

INTEGRATED DILUTION REFRIGERATORS

BACKGROUND

Dilution refrigerators rely on the heat of mixing of the ^3He and ^4He isotopes to reach temperatures between approximately 2mK and 1K.

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BRIEF DESCRIPTION OF DRAWINGS

The patent or application file contains at least one drawing executed in color. Copies of this patent or patent application publication with color drawing(s) will be provided by the Office upon request and payment of the necessary fee.

10 The accompanying drawings are not intended to be drawn to scale. In the drawings, each identical or nearly identical component that is illustrated in various figures is represented by a like numeral. For purposes of clarity, not every component may be labeled in every drawing. In the drawings:

FIG. 1 is a schematic diagram of a closed-cycle dilution refrigerator, in accordance
15 with some embodiments described herein.

FIGs. 2A and 2B are schematic diagrams of a dilution refrigerator configured to be integrated with a server rack-type container, in accordance with some embodiments described herein.

FIG. 3 is a schematic diagram of a distributed cooling system, in accordance with
20 some embodiments described herein.

FIG. 4 is a schematic diagram of a dilution refrigerator including a heat exchanger configured to transfer heat from the incoming condensing line to the return mixture at a location above the first impedance stage, in accordance with some embodiments described herein.

25 FIG. 5 is a schematic diagram of a still including a device to separate ^3He and ^4He using second sound effects, in accordance with some embodiments described herein.

FIGs. 6A-6F are schematic diagrams of exemplary ^4He separation devices, in accordance with some embodiments described herein.

FIG. 7A is an image of nanoparticles for use in a heat exchanger.

30 FIG. 7B is an image of nanowires for use in a heat exchanger, in accordance with some embodiments described herein.

FIG. 8A is a schematic diagram of an inverted dilution refrigerator, in accordance with some embodiments described herein.

FIGs. 8B and 8C are schematic diagrams of exemplary components of an inverted dilution refrigerator, in accordance with some embodiments described herein.

DETAILED DESCRIPTION

I. Air-Cooled, Closed-Cycle Dilution Refrigerators

$^3\text{He}/^4\text{He}$ dilution refrigerators have been a primary tool used to achieve sub-Kelvin temperatures for scientific research and other low-temperature applications. Today, “dry,” “cryogen-free,” or “closed-cycle” dilution refrigerators typically use cryocoolers (e.g., pulse tubes, Gifford-McMahon cryocoolers) integrated with the dilution refrigerator to cool the dilution refrigerator’s radiation shields and heat sink surfaces and to initially cool the ^3He - ^4He mixture to a temperature at or below approximately 4-5K. Thereafter, the ^3He - ^4He mixture is further cooled by passing through a series of thermal stages until reaching a final base temperature below 20mK in the last thermal stage, the mixing chamber.

Conventional closed-cycle dilution refrigerators typically rely on water-cooling to remove waste heat generated by the integrated cryocooler. This waste heat is generated, for example, as the cryocooler operates a compressor to perform cooling. Water-cooling of the cryocooler, however, requires installing a large and/or expensive water-cooling system in conjunction with the dilution refrigerator. Additionally, such water-cooling systems are not typically integrated with commercial computing facilities, which typically rely on air-cooling as it is less expensive and does not present hazards (e.g., leaking coolant, flooding, etc.) to the electronic equipment. The inventors have accordingly recognized that using air-cooling to remove heat from the cryocooler of the dilution refrigerator may reduce the costs of manufacturing dilution refrigerators and enable their use in commercial computing facilities.

FIG. 1 is a schematic diagram of a closed-cycle, air-cooled dilution refrigerator 100, in accordance with some embodiments described herein. In some embodiments, the dilution refrigerator 100 includes an outer vacuum chamber 106 at room temperature (e.g., approximately 300K) and a number of inner radiation shields 108a-108c held at decreasing temperature intervals (e.g., approximately 50K, 9-10K, 3K, etc.). The dilution refrigerator 100 may include a pump system 102 that pressurizes ^3He gas (e.g., to a pressure at or near 1 bar). The ^3He gas enters the outer vacuum chamber 106 and travels through the inner radiation shields 108a-108c through ^3He inlet 102a. The ^3He returns to the pump system through ^3He outlet 102b.

In some embodiments, the ^3He is progressively cooled as it travels along the ^3He inlet path. A first heat exchanger 110 may be the first cooling stage for the ^3He . The first heat exchanger may be, for example, a filter and mesh heat exchanger, in some embodiments.

5 Thereafter, in some embodiments, the ^3He may be cooled by a cