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[54] **ULTRA LOW TEMPERATURE THERMAL REGENERATOR**

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[73] Assignee: **General Electric Company**

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[52] **U.S. Cl.** **165/10,** 165/32, 62/6, 60/24

[51] **Int. Cl.**.....**F28d 17/00**

[58] **Field of Search** 165/2, 10, 31, 32, 39; 62/6; 60/24

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[57] **ABSTRACT**

Temperatures below 10° K can be achieved operating on a Gifford-McMahon cycle by the utilization of a thermal regenerator having a pressure-regulated helium reservoir positioned within an annulus circumferentially disposed about a helium refrigerant flow channel. Thermal conduction between the cyclically flowing helium refrigerant and the helium reservoir is effected by a plurality of porous metallic plates disposed at a perpendicular attitude relative to the refrigerant flow stream with adjacent plates being separated by thermal insulators, e.g. plastic rings, bonded to the plates to inhibit longitudinal thermal conduction in the regenerator. Preferably the bonded rings are concentrically disposed to form external sidewalls defining the helium refrigerant flow channel and to contain the helium reservoir. Because the helium heat reservoir is situated at a location remote from the channel wherein the helium refrigerant flows, the heat capacity of the reservoir can be varied by adding or removing helium from the reservoir without adversely effecting the helium refrigerant flow through the regenerator.

11 Claims, 7 Drawing Figures

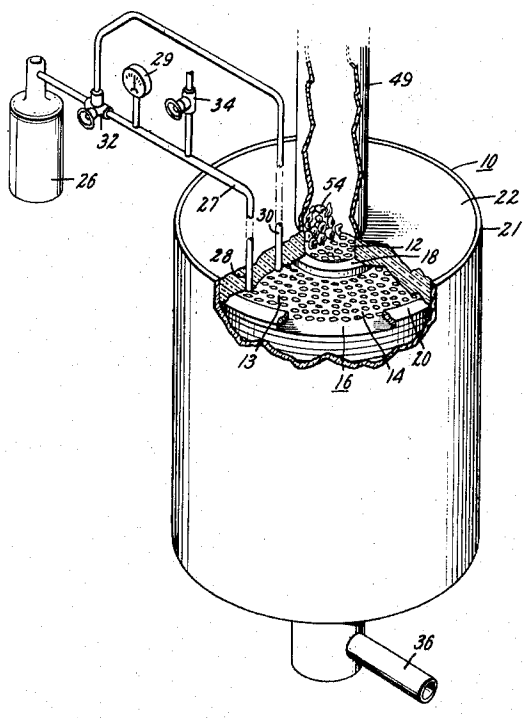

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Fig. 1.

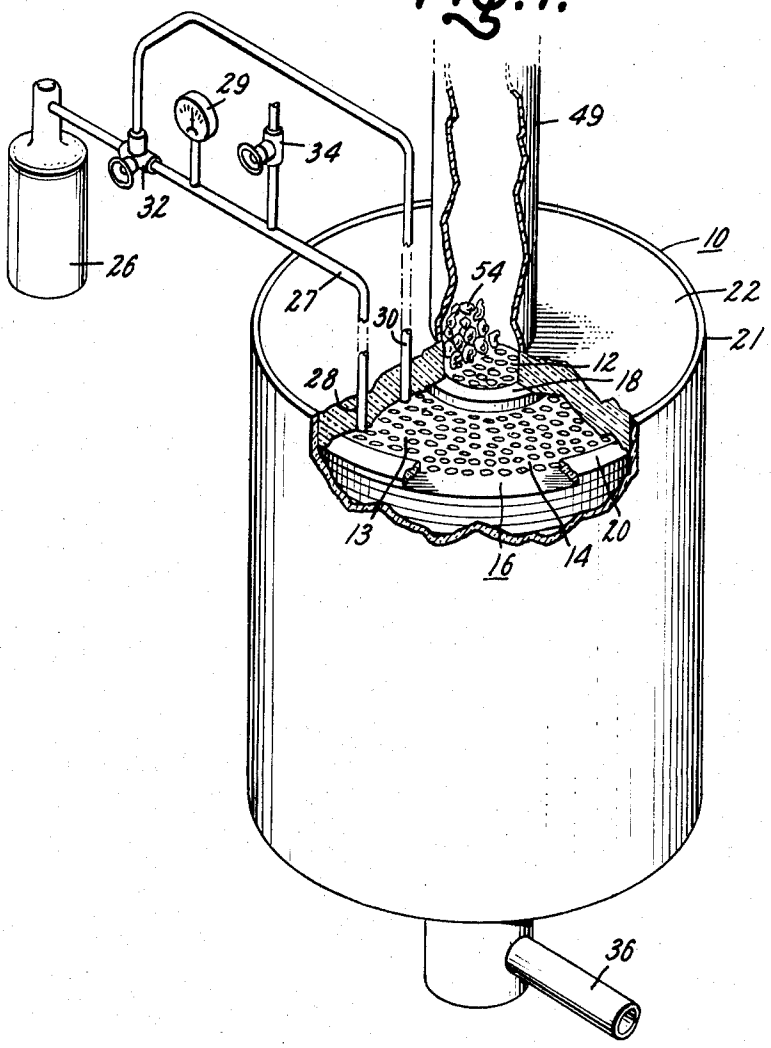

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Fig. 2.

