NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
WASHINGTON, D.C. 20546

OCT 29 1970

REPLY TO
ATTN OF: GP

TO: USI/Scientific & Technical Information Division
Attention: Miss Winnie M. Morgan

FROM: GP/Office of Assistant General Counsel for Patent Matters

SUBJECT: Announcement of NASA-Owned U. S. Patents in STAR

In accordance with the procedures agreed upon by Code GP and Code USI, the attached NASA-owned U. S. Patent is being forwarded for abstracting and announcement in NASA STAR.

The following information is provided:

U. S. Patent No. : 3,490,718

Government or Corporate Employee : GOVERNMENT

Supplementary Corporate Source (if applicable) : NA

NASA Patent Case No. : ~~XLE-3307~~ XLE-03307

NOTE - If this patent covers an invention made by a corporate employee of a NASA Contractor, the following is applicable:
Yes ☐ No ☒

Pursuant to Section 305(a) of the National Aeronautics and Space Act, the name of the Administrator of NASA appears on the first page of the patent; however, the name of the actual inventor (author) appears at the heading of Column No. 1 of the Specification, following the words ". . . with respect to an invention of . . ."

Elizabeth A. Carter

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Enclosure
Copy of Patent cited above

FACILITY FORM 602

N71-14035 (ACCESSION NUMBER)	00 (THRU)
8 (PAGES)	(CODE) 33
(NASA CR OR TMX OR AD NUMBER)	(CATEGORY)

33

Jan. 20, 1970 A. VARY 3,490,718

CAPILLARY RADIATOR

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FIG. 17

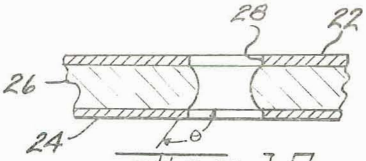


FIG. 2

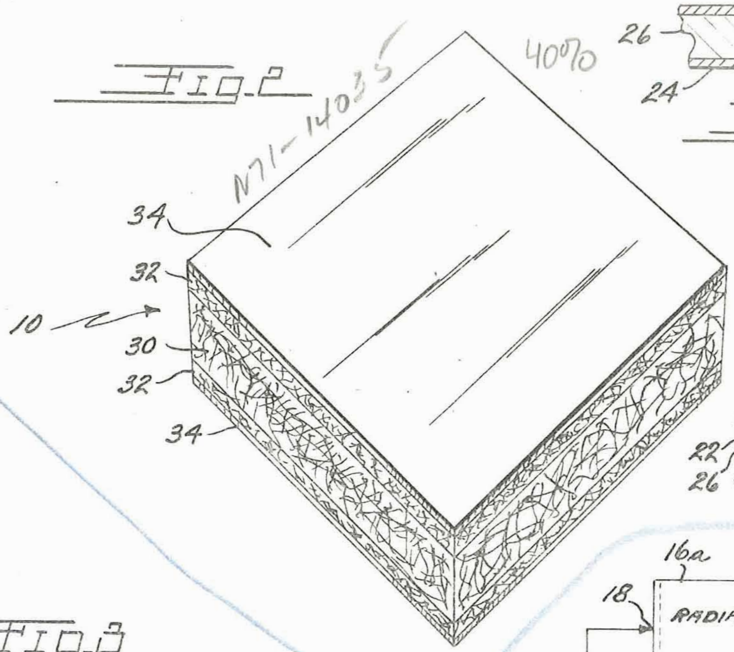
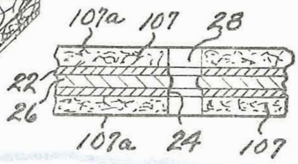


FIG. 18



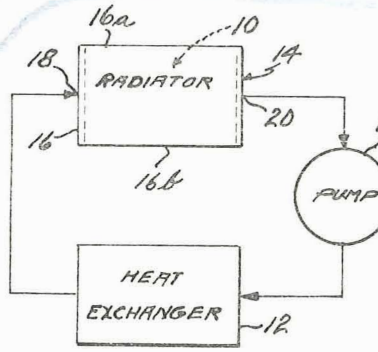
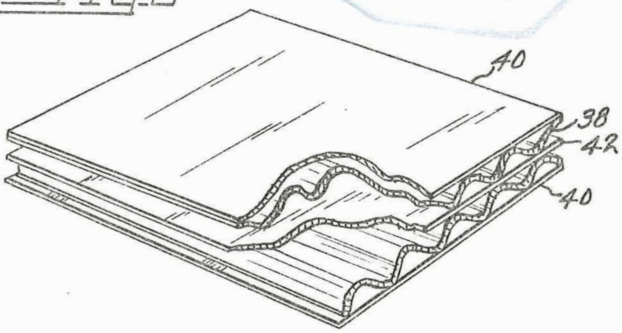


