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(54) **FLEXIBLE HEAT EXCHANGERS**

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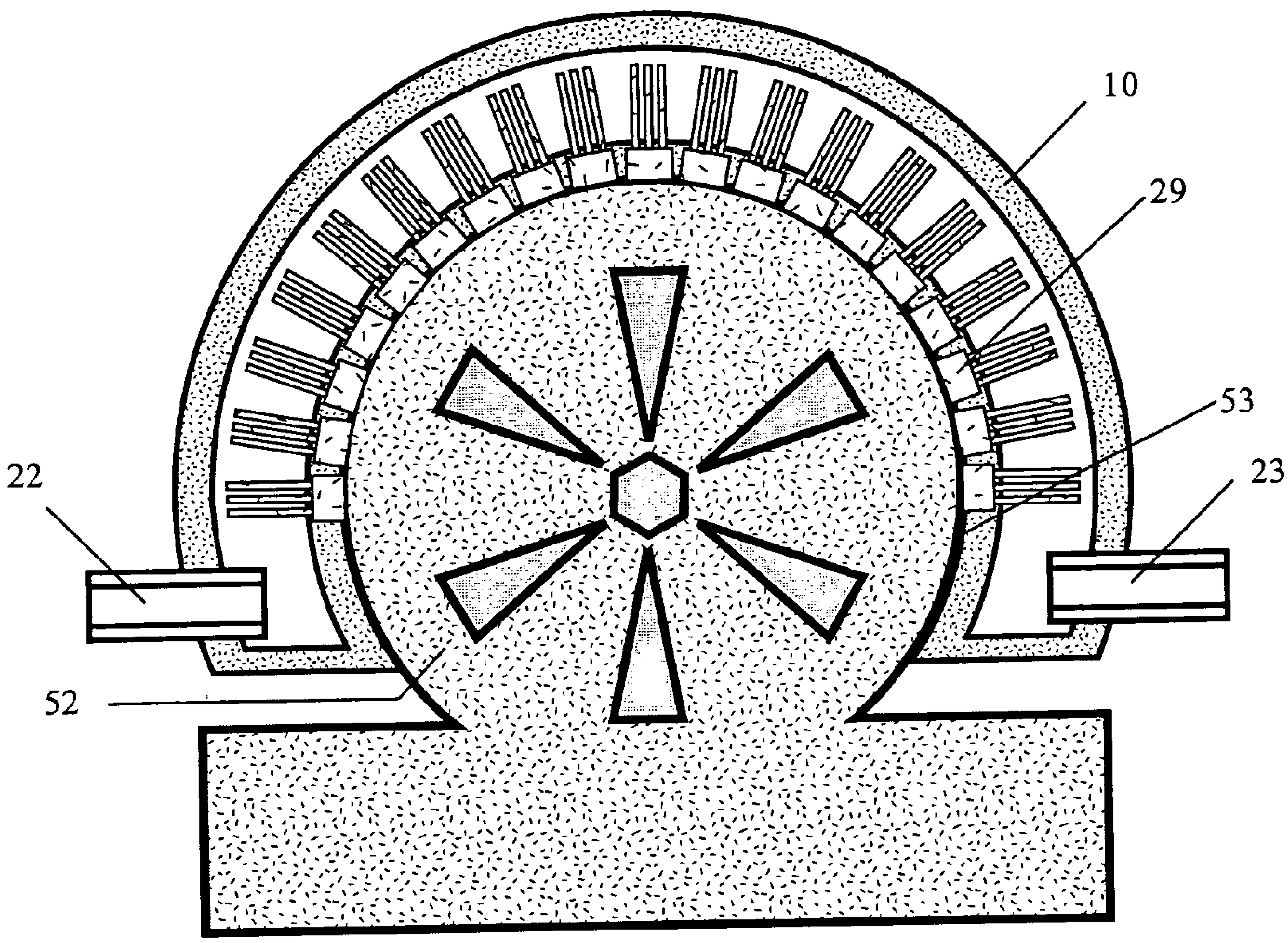
(57) **ABSTRACT**

A heat exchanger for heating or cooling objects is flexible and can conform to surface profiles of objects to be warmed or cooled. The heat exchanger has a volume having at least one inlet for receiving a heat exchange fluid and at least one outlet. A flexible plate essentially impermeable to the heat exchange fluid is penetrated by substantially rigid thermally conductive members. The members provide paths of high thermal conductivity through the plate. The heat exchange fluid may be water based.