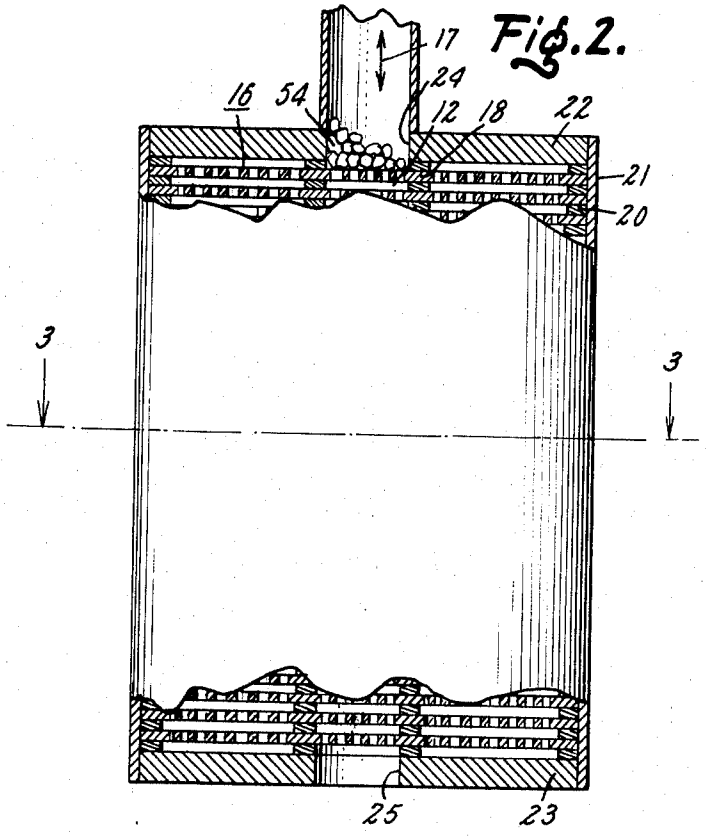

Fig. 3.

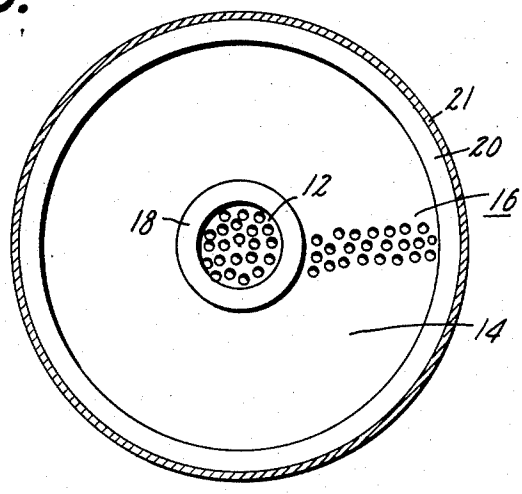

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Fig. 4.

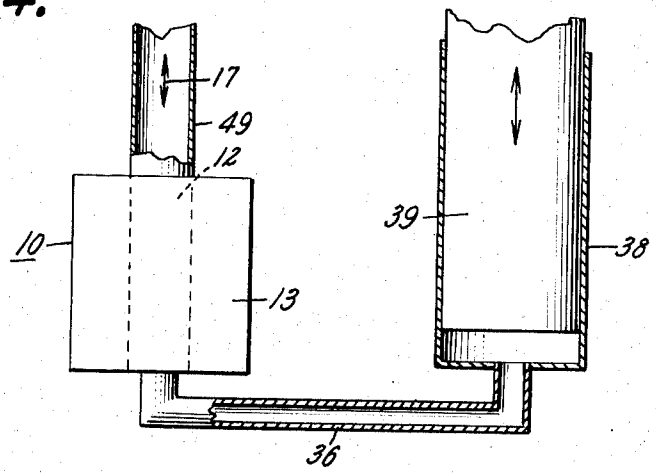

Fig. 5.

