

July 20, 1965

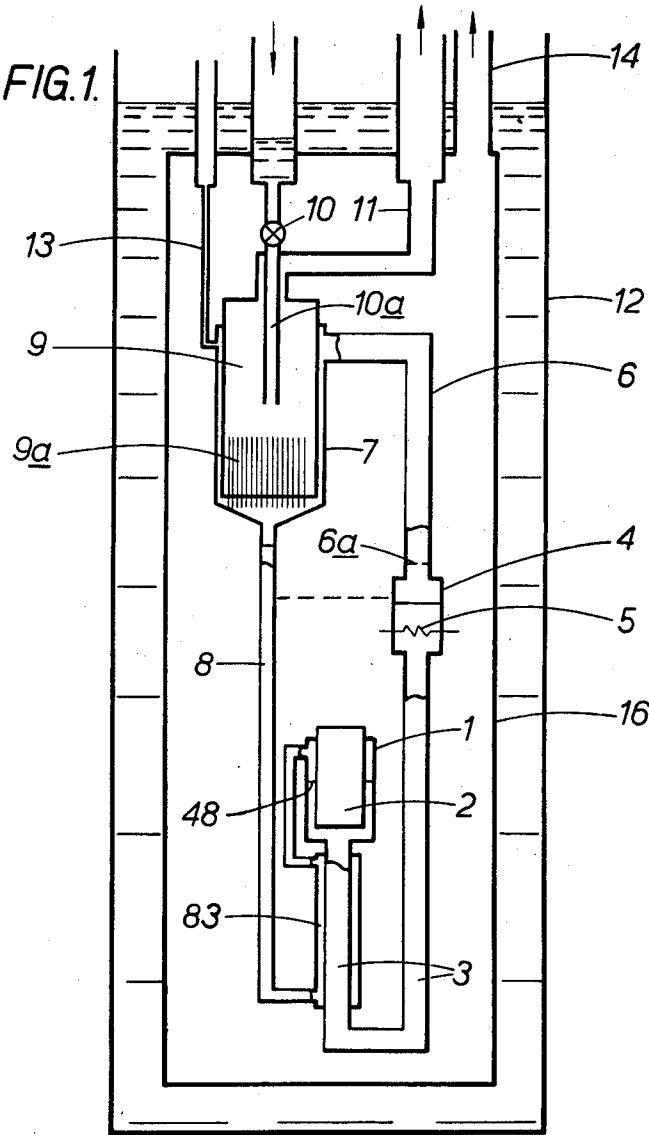
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REFRIGERATOR EMPLOYING HELIUM

Filed Sept. 17, 1962

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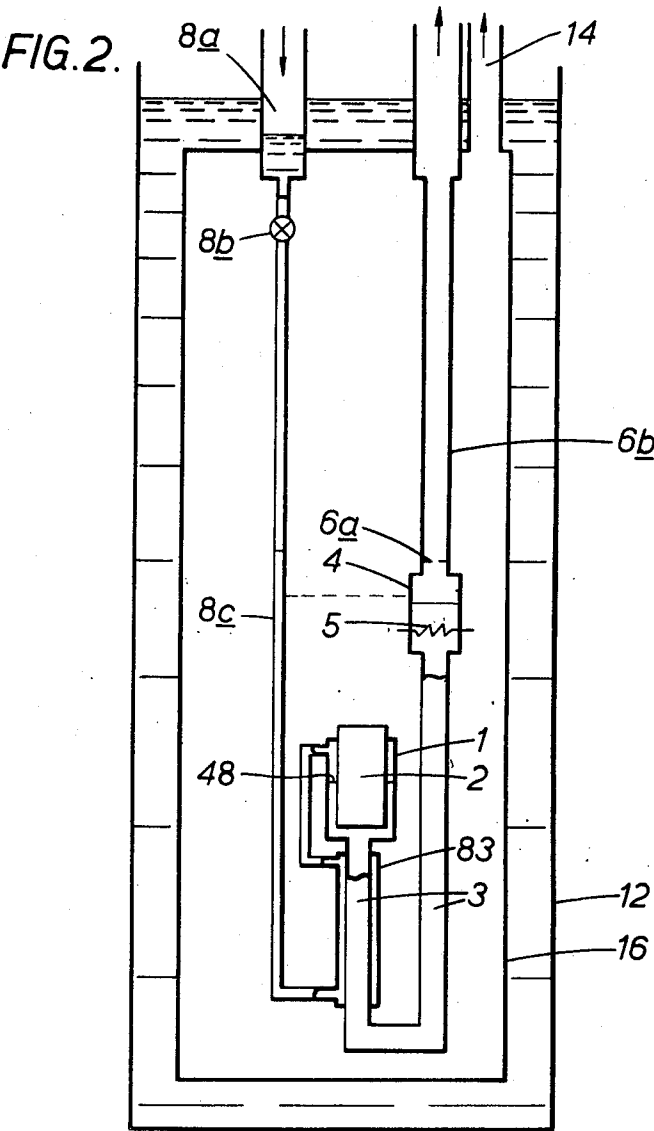
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REFRIGERATOR EMPLOYING HELIUM