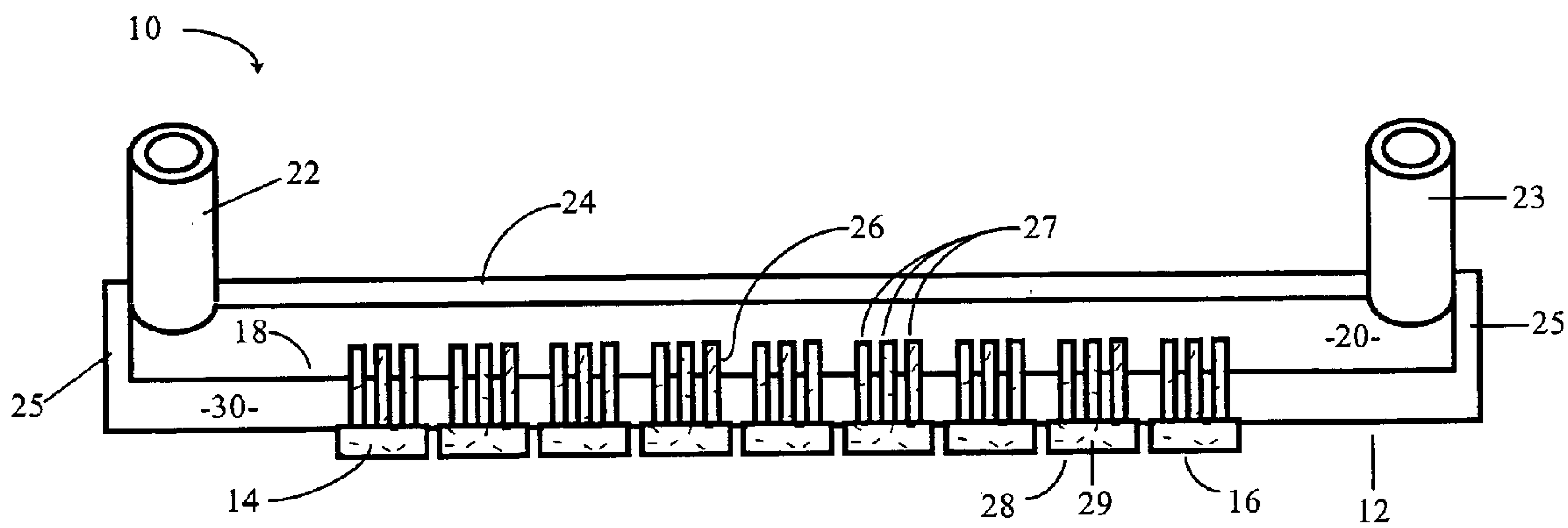


Figure 1A

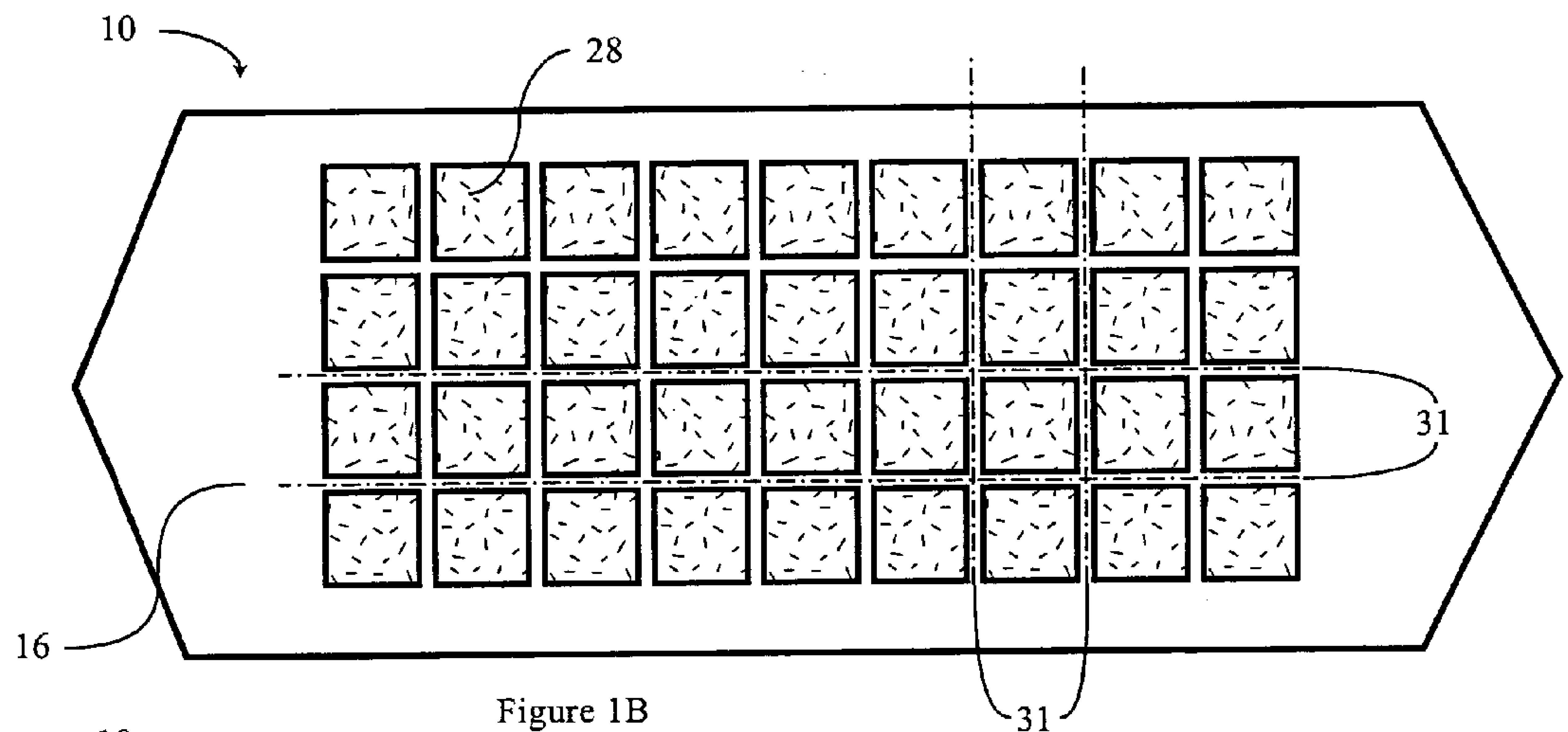


Figure 1B

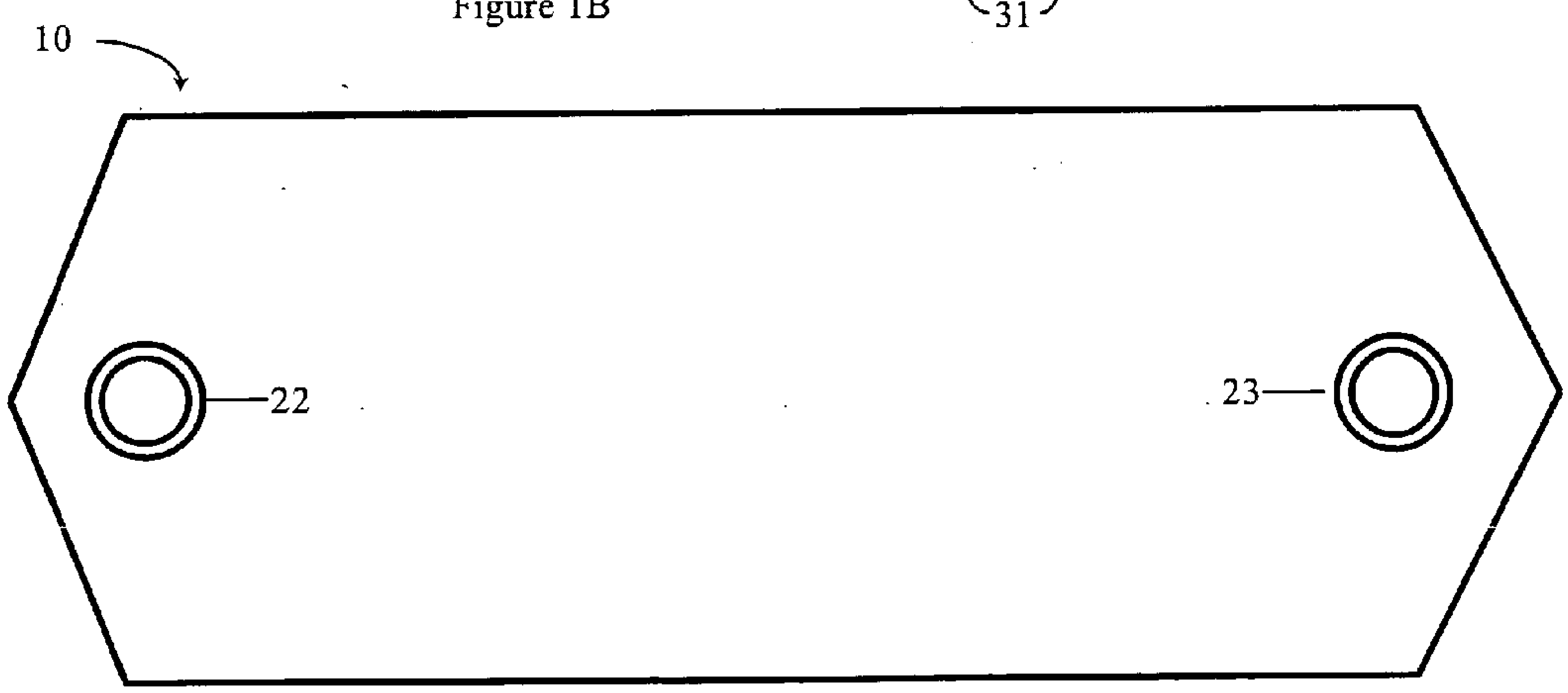


Figure 1C

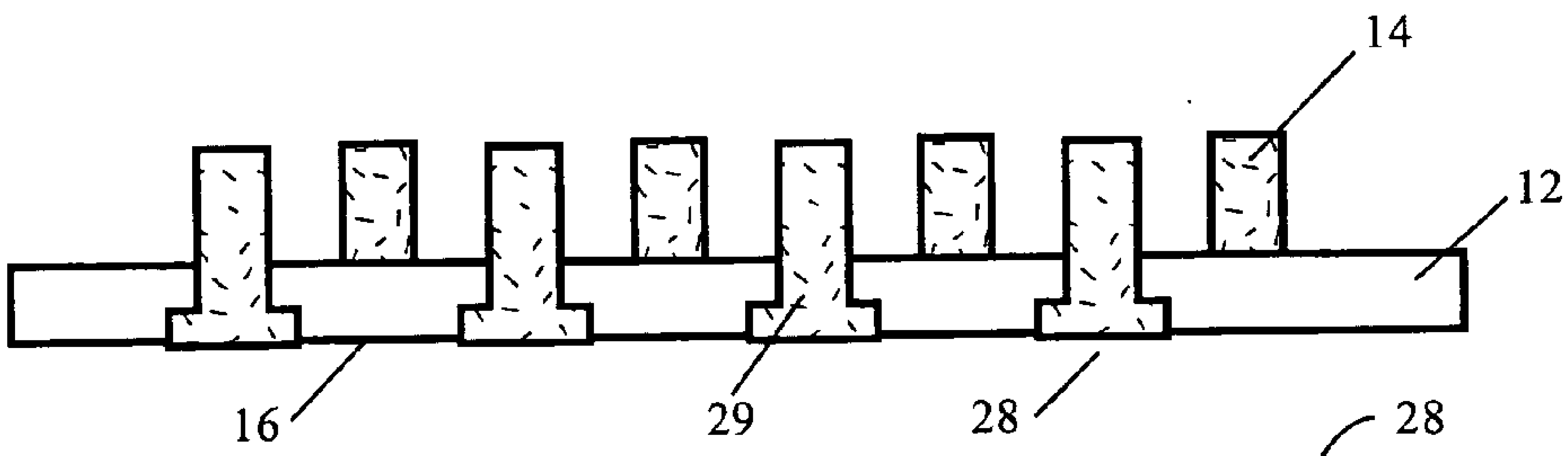


Figure 2A

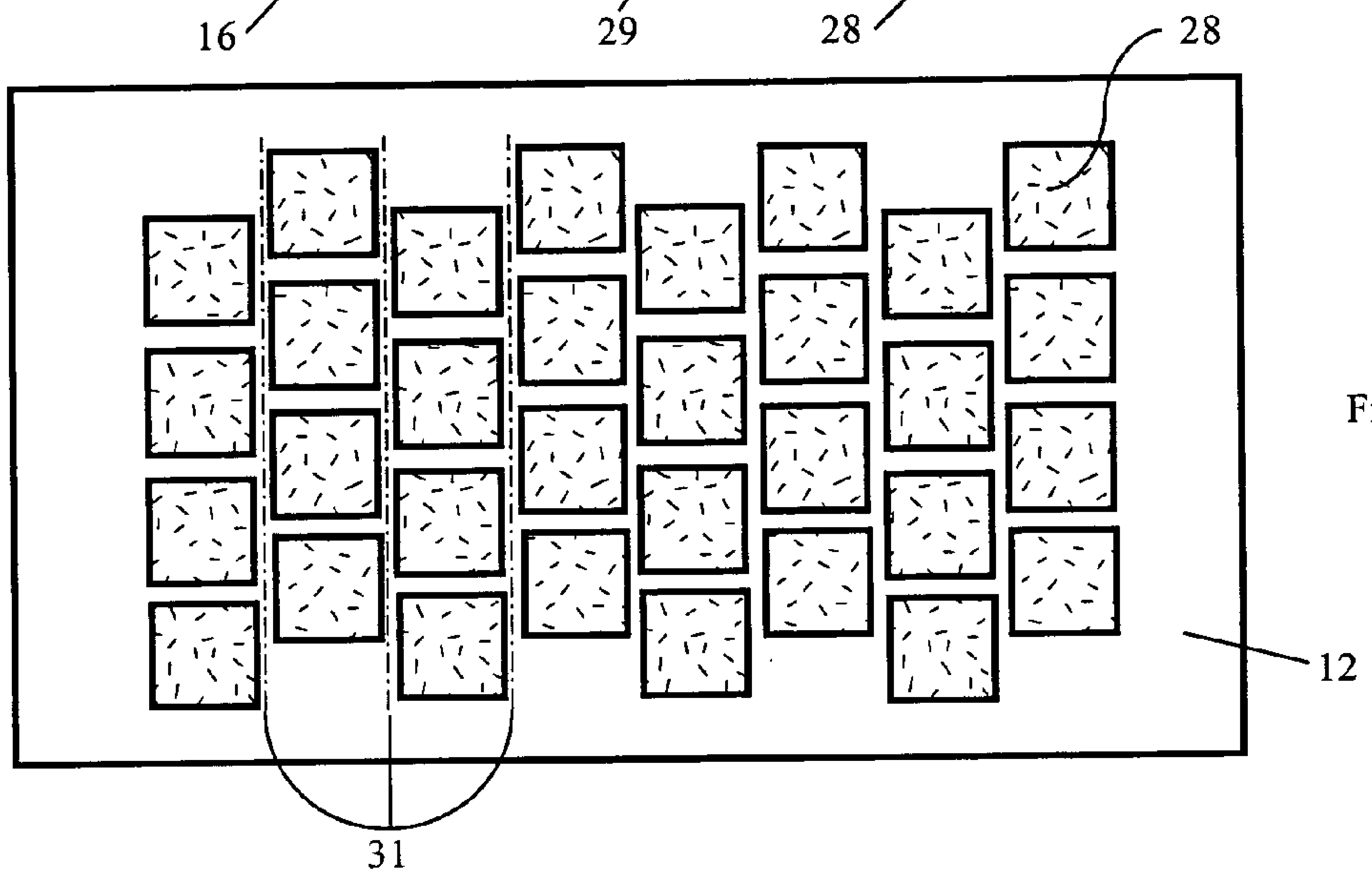
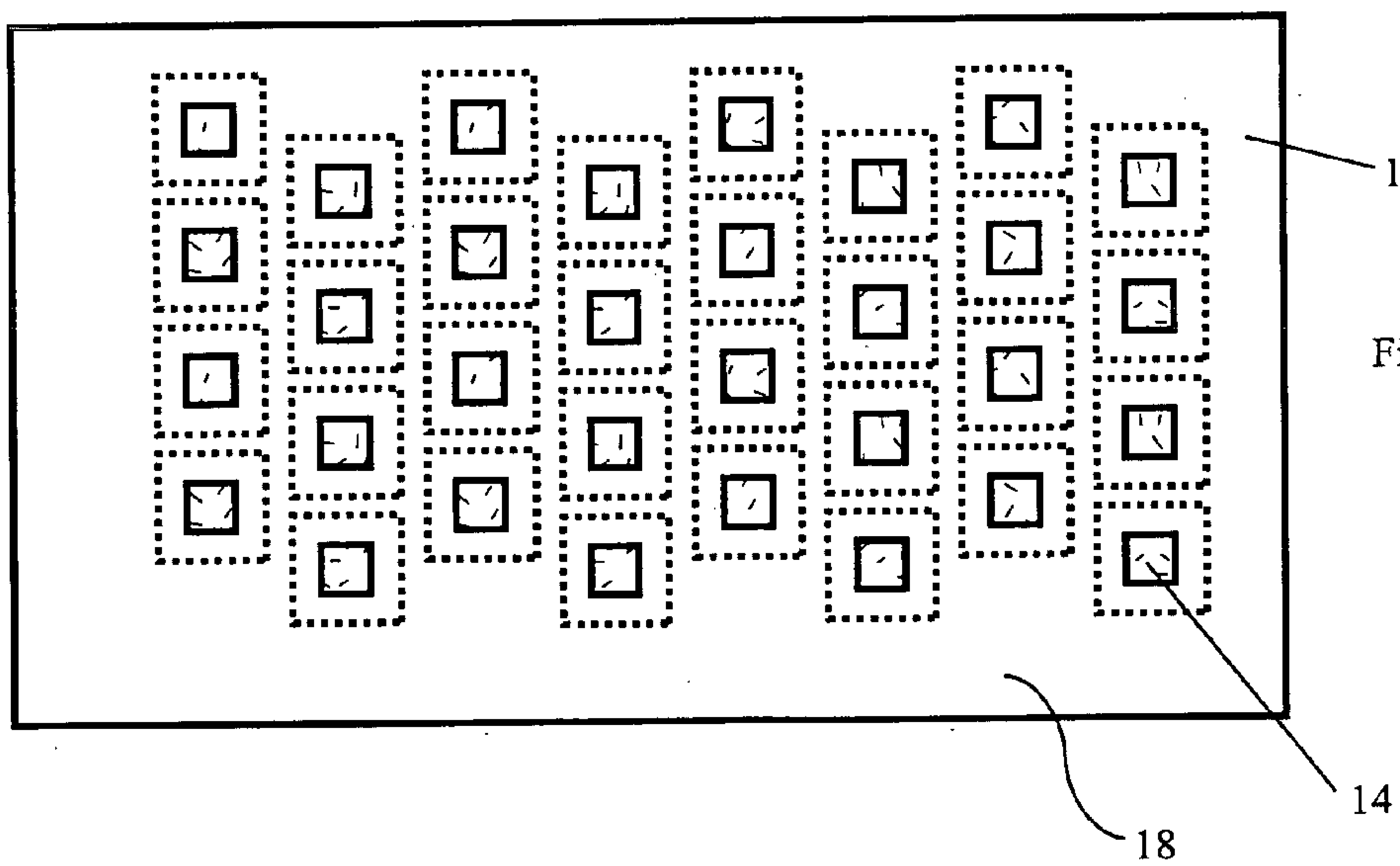


Figure 2B



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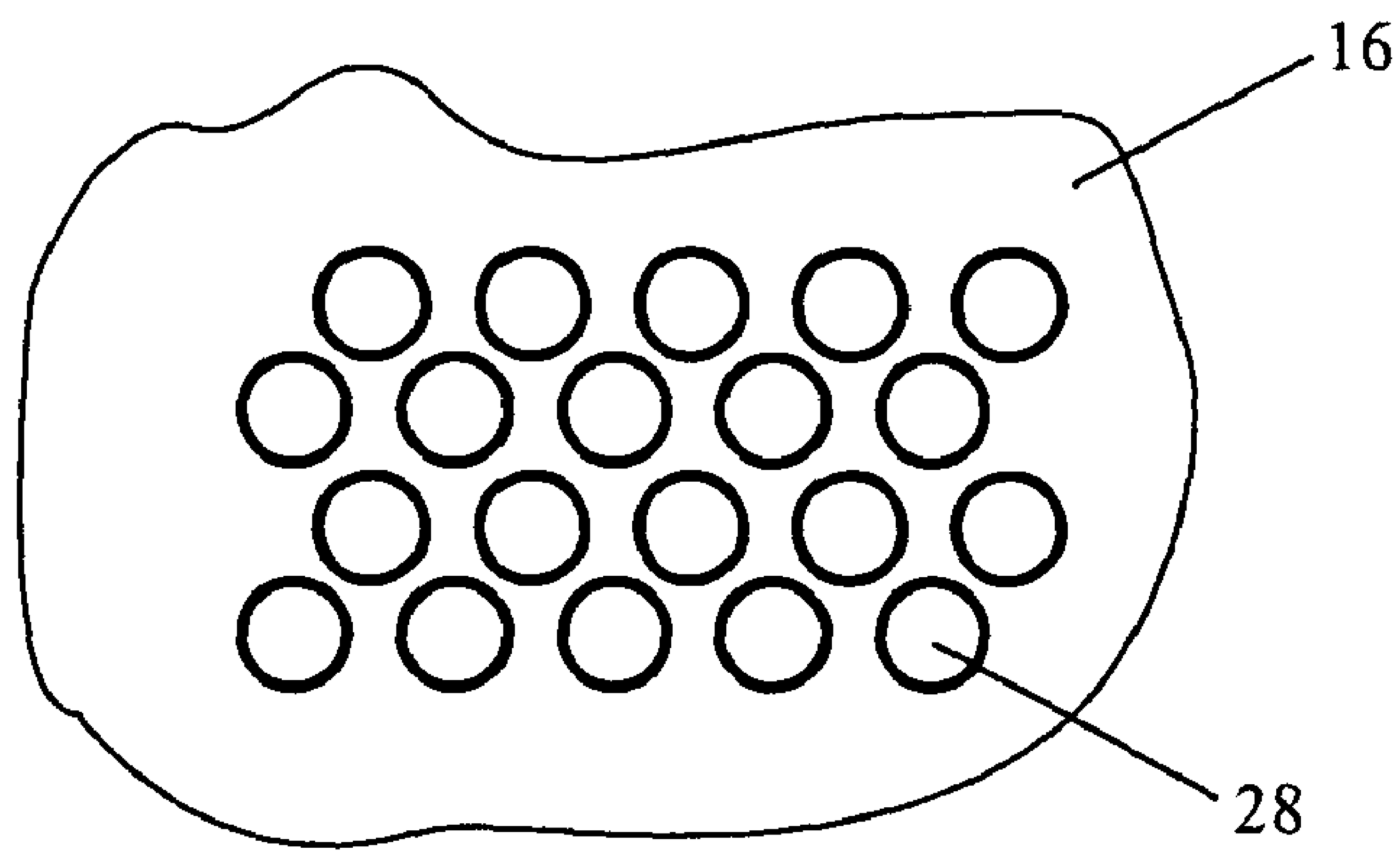