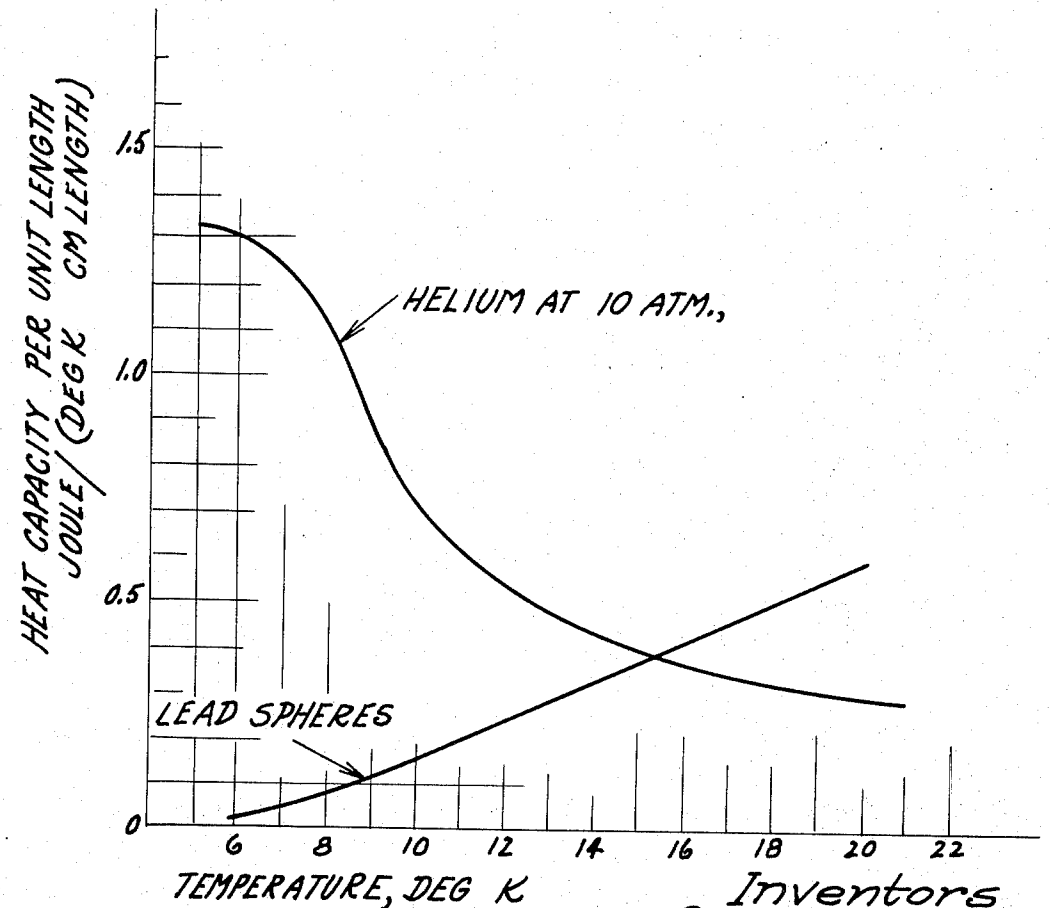

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Fig. 6.

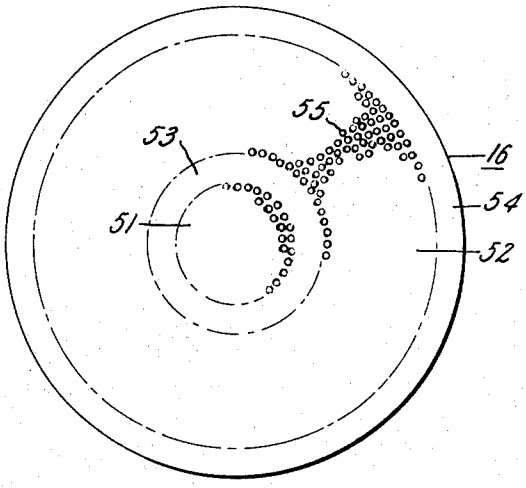
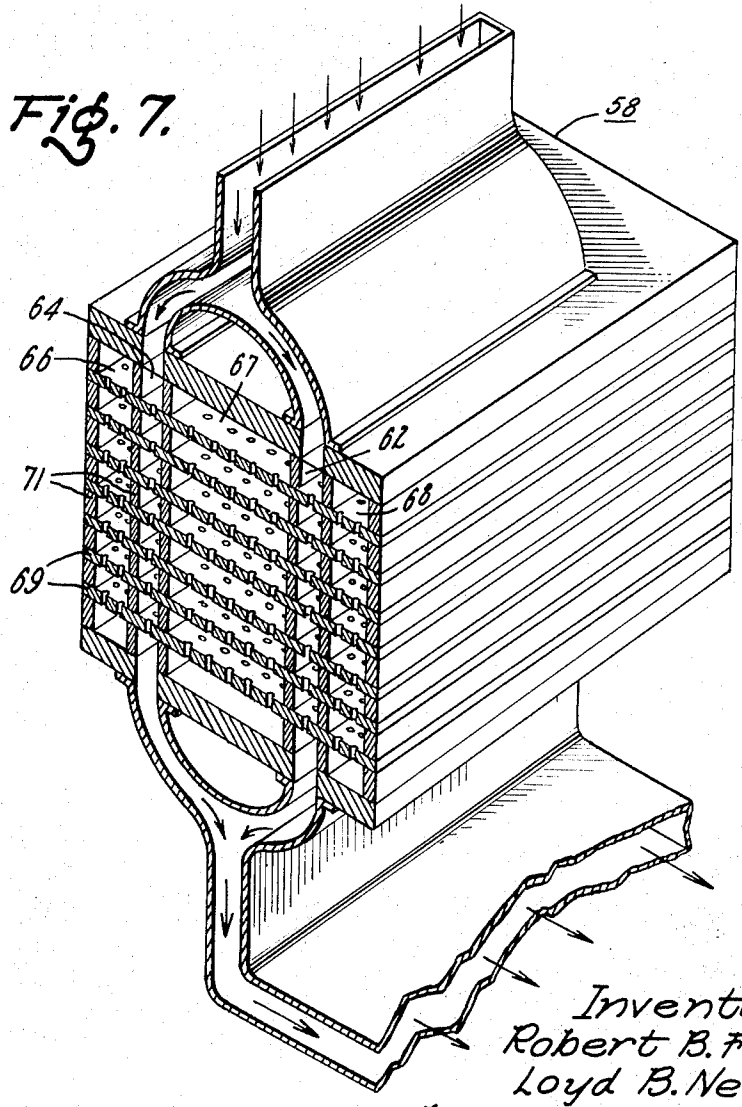