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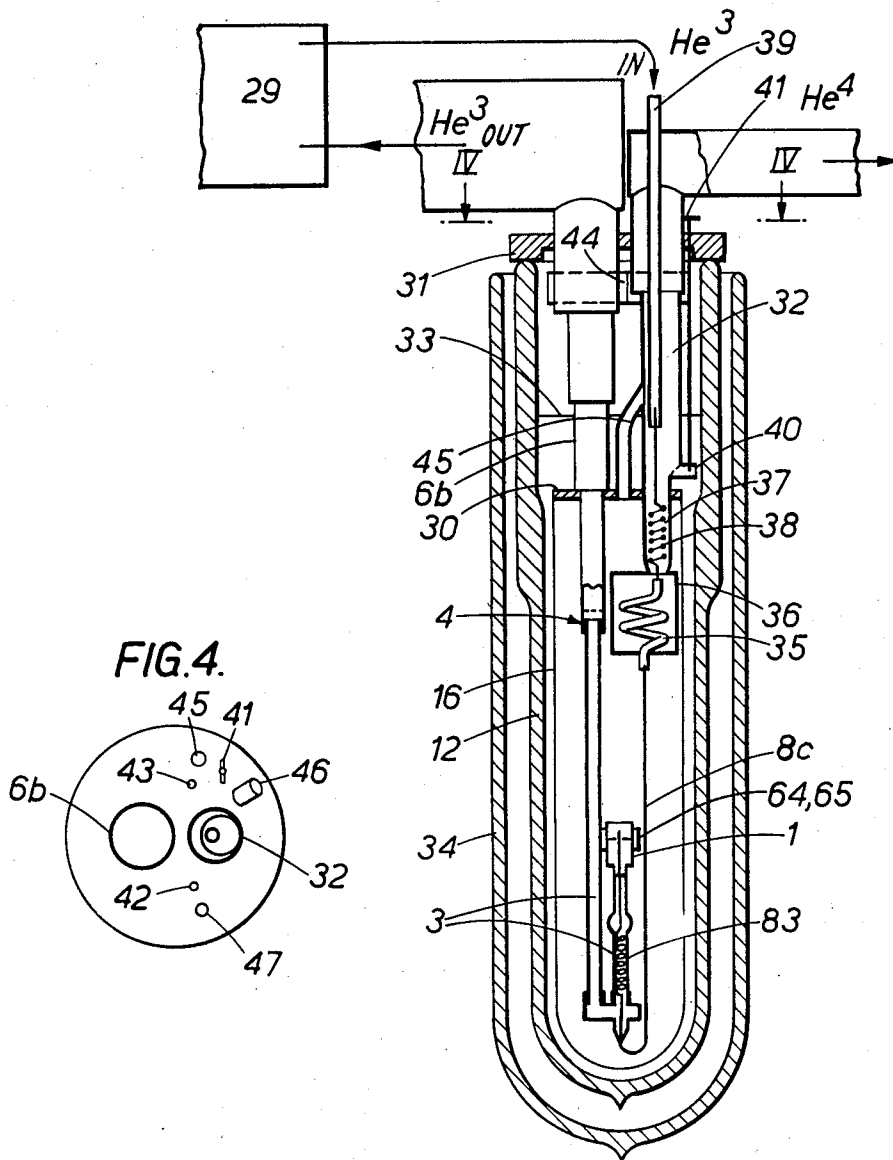
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FIG. 3.



