

Jan. 20, 1970

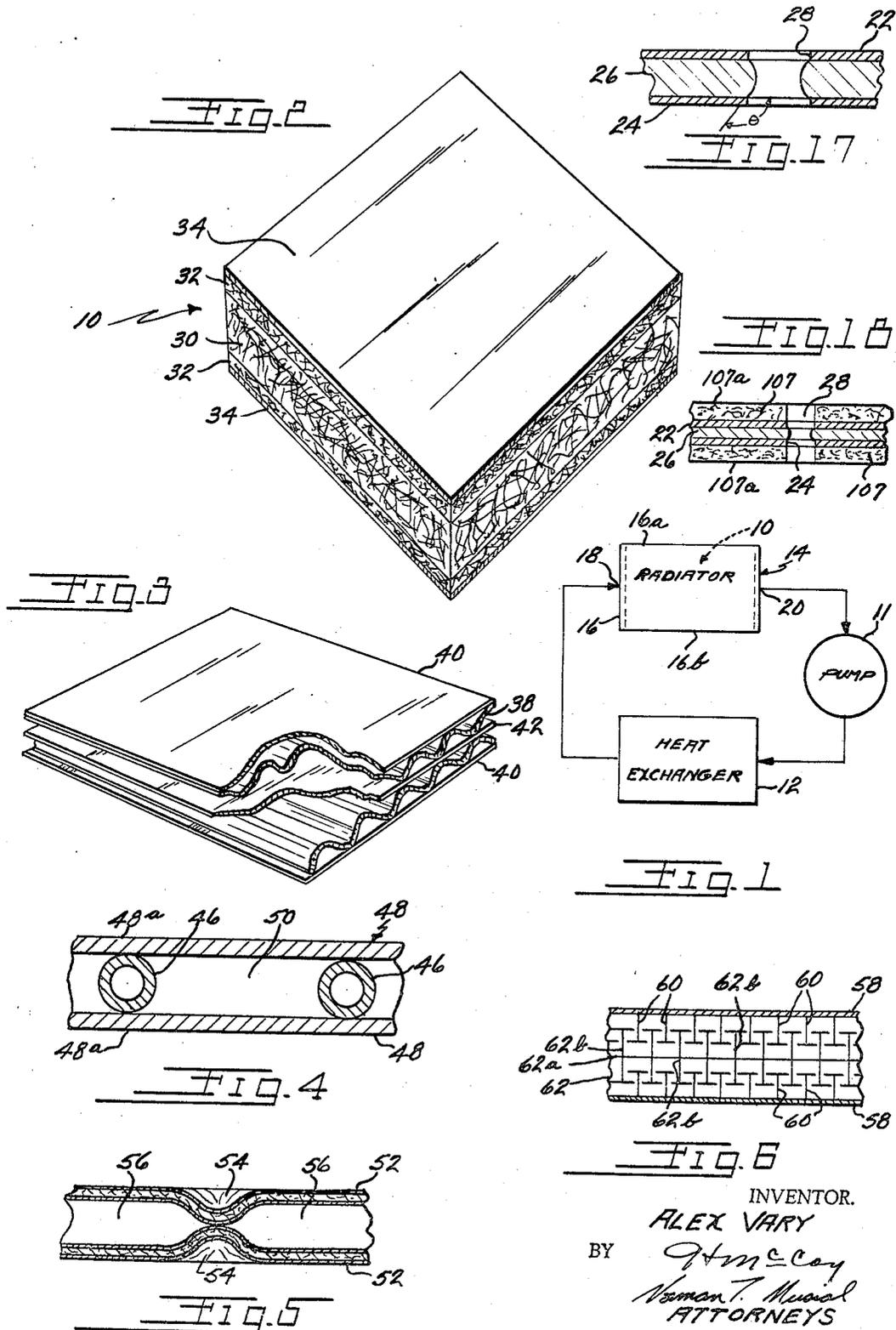
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3,490,718