Fig. 7.



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ULTRA LOW TEMPERATURE THERMAL REGENERATOR

This invention relates to thermal regenerators for use in cryogenic refrigerators of the Gifford-McMahon or Stirling variety and in particular to a regenerator utilizing a pressure controlled helium heat reservoir positioned at a location remote from the cyclic flow stream of the refrigerant. The invention herein described was made in the course of or under a contract or subcontract thereunder with the department of the Air Force.

Cyclically operating thermal regenerators of the Gifford-McMahon or Stirling variety generally include a packing material which receives heat from a relatively high pressure fluid stream flowing in a first direction and stores the heat for a short period, e.g., usually less than one second, before transferring the heat back to a lower pressure fluid stream flowing in the opposite direction. Use of a Gifford-McMahon or Stirling refrigerator at temperatures below about 15° K, however, generally has been limited because the heat capacity of conventional packing materials, such as lead, decreases rapidly at cryogenic temperatures thereby severely restricting the ability of the packing material to function properly as a heat storage medium. In attempts to reduce the minimum permissable operating temperatures of cyclically operating regenerators, the heat capacity of helium gas, which has the highest heat capacity of any known substance below about 10° K, heretofore has been employed with limited success. For example, it has been proposed that small diameter helium-filled sealed tubing be positioned within the flow channel of a helium refrigerant stream to serve as a heat reservoir as the helium refrigerant is cyclically surged through the channel. At reduced temperatures however, the helium pressure within the sealed tubes is reduced thereby substantially limiting the heat capacity of each tube for a given volume coil in the flow chamber. Similarly, because the coils are positioned within the flow channel of the refrigerant, the heat capacity of the helium packing coils cannot be varied, e.g., by an increase in the number of coils or coil volume, without adversely effecting the void volume in the refrigerant flow channel, and the packing coils often produce a poor flow distribution in the refrigerant passing therethrough. Furthermore, thermal contact between the flowing refrigerant and the helium within the packing coils is necessarily limited by coil configurations required to effect maximum helium storage within a minimum volume of the refrigerant flow channel.

It is therefore an object of this invention to provide an ultra-low temperature thermal regenerator having an enlarged heat transfer surface in contact with the refrigerant stream.

It is also an object of this invention to provide an ultra-low temperature thermal regenerator having a refrigerant flow independent of the thermal capacity of the heat reservoir employed therein.

It is a further object of this invention to provide a thermal regenerator capable of high efficiency operation at temperatures below 16° K and having limited heat transfer in the longitudinal direction of the refrigerant flow channel.

These and other objects of this invention are accomplished in a thermal regenerator for operation in a Gifford-McMahon or Stirling refrigerator by positioning a helium reservoir at a location remote from the refrigerant flow stream and by regulating the helium pressure within the reservoir to control the heat capacity of the regenerator reservoir. Thus a cyclically operating thermal regenerator in accordance with this invention generally is characterized by a channel for the cyclic flow of a fluid refrigerant therethrough and a remotely situated helium reservoir thermally linked at intermittent intervals to the refrigerant flow stream to sequentially receive, store and transmit heat to the cyclically flowing refrigerant. Heat is transmitted between the refrigerant and the reservoir preferably by a plurality of spaced apart, high heat conductivity metallic plates which form a porous obstruction within the refrigerant flow channel and extend into the helium reservoir to reduce thermal gradients between the flowing refrigerant and the helium reservoir. External means also are provided for controlling the pressure of helium within the regenerator by a variation in the quantity of helium in the reservoir as the temperature of helium in the reservoir changes.