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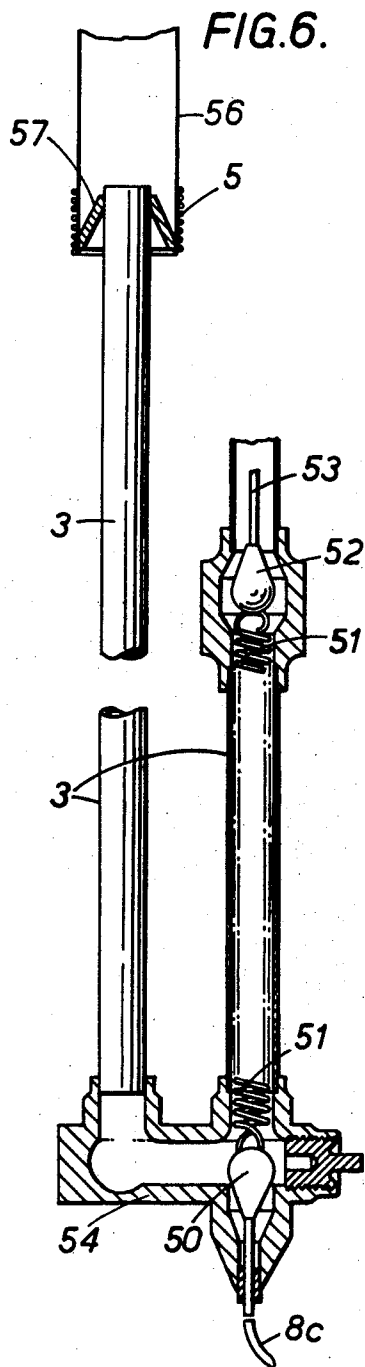
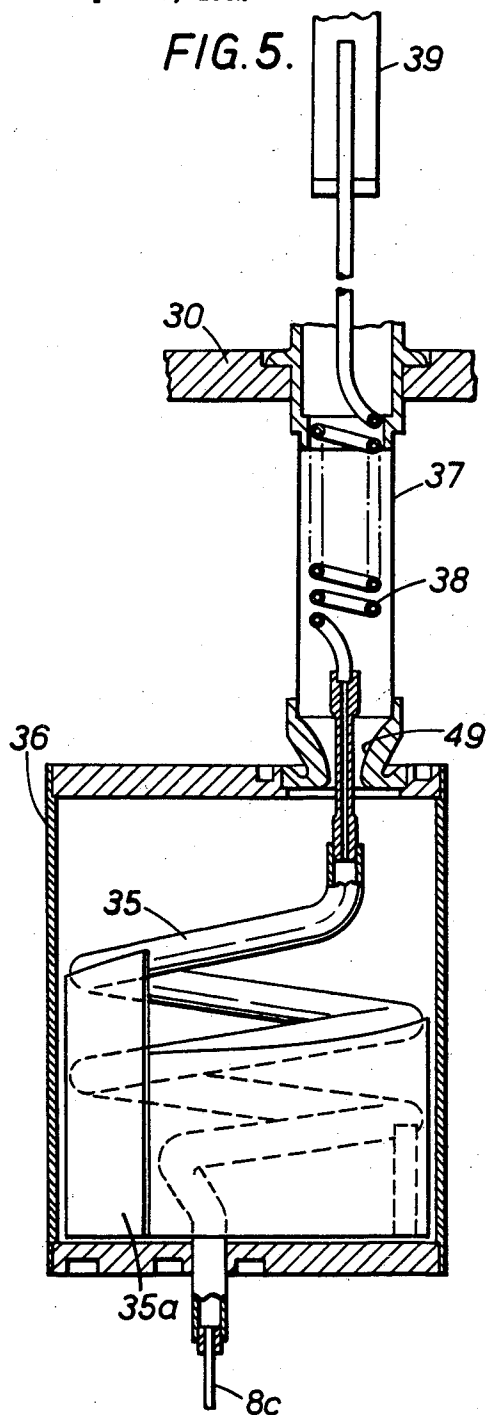
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REFRIGERATOR EMPLOYING HELIUM

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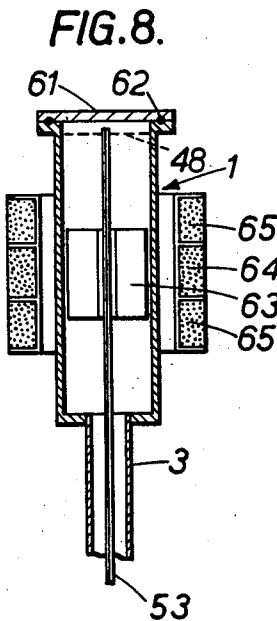
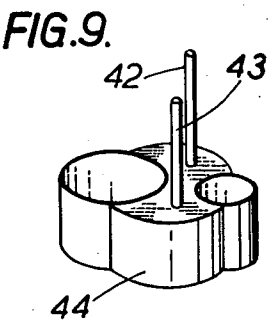
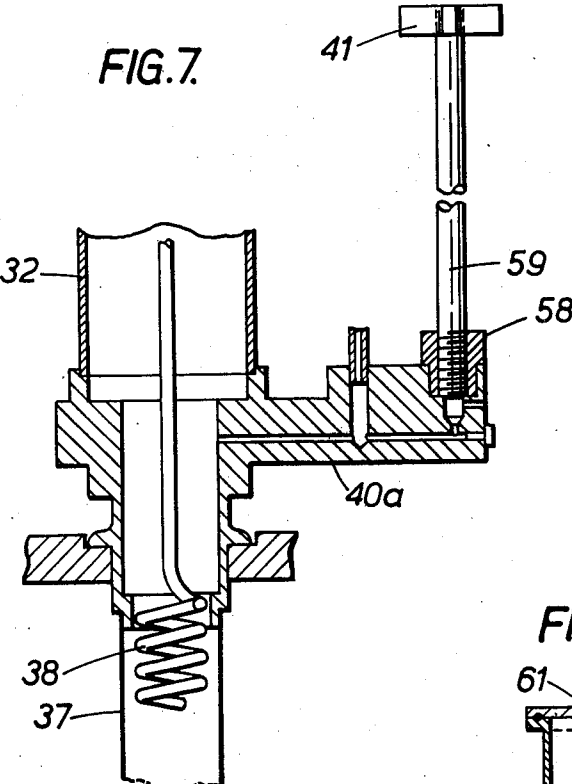
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REFRIGERATOR EMPLOYING HELIUM

