGENIC
REFRIGERATION
UNIT
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52
216
222
224
88e
214
220
226
98
88f
232
50k
228
212
230
50x
217
50m
50y
50n
89
210a
210b
210c

FIG. 10

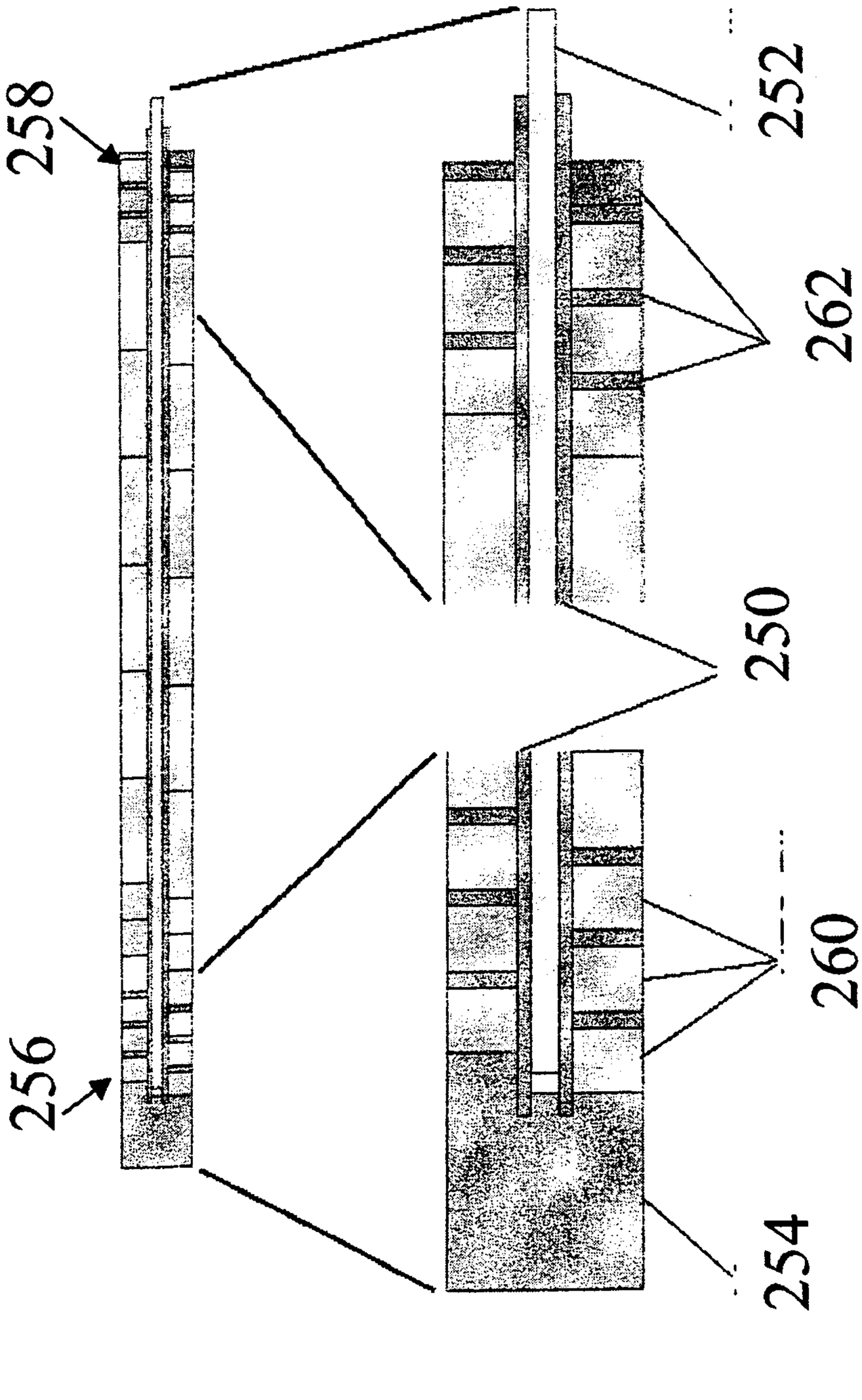


FIG. 11