Figure 2D

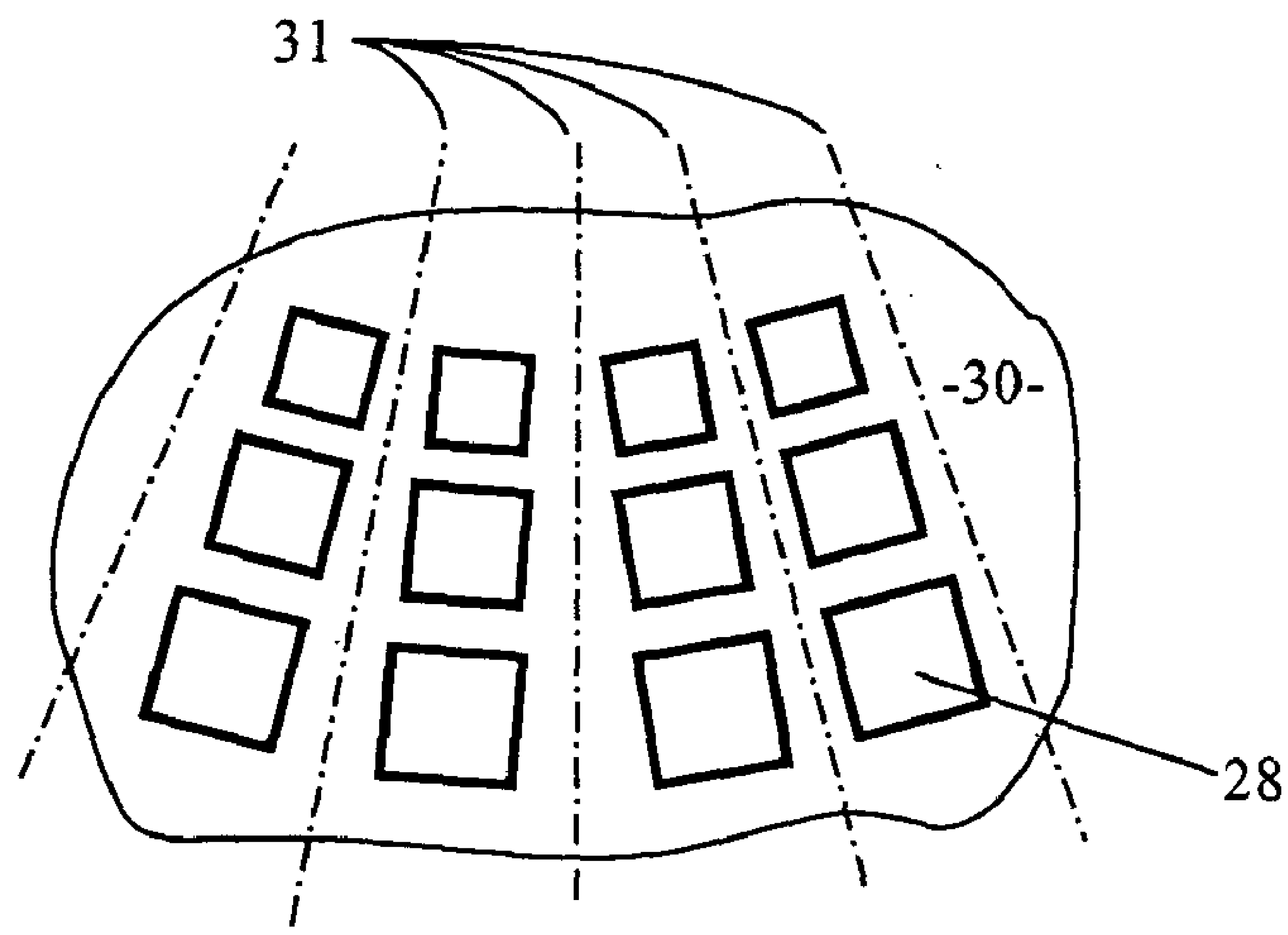


Figure 2E

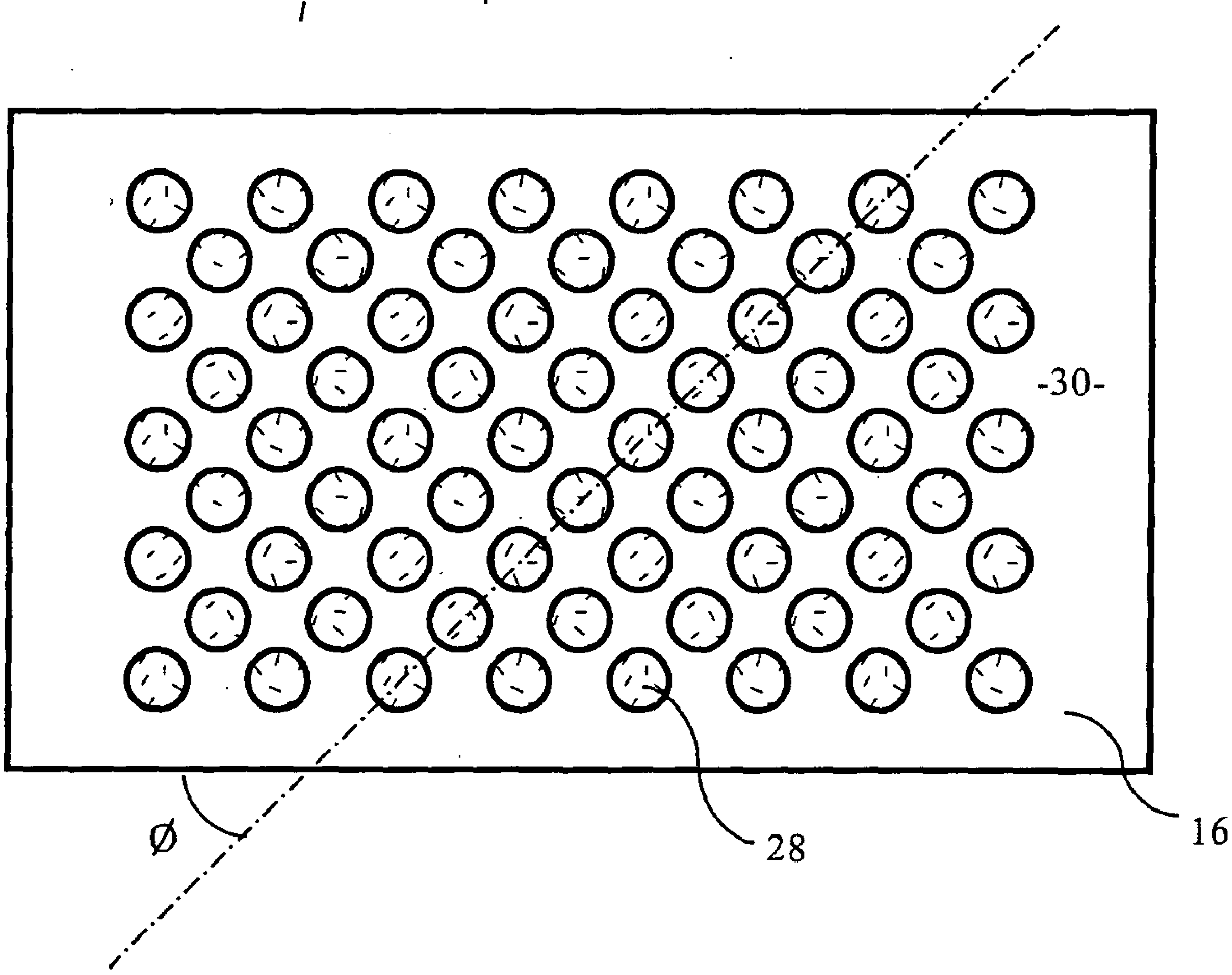


Figure 2F

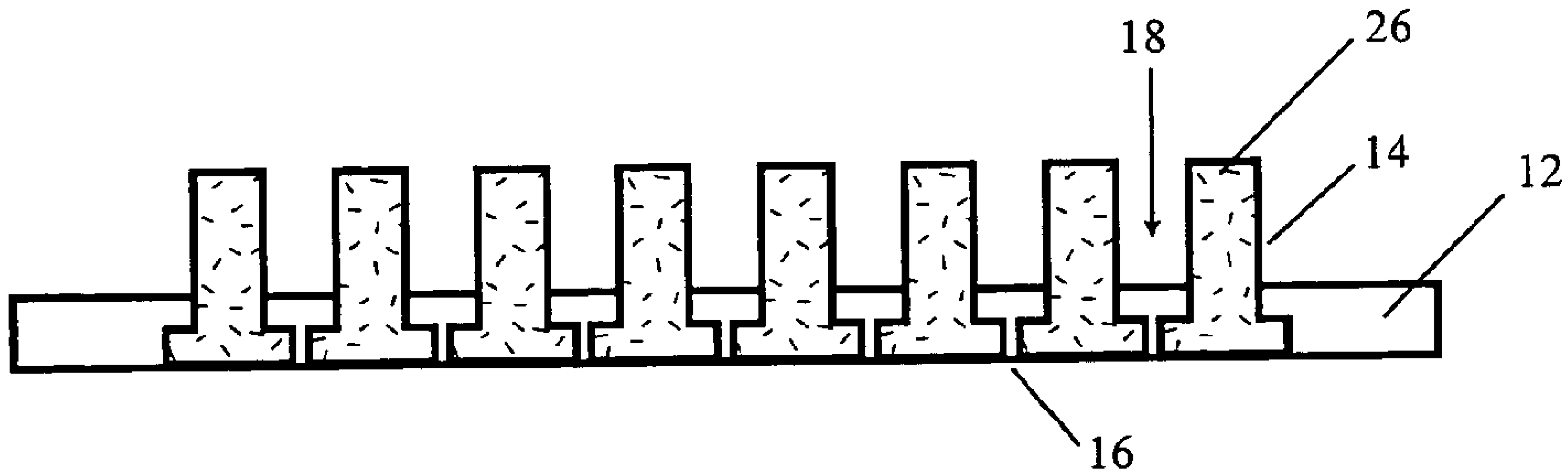
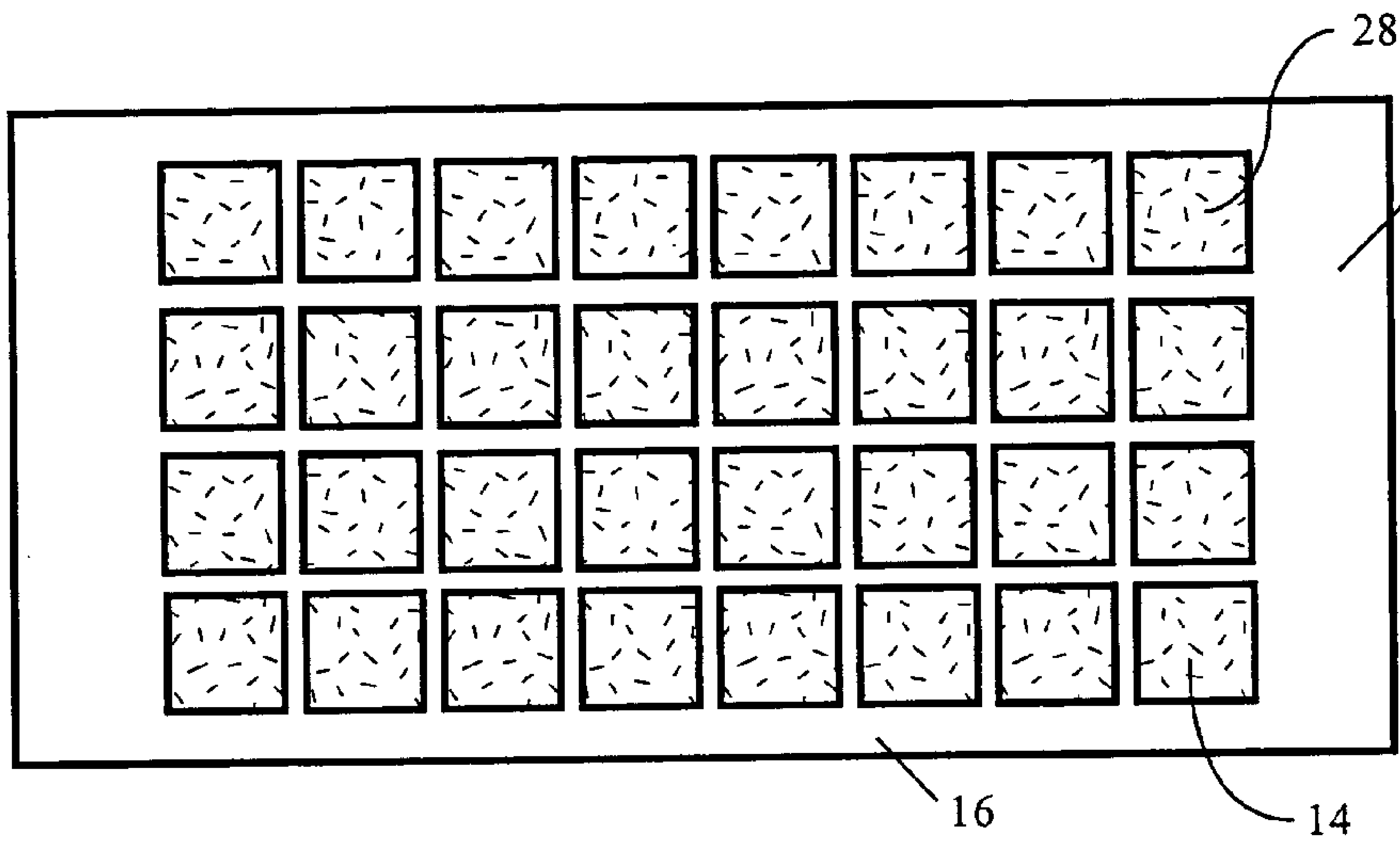


Figure 3A



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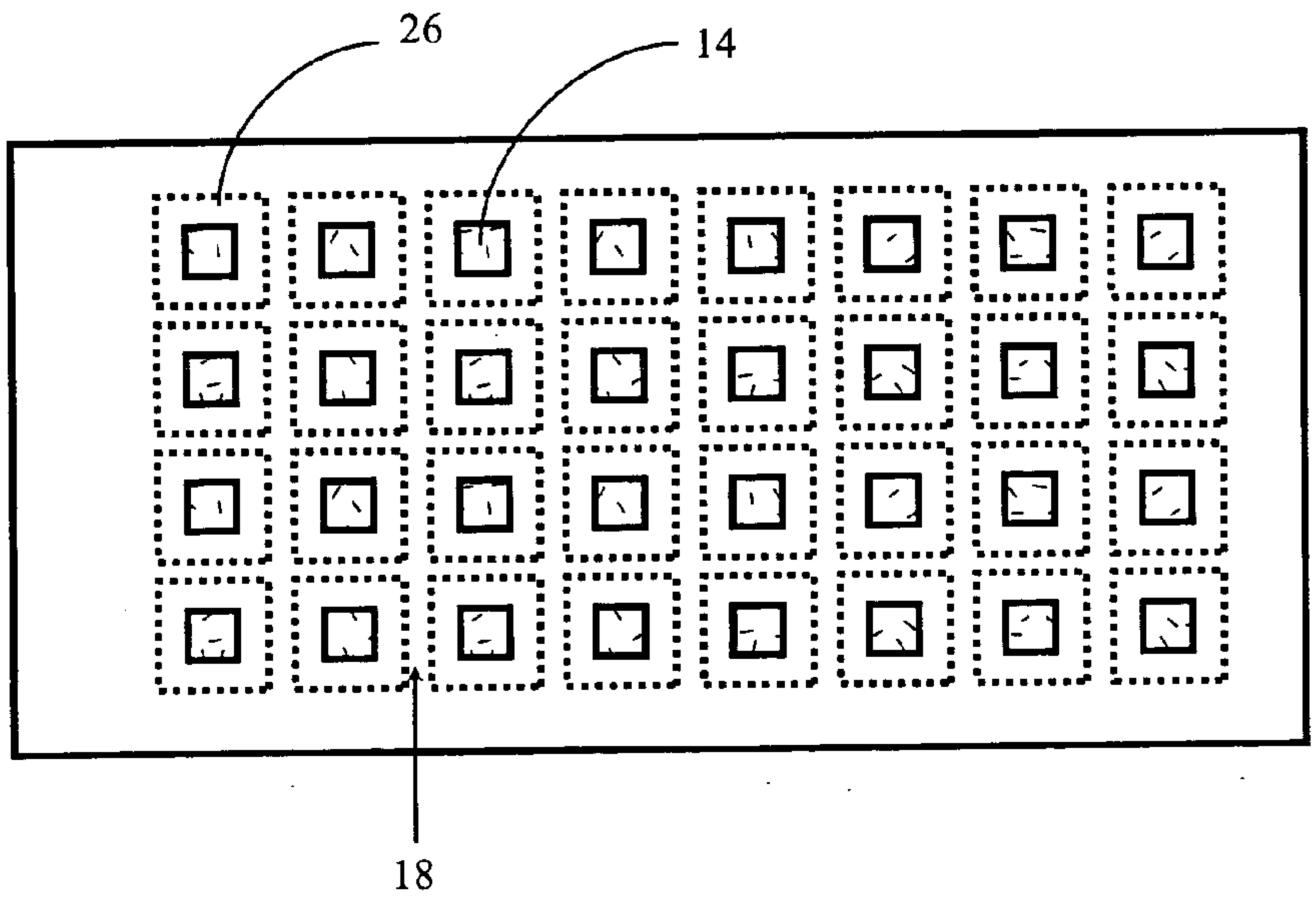

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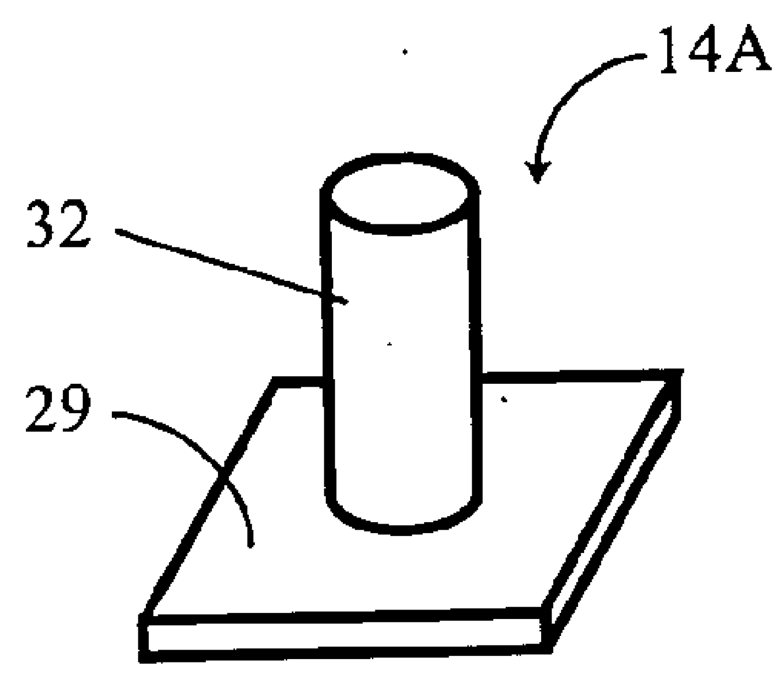
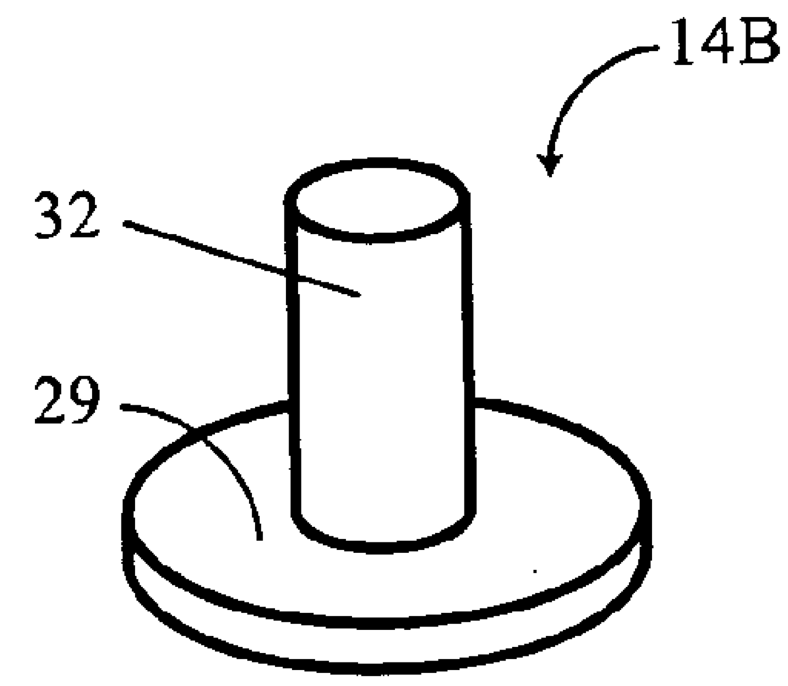


Figure 4A



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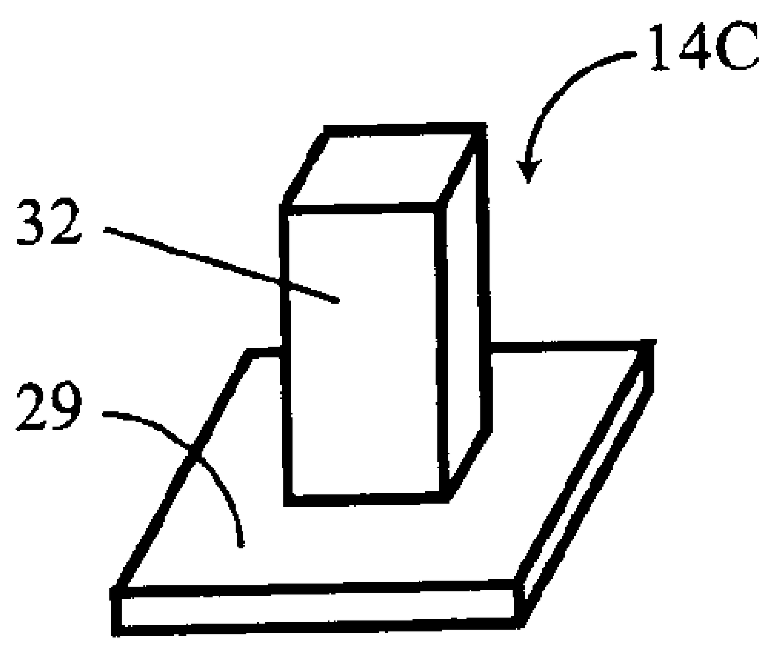

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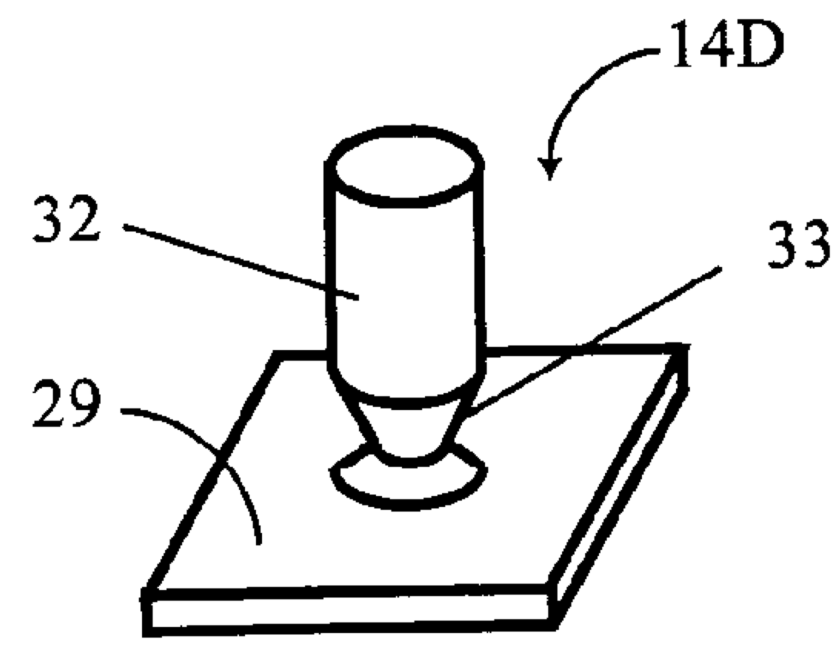

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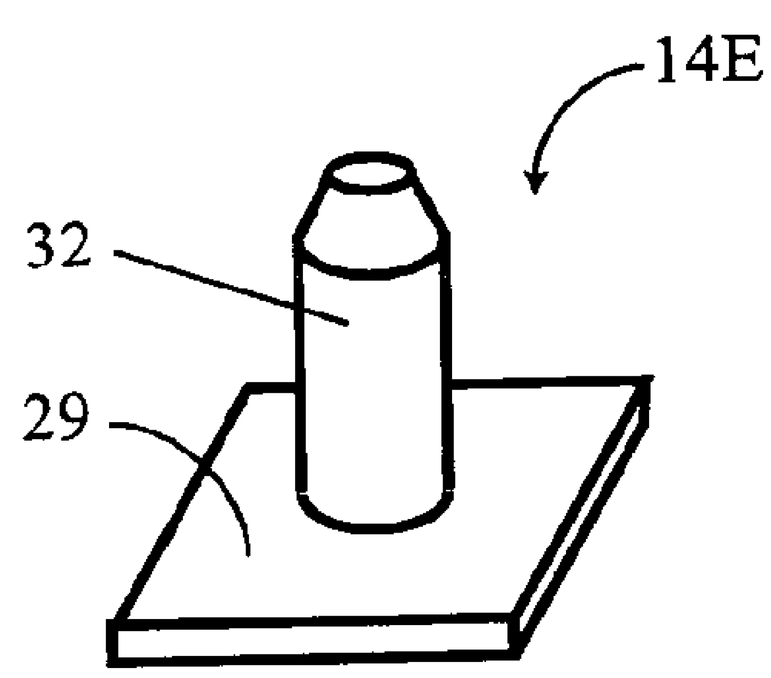

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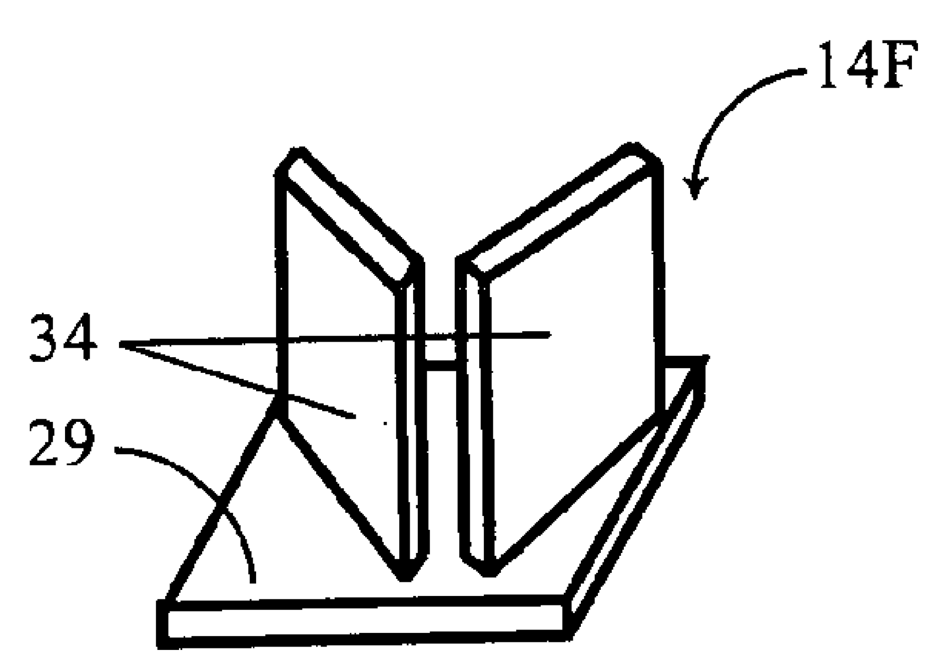

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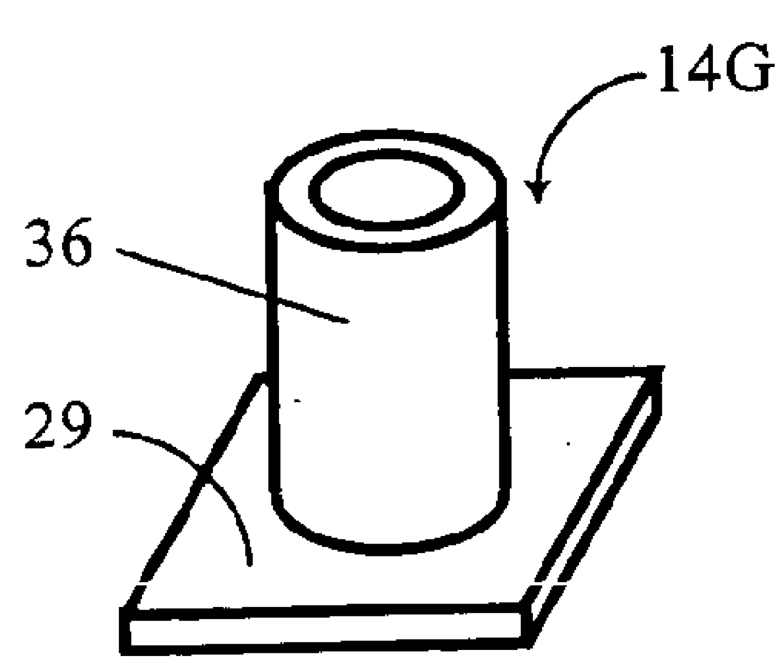