The novel features believed characteristic of the invention are set forth in the appended claims. The invention itself, together with further objects and advantages thereof may best be understood by reference to the following description, taken in connection with the accompanying drawings, in which:

FIG. 1 is a cutaway isometric view of a thermal regenerator constructed in accordance with this invention,

FIG. 2 is a plan view of the thermal regenerator of FIG. 1,

FIG. 3 is a sectional view taken of the thermal regenerator along lines 3—3 of FIG. 2,

FIG. 4 is a simplified partially sectionalized illustration of the thermal regenerator of this invention connected for operation on the coldest stage of a Gifford-McMahon cycle,

FIG. 5 is a graph depicting the low temperature heat capacity of lead spheres and helium at constant pressure, for a particular regenerator design,

FIG. 6 is an enlarged portrayal of the perforated thermal conductors employed in the regenerator, and

FIG. 7 is an isometric view of an alternate thermal regenerator construction in accordance with this invention.

A preferred thermal regenerator **10** constructed in accordance with this invention is depicted in FIGS. **1-3** and generally includes a centrally disposed channel **12** for the cyclic flow of a helium refrigerant therethrough with a relatively stagnant helium reservoir **13** being confined within an annulus **14** circumferentially disposed about the central channel to serve as a matrix material for sequentially receiving, storing and returning heat to the flowing refrigerant. A plurality of porous plates **16** are situated at a perpendicular attitude relative to the cyclic flow direction of the thermal refrigerant within channel **12** (as shown by dual headed directional arrow **17**) and function as hear conductors during regenerator operation to rapidly reduce any thermal gradient existing between the helium reservoir and the flowing refrigerant. Thus the porous plates should be of a material having a high thermal diffusivity, i.e., the thermal time constant (the time required to effect about two-thirds the total temperature change at

the center of the plate in response to a temperature change at the periphery of the plate) should be a small fraction, e.g., less than one-half of the thermal cycle period. To inhibit heat conduction in the direction of refrigerant flow, e.g., along the longitudinal axis of the regenerator, adjacent plates **16** within the thermal regenerator are separated by concentrically disposed insulating gaskets **18** and **20** with interiorly positioned gaskets **18** functioning to form a sidewall separating the helium refrigerant from helium reservoir **13** thereby defining flow channel **12** for the helium refrigerant while externally disposed gaskets **20** serve to form an exterior sidewall for the helium reservoir within annulus **14**. Preferably, annulus **14** has a volume considerably larger than, e.g., at least eight-fold, the volume of central channel **12** to assure a sufficient heat capacity in helium reservoir **13** during regenerator operation. While the thermal regenerator of this invention preferably is disposed within a vacuum during operation and ideally needs no exterior insulation for thermal isolation, an outer sheathing **21** of plastic coating the exterior sidewall of the regenerator can serve as a sidewall mechanical support. Top and bottom plates **22** and **23** having centrally disposed apertures **24** and **25**, respectively, for the passage of helium refrigerant therethrough serve to generally seal the ends of annulus **14** thereby defining the volume of helium capable of being stored by the regenerator.

The interior of annulus **14** is connected to an external source of helium **26** through tubing **27** inserted in aperture **28** within top plate **22** to permit external control of the pressure within the annulus and a pressure gauge **29** is positioned along the length of tubing **27** to permit continuous visual monitoring of the helium reservoir pressure. For automatic regulation of the pressure within annulus **14** to a tollerable lever, e.g., preferably above **5** atmospheres, a suitable sensor **30** is fixedly secured within top plate **23** and extends into helium reservoir **13** to automatically control the operation of value **32** within tubing **27**. Thus external source **26** permits the addition of helium to annulus **14** as the regenerator cools during operation thereby maintaining a reservoir pressure above 5 atmospheres notwithstanding a reduction in the reservoir temperature below 16° K to assure a high heat storage capacity (which capacity is dependent upon helium pressure) for a regenerator of a fixed volume. Suitable means, such as relief valve **34** in tubing **27**, serves to exhaust gas from the helium reservoir upon a heating of the helium thereby avoiding a 60-fold increase in pressure within annulus **14** which would occur if a fixed volume of helium were warmed to room temperature from a temperature of 8° K at a pressure of 10 atmospheres. Valve **32** and relief valve **34** generally do not admit or remove helium from reservoir **13** during pressure fluctuations associated with each thermal cycle of the regenerator but rather respond only after a prolonged period, e.g., a period preferably of three cycles or more, of reservoir pressure outside a set pressure range. Because plates **16** are porous within annulus **14**, a single connection to the annulus through aperture **28** permits pressure control over the entire length of the annulus.