CAPILLARY RADIATOR

Filed Feb. 1, 1967

3 Sheets-Sheet 1



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CAPILLARY RADIATOR

Filed Feb. 1, 1967

3 Sheets-Sheet 2

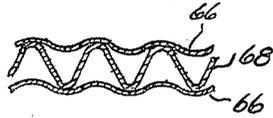


FIG. 7

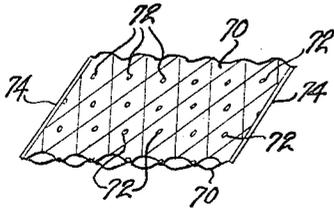


FIG. 8

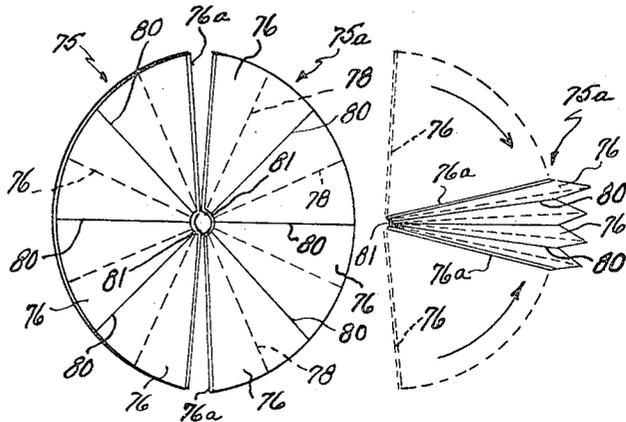


FIG. 9

FIG. 10

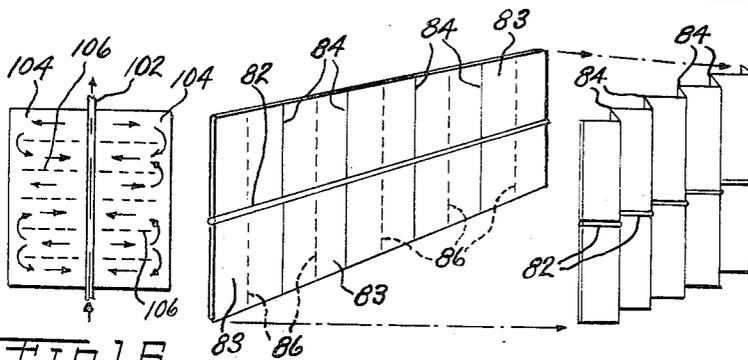


FIG. 11

FIG. 11

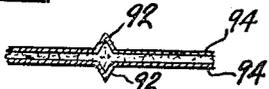


FIG. 14

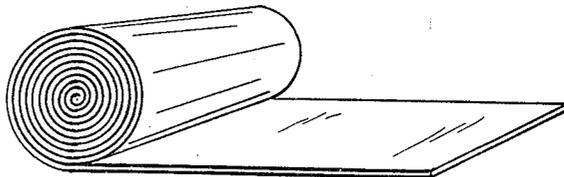


FIG. 12

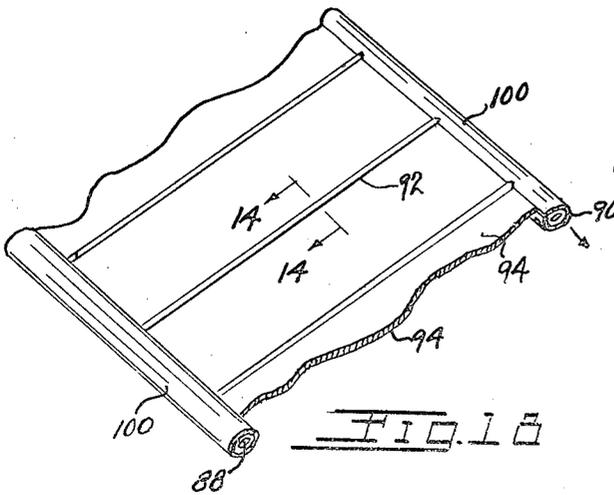


FIG. 13

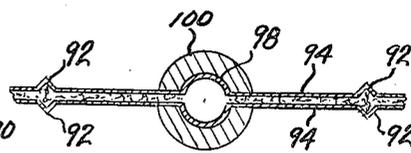


FIG. 15

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CAPILLARY RADIATOR

Filed Feb. 1, 1967

3 Sheets-Sheet 3

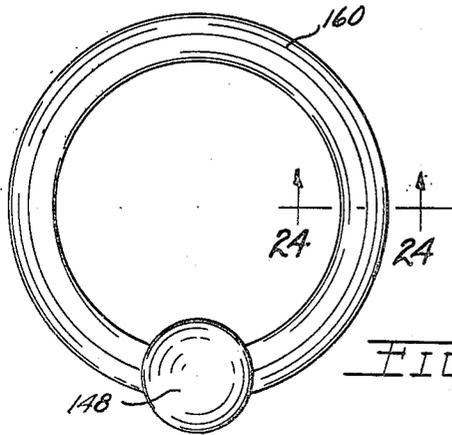


FIG. 23

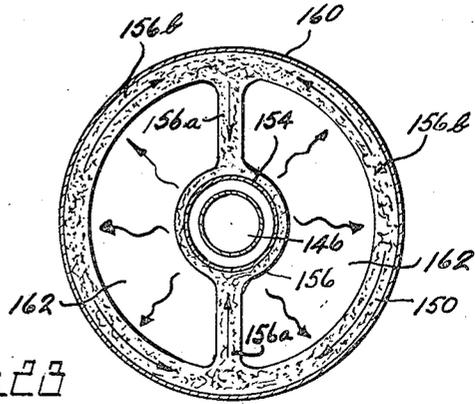


FIG. 24

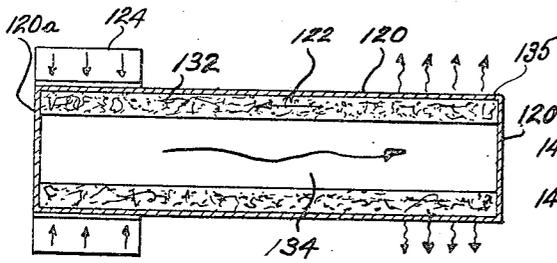


FIG. 21

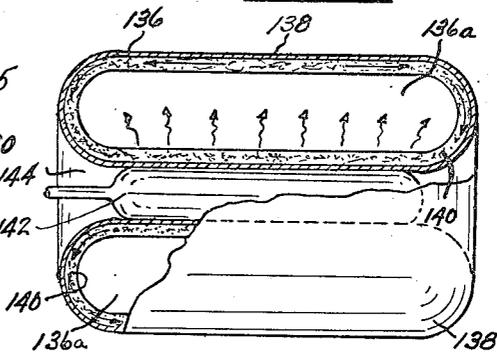


FIG. 22

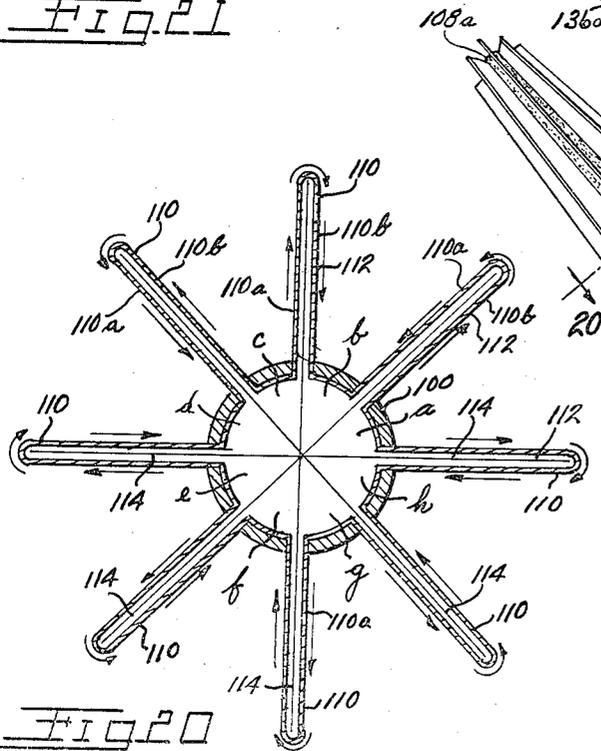


FIG. 20

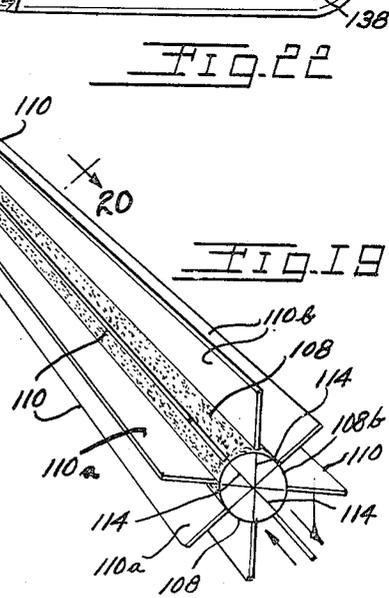


FIG. 19

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3,490,718

**CAPILLARY RADIATOR**

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 Filed Feb. 1, 1967, Ser. No. 613,979  
 Int. Cl. B64g 1/00

U.S. Cl. 244—1

15 Claims

**ABSTRACT OF THE DISCLOSURE**

The radiator construction is adapted for planetary space applications and comprises a core unit having capillary passages therein for the flow of heat transfer liquid therethrough as the latter flows from the inlet of the core to the outlet thereof. If the capillary core is penetrated by meteoroids and particularly micrometeoroids, a material loss of the heat transfer liquid will not occur. Heat transfer mediums such as mercury and the alkali metals, potassium sodium and lithium in liquid form are contemplated. The radiator core may also be flexible or foldable for reducing the size thereof for interplanetary space transportation problems and for reducing the area exposed to meteoroid penetration. A heat pipe combined with a capillary radiator mechanism is also disclosed, with such combined heat pipe-capillary radiator providing a self-contained unit for causing circulation of the heat transfer liquid through the radiator core, thereby eliminating a separate pump mechanism conventionally used for this purpose.

The invention described herein may be manufactured and used by or for the Government of the United States of America for Governmental purposes without the payment of any royalties thereon or therefor.

The present invention provides a novel capillary radiator mechanism for cooling a heat transfer fluid, and a novel heat pipe-capillary radiator combination providing a self-contained unit for circulation and cooling of the heat transfer fluid.

An object of the invention is to provide a capillary type radiator mechanism wherein the capillary core portion thereof may be punctured as for instance by micrometeoroids, without material loss of heat transfer fluid.