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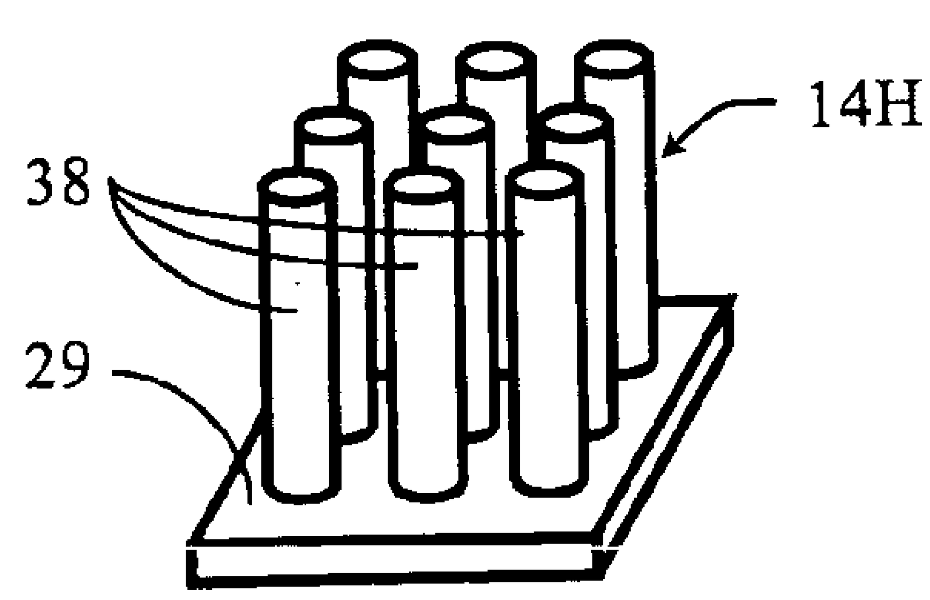

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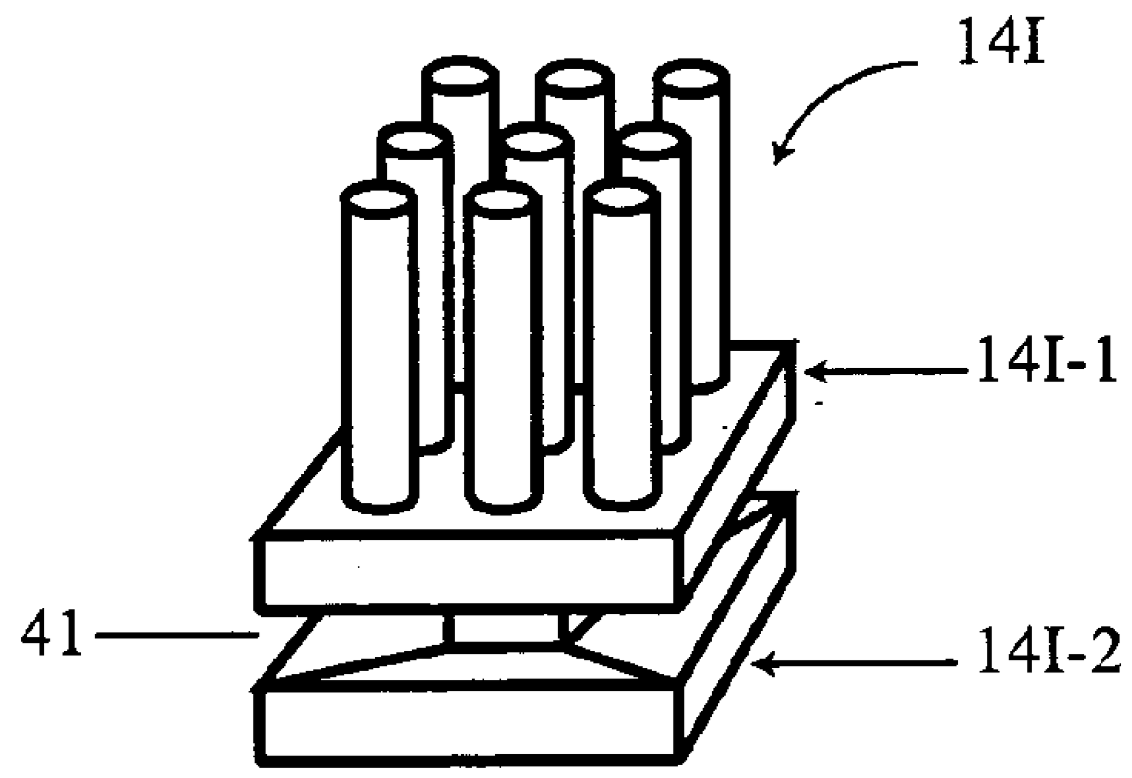


Figure 4I

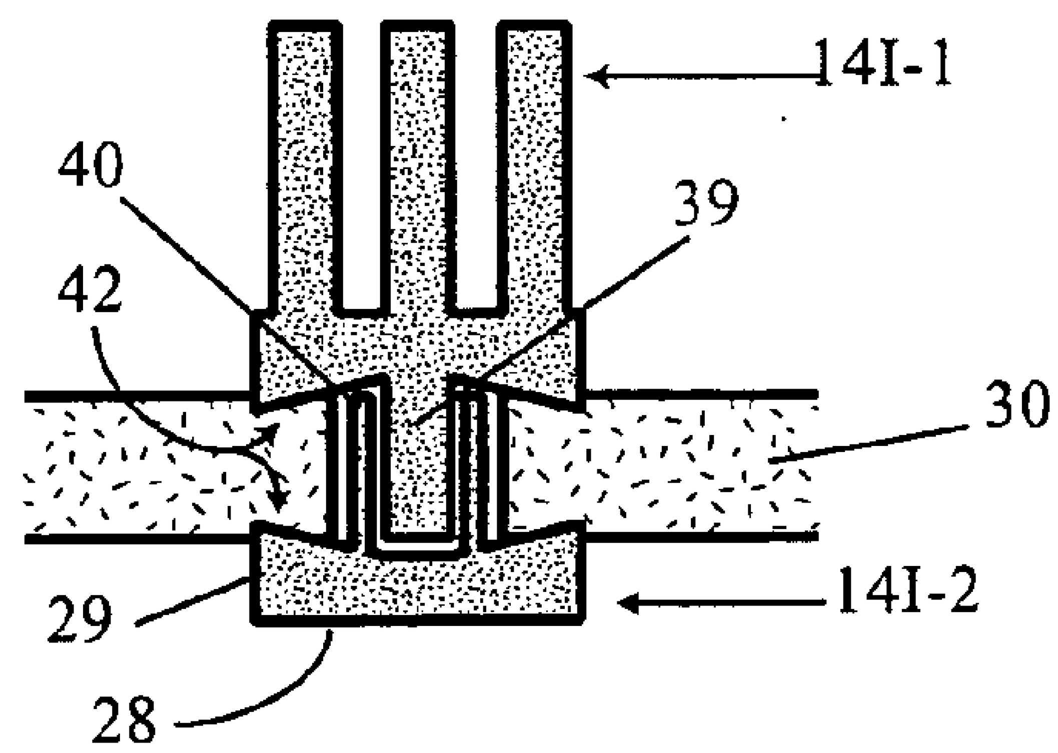
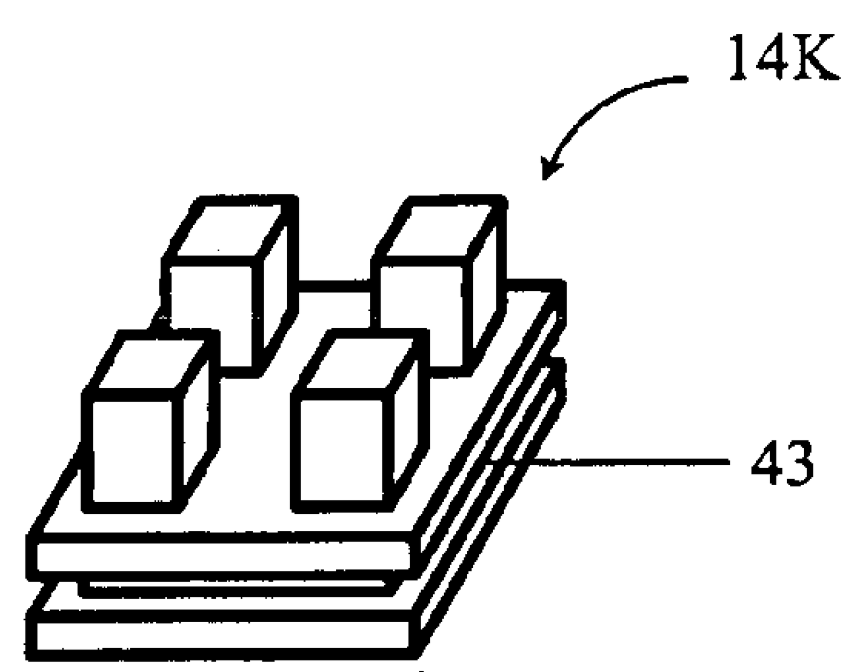


Figure 4J



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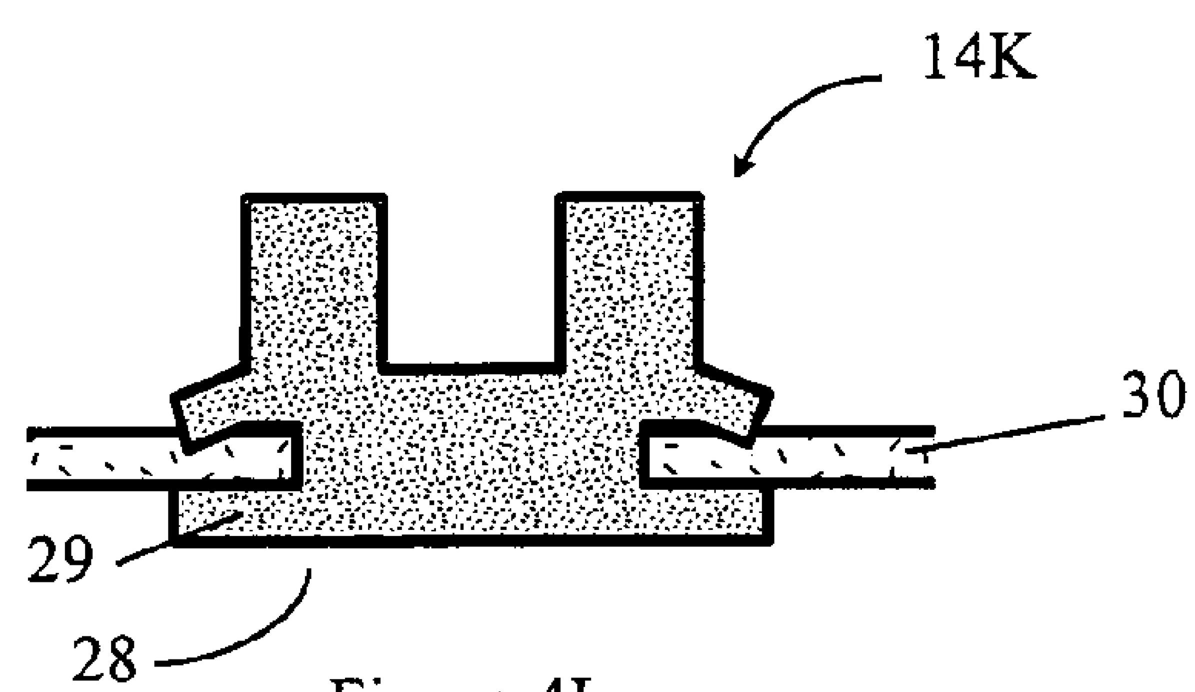

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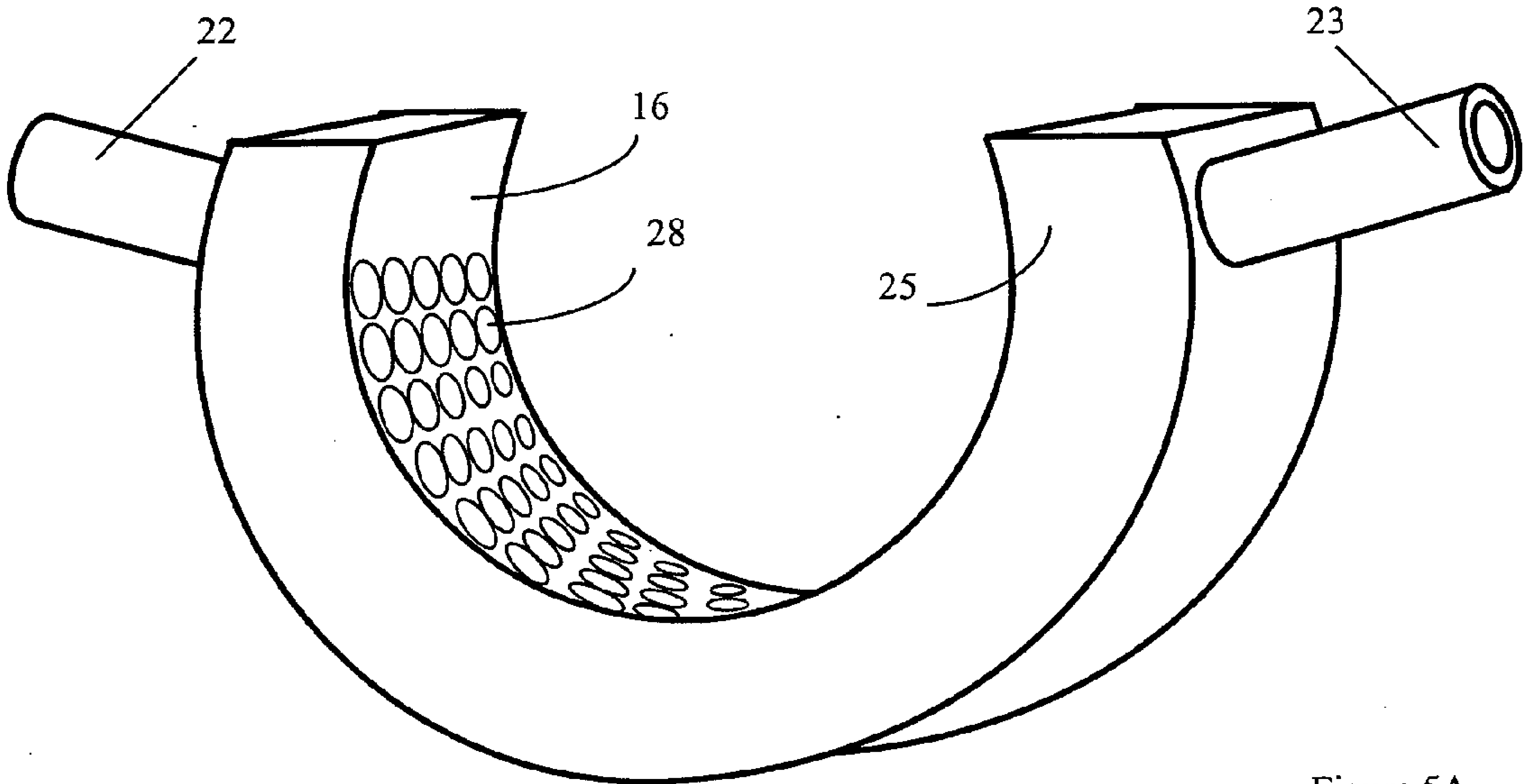


Figure 5A

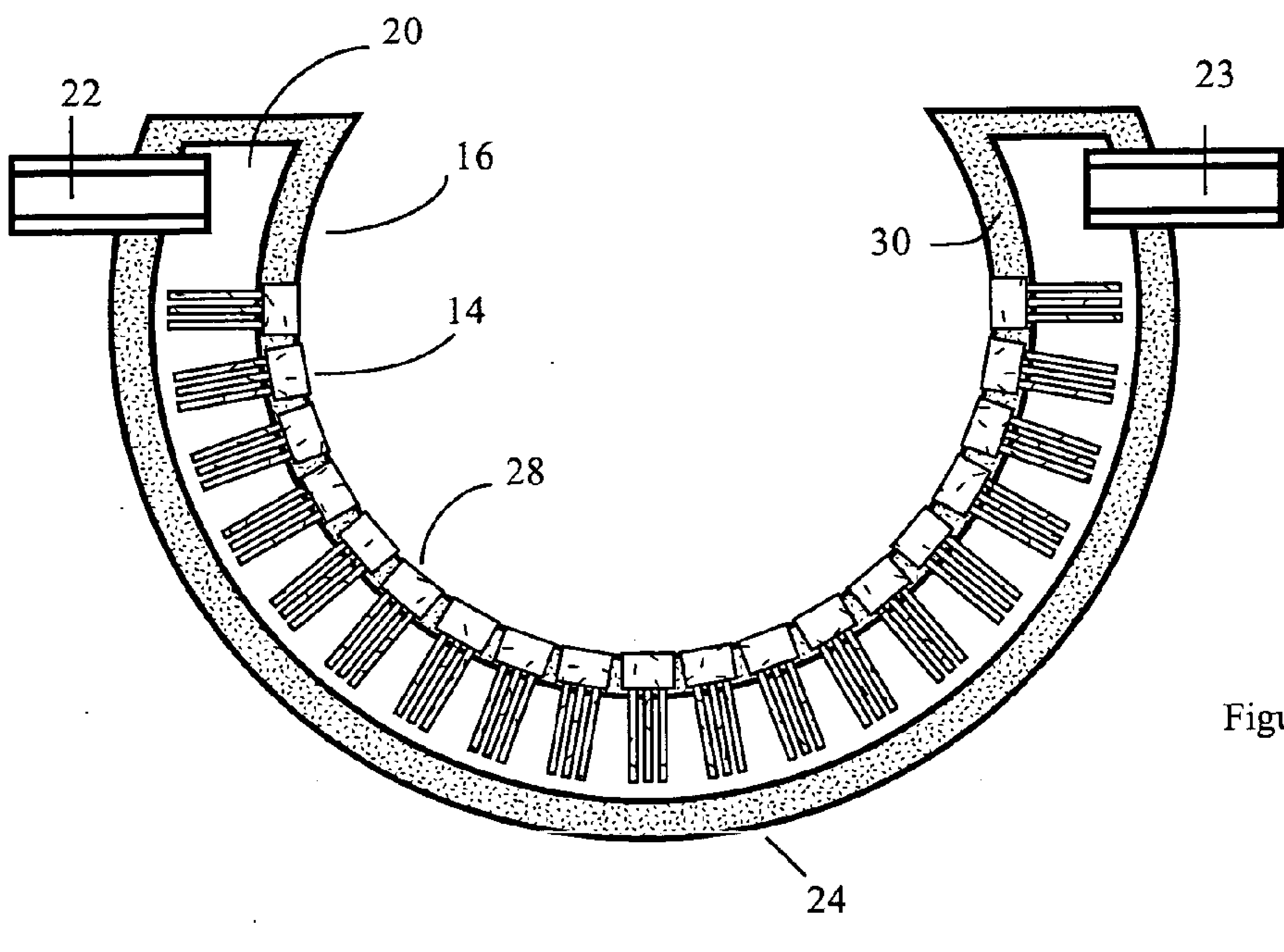


Figure 5B

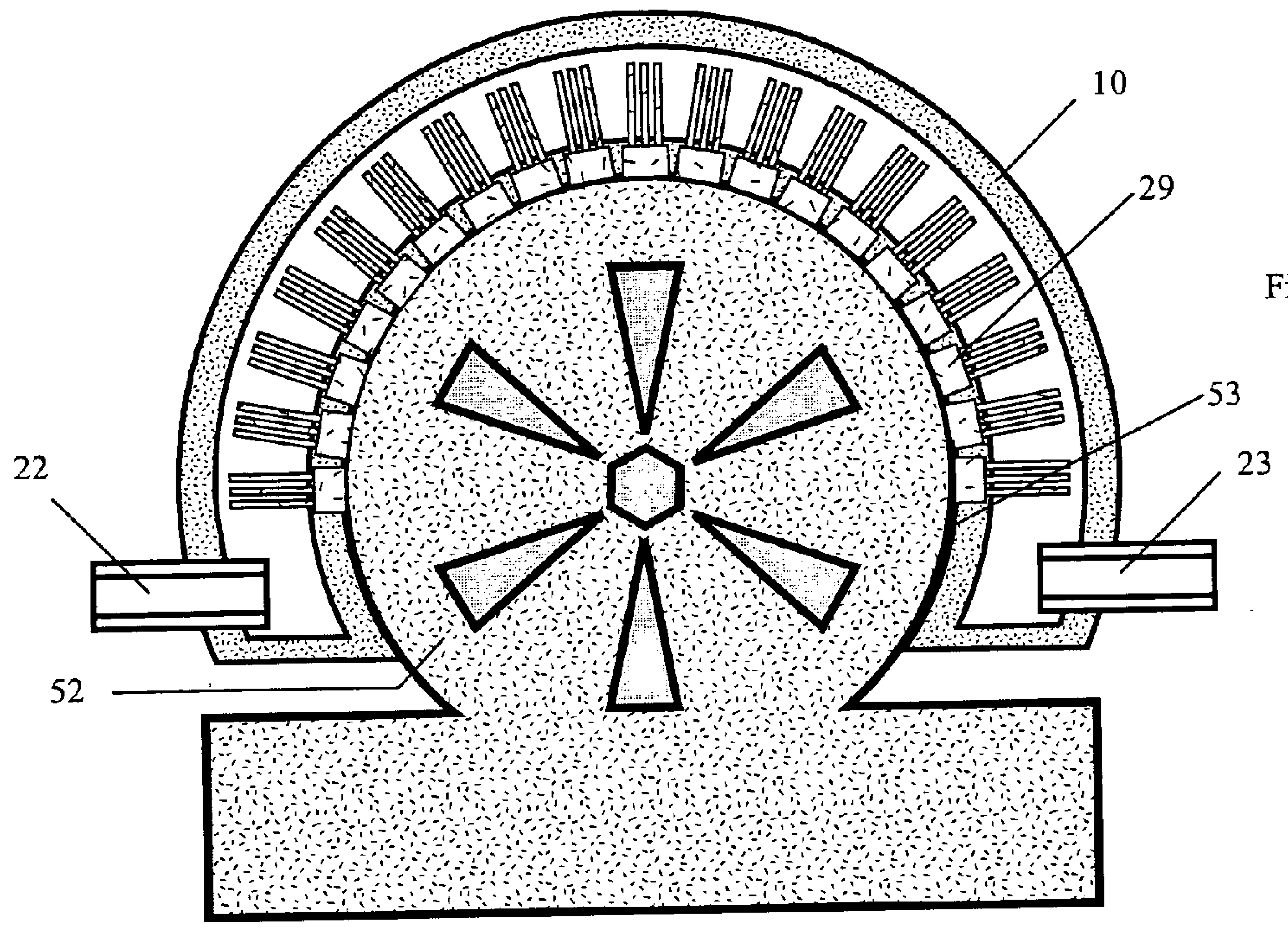


Figure 6A

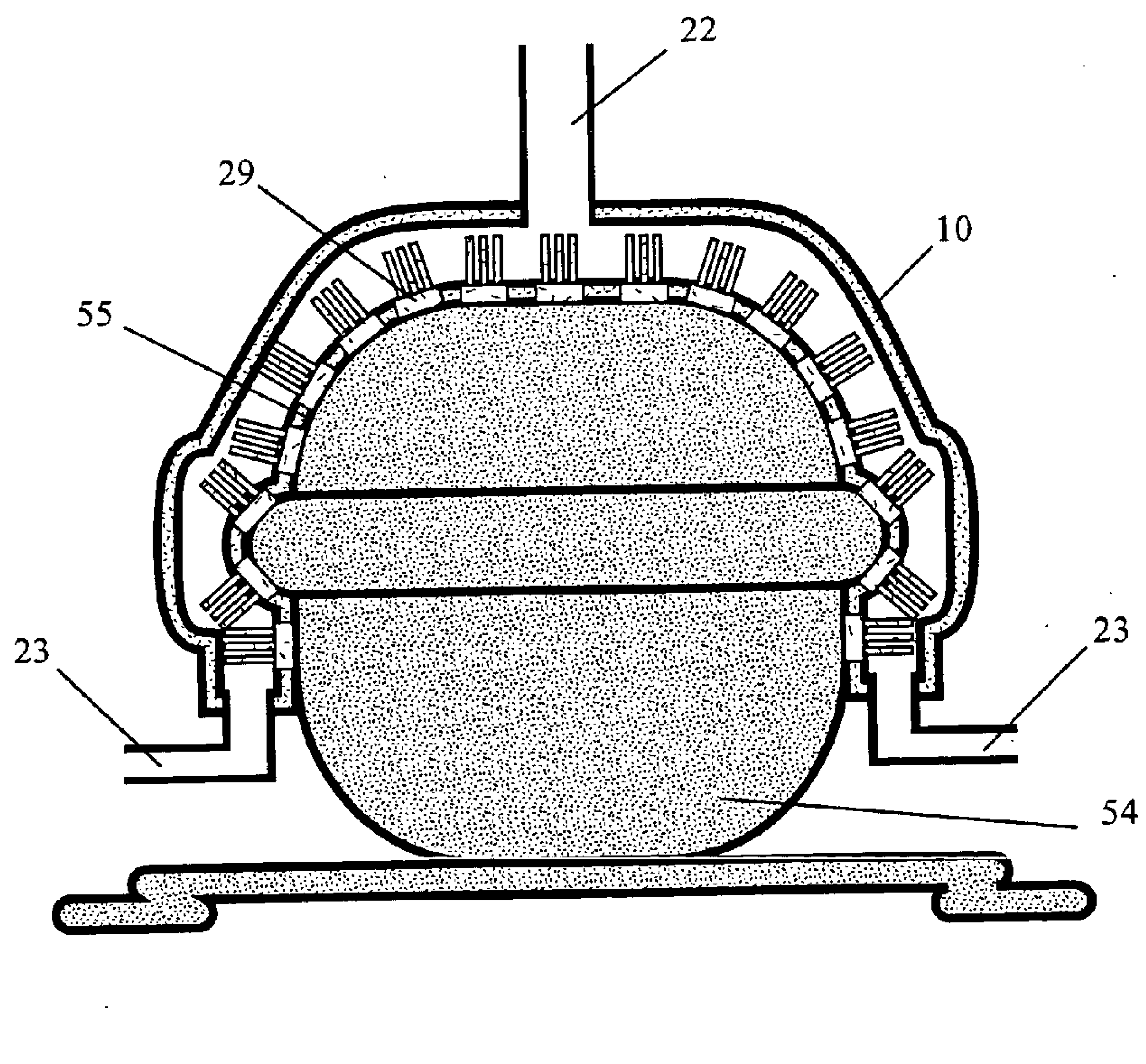


Figure 6B

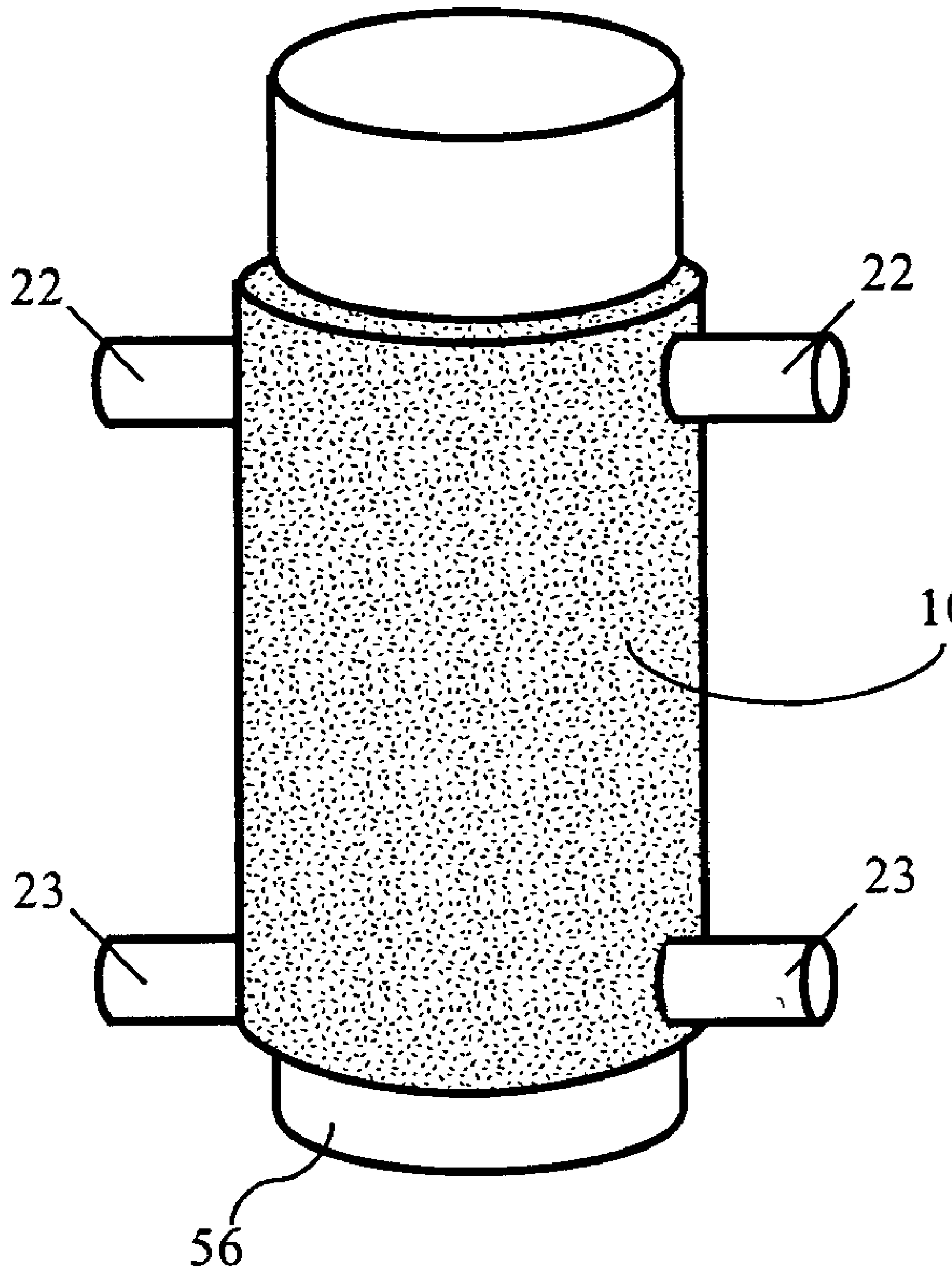


Figure 6C

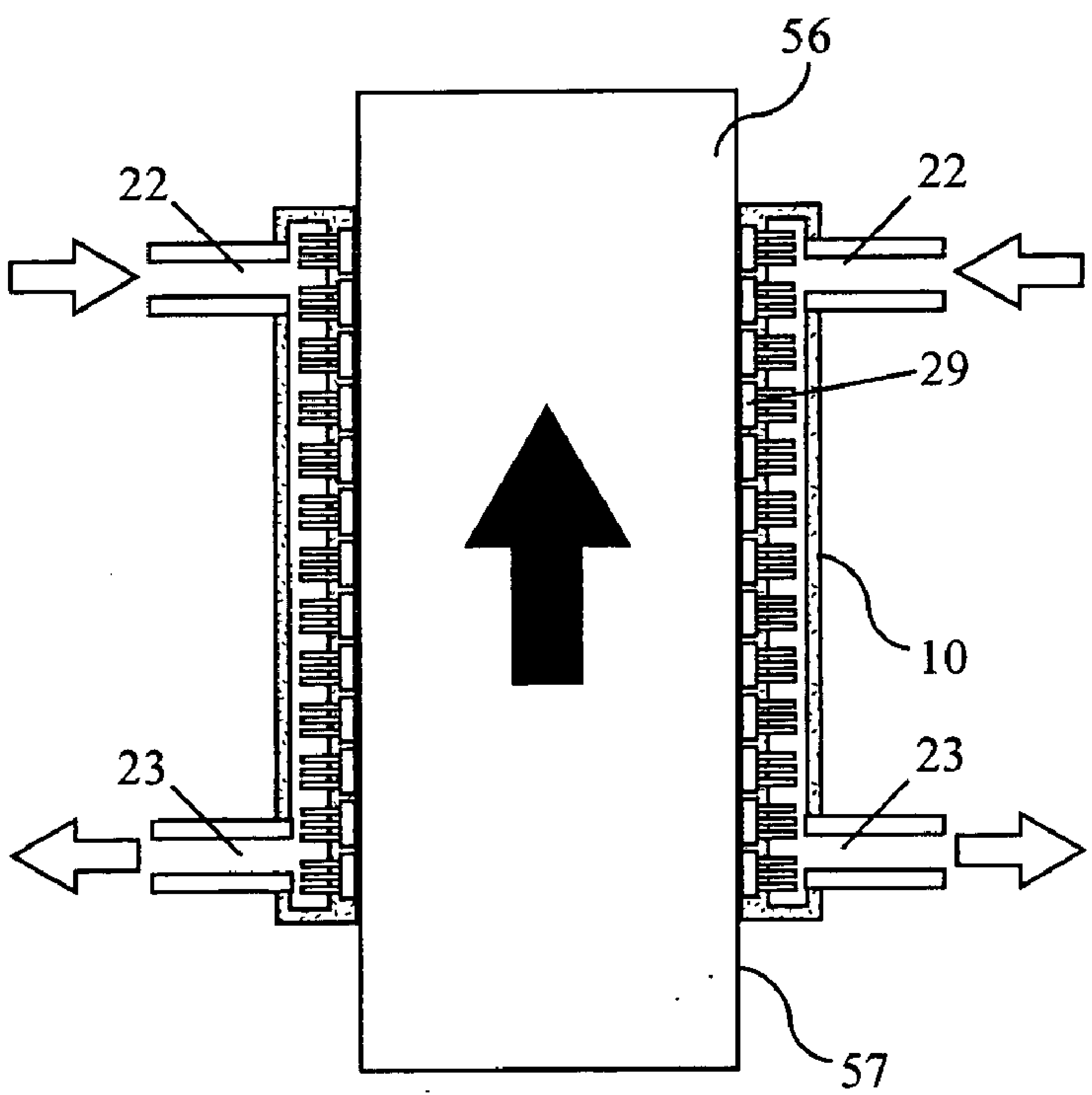


Figure 6D

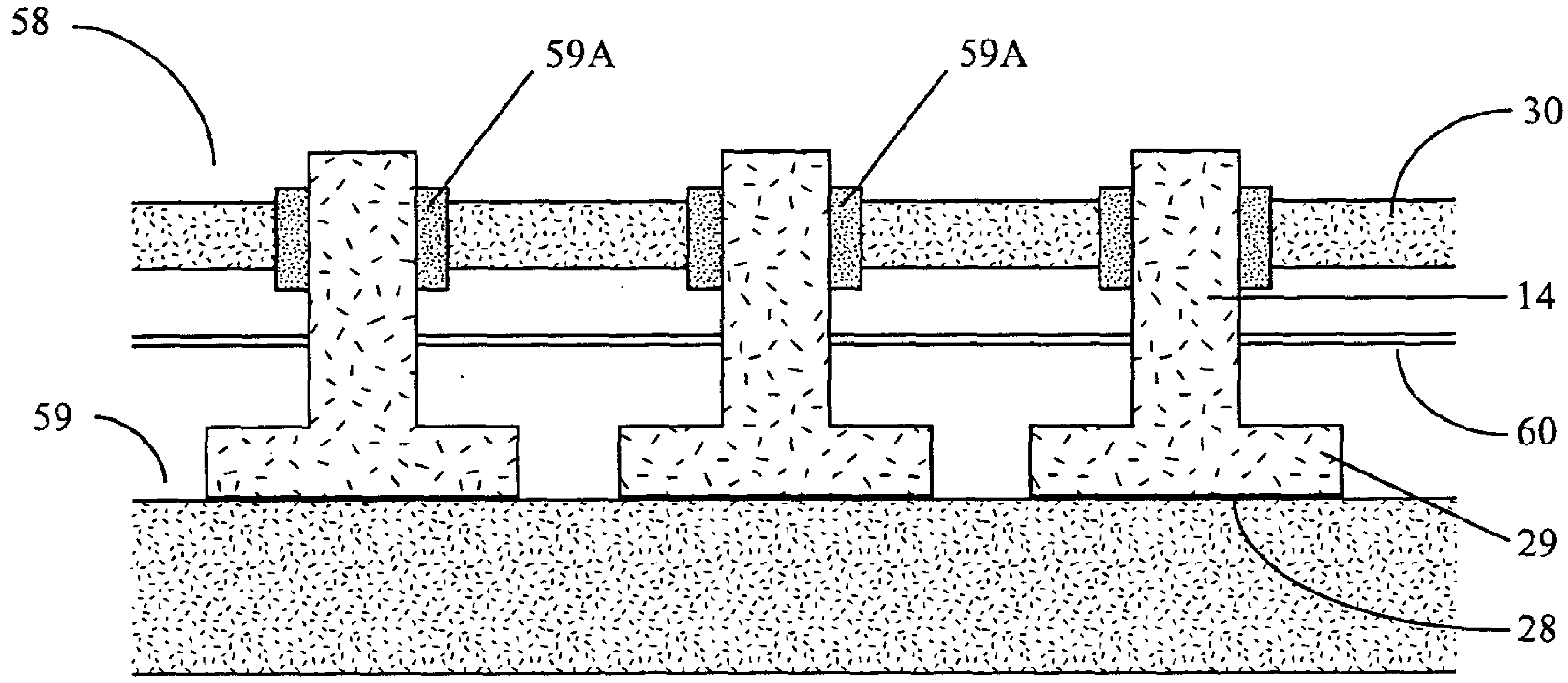


Figure 7

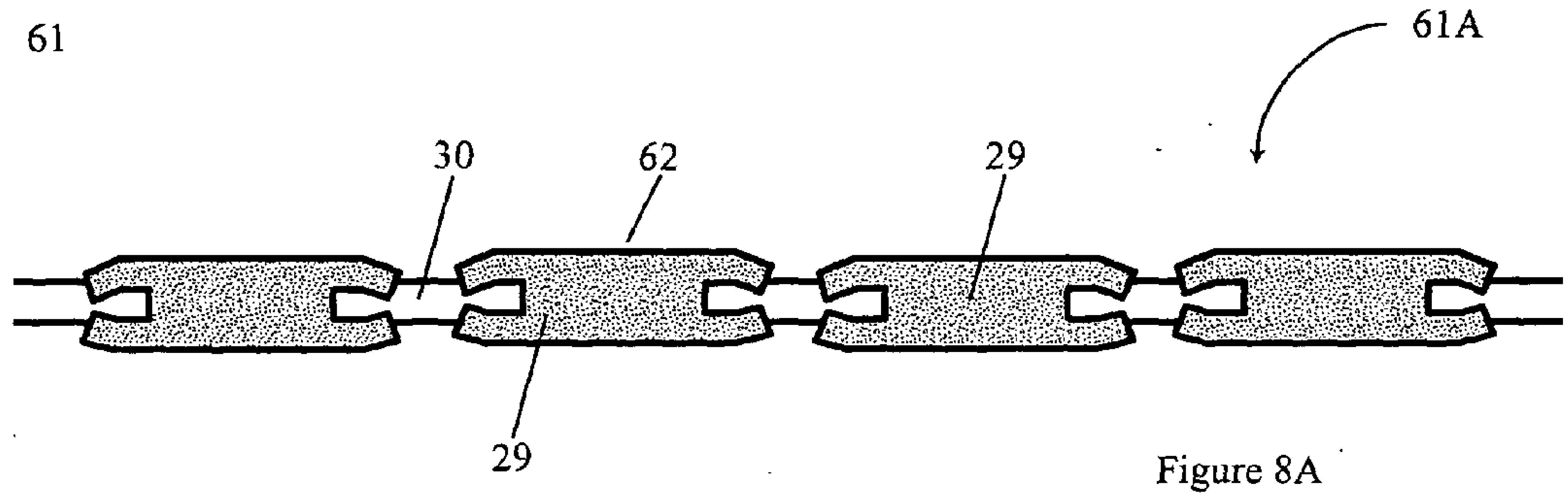


Figure 8A

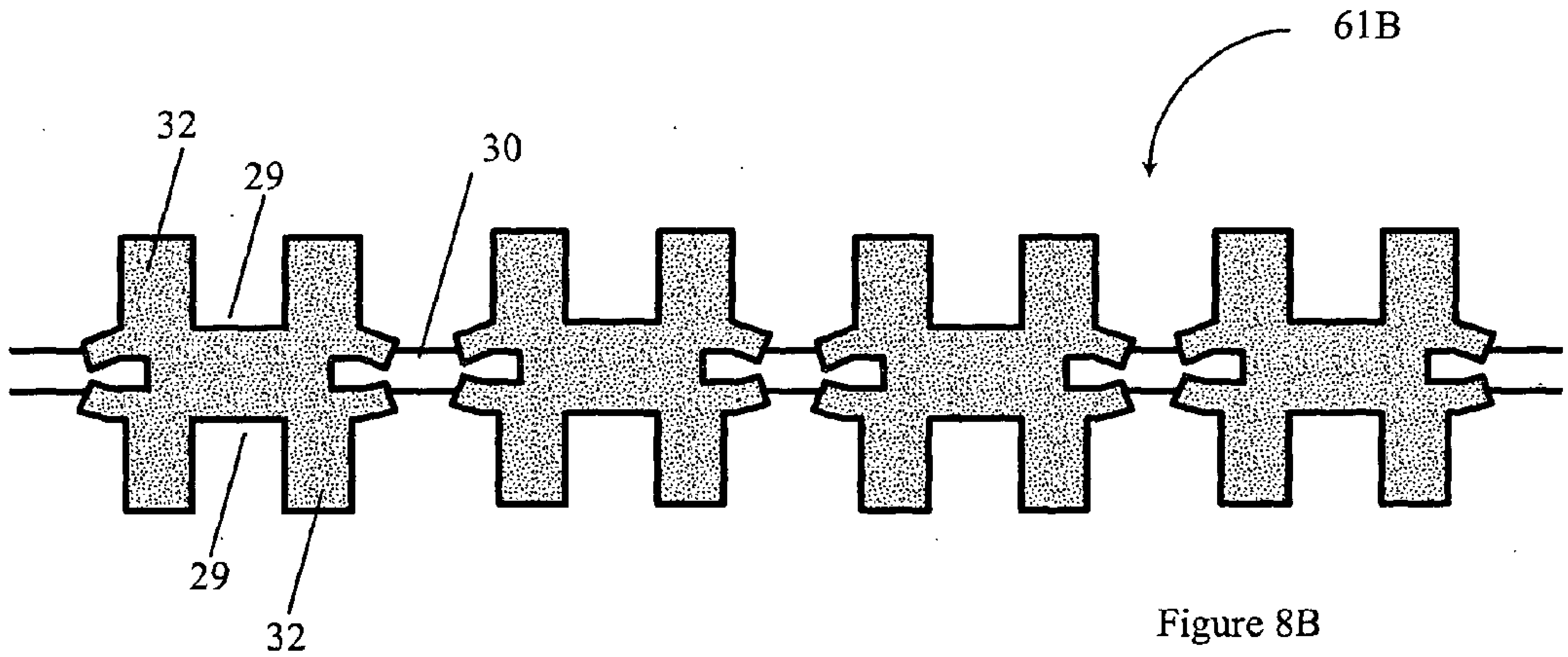


Figure 8B

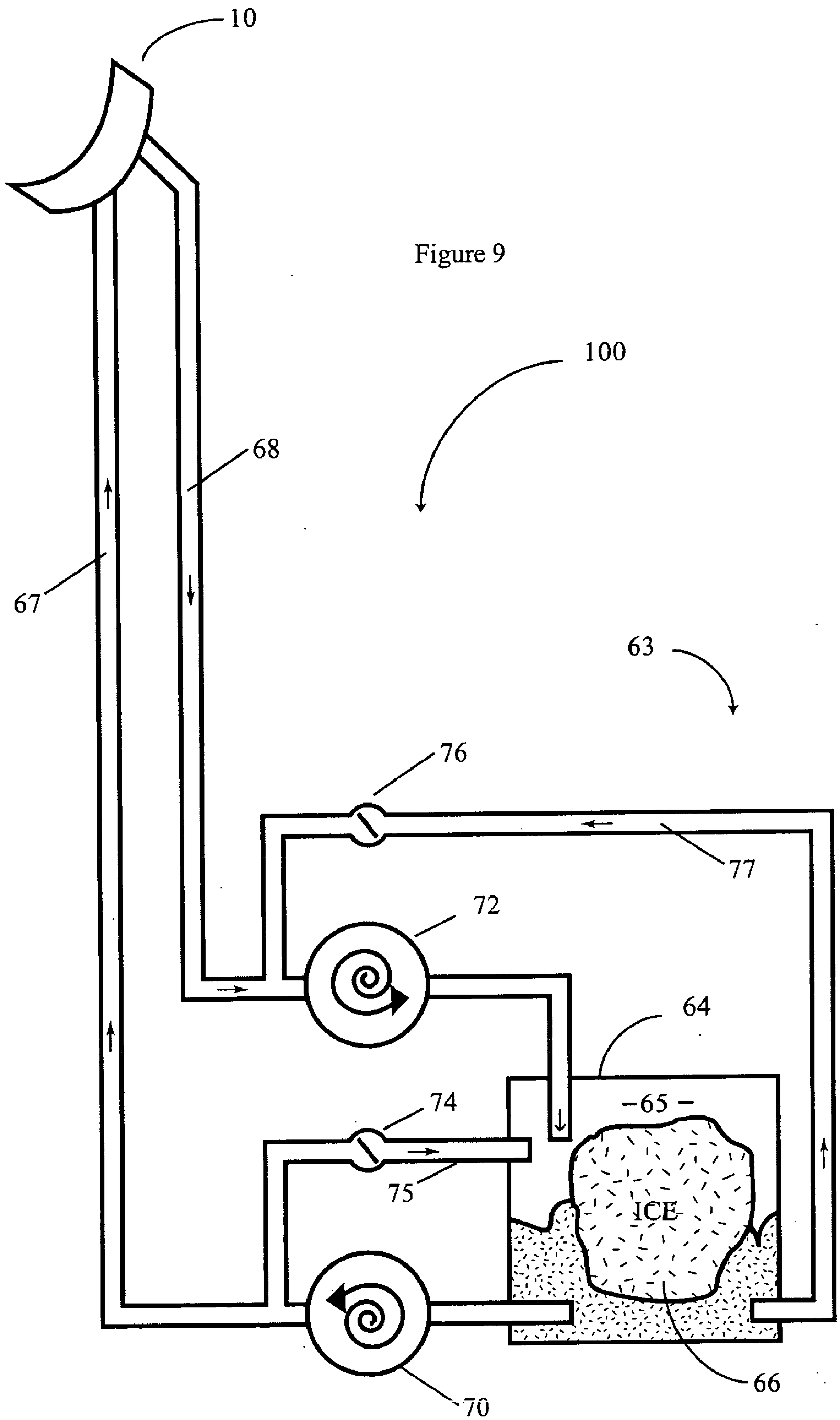
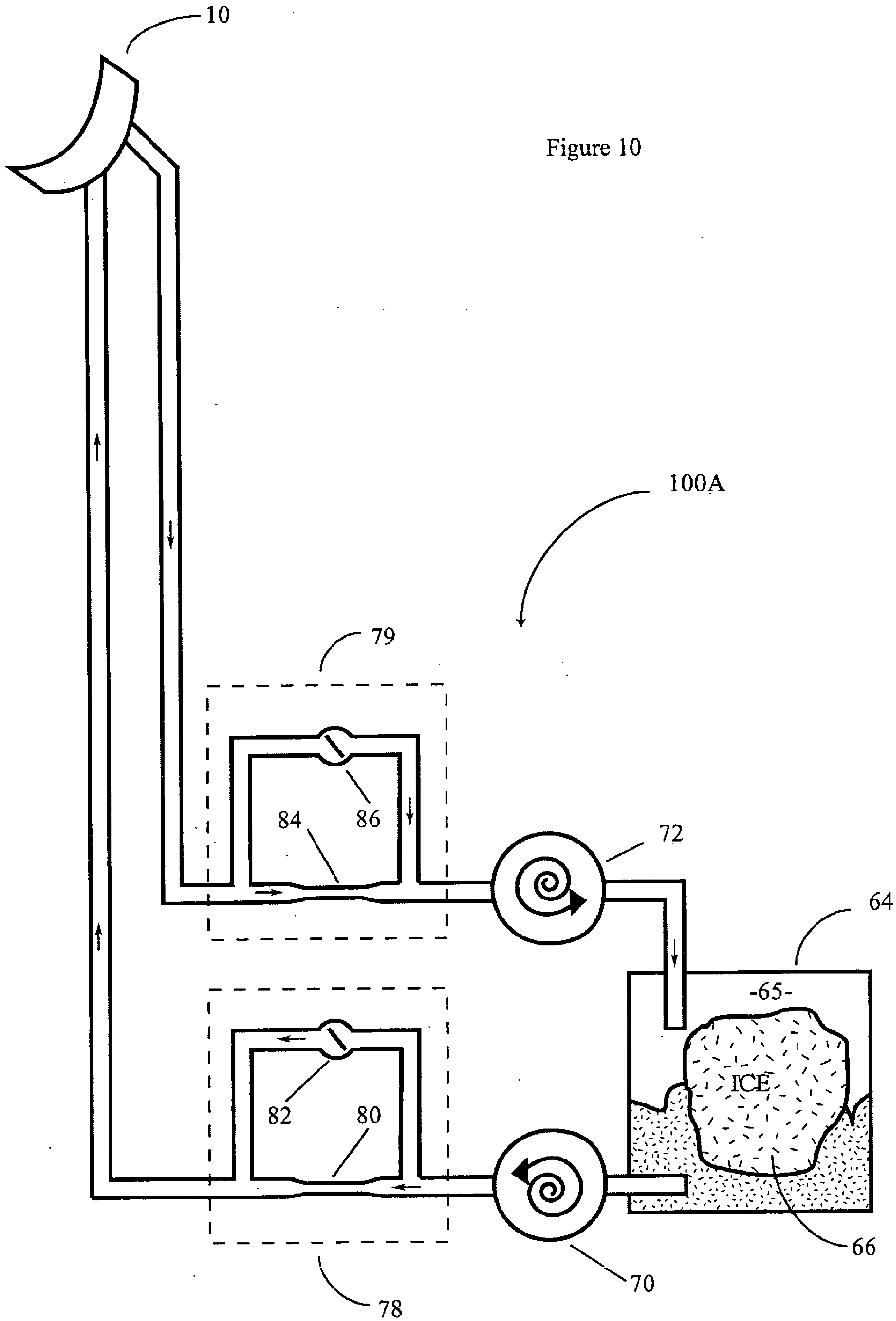


Figure 9

Figure 10



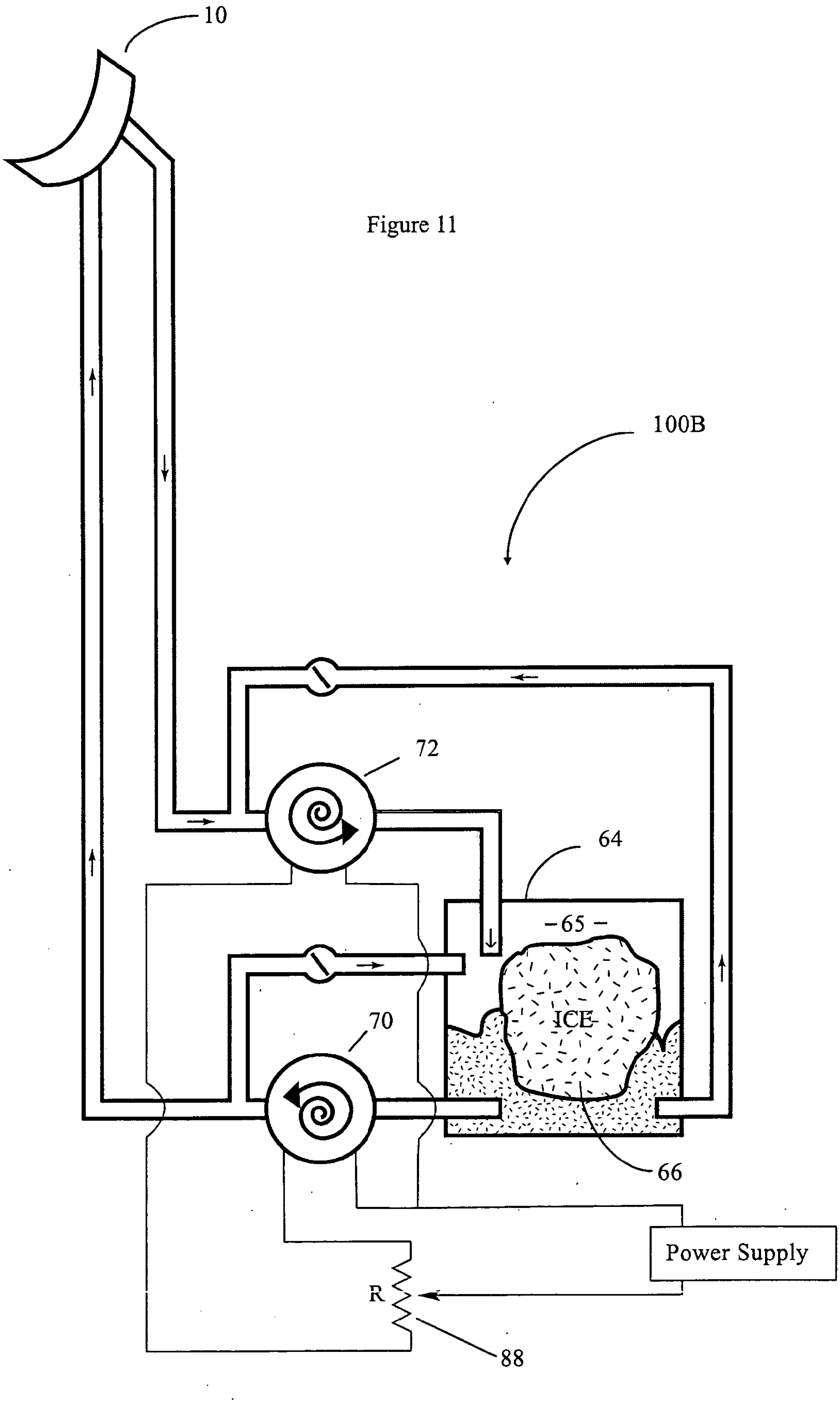


Figure 11

FLEXIBLE HEAT EXCHANGERS

TECHNICAL FIELD

[0001] The invention relates to heat exchangers. The invention has broad application to heat exchangers used to deliver heat to or remove heat from objects as diverse as electrical or electronic devices or equipment, mechanical devices such as transmissions, spindles, compressors and engines, scientific and medical apparatus, living creatures, and the like.

BACKGROUND

[0002] There are numerous situations where it is desirable to remove heat from an object or to deliver heat to an object. Various types of heat exchanger exist. Air cooled heat sinks are structures which take heat from an object and dissipate the heat into ambient air. Such heat sinks typically consist of a finned piece of thermally conductive material having a face which can be placed in thermal contact with an object, such as an electronic component, to be cooled. Some heat sinks are equipped with fans located to flow air past the fins to improve the rate at which heat is dissipated.

[0003] U.S. Pat. No. 6,549,411 B1 discloses a flexible heat sink that can be attached to a generally flat surface of an object. The heat sink can flex to conform to the surface of the object to achieve improved contact with the object, and hence increase the efficiency of heat transfer between the heat sink and the object. U.S. Pat. No. 6,367,541 B2 discloses a heat sink that can be attached to multiple electronic chips which have different heights. The heat sink dissipates heat from the chips into ambient air.