The mode of operation of the thermal regenerator of this invention preferably is in a Gifford-McMahon, or Stirling, refrigerator such as is shown in simplified form in FIG. **4** wherein thermal regenerator **10** is connected through a cross-over tube **36** to an expansion chamber **38**. While FIG. **4** shows only a single, i.e., the coldest regenerator and piston of the refrigerator, in actual practice a plurality of such stages would be cascaded to obtain temperatures below 16° K. A piston **39** is axially disposed within chamber **38** and suitable means (not shown) are connected to the upper end of the piston to reciprocate the piston within the chamber at a convenient rate generally between 100 and 200 strokes per minute. In the operation of regenerator **10**, high pressure helium refrigerant is admitted to the regenerator through conduit **49** connected to channel **12** of the regenerator and piston **39** is raised approximately one-fourth the length of its stroke within chamber **38** whereupon admission of high pressure gas is terminated and the system is sealed. The admission of the high pressure helium refrigerant to channel **12** also effects a heat transfer from the refrigerant to helium reservoir **13** through porous plates **16** to reduce any thermal gradients therebetween. Further upward motion of piston **39** causes a reduction in pressure of the closed system, and a consequent cooling of the gas by adiabatic expansion. The system then is opened above the regenerator and piston **39** is returned to a downward position to exhaust the cooled helium refrigerant through conduit **49**. As the cooled helium flows through the central channel **12** of the regenerator, the heat which had been stored by the helium reservoir **13** within annulus **14** during the admission of the high pressure gas to the regenerator is returned to the expanded helium refrigerant gas and the helium reservoir is further cooled by heat conductivity through porous plates **16** to effect an approximately zero thermal gradient between the expanded exhaust helium refrigerant and the helium reservoir. Upon exhaust of the expanded helium refrigerant from the regenerator, high pressure gas is readmitted to regenerator **10** to repeat the cooling cycle. Thus the temperature of the helium reservoir of the regenerator is incrementally reduced with each cycle until the portion of the reservoir proximate bottom plate **23** reaches a desired lower limit of approximately 6° K. Because a reduction in the helium reservoir temperature tends to lower the reservoir pressure, helium is intermittently leaked into reservoir **13** from source **26** during operation to maintain the pressure of the reservoir at a suitable level of about 10 atmospheres notwithstanding the reduced temperature of the reservoir.

Because the helium within annulus **14** of thermal regenerator **10** must accept heat from the high pressure gas during the initial portion of each cycle and retain the heat until the expanded low pressure gas passes in the opposite direction through channel **12** of the regenerator, a high heat capacity per unit length of the regenerator is desirable to limit the size of the regenerator and the heat losses associated therewith. As will be noted from FIG. **5** wherein the heat capacity per unit length of both helium at **10** atmospheres and lead is depicted, the thermal capacity of lead drops swiftly at temperatures below 16° K to an order of slightly above zero at 6° K generally negating the utilization of conventional lead packed regenerators at temperatures below 16° K. Helium at constant pressure

however shows a generally rising heat capacity with decreasing temperatures and, in fact, shows an approximately two-fold increase in heat capacity between 15° K and 8° K. Because the amount of heat capable of being retained by helium reservoir **13** is dependent upon the density of the helium gas within annulus **14**, the heat capacity of the helium reservoir can be altered simply by an adjustment of valve **32** and/or relief valve **34** to vary the pressure of the helium within annulus **14** without affecting the void volume in channel **12**. Similarly, the heat capacity of helium reservoir **13** can be increased by an outward enlargement of annulus **14** thereby increasing the volume of helium stored within the annulus without producing an adverse effect on the flow of refrigerant through central channel **12**.

Because the heat capacity of randomly packed lead spheres is greater at temperatures above 16° K than the heat capacity of helium at approximately 10 atmospheres, the portion of conduit **49** proximate central channel **12** can be packed with lead spheres **54** to provide increased heat capacity at temperatures above 16° K with helium reservoir **13** within thermal regenerator **10** producing the majority of heat capacity at operating conditions below 10° K. Thus, at 5° K where at the specific heat of helium at 10 atmospheres pressure is about 2.4 joule/g°K, as compared to about 0.0015 joule/g°K for lead, e.g. a ratio of 1,600 to 1, the helium stores 20-fold the quantity of heat stored by the lead per unit volume to effectively negate the effect of the heat capacity of the lead spheres upon the regenerator. At temperatures of 16° K or higher, however, the lead spheres have an appreciable effect on the heat capacity of the regenerator and serve to rapidly reduce the regenerator to cryogenic temperatures.