A further object of the invention is to provide a radiator mechanism of the latter mentioned type wherein retention of the heat transfer fluid at the penetration locations due for instance to the aforementioned micrometeoroids, depends upon the capillary action and surface tension characteristics of the heat transfer medium, the latter preferably being of metallic liquid form.

Another object of the invention is to provide a capillary radiator comprising exterior heat radiating surfaces between which is sandwiched capillary means through which the heat transfer medium or liquid is adapted to flow under predetermined pressure, and with the heat transfer medium being adapted to wet the defining capillary passage surfaces in a manner to aid the movement of the heat transfer liquid through the capillary core section of the radiator mechanism, but in a manner wherein there will be no material loss of heat transfer liquid in the event that the capillary core of the radiator mechanism is punctured by relatively small particles such as micrometeoroids.

Another object of the invention is to provide a combined heat pipe-capillary radiator mechanism resulting in a self-contained unit for circulation and cooling of the heat transfer liquid of the radiator mechanism.

Other objects and advantages of the invention will be

apparent from the following description taken in conjunction with the accompanying drawings wherein:

FIGURE 1 is a diagrammatic illustration of a cooling system embodying the capillary radiator mechanism of the invention;

FIGURE 2 is a fragmentary, perspective, view illustrating a core construction for the capillary radiator mechanism and with the core construction comprising spaced exterior heat radiating surfaces or members between which is sandwiched capillary passage means through which the heat transfer medium is adapted to flow under pressure and by capillary action, and with the particular capillary passage means illustrated comprising metal foam material;

FIGURE 3 is a fragmentary, perspective, partially broken, enlarged view of another embodiment of radiator core utilizing corrugated passage means intermediate the exterior heat radiating surfaces of the radiator construction;

FIGURE 4 is an enlarged, fragmentary, horizontal sectional view of a further embodiment of capillary radiator mechanism wherein the capillary passages are formed by generally vertically extending tubular members sandwiched between the side heat radiating plates or surfaces of the radiator construction;

FIGURE 5 is an enlarged, fragmentary, horizontal sectional view of a radiator mechanism illustrating another form of construction of the capillary core and more particularly a construction wherein the outer heat radiating plates or members of the radiator construction are provided with hemispherical dimples therein which form spacing means between the radiating plates defining the capillary passages;

FIGURE 6 is an enlarged, fragmentary, horizontal sectional view of a further embodiment of radiator mechanism utilizing interlocking spacer partition means to define the capillary passages in the core.