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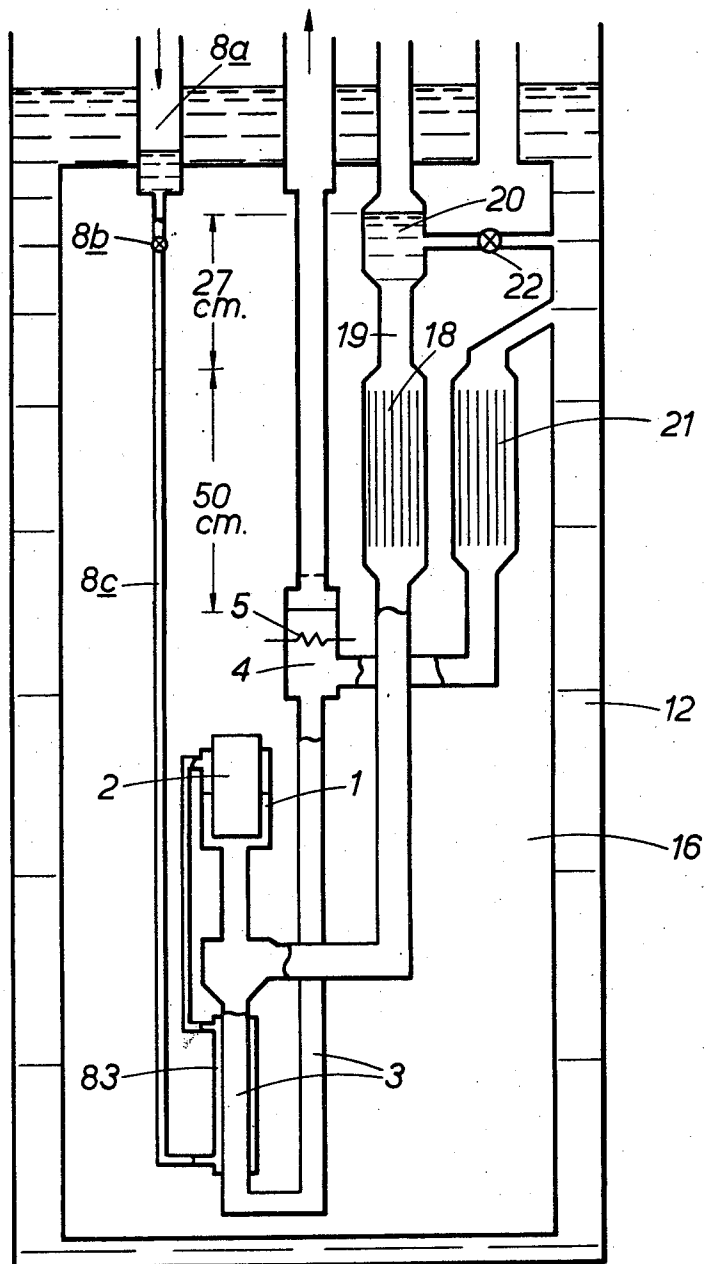
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FIG. 10.



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REFRIGERATOR EMPLOYING HELIUM

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Claims priority, application Great Britain, Sept. 22, 1961,
34,004/61

11 Claims. (Cl. 62—467)

This invention relates to refrigerators.

An object of the invention is to provide a refrigerator capable of operating at and maintaining a temperature lower than can be obtained by the method of evaporative cooling, i.e. a temperature lower than about 0.3° K. below which temperature the vapour pressure of helium 3 is too low for useful cooling by evaporation.

In a refrigerator in accordance with the present invention, a volume of liquid helium 3 is continuously diluted with liquid helium 4, heat being absorbed from a load to provide the heat of mixing.

Very desirably the mixture of helium 3 and helium 4 is subjected to a distillation operation to maintain the proportion of helium 3 below the equilibrium concentration to permit the helium 3 continuously to dissolve in the helium 4. Conveniently the helium 3 removed by the distillation operation is used for subsequent mixing with the helium 4, thereby setting up a closed cycle.

At the temperatures with which the invention is concerned, helium 3 and helium 4 separate into two phases each containing only a few percent of the other isotope, the equilibrium concentration varying with temperature until at absolute zero each phase consists of the pure isotope. At 0.1° K. the phase rich in helium 3 contains about 0.5% helium 4 and the phase rich in helium 4 contains about 2% helium 3. In carrying out the invention the volume of liquid helium 3 may contain a small percentage of helium 4.

The continuous extraction of the helium 3 may be effected by diffusion through the superfluid helium 4 and subsequent evaporation therefrom at a temperature of about 0.6° K., at which temperature the vapour pressure of helium 4 is negligible.