FIG. 1

FIG. 3



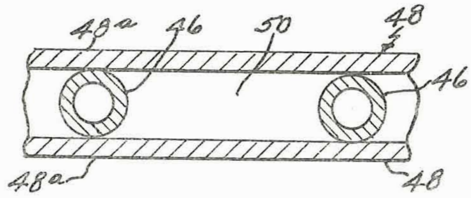


FIG. 4

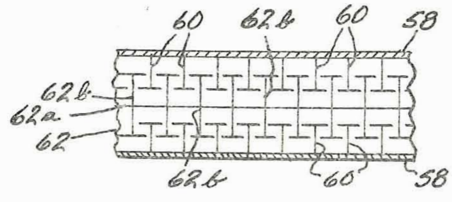


FIG. 6

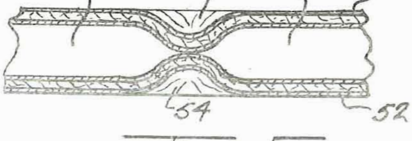


FIG. 5

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CAPILLARY RADIATOR

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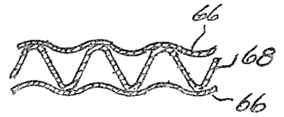

Fig. 7

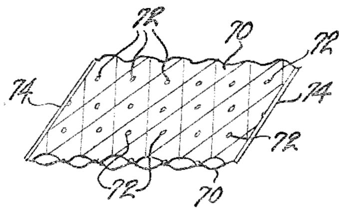

Fig. 8

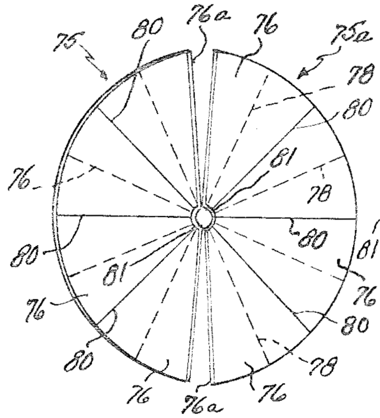

Fig. 9

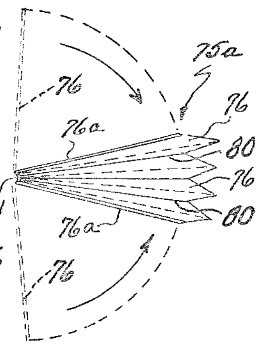

Fig. 10

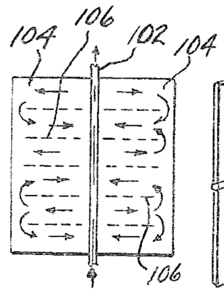

Fig. 16

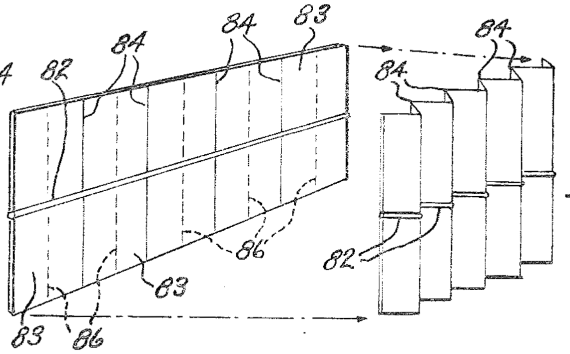

Fig. 11

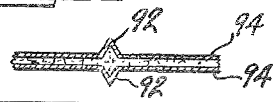

Fig. 14

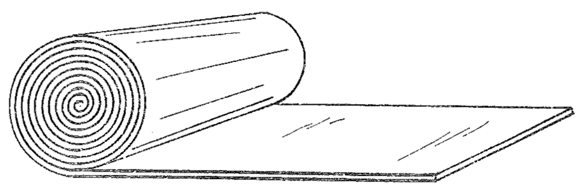

Fig. 12

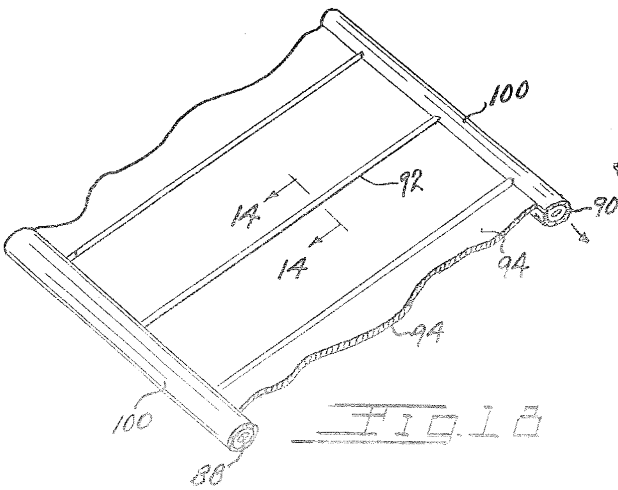

Fig. 13

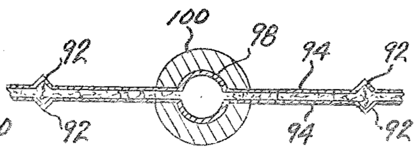

Fig. 15

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CAPILLARY RADIATOR

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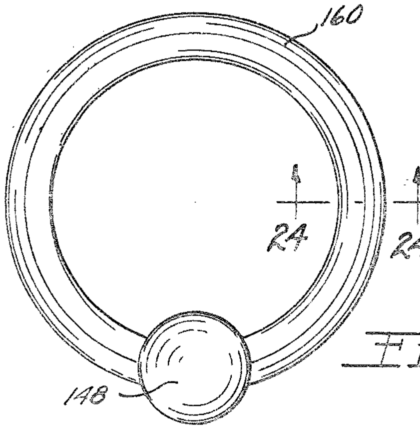