FIGURE 7 is an enlarged, fragmentary, horizontal sectional view of a further embodiment of radiator mechanism utilizing corrugated radiating panels and corrugated intermediate spacer means;

FIGURE 8 is a fragmentary, perspective, diagrammatic view of a radiator mechanism which is flexible and formed of for instance quilted metal foil for giving flexibility to the radiator core;

FIGURE 9 is a diagrammatic plan view of a capillary radiator mechanism formed in accordance with the invention and wherein the radiator mechanism comprises a plurality of sections which are foldable with respect to one another permitting the radiator to be reduced to a more compact sized unit;

FIGURE 10 is a diagrammatic illustration of one portion of the FIGURE 9 fan type radiator folded into compact condition;

FIGURE 11 is a diagrammatic illustration of a capillary radiator construction of accordian-like structure so that the radiator mechanism can be disposed in compact or reduced size condition; FIGURE 11 discloses the radiator in unfolded condition on the left-hand side and in a folded condition on the right-hand side thereof;

FIGURE 12 is a diagrammatic illustration of a roll-up type capillary radiator formed in accordance with the present invention;

FIGURE 13 is a perspective, fragmentary, diagrammatic illustration of another type of capillary radiator mechanism in accordance with the invention;

FIGURE 14 is an enlarged, fragmentary, sectional view taken generally along the plane of line 14—14 of FIGURE 13 looking in the direction of the arrows;

FIGURE 15 is an enlarged, fragmentary, horizontal sectional view of a capillary type radiator of the general

type disclosed for instance in FIGURE 13, but also including subheader tubes adapted for communicating with the main header tubes and communicating with the capillary passage means of the capillary core, for increasing the flow of heat transfer medium through the radiator mechanism, and with the subheader tube being encased in an armored coating or layer for preventing puncturing thereof by meteoroid particles;

FIGURE 16 is a reduced size diagrammatic illustration of the fluid circulation through a capillary radiator mechanism constructed in accordance with the instant invention and illustrating diagrammatically an arrangement whereby peripheral arterial headers may be eliminated in the capillary core panels by the flow pattern of the heat transfer medium as illustrated through a central header;

FIGURE 17 is an enlarged diagrammatic horizontal sectional view of a capillary radiator mechanism and illustrating diagrammatically a puncture therein occasioned for instance by a meteoroid particle passing through the capillary core;

FIGURE 18 is an enlarged size, horizontal, sectional, fragmentary illustration of a capillary radiator mechanism in accordance with the invention and having a coating on the exterior heat radiating surface thereof for aiding in preventing egress of the heat transfer medium or fluid from the radiator core in the event of penetration or rupture of the capillary core by meteoroid particles;

FIGURE 19 is a perspective view of a generally star shaped capillary radiator mechanism formed in accordance with the invention, and wherein the supply and return headers are combined in a central header system with ingress and egress of heat transfer liquid occurring at one end thereof, to eliminate the need for peripheral supply and return headers;

FIGURE 20 is an enlarged cross-sectional view taken generally along the plane of line 20—20 of FIGURE 19, looking in the direction of the arrows, and illustrating generally diagrammatically the internal construction of the FIGURE 19 capillary radiator mechanism;

FIGURE 21 is a longitudinal sectional diagrammatic illustration of a heat pipe mechanism incorporating the capillary radiator construction therein, to provide a self contained closed circuit unit for circulating and cooling heat transfer liquid;

FIGURE 22 is a diagrammatic, partially sectioned, elevational view of a capillary radiator mechanism in conjunction with another embodiment of heat pipe mechanism;

FIGURE 23 is a diagrammatic illustration of another embodiment of heat pipe mechanism combined with the capillary radiator mechanism;

FIGURE 24 is an enlarged, sectional view taken generally along the plane of line 24—24 of FIGURE 23 looking in the direction of the arrows, and illustrating the vapor and liquid flow in the mechanism.

Referring now again to the drawings, the capillary radiator mechanism of the invention may comprise one or more means 10 forming capillary passages through which the heat transfer medium or liquid is adapted to flow, and with such capillary passage matrix being enclosed by exterior radiating surfaces which transfer the heat from the heat transfer liquid to the surrounding space after which the heat transfer liquid flows back to the mechanism that is being cooled by the heat transfer liquid. FIGURE 1 diagrammatically illustrates a conventional system including a pump 11, the heat exchanger mechanism 12 (FIGURE 1) that is to be cooled by the heat transfer liquid, and such as, for instance, an engine or power unit of some general type for powering a space vehicle, and a radiator mechanism 14 with which the present invention is particularly concerned. The radiator mechanism 14 may have an enclosing housing or collar 16 of any desired configuration open at the front 16a and rear 16b thereof, so as to expose

the heat radiating surfaces of the radiator core 10 which may be of the type illustrated for instance in FIGURE 2. The inlet 18 to the radiator core may pass through the housing 16 wherein the heat transfer medium or liquid flows through the capillary passages in the core 10, after which the heat transfer medium exits at exit 20 through the collar or housing 16.

Since this radiator mechanism is particularly adapted for use on for instance vehicles which may be used in outer space at temperatures and pressures completely different from those found here on earth, the heat transfer medium or liquid is contemplated as being selected from an alkali metal or mercury, instead of the conventionally utilized water as found here on the planet earth. Such alkali metals, as for instance potassium, sodium and lithium are known good conductors of heat and have melting points varying from for instance a  $-38^{\circ}$  F. for mercury to  $357^{\circ}$  F. for lithium, to boiling points of  $674^{\circ}$  for mercury to  $2437^{\circ}$  for lithium. Since in space, penetration of a radiator by meteoroids and more particularly micrometeoroids presents considerable hazard to loss of the heat transfer medium, the present invention with its capillary flow passages will prevent the loss of any material amount of heat transfer medium in the event of a puncture of the radiator core by meteoroid particles. It has been decided that large punctures by meteoroids are relatively unlikely and that most of the hazard lies in high frequency punctures by micrometeoroids. The present invention permits the penetration of the radiator core by meteoroid particles without material loss of heat transfer medium or liquid from the radiator.