In order to enable the nature of the invention to be more readily understood reference is directed to the accompanying drawings in which:

FIGURE 1 is a diagrammatic illustration of a first embodiment of the invention;

FIGURE 2 is a diagrammatic illustration of a second embodiment of the invention;

FIGURE 3 is a semi-diagrammatic view of the preferred embodiment;

FIGURE 4 is a sectional plan on the line IV—IV of FIGURE 3;

FIGURE 5 is a sectional elevation, drawn to an enlarged scale, of a condenser shown in FIGURE 3;

FIGURE 6 is a sectional elevation, drawn to an enlarged scale, of a pipe connecting a boiler to a working chamber shown in FIGURE 3;

FIGURE 7 is a sectional elevation, drawn to an enlarged scale of a heat exchanger and valve shown in FIGURE 3;

FIGURE 8 is a sectional elevation, drawn to an enlarged scale of the working chamber shown in FIGURE 3;

FIGURE 9 is a perspective view of a liquid nitrogen tank shown in FIGURE 3; and

FIGURE 10 is a diagram of a modified apparatus.

In FIG. 1 a refrigerator is shown as comprising a closed circuit in which a working chamber 1 enveloping a container 2 for an article to be refrigerated is connected at its lower end through a U-tube 3 to the bottom of a boiler

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4 heated by an electric heater 5. A vapour outlet duct 6 leads from the boiler 4 to a condenser 7 the bottom of which is connected by a pipe 8, through a heat exchanger 83 associated with pipe 3, to the top of the working chamber 1.

The condenser 7 is cooled by pure liquid helium 3 fed at 1.1° K. from an external source through a valve 10 and pipe 10a into an inner container 9 and continuously evaporated through an exhaust pipe 11 connected to a vacuum pump (not shown) to provide a temperature of 0.3° K. within the container 9.

Cooling is effected across an extended surface consisting of high purity copper fins 9a extending upwardly and downwardly from the bottom of container 9. Evaporation of the helium 3 in the container 9 on these fins ensures that the condenser 7 is maintained at about 0.35° K.

The whole of the closed circuit described is contained in a jacket 16 immersed in a flask 12 containing liquid helium 4 at 1.1° K. also derived from an external source and provision is made for evacuating the jacket 16 through a tube 14 to maintain this low temperature.

In operation the closed circuit is initially filled to the level indicated by the broken line by condensing a mixture of approximately equal parts of helium 3 and helium 4 through a capillary 13.

As the condenser 7 is further cooled by the evaporation of helium 3 in the container 9, the vapour in the condenser 7 is condensed, causing the liquid helium in the boiler 4 to cool by evaporation. The helium 3 concentration in the boiler decreases since the helium 3 evaporates at a much faster rate than the helium 4. At a certain low concentration of helium 3, the liquid in the boiler 4 becomes superfluid and this causes a flow of helium 3 relative to the helium 4 in U-tube 3 and the spreading of the superfluid region of low helium 3 concentration towards the working chamber 1, cooling it in the process. The concentrated helium 3 which is distilling over from the boiler 4 to the condenser 7 runs down the pipe 8 and cools the working chamber 1 from the other end.

As the concentration gradient in the working chamber steepens and the temperature falls, phase separation sets in and a phase boundary 43 is formed. The levels in the boiler 4 and the pipe 8 then readjust themselves according to the different densities of the two phases. Since the thermal conductivity of both phases is low the container 2 is arranged to be in good thermal contact with the liquid at the phase boundary where dilution takes place. As the temperature in the boiler 4 falls, the heater 5 is put into operation to maintain the temperature at about 0.65° K. Finally a steady state is reached in which the design performance is attained, when the helium 3 concentration of the vapour and of the liquid in pipe 8 is about 95%, the dilute phase (helium 4) in the working chamber 1 contains 2% helium 3 and the liquid in the boiler 4 contains about 0.3% helium 3.

The helium 3 in the dilute phase, which phase is mostly helium 4 and is superfluid in the temperature range of operation, behaves thermodynamically and hydrodynamically as an ideal gas of the same molar density. The only function of the helium 4 is to make the ideal gas behaviour possible at these high molar densities and low temperatures. This quasigas can move with little friction within the helium 4. The pressure can be measured, if desired, as an osmotic pressure by means of a "superleak," i.e. a filter of pore size of less than 10^{-6} cm. which is permeable only for helium 4.

Owing to the free mobility of the helium 3 atoms the osmotic pressure is constant within the tube 3 containing the superfluid. Since the temperature varies along the tube the concentration will vary approximately inversely with the absolute temperature like the density of a gas,

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and a slight gradient of osmotic pressure will cause a movement of helium 3 in the tube 3 relative to helium 4. This gradient is provided by the continuous removal of helium 3 from the boiler 4. As the dilute phase (helium 4) can be likened to a gas, the concentrated phase (helium 3) can be considered as a liquid and the dilution process as an evaporation. Only because of the incidental fact that the specific gravity of liquid helium 4 is greater than that of helium 3, the liquid is situated above the quasigas. Turning FIG. 1 upside down, the part of system from pipe 8 via chamber 1 to tube 3 represents an evaporative refrigerator. The tube 3 is arranged to extend downwardly from chamber 1 to avoid thermogravitational convection, the more dilute warmer solution being heavier than the colder solution.