The porous plates **16** employed in thermal regenerator **10** are shown in FIG. **6** and comprise two annular porous zones **51** and **52** for disposal in the refrigerant flow stream and helium reservoir, respectively. Those portions **53** and **54** of plate **16** to be positioned intermediate insulating gaskets **18** and **20**, respectively, preferably are unperforated to strengthen the bond between the plates and gaskets. Plate **16** generally can be of any material having a high thermal conductivity and a low specific heat with any conventional method such as drilling, punching, etching or the use of sintered matrices of spheres, chips, wires, etc. being suitable to obtain a porous structure through which the cyclically flowing helium refrigerant can pass. Aluminum, copper and sapphire generally are quite suitable as porous plate materials, although aluminum generally is preferred because aluminum is easily worked and bonds well to epoxy plastics. When aluminum is used to form the porous plates in regenerator **10**, preferably insulating gaskets **18** and **20** are fabricated of an inorganic plastic which is bonded to the porous aluminum plates by the use of an epoxy or polyesther adhesive such as EPON resin No. 820 and EPON curing agent V–40. Because both the helium within annulus **14** and insulating gaskets **18** and **20** do not conduct heat very rapidly, heat transfer in the direction of refrigerant flow is impeded and a thermal gradient of about 8° K may be formed between top plate **22** and bottom plate **24** of regenerator **10** during operation. Preferably, the density of plates **16** per unit length of regenerator **10** is high, e.g., greater then 30 plates per cm, to minimize the length of the regenerator while assuring maximum thermal contact between the cyclically flowing refrigerant and the helium reservoir.

Preferably the porous plates **16** exhibit low resistance to heat transfer at cryogenic temperatures, e.g., at 10° K very pure aluminum has a thermal conductivity about 30-fold that at room temperature while exhibiting very little transient "lag" in the cyclical conduction of heat, e.g., at 10° K the heat capacity of aluminum is about 1/700 the room temperature value. Thus, the thermal diffusivity, e.g., thermal conductivity divided by the product of the density and the specific heat, is increased by a factor of about 21,000 relative to the thermal diffusivity of aluminum at room temperature and very rapid temperature changes in the plates can be effected at cryogenic temperatures.

Plates **16** must be thick enough for mechanical strength, but thin enough to provide sufficient heat transfer area. Generally, plate thicknesses in the range 0.1 mm to 0.3 mm can be employed. The thickness of the porous plates and the perforated area of the plates however generally will vary with factors such as the rate of helium refrigerant flow through channel **12** and the tolerable mechanical strength of plates **16** to permit ease of manufacturing and material handling.

The perforations **55** in porous plates **16** preferably should be of high density and small diameter to maximize the heat transfer surface in contact with the flowing refrigerant through channel **12**. However if the metal partitions between perforations become too thin, thermal flow in a radial direction through plates **16** can be impeded thereby adversely affecting the high thermal diffusivity of the metal plate. Plates having between a 30 and 60 percent open area generally have been found to provide good thermal flow while occupying a minimum area. For example, 40 percent open aluminum plates having 8 mil holes exhibit excellent thermal transfer at 8° K while producing negligible pressure drop in a helium refrigerant flowing at the rate of about 3 grams per second through channel **12**. The 40 percent open aluminum plates also are characterized by a uniformly distributed heat transfer surface of 94 sq. centimeters per cubic centimeter of helium in comparison to a heat transfer surface of approximately 5 – 10 sq. centimeters per cubic centimeter refrigerant flow exhibited by coils positioned within the flow channel.

Although the portion **52** of perforated plate **16** within annulus **14** is shown as being apertured, porosity is not essential in the stored helium volume. Porosity however is advantageous not only because the stored volume of helium in annulus **14** is increased but also because of the increase in surface area contact between the plates and the stored helium. The latter advantage is especially noticeable when plates **16** are of substantial thickness, e.g., of a thickness equal to or greater than the hole diameter. To further increase the heat transfer characteristics between the plates and the helium, conventional techniques such as the employment of fins, or a slight rippling in the aluminum plate can be utilized.

When it is desired to reduce the distance along which heat must travel through plates **16** and thereby increase the operating speed of the regenerator, a thermal regenerator **58** of the type depicted in FIG. **7** having

dual rectangular channels **62** and **64** for the cyclic flow of helium refrigerant can be employed. The helium reservoir for the reception, storage and return of heat from the cyclically flowing refrigerant during the regenerator cycle is positioned within sections **66, 67** and **68** to obtain close proximity to, while remaining outside, the refrigerant flow channels. A plurality of porous aluminum plates **69** are disposed at a perpendicular attitude relative to the direction of refrigerant flow within channels **62** and **64** with adjacent plates being thermally separated by and fixedly secured to plastic insulating gaskets **71** which gaskets also serve to define the sidewalls both of refrigerant flow channels **62** and **64** and helium reservoirs **66, 67** and **68**. Ideally each of reservoirs **66, 67** and **68** are communicated with each other as well as an external helium source (not shown) to assure uniformity in the helium pressure (and therefore the heat capacity per unit volume) of each reservoir with central channel **67** preferably having a volume double the volume of end channels **66** and **68**, e.g., double heat capacity, for maximum efficiency.