The choice of the size of the capillary passageways for the radiator mechanism depends on balancing the surface tension of the heat transfer fluid against the internal pressure which is imposed partly by the vapor pressure of the heat transfer medium and also by the pumping action of the pump mechanism (e.g. 11) of the cooling system.

FIGURE 17 diagrammatically illustrates a capillary radiator core construction consisting of exterior or defining heat radiating surfaces or plate members 22 and 24 defining capillary passageway means 26 therebetween. As illustrated, a micrometeoroid particle has perforated the radiator core and produced a rupture thereof as at 28. However, due to the capillary action, little loss of the heat transfer liquid or medium in capillary passage 26 occurs. The nature of the meniscus of the heat transfer liquid at the break 28 in the radiator depends primarily on two factors: first, the degree of wetting of the material of the radiating plates 22, 24 by the heat transfer liquid, such as for instance, the aforementioned mercury, and second, the behavior of the liquid at the sharp corners or surface discontinuities produced by the break 28. Although the usual contact angle  $\theta$  between the heat transfer medium or liquid and the radiator core composition may be less than  $90^{\circ}$ , the meniscus of the heat transfer liquid at the break will tend to be convex because, first of all, the pressure in the liquid is higher than the pressure externally of the radiator, and secondly, the liquid generally will not climb over a break in the enclosing capillary surface, and hence the contact angle of the liquid with the defining surface of the enclosing capillary passage will generally be greater than  $90^{\circ}$  and as shown for instance in FIGURE 17.

The equilibrium diameter for which the force of surface tension of the liquid just balances the force of fluid pressure in a capillary passage may be determined by the equation

$$\delta_e = \frac{\sigma \cos \theta}{3P}$$

where,  $\delta_e$  is the equilibrium capillary diameter in inches;  $\sigma$ , is the surface tension of the fluid in pounds per foot; and P is the pressure of the fluid in pounds per square

inch gage. As above discussed, the contact angle,  $\theta$ , is between 90 and 180 degrees. A judicious choice of contact angle when determining suitable capillary diameters, may be approximately 120°. A suitable figure for surface tension when for instance lithium is utilized as a heat transfer medium, would range between 0.022 and 0.024 pound per foot.

A radiator mechanism based on the capillary concept of this invention must generally be a relatively low pressure system in which the combined header and vapor pressures must remain below about 10 p.s.i.a. At temperature below 700° F. the vapor pressure of the heat transfer liquid (e.g. lithium) may be ignored relative to the header pressure in the radiator mechanism. Therefore, in the above equation, P is taken as the radiator header inlet pressure. Accordingly, it has been determined that the capillary diameter for the aforesaid types of heat transfer medium preferably range between approximately 0.1 inch to 0.001 inch.

While the impact of meteoroids on the radiator core and penetration thereof carry away a certain amount of the heat-transfer medium or liquid due to passage of the meteoroid particles through the heat transfer medium, the great majority of liquid losses will be the result of vaporization to space. Because of the sporadic nature of meteoroid bombardment, avoidance of the high-frequency impacts by retracting or folding the radiator mechanism into a more compact package may be possible. This feature will be hereinafter discussed in greater detail.

Because the capillary radiator is predicated on fluid retention by surface tension, good wetting between the heat transfer medium or liquid and the containment material of the radiator core is required. This is because the capillary arrangement concept is based in part on the capillary transfer or pumping of the fluid within the capillary passages, and secondly, heat transfer to the radiating surfaces or members of the radiator core is dependent on the degree of wetting between the heat transfer liquid and the radiating plate material (e.g. 22, 24 FIG. 17) of the core. Materials such as iron, beryllium, columbium, molybdenum, 316 and 340 steels, tantalum and titanium are considered satisfactory for the radiating plate materials.

Referring now to FIGURE 2, there is shown an embodiment of capillary radiator core comprising an inner layer 30 of foam metal which has a network of capillary passages therethrough disposed in completely random communicating fashion. Such inner layer 30 may be formed of foam metal or metallic oxides of known types and is of relatively low density to provide for substantial capillary flow therethrough. Foam metals can be produced with pore sizes ranging from 0.8 inch to a few microns corresponding to from 2 to 75 percent of the density of the solid metal. Examples of suitable metallic foams are stainless steel foam, titanium foam and columbium foam, and suitable metallic oxides are alumina and zirconia. The inner layer 30 may be sandwiched between spaced outer layers 32 which may be formed of a relatively high density metal foam or metal oxide layers, and with such inner layer 30 being bonded, as by metallurgical bonding, at its confronting faces with the high density layers 32. Layers 32 are bonded to the high density heat radiating layers or plate members 34, which are adapted as aforesaid to transmit the heat from the heat transfer medium passing through the capillary passages of the capillary layers 30 and 32, to the surrounding atmosphere or space. The exteriors of the radiating plates 34 are preferably burnished or coated so as to make them fluid tight against the passage therethrough of the heat transfer liquid. The use of a foam metal or ceramic matrix affords tremendous advantages for providing capillary suspension and transmission of heat transfer fluids in a capillary radiator mechanism, and affords a high degree of invulnerability against adverse effects of meteoroid penetration damage.