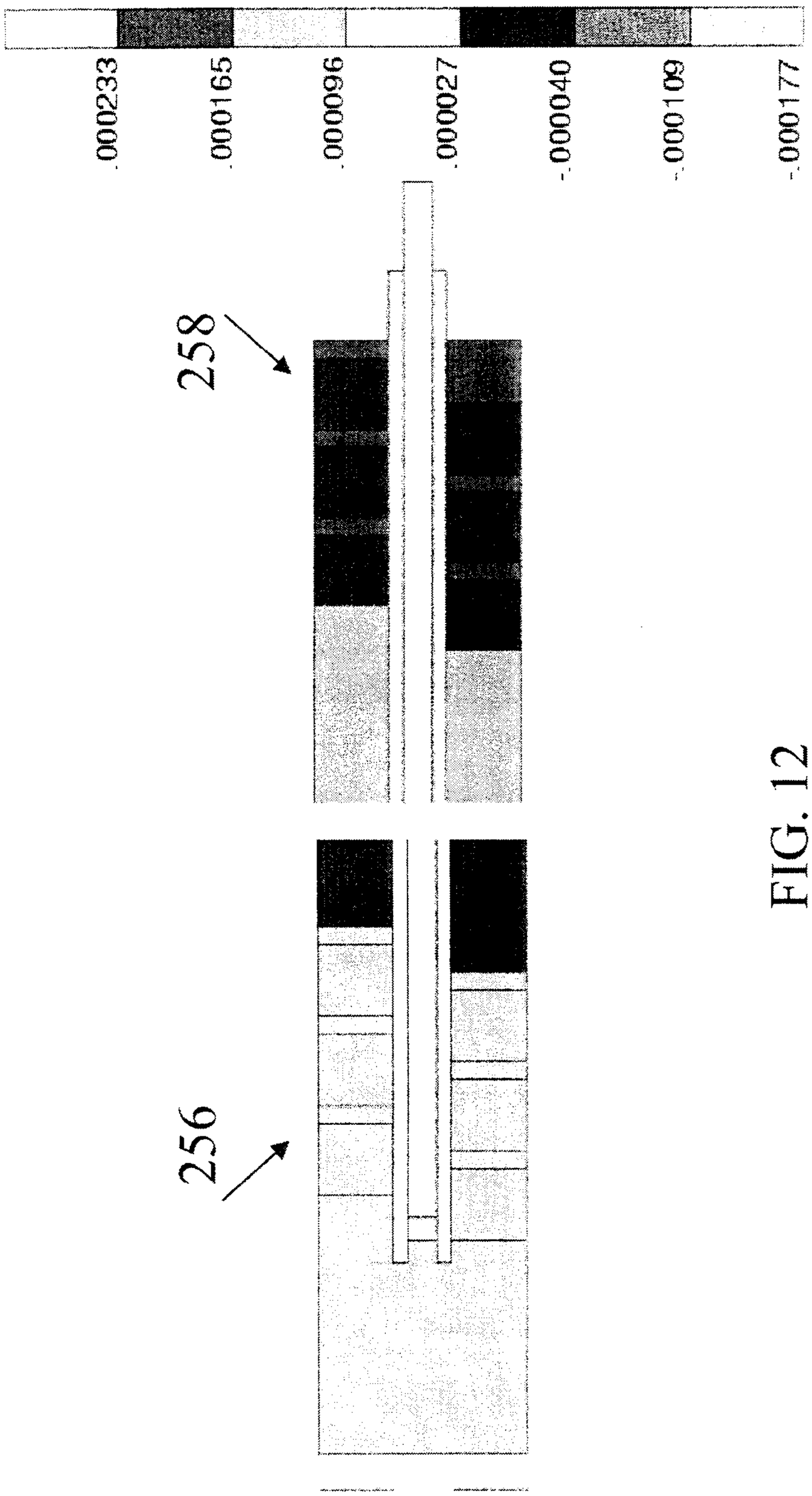


FIG. 12

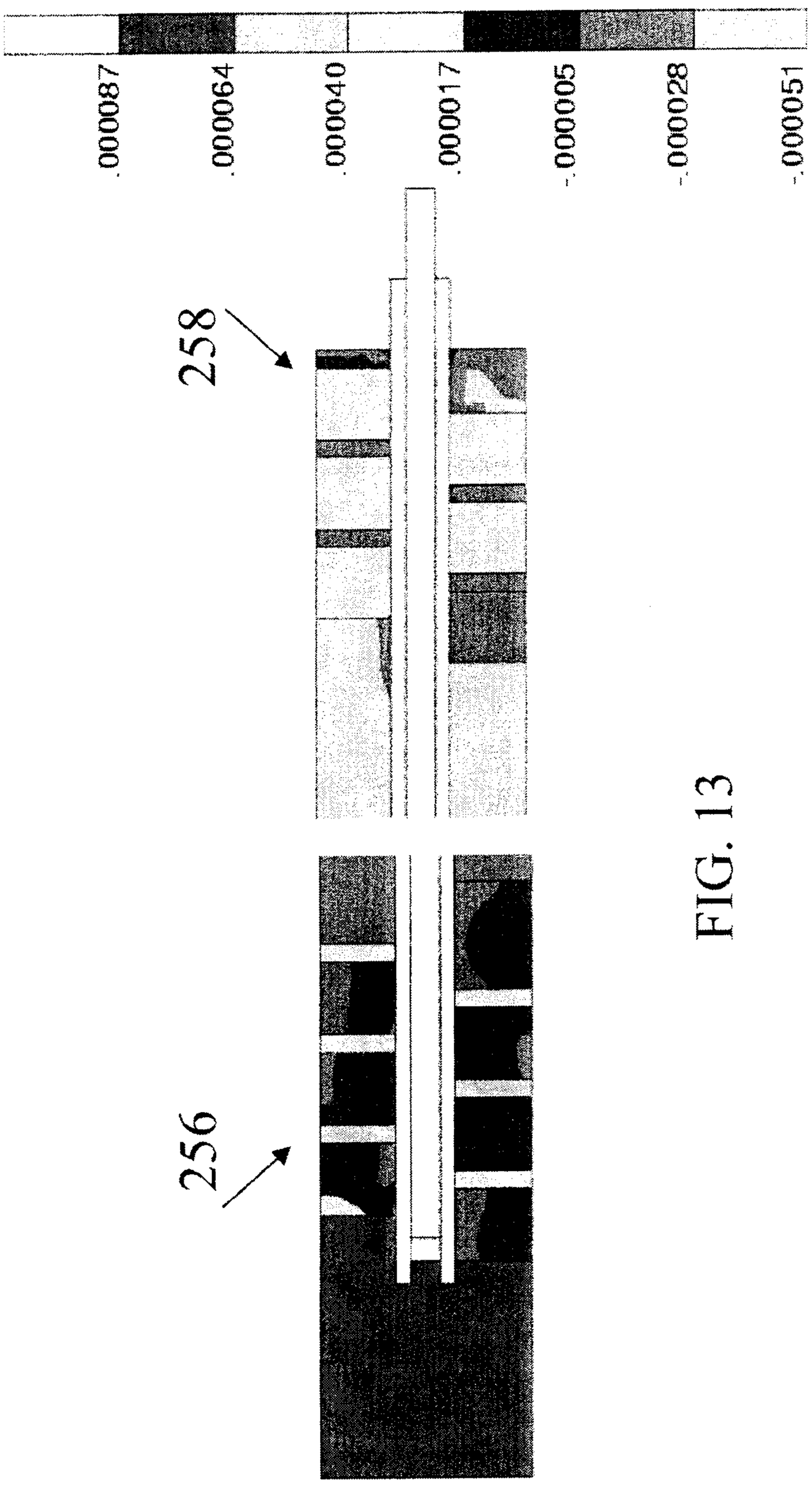


FIG. 13