Although the bulk of the helium 4 remains stationary despite the flow of helium 3 and although very little will be evaporated in the boiler 4, it will tend to creep up the walls of the boiler due to the so-called film phenomenon associated with superfluidity. This creep can be minimised by providing a diaphragm 6a in the exhaust duct 6, such diaphragm having an aperture of the minimum size necessary to pass the helium 3 vapour.

An alternative arrangement illustrated in FIG. 2 dispenses with the condenser 7 and its associated pure helium 3 circuit. Instead the vapour from the boiler 4 is taken out through an outlet duct 6b and recompressed externally of the jacket 16 from its original pressure of about 0.002 mm. Hg to a pressure of about 15 mm. Hg at which it can be condensed in pocket 8a by the liquid helium 4 boiling in the flask 12 at 1.1° K., by a vacuum pump (not shown) having a capacity of 900 litres per sec. at 0.002 mm. Hg. It is then fed into pipe 8c (corresponding to pipe 8 of FIG. 1) through a control valve 8b. The heat exchanger 83 which is now almost essential, whereas it was optional in the previous embodiment, cools the helium 3 in pipe 8c from 1.1° K. to about 0.2° K. while the helium 4 in tube 3 which has a much larger specific heat, warms up from 0.1° K. to 0.3° K.

The embodiment of FIG. 2 represents a great simplification, as the facilities for re-compression and condensation have to be provided also in the former scheme in connection with the pure helium 3 circuit. The helium 3 flow rate and the refrigeration duty will be about the same for an apparatus of similar dimensions.

The preferred embodiment of the invention which is shown less diagrammatically in FIGS. 3 and 4 is, however, similar in principle to that of FIG. 2 and equivalent parts have been given identical references for ease of understanding. It differs only from the arrangement of FIG. 2 in the omission of the valve 8b and the replacement of the condenser pocket 8a by a separate condenser unit operating at 0.9° K. At this temperature the condensation pressure of helium 3 is only about 5 mm. of mercury which corresponds to a liquid head of helium 4 of about 50 cm. and this can conveniently be accommodated in the apparatus. Thus the liquid helium 4 in the flask 12 can be allowed to boil at atmospheric pressure to give a temperature of 4.2° K. and the associated large vacuum pump is not necessary.

The embodiment is designed for a flow rate of 3×10^{-4} gram/sec. of helium 3, giving a refrigeration duty of about 10^{-4} watt at 0.1° K.

This preferred embodiment will now be described briefly in relation to FIGS. 3 and 4 and then in greater detail in relation to FIGS. 5 to 9.

The vacuum jacket 16 consists of a 6 in. outside diameter brass tube with a hemispherical copper spinning for its bottom and a flat brass lid 30.

The lid 30 is suspended from a cover plate 31 by the helium 3 vapour outlet duct 6b and a helium 4 vapour outlet duct 32. The duct 6b is connected to a 9 in. diffusion pump and mercury booster 29 (shown in block schematic) and the duct 32 to a 6 in. diffusion pump (not

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shown) both ducts are painted internally with colloidal graphite (e.g. Aqua dag) to reduce heat radiation down the ducts. The cover plate 31 closes a Dewar flask 12 containing liquid helium 4 in which the vacuum jacket 16 is thus immersed, the surface of the helium 4 being indicated at 33. The Dewar flask 12 is in turn immersed in a further Dewar flask 34 containing liquid nitrogen.

Inside the vacuum jacket 16, the outlet duct 6b leads down to the boiler or still 4, and thence downwardly as one limb of the U-tube 3, the other limb of which constitutes the outer tube of the heat exchanger 83 and supports the working chamber 1 in which the phase boundary 48 forms and within which is the container 2 for the article or substance to be refrigerated.

The pipe 8c through which helium 3 is fed to the working chamber is in the form of a capillary and is fed from a condenser coil 35 housed in a chamber 36 supported inside the vacuum jacket 16 by a tube 37 depending from the lid 30. Inside the tube 37 is a heat exchanger coil 38 which is fed from a helium 3 vapour inlet tube 39 to which the exhaust from the diffusion pump and booster 29 is connected. This heat exchanger coil 38 is not necessary but it assists in reducing the rate of evaporation of helium 4 in the chamber 36 and the consequent load on the pump connected to the duct 32.

The chamber 36 is filled with helium 4 through a valve 40 (FIG. 7) from the bulk supply contained in the flask 12, the valve being controlled from a handle 41 (FIG. 4) on the cover plate 31. In the plan view (FIG. 4) of the cover plate can also be seen an inlet pipe 42 and an outlet pipe 43 for a liquid nitrogen tank 44 (FIG. 9) which serves as a heat shield between the surroundings and the surface of the liquid helium 4 in the flask 12. There is also a pipe 45 through which the vacuum jacket is evacuated and a pipe 46 for venting the flask 12. Pipe 47 is a space through which various other gas or electrical connections (such as those to the boiler 4) may be taken as necessary.