While from FIGURE 2 and due to the necessity of illustration it might appear that the radiator core 10 is of substantial thickness, it is generally preferable that the overall thickness of the radiator be kept to a relatively small dimension. In those embodiments wherein the radiator comprises a single capillary matrix sandwiched between two outer radiating plates, the overall thickness may be for instance 0.105 inch, with the radiating plates 22, 24 (FIG. 17) being for instance 0.01 inch thick. In those embodiments wherein the radiator mechanism is highly flexible, the radiating plate thickness might be approximately 0.001 inch with the overall thickness of the radiator core being approximately 0.087 inch.

FIGURE 3 discloses another embodiment of capillary radiator comprising corrugated spacer members 38 sandwiched between radiating plate-like members 40. The corrugations in the corrugated members 38 provide the capillary passages through which the heat transfer liquid is adapted to flow, and into engagement with the exterior radiating plates 40, for cooling the heat-transfer medium. In the embodiment illustrated, a plurality of layers of corrugated members are shown with a dividing intermediate plate member 42 separating the capillary passages of the corrugated plates. All of members 38, 40 and 42 are preferably bonded together into an integral unit.

FIGURE 4 discloses a capillary construction utilizing tubular members 46 disposed between and preferably bonded to radiating plate members 48 to define the capillary passages 50 therebetween, thus providing an effective capillary radiator mechanism. It will be understood that the surfaces 48a of the plates 48 are adapted to cool the heat transfer medium flowing in passages 50.

FIGURE 5 discloses an embodiment wherein no separate intermediate spacer means is utilized, but instead the radiating plates 52 are provided with indentations or inwardly directed generally hemispherical shaped embossments 54 thereon, which coact to form the capillary passages 56 through the radiator structure.

FIGURE 6 discloses a capillary radiator mechanism wherein the exterior radiating plates 58 have generally T-shaped (in plan) projections 60 attached to and extending inwardly from the respective radiating plate, and with there being provided a floating baffle member 62 which is not attached to either of the plates 58, but which comprises a central partition 62a with T-shaped projections 62b extending outwardly from the partition 62a and being disposed in overlapping, generally mating relationship with the stationary projections 60 on the plates 58, to form capillary passages for the pumping by capillary action of the heat transfer medium therethrough. It will be seen that with such an arrangement, the capillary size can vary depending upon movement of the floating central baffle portion 62 of the core.

FIGURE 7 discloses a capillary radiator mechanism comprising exterior radiating plate members 66 having an intermediate spacer 68 which is a generally corrugated or wave-like configuration dividing the space between the radiating plates 66 into capillary passageways. The plates 66 are preferably of corrugated construction as illustrated and spacer 68 may be in floating relation between plates 66.

FIGURE 8 discloses a quilted-type of flexible radiator mechanism wherein relatively thin sheets form the exterior heat radiating members 70, and such sheets are attached such as by spot welding, as at 72, and with the sides of the thin metal sheets being sealed as at 74. The sheets 70 may be thin metal foil formed for instance from columbium. Such an arrangement provides a flexible radiator mechanism, for reducing the concentration of meteoroid penetration and for convenience in packaging and transporting of the radiator mechanism in space.

Other examples of suitable capillary matrices that could be used within spaced panels are laminations of wire mesh screen, interlocking twisted ribbon or wire segments, and fiber metal wicks and sponges.

FIGURE 9 discloses a fan-like foldable radiator comprised of left and right-hand portions 75, 75a, each of which includes a plurality of capillary panel sections 76 extending outwardly from and in communication with a respective header pipe 76a through which the heat transfer medium or liquid is passed from the heating section of the cooling system to the capillary radiator panel mechanism, for cooling of the heat transfer medium. The panel sections 76 have fold line hinge connections 78, and preferably have more or less rigid support rib means 80 for strengthening and stabilizing the radiator arrangement. Such radiator mechanism may be folded into a compact unit as illustrated in FIGURE 10. The header pipes 76a of the fan-type capillary radiator mechanism may be flexible in at least the central portions thereof and as at 81, to enable ready folding of the mechanism.

FIGURE 11 discloses an accordian-type of foldable, capillary radiator mechanism which includes a heat transfer liquid carrying header pipe 82 in communication with and common to all of the capillary panels 83 the latter preferably having support rib means 84, and with such panels being provided with fold lines or means 86, for folding the radiator mechanism from the flat extended condition of FIGURE 11 into the accordian shaped reduced size condition illustrated in FIGURE 11. It will be understood that the header pipe 82 is preferably of flexible material or which may be universally jointed along its lengthwise extent, so that folding of the radiator mechanism can occur without rupturing the header pipe. It will be understood that the capillary panels comprise exterior radiating plates or surfaces between which is sandwiched a capillary matrix, and as aforesaid.

FIGURE 12 discloses a flexible-type of capillary radiator mechanism (such as for instance the type illustrated in FIGURE 8) rolled into a compact bundle, for convenient transporting of the radiator mechanism and avoidance of micrometeoroid concentrations.

FIGURE 13 discloses a capillary radiator mechanism comprising an inlet or supply header pipe or line 88 and a return or exit header pipe or line 90. Disposed intermediate the supply header 88 and the return header 90 and in communication therewith, there may be provided capillary radiator panel members 92 produced in accordance with the present invention or in other words comprising exterior radiating surfaces or panels enclosing a capillary matrix therebetween, and providing for the capillary flow and cooling of heat transfer medium through the radiator mechanism. The heat radiating exterior panels of the radiator may be provided with strengthening ribs 92 formed integral with the panel surface, which rigidify and strengthen the capillary passage spacing between the outer radiating members or plates 94 (FIGURE 14) thereof. The heat transfer medium or liquid flows into supply header 88 through the passages of the capillary means and then into the exit or return header pipe 90.

As shown in FIGURE 15, the capillary panel members may be provided with sub-header tubes 98 communicating with the supply and return headers and with the capillary panels containing the capillary passageways, for aiding in passing the heat-transfer medium or liquid from the supply header to the return header. The sub-header pipes 90 are preferably provided with an armored layer 100 for preventing meteoroid rupture of the sub-header tubes, as are also the supply and return headers 88 and 90.

Referring to FIGURE 16, there is disclosed another embodiment wherein peripheral supply header and the return header pipes have been eliminated, and instead the fan capillary radiator structure utilizes a single centrally-disposed combination supply and return header 102 which communicates with the capillary panels 104 in cooling the heat transfer medium flowing into one end of the supply and return header and exiting at the other end hereof. With dotted lines there is shown the flow of fluid through the capillary structure, and with the capillary panels 104 being divided by partitions 106 extending out-

wardly from the centrally-disposed header, for separating the outward flow of heat transfer liquid from the inward flow. With such an arrangement, circulation and pressure stability might be enhanced by centrifugal action produced for instance by rotating the radiator mechanism about the lengthwise axis of the supply and return header tube 102. It will be seen that the flow of liquid through the capillary panels radiates outwardly from the central header pipe to be exposed to the radiating surfaces of the capillary panel mechanism thus cooling the heat transfer medium or liquid, whereupon it gravitates back or flows by capillary pressure back to the header pipe for transmittal back to the unit being cooled by the heat transfer medium.

FIGURE 18 discloses a capillary radiator mechanism wherein a low specific weight oxide coating 107 covers the exterior radiating plates 22, 24. The outer surface 107a is preferably a high emissivity surface for good heat radiation. Such oxide layer helps retain the heat transfer liquid in the capillary matrix 26 at a meteoroid puncture (e.g. 28) since wetting between the heat transfer liquid and the oxide layer will not occur, and thus the heat transfer liquid is prevented from spreading over the surfaces at the puncture location. Magnesium oxide, calcium oxide, barium oxide and uranium oxide are examples of workable oxides for the coating 107.

FIGURE 19 discloses a capillary radiator mechanism in which supply and return headers are combined in one central header system, comprising a central tube or transmission line 108 which may be closed at one end, say at end 108a, and which may be open at the other end (108b). The tube 108 may be subdivided to a plurality of separate channels (a through h—FIG. 20) and each channel is associated with a pair of capillary panels 110. Each capillary panel has exterior heat-radiating surfaces 110a, 110b holding therebetween a matrix of capillary passage means 112. A partition 114 extends through the matrix and divides each panel into an outward and inward path for the capillary flow of heat-transfer medium there-through. For instance, channel a may be an inlet channel wherein the heat transfer medium flows into the channel then up through along the capillary passage means between radiating surface 110b and partition 114, then back down along the capillary passage means intermediate partition 114 and radiating surface 110a, and then into channel b for outflow of the heat transfer medium. While the radiator mechanism illustrated has been shown in the form of a star in cross-section, it will be understood that it could be formed in other shapes.

FIGURE 21 illustrates a heat pipe mechanism in conjunction with the capillary radiator means. The combined heat pipe-capillary radiator is a device that utilizes latent heat of vaporization of a liquid to transfer heat along its length, and capillary pumping to circulate the heat transfer liquid. The arrangement illustrated in FIGURE 21 comprises a closed cylinder 120 into which an annular wick 122 of capillary construction is fitted. Wick 122 is saturated with heat transfer liquid. When one end, say for instance end 102a of the tube is heated by some suitable heating means 124 as for instance by a motor unit being cooled, evaporation initiates surface tension forces that draws additional heat transfer liquid into the heated portion 132 of the capillary core of wick 122. The vapor flows longitudinally through the passage 134 of the heat tube (as illustrated by the wavy lined arrow) and the vapor condensing at the cooled end of the heat tube replenishes the supply of heat transfer medium or liquid in the wick. Cooling of the heat transfer medium occurs at the end 135 of the tube, and the cooled heat transfer liquid flows back in the direction of the straight-line arrows to the heated end of the tube, and in a continuous closed cycle. It will be seen that such arrangement is in effect a self-contained capillary pump, and that such mechanism may be punctured by meteoroid penetration without any material loss of the heat transfer liquid.

FIGURE 22 discloses a heat pipe-capillary radiator mechanism of the general shape of an axially elongated torus. Such radiator mechanism comprises a hollow, axially elongated donut-shaped housing 136 defining a vapor cavity 136a therein, with the housing comprising outer radiating surface 138, and with there being provided a capillary passageway layer 140 extending about the interior surface of the housing. A source of heat 142, which in the embodiment illustrated is of elongated generally-cylindrical configuration, is disposed within the opening 144 through the housing, and is in close contact with the surface thereof, whereby the heat is transmitted through the housing 136, to cause evaporation of the heat transfer medium or liquid in the capillary wick layer 140, thereby causing evaporation. The vapor travels through the vapor passage cavity into contact with the wick layer on the outer radiating wall of the housing to be cooled, and flows by capillary pumping action back to the heated portion of the housing. The surface 138 radiates the heat from the heat transfer liquid outwardly to space.

The vapor pressure in the mechanism is determined by the temperature of the coldest wall and it is assumed that the mean free path of the vapor molecules is small compared to the dimensions of the vapor cavity. The molecules should, therefore, suffer sufficient collisions to insure thermostability to ambient velocities corresponding to the temperature of the coldest wall. Therefore, although evaporation at the core is copious, the rate of vapor escape at meteoroid puncture sites can be maintained at low tolerable levels by suitable temperature gradients in the vapor cavity. Accordingly, the condenser-to-evaporator area ratio can be made suitably large.