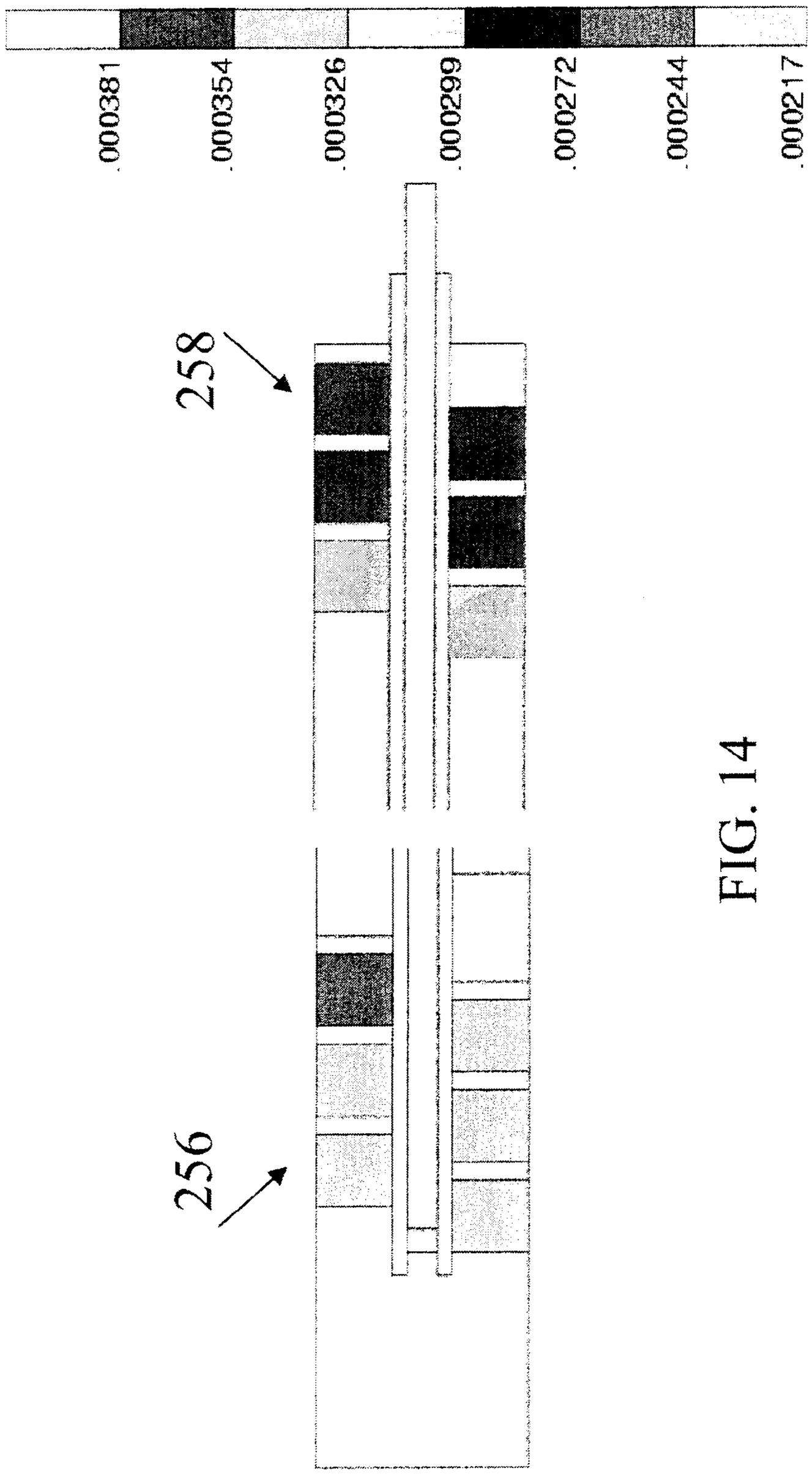


FIG. 14

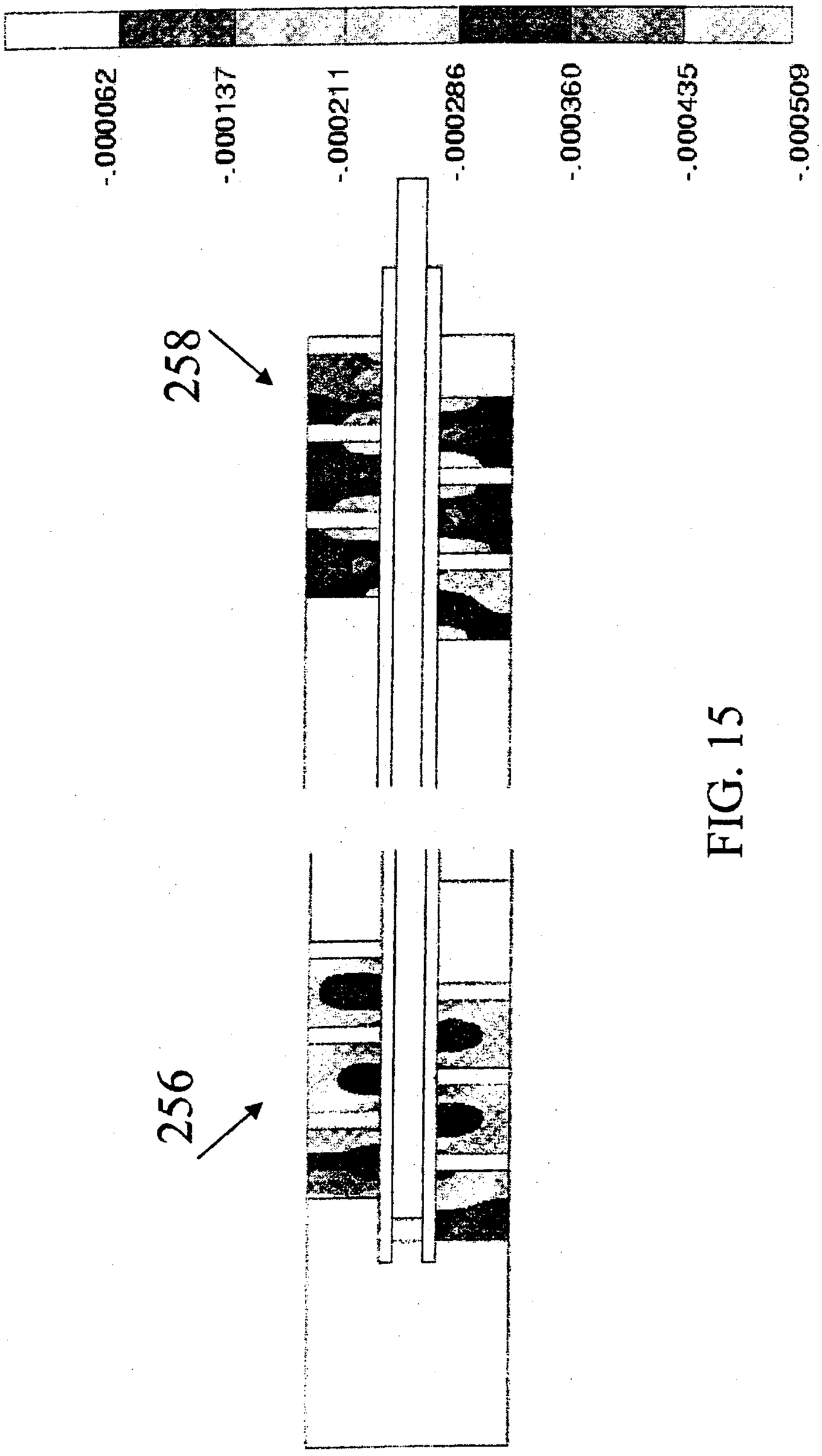
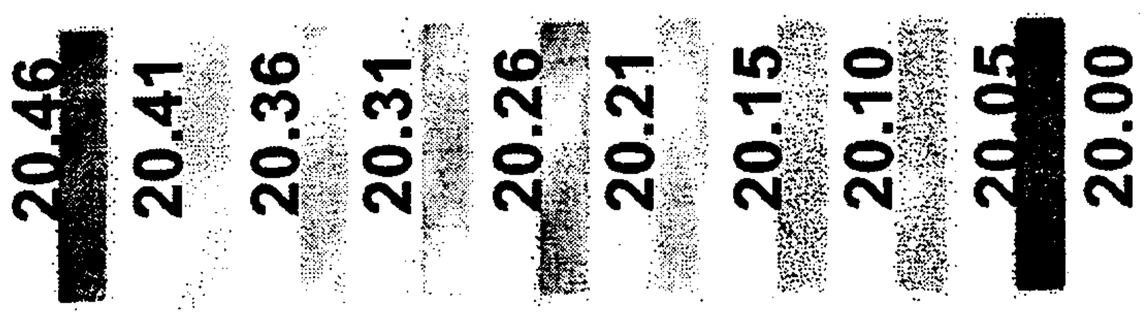


