United States Patent

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[45] **May 9, 1972**

[54] **HEAT TRANSFER APPARATUS WITH IMPROVED HEAT TRANSFER SURFACE**

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[21] Appl. No.: **143,459**

Related U.S. Application Data

[62] Division of Ser. No. 52,642, July 6, 1970, Pat. No. 3,598,180.

[52] **U.S. Cl.** **165/105**
[51] **Int. Cl.** **F28d 15/00**
[58] **Field of Search** 165/105, 133

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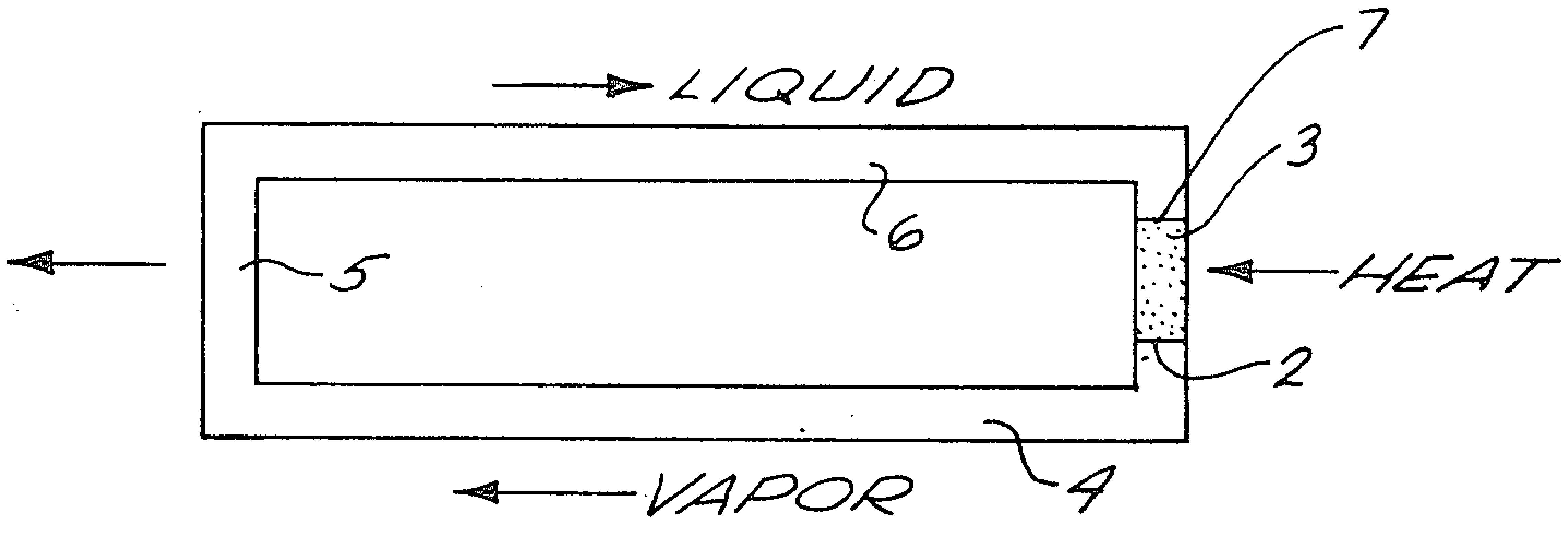
[57] **ABSTRACT**

A heat transfer device, defined here as a heat link, having a capillary vaporizer adjacent a heat source, transfers heat to a heat sink by vaporization and condensation of a heat transfer fluid within the device. A first passage is provided for conveying vapor from the capillary vaporizer to the heat sink. Another passage which is essentially a continuation of the first passage, conveys condensed liquid from the heat sink to the vaporizer, thus allowing the distance that the liquid must flow through capillary material to be quite short. Contact of the returning liquid with the surface of the vaporizer is assured by providing means for maintaining the temperature of the liquid in the return line at a sufficiently low temperature that any vapor will condense; or, alternatively, by having means for extracting any vapor formed in the returning liquid. In this manner, the heat link operates with high heat flux without any substantial resistance to liquid flow through a long capillary flow path. By thus replacing almost all of the liquid return wick, with its high resistance to fluid flow, of heat pipes with a low flow resistance liquid passage or conduit, the heat flux capacity of the heat link is greatly increased over that of the heat pipe while the quantity of porous material used and the heat link weight are considerably reduced so that a heat link typically has 10 to 1,000 times the heat flux capacity of a heat pipe having the same weight. "Boosted" embodiments of the heat link employing additional means for circulating the fluid, such as vapor jet pumps, powered at least in part by vapor from the capillary vaporizer, are also described. Some "-boosted" heat links are capable of handling heat fluxes in the multi-megawatt range while having no moving parts except for check valves and the fluid itself.

20 Claims, 21 Drawing Figures



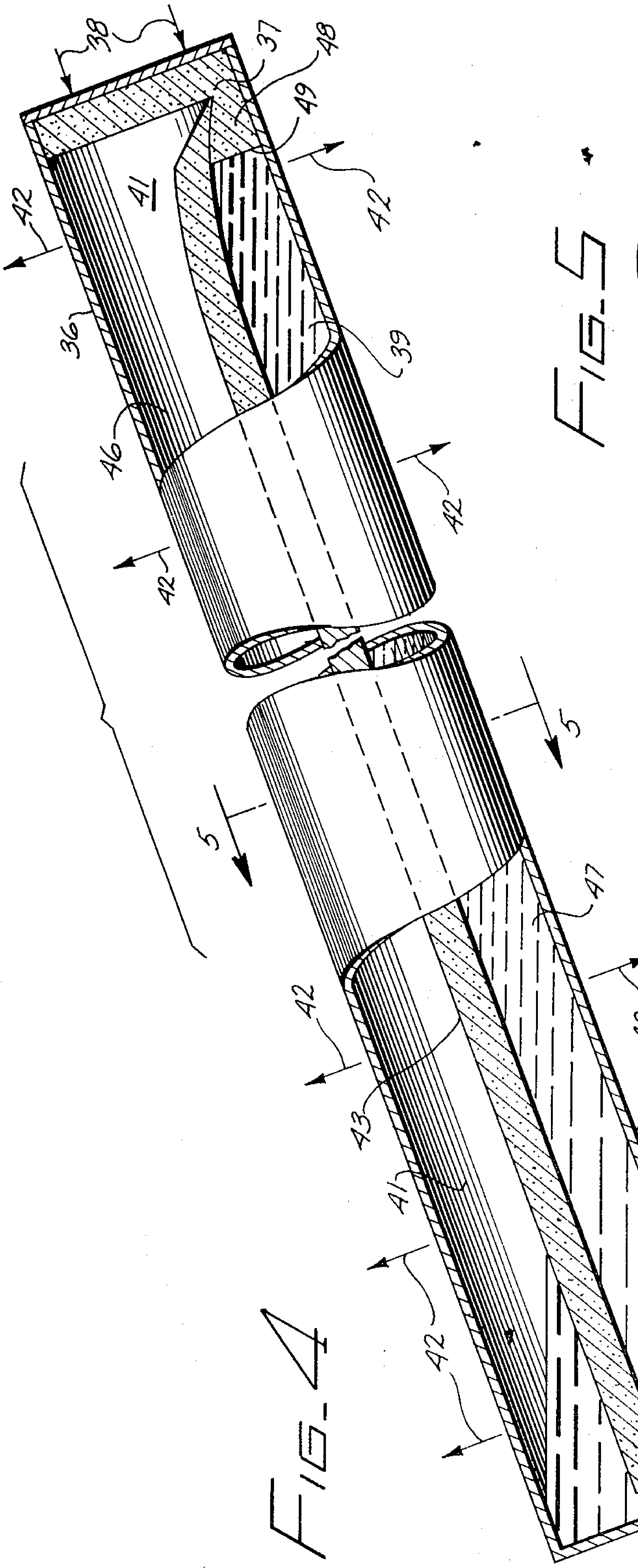


FIG. 4

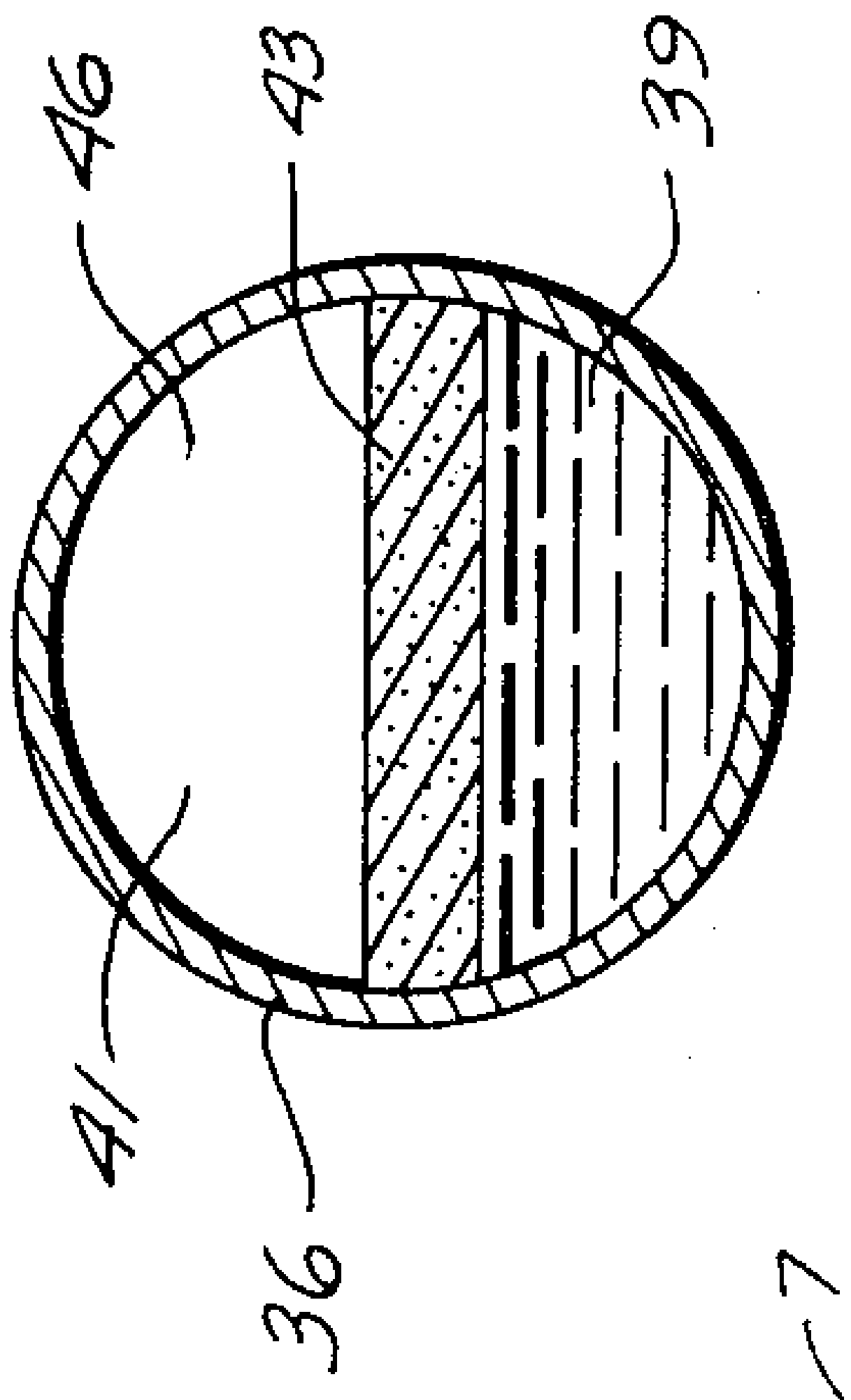


FIG. 5

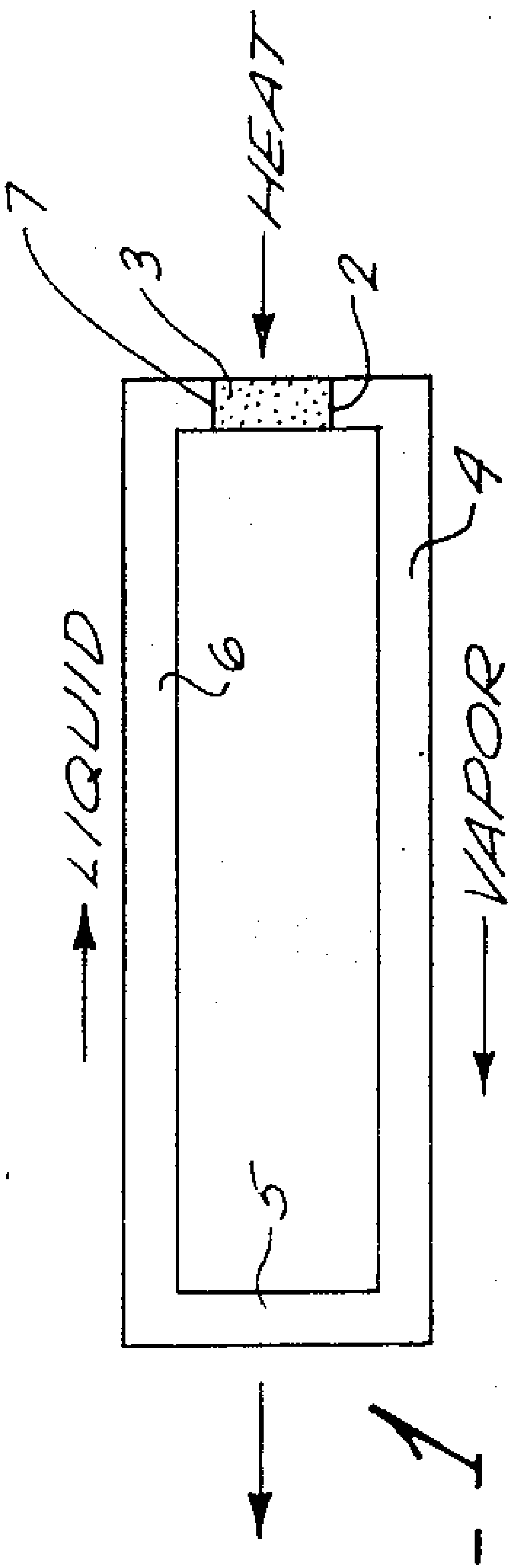


FIG. 1

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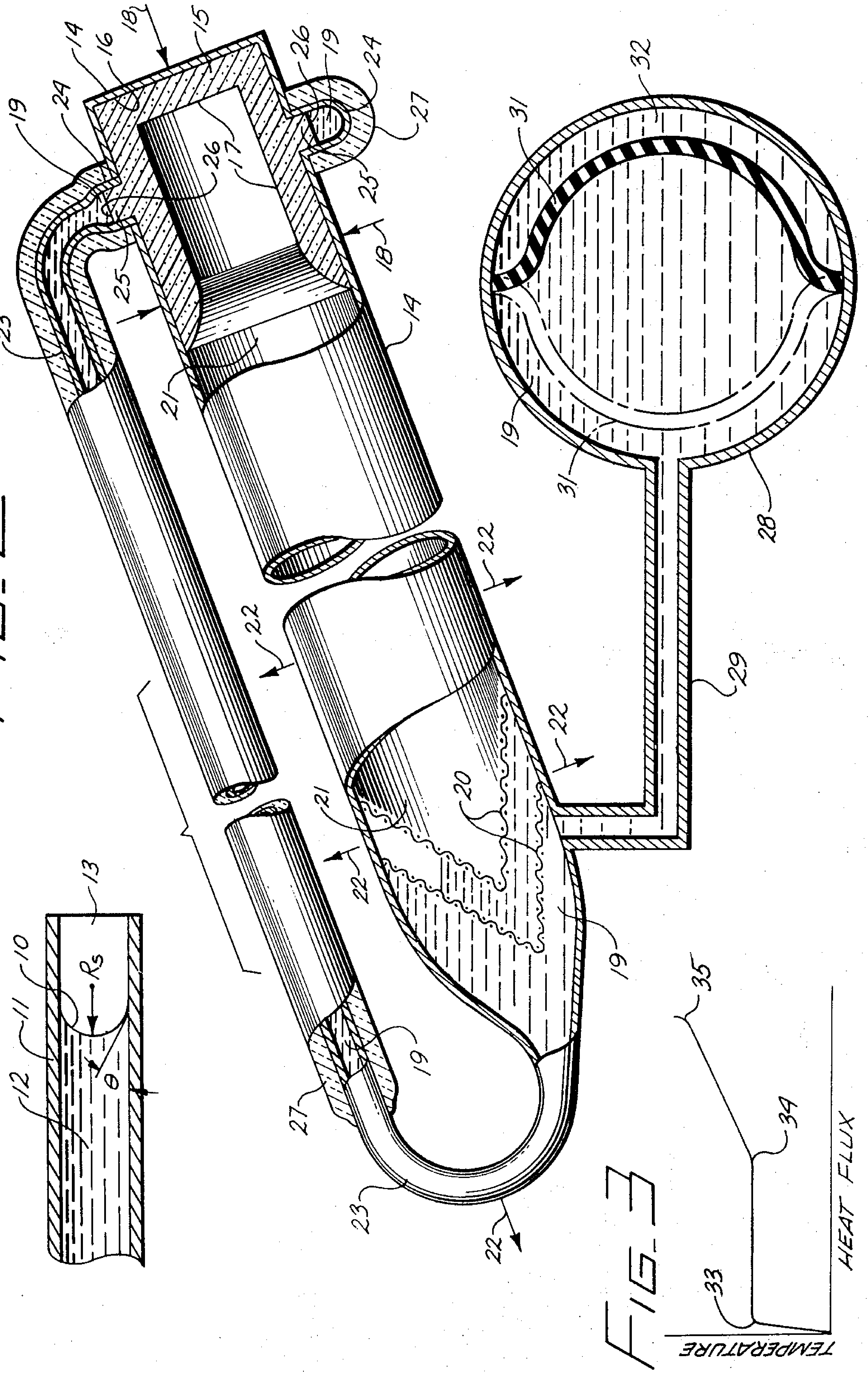


FIG. 1A

FIG. 2

FIG. 3

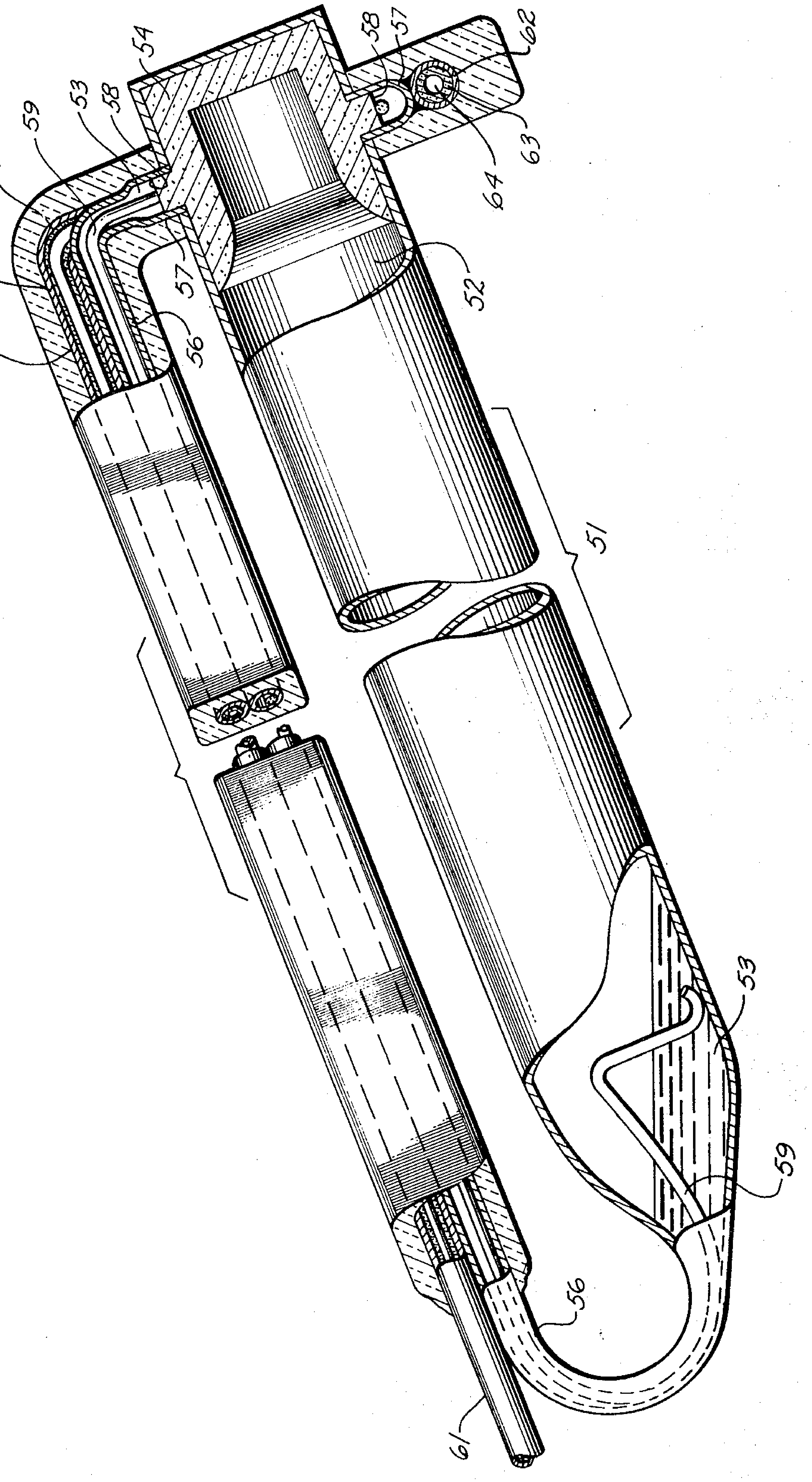


Fig. 6

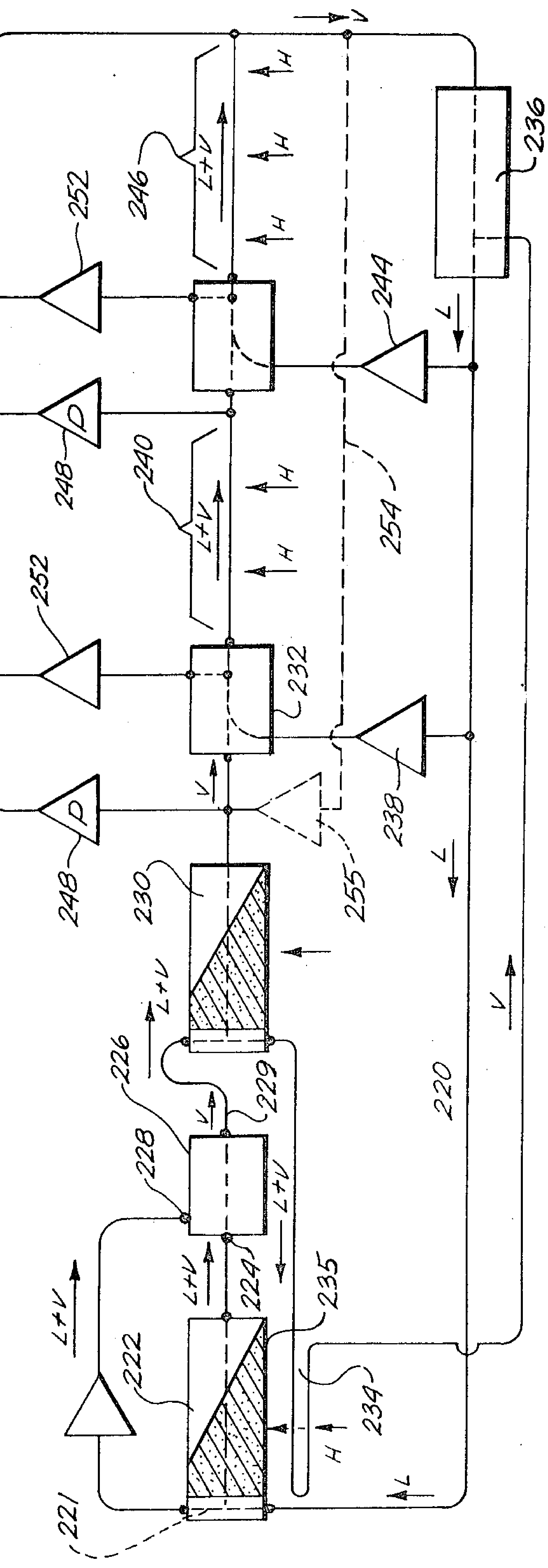


Fig_18

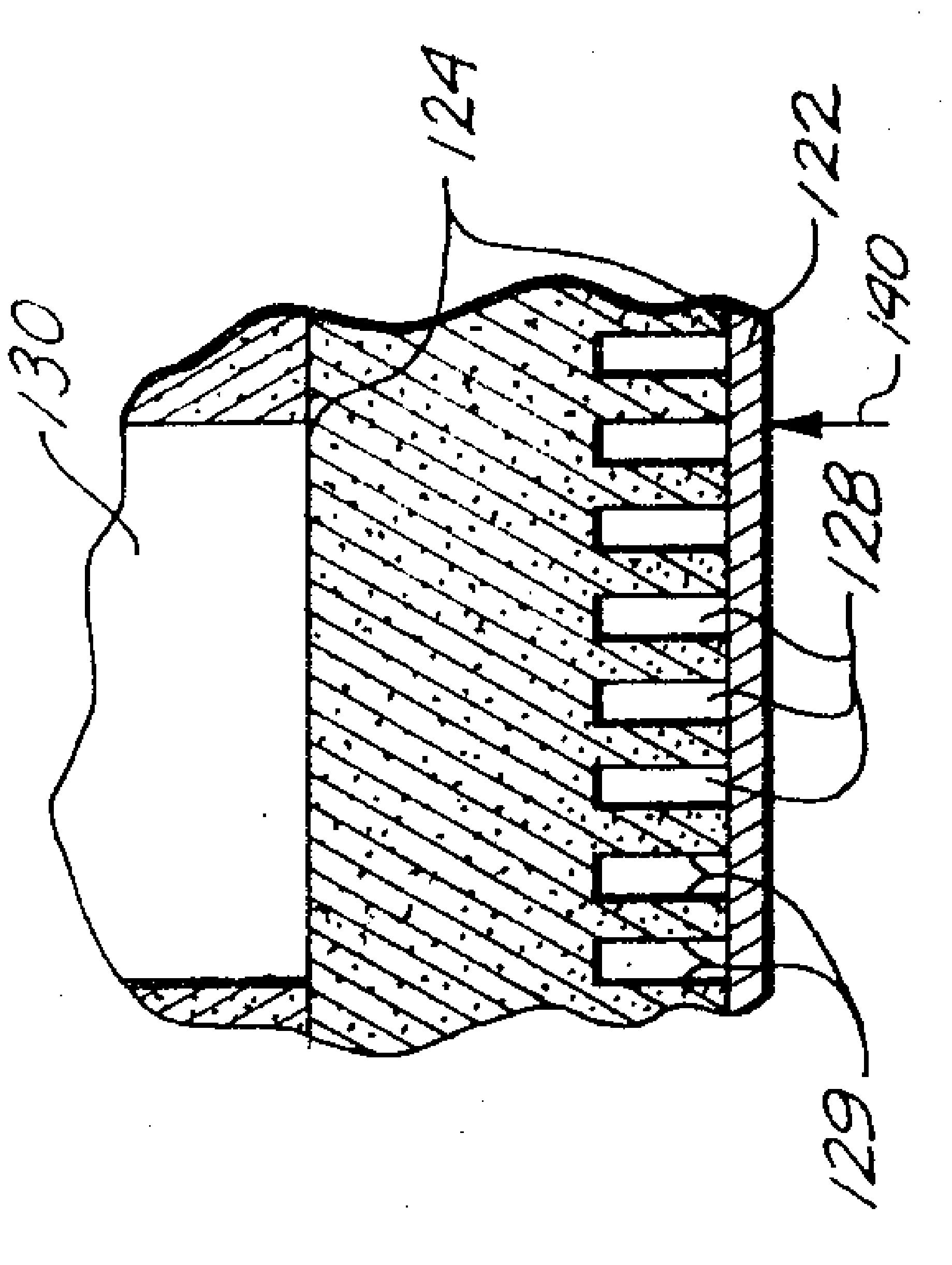


Fig_12

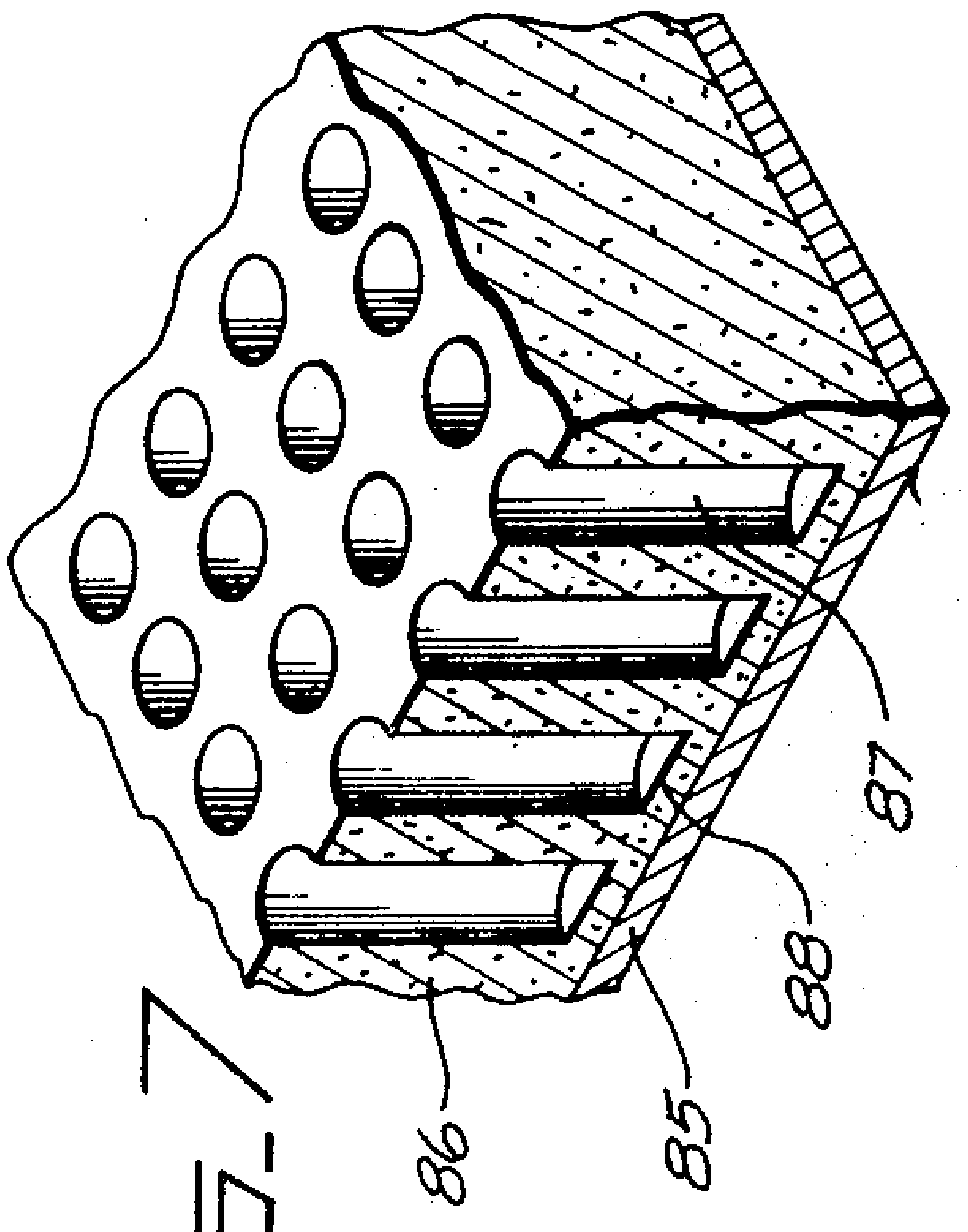


Fig_7

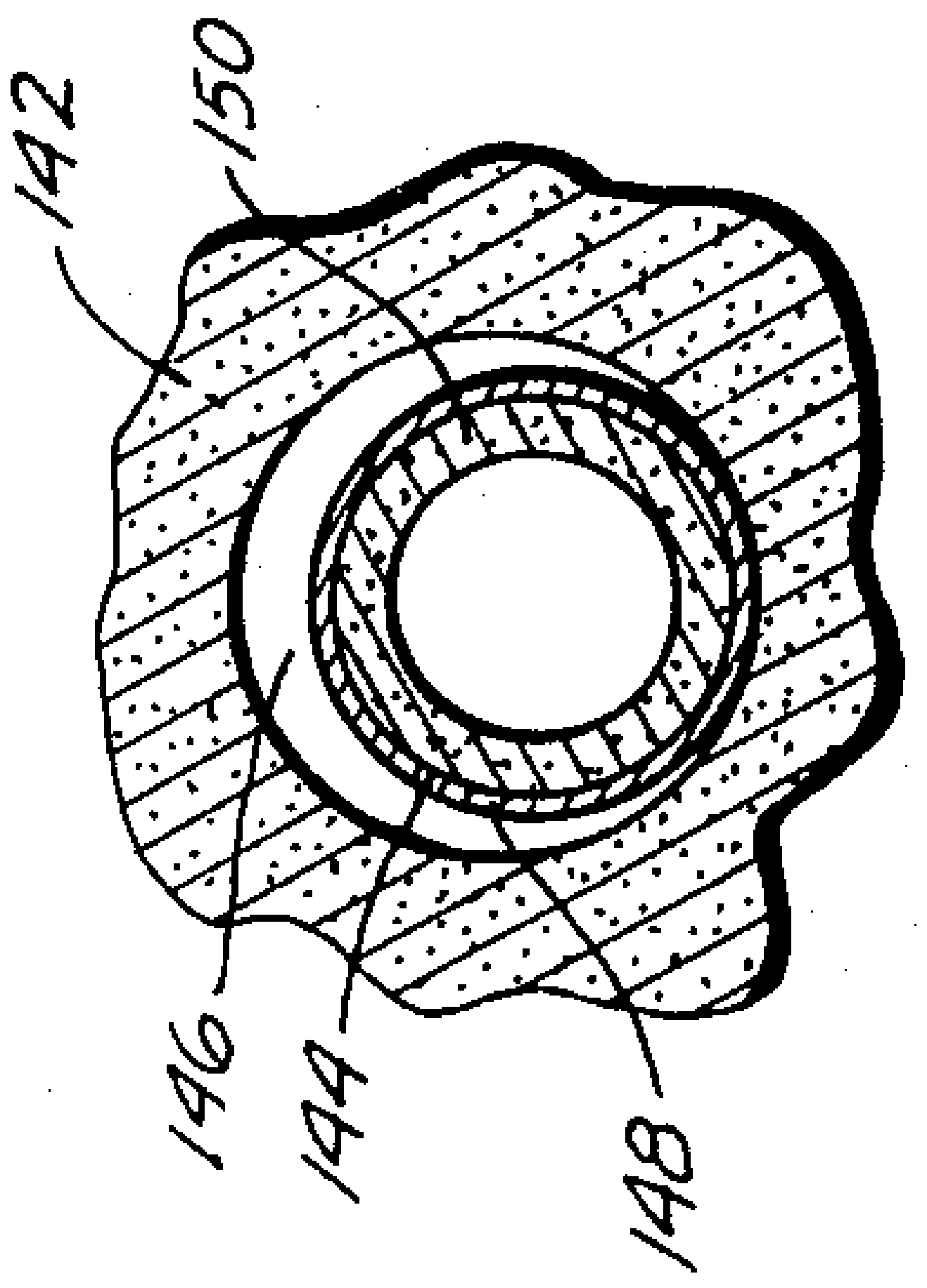


Fig_13A

FIG_8

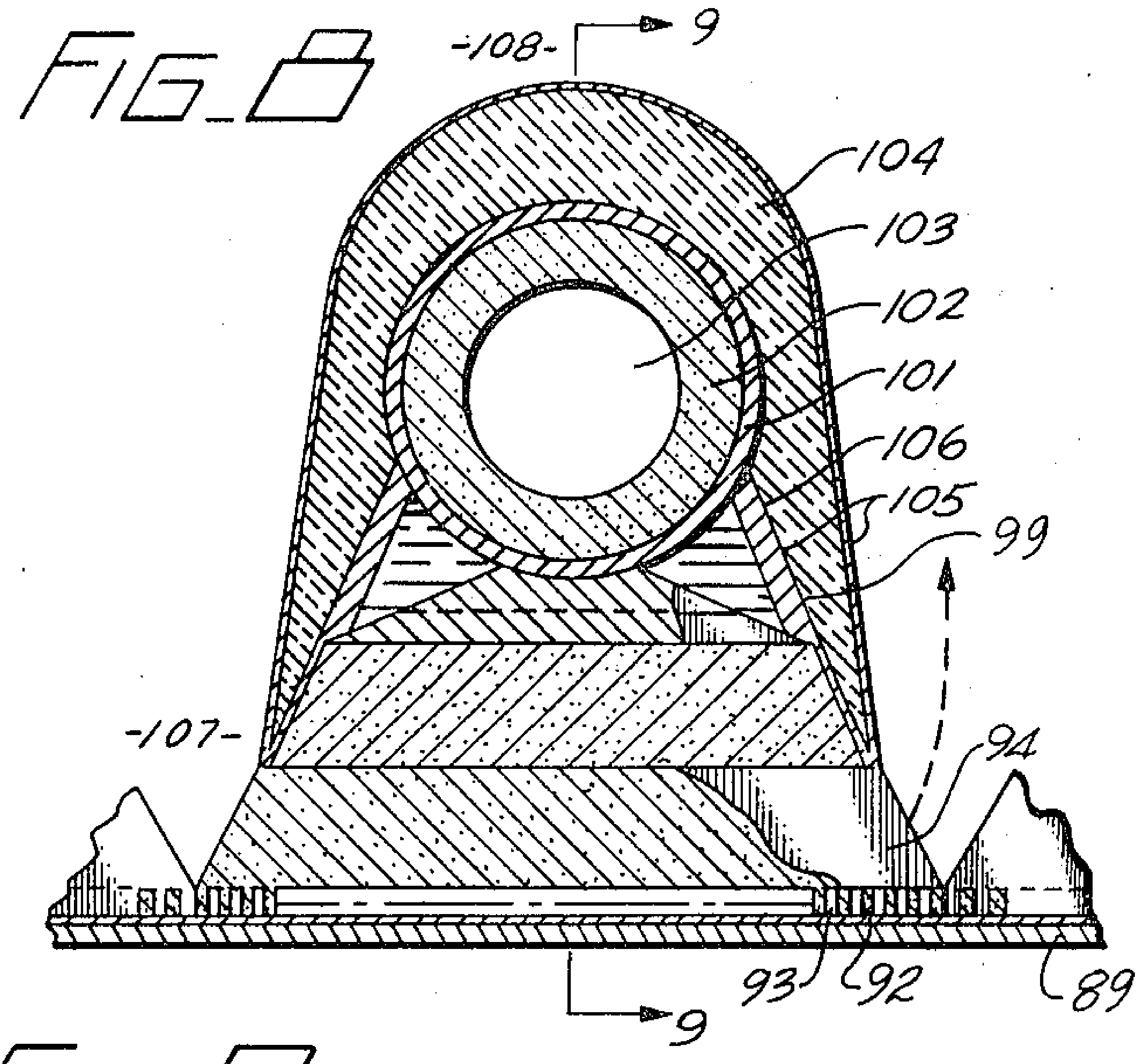


FIG_9

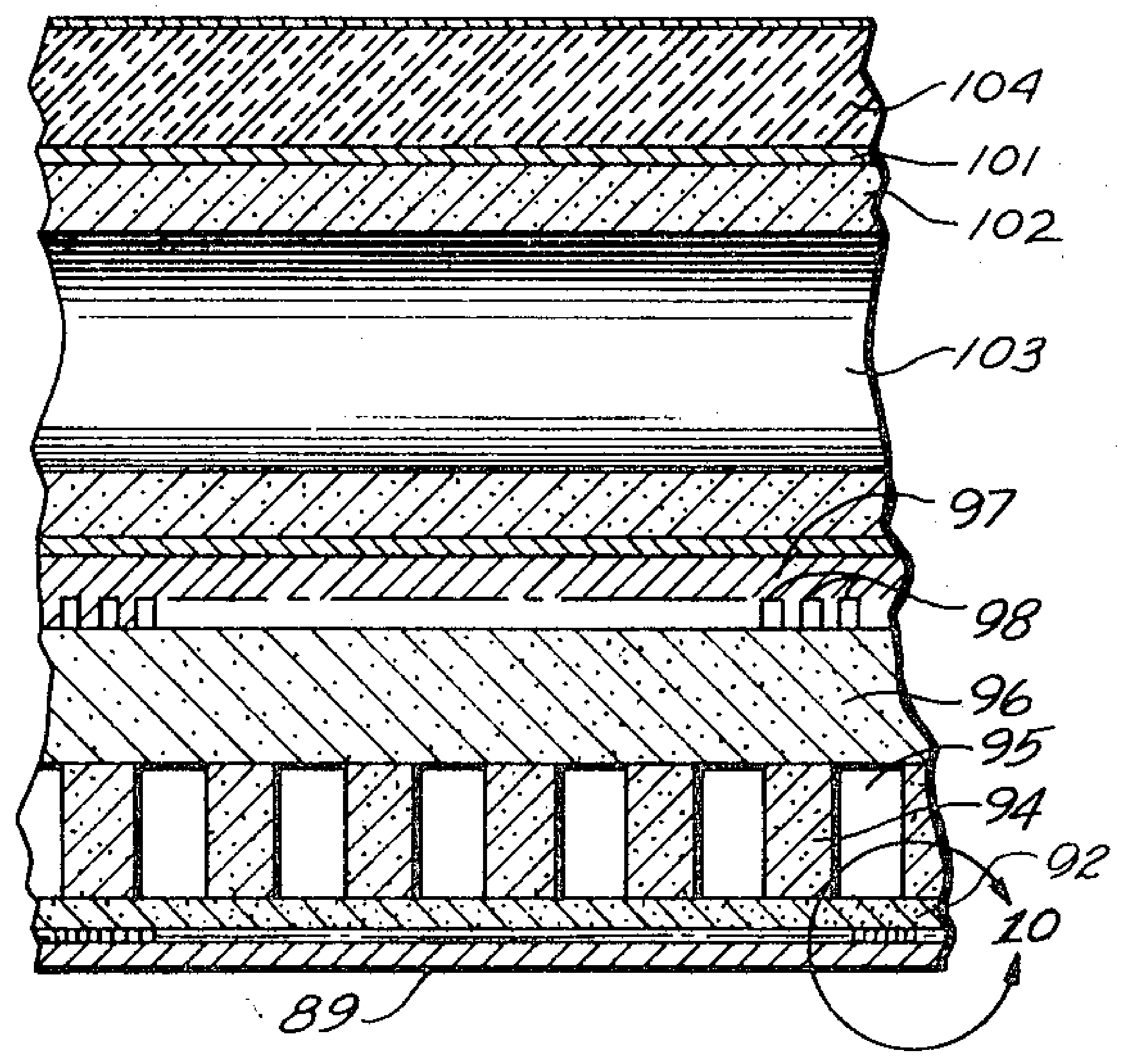


FIG_10

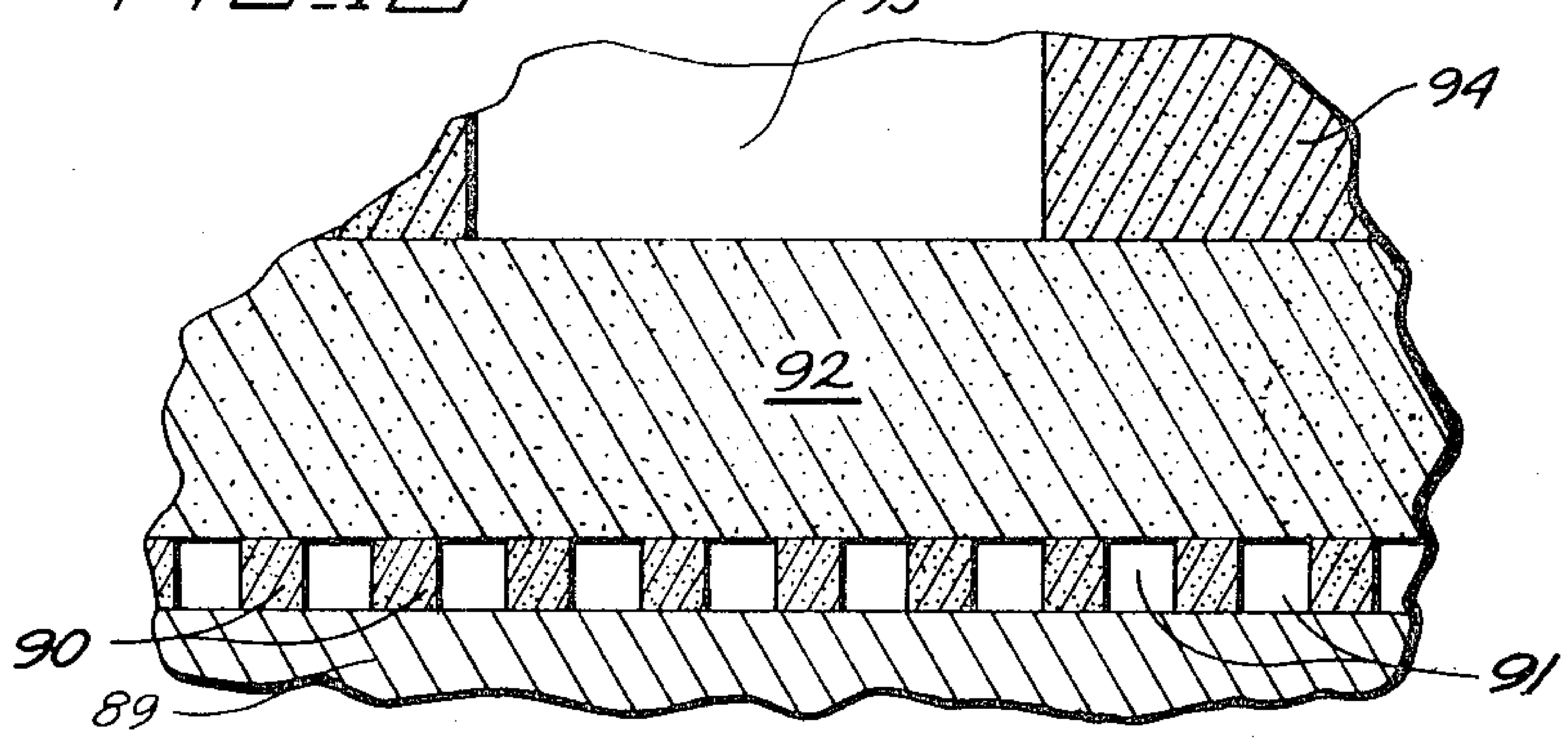


FIG_13

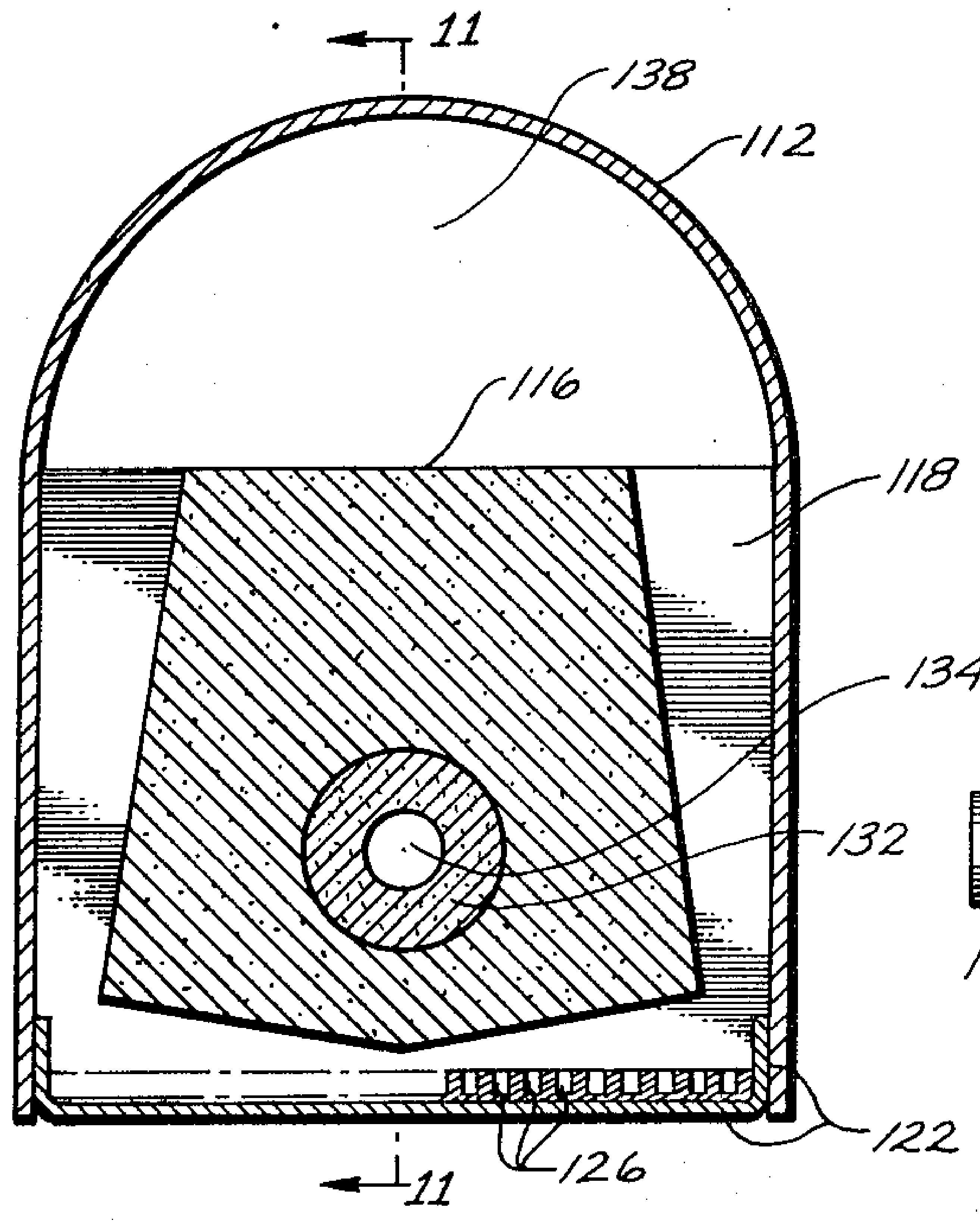


FIG_11

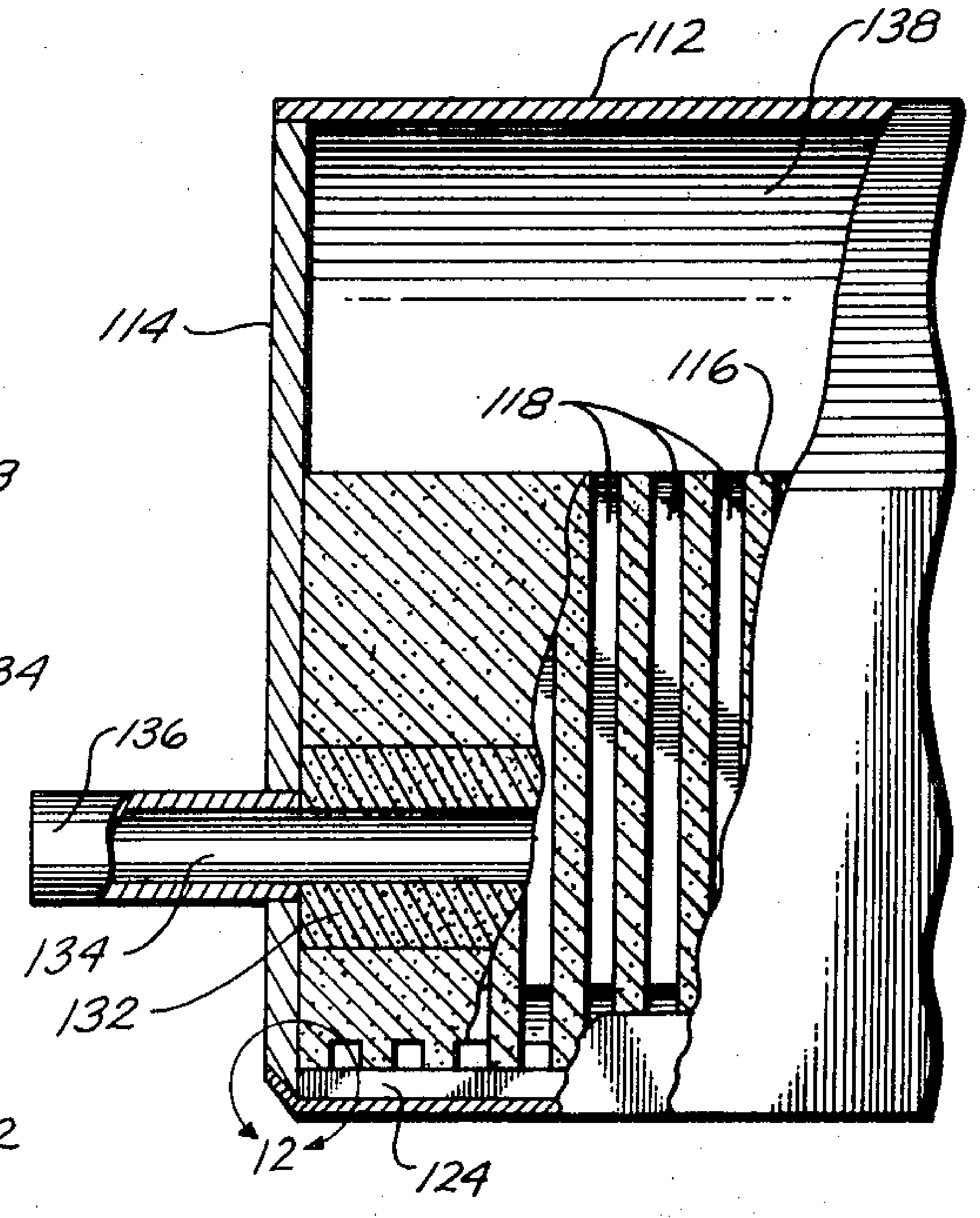


FIG_14

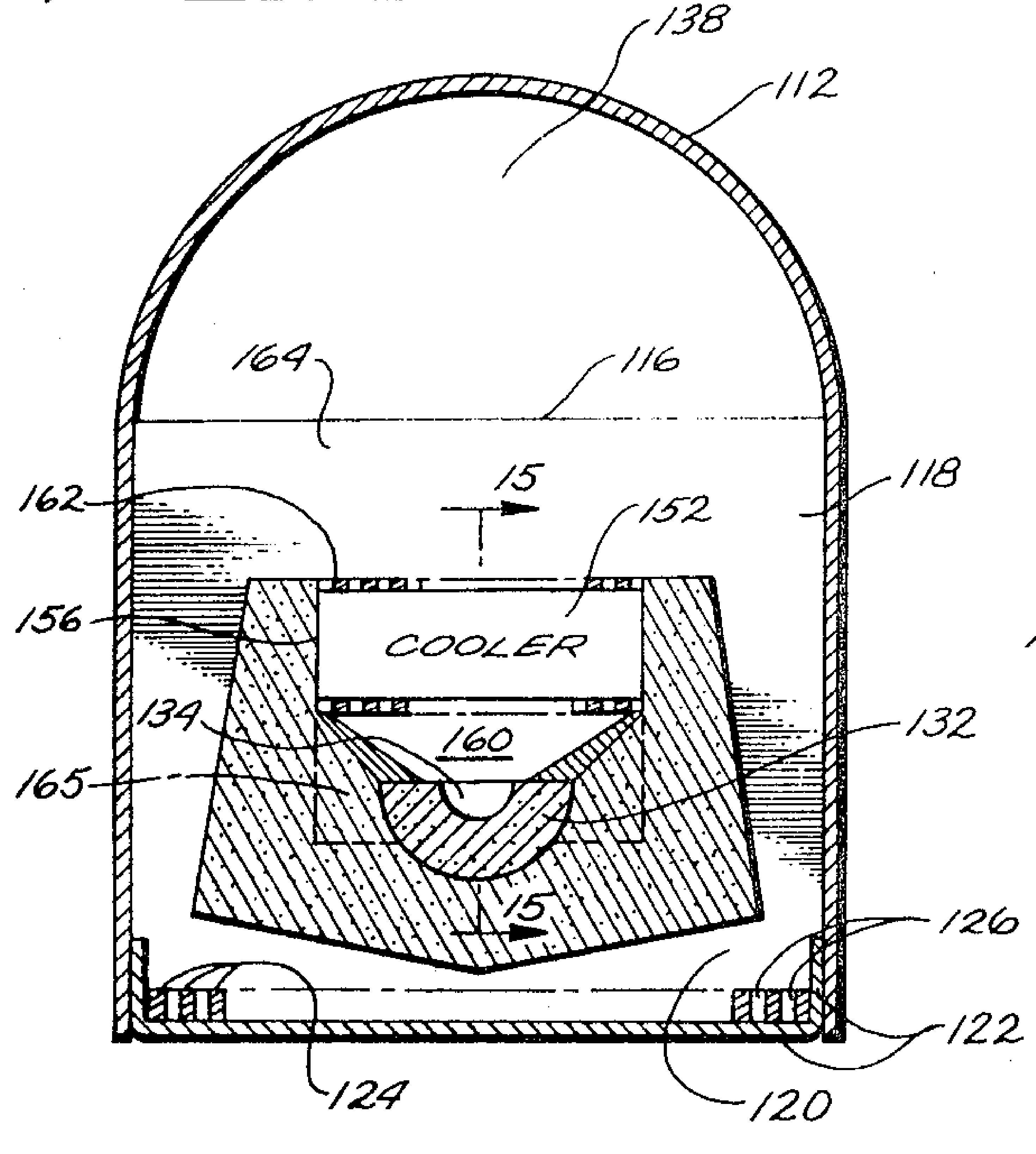
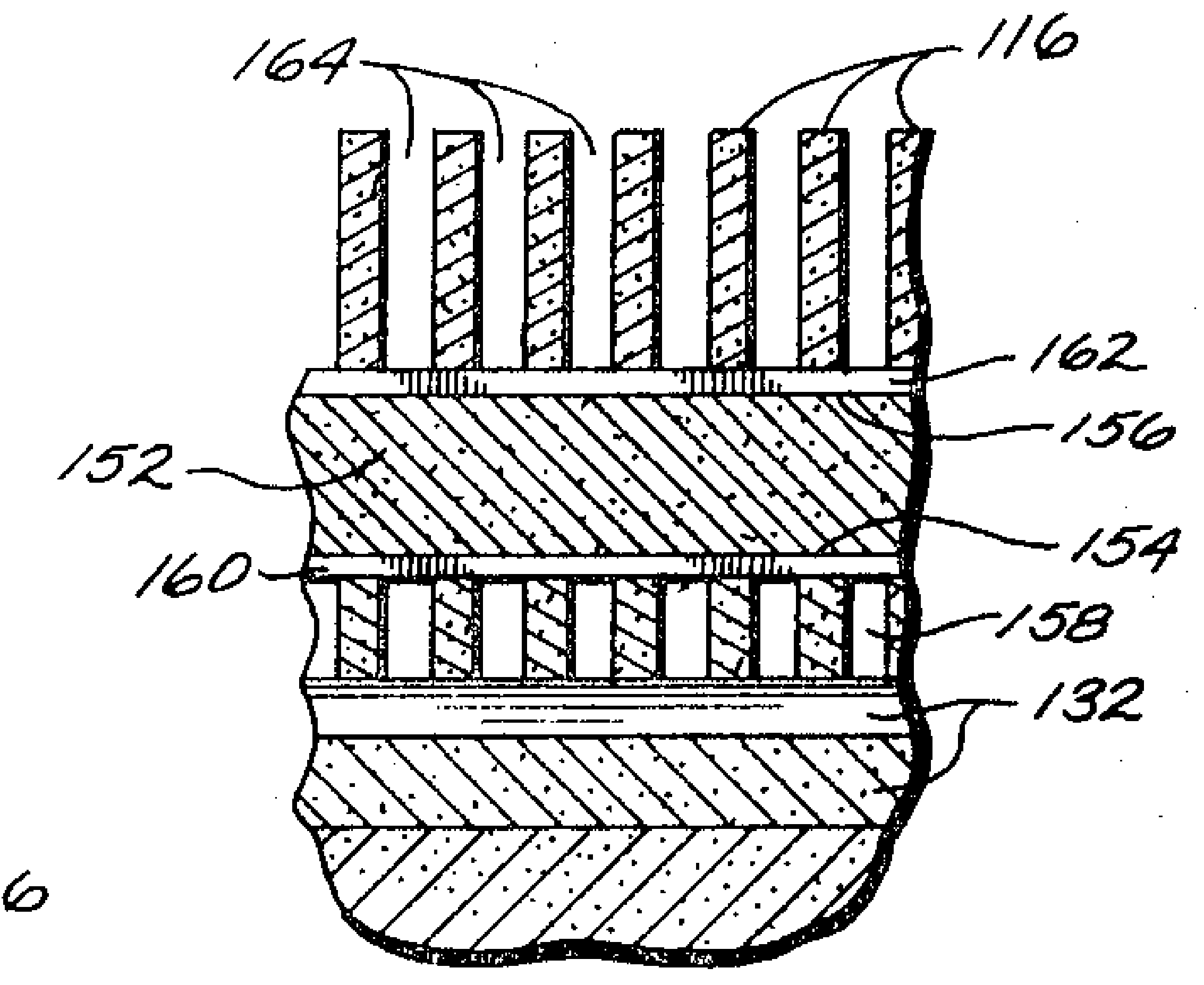


FIG_15



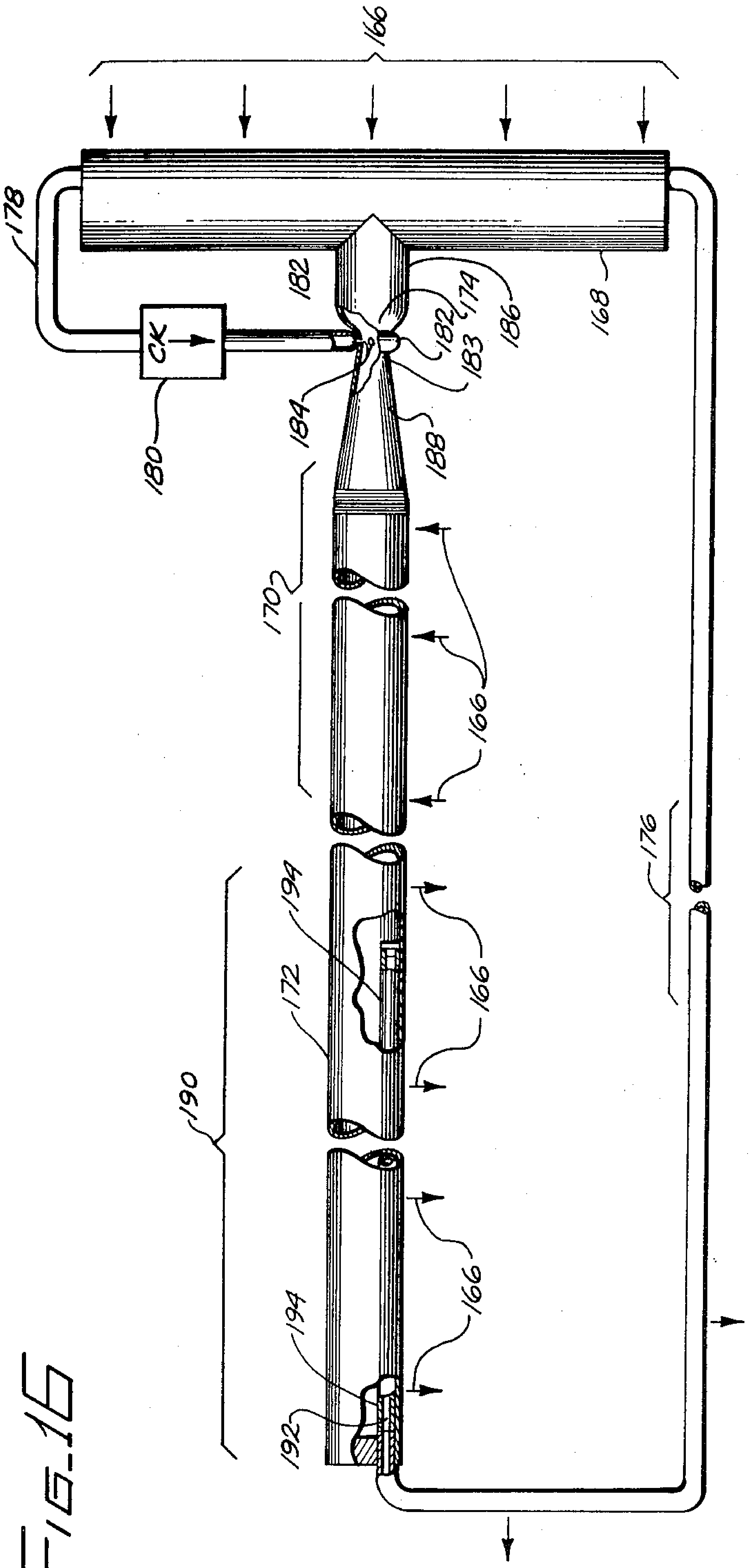


Fig.16

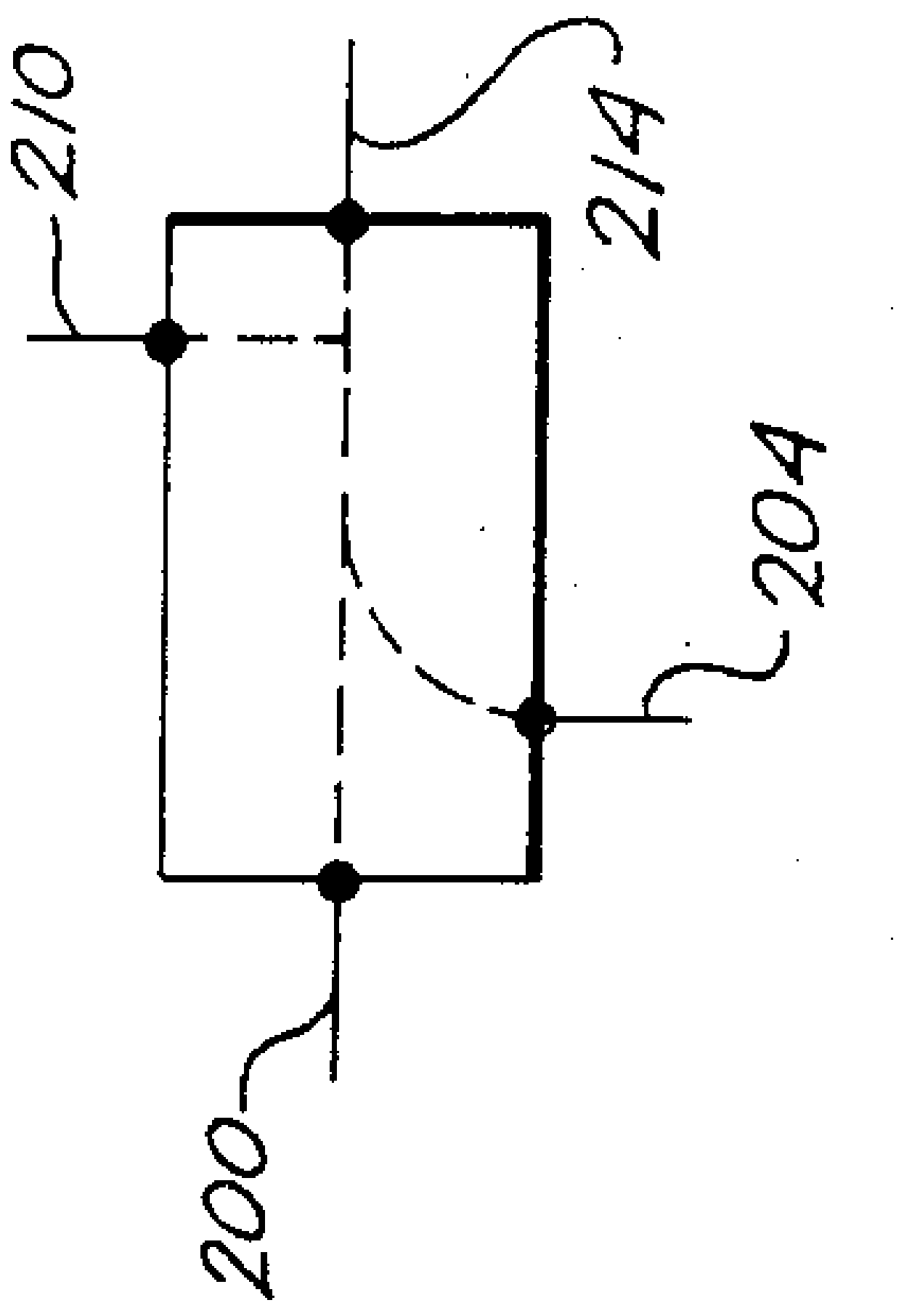


Fig.17A

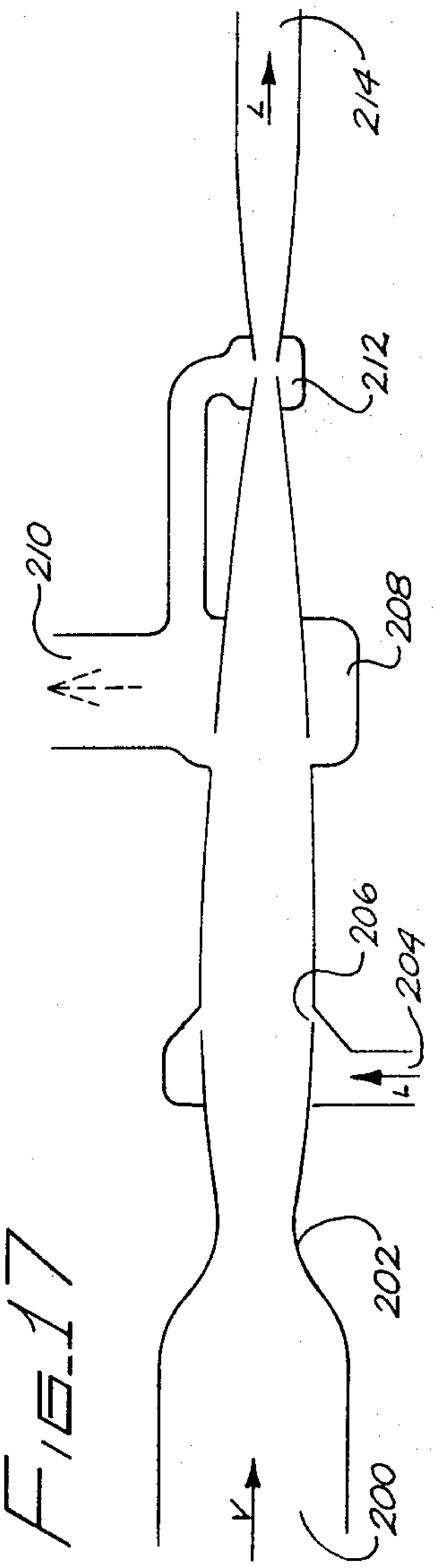


Fig.17

HEAT TRANSFER APPARATUS WITH IMPROVED HEAT TRANSFER SURFACE

BACKGROUND

This is a division of patent application Ser. No. 52,642 filed 7-6-70. This patent application is related to copending U.S. patent application, Ser. No. 52,609, now U.S. Pat. No. 3,598,180, granted Aug. 10, 1971, entitled "Heat Transfer Surface Structure," by Robert David Moore, Jr. The contents of this copending U.S. patent application is hereby incorporated by reference for full force and effect as if set forth in full herein.

In recent years, so-called heat pipes have become of considerable interest for transfer of heat because of a variety of highly useful characteristics such as substantially isothermal operation, low weight per unit heat transferred, high heat flux densities, and probably most significantly, the reliability inherent from absence of any moving parts. In addition, heat pipes can be made in a broad variety of shapes and sizes for special heat transfer situations.

In a heat pipe, a closed chamber is charged with a material that coexists in vapor and liquid phases at the operating temperature of the heat pipe. Other gases are generally excluded. Although a variety of heat transfer materials have been employed, water and liquid metals are among the most successful in the appropriate temperature ranges. A permeable, liquid wettable, capillary wick material is provided between the heat sink where liquid condenses and the heat source region where the liquid is vaporized. Since vapor at the heat source is at a higher temperature than vapor at the heat sink, a pressure differential in the vapor is present in the heat pipe, and a substantial mass flow of vapor occurs to carry heat from the heat source to the heat ink, principally as the latent heat of vaporization of the material within the heat pipe. The condensed liquid is returned from the heat sink to the heat source by capillary flow through the wick. The nature of heat pipes, heat transfer fluids, and construction details are included in an article entitled "The Heat Pipe," by G. Yale Eastman, in *Scientific American*, May 1968, at page 38.

As pointed out in detail hereinafter, a pressure differential between the liquid and the vapor is supported by surface tension forces at the liquid-vapor interface extending across the capillary pores. The liquid-vapor interface is, in turn, supported at the edges by the pore walls due to decrease in surface free energy when the liquid wets the solid surfaces. This pressure differential causes the liquid to flow against the vapor pressure differential within the heat pipe and against any superimposed gravity head. As the liquid flows through the capillary material, however, there is a resistance to liquid flow dependent on the properties of the liquid and the channel size through which the liquid must flow.

It turns out that, in order to obtain a high pressure differential, it is desirable to have a small pore size in the capillary material. On the other hand, the resistance to flow increases with decreasing pore size. In order to transfer a large heat flux, it is necessary to have a substantial quantity of liquid returning from the heat sink for revaporization. The trade off of small pore size to obtain a high pressure differential and large pore size to minimize fluid friction limits the heat flux capacity and the distance over which practical quantities of heat can be transferred, particularly when the liquid must rise in the capillary material against a gravity head. It is, therefore, desirable to provide a heat transfer device which retains the advantages of a heat pipe but whose heat flux capacity is not limited by the fluid resistance of a long capillary wick; that is, a heat transfer device that can be very long and operate against a high gravity head while still carrying high heat fluxes.

BRIEF SUMMARY OF THE INVENTION

Thus, in practice of this invention according to a preferred embodiment, there is provided a heat transfer apparatus, termed a heat link, having a porous vaporizer in fluid communication with both ends of a heat transfer passage. The vaporizer is in thermal contact with a heat source and a portion of the passage between the ends is in thermal contact with a heat sink. A vaporizable liquid fills the portion of the passage between the heat sink region and the end in communication with the vaporizer. Vapor of the liquid fills the balance of the passage. Means are provided either for maintaining the temperature of the liquid up to and including its contact with the porous vaporizer at a sufficiently low temperature that the vapor pressure at any point therein is no greater than the total liquid pressure at that point so that vapor bubbles would condense in the liquid going to the vaporizer or, alternatively, for removing vapor bubbles.

DRAWINGS

The above mentioned and other features, and many attendant advantages of this invention will be readily appreciated as the same becomes better understood upon consideration of the following detailed description of a presently preferred embodiment, when considered in connection with the accompanying drawings, wherein:

FIG. 1 illustrates schematically a heat link;

FIG. 1A illustrates schematically liquid in a capillary;

FIG. 2 illustrates in partial cutaway a heat link constructed according to principles of this invention;

FIG. 3 is a graph of temperature vs. heat flux according to principles of this invention;

FIG. 4 illustrates another embodiment of heat link;

FIG. 5 is a transverse cross section of the heat link of FIG. 4;

FIG. 6 illustrates in partial cutaway another embodiment of heat link incorporating principles of this invention;

FIG. 7 illustrates a fragment of a type of vented capillary vaporizer useful in the preceding embodiments;

FIG. 8 illustrates in cross section a fragment of another type of vented capillary vaporizer useful in the preceding embodiments.

FIG. 9 is another cross section of the vaporizer of FIG. 8;

FIG. 10 is an enlarged portion of the view of FIG. 9;

FIG. 11 illustrates in partial cutaway an end portion of still another vented capillary vaporizer;

FIG. 12 is an enlarged portion of the capillary vaporizer in FIG. 11;

FIG. 13 is a cross section of the capillary vaporizer in FIG. 11;

FIG. 13A is an alternate portion of FIG. 13 showing a heat pipe for cooling liquid and vapor in the liquid passage;

FIG. 14 is a cross section of the capillary vaporizer of FIG. 11 equipped with a thermo-electric cooler;

FIG. 15 is a portion of a cross section of the vaporizer of FIG. 14;

FIG. 16 illustrates an embodiment of the heat link utilizing a vapor jet booster pump;

FIG. 17 and 17A illustrate an injector type of vapor jet booster pump; and

FIG. 18 illustrates schematically another embodiment of the heat link with booster pumps.

DESCRIPTION

FIG. 1 illustrates quite schematically a heat link to provide preliminary insight into the nature of the device. Broadly, the heat link is a long passage having one end 2 open to a surface of a capillary vaporizer 3 which accepts heat from outside the heat link. The passage is filled with a fluid that coexists therein in its liquid and vapor states. Heat flowing into the capillary vaporizer 3 causes liquid to vaporize at the end 2 of the passage and the resultant vapor flows along a portion 4 of the passage to a heat sink portion 5 that dissipates heat to outside the heat link. The loss of heat causes vapor condensation to form liquid that flows through another portion 6 of the passage to the second end 7 where it contacts another surface of the capillary vaporizer. Why the heat link operates in this manner without vaporizing liquid at the surface 7 and more detailed structure to effect such operation are set forth in detail hereinafter.

In the operation of heat pipes and heat links, a significant element is the capillary material for conveying liquid to the heat source region accepting heat from the outside, so that the liquid can be vaporized. In a heat pipe, the capillary material extends all the way from the heat sink to the heat source. In the heat link hereinafter described, the fluid is transported mainly through passages quite large relative to the pores of the capillary material, which is employed in the region where vaporization occurs, and only a short distance therefrom, so that resistance to capillary flow is minimized. The properties of the capillary material are thus of interest.

In order to make fluid flow from one point in a system to another point, a pressure differential must exist across the fluid to cause it to flow. In a conventional vaporization-condensation heat transfer system such as an ordinary refrigerator, a pressure differential is applied to the fluid either by means of mechanical pumps or the like, or by gravity by locating the evaporator at a lower point in the system than the condenser. In the heat pipe and the heat link surface tension forces provide the pressure differential.

The behavior of the liquid-vapor interfaces in porous materials where surface tension forces are significant is of interest. Of particular importance is whether the liquid or the vapor will fill a given capillary space under given conditions of pressure and temperature. The situation can be analyzed in terms of a liquid-vapor interface **10** in a cylindrical capillary **11**, as illustrated in FIG. **1**. As illustrated therein, it is assumed that a liquid **12** fills a portion of the capillary **11** and wets the walls, i.e., that its contact angle θ with the walls is less than 90° so that the cosine of θ is positive. Across the interface **10** is a vapor **13** in an open end of the capillary. It should be noted that the liquid **12** and vapor **13** are of the same material which is coexistent in vapor and liquid phases at the temperature of the capillary. Generally other gases, such as air, are excluded from such a system, and the consideration is only of the equilibrium between a liquid and its own vapor. In order to simplify the analysis herein, it is assumed that the contact angle θ between the liquid and the capillary wall is zero. Real liquids and capillary materials may have a slightly higher contact angle but, as long as θ is less than 90°, the pressure differential across the liquid-vapor interface discussed herein need only be multiplied by the cosine of the contact angle in order to be correct. Alternatively, the surface tension σ (as defined subsequently) may be replaced by $\sigma \cos \theta$ in all formulae where it appears with the pore radius or effective surface to volume ratio δ.

The capillary **11** is assumed to be a cylinder having a radius R_P and under equilibrium conditions the interface **10** will be a spherical surface having a radius R_s. It will be recognized, of course, that in a typical porous material the pores may not be cylindrical capillaries as illustrated in FIG. **1**; however, the factor of shape of the pores only complicates the discussion here and can be dealt with by using a measured "bubble pressure" which defines an effective pore surface to volume ratio δ as subsequently described herein.

If one considered the interface **10** to be a general surface, its curvature can be expressed as two radii R_1 and R_2 which define the shape of the surface over a limited area. The pressure difference ΔP across a curved liquid vapor interface is given by $\Delta P = \sigma(1/R_1 + 1/R_2)$ where σ is the surface tension of the liquid against its own vapor. It is apparent that when $R_1 = R_2$ as in the case of a spherical bubble or the interface **10** of the liquid **12** in the circular capillary **11**, then $R_1 = R_2 = R_s$. The pressure across the interface **10** is then $\Delta P = 2\sigma/R_s$.

In the sketch of FIG. **1** the pressure in the vapor is higher than the pressure in the liquid; therefore, the radius of curvature is drawn from the vapor side. Thus, for example, in a liquid with a vapor bubble having a radius R_s the pressure differential across the bubble wall is $\Delta P = 2\sigma/R_s$ with the higher pressure inside the bubble if it is stable in size. Likewise, assuming that the liquid wets the wall of the capillary **11** with a zero contact angle between the liquid and the wall, then the radius of curvature of R_s of the interface **10** is equal to, or greater than the radius of the capillary R_P.

Therefore,

$$\Delta P \leqslant \frac{2\sigma}{R_p}$$

In situations where the capillary material has non-circular or irregular pores an "effective capillary surface to volume ratio," δ, is hereby defined as

$$\delta \equiv \frac{\Delta P_B(\sigma_L)}{\sigma_L}$$

where $\Delta P_B(\sigma L)$ is the bubble pressure of the capillary material with a liquid that wets the material with a zero contact angle and has a surface tension σ_L. Since the bubble pressure measured is proportional to σ_L, the σ_L's cancel out and δ is a property of the capillary structure only. This is further described in the previously referenced co-pending patent application. Thus we can also write ΔP $\sigma\delta$ *for the more general case. Thus a larger value of* δ *is equivalent to a smaller pore radius and vice-versa.*

The free surface vapor pressure P_r for any selected liquid is determined by the temperature and is conventionally expressed as the vapor pressure of the liquid with a flat liquid-vapor interface. The interface involved in capillary size pores is, however, curved, and when the vapor pressure is greater than the liquid pressure, as is the situation here for the cases of interest, it is concave toward the vapor side. Broadly speaking, the vapor pressure of a liquid with a concave curved interface is very slightly less than that of the same liquid at the same temperature with a flat liquid-vapor interface. Assuming that the vapor pressure of a liquid with a concave interface with radius R_s is P_c then

$$P_c = P_r - \frac{\rho_r}{\rho_L} \Delta P = P_r - \frac{2\rho_r\sigma}{\rho_L R_s}.$$

where ρ_r and ρ_L are the mass densities of the vapor and liquid respectively. At the temperatures and pressures involved in heat pipes, the pressure difference ΔP across the liquid-vapor interface is less than the vapor pressure P_r of the liquid. Also, the mass density ρ_r of the vapor is much lower than the mass density ρ_L of liquid, so that the ratio ρ_r/ρ_L is very much less than one. This means that

$$P_r - P_c = \frac{\rho_r}{\rho_L} \Delta P \ll \Delta P < P_r$$

The correction due to the curvature of the liquid vapor interface is, therefore, quite small as compared with other factors, and is neglected hereinafter. That is $P_c \cong P_r$. It should be noted that the term $P_r - P_c$ cannot be neglected in a thermodynamic consideration of the system since it is intimately associated with free energy difference necessary to transfer material across the liquid-vapor interface.

Whether the interface **10** remains in a static position within the capillary **11**, or the liquid advances or vapor advances, depends on the pressures in the capillary. If the pressure of the liquid P_L plus the pressure difference ΔP across the interface due to surface tension is greater than the vapor pressure P_r on the other side of the interface, the liquid will move forward, that is, to the right in FIG. **1**. If, on the other hand, the vapor pressure P_r is greater than the pressure of the liquid P_L plus the interface pressure difference ΔP, the liquid will be forced back by the vapor. If these two are equal, the interface will remain stationary. Thus, employing the simplifying assumptions that the interface is spherical, the contact angle between the liquid and solid is zero, and the contribution of curvature to the vapor pressure is negligible, the liquid vapor interface remains stationary when

$$P_L + (2\sigma/R_s) = P_r \text{ or } P_L + \sigma\delta = P_r$$

Similarly, when

$$P_L + (2\sigma/R_x) > P_r \text{ or } P_L + \sigma\delta > P_r$$

the liquid moves forward. And when

$$P_L + (2\sigma/R_s) < P_r \text{ or } P_L + \sigma\delta < P_r$$

the liquid moves backward.

Significantly, if the pressure in the liquid and the temperature, hence vapor pressure, remain constant, the stability of a bubble, or of an interface in a capillary, is dependent only on size. Thus, a very small bubble will collapse even though the vapor pressure within the bubble is greater than the liquid pressure since the surface tension forces introduce a large pressure difference across the sharply curved interface (small R_s) of the small bubble. Under the very same conditions of pressure and temperature, a larger bubble may grow since R_s is larger and the surface tension contribution is lower than in a small bubble. Similarly, in a capillary wherein the walls are wetted, R_s is small and surface tension forces may cause the liquid to advance. In a larger diameter tube, surface tension forces are smaller and the liquid may retreat.

In a heat pipe, pore sizes in the range of about 0.01 centimeters or 100 microns are typical, although appreciably larger pores are used in zero gravity liquid metal systems, and considerably smaller pores are employed where the liquid must be moved upwards against a large gravity head.

The flow F of a liquid through a cylindrical passage such as a capillary pore or a larger conduit (under viscous flow conditions) is given by the formula

$$F = \pi R^4 \Delta P / 8 \eta L$$

where R is the radius of the conduit, ΔP the pressure drop along the length L of the conduit, and η is the viscosity of the liquid. Since the radius of the capillary enters the formula as the fourth power, it has a very pronounced effect upon the flow, and it is highly desirable to employ a large diameter passage for liquid flow.

Thus, for example, in a conduit 100 centimeters long, with a pressure drop of 10^5 dynes/cm^2 and a radius of 0.1 centimeter, a liquid with a viscosity of one centipoise has a flow rate of 3.9 cm^3/sec. In order to get the same total flow rate as a single tube having a 0.1 centimeter radius, a capillary material having a pore size of 30 microns would require an open pore area in the order of about 34 cm^2 not to mention the area required for the solid material making up the porous body. If in order to obtain a suitable pressure differential, for example, when the liquid must rise against a considerable gravity head, it is desirable to go to a porous material having an average pore size of about 3 microns, the required pore area to obtain the same flow rate is in the order of 3,400 cm^2.

Thus, it can be seen that a very large area of capillary material may be required in a heat pipe in order to convey sufficient fluid as compared with the quantity of liquid that can flow through a single conduit of relatively small diameter, as is used in the heat link.

A major difference between a heat pipe and a heat link lies in the heat link's capability of returning the fluid nearly to the surface where it is vaporized *before* it re-enters the capillary material. The mean distance of liquid flow through the capillary material in a heat link is thus much shorter than the mean distance of fluid (liquid and vapor) flow through the passage. Conversely, in a heat pipe the mean distance of liquid flow through the capillary material must approximately equal the mean distance of fluid flow through the passage. This is so since the passage and the capillary material are in parallel with the passage only serving to carry the fluid away from the vaporizer so that the capillary material must return the fluid approximately the same distance.

The distinction between passages and capillary pores cannot be based purely on size alone, since perfectly satisfactory capillary materials for use in zero gravity environments may have capillary pores larger than the passage required for a small heat link operating against a high gravity head. Instead, the boundary between a passage and a capillary pore is defined operationally depending on whether the capillary force therein appreciably affects the operation. Thus the liquid in a capillary pore is held in place by capillary forces while the capillary forces in a passage are insufficient to restrain the liquid. More precisely a passage becomes a capillary pore when it is sufficiently small that the interfacial pressure drop that it will support, $\sigma\delta$ cos. θ is of the same order of magnitude as the difference between the vapor pressure P_v at the vaporizer and the static pressure P_L of the local liquid

$$\sigma\delta \cos. \theta \geqq P_v - P_L$$

otherwise it is a passage. Furthermore, the passage carrying the vapor from the vaporizer and the liquid back to vaporizer will be considered one continuous passage despite the addition of capillary plugs to separate fluids, pumps driven by energy from the vapor, or various arrangements of the condensor section, etc., as long as these allow the vapor or liquid, as appropriate, to flow through them.

The mean distance of fluid flow through the passage is defined as the integral with respect to distance along the flow path completely around the heat link of the fluid mass flow rate through the passage, except that through capillary material in the passage, divided by the total fluid mass flow rate, thus giving the distance that an average particle of fluid flows through the passage in going once around the heat link. The mean distance of liquid flow through capillary material is derived similarly except that only the liquid mass flow rate through capillary material is considered. A rough efficiency factor showing the relative heat flux capability of the heat link relative to a similar heat pipe may be obtained by dividing the sum of the two distances by twice the mean distance of flow through the capillary material. This assumes a vaporizer capillary material cross-sectional area approximately the same as the wick cross section in the corresponding heat pipe, however, in practice the vaporizer area may be considerably larger while still using much less capillary material than the heat pipe.

As described previously the entire pressure difference necessary to drive the fluid around a heat pipe or a heat link is supported across the liquid-vapor interface at the vaporizing surface of the capillary material. Since these devices will generally be used only where natural convection, such as is used in a boiler and steam radiator system, is insufficient or is inapplicable as in "zero gravity" environments or when the vaporizer must be above the condenser, the fluid returning to the vaporizing surface will generally be at a lower pressure than that leaving it. On the other hand, liquid must return to the vaporizing surface and not vaporize on the way back to it or there is no net heat transport. In the heat pipe the returning liquid is in capillary material which can support the pressure differential and limit the possible diameter of bubbles in the returning liquid to that of the capillary diameter, thus insuring that surface tension will collapse any vapor bubbles, as previously described, even with the capillary material at the same temperature as vapor leaving the vaporizer. In the heat link, on the other hand, the passage returning liquid to the vaporizer is too large to support appreciable capillary pressure differences and a large bubble, once formed, would continue to grow if the temperature of the liquid in the passage is not somewhat cooler than the vapor leaving the vaporizer. This must be avoided since the vapor cannot penetrate the liquid filled vaporizer capillary material and the resulting vapor would eventually form a vapor block preventing liquid access to the vaporizer.

One method for preventing a vapor block is to avoid the initial formation of a bubble large enough to expand. This is quite possible even when the temperature of the liquid is high enough that its vapor pressure is considerably above its static pressure, in which case it is known as a "superheated" liquid. The situation is only quasi-stable when the liquid is superheated appreciably, however, since a number of things, including impurities and cosmic rays, can initiate a bubble large enough to grow. Also it is desirable to be able to start the heat link even when there is some vapor in the return passage. Thus operation with the returning liquid superheated does not appear practical except possibly when the pressure differentials and thus the degree of superheating are very low.

Another method of preventing a vapor block or removing an already formed vapor block is to maintain the returning liquid at a temperature where its vapor pressure is low enough that even large vapor bubbles will condense. This in not generally difficult since the required temperature is generally only a few degrees below the temperature of the vapor leaving the vaporizer and is usually actually hotter than the heat sink. Several embodiments of the heat link which operate in this manner will be described herein.

A third method of preventing or removing vapor blocks involves exhausting the vapor from the liquid adjacent the vaporizer. This not only gets the vapor out of the way of the liquid but also cools the liquid and surrounding material as more of the liquid vaporizes under the reduced pressure. This method is particularly applicable to embodiments of the heat link utilizing "boost pumps" and is generally necessary in embodiments where a second fluid is used directly in the heat link passage, both described subsequently.

The second and third methods of preventing vapor blocks require, at least for practical purposes, that the liquid returning to the vaporizer be thermally isolated from the hotter vapor coming from the vaporizer to at least the extent that the various means for keeping the liquid cool are small relative to the basic heat link. This is particularly important where the returning liquid must pass through a region where it cannot pass on the heat to an external heat sink easily, i.e., the surroundings may be hotter than the returning liquid so that the heat may have to be transported a considerable distance. Generally the returning stream should be isolated as well as feasible from the outgoing stream and at least to the extent that the heat passed directly from the outgoing stream to the ingoing stream and such surrounding material as is in close thermal contact with it is a small fraction (on the order of one-fourth or less) of the heat carried by the heat link. This at least assures that the heat transport capacity needed to keep the returning fluid cool is enough smaller than the heat transport capacity of the heat link that the heat link represents a useful gain in heat transport capacity. By directly passing heat to the fluid in the return stream and surrounding material in close thermal contact with it is meant flow of heat from the outgoing stream to the ingoing stream and any adjacent material in such good thermal contact with the ingoing stream that it must be cooled in order to keep the ingoing stream cool. This is to be distinguished from heat carried along the passage as heat of vaporization.

Careful isolation of the returning liquid from both the outgoing stream and any portions of the ambient environment that are hotter than the returning liquid can reduce the heat input to the liquid to the point that, once operating, the returning liquid may be kept sufficiently cool merely by cooling it a few degrees below the maximum allowable temperature in the heat sink region. The small remaining heat input is then insufficient to raise the liquid to the temperature where vapor blocks are formed. Sometimes, however, additional cooling means are required. These may either be passive in that the heat is simply conducted or radiated to the surrounding environment or they may be active in that the heat is transferred by fluid flow in addition to any natural fluid flow occurring in the external environment. Fluid flow, as used in this context only, is defined to include the flow of electricity.

FIG. 2 illustrates in partial cutaway a heat transfer device or heat link constructed according to principles of this invention. As provided in this embodiment, a simple cylindrical chamber or conduit **14** forms the main body of the heat link. A body of porous capillary material **15** is provided inside the heat link adjacent one end for receiving heat into a first surface **16** of the capillary material from the outside as indicated by the inwardly directed arrows **18**. Heat transfer liquid **19** is supplied to a second surface **26** of the porous capillary vaporizer **15** as hereinafter described and flows through the porous material to a third surface **17** where the heat conducted through the capillary material evaporates the liquid to form a vapor **21**.

Heat is extracted from another cooler portion of the chamber **14** as indicated by the outwardly directed arrows **22**, thereby causing condensation of vapor on the walls of the chamber, and the resultant liquid **19** is collected in the cooler end of the chamber **14** to which it is driven by the streaming vapor or the vapor pressure differential even in the absence of gravity. A liquid retainer **20**, shown here as two cones, each consisting of several layers of fine screen wire, may be provided in the cooler end of the passage **14**. Each cone allows the free passage of liquid and, when wet by liquid, blocks the passage of vapor due to surface tension forces sufficiently to maintain a small pressure differential which keeps the liquid from escaping. Incoming liquid **19** can then collect between the cones forming a reserve of liquid that is free to flow through the second cone as required. It will be apparent that in most embodiments, including that illustrated, the liquid retainer is not needed since gravity or merely a narrow portion at the end of the vapor passage can restrain the liquid sufficiently that it flows into the liquid return conduit. Often the vapor passage itself is sufficiently narrow to ensure that the liquid is entrained in the vapor and forced into the liquid return conduit.

The capillary vaporizer **15** receives heat **18** from a heat source for the heat link, and the walls of the chamber **14** lose heat **22** to a heat sink. Heat is, therefore, transferred from the warmer capillary vaporizer **15** to the cooler walls of the chamber remote therefrom as latent heat of vaporization of the vapor **21**.

To this point, it will be recognized that the described heat link operates in substantially the same manner as a heat pipe. It will also be apparent that although the chamber **14** has been described as a simple cylindrical conduit that a tortuous vapor path, or even multiple parallel vapor paths, can be employed, or the relative sizes and shapes of the heat source and heat sink regions can be varied within wide extremes.

A second or liquid return conduit **23** extends from the end of the chamber **14** to a manifold **24** extending around the chamber **14** adjacent the capillary vaporizer **15**. The interior of the manifold **24** is in fluid communication with a surface **26** of the capillary vaporizer **15**. There is thus a passage for the fluid extending from the vaporizing surface **17** of the capillary vaporizer through the region where the vapor condenses and the heat is transferred to a heat sink and to the surface **26** of the capillary vaporizer which accepts liquid from the passage. A layer of thermal insulation **27** surrounds at least a portion of the conduit **23** and the manifold **24**. In the illustrated embodiment the vaporizer **15** includes a portion **25** within the manifold **24** so that the surface **26** contacted by liquid in the manifold is further away from and somewhat insulated from the balance of the vaporizer so that it can be cooler than the balance. The portion **25** of vaporizer in the manifold is preferably made of a material having a lower thermal conductivity than the main portion of the vaporizer so that maintaining the liquid contacting surface **26** cooler is made easier. If desired, the pore size of the portion **25** in the manifold can also be somewhat larger than the pore size of the balance of the vaporizer.

During operation of the heat link, as hereinafter described in greater detail, liquid is vaporized at the vaporizing surface **17** of the capillary vaporizer **15** and condenses in the cooler portion of the chamber **14**. Liquid **19** accumulates in the cooler portion and flows through the conduit **23** to the manifold **24** so as to return to the surface **26** of the capillary vaporizer. As pointed out hereinabove, in order to make the liquid flow through the conduit **23**, a pressure gradient must be provided across the liquid to cause flow. Since the conduit **23** has a substantial cross sectional area compared with a capillary, there is very little resistance to flow due to fluid friction and the only substantial pressure gradient required is that needed to overcome the gravity head in the illustrated embodiment.

The principal limitation on heat flux is the resistance to liquid flow in the return path from the heat sink to the heat source. In a heat pipe 6 feet long, for example, the liquid flows through 72 inches of capillary material with consequent flow resistance. In a heat link as illustrated in FIG. 2 the mean distance the liquid must flow through capillary material is only about one-half inch. With such an arrangement the liquid flow resistance is thus only one one hundred and forty-fourth of flow resistance in a conventional heat pipe so that the maximum heat flux is proportionately higher, while the mass of capillary material required is much lower. Improvements in the maximum heat flux per unit of device weight by factors of from 10 to 1,000 as compared with conventional heat pipes are typically obtained, particularly when optimized capillary vaporizers as shown in FIGS. **7** through **10** are used.

It will be recalled that the heat link is charged with a fluid material that coexists as a liquid **19** and a vapor **21** and that other gases are excluded from it. Thus, once a column of liquid is established in the return conduit **23**, it will remain unless a bubble of vapor forms in the conduit to break the fluid column. The only way such a vapor bubble can form is when the vapor pressure of the liquid is greater than the pressure of the liquid itself at the point where a bubble might form. In the illustrated embodiment, the pressure in the liquid at, for example, the top of the conduit **23** is the pressure operating on the surface of the liquid in the lower end of the chamber **14**, less the gravity head due to the weight of liquid in the conduit **23** and the small pressure differential necessary to produce the required liquid flow through the conduit. If this pressure is greater than the vapor pressure of the liquid, a vapor bubble will not form in the liquid, and a bubble introduced will immediately collapse.

As is well known, the vapor pressure of a liquid is highly dependent on temperature, with the vapor pressure increasing rapidly with increasing temperature, and by the same token decreasing rapidly with decreasing temperature. Thus, the temperature tending to cause a bubble and, hence, vapor block of liquid flow in the conduit **23**, is of considerably interest. When the temperature in the liquid is low enough that the vapor pressure of the liquid is below the pressure acting on the liquid, bubbles will not form and liquid will continue to flow through the conduit.

In order to maintain the temperature of the liquid sufficient low that bubbles will not form, the liquid is cooled in the heat sink region to a temperature several degrees below the temperature at which bubbles will foam, and thermal insulation **27** is provided which effectively prevents heat from flowing into the liquid **19** in the liquid return line **23**. It is of importance to maintain the temperature of the interface **26** and the liquid adjacent the interface sufficiently low that the vapor pressure of the liquid at than temperature is below the pressure of the liquid at that point, so that the formation of vapor bubbles at the surface is prevented. Therefore, insulation **27** is provided around the manifold **24** so that the liquid in the manifold remains at a low temperature and the region adjacent the surface **26** is also thermally insulated. The lower thermal conductivity of the portion **25** of the vaporizer **15** in the manifold also helps keep the surface **26** cooler. These measures prevent the formation of vapor bubbles in the manifold or at the surface **26**, therefore, a continuous column of liquid is maintained and liquid is continuously supplied to the porous vaporizer for heat transfer.

Maintaining the vapor pressure of the liquid sufficiently low involves keeping the liquid and the back surface **26** of the vaporizer sufficiently cool. The liquid is kept cool by simply insulating the liquid return line after the liquid **19** is cooled sufficiently in the heat sink. The required cooling is only a few degrees centigrade below the temperature at which the liquid condenses and is not a significant factor in operation of the heat link. The interface **26** must actually be cooled since it must be maintained at approximately the temperature of the liquid, which may be several degrees below the temperature of the portion of the vaporizer where the liquid is vaporized. The actual amount of heat that must be removed from the region of the interface **26** is dependent on the size and thermal conductivity of the vaporizer material. If the vaporizer is made of two different materials, for example, metal and glass, one having relatively high thermal conductivity in the region where evaporation occurs and one having a relatively low thermal conductivity in the portion **25** adjacent the interface **26** and, particularly, if vented vaporizer structures as shown in FIGS. **7** through **10** are used, only a small quantity of heat need by removed. An optimized composite capillary vaporizer requires the removal of less than one one-hundredth RPM of the heat at the interface **26** as compared with the quantity of heat removed from the front surface of the vaporizer by vaporization of the liquid. With such an arrangement, the back surface **26** is adequately cooled by simply precooling the return liquid **19** by about 6° centrigrade below the temperature required by vapor pressure considerations along and the flow of cooler liquid will maintain the surface **26** at a sufficiently low temperature. The structure of a suitable composite capillary vaporizer is shown in FIGS. **7** through **10** and described more thoroughly in the aforementioned copending patent application entitled " Heat Transfer Surface Structure."

The description to this point of the embodiment of FIG. **2** has been concerned with a heat link already in operation with liquid being vaporized from the vaporizer **15** and returning through the conduit **23**. Once normal operation has been established in such a heat link, there is generally no difficulty in maintaining continuity; however, under some circumstances the commencement of operation or the maintenance of operation at very low heat flux levels, or under other adverse conditions may require special techniques. Therefore, in order to assure ready starting of the heat link, a reservoir **28** is connected to the main body of the heat link by a conduit **29**. The conduit **29** is connected to the chamber **14** at a point in the chamber that is normally occupied by liquid **19** during operation of the heat link. In the illustrated embodiment, this in on the liquid side of the porous liquid retainer **20**. The reservoir connection can also be made in any other portion of the system normally occupied by liquid, such as, for example, in a portion of the conduit **23** where all entrapped vapor bubbles have had a chance to condense (even when there is no porous liquid retainer in the system).

The reservoir **28** is divided into two sections by a flexible diaphragm **31** extending across the center of the reservoir. Heat transfer liquid **19** from the heat link fills the portion of the reservoir between the diaphragm and the conduit **29** leading to the heat link. A second fluid **32** fills the space within the reservoir on the other side of the diaphragm **31**, and during normal operation of the heat link, the second fluid **32** is in a liquid state as illustrated in FIG. **2**. The fluid **32** behind the diaphragm in the reservoir is selected to have a slightly higher vapor pressure at the reservoir temperature than the heat transfer fluid **19** has at the temperature where the heat link is to be started. A suitable combination would be a Freon refrigerant (halogenated methane or ethane) as the second fluid and water as the heat transfer fluid. When the heat link and reservoir are all at substantially the same temperature prior to starting, the second fluid **32** in the reservoir **28** is at least partly vaporized, thereby displacing the diaphragm **31** to a position as shown in phantom in FIG. **2** which displaces heat transfer liquid **19** into the chamber **14** with consequent condensation of vapor **21** within the chamber. The volume of vapor **21** condensed is the same as the volume of vapor formed by the liquid **32**. The liquid forced into the chamber plus the condensed vapor present serve to fill the chamber **14** with liquid at least to a level wherein liquid contacts a surface of the capillary vaporizer. The capillary vaporizer **15** is thus wetted by liquid prior to starting the heat link.

The heat link is started by applying heat to the capillary vaporizer, as indicated by the arrows **18**, which causes vaporization of a portion of the heat transfer fluid **19**. The increasing temperature of the heat transfer fluid as the heat link warms up, which occurs rapidly due to the greatly decreased available surface for vapor condensation and transfer of heat to the heat sink **22**, increases the vapor pressure of the heat transfer fluid until it becomes greater than the vapor pressure of the pressurizing fluid **32** in the reservoir. Displacement of the liquid **19** from the chamber **14** follows. This displacement of liquid is into the reservoir **28**, thereby causing condensation of vaporized fluid **32** which is now at a lower temperature than the vapor filled portion of the heat link. The vaporizer temperature rise is thus so rapid that the back face **26** of the vaporizer remains sufficiently below the vapor temperature to prevent vapor lock in the manifold **24**. Additional heat transfer liquid is continuously supplied to the vaporizer through the interface **26** to produce additional vapor until the heat link is in full operation at its normal operating temperature. Excess heat transfer liquid is displaced from the chamber **14** into the reservoir **28** and some of the fluid **32** is condensed. Start-up under high gravity head conditions is particularly aided in this manner since the gravity head between the free liquid in the vapor chamber and liquid at the interface **26** is greatly reduced during the critical initial portion of the start-up.

For starting the only requirement for operation of the reservoir is that the vapor pressure of the fluid **32** be sufficiently greater than the vapor pressure of the heat transfer fluid at the starting temperature of the heat link that the liquid **19** will be forced up to the vaporizer against the gravity head, if any. The vapor pressure of the starting fluid **32** may be kept lower than the vapor pressure of the heat transfer fluid **19** during operation of the apparatus by thermally isolating the reservoir from the hotter portions of the heat link and providing good thermal contact to a cooler heat sink (not shown). A liquid or combination of liquids and gases having a lower change of pressure with temperature than does the heat transfer fluid may also be used as the fluid **32** in the reservoir.

FIG. 3 is a graph of the temperature of the vaporizer **15** of the heat link of FIG. 2 as a function of the heat flux therethrough while the reservoir **28** acts as a nearly constant pressure source or sink to the heat transfer passage of the heat link. This graph shows three prominant regions. In the low heat flux region between the origin and the point **33** the vaporizer temperature increases rapidly with heat flux. This region ends at the heat flux at which the temperature of the small portion of the conduit **14** in contact with vapor becomes sufficiently high (approximately at the vaporizer temperature) that the resulting vapor pressure is great enough to commence forcing liquid out of the passage **14** and into the reservoir. At lower heat flux the total heat can be dissipated through the walls of the conduit **14** without raising the temperature of the walls enough to force liquid out of the heat link.

This heat flux value where a small increase in temperature would result in driving most of the liquid out of the passage **14** and into the reservoir marks the beginning of a substantially isothermal region extending from point **33** to point **34**. The liquid is not driven out all at once, however, since as the heat flux increases, and the liquid-vapor interface retreats, more of the wall of the conduit **14** is exposed for the vapor to condense on, and to transfer heat to for transfer, in turn, to the heat sink. As a result the temperature of the heated portion of the passage **16** and of the vaporizer increase only slightly with increasing heat flux until either the reservoir is completely filled with liquid, or the heat transfer liquid is completely driven out of the portion of the heat link capable of dissipating heat to the heat sink. When either of these happen, the temperature once again increases, though more gradually than at first, as shown by the third region on the graph between point **34** and point **35**. Point **35** indicates where the maximum heat capacity of the heat link is exceeded and a runaway condition occurs. Thus by suitably sizing the reservoir and the heat sink area and the rate of heat loss per unit area of the walls of the conduit **16**, the heat link will operate in the constant temperature region over a wide selected range of heat flux. A heat link so formed thus serves to hold the temperature of the vaporizer, and in turn, the heat source, nearly constant despite a wide variation in the heat source output.

It will be apparent to one skilled in the art that in lieu of employing a reservoir with a diaphragm and a starting fluid **32** that other starting reservoir mechanisms may be employed. Under certain conditions subsequently considered the diaphragm may be omitted and a pressurizing gas or vaporizable liquid used in direct contact with the working fluid, sometimes even dispensing with the reservoir. Alternatively, the reservoir may have a diaphragm or bellows loaded with a spring or pressurized gas, or even ambient atmosphere in some circumstances so as to displace working fluid into the heat link when the vapor pressure of the heat transfer fluid is low and to retreat and provide a reservoir for heat transfer fluid when its vapor pressure is higher during operation of the heat link. All of these systems are passive in that they are powered directly by the vapor pressure of the working fluid in the heat link, and it will also be apparent that active systems employing temperature sensors and feedback mechanisms can be employed for supplying heat transfer fluid to the heat link for starting or temperature control.

It can also be noted that it if is desired to start the heat link only once and thereafter maintain it in operation, then a simple pressure relief valve can be substituted for the reservoir system. The heat link passages are initially filled with liquid for start up and the excess liquid is vented by a pressure relief valve as the heat pipe warms up and begins operating. It is desirable if a bleed valve responsive to the amount of liquid remaining is employed to also provide means for positively closing the liquid bleed when a sufficient quantity of liquid has been removed for normal operation. This may, for example, be a spring loaded normally closed valve restrained in the open position by a fusible link and mounted in series with the relief valve at the far end of the vapor passage from the vaporizer. The fusible link melts when enough liquid has escaped that hot vapor reaches the valve. This prevents excessive loss of heat transfer fluid if the heat link is operated above its design temperature.

FIGS. 4 and 5 illustrate in partial cutaway and transverse cross section, respectively, a modification of the heat link incorporating principles of this invention. As illustrated in this embodiment, a single cylindrical chamber **36** is provided with a porous capillary material **37** at one end for receiving heat as indicated by the inwardly directed arrows **38**. It is from the capillary vaporizer **37** that liquid **39** is evaporated to form a vapor **41**. Heat is extracted from a cooler portion of the chamber **36** as indicated by the outwardly directed arrows **42**, thereby causing condensation of vapor. The walls of the chamber **36** therefore lose heat **42** to a heat sink in substantially the same manner hereinabove described. The capillary vaporizer **37** receives heat **38** as a heat source for the heat link. Liquid **39** condensed on the walls of the chamber accumulates in the cooler portion of the chamber.

Arranged within the chamber **36** so as to divide it into two separate longitudinally extending conduits is a vapor barrier **43** of thermal insulating material. Although usually impermeable, the barrier **43** may be porous so long as it is liquid wettable, the liquid thermal conductivity is low, and the pore size in the barrier is sufficiently small that the liquid effectively seals the pores against vapor transport through the barrier even though it may pass liquid. The vapor barrier **43** may terminate a short distance from, or have an opening (not shown) near, the cooler end **44** of the heat link so that condensed liquid **39** can flow around or through the end of the barrier **43**. This is not necessary if the barrier is porous. Thus, the barrier **43** serves to divide the chamber **36** into a vapor flow path **46** and a liquid flow path **47**.

A portion **48** of the capillary vaporizer **37** extends into the liquid return path **47** and a portion of the insulating material of the barrier **43** is provided between the porous portion **48** and the vapor **41**. This helps maintain a liquid contacting face **49** of the capillary portion **48** at a somewhat lower temperature than the vapor. Since the surface **49** is contacted by liquid **39** in the liquid return path **47** and is at a lower temperature than the balance of the vaporizer, it will be apparent that this heat link arrangement operates in substantially the same manner as the heat link arrangement described and illustrated in FIG. 2. If desired the extending portion **48** of the vaporizer can be somewhat coarser pored and of lower thermal conductivity than the valance of the vaporizer. When the vapor barrier 43 is porous it acts like a wick and assures that the vaporizer is wetted by liquid for reliable starting of the heat link in the absence of a reservoir as hereinabove described. The wick is not needed if the gravity field at the time of starting is such that wetting of the vaporizer by liquid is assured. It will be apparent that if desired a reservoir can be employed for providing a quantity of starting liquid for the heat link of FIGS. 4 and 5. Likewise, a wick could be used along with, or instead of, the reservoir in the embodiment illustrated in FIG. 2. Starting of such a heat link can, if desired, be obtained merely by tilting the heat link so as to fill the liquid return path 47 and then starting the heat link. Other arrangements for starting the heat link can be provided by one skilled in the art, and in zero gravity little, if any, special structure is needed since the heat link will start virtually automatically.

Thus, liquid is vaporized from the capillary vaporizer 37 and condenses in the cooler portion of the chamber 36. The vapor in the cooler portion has a sufficient vapor pressure to operate on the liquid and maintain a column of liquid in the liquid return path 47 against a head of gravity or the like. The pressure of the liquid at the interface 49 is greater than the vapor pressure of the liquid at the temperature of the face 49 and therefore vapor bubbles do not form at this point. The continuous contact of cooler liquid at the face 49 of the capillary vaporizer assures a supply of liquid to the vaporizer for vaporization and operation of the heat link and also to maintain the surface 49 at a sufficiently low temperature to prevent vapor lock.

FIG. 6 illustrates another heat link incorporating principles of this invention. It may in some circumstances be insufficient to merely provide thermal insulation on the liquid return path and adjacent the interface where liquid contacts the capillary vaporizer. If the return liquid has too little flow or is too warm, particularly if the return liquid flows through a region of high ambient temperature, the interface may heat up and vapor bubbles form to block liquid flow. In the illustrated embodiment of FIG. 6, additional active cooling of the liquid and manifold walls and, hence, the interface is provided.

As illustrated in this embodiment, a heat link has a cylindrical heat transfer section 51 in the form of a cylinder, which during normal operation of the heat link is filled with vapor 52, except at the cooler end where liquid 53 will collect. A porous capillary vaporizer 54 is provided in the warmer end of the heat link, and heat transfer occurs between the vaporizer 54 and the cooler walls of the chamber 51 through the latent heat of vaporization of the working fluid in substantially the same manner hereinabove described in relation to other embodiments of this invention.

A liquid return conduit 56 returns liquid from the end of the chamber 51 to a manifold 57 in fluid communication with a back surface 58 of the vaporizer 54. The similarity of this much of the heat link of FIG. 6 to that herein above described and illustrated in FIG. 2 will be apparent.

Arranged within the liquid conduit 56 is a porous wick 59 which extends from the lower portion of the chamber 51 in contact with liquid 53 accumulated therein and to the manifold 57 where it extends along at least a portion of the back surface 58 of the capillary vaporizer. The wick 59 serves as a means for starting the illustrated heat link and provides a very limited quantity of liquid to the porous vaporizer in substantially the same manner as a conventional heat pipe. Because of the substantial resistance to fluid flow through the wick 59 the quantity of liquid supplied to the vaporizer thereby is insufficient for handling the full liquid flow during maximum heat transfer by the vaporizer. The wick is sufficient, however, to supply enough liquid to the vaporizer for the resulting vapor to heat the portion of the chamber 51 accessible to the vapor to the point where the vapor pressure in the chamber 51 is high enough above the vapor pressure in the liquid return line 56 to fill it with liquid, and thereafter the principal liquid flow is through the conduit 56 in substantially the same manner as hereinabove described.

In order to maintain the temperature of the liquid 53 in the manifold 57 and liquid return line 56 at a low enough temperature that the vapor pressure is less than the pressure of the liquid, a heat pipe 61 is arranged adjacent the liquid return line and around the manifold 57 so as to be in thermal contact therewith. The heat pipe 61 has an impermeable tube 62 lined with a capillary material 63 so as to leave a central vapor path 64. In operation, heat is transferred from the liquid 53 in the liquid return line and manifold 57 into the heat pipe 61. A heat transfer liquid (not shown) in the porous material 63 is vaporized by this heat, and the heat is transferred to cooler portions (not shown) of the heat pipe 61 as a vapor passing through the central open core 64, all in a quite conventional manner.

The quantity of heat that must be removed by the heat pipe 61 from the returning liquid 53 is very small compared with the quantity of heat transferred by the heat link constructed according to principles of this invention, and would normally be less than about 1 percent of the total heat transferred. This is sufficient to maintain the improved heat transfer device in operation. The combination of both the starting wick 59 and the heat pipe 61 is particularly useful in assuring start up and/or operation at very low heat fluxes under adverse conditions.

The active cooling of the liquid return line and manifold by the heat pipe 61 may be highly advantageous as compared with merely insulating the liquid return line. Under conditions where the auxiliary heat pipe 61 is in good thermal contact with a heat sink at a somewhat lower temperature than the chamber 51, it can maintain the liquid in the liquid return line at a sufficiently low temperature when the heat link is shut off that vaporization is prevented, and the liquid return line will remain filled so that auxiliary starting arrangements for the heat link are not required. This obviates any requirement for a starting reservoir such as illustrated in FIG. 2.

The active cooling of the liquid return line will permit the heat link to continue to operate at very low heat fluxes as compared with the maximum heat flow of which it is capable. The quantity of heat that must be removed from the back surface 58 of the vaporizer decreases much less rapidly than the liquid flow rate when heat fluxes are lowered. In a heat link wherein the returning liquid is maintained cooler by insulation of the return line and manifold, the flow rate of liquid at reduced heat fluxes may not be sufficient to maintain the back face of the vaporizer at a sufficiently low temperature to keep the vapor pressure from exceeding the maximum permissible vapor pressure and vapor blockage of the liquid return line may occur. With active cooling of the liquid return line by a heat pipe 61, vapor blockage, even at low flux rates or in other difficult operation conditions, is effectively prevented.

Active cooling of the liquid return line may be highly advantageous when liquid metals are employed as the working fluid in the heat link. Liquid metals have such a high thermal conductivity that they effectively limit the minimum thermal conductivity that can be obtained in a liquid filled porous capillary material. As mentioned hereinabove, in order to maintain the liquid contacting interface of the vaporizer at a sufficiently low temperature, it is desirable to employ a relatively low thermal conductivity porous material as a thermal barrier between the liquid contacting surface and the higher thermal conductivity porous vaporizer material. If the low conductivity porous matrix is filled with a high thermal conductivity liquid which greatly increases its overall thermal conductivity, it may be virtually impossible to obtain a sufficiently cool interface between the liquid and the porous material in the absence of active cooling.

Even with other heat transfer fluids than liquid metals, it may not be feasible to employ a low thermal conductivity capillary material due to reaction with the heat transfer fluid. Thus, if there is any appreciable solubility of the capillary material in the heat transfer fluid, dissolution and redepositing of the capillary material may plug the vaporizer capillaries. With active cooling, relatively high thermal conductivity vaporizer materials can be safely employed. It is obvious that other forms of cooling may be substituted for the heat pipe depending on the particular circumstances. A thermoelectric cooler used in this way is shown in FIG. 14.

FIG. 7 illustrates a portion of a simple type of vented capillary vaporizer surface structure particularly well adapted for use with the preceding embodiments to greatly increase the heat flux density capability of the capillary vaporizers. A more detailed description of these and other vented capillary vaporizers along with their performance characteristics is given in the aforementioned copending patent application entitled "HEAT TRANSFER SURFACE STRUCTURES." The portion of capillary vaporizer illustrated in FIG. 7 could be a portion of any of the capillary vaporizers in FIGS. 2, 4, or 6. Taking FIG. 2 as an example; the heat source wall **85** in FIG. 7 would correspond to the chamber walls **14** in FIG. 2 and the body of porous capillary material **86** in FIG. 7 corresponds to the equivalent body of porous capillary material **15** in FIG. 2. Vapor passages **87** penetrate almost through the capillary material **86** forming many closely spaced vaporizing surface regions **88** near the heat source wall **85**. These vaporizing surface regions **88**, taken together, correspond to the vaporizing surface **17** in FIG. 2 but are very much nearer the heat source wall **85**, so that the distance that the incoming heat must be conducted through the capillary material is minimized. The passages **87** also allow the resulting vapor to escape easily, and form a large surface area in the capillary material that is isothermal with the vapor so that the temperature in the bulk of the capillary material remains sufficiently low that the liquid in the capillaries is not replaced by vapor. For maximum heat flux densities it is also desirable that the matrix material between the heat source wall **85** and the vaporizing surface region **88** have as high a heat conductivity as possible and also have a higher effective capillary surface to volume ratio δ i.e., smaller capillaries, than the rest of the capillary material. The net result of these modifications is to greatly increase the maximum heat flux density capabilities of the capillary vaporizers, generally by more than an order of magnitude.

FIGS. **8** through **10** illustrate a more sophisticated type of vented capillary vaporizer which can profitably be employed in a heat link since it is capable of producing output vapor at a considerably higher pressure than the input bulk liquid pressure while handling extremely high heat flux densities with low temperature drops. FIGS. **8** and **9** are cross sections through a single region of heat transfer surface structure at an end of a heat link and it should be understood that a plurality of side-by-side structures such as illustrated in FIG. **8** may be repeated indefinitely to cover a large surface area if desired. A single repetition of the structure such as illustrated in FIG. **8** may, for example, be provided every one-half inch or more along the surface, and such a structure may have an indefinite length in a direction along that of FIG. **9** as may be limited only by the flow capacity of the liquid flow conduits and cooling means provided as hereinafter described.

FIG. **10** is an enlarged detail of the structure adjacent a heat source wall **89**. Immediately adjacent the wall, and in thermal contact therewith, are a multiplicity of rectangular strips **90** forming a multiplicity of channels **91** and an equal number of regional areas of vaporization, also called vaporizing surface regions, at the interfaces between the channels **91** and the capillary material forming the channel walls. The regional areas of vaporization are further described and defined in the previously mentioned copending patent application, "HEAT TRANSFER SURFACE STRUCTURE." Running transversely to the fine strips **90** are larger strips **92**, having channels **93** therebetween, and these larger strips **92** are in contact with still larger strips **94**, having channels **95** therebetween. Thus, the structure nearest the heat source provides a hierarchy of strips **94**, **92** and **90** of decreasing size and increasing number for conducting liquid toward the heat source wall, and a hierarchy of channels **91**, **93** and **95** of increasing size and decreasing number. These, along with the spaces **107** between the structure and the interior **108** of the chamber containing the structure, form a vapor manifold which delivers the vapor into the vapor passage of the heat link.

Liquid is delivered to the larger strips **94** by a thermal isolation matrix **96** in contact therewith. The thermal isolation matrix is a porous material having a high wicking efficiency or ability to convey liquid and as low a thermal conductivity as possible. In the structure illustrated in FIGS. **8** and **9** the vapor generated adjacent the heat source surface is collected in a vapor way (the main undivided passage of the heat link) external to the liquid delivery structures while remaining well isolated from the incoming bulk liquid by the thermal isolation matrix **96**.

The thermal isolation matrix **96** is in intimate thermal contact with a matrix cooler plate **97** formed of a high thermal conductivity metal. Transverse grooves **98** in the cooler plate **97** transmit liquid from conduits **99**, which are connected to the heat link liquid return line, to the surface of the thermal isolation matrix **96**. One wall of each of the liquid conduits **99** is formed by the wall **101** of a heat pipe. The heat pipe also comprises a conventional wick **102** and an open vapor passage **103** for extracting heat from liquid in the conduits **99** and from the matrix cooler plate **97** for delivery to a cooler heat sink (not shown). This heat pipe might, for instance, extend down the liquid return line as shown in FIG. **6** or be cooled by a thermoelectric cooler as shown in FIG. **14** and subsequently described. A layer of thermal insulation **104** surrounds the heat pipe and a metal sheath **105** and channel wall **106** prevent liquid in the conduits and vapor surrounding the structure from contacting the insulation. The liquid channel wall **106** conducts heat to the heat pipe to help keep the liquid in the channel cool.

In both of the above described vented capillary vaporizers of FIGS. **7** to **10** it is preferred that the vaporizing surface regions in the portion immediately adjacent the heat transfer surface be spaced apart by less than about 0.1 inch. If the passages are spaced apart by appreciably more than about 0.1 inch, the additional expense of preparing the structure is not justified by the increase obtained in heat flux density. The vented capillary vaporizer structure is more expensive to fabricate than most simple heat transfer structures. Its major advantage is that it is capable of handling much higher heat flux densities than any but the most expensive and complex systems, which must use high pressure pumps and undercooled liquids in order to obtain comparable heat flux densities. This is true of those devices that exploit in full the highly advantageous characteristics of the vented capillary vaporizer. Detailed analysis of size relations in capillary vaporizers is set forth in the aforementioned copending patent application entitled "HEAT TRANSFER SURFACE STRUCTURE."

In operation, the capillary pump-type of vented vaporizer, illustrated in FIGS. **8** and **9**, takes bulk liquid (liquid that is not in a capillary structure) from the heat link liquid return line into the channels **99** for delivery to the porous thermal isolation matrix **96** by way of the transverse grooves **98**.

The bulk liquid entering the conduits **99** is at a relatively lower pressure than the vapor escaping from the channels **95** nearer the heat source surface, and the liquid pressure continues to drop as it flows through the conduits **99**, grooves **98**, and the various capillary matrix structures. In order to prevent the occurence of vapor in the liquid flow path, the temperature of the liquid must be sufficiently low at any point that its vapor pressure at that temperature is less than the sum of the liquid pressure and the bubble pressure at that point. In the macroscopic structures, such as the conduits **99** and grooves **98**, the distances between the walls are so large that the bubble pressure is negligible, and the liquid in them must remain cool enough that the vapor pressure of the bulk liquid is less than the liquid pressure. In the very small pores of the capillary matrix, however, the effective pore surface to volume ration is large, so that the bubble pressure is quite high, and the vapor pressure may be considerably greater than the liquid pressure without any bubbles forming. Thus, the temperature within such a capillary matrix may be slightly greater than the temperature of the vapor formed at a free surface of the capillary matrix without forming vapor bubbles in the matrix, while the temperature of the bulk liquid must be kept enough cooler than the temperature of the vapor formed at the free surface of the capillary matrix to balance the liquid-vapor pressure difference.

In order to keep the bulk liquid sufficiently cool to prevent its vaporization, the thermal isolation matrix **96** is selected with as low a thermal conductivity as possible for minimizing the quantity of heat transferred from the vapor within the channels **95** through the matrix to the face in contact with the bulk liquid while the bulk liquid is cooled to as low a temperature as possible in the heat sink. If the thermal isolation is not sufficient, a heat pipe such as illustrated in FIGS. **8** and **9** is provided in thermal contact with the bulk liquid for extracting surplus heat therefrom for preventing vaporization. A heat pipe is preferred in such an application because of the high rate of heat transfer available with relatively small temperature difference, however, it is to be understood that other active or passive cooling means than the heat pipe can be employed as desired, such as, for example, a fluid flow cooling tube, or a heat radiating or conducting rod or fin, or a thermoelectric cooling device, as subsequently described.

FIGS. **11** through **13** illustrate another version of capillary vaporizer having a structure somewhat simpler and more readily manufactured than that shown in FIGS. **8** through **10**. It is particularly well adapted to use in situations wherein means as subsequently described are available for exhausting vapor from the liquid return passage in the vaporizer. In FIG. **11** the end of the vaporizer shell **112**, closed on the end by the shell end plate **114**, is broken away to show the main capillary structure **116** of low thermal conductivity capillary material which has grooves **118** on the sides which join grooves **120** on the bottom. A thin heat input surface foil **122** of copper or other high heat conductivity material seals the bottom of the shell and is bent up at the edges to seal to the shell **112** and shell end plate **114**. Breaking a portion of the foil **122** away in FIG. **11** exposes the vaporizing structure **124** of high thermal conductivity capillary material which generally also has a somewhat higher capillary surface to volume ratio δ than the main capillary structure **116**. This structure contains two sets of grooves transverse to, and connecting with, each other. The largest set of grooves or channels **126** can be seen in FIG. **13**, which is a transverse cross section of FIG. **11**, while the smaller set of grooves **128** and the vaporizing surface regions **129** formed by the grooves adjacent the heat input surface foil **122**, are shown in FIG. **12**, which is a magnified view of a small portion of the vaporizing structure **124**.

Cutting away a portion of the main capillary structure **116** in FIG. **11** exposes a cylindrical insert **132** of low thermal conductivity capillary material having a lower capillary surface to volume ratio δ, and thus higher liquid conductivity than the main capillary structure **116**. The insert **132** is penetrated by a liquid supply passage **134** which is continued at the end by a liquid supply passage tube **136**. The space left between the shell **112** and the main capillary structure **116** forms a large vapor passage **138**. The entire structure is bonded together so that the main capillary structure **116** supports the shell **112**, end plate **114**, and vaporizing structure **124**. The vaporizing structure **124** in turn supports the heat input surface foil **122** so that the foil may be made very thin to decrease the temperature drop across it.

In operation liquid flows from the tube **136** down the liquid passage **134**, through the capillaries in the insert of low δ capillary material **132** and the main capillary structure **116** and, finally, through the capillaries of the capillary material comprising the vaporizing structure **124** to the multitude of vaporizing surface regions **129**. Heat, represented by the arrows **140**, in FIG. **12** flows through the heat input surface foil **122** and a short distance through the high heat conductivity capillary material between the smallest grooves **128** to the vaporizing surface regions **129**, where it evaporates the liquid delivered there. The resulting vapor proceeds through the successively larger grooves or channels **128**, **126**, **120**, **118** until it reaches the large vapor passage **138** down which it proceeds. Thus incoming liquid and heat are converted into outgoing vapor, which, in the complete heat link will proceed down the vapor passage and transmit its heat of vaporization to a heat sink, condense, and return to the vaporizer via the liquid return line **136** as in preceding embodiments.

The liquid is thermally insulated by the low thermal conductivity capillary material of the insert **132** and a large portion of the main capillary structure **116**. The thermal conductivity of most usable capillary materials, for example, stainless steel, or porous glass or ceramic is considerably higher than that of most insulating materials as used in the vaporizer designs shown in FIGS. **8–10** so that the heat flux in this example should be further reduced. This is accomplished by keeping the area in contact with the bulk liquid as small as possible. Thus the heat pipe in FIGS. **8** and **9** is not present in the passage **134** and the passage **134** is made as small as practical. Reducing the size of the passage **134** increases the resistance to fluid flow from the passage through the capillary material. This is offset, however, using an insert **132** of capillary material having a lower capillary surface to volume ratio δ, and thus higher fluid conductivity in the cooler region around the passage **134** and by the fact that liquid can initially flow outward from the passage **134** in all directions as compared to the one-directional flow of the liquid in the capillary vaporizer shown in FIGS. **8–10**. The lower δ capillary material of the insert **132** can be used in the cooler region about the passage since the pressure differential between the vapor pressure and the liquid pressure is low enough there that vapor will not push the liquid out of the capillaries. Conversely, higher δ capillary material is needed and used for the vaporizing structure **124**, or at least that portion of it between the smallest set of channels **128**. Since the fluid conductivity of the higher δ capillary material, particularly when optimized for high heat conductivity, is low, the distance that the liquid must travel through it is kept as short as practical, so that the high δ material is limited to a relatively thin layer adjacent the heat input surface foil. The overall design, however, makes it advantageous to form the channels **118** and **120** as grooves in the main capillary structure while with available construction techniques, it is simpler to construct the sets of channels in pairs, i.e., a homogenous slab of material with two sets of channels, one set on each face, transverse to each other and deep enough for their bottoms to intersect. Thus the vaporizing structure **124** includes both sets of channels **118** and **120** and is somewhat thicker than optimum. This is largely compensated for, however, by using a somewhat lower δ material in the vaporizing structure **124** than in the vaporizing strips **90** in FIG. **10** while increasing the height to width ratio of the channels **128**. The overall theory behind this is explained in the previously mentioned co-pending patent application entitled "HEAT TRANSFER SURFACE STRUCTURE."

Generally it is necessary to provide means for removing either or both heat or vapor from the fluid in the passage **134** in order to prevent vapor from blocking the liquid passage. This is needed when continuously operating at low heat flux densities where the flow of liquid into the passage **134** is insufficient to provide adequate cooling, even when the liquid is cooled before entering the vaporizer to a temperature considerably below the temperature at which vapor bubbles will form in the passage. With a very small passage **134** it is generally more feasible to remove the vapor than to directly cool the liquid. One technique for doing this is illustrated in FIG. **13A** showing an alternate construction for a portion **142** of the cross section of insert **132** shown in FIG. **13**, but where the cross section is taken near the end of the capillary vaporizer opposite that where the liquid enters. Here a portion of the insert **132** adjacent the end is replaced by a heat pipe **144** entering the capillary vaporizer through the shell end plate on that end (not shown). The heat pipe **144** has a smaller diameter than the insert **132** so that a gap or passage **146** remains allowing the passage of fluid as far as the shell end plate. The heat pipe comprises a short thin walled tube **148** sealed at the ends and containing an annular layer of capillary material **150** having a very small capillary surface to volume ratio δ and thus a high fluid conductivity and a fluid (not shown), the liquid of which wets the capillary material. Both the portion of the insert **132** that is removed and the heat pipe **144** are kept as short as possible in order to minimize the heat flux into the passage **146**, which is about twice the heat flux per unit length of passage as in the region where the insert **132** is in place, and to maximize the heat flux capacity of the heat pipe. The heat pipe, shortly after leaving the capillary vaporizer, may in turn transmit the heat to another larger diameter heat pipe connected to a heat sink or any of a large variety of other means for conveying the heat away. The heat pipe **144** thus condenses any vapor formed in the passage **134** while the resulting liquid flows into the capillary material of the main capillary structure surrounding the heat pipe **144**. The off-center position of the heat pipe **144** in the hole left by removing the portion of the inset **132** also helps transport liquid back to any dry regions through the narrower portion of the passage **146** while simultaneously allowing vapor access to the heat pipe through the wider portions of the passage **146**. Vapor is thus removed from the passage **134**.

Another technique which can be used to cool the liquid in the passage or remove vapor from the passage **134** by condensing it uses a thermoelectric cooling device as shown in FIG. **14** which shows a cross section of the capillary vaporizer of FIGS. **11** to **13** near the end opposite the end the liquid enters. A portion of the insert **132** and of the surrounding capillary material **116** is replaced as shown with a thermoelectric cooling device **152** having a cool face **154** and a hot face **156** when driven with an electric current. The thermoelectric cooler is also fitted with channeled portions of capillary material **158**, **160**, and **162** to distribute liquid and heat. Transverse channels **164** are formed across the top of the main capillary structure **116** as shown in FIG. **15**, which is a cross section of a portion of FIG. **14**.

Electric power (leads not shown) is supplied to the thermoelectric cooler causing the face **154** to become colder and the face **156** to become hotter. Vapor received through the passage **134** flows through the transverse channels in the piece **158** and the capillary material **160** to condense on the channel walls of the piece **160** adjacent the cold surface **154** of the thermo-electric cooler. The resulting liquid flows through the capillaries of the pieces **158** and **160** into the main capillary material **116** and the insert **132**. The pieces **158** and **160** are of high thermal conductivity, low δ capillary material. The vapor is thus removed from the passage **134**. At the same time liquid flows through the porous capillary material between the channels **164** and through the porous capillary material of the piece **162** to the channel walls of the piece **162** adjacent the hotter surface **156** of the thermo-electric cooler where it is evaporated by heat from the hotter thermo-electric cooler surface **156**. The resulting vapor escapes through the channels in the piece **162** and the channels **164** into the passage **138**. The hotter surface of the thermo-electric cooler is thus cooled and the heat transferred to vapor in the passage **138**.

The thermoelectric cooler **152** is not limited to removing heat from the vapor but may be extended along the length of the capillary vaporizer passages to remove heat directly from the liquid. In this case it is best to remove the inserts **158** and **160**. It may also be used to cool a heat pipe as used to cool the liquid in the capillary vaporizer in FIGS. **8** and **9**. A cross section of the thermo-electric cooler-heat pipe combination is similar to that shown in FIG. **14** except that the capillary structure **132**, **158**, and **160** are all enclosed within the heat pipe wall (not shown) with **132** being a continuation of the heat pipe wick. Liquid passages, the boundaries being shown as the dashed lines **165** are run adjacent the heat pipe wall.

Thermo-electric coolers are sufficiently efficient that one watt of electric power is sufficient to transfer about 4 watts of heat flux from the cooler surface **154** to the hotter surface **156** of the thermo-electric cooler against a 10° C temperature differential. Thus for 1 watt of electric power about 4 watts of heat are extracted from the vapor in the passage **134** and 5 watts of heat are passed into the passage **138** as heat of vaporization. The net loss rate of liquid necessary to remove 4 watts of heat from the vapor in the passage **134** is thus equivalent to only the amount that would be evaporated by 1 watt, which simplifies the task of supplying liquid to the capillary vaporizer for starting since relatively little is needed. Furthermore, generally far less heat has to be extracted from the liquid passage, which is usually thermally isolated, than must be added to the vapor passage, which is usually larger and in good thermal contact with the environment, to obtain a sufficient temperature differential to force the bulk liquid up the return line against a gravity head. Furthermore, in condensing the vapor, and thus lowering the pressure in the liquid return line, the thermo-electric cooler often causes bubbles to form in the returning liquid which greatly lower its density, and thus the effects of gravitational forces. This version of the capillary vaporizer thus makes the heat link particularly easy to start. The electric power required is also relatively small since the 1 watt of electric power removing about 4 watts of heat from the passage **134** is sufficient cooling for the capillary vaporizer of a heat link having a maximum heat flux capacity of about 1 kilowatt.

Embodiments of the heat link described so far have preformed capillary vaporizers and lack the flexibility that can be achieved when the cooling surface can be bent and twisted, as with the copper tubing typically used for refrigeration cooling coils. The "boosted" heat link shown in FIG. **16** largely escapes this limitation since only about 10 percent or less of the heat (arrows **166** signifying heat flow) need go into the capillary vaporizer **168** while the remaining heat can be received by a vaporizing section **170** of flexible tubing **172** containing liquid (not shown) sprayed into it by a venturi or ejector type of vapor jet pump **174** driven by vapor from the capillary vaporizer. Here the liquid return line **176** supplies part of its liquid to a capillary vaporizer **168** similar to that shown in FIGS. **11** through **13**, with the remaining liquid flowing completely through the capillary vaporizer liquid passage and the line **178** through a check valve **180** into a manifold **182** about the throat **183** of the ejector pump from where it is sucked through orifices **184**. The pressure differential required to suck the liquid through the orifices **184** is created by vapor flowing from the middle of the large vapor passage (**138** in FIG. **11**) through a short length of tubing **186** into the ejector pump **174** where the velocity increases and the static pressure drops in the restricted throat or venturi region **183**. Much of the static pressure is recovered in the diffusing cone **188** as the velocity of the mixed liquid and vapor stream decreases. The mixed liquid and vapor stream then passes through the vaporizing section **170** of tubing where about 10 or more times the heat delivered to the capillary vaporizer may be transformed into heat of vaporization. The vapor and any remaining liquid then pass into the heat sink or condenser section **190** wherein the vapor condenses into liquid with the resulting heat of condensation passing through the walls of the tube **172** to a heat sink (not shown).

The liquid return line **176** may directly tap the liquid at the cold end **192** of the heat link or a separator tube **194** may be employed to collect the liquid as shown here. The separator tube **194** has thin walls of a capillary material which is wet by the working liquid but not by the pressurizing liquid, if any. It is used in conjunction with either direct vapor (gas) or direct liquid-vapor pressurizing or control to keep the pressurizing liquid or vapor out of the fluid line.

The pressurizing fluid and the separating tube material are chosen so that the permeable walls of the separator tube are wet by the working liquid in preference to the pressurizing liquid and thus bar the passage of both the vapor and the pressurizing liquid while allowing the working liquid, i.e., the heat transfer liquid, to pass. Other liquid wetted permeable arrangements can also be provided for separating pressurizing and working liquids.

Start up and low heat flux operation may be achieved by the means previously described, that is, a wick, reservoir, or means for condensing vapor in the liquid passage of the capillary vaporizer such as a heat pipe or thermo-electric cooler as applicable to the particular situation. There are certain circumstances where none of these methods of starting or any combination of them, are attractive. The most important example is that of a boosted heat link having a large internal volume and very high heat conductance to the heat sink and where the heat sink temperature is so low that the vapor pressure of the working fluid is insufficient to lift the liquid up to the vaporizer against the gravity head in the liquid return line, so that it forms a vapor block, even when a thermo-electric cooler "pumps" on the fluid. A wick would have to be very massive since it would have to provide sufficient fluid to raise the temperature of the condensing or heat sink section of the heat link to the point where a sufficient vapor pressure differential was generated to force the fluid up the liquid return line, which is difficult because of the high heat conductance to the heat sink. The reservoir, of course, would operate satisfactorily but would have to be large enough to contain a volume of fluid nearly equal to the internal volume of the heat link.

The reservoir volume can be reduced substantially by eliminating the diaphragm and pressurizing the combined reservoir-heat link volume with a vapor that is non-condensable at the temperatures involved. The reservoir can be essentially eliminated by providing the heat link with a pressuring fluid that has a high enough vapor pressure for startup but will condense in the cooler portions of the heat link under normal operating conditions. The major difficulty involved with applying either type of direct fluid pressurization to a standard heat link without "boost" devices is that even a small amount of the pressurizing fluid in the liquid return stream will cause a vapor block at the liquid-capillary material interface. In the illustrated embodiment the separator tube **194** keeps bulk pressurizing fluid, either liquid or vapor, from entering the liquid return line since the working fluid wets and fills the separating tube capillaries, blocking vapor and pressurizing fluid, but cannot prevent the entry of small amounts of pressurizing fluid dissolved in the working fluid. Ideally the pressurizing fluid would be completely insoluble in the working fluid but this is not generally the case and the dissolved pressuring fluid tends to form vapor bubbles as the working liquid becomes warmer in the liquid return line and vaporizer. Thus either a vapor exhaust means or very careful temperature control is necessary. This problem is no longer so severe in a "boosted" heat link like that shown in FIG. 16, however, since during normal operation any such vapor is exhausted by the ejector pump **174**. Thus direct pressurization is practical with the "boosted" heat link of FIG. 16, a small amount of fluid being added that will not wet the material of the separator tube **194** when it is already wet by the working fluid. The pressurizing fluid must also have a vapor pressure sufficiently high to maintain liquid in the vaporizer but not so high as to prevent the vapor from condensing in the colder end of the heat sink region **190** when the heat link is operating at high heat flux levels. The check valve **180** prevents vapor from entering and helps maintain liquid in the liquid feed passage during shutdown, startup, and low heat flux level operating conditions. If the heat link is to be operated for long periods at heat flux levels too low to power the ejector pump it is advisable to modify the design shown in FIG. **16** by incorporating a pressure relief valve (not shown) in the line **186** from the capillary vaporizer to the ejector pump. The pressure relief valve is then bypassed by a line containing another, very small, ejector pump (not shown) to which line **178** is connected via another check valve (not shown) similar to **180** so that the small ejector pump exhausts vapor from the capillary vaporizer liquid line when the heat flux, and the resulting vapor flow is low, while the pressure relief valve opens at the main ejector pump operates at higher heat flux conditions. The pressure relief valve also helps keep liquid in the capillary vaporizer during off periods since on shutdown it seals in time to prevent pressurizing vapor from entering, while any working fluid vapor trapped in the capillary vaporizer condenses and is replaced by liquid coming through the liquid return line, thus leaving the capillary vaporizer full of working liquid.

Other means may be used to keep the pressurizing fluid out of the returning liquid. In particular, gravitational (or other acceleration) forces may be used to separate the liquids or liquid and vapor as, for example, in a small well where the heavier working liquid is drawn off at the bottom while the lighter pressurizing fluid or vapor remains on top.

Another type of vapor jet pump is particularly useful in large "boosted" heat link systems since it has the capability of delivering a liquid output at a higher pressure than either of the vapor or liquid input streams. It was used extensively in the past to inject feed water into steam boilers, using steam from the same boiler as the power source and is thus known as an injector pump. It is described in the fourth edition of the "-Mechanical Engineers Handbook" edited by Lionel S. Marks, McGraw-Hill Book Co. and also to some extent in later editions. A schematic diagram of an injector pump is shown in FIG. **17**. Vapor enters the vapor inlet **200** and is expanded and accelerated in a converging-diverging nozzle **202**, leaving the nozzle with a low enough static pressure to suck cold liquid entering the liquid inlet **204** through multiple orifices **206**. The cold liquid is accelerated and mixes with the vapor so as to condense the vapor and form a high velocity liquid stream. The liquid stream has much higher density than the average density of the liquid-vapor mixture and thus gives a higher static pressure when decelerated, accounting for the overall pressure gain in the pump. During start-up of the injector pump a large flow of vapor is necessary before the liquid enters the pump. To accommodate this vapor flow without choking, an overflow manifold **208** and port **210** are provided. Since some liquid sprays into the manifold **208** a jet pump **212** operated by the high pressure output liquid is added to entrain any liquid in the overflow manifold into the liquid stream so that the liquid leaving the main outlet **214** includes all of the input vapor, now condensed, and liquid. The overflow port **210** is thus only operational during start-up. FIG. **17A** is a symbolic diagram of FIG. **17** indicating the placement various inlets and outlets as they correspond to FIG. **17**.

FIG. **18** shows a more complicated "boosted" heat link where several boost pumps, similar to those previously described, are used to increase the maximum heat flux capability of the initial capillary vaporizer by a factor between 1,000 and 10,000. Thus if the initial capillary vaporizer can handle a small heat flux of 1 kilowatt, the entire boosted heat link is capable of from 1 to 10 megawatts. Even in a system of this size and complexity the only moving parts, except for fluids, are five check valves and two pressure relief valves, all of which normally remain in one position during operation. The system operates in the following manner.

Liquid from a liquid return line **220** enters the liquid passage **221** of a first capillary vaporizer **222** similar to that illustrated in FIGS. **11–13** and FIG. **16**. A part of the liquid is vaporized and goes to the vapor inlet **224** of an ejector pump **226** similar to the one shown in FIG. **16**, while the remaining liquid flows on through the capillary vaporizer liquid passage and a check valve **227** to the liquid inlet **228** of ejector pump **226**. The output **229** of mixed vapor and liquid from the ejector pump **226** goes to a second capillary vaporizer **230** of 10 to 20 times the heat flux capacity of the first capillary vaporizer. Again part of the liquid is vaporized, the vapor going to the vapor inlet of a first injector pump **232** while the remaining liquid and vapor flowback through a thermal feedback loop **234** where it is in close thermal contact with the heat source surface **235** of the initial capillary vaporizer **222**. This serves as a negative feedback loop to limit the heat input into the first capillary vaporizer to that necessary to drive the ejector pump sufficiently to supply enough liquid for the capillary vaporizer **230**, since the heat source surface **235** of the initial capillary vaporizer **222** is cooled by any excess liquid. The fluid leaving the loop **234** goes to the heat sink or condensing section **236** of the system.

The vapor entering the first injector pump **232** from the capillary vaporizer **230** draws liquid from the liquid return line **220** through a check valve **238** into the first injector pump **232**. The fluid leaving the first injector pump **232**, having 10 to 20 times the mass flowrate of the vapor entering the injector pump **232**, passes through a vaporizing region **240**, where at least a portion of the liquid is vaporized, and into a second injector pump **242** of 10 to 25 times the capacity of the first injector pump. The second injector pump also draws liquid from the liquid return line **220** through a check valve **244** and delivers the output fluid into second vaporizing region **246**. Pressure relief valves **248** are placed between the vapor inlets of the injector pumps and a bypass line **250** to bypass excess vapor and check valves **252** are placed between the overflow parts of the injector pumps and bypass line **250**. Bypass line **250** joins the line carrying fluid from the second vaporizing region **246** and proceeds to the heat sink or condenser **236**. The vapor is condensed in the condenser **236** and flows into the liquid line **220**, thus completing the cycle.

It is apparent that as many injector pumps as desired by be added in series in the same manner as injector pumps **232** and **242**, each injector pump picking up liquid from the liquid return line and delivering it into a vaporizing region; the vapor from said vaporizing region then driving a 10 to 25 times larger injector pump. As an alternative each combination of an injector pump and region of vaporization may be replaced by an ejector pump and a capillary vaporizer arranged as the ejector pump **226** and capillary vaporizer **230** are arranged.

Additional thermal feedback loops (not shown here) may be added to stabilize operation. A negative feedback loop carrying fluid leaving the vaporizing region **240** to where it makes good thermal contact with the heat source surface of the capillary vaporizer **230** and back to the injector pump **242** is particularly useful in insuring that the capillary vaporizer **230** is not exposed to excessively high heat fluxes. A vapor recycling line **254** and check valve **255**, both shown in dashed lines, may be added to smooth out operation and to further reduce or eliminate the load on the capillary vaporizers once operation is underway.

Startup of the system is simple since it involves starting only the first small capillary vaporizer. A thermo-electric cooler inserted into the capillary vaporizer as shown in FIG. **14**, or if a heat sink cooler than the condenser section is available, the use of a heat pipe insert as shown in **13A** thermally connected to said heat sink are particularly simple means of starting this large a system. Other means, such as the wick or reservoir, are more massive since a wick must supply liquid rapidly enough to start the ejector pump **226** while a reservoir must either hold enough liquid to fill a large part of the system or special valves are required and the capacity of the system to operate at very low heat fluxes is limited. If the vapor pressure of the liquid is so low at startup that a pressure differential sufficient to drive the liquid to the capillary vaporizer or into the other pumps cannot be developed, however, then either a reservoir as shown in FIG. **2** or a direct acting pressurizing fluid and a separating tube or other separating device as previously described can be used.

The vapor jet pumps are simple and reliable. It should be evident, however, that many different types of pumps, driven directly or indirectly by energy coming, at least in part, from vapor produced by the capillary vaporizer, may be used in place of the jet pumps. Typical examples being coupled diaphragm pumps, hydraulic rams, fluid displacement pumps, and gas or vapor lift pumps.

Although several embodiments of apparatus incorporating principles of this invention have been described and illustrated herein, it will be apparent that many modifications and variations can be made by one skilled in the art. Thus, for example, in the embodiment described and illustrated in FIG. **6**, a conventional heat pipe is employed for active cooling of the returning liquid. If desired, a radiating fin, water cooling coil or other direct heat sink can be employed in lieu of the auxiliary heat pipe. Likewise, in the described and illustrated embodiments, the shape of the vapor carrying heat transfer passage and the liquid return passage have been relatively simple geometric shapes. It will be apparent that substantial variations can be made in such shapes in terms of cross section and also length or shape of the path in order to provide a heat link having a geometry to fit a selected application. Thus, for instance, the vapor and liquid return lines may consist of a single tube of uniform diameter, bent and coiled as desired, with the liquid containing portion possibly being very short in comparison with vapor condensing portion. In another configuration, the vapor conduit may lead to a condensing section composed of a complex branched array of passages so as to increase heat transfer, with the resulting liquid manifolded back into the liquid return line. Also, when the entire heat link is contained within a vessel it is often possible to omit portions of the conduit or passage walls while still providing sufficient means to ensure that the vapor leaving the capillary vaporizer passes through the heat sink region and that the returning liquid is sufficiently isolated from the hot vapor and heat therefrom. While the vaporizer has generally been shown above the heat sink region, this was to indicate that the heat links would operate where the liquid must be lifted against a gravity head. The embodiments shown will operate satisfactorily in any position or in a "zero g" environment.

Many other modifications, variations and adaptations will be apparent to one skilled in the art. It is therefore to be understood that, within the scope of the appended claims, the invention may be practiced otherwise than as specifically described.

What is claimed is:

1. Heat transfer apparatus comprising:

a vaporizer of capillary material having a first surface portion in thermal contact with a heat source, a second surface portion, and a third surface portion;

a partly condensed fluid, a portion of said fluid being liquid and another portion being vapor, said liquid wetting said vaporizer capillary material;

wall means defining a passage extending between the second surface portion of the vaporizer and the third surface portion of the vaporizer with a heat sink region therebetween, whereby fluid traversing the passage is in thermal contact with the heat sink region in said intermediate passage, for preventing vapor from flowing from the third surface portion to the second surface portion of the vaporizer without passing through said heat sink region;

the second surface portion of the vaporizer receiving liquid from the portion of the passage extending to it;

the third surface portion of the vaporizer comprising a multiplicity of vaporizing surface regions; an

said passage further comprising a multiplicity of intermediate branch vapor passages extending between the vaporizing surface regions and the balance of the passage;

said vapor being released from vaporizing surface regions into branch vapor passages at a higher pressure than that of the liquid entering the second surface portion; and wherein a sufficient area of the second surface portion is sufficiently close to the first and third surface portions of the vaporizer that the mean distance the liquid flows through capillary material is substantially less than the mean distance the fluid flows through the passage; and wherein a multiplicity of said branch vapor passages are embedded substantially into the capillary material.

2. Apparatus as defined in claim **1** wherein said vaporizing surface regions are spaced apart by less than 0.1 inch.

3. Apparatus as defined in claim **1** wherein the first surface portion is substantially uniformly separated throughout its extent from the second surface portion.

4. Heat transfer apparatus comprising:

a vaporizer of capillary material having a first surface portion in thermal contact with a heat source, a second surface portion, and a third surface portion:

a partly condensed fluid, a portion of said fluid being liquid and another portion being vapor, said liquid wetting said vaporizer capillary material;

wall means defining a passage extending between the second surface portion of the vaporizer and the third surface portion of the vaporizer with a heat sink region therebetween, whereby fluid traversing the passage is in thermal contact with the heat sink region in said intermediate passage, for preventing vapor from flowing from the third surface portion to the second surface portion of the vaporizer without passing through said heat sink region;

the second surface portion of the vaporizer receiving liquid from the portion of the passage extending to it;

the third surface portion of the vaporizer comprising a multiplicity of vaporizing surface regions; and

said passage further comprising a multiplicity of intermediate branch vapor passages extending between the vaporizing surface regions and the balance of the passage;

said vapor being released from vaporizing surface regions into branch vapor passages at a higher pressure than that of the liquid entering the second surface portion; and wherein a sufficient area of the second surface portion is sufficiently close to the first and third surface portions of the vaporizer that the mean distance the liquid flows through capillary material is substantially less than the mean distance the fluid flows through the passage; and wherein a multiplicity of said branch vapor passages pass through vaporizer capillary material.

5. Apparatus as defined in claim 4 wherein the vaporizer comprises a multiplicity of bodies of capillary material separated at least in part by intervening vapor passages.

6. Heat transfer apparatus comprising:

a vaporizer of capillary material having a first surface portion in thermal contact with a heat source, a second surface portion, and a third surface portion;

a partly condensed fluid, a portion of said fluid being liquid and another portion being vapor, said liquid wetting said vaporizer capillary material;

wall means defining a passage extending between the second surface portion of the vaporizer and the third surface portion of the vaporizer with a heat sink region therebetween, whereby fluid traversing the passage is in thermal contact with the heat sink region in said intermediate passage, for preventing vapor from flowing from the third surface portion to the second surface portion of the vaporizer without passing through said heat sink region;

the second surface portion of the vaporizer receiving liquid from the portion of the passage extending to it;

the third surface portion of the vaporizer comprising a multiplicity of vaporizing surface regions spaced apart less than 0.1 inch; and

said passage further comprising a multiplicity of intermediate branch vapor passages extending between the vaporizing surface regions and the balance of the passage;

said vapor being released from vaporizing surface regions into branch vapor passages at a higher pressure than that of the liquid entering the second surface portion; and wherein a sufficient area of the second surface portion is sufficiently close to the first and third surface portions of the vaporizer that the mean distance the liquid flows through capillary material is substantially less than the mean distance the fluid flows through the passage.

7. Apparatus as defined in claim 6 wherein the vaporizer comprises:

a first volumetric portion of capillary material relatively nearer the first surface portion and having a relatively higher thermal conductivity; and

a second volumetric portion of capillary material relatively further from the first surface portion and having a relatively lower thermal conductivity.

8. Heat transfer apparatus comprising:

a vaporizer of capillary material having a first surface portion in thermal contact with a heat source, a second surface portion, and a third surface portion;

a partly condensed fluid, a portion of said fluid being liquid and another portion being vapor, said liquid wetting said vaporizer capillary material;

wall means defining a passage extending between the second surface portion of the vaporizer and the third surface portion of the vaporizer with a heat sink region therebetween, whereby fluid traversing the passage is in thermal contact with the heat sink region in said intermediate passage, for preventing vapor from flowing from the third surface portion to the second surface portion of the vaporizer without passing through said heat sink region;

the second surface portion of the vaporizer receiving liquid from the portion of the passage extending to it;

the third surface portion of the vaporizer comprising a multiplicity of vaporizing surface regions; and

said passage further comprising a multiplicity of intermediate branch vapor passages extending between the vaporizing surface regions and the balance of the passage;

said vapor being released from vaporizing surface regions into branch vapor passages at a higher pressure than that of the liquid entering the second surface portion; and where a sufficient area of the second surface portion close is sufficiently close the first and third surface portions of the vaporizer that the mean distance the liquid flows through capillary material is substantially less than the mean distance the fluid flows through the passage; and said branch passages further comprising:

a first multiplicity of passages spaced relatively more closely together an situated so as to receive vapor from the vaporizing surface regions; and

a second multiplicity of passages spaced relatively less closely together and in fluid communication between the first plurality of passages and the undivided portion of the passage.

9. Heat transfer apparatus comprising:

a vaporizer of capillary material having a first surface portion in thermal contact with a heat source, a second surface portion, and a third surface portion, and further comprising a first volumetric portion relatively nearer the first surface portion and having a relatively larger capillary surface to volume ratio δ and a second volumetric portion relatively further from the first surface portion and having a relatively smaller effective surface to volume ratio δ;

a partly condensed fluid, a portion of said fluid being liquid and another portion being vapor, said liquid wetting said vaporizer capillary material;

wall means defining a passage extending between the second surface portion of the vaporizer and the third surface portion of the vaporizer with a heat sink region therebetween, whereby fluid traversing the passage is in thermal contact with the heat sink region in said intermediate passage, for preventing vapor from flowing from the third surface portion to the second surface portion of the vaporizer without passing through said heat sink region;

the second surface portion of the vaporizer receiving liquid from the portion of the passage extending to it and the third surface portion of the vaporizer releasing vapor into another portion of the passage extending to it, said vapor being released from the third surface portion of the vaporizer at a higher pressure than that of the liquid entering the second surface portion; and wherein a sufficient area of the second surface portion is sufficiently close to the first and third surface portions of the vaporizer that the mean distance the liquid flows through capillary material is substantially less than the mean distance the fluid flows through the passage.

10. Heat transfer apparatus as defined in claim 9 wherein said third surface portion of the vaporizer comprises a multiplicity of vaporizing surface regions and wherein the portion of the passage extending to the third surface portion of the

vaporizer comprises a multiplicity of intermediate branch vapor passages extending to the vaporizing surface regions.

11. Heat transfer apparatus comprising:

a vaporizer of capillary material having a first surface portion in thermal contact with a heat source, a second surface portion, and a third surface portion, and further comprising a first volumetric portion relatively nearer the first surface portion having a relatively higher thermal conductivity and a second volumetric portion relatively further from the first surface portion and having a relatively lower thermal conductivity;

a partly condensed fluid, a portion of said fluid being liquid and another portion being vapor, said liquid wetting said vaporizer capillary material;

wall means defining a passage extending between the second surface portion of the vaporizer and the third surface portion of the vaporizer with a heat sink region therebetween, whereby fluid traversing the passage is in thermal contact with the heat sink region in said intermediate passage, for preventing vapor from flowing from the third surface portion to the second surface portion of the vaporizer without passing through said heat sink region;

the second surface portion of the vaporizer receiving liquid from the portion of the passage extending to it and the third surface portion of the vaporizer releasing vapor into another portion of the passage extending to it, said vapor being released from the third surface portion of the vaporizer at a higher pressure than that of the liquid entering the second surface portion; and wherein a sufficient area of the second surface portion is sufficiently close to the first and third surface portions of the vaporizer that the mean distance the liquid flows through capillary material is substantially less than the mean distance the fluid flows through the passage.

12. Heat transfer apparatus as defined in claim **11** wherein said third surface portion of the vaporizer comprises a multiplicity of vaporizing surface regions and wherein the portion of the passage extending to the third surface portion of the vaporizer comprises a multiplicity of intermediate branch vapor passages extending to the vaporizing surface regions.

13. Heat transfer apparatus comprising:

a vaporizer of capillary material having a first surface portion in thermal contact with a heat source, a second surface portion, and a third surface portion;

a partly condensed fluid, a portion of said fluid being liquid and another portion being vapor, said liquid wetting said vaporizer capillary material;

wall means defining a passage extending between the second surface portion of the vaporizer and the third surface portion of the vaporizer with a heat sink region therebetween, whereby fluid traversing the passage is in thermal contact with the heat sink region in said intermediate passage, for preventing vapor from flowing from the third surface portion to the second surface portion of the vaporizer without passing through said heat sink region;

the second surface portion of the vaporizer receiving liquid from the portion of the passage extending to it and the third surface portion of the vaporizer releasing vapor into another portion of the passage extending to it, said vapor being released from the third surface portion of the vaporizer at a higher pressure than that of the liquid entering the second surface portion; and wherein a sufficient area of the second surface portion is sufficiently close to the first and third surface portions of the vaporizer that the mean distance the liquid flows through capillary material is substantially less than the mean distance the fluid flows through the passage; and

means for removing heat from the fluid adjacent the second surface portion of the vaporizer, said means being capable of removing said heat even when, without said means, the region surrounding said fluid would have at least as high a temperature as the fluid.

14. Heat transfer apparatus as defined in claim **13** wherein said third surface portion of the vaporizer comprises a multiplicity of vaporizing surface regions and wherein the portion of the passage extending to the third surface portion of the vaporizer comprises a multiplicity of intermediate branch vapor passages extending to the vaporizing surface regions.

15. Heat transfer apparatus comprising:

a vaporizer of capillary material having a first surface portion in thermal contact with a heat source, a second surface portion, and a third surface portion;

a partly condensed fluid, a portion of said fluid being liquid and another portion being vapor, said liquid wetting said vaporizer capillary material;

wall means defining a passage extending between the second surface portion of the vaporizer and the third surface portion of the vaporizer with a heat sink region therebetween, whereby fluid traversing the passage is in thermal contact with the heat sink region in said intermediate passage, for preventing vapor from flowing from the third surface portion to the second surface portion of the vaporizer without passing through said heat sink region;

the second surface portion of the vaporizer receiving liquid from the portion of the passage extending to it and the third surface portion of the vaporizer releasing vapor into another portion of the passage extending to it, said vapor being released from the third surface portion of the vaporizer at a higher pressure than that of the liquid entering the second surface portion; and wherein a sufficient area of the second surface portion is sufficiently close to the first and third surface portions of the vaporizer that the mean distance the liquid flows through capillary material is substantially less than the mean distance the fluid flows through the passage; and

active means for removing heat from the fluid adjacent the second surface portion of the vaporizer.

16. Apparatus as defined in claim **15** wherein the active means for removing heat comprises a heat pipe.

17. Apparatus as defined in claim **15** wherein the active means for removing heat comprises a thermoelectric cooling device.

18. Heat transfer apparatus as defined in claim **15** wherein said third surface portion of the vaporizer comprises a multiplicity of vaporizing surface regions and wherein the portion of the passage extending to the third surface portion of the vaporizer comprises a multiplicity of intermediate branch vapor passages extending to the vaporizing surface regions.

19. Closed loop heat transfer apparatus comprising:

a vaporizer of capillary material having a first surface portion in thermal contact with a heat source, a second surface portion, and a third surface portion;

a partly condensed fluid, a portion of said fluid being liquid and another portion being vapor, said liquid wetting said vaporizer capillary material;

wall means defining a passage extending between the second surface portion of the vaporizer and the third surface portion of the vaporizer with a heat sink region therebetween, whereby fluid traversing the passage is in thermal contact with the heat sink region in said intermediate passage, for preventing vapor from flowing from the third surface portion to the second surface portion of the vaporizer without passing through said heat sink region;

the second surface portion of the vaporizer receiving liquid from the portion of the passage extending to it and the third surface portion of the vaporizer releasing vapor into another portion of the passage extending to it, said vapor being released from the third surface portion of the vaporizer at a higher pressure than that of the liquid entering the second surface portion; and wherein a sufficient area of the second surface portion is sufficiently close to the first and third surface portions of the vaporizer that the mean distance the liquid flows through capillary material is substantially less than the mean distance the fluid flows through the passage; and means for transferring vapor from the region adjacent the second surface portion of the vaporizer to another region within the heat transfer apparatus where at least a portion of the fluid is available for continuing heat transfer.

20. Heat transfer apparatus as defined in claim 19 wherein said third surface portion of the vaporizer comprises a multiplicity of vaporizing surface regions and wherein the portion of the passage extending to the third surface portion of the vaporizer comprises a multiplicity of intermediate branch vapor passages extending to the vaporizing surface regions.

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UNITED STATES PATENT OFFICE

CERTIFICATE OF CORRECTION

Page 1 of 2

Patent No. 3,661,202 Dated May 9, 1972

Inventor(s) Robert David Moore, Jr.

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

The address of the inventor should be changed from "Camino Road" to --Camino Real--.

In FIG. 6, stipple wick 59.

In FIG. 8, line from reference numeral 99 should be extended to triangular portion of liquid.

In FIG.12, "130" should read --120--.

In Figs. 11, 13 and 14, all the bars of capillary material comprising the vaporizing structure 124 should be stippled.

In FIG. 18, the triangle in the upper left portion of the figure should bear reference numeral --227--;

In FIG. 18, the rectangle between elements "240" and "246" should bear reference numeral --242--;

In FIG. 18, the character "V" along with the arrow below it should be deleted in the portion of the figure immediately above reference numeral "229";

In FIG. 18, the characters "L+" should be deleted immediately above reference numeral "224".

In FIG. 15, stippling on element "152" should be deleted.

In FIG. 16, the separator tube 194 should be stippled.

Column 1, line 35, "ink" should be --sink--.

Column 4, line 13, "σL" should be --σ_L--;

line 19, after "ΔP" insert -- $\leqq$ --;

...to page 2

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UNITED STATES PATENT OFFICE
CERTIFICATE OF CORRECTION

Page 2 of 2

Patent No. 3,661,202 Dated May 9, 1972

Inventor(s) Robert David Moore, Jr.

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

Column 4, line 71, "R_x" should be --R_s--.

Column 9, line 32, "considerably" should be --considerable--;
line 37, "sufficient" should be --sufficiently--;
line 40, "foam" should be --form--.

Column 10, line 4, delete "RPM";
line 10, "along" should be --alone--.

Column 12, line 45, "as" should be --from--.

Column 14, line 51, "operation" should be --operating--.

Column 24, line 50, "an" should be --and--.

Column 26, line 25, delete "close" (first occurrence).

Signed and sealed this 9th day of January 1973.

(SEAL)
Attest:

EDWARD M.FLETCHER,JR.
Attesting Officer

ROBERT GOTTSCHALK
Commissioner of Patents