FIGURES 23 and 24 illustrate another type of heat pipe-capillary radiator mechanism comprising a heated core 146 which is adapted for attachment to a source of heat or other equipment which generates heat (e.g. 148). Surrounding the core 146 there is an anode 152 and a cathode 154 of a thermionic energy converter, and with the cathode being enclosed with an open-core capillary layer 156 which includes spoke portions 156a extending radially outwardly in axial relation to the heated core to merge with the capillary layer portions 156b engaging the outer radiating surface 160 of the heat pipe, to provide a closed path for the flow of the heat transfer medium or liquid through the capillary portions. It will be seen that the heated core portion causes vaporization of the heat transfer medium as shown in wavy lines, whereupon it flows through the vapor cavities 162 into engagement with the colder portions 156b of the capillary means, whereupon the vapor is condensed into liquid and drawn by capillary action back to the heated portion as shown by the full line arrows in FIGURE 24. The heat from the condensed vapor is radiated from outer radiating surface 160 of the housing.

In all the radiator configurations presented herein and especially in the heat pipe-capillary radiator concept, FIGURES 21, 22, 23 and 24, partitions to guide and channel large elements of liquid and vapor flow are thought to be part of the invention. In the case of the heat pipe combination, for example, either impervious or porous partitions may serve severally to compartmentalize the radiator, to provide structural support, to aid in thermal degradation of vapor and to provide recirculation passages.

Although a number of substances such as the alkali liquid metals and mixtures thereof suitable for use as the heat transfer liquid in a capillary radiator are existent, it should not be construed that those mentioned herein are the sole media contemplated by this invention, for, it is possible to concoct other liquids that possess suitable and perhaps superior properties with reference to the liquids already mentioned. In general, the heat transfer liquid should have low vapor pressure and low value of the quantity

$$\left(\frac{\eta}{c\epsilon\sigma}\right)$$

where  $\eta$  is viscosity in pound-hours per square foot,  $c$  is specific heat in B.t.u. per pound-degree Fahrenheit,  $\epsilon$  is density in pound per cubic foot, and  $\sigma$  is surface tension in pounds per foot. The use of additives of other substances may be used to alter properties in order to meet special requirements and adaptations.

From the foregoing discussion and accompanying drawings, it will be seen that the invention provides a novel capillary type radiator construction which can operate satisfactorily in the event of penetration by meteoroids or like means causing relatively small ruptures of the radiator core material, and also radiator mechanism which is flexible or foldable so that it may be reduced in size if desired for ease in transporting or for reduction in the concentration of meteoroid penetration of the radiator. The invention also provides a combined heat pipe and capillary radiator mechanism, providing a self-contained unit for the cooling of a heat transfer liquid.

The terms and expressions which have been used are used as terms of description and not of limitation, and there is no intention in the use of such terms and expressions of excluding any equivalents of any of the features shown or described, or portions thereof, and it is recognized that various modifications are possible within the scope of the invention claimed.

What is claimed is:

1. In a space vehicle subject to puncture by micro-meteorites, a heat transfer system comprising a heat transfer fluid, a pumping means to circulate said heat transfer fluid and a radiator having a core unit comprising sheet-like members forming capillary passageway means adapted to provide for the flow of heat transfer fluid there-through wherein the diameter of each of the capillary passageways is determined by the formula

$$\delta_e = \frac{\sigma \cos \theta}{3P}$$

where  $\delta_e$  is the equilibrium capillary diameter in inches,  $\sigma$  the surface tension of the heat transfer fluid in pounds per foot;  $P$  the pressure of the heat transfer fluid in p.s.i., and  $\theta$  is the contact angle of the fluid with said sheet-like members at a puncture in said core.

2. A radiator in accordance with claim 1 wherein said core unit is flexible.

3. A radiator in accordance with claim 1 wherein said core unit comprises a relatively thin panel-like capillary matrix which is rollable into a cylindrical bundle.

4. A radiator in accordance with claim 1 wherein said core unit comprises a plurality of core sections, and means movably coupling said core sections together whereby said core unit is foldable.

5. A radiator in accordance with claim 1 wherein said sheet-like members are corrugated forming said capillary passageway means by the corrugations in said sheet-like members.

6. A radiator in accordance with claim 1 wherein said sheet-like members are quilted to define said capillary passageway means therebetween.

7. A radiator in accordance with claim 1 wherein said sheet-like members are dimpled inwardly in confronting locations to define said capillary passageway means therebetween.

8. A radiator in accordance with claim 1 having spacer means between said sheet-like members and in engagement therewith defining said capillary passageway means therebetween.

9. A radiator in accordance with claim 1 including a liquid metal heat transfer fluid selected from the group consisting of mercury, potassium, sodium or lithium.

10. A radiator in accordance with claim 1 wherein said capillary passageway means comprises a foam metal.

11. A radiator in accordance with claim 1 wherein said

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core unit comprises at least two spaced layers of high density metal foam bonded to an inner layer of low density metal foam, the outer surfaces of said high density layers being impervious to fluid passage therethrough.

12. A radiator in accordance with claim 1 comprising a tube-like header means, and said core unit comprising radially-extending panels having capillary passageway means therein communicating with said header means for permitting flow therethrough of heat transfer fluid.

13. A radiator in accordance with claim 12 wherein said radiator in transverse cross-section is of star-like configuration and including partitioning means separating the in and out heat transfer fluid flow into and from said header means.

14. A radiator in accordance with claim 10 including supply header means and return header means communicating therewith for supplying ingress and egress of heat transfer fluid to and from said core unit.

15. A radiator in accordance with claim 14 wherein said supply and return header means are peripherally arranged with respect to said core unit and including sub-header tube means extending between said supply header means and said return header means and communicating therewith and with said capillary passageway means.

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