FIG. 15



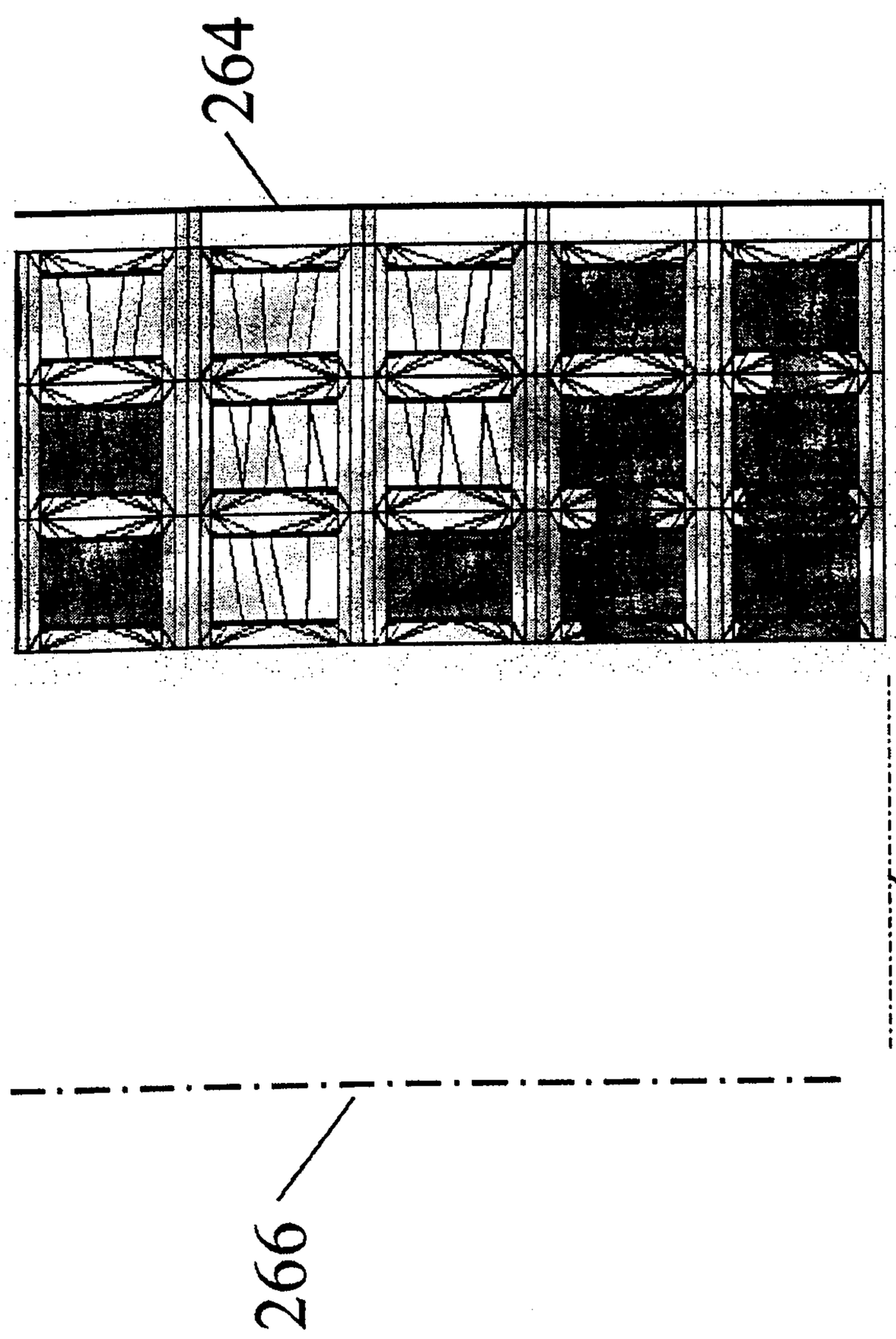
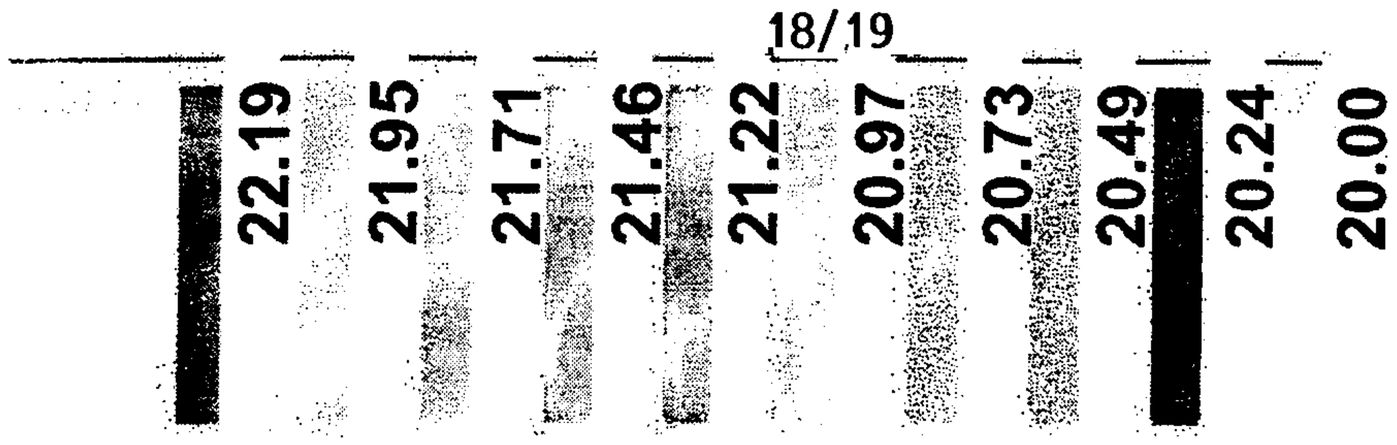