Referring now to the detailed views of FIGS. 5 to 9, FIG. 5 shows the condenser coil 35 within its chamber 36. The coil is made from $\frac{3}{16}$ nominal bore copper tube and is about 20 in. long. A curtain 35a of copper foil is brazed to the coil 35 as shown. The function of this curtain is to permit the continued operation of the condenser after the level of helium 4 has fallen below the coil 35, for superfluid helium 4 will form a liquid film thereon and thus cool the coil. The chamber 36 is made from 3 in. diameter copper tube with stainless steel end discs and between the chamber and the thin stainless steel tube 37 is a nozzle 49 with a polished bore which is intended to counteract the flow of a film of superfluid helium 4 out of the chamber 36. The heat exchanger coil 38 is also made of stainless steel tube $\frac{1}{8}$ in. O.D. by 26 S.W.G.

The pipe 8c connected to the bottom of the coil 35 is a stainless steel capillary of 0.058 inch inside diameter. The pipe enters the bottom of the heat exchanger 83 (FIG. 6) and enters a manifold 50 from which three capillaries each of 0.014 inch inside diameter, 0.028 inch outside diameter and 17 inches long emerge as a three-start helix 51 to be reunited again in a further manifold 52 from whence a single capillary 53 of 0.014 inch inside diameter and 6 inches long rises to the working chamber. The outer casing of the heat exchanger (which is the short limb of the U-tube 3 in FIG. 3) is a thin walled $\frac{3}{8}$ in. diameter stainless steel tube and the bottom fitting 54 is made from the solid out of a stainless steel plate. The space between the capillary 53 and tube 3 is packed with a roll of 200 mesh stainless steel wire gauze in order to reduce upward heat conduction by phonons.

FIG. 6 also shows the boiler 4 as consisting of a heater winding 5 (80 turns of 42 S.W.G. Manganin in one layer) on the lower end of a $\frac{3}{4}$ in. O.D. thin walled stainless steel tube 56 which forms the beginning of the helium 3 vapour outlet duct 6b and extends a short distance over

the long limb of U-tube 3 which is a $\frac{3}{8}$ in. diameter thin walled stainless steel tube. The gap at the join between the large and small diameter tubes is filled by a cone shaped member 57.

The heat exchanger coil 38 in its tube 37 is shown again in FIG. 7 which also illustrates the valve 40 of FIG. 3 but in greater detail. The valve which actually sticks out below the plane of the paper in FIG. 3 and not sideways as shown diagrammatically, consists of a copper body 40a into which the tubes 32 and 37 are brazed and a lateral extension carrying a stainless steel boss 58 into which is screwed a needle valve 59 which extends up through the cover plate 31 and is furnished with the handle 41 shown also in FIG. 3.

The liquid nitrogen tank 44 (FIG. 3) is a complicated shape and is shown in perspective in FIG. 9. It is shaped to occupy most of the space between the vapour outlet ducts 6b and 32, and the Dewar flask 12. The inlet pipe 42 and outlet pipe 43 are shown attached to the tank.

FIG. 8 shows the working chamber 1 in more detail and also shows the capillary 53 and the top of tube 3 upon which the working chamber is mounted. This working chamber is made of brass and has a brass cover 61 which is secured to the chamber by means of screws (not shown), a gold sealing gasket 62 being interposed. The working chamber houses a cylindrical pellet 63 pressed from a paramagnetic salt and shaped to fit over the capillary 53. A mutual inductance comprising a primary coil 64 and two secondary coils 65 is located outside of the chamber 1 and is supported from and in thermal contact with the condenser case 36. It co-operates with the salt in the container 63 to form a magnetic thermometer. The container for the load is not shown but may conveniently rest on the container 63, access in the latter case being effected via the cover 61.

If a temperature of less than about 0.08° K. is required in the working chamber 1, a difficulty arises in that it can be shown that, since the concentration in the tube 3 varies inversely with temperature, and the equilibrium concentration in the working chamber 1 decreases with temperature, then for a temperature less than 0.1° K. in the chamber 1 and a temperature of 0.65° K. in the boiler 4 the concentration of helium 3 in the boiler will be too low to distill off.

FIG. 10 shows a circuit similar to FIGS. 2 or 3 but provided with an alternative means for transporting the helium 3 from the chamber 1 to the boiler to overcome the above difficulty. The general dimensions and duty may be similar.

If liquid helium 4 is caused to flow at a velocity greater than about 10 cm./sec. vortex lines are created in the superfluid which are carried with the liquid and interact with any dissolved helium 3, carrying it along with the helium 4. Under these conditions the liquid mixture moves as a whole, there is no relative motion between the helium 3 and helium 4 (as in tube 3 of the above embodiments) and consequently concentration of helium 3 is not established in a gradient inversely with temperature.