The regenerator portrayed in FIG. **7** functions in a manner identical to the operation of the regenerator of FIG. **1** except for the fact that the cyclically flowing refrigerant is divided into two channels **62** and **64** in regenerator **58** to reduce the heat transfer interval between the refrigerant and the surrounding reservoirs. It will be appreciated that any number of flow channels and reservoirs in any geometrical configuration can be employed in regenerators constructed in accordance with this invention provided the helium heat reservoir is positioned outside the refrigerant flow channel with heat transfer from the flowing refrigerant to the helium reservoir being effected by a heat conductor in contact with both mediums. We intend, therefore, by the appended claims, to cover all such modifications and changes as fall within the true spirit and scope of our invention.

What we claim as new and desire to secure by Letters Patent of the United States is:

1. In a cyclically operating thermal regenerator for operation at temperatures below 16° K wherein heat from a fluid stream flowing in a first direction is received and stored for a finite period by a helium reservoir prior to transfer of said heat to a fluid stream flowing in the opposite direction, the improvement comprising means for controlling the pressure of helium within said reservoir by varying the quantity of helium in said reservoir as the helium temperature changes within said reservoir.

2. A cyclically operating thermal regenerator according to claim **1** wherein said helium reservoir is situated within a housing externally located relative to said fluid stream flow channel, said thermal contact between said helium reservoir and said fluid streams being effectuated by a high thermal conductivity material protruding through the walls of said helium reservoir housing and extending into both said helium reservoir and said fluid streams flow channel.

3. A cyclically operating thermal regenerator according to claim **1** wherein the helium within said reservoir is at a pressure above 5 atmospheres and at a temperature of below 16° K.

4. A cyclically operating thermal regenerator according to claim **2** wherein said high thermal conductivity material is selected from the group consisting of aluminum, copper, and sapphire, said material being a porous structure disposed substantially uniformly in said fluid streams flow channel to assure uniform distribution of flow at any cross-section of said flow channel.

5. A cyclically operating thermal regenerator according to claim **2** wherein said thermal contact between the reservoir and the flow streams is effectuated by a plurality of porous metallic plates spaced in insulated relationship with respect to one another within the path of said fluid streams at a generally perpendicular attitude to the direction of fluid flow.

6. A cyclically operating thermal regenerator for operation at temperatures below 16° K comprising a channel for the cyclic flow of a fluid refrigerant therethrough, a reservoir containing a gaseous medium, said reservoir being positioned adjacent said flow channel to sequentially receive, store and transmit heat to said fluid refrigerant during a complete flow cycle of said fluid refrigerant, means for controlling the pressure of the gaseous medium within said reservoir by varying the quantity of said medium in said reservoir as the temperature within said reservoir changes, and a plurality of spaced-apart, high conductivity metallic elements spaced in insulated relationship with respect to one another, said elements forming an apertured obstruction within said refrigerant flow stream and protruding through the sidewalls separating said flow channel from said reservoir to extend into said gaseous medium.

7. A cyclically operating thermal regenerator for operation at temperatures below 16° K comprising a channel for the cyclic flow of a refrigerant therethrough, a generally stagnant helium heat reservoir positioned adjacent said channel, and a plurality of porous, high heat conductivity elements disposed within said cyclic flow channel and extending into said helium reservoir to conduct heat between said reservoir and said refrigerant upon the existence of a thermal gradient between said helium and said refrigerant.

8. A cyclically operating thermal regenerator according to claim **7** wherein said refrigerant cyclically flows through a plurality of channels and said helium reservoir is disposed on opposite sides of each of said channels.

9. A cyclically operating thermal regenerator according to claim **7** wherein said heat conductivity elements are a plurality of porous metallic plates disposed at a perpendicular attitude relative to the refrigerant flow, adjacent of said plates being separated both by peripherally positioned thermal insulators and by interiorly positioned thermal insulators, said interiorly positioned thermal insulator functioning to define the sidewalls for said cyclic flow channel and said peripherally positioned thermal insulators functioning to form a sidewall for said helium reservoir.

10. A cyclically operating thermal regenerator according to claim **8** wherein helium in said reservoir is at a pressure above **5** atmospheres at temperatures below 16° K and said plate has between 30 to 60 percent open area.

11. A cyclically operating thermal regenerator according to claim **9** wherein said metallic plates are aluminum and said thermal insulators are a thermoplastic.

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