FIG. 16



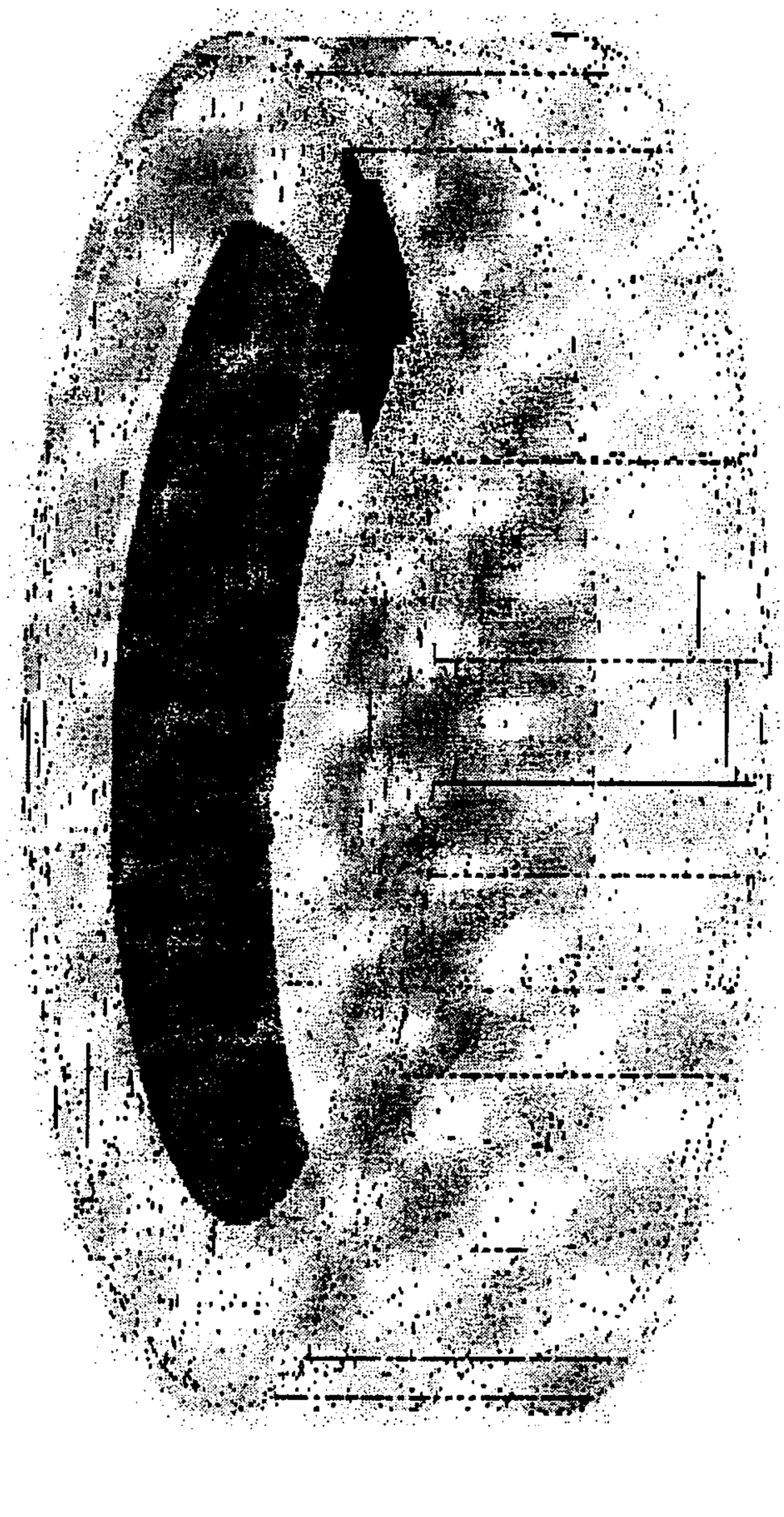


FIG. 17