FIG. 23

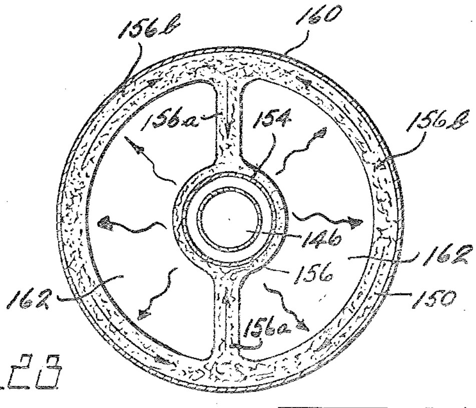

FIG. 24

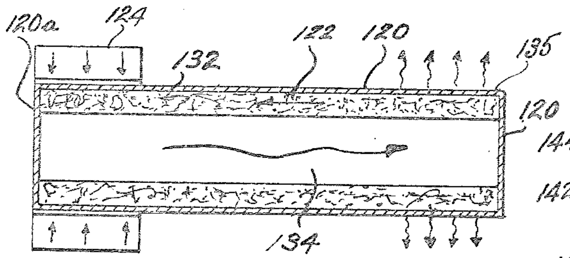

FIG. 21

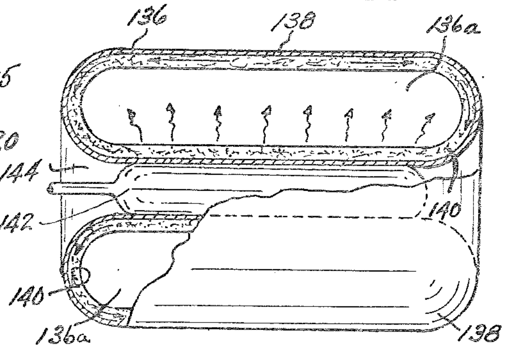

FIG. 22

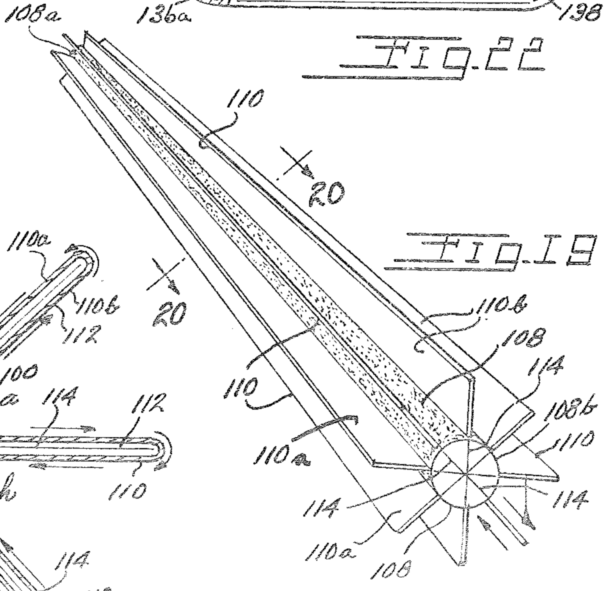

FIG. 19

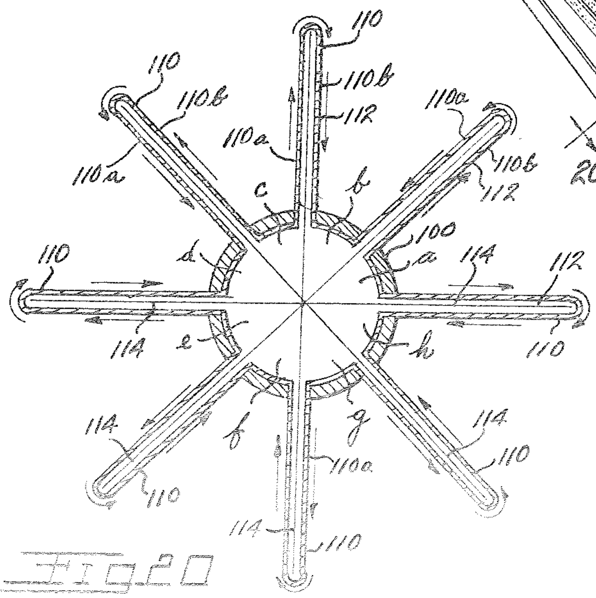

FIG. 20

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United States Patent Office
3,490,718
Patented Jan. 20, 1970

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 core means **10** forming capillary passages through which a 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 **16***a* and rear **16***b* 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° F. for mercury to 357° F. for lithium, to boiling points of 674° for mercury to 2437° for lithium. Since in space, penetration of a radiator by meteroids and more particularly micrometeroids 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 meteroid particles. It has been decided that large punctures by meteroids are relatively unlikely and that most of the hazard lies in high frequency punctures by micrometeroids. The present invention permits the penetration of the radiator core by meteroid 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 θ between the heat transfer medium or liquid and the radiator core composition may be less than 90°, 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° 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, δ_e is the equilibrium capillary diameter in inches; σ, 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, θ, 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 aforediscussed types of heat transfer medium preferably range between approximately 0.1 inch to 0.001 inch.

While the impact of meteroids on the radiator core and penetration thereof carry away a certain amount of the heat-transfer medium or liquid due to passage of the meteroid 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 meteroid 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 aforediscussed 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 invulnerability against adverse effects of meteroid 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 **48***a* 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 **62***a* with T-shaped projections **62***b* extending outwardly from the partition **62***a* 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, 75*a*, each of which includes a plurality of capillary panel sections 76 extending outwardly from and in communication with a respective header pipe 76*a* 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 **76***a* 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 aforediscussed.

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 thin 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 thereof. 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 outwardly 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 **107***a* 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 **108***a*, and which may be open at the other end (**108***b*). 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 **110***a*, **110***b* 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 therethrough. 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 **110***b* and partition **114**, then back down along the capillary passage means intermediate partition **114** and radiating surface **110***a*, 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 **102***a* 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 **136***a* 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 thermodegradation 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 **156***a* extending radially outwardly in axial relation to the heated core to merge with the capillary layer portions **156***b* 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 **156***b* 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 η is viscosity in pound-hours per square foot, c is specific heat in B.t.u. per pound-degree Fahrenheit, ϵ is density in pound per cubic foot, and σ 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 micrometeorites, 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 therethrough wherein the diameter of each of the capillary passageways is determined by the formula

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

where δ_e is the equilibrium capillary diameter in inches, σ 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 θ 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 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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U.S. Cl. X.R.

62—514; 165—105, 107, 168