In FIG. 10 a continuous turbulent flow of helium 4 in the superfluid state is arranged to take place through the pipe 3 from the end adjacent the chamber 1 to the boiler 4. The inherent flow resistance of the turbulent flow plus that due to the osmotic pressure gradient will introduce a difference in level between the liquid in the down pipe 8c and in the boiler 4 as shown. The flow is achieved by the use of the two super-leaks through which superfluid helium 4 will pass but which obstruct the flow of helium 3. One of the superleaks 18 is arranged to pass helium 4 from a pipe 19 fed from a head vessel 20 to the working chamber end of the pipe 3 and the other superleak 21 is arranged selectively to discharge helium 4 from the boiler 4 into the outer flask 12.

The superleaks 18 and 21 may consist of tubes densely packed with a fine inert powder or they may be made from porous glass. Such a leak is impermeable to helium 3 but offers no flow resistance to superfluid helium 4.

The flow of helium 4 through the superleaks is caused by the fountain phenomenon according to which helium 4 will flow through a superleak against a pressure gradient if the temperature at the entrance to the superleak is lower than at the exit. By maintaining the head vessel 20 at 1° K. and the temperature in flask 12 at 1.25° K. an effective pressure head of 50 cm. can be maintained. It is a property of a superleak that no heat is conveyed through it although heat is evolved at the entrance, but this difficulty is overcome by continuously evaporating the helium 4 in the head vessel 20. By arranging the liquid level in the flask 12 to be slightly higher than in the head vessel 20, the liquid in the flask 12 can be continuously fed back into the vessel 20 through a capillary tube 22 acting as a valve sufficiently small not to pass too much heat into the flask 12, superfluid helium 4 having very high heat conductivity.

The flow through the tube 3 is required to have the required degree of turbulence to create the vortex lines which interact with the helium 4 and a valve providing a degree of adjustment may be necessary.

The arrangement may be expected to maintain a helium 3 concentration in the boiler 4 of 0.3% as in the arrangement of FIGS. 1, 2 or 3 despite a concentration of helium 3 in the chamber 1 of only 0.2% at a temperature of about 0.03° K.

In order to convey 3×10^{-4} gram/sec. of helium 3 at a concentration of 0.2% requires a concentration rate of 0.2 gram/sec. of helium 4 through the superleaks.

I claim:

1. A refrigerator having liquid helium 3 as its working fluid and comprising a working chamber, a boiler, a condenser, conduit means to provide a superfluid helium 4 link between said working chamber and said boiler, means to pass liquid helium 3 to the working chamber to mix therein with superfluid helium 4 whereby heat is extracted, and heating means associated with said boiler to evaporate helium 3 from the helium 4 therein and means to remove the helium 3 vapour from the boiler.

2. A refrigerator according to claim 1, including means to feed the helium 3 to the working chamber in heat exchange relationship with said conduit means leading to the boiler.

3. A refrigerator according to claim 1, wherein the said conduit means leading from the working chamber to the boiler is a U-tube.

4. A refrigerator according to claim 1, including an external source of helium 3 connected to said means to pass liquid helium 3 to said working chamber.

5. A refrigerator according to claim 4, including a chamber cooled by the evaporation of helium 4 and housing a coil in which the helium 3 fed to the working chamber is subjected to preliminary cooling.

6. A refrigerator according to claim 1, wherein said working chamber, said boiler, said condenser and said conduit means are located in an evacuated jacket immersed in a bath of liquid helium 4 boiling at atmospheric pressure.

7. A refrigerator according to claim 1, including two superleak means through which helium 4 flows under the influence of the fountain effect, said superleaks being connected to provide a turbulent flow of helium 4 assisting the flow of helium 3-4 mixture from the working chamber to the boiler.

8. A refrigerator comprising a working chamber wherein liquid helium 3 is mixed with liquid helium 4, the heat necessary for such operation being extracted from a load, a boiler to evaporate helium 3 from admixture with helium 4, a tube connecting the said working chamber to the boiler and serving to permit the flow of helium 3 to the

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boiler for evaporation therein and means to condense the helium 3 evaporated in the boiler and to return the same to the working chamber.

9. A refrigerator according to claim 8, wherein said means includes a condenser cooled by the evaporation of liquid helium 3 from an external supply, a duct leading from said boiler to said condenser and a pipe leading from said condenser to said working chamber.

10. A refrigerator according to claim 9, including, in said duct, a diaphragm having an aperture to the minimum size sufficient to permit the passage of helium 3 vapour.

11. A refrigerator having helium 3 as its working fluid and comprising a boiler, a condenser and a working chamber, a superfluid helium 4 link between said working chamber and said boiler, means passing said helium 3 in liquid form from the condenser to the working chamber where it mixes with said superfluid helium 4, there-

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by to extract heat from a load adjacent to said working chamber, a heater in said boiler to evaporate helium 3 from the helium 4 therein and means passing the helium 3 from the boiler to the condenser to be condensed therein.

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