[0004] U.S. Pat. No. 5,368,093 discloses a flexible bag filled with thermal transfer fluid useful for thawing frozen foods. U.S. Pat. No. 4,910,978 discloses a flexible pack containing a gel. The pack can be cooled and applied to a patient for cold therapy. The pack conforms to surface contours of the patient's body. These devices have limited cooling capacities.

[0005] More sophisticated heat exchangers use a heat exchange fluid, typically a liquid, instead of ambient air to carry heat away from or provide heat to an object to be cooled or heated. U.S. Pat. No. 5,757,615 discloses a flexible heat exchanger with circulating water as a coolant for cooling a notebook computer. U.S. Pat. No. 5,643,336 discloses a flexible heating or cooling pad with circulating fluid for therapeutically treating the orbital, frontal, nasal and peri-oral regions of a patient's head. U.S. Pat. No. 6,551,347 B 1 discloses a flexible heat exchange structure having fluid-conducting channels formed between two layers of flexible material for heat/cold and pressure therapy. U.S. Pat. Nos. 6,197,045 B1 and 6,375,674 B1 disclose a flexible medical pad with an adhesive surface for adhering the pad to the skin of a patient. U.S. Pat. No. 6,030,412 discloses a flexible enveloping member for enveloping a head, neck, and upper back of a mammal for cooling the brain of the mammal suffering a brain injury. All of these heat exchangers require heat to pass through a layer of some flexible material such as rubber, or a flexible plastic such as polyurethane. In addition, heat is exchanged between the surface of the flexible material and a circulating fluid. Water is the most commonly used circulating fluid.

[0006] Rubber and flexible plastics are poor conductors of heat. To provide a high heat transfer efficiency in a flexible heat exchanger in which heat is transferred across a layer of rubber or plastic the layer must be very thin. This makes such heat exchangers prone to damage. In addition, water is a poor heat conductor. Heat exchange between the flexible material and water is largely dependent on convection. Water flowing over a relatively flat surface will not result in efficient heat exchange.

[0007] U.S. Pat. No. 3,825,063 discloses a heat exchanger having metal screens of fine mesh with internal plastic barriers that at least partly penetrate the screens. The screens are stacked to provide transverse heat conduction relative to longitudinal flow paths. U.S. Pat. No. 4,403,653 discloses a heat transfer panel comprising a woven wire mesh core embedded in a layer of plastic material. The mesh and closure layer extend in the same longitudinal direction. U.S. Pat. No. 5,660,917 discloses a sheet with electrically insulating thermal conductors embedded in it. The apparatus disclosed in those patents is not adapted for warming or cooling living subjects.

[0008] There remains a need for heat exchangers capable of providing high heat transfer rates between the heat exchangers and objects that are not flat, are vibrating or are otherwise difficult to interface to. There is a particular need for such heat exchangers which have high ratio of heat-transfer capacity to contact area.

SUMMARY OF THE INVENTION

[0009] The invention relates to heat exchangers. One aspect of the invention provides flexible heat exchange interfaces. The interfaces have plates of elastomeric material penetrated by substantially rigid thermally conductive members. The thermally conductive members have enlarged pads on at least one side of the plate.

[0010] The elastomeric material allows the interfaces to flex while the thermally conductive members are operative to channel heat from a higher-temperature side of the interface to a lower-temperature side of the interface.

[0011] Another aspect of the invention provides a flexible heat exchanger comprising a volume having an inlet and an outlet. The volume can receive a heat exchange fluid, for example, water or a water-based coolant. The heat exchanger includes a flexible plate. Substantially rigid thermally conductive members extend through a flexible material of the flexible plate from an outside surface of the flexible plate into the volume.

[0012] In preferred embodiments the thermally conductive members each have a thermal conductivity of at least 50 $Wm^{-1}K^{-1}$ and preferably at least 100 $Wm^{-1}K^{-1}$. The thermally conductive elements may be made of materials such as aluminum, copper, gold, silver, alloys of two or more of aluminum, copper, gold, or silver with one another, alloys of one or more of aluminum, copper, gold, or silver with one or more other metals, carbon, graphite, diamond, or sapphire.

[0013] The thermally conductive members may cover a substantial portion of the outer surface of the flexible heat exchange plate. For example, the thermally conductive members may be exposed in an area of at least 50%, preferably at least 70% and, in some embodiments, at least 80% of an area of the flexible heat exchange plate.

[0014] The flexible material of the plate may comprise an elastomer material. The thermally conductive members may be embedded in the elastomer material by any suitable process. The elastomer material may comprise, for example, natural rubber, polyurethane, polypropylene, polyethylene, ethylene-vinyl acetate, polyvinyl chloride, silicone, or a combination of two or more of polyurethane, polypropylene, polyethylene, ethylene-vinyl acetate, polyvinyl chloride, and silicone. In some embodiments the elastomer material has a thermal conductivity not exceeding 5 $Wm^{-1}K^{-1}$.

[0015] A further aspect of the invention provides a temperature control system comprising a heat exchanger according to the invention, a reservoir containing a heat exchange fluid; a first feed pump connected to feed heat exchange fluid from the reservoir into the heat exchanger and a second feed pump connected to withdraw the heat exchange fluid from the reservoir.

[0016] Further aspects of the invention and features of specific embodiments of the invention are described below.

BRIEF DESCRIPTION OF THE DRAWINGS

[0017] In drawings which illustrate non-limiting embodiments of the invention:

[0018] **FIGS. 1A, 1B** and 1C are respectively a longitudinal elevational cross-section view; a top plan view and a bottom plan view of a flexible heat exchanger;

[0019] **FIGS. 2A, 2B** and **2C** are respectively a cross-section view; a bottom view; and a top view of the flexible plate of a heat exchanger according to an alternative embodiment of the invention;

[0020] **FIG. 2D** is a partial view of the outside surface of a heat exchanger having thermally conductive members arranged in a triangular array;

[0021] **FIG. 2E** is a partial view of the outside surface of a heat exchanger having thermally conductive members arranged to provide converging lines of flexible material;

[0022] **FIG. 2F** is a view of the outside surface of a heat exchanger having thermally conductive members arranged in a rectangular array oriented at an angle to a long axis of the heat exchanger;

[0023] **FIGS. 3A, 3B** and **3C** are respectively a cross-section view; a bottom view; and a top view of a heat exchanger according to one embodiment of the invention;

[0024] **FIGS. 4A through 4L** are views of different heat conductors that can be used in heat exchangers according to different embodiments of the invention;

[0025] **FIGS. 5A and 5B** are respectively an isometric view and a longitudinal elevational section through a pre-curved flexible fluid heat exchanger;

[0026] **FIGS. 6A, 6B, 6C** and 6D are schematic views of heat exchangers according to the invention being applied to cool various types of apparatus;

[0027] **FIG. 7** is a schematic view of a heat exchanger according to the invention being used to exchange heat with a very hot object;

[0028] **FIGS. 8A and 8B** are cross-section views of heat exchange interfaces having pads on two sides; and,

[0029] **FIGS. 9, 10** and **11** are schematic views of cooling systems according to the invention.

DESCRIPTION

[0030] Throughout the following description, specific details are set forth in order to provide a more thorough understanding of the invention. However, the invention may be practiced without these particulars. In other instances, well known elements have not been shown or described in detail to avoid unnecessarily obscuring the invention. Accordingly, the specification and drawings are to be regarded in an illustrative, rather than a restrictive, sense.

[0031] Heat exchangers according to the invention have thermally conductive members which can be placed in thermal contact with an object to be heated or cooled. The thermally conductive members pass through a membrane of a flexible material. In some embodiments the membrane is essentially impermeable to a heat exchange fluid that contacts portions of the thermally conductive members that are distal to the object. The membrane permits the heat exchange members to move relative to one another to conform with surface contours of the object. For example, the membrane may permit the members to conform to a convex and/or concave curved surface on the object.

[0032] The thermally conductive members accept heat from a higher-temperature side of the membrane, channel the heat through the membrane, and release the heat to a lower-temperature side of the membrane. The members provide much lower thermal resistance than would be the case if the members were not present.

[0033] In some embodiments, the members have pads on their ends proximate to the object. The pads are dimensioned and distributed in such a manner that the pads cover a large proportion of a heat exchange area of the membrane. In certain embodiments of the invention, pads of a plurality of the thermally conductive members cover at least 50%, preferably at least 70%, and most preferably at least 80% of an area of the outer side of the membrane.

[0034] An inner side of the membrane may define one side of a channel which carries a heat exchange fluid. Heat exchange fluid may be driven to flow through the channel by way of a suitable pumping system to deliver heat to, or draw heat from, the thermally conductive members.

[0035] In some embodiments of the invention a plurality of the thermally conductive members have thermally conductive projections, which may comprise, for example, pins, fins, bars, plates or the like that project into the volume of a heat exchanger to form an efficient heat exchange interface with heat exchange fluid in the volume. The projecting pins, fins, bars, plates or the like may or may not be similar in shape or other physical characteristics to the parts of the thermally conductive members that extend through the membrane to form thermal channels through the membrane.

[0036] The thermally conductive members may be made of any suitable thermally conductive materials including thermally conductive metals, for example, aluminum, copper, gold, silver, or alloys of these metals with one another and/or with other metals. The thermally conductive members may also be made of non-metals which have high thermal conductivities such as carbon, suitable grades of graphite, diamond, sapphire or the like. Preferably the thermally conductive members are made from materials having thermal conductivities, k, of at least 50 $Wm^{-1}K^{-1}$ and preferably at least 100 $Wm^{-1}K^{-1}$.

[0037] **FIGS. 1A through 1C** show a heat exchanger **10** according to an embodiment of the invention. Heat exchanger **10** has a heat exchange plate **12** penetrated by a number of thermally conductive members **14**. Plate **12** has an outer face **16** and an inner face **18**. Heat exchanger **10** has an inside volume **20** and ports **22**, **23** by way of which a heat exchange fluid can flow through volume **20**. Volume **20** is defined on a front side by plate **12** and on a rear side by a rear wall **24**. Side walls **25** extend between plate **12** and rear wall **24**. Plate **12**, rear wall **24** and side walls **25** are all flexible so that the outer surface **16** of heat exchanger **10** can conform to the local contours of a portion of an object to be heated or cooled.

[0038] Thermally conductive members **14** pass through the material **30** of plate **12**. Inside ends **26** of thermally conductive members **14** project into volume **20**. Ends **26** preferably project significantly into volume **20**. In the embodiment shown in **FIG. 1**, ends **26** are cut away to provide increased surface area for heat transfer with fluid in volume **20**. Each inner end **26** comprises a number of prongs **27**. Outer faces **28** of pads **29** on the proximal ends of thermally conductive members **14** can be placed against an object. Pads **29** are separated sufficiently to permit heat exchanger **10** to flex in a desired degree but are preferably closely spaced to maximize the area of outer faces **28** that can be placed against a desired region on an object. For example, in some embodiments, pads **29** are spaced apart from one another by spacings in the range of 0.5 mm to 50 mm. For smaller heat exchangers the spacing between pads **29** is typically at the lower end of this range (i.e. in the range of 0 mm to 5 mm).

[0039] In some embodiments, pads **29** have thicknesses in the range of 0.5 mm to 5 mm. Preferably, pads **29** have thicknesses in the range of 1 mm to 2.5 mm. The sizes and dimensions of pads **29** in the plane of plate **12** may be chosen to suit the application, taking into consideration the contours of the object to be cooled or heated.

[0040] Thermally conductive members **14** may have reduced cross sectional areas in their portions toward inner face **18** from pads **29**. The cross-sectional area of thermally conductive members **14** at the point that thermally conductive members **14** emerge from material **30** on inner face **18** of plate **12** may, for example, be in the range of 20% to 100%, and in some embodiments is 35% to 65%, of the area of pads **29**.

[0041] Thermally conductive members **14** have lengths sufficient to pass through material **30**. In preferred embodiments, members **14** project into volume **20**. Thermally conductive members **14** may, for example, project into volume **20** for a distance in the range of 0 mm to 100 mm. For small heat exchangers the projection may be at the lower end of this range (i.e. in the range of 0 mm to 20 mm). The portions of members **14** which project into volume **20** may also function as supports to maintain a minimum spacing between wall **24** and plate **12**. These portions may constitute spacing means for preventing rear wall **24** from collapsing against plate **12**.

[0042] It is not necessary that all thermally conductive members **14** be identical or that all thermally conductive members **14** have equal-sized pads **29** although it is convenient to make heat exchanger **10** with thermally conductive members **14** substantially the same as one another.

[0043] Material **30** constitutes a flexible membrane through which thermally conductive members **14** extend. In some embodiments, rear wall **24** is made of material **30**. Substantially all of heat exchanger **10**, except for thermally conductive members **14**, may be made of the same material **30**. Material **30** is preferably both flexible and elastically stretchable. Material **30** may, for example, comprise natural rubber or any of a variety of suitable flexible polymers such as polyurethane, polypropylene, polyethylene, ethylene-vinyl acetate, polyvinyl chloride, silicone, a combination of these materials or the like. Material **30**, or portions of material **30** may optionally be loaded with particles of one or more thermally conductive materials such as metal or graphite. However, since material **30** is not required to play a significant role in conducting heat, material **30** may be a material having a relatively low thermal conductivity (i.e. a thermal conductivity not exceeding 5 $Wm^{-1}K^{-1}$) without significantly impairing the function of heat exchanger **10**. In some embodiments, material **30** has a hardness in the range of 10 to 80 on the Shore A hardness scale.

[0044] Plate **12** may be fabricated using any suitable process. For example, plate **12** may be made by making holes in a sheet of material **30** and inserting thermally conductive members **14** through the holes. The holes may initially have dimensions smaller than corresponding dimensions of thermally conductive members **14** so that material **30** seals around thermally conductive members **14** sufficiently to prevent any significant loss of heat exchange fluid from volume **20**. Additionally, or in the alternative, a sealant, such as a suitable glue, may be provided to enhance the seal between thermally conductive members **14** and material **30**. Plate **12** may also be made by a suitable plastic manufacturing process such as thermal injection molding, reaction injection molding, compression molding, vacuum forming or casting. In this case, thermally conductive members **14** may be molded into plate **12**.

[0045] The thickness of material **30** in plate **12** can be selected to provide a desired compromise between flexibility and durability. Since heat exchanger **10** does not rely on material **30** to conduct heat, it is not necessary to make material **30** extremely thin to improve heat conduction. Material **30** may, for example, have a thickness in the range of about 1 mm to 20 mm. In some currently preferred embodiments of the invention, material **30** has a thickness in the range of 3 mm to 7 mm in plate **12**.

[0046] Projections of material **30**, or some other material, may optionally extend into volume **20**. Such projections may be positioned to support wall **24** relative to plate **12**, to direct the flow of fluid **65** within volume **20** and/or to induce turbulence at selected locations in the flow of fluid **65** in order to provide enhanced thermal contact between thermally conductive members **14** and heat exchange fluid **65**. Such projections may constitute spacing means for preventing rear wall **24** from collapsing against plate **12**.

[0047] Thermally conductive members **14** may be arranged in a wide range of patterns. For example, as shown in **FIG. 1**, members **14** may be arranged in rows and columns to form a rectangular array, which could be a square array. In some embodiments, members **14** are arranged in rows or columns which are shifted relative to one another as shown in **FIGS. 2B and 2C**. This arrangement creates increased turbulence in fluid flowing through volume **20** and hence increases the efficiency of heat transfer between the inner ends of thermally conductive members **14** and fluid **65**. In some embodiments, pads of members **14** are arranged in a rectangular array as illustrated, for example, in **FIG. 1**, while portions of members **14** which project into volume **20** are arranged in rows or columns which are shifted relative to one another as shown in **FIGS. 2B and 2C**. In some embodiments, members **14** are arranged in a triangular array, as shown in **FIG. 2D**.

[0048] Flexing of plate **12** may be facilitated by arranging members **14** to provide substantially unbroken lines **31** of material **30** extending generally parallel to one or more axes about which heat exchanger **10** may be flexed. The embodiment shown in **FIG. 1B** shows two sets of lines **31** of material **30** which extend between adjacent rows and columns of members **14**. The embodiment illustrated in **FIG. 2B** has one set of parallel lines **31**. Lines **31** are not necessarily parallel to one another. For example, **FIG. 2E** illustrates an arrangement of members **14** which facilitates flexing in such a way as to conform to a portion of the surface of a cone. The array of members **14** is not necessarily aligned with any axis of heat exchanger **10**. For example, **FIG. 2F** shows the outside face of a heat exchanger wherein thermally conductive members **14** are arranged in a rectangular array oriented at an angle, ϕ, to a long axis of the heat exchanger.

[0049] **FIGS. 2**A to **2**F and **3**A to **3**C illustrate heat exchangers in which faces **28** are substantially flush with material **30** on outer face **16**. This arrangement facilitates cleaning, as outer face **16** is substantially smooth. **FIGS. 1A** to **1**C illustrate an embodiment of the invention wherein pads **29** project from material **30** on outer surface **16** of heat exchanger **10**. The embodiment illustrated in **FIGS. 1A** to **1**C can be fabricated, for example, by inserting thermally conductive members **14** though holes formed in a sheet of material **30**.

[0050] Thermally conductive members **14** may take any of a wide variety of forms which provide effective means to transfer heat from a higher-temperature side to a lower-temperature side of the membrane. The members preferably provide good thermal interface between the thermally conductive members and the object to be cooled or heated, good thermal channels across membrane material **30**, and good thermal interface between the thermally conductive members and the heat exchange fluid in volume **20** of the thermal exchanger.

[0051] Some possible forms for members **14** are illustrated in **FIGS. 4A through 4K**. It is understood that these possible forms are illustrated as examples and modifications to these examples can be made to obtain a much larger list of examples. In addition, features illustrated in these examples can be swapped or combined partially or fully to obtain an even larger list of examples. **FIG. 4A** shows a thermally conductive member **14**A having a square pad **29** and cylindrical pin **32** as means to channel heat through material **30** and to release heat into (or take heat from) the fluid in volume **20** of the heat exchanger. **FIG. 4B** shows a thermally conductive member **14**B having a circular pad **29** instead of a square pad.

[0052] **FIG. 4C** shows a thermally conductive member **14**C wherein both pad **29** and the pin **32** are square in cross-section (like the thermally conductive members of **FIGS. 2A** to 2C). **FIG. 4D** shows a thermally conductive member **14**D similar to member **14**A except that pin **32** has a circumferential groove **33** in its part close to pads **29**. Groove **33** receives extra material **30** in an injection molding or casting process to better seal member **14**D to material **30**. **FIG. 4E** shows a thermally conductive member **14**E wherein a tip of pin **32** is tapered to facilitate insertion into a hole in a sheet of material **30**.