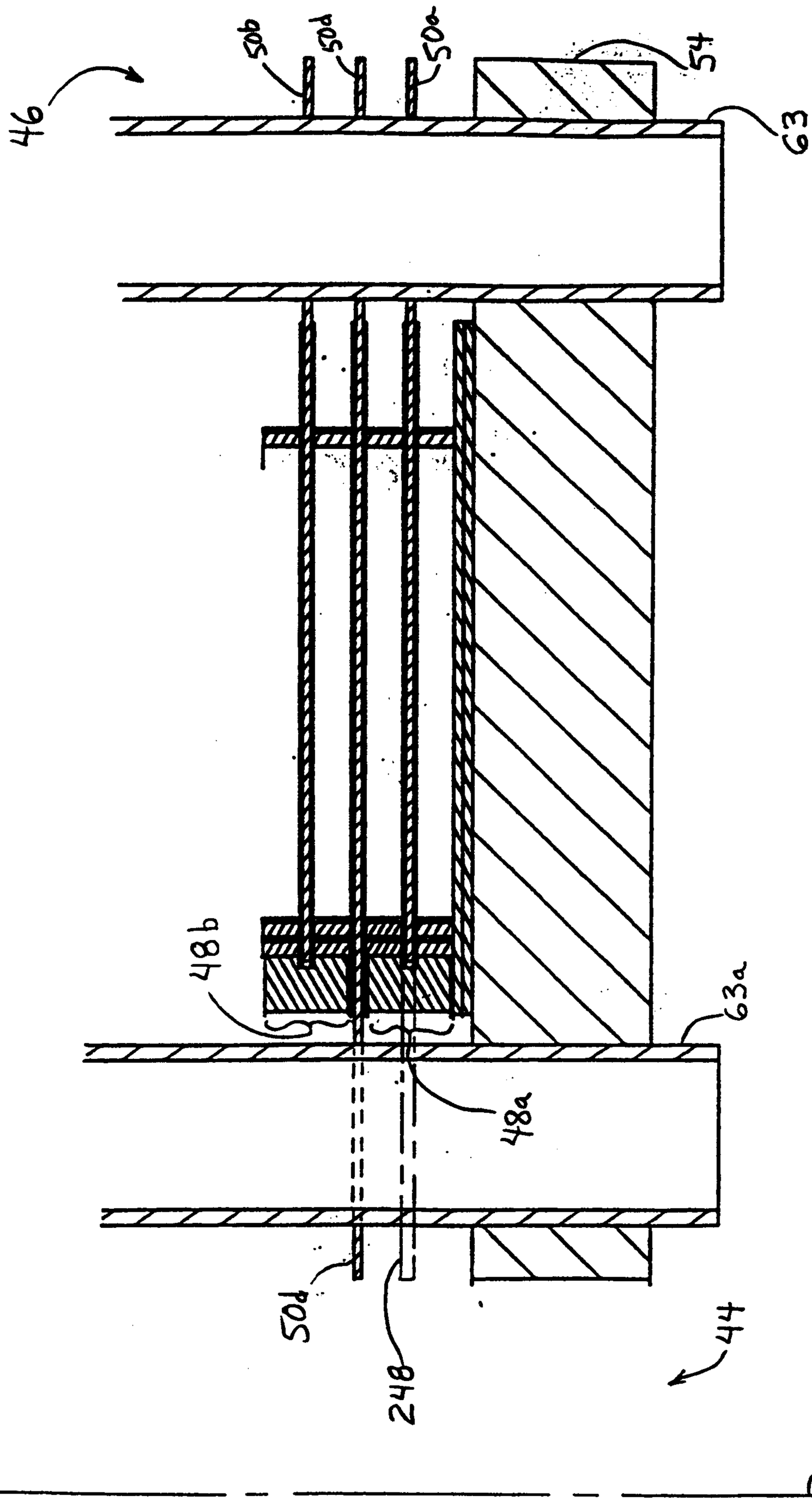
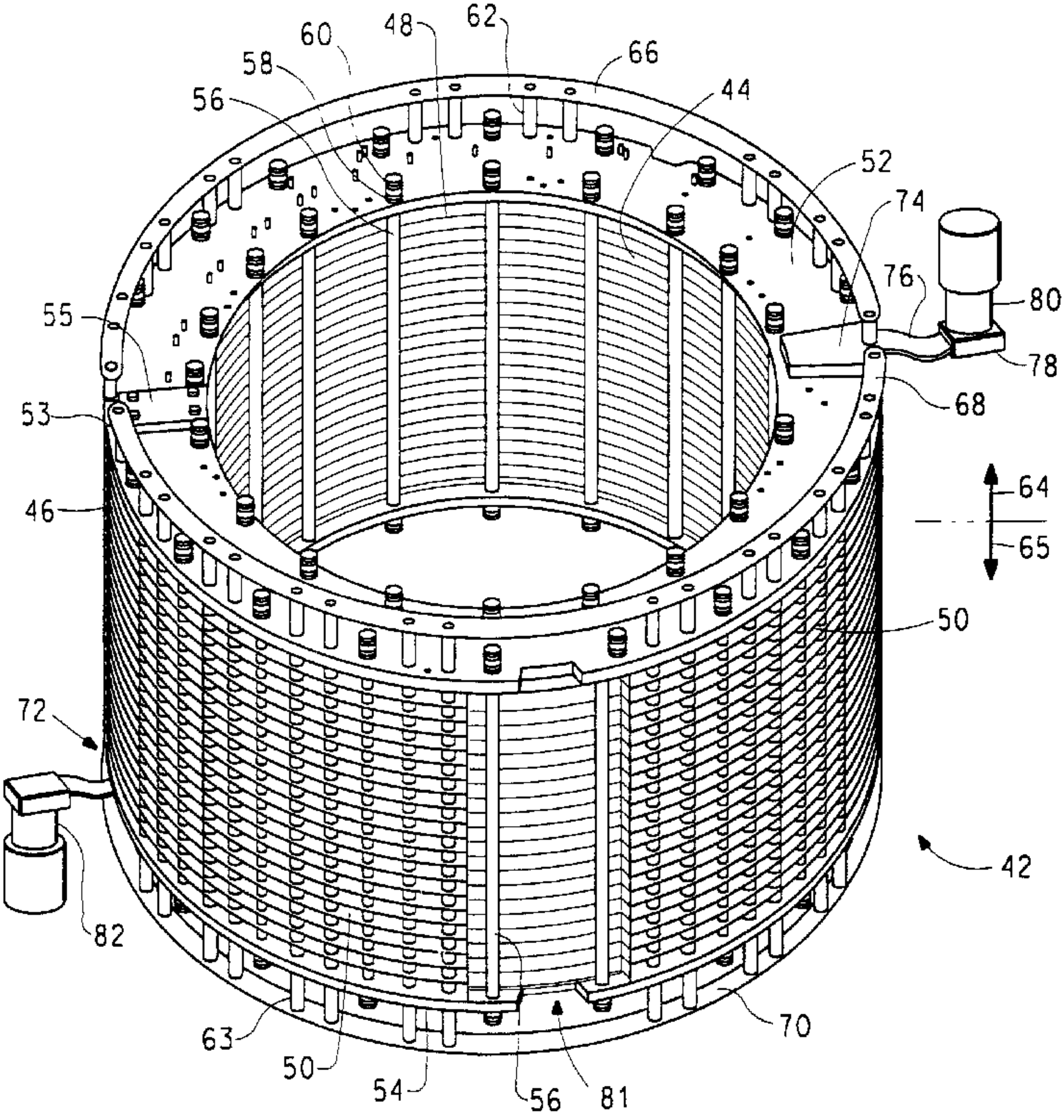


Fig 18


60
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