[0053] **FIG. 4F** shows a thermally conductive member **14**F having a pair of platelike rectangular conductors **34**. Conductors **34** carry heat through material **30** and provide a mechanism for releasing heat into (or taking heat from) heat exchange fluid in volume **20**. Conductors **34** may be arranged in a V-shape to better transfer heat to fluid flowing past plates **34**. Plate-like conductors could also be arranged in other manners such as being parallel with each other. Thermally conductive member **14**F has the advantage that it can be made by cutting and folding a thermally conductive sheet material.

[0054] **FIG. 4G** shows a thermally conductive element **14**G having a thermal channel portion provided by a tubular pin **36**. **FIG. 4H** shows a thermally conductive member **14**H having multiple pins **38** extending from pads **29**. Pins **38** provide multiple thermal channels extending from the same pad **29** and projecting into volume **30**. Conductive member **14**H advantageously provides increased contact area between conductive member **14**H and a heat transfer fluid in volume **20**. **FIGS. 4I and 4J** show a thermally conductive member **14I** that is designed to reduce the possibility of fluid leaking between material **30** and member **14I**. Member **14I** may be fabricated in two-pieces **14I-1** and **14I-2** that can be assembled together in a manner that provides good thermal contact between pieces **14I-1** and **14I-2**. In the illustrated embodiment, one of the pieces of member **14I** has a pin **39** which is received in a corresponding socket **40** (see **FIG. 4J**) in the other piece. Pin **39** may have an interference fit in socket **40** to keep the two pieces tightly together and to provide good heat transfer between the pieces. A circumferentially extending groove **41** is defined between pieces **14I-1** and **14I-2**. Groove **41** receives material **30**. The faces of pieces **14I-1** and **14I-2** which contact material **30** may be undercut to provide ridges **42** which help to prevent fluid from leaking past member **14I**. The pieces of multi-piece thermally conductive members may be fastened together in other ways which provide thermal contact between the pieces. For example, fastening means such as screws, rivets, or the like may be provided. **FIGS. 4K and 4L** show a thermally conductive member **14**K that is similar to member **14I** but is an integral part. Member **14**K is designed to be cramped onto material **30**. Material **30** projects into a groove **43**. The sides of the groove **43** may be cramped together to hold material **30** around the edges of member **14**K as shown in **FIG. 4L**.

[0055] **FIGS. 5A and 5B** show a flexible fluid heat exchanger **50** which is normally curved in the absence of applied forces. Heat exchanger **50** may be used to apply heat to or to cool a substantially cylindrical object. Apart from being curved, heat exchanger **50** is similar to heat exchanger **10** of **FIGS. 1A through 1C**.

[**0056**] Heat exchangers according to the invention may be pre-formed so that surface **16** has a concave and/or convex curvature in the absence of applied forces. **FIGS. 5A and 5B** show a heat exchanger in which surface **16** has a pre-formed concave curvature.

[**0057**] Heat exchangers according to the invention may be applied to heating or cooling objects of diverse types. For example, **FIG. 6A** shows a heat exchanger **10** being used to cool an electric motor **52**. Pads **29** contact the curved outer surface **53** of motor **52**. **FIG. 6B** shows a heat exchanger **10** being applied to cool a compressor **54** having an outer housing **55** which has a profile having compound curvature. Pads **29** contact surface **55**. Compressors having compound curves are frequently used in refrigeration and air conditioning systems. **FIGS. 6C and 6D** show a heat exchanger **10** being applied to cool an exchange pipe **56**. Pads **29** contact an outer cylindrical surface **57** of exhaust pipe **56**.

[**0058**] **FIG. 7** illustrates schematically a heat exchanger **58** being used to cool an object **59** having a temperature high enough that it could cause degradation of material **30**. Heat exchanger **58** is similar to heat exchanger **10** except that pads **29** are spaced away from material **30**, members **14** are longer and a heat shield **60** is provided between pads **29** and material **30**. Each of thermally conductive members **14** extends through a thermally insulating sleeve **59**A. Sleeves **59**A protect material **30** from becoming overheated through contact with members **14**. Shield **60** protects material **30** from heat radiated by object **59**.

[**0059**] Heat exchangers according to the invention may also be used to transfer heat between fluids and/or between solid objects. **FIG. 8A** shows a heat exchanger **61** comprising a membrane of a material **30** penetrated by thermally conductive members **62**. Members **62** have pads **29** on both sides of material **30**. As shown in **FIG. 8B**, pads **29** can optionally comprise fins, pins or other thermally conductive elements disposed to provide improved thermal contact between pad **29** and a surrounding fluid. The heat exchanger **61**A illustrated in **FIG. 8B** has pins **32** projecting from each pad **29**. Pads **29** are larger in area than the central portions of members **14** which pass through material **30**. The edges of the pads press against the membrane to seal any gap between the member and the membrane so that fluid will not leak from one side to the other.

[**0060**] A suitable circulation system may be used to circulate a heat exchange fluid through the volume **20** of one or more heat exchangers as described herein. Water has a high specific heat capacity which makes water or water-based coolants good for use as a circulating fluid **65** in cases where fluid **65** can operate at temperatures where such coolants are liquid.

[**0061**] It is generally desirable to maintain the pressure of fluid in volume **20** approximately equal to the ambient air pressure surrounding heat exchanger **10**. If the pressure within volume **20** is significantly smaller than the ambient air pressure then pressure differences across the walls of volume **20** will tend to collapse volume **20**. The projected ends **26** of thermally conductive members **14** or other supports provided in heat exchanger **10** may prevent the walls from complete collapse. If the pressure within volume **20** is significantly larger than the ambient air pressure then heat exchanger **10** will tend to balloon.

[**0062**] **FIG. 9** is a schematic view of a cooling system **100** which includes a heat exchanger **10** and a fluid circulating system **63**. Circulation system **63** has an insulated reservoir **64** containing a volume of ice **66**. System **63** contains a suitable heat exchange fluid **65**, which may be liquid water. System **63** delivers fluid **65** to heat exchanger **10** through delivery conduit **67** and returns coolant to reservoir **63** through a return conduit **68**.

[**0063**] A first feed pump **70** upstream from heat exchanger **10** delivers fluid **65** from reservoir **64** to heat exchanger **10**. A second feed pump **72** is located downstream from heat exchanger **10**. Second feed pump **72** draws fluid **65** from heat exchanger **10** and returns the fluid to reservoir **64**. First and second feed pumps **70** and **72** are balanced so that the pressure of fluid **65** within volume **20** of heat exchanger **10** is substantially equal to the ambient air pressure.

[**0064**] One or more bypass valves may be provided to provide better control over fluid pressure within volume **20**. In system **100**, an adjustable bypass valve **74** is connected between the output of first feed pump **70** and reservoir **64**. Bypass valve **74** indirectly regulates the pressure within volume **20**. When bypass valve **74** is opened, a larger proportion of fluid **65** is returned to reservoir **64** by way of bypass conduit **75** and the amount of fluid **65** flowing into heat exchanger **10** is reduced. Bypass valve **74** may be pressure-operated.

[**0065**] System **100** has a second bypass valve **76** connected in parallel with second feed pump **72**. When second bypass valve **76** is open, second feed pump **72** can draw fluid **65** from reservoir **64** by way of conduit **77**. Opening second bypass valve **76** increases pressure at the input of second feed pump **72** and consequently increases the pressure within volume **20**.

[**0066**] Many variations of system **100** are possible. Although two bypass valves are shown in **FIG. 9** for maximum flexibility, one bypass valve connected in parallel with either one of pumps **70** or **72** or in parallel with heat exchanger **10** may be sufficient to permit pressure inside heat exchanger **10** to be maintained within a desired range. In addition, depending upon the construction of pumps **70** and **72** and the fluid flow properties of the circuit which includes conduits **67**, **68** and heat exchanger **10** it may be possible to maintain the fluid pressure in volume **20** within the desired range without the need for bypass valves **74** and **76**. Where bypass valves are provided it is not necessary that they be connected directly to reservoir **64** as illustrated. Other connections may be provided which have the result of maintaining pressures upstream and/or downstream from heat exchanger **10** at values which keep the pressure within volume **20** at a desired level while maintaining fluid flow through volume **20**.

[**0067**] In some cases it may be convenient to provide a single reservoir **64** for providing heat exchange fluid for multiple heat exchangers **10**. In such cases it is best to provide upstream and downstream pumps **70** and **72** for each heat exchanger **10**. In the alternative, suitable manifolds, such as T-connectors, could be provided to allow a number of heat exchangers **10** to be connected in parallel between a single upstream pump system and a single downstream pump system.

[0068] **FIG. 10** illustrates another fluid circulating system **100**A. In system **100**A, a first flow regulator **78** comprising a restrictor **80** and a bypass valve **82** is provided between first feed pump **70** and heat exchanger **10**. Bypass valve **82** is connected in parallel with restrictor **80**. When fluid **65** is flowing through flow regulator **78** then a pressure drop across flow regulator **78** depends upon the fluid flow rate and upon the degree to which bypass valve **82** is open.

[0069] System **61**A has a second flow regulator **79** which includes a second flow restrictor **84** and a bypass valve **86**. Bypass valve **86** is connected in parallel with restrictor **84**. In system **100**A, bypass valves **82** and **86** are adjustable. The fluid pressure within volume **20** can be controlled by adjusting one or both of bypass valves **82** and **86**.

[0070] Some alternative embodiments of the invention lack one of flow regulators **78** and **79**. When system **100**A is connected to supply fluid **65** to a plurality of heat exchangers **10** it is preferable to provide for each heat exchanger **10** at least one adjustable flow regulator **78** or **79** located where only fluid going to or from that heat exchanger passes through the flow regulator. This permits the pressure within each heat exchanger **10** to be individually regulated. In the alternative, as described above, suitable manifolds may be provided to split the flow of fluid **65** between a number of heat exchangers **10** connected in parallel.

[0071] **FIG. 11** illustrates another fluid circulating system **10**B. In system **100**B the pressure within volume **20** of heat exchanger **10** is controlled by adjusting the rate of operation of one or both of upstream and downstream feed pumps **70** and **72**. In some embodiments of the invention a control system simultaneously increases the rate of operation of feed pump **70** and decreases the rate of operation of feed pump **72** or vice versa. The rate of operation of pumps **70** and **72** may be controlled by adjusting the rate of rotation of motors which drive the pumps, by adjusting displacements of the pumps, or the like.

[0072] In the illustrated embodiment, control is accomplished by operating a power splitter **88** (illustrated schematically by a potentiometer). Power splitter **88** can be operated to increase the speed of a motor driving pump **70** and to decrease the speed of a motor driving pump **72** or vice versa.

[0073] Systems **100**, **100**A and **100**B may be automatically controlled using any suitable control system. For example, a controller may be provided to operate bypass valves and/or control pump speeds or displacements by way of suitable actuators (not shown) as necessary to control pressure within volume **20** to stay within a desired range. Those skilled in the art are familiar with suitable controllers. The controller may, for example, comprise a suitably programmed programmable controller or a hardware control circuit. One or more pressure sensors and/or flow sensors (not shown) may be included to provide feedback to the controller.

[0074] Any of cooling systems **100**, **100**A or **100**B may be adapted for warming by replacing ice **66** with a suitable heating element which can be operated to warm fluid **65** in reservoir **64** to a desired temperature. Instead of ice **66**, any of systems **100**, **100**A or **100**B could include a refrigeration system to cool fluid **65**.

[0075] Where a component (e.g. a member, assembly, element, device, circuit, etc.) is referred to above, unless otherwise indicated, reference to that component (including a reference to a "means") should be interpreted as including as equivalents of that component any component which performs the function of the described component (i.e., that is functionally equivalent), including components which are not structurally equivalent to the disclosed structure which performs the function in the illustrated exemplary embodiments of the invention.

[0076] As will be apparent to those skilled in the art in the light of the foregoing disclosure, many alterations and modifications are possible in the practice of this invention without departing from the spirit or scope thereof. For example:

> [0077] Thermally conductive members **14** may have any suitable shapes and arrangements. Those illustrated herein are but examples.
>
> [0078] Flexible material **30** may have different compositions in different parts of a heat exchanger according to the invention. Different suitable flexible materials **30** may be used for material **30** in different parts of a heat exchanger.
>
> [0079] A heat exchanger according to the invention is not necessarily rectangular or parallel-sided. A heat exchanger according to the invention could have other shapes. Heat exchangers according to some currently preferred embodiments of the invention are elongated and have fluid inlets and fluid outlets located in areas at opposed ends of a long axis.

[0080] Accordingly, the scope of the invention is to be construed in accordance with the substance defined by the following claims.

What is claimed is:

1. A flexible heat exchange interface for use in a heat exchanger, the flexible interface comprising a plate of an elastomer material penetrated by a plurality of substantially rigid thermally conductive members, each of the plurality of thermally conductive members having a first enlarged pad on at least a first side of the plate.

2. A flexible heat exchange interface according to claim 1 wherein each of the plurality of thermally conductive members project from a second side of the plate opposed to the first side of the plate.

3. A flexible heat exchange interface according to claim 1 wherein each of the plurality of thermally conductive members has a second enlarged pad on a second side of the plate opposed to the first side of the plate.

4. A flexible heat exchange interface according to claim 3 wherein at least one of the first and second enlarged pads is cramped around its edge against the elastomer material.

5. A flexible heat exchange interface according to claim 3 wherein each of the plurality of thermally conductive members comprises first and second parts, the first part including the first pad and comprising a pin engaging a socket on the second part, the second part including the second pad.

6. A flexible heat exchange interface according to claim 3 wherein at least one of the first and second enlarged pads comprises a plurality of projections, the projections projecting away from the plate.

7. A flexible heat exchanger comprising:

a volume having at least one inlet for receiving a heat exchange fluid and at least one outlet; and,

a flexible plate essentially impermeable to the heat exchange fluid, the plate comprising a plurality of substantially rigid thermally conductive members extending through a flexible material of the plate from an outside surface of the plate into the volume.

8. A flexible heat exchanger according to claim 7 wherein the volume is defined between the plate and a flexible back wall spaced apart from the plate.

9. A flexible heat exchanger according to claim 7 wherein the thermally conductive members are arranged in a rectangular array.

10 A flexible heat exchanger according to claim 9 wherein the thermally conductive members each comprise a generally rectangular pads on the outside surface of the plate.

11. A flexible heat exchanger according to claim 7 wherein the thermally conductive members are arranged in a triangular array.

12. A flexible heat exchanger according to claim 7 wherein the thermally conductive members are arranged to provide a plurality of substantially unbroken lines of the flexible material extending between the thermally conductive members.

13. A flexible heat exchanger according to claim 7 wherein the thermally conductive members each have a thermal conductivity of at least 50 $Wm^{-1}K^{-1}$.

14. A flexible heat exchanger according to claim 7 wherein the thermally conductive members each have a thermal conductivity of at least 100 $Wm^{-1}K^{-1}$.

15. A flexible heat exchanger according to claim 14 wherein the thermally conductive members are made of a material selected from the group consisting of: aluminum, copper, gold, silver, alloys of two or more of aluminum, copper, gold, or silver with one another and alloys of one or more of aluminum, copper, gold, or silver with one or more other metals.

16. A flexible heat exchanger according to claim 13 wherein the thermally conductive members are made of materials selected from the group consisting of: carbon, graphite, diamond, and sapphire.

17. A flexible heat exchanger according to claim 7 wherein a plurality of the thermally conductive members covers at least 70% of an area of the outer side of the heat exchange plate.

18. A flexible heat exchanger according to claim 7 wherein the flexible material of the plate comprises an elastomer material and the thermally conductive members are embedded in the elastomer material.

19. A flexible heat exchanger according to claim 18 wherein the elastomer material comprises a material selected from the group consisting of: polyurethane, polypropylene, polyethylene, ethylene-vinyl acetate, polyvinyl chloride, silicone, natural rubber and a combination of two or more of polyurethane, polypropylene, polyethylene, ethylene-vinyl acetate, polyvinyl chloride, and silicone.

20. A flexible heat exchanger according to claim 7 wherein the thermally conductive members project into the volume.

21. A flexible heat exchanger according to claim 20 wherein the thermally conductive members project into the volume from the inner surface of the plate by distances of at least 3 mm.

22. A flexible heat exchanger according to claim 7 wherein the flexible material of the plate has a thermal conductivity not exceeding 5 $Wm^{-1}K^{-1}$.

23. A flexible heat exchanger according to claim 7 wherein a plurality of the thermally conductive members each comprise an outer end comprising a pad on the outer side of the plate and an inner end projecting into the volume.

24. A flexible heat exchanger according to claim 23 wherein the inner end of each of the plurality of thermally conductive members comprises a plurality of spaced apart projections.

25. A flexible heat exchanger according to claim 23 wherein a plurality of the thermally conductive members each comprise a first part connected to the second part wherein the first and second parts define a circumferentially extending groove and the flexible material of the plate is received in the groove.

26. A flexible heat exchanger according to claim 23 wherein the inner end of each of the thermally conductive members is tubular, square, rectangular, cylindrical or spherical.

27. A flexible heat exchanger according to claim 7 wherein the outer surface has a concave curved configuration in the absence of bending forces acting on the heat exchanger.

28. A flexible heat exchanger according to claim 7 wherein the outer surface has a convex curved configuration in the absence of bending forces acting on the heat exchanger.

29. A flexible heat exchanger according to claim 7 wherein a portion of the outer surface of the heat exchanger on which the thermally conductive members are disposed is dimensioned to be applied exclusively to an area of a subject's anatomy overlying a carotid artery of the subject.

30. A flexible heat exchanger according to claim 7 wherein a total area of the thermally conductive members exposed on the outside surface of the plate exceeds a total cross sectional area of the thermally conductive members at a point where the cross sectional members enter the volume.

31. A flexible heat exchanger according to claim 7 wherein the volume is defined between a flexible rear wall and the flexible plate and the heat exchanger comprises spacing means for preventing the rear wall from collapsing against the flexible plate.

32. A flexible heat exchanger according to claim 7 wherein the volume is defined between the flexible plate, a flexible rear wall made of the flexible material and flexible side walls made of the flexible material.

33. A temperature control system comprising:

a heat exchanger according to claim 7;

a reservoir containing a heat exchange fluid;

a first feed pump connected to feed the heat exchange fluid from the reservoir into the input of the heat exchanger;

a second feed pump connected to withdraw the heat exchange fluid from the output of the heat exchanger.

34. A system according to claim 33 comprising a controller connected to control operation of the first and second feed pumps to maintain a pressure of the heat exchange fluid within the volume within a desired range of an ambient air pressure outside the volume.

35. A system according to claim 34 comprising an adjustable bypass valve connected in parallel with one of the first and second feed pumps wherein the controller is configured to operate an actuator to adjust the bypass valve.

36. A system according to claim 33 comprising an adjustable bypass valve connected in parallel with one of the first and second feed pumps.

37. A system according to claim 36 wherein the adjustable bypass valve is configured to be opened by a pressure differential across the bypass valve.

38. A system according to claim 33 comprising a variable restriction connected between the heat exchanger and one of the feed pumps.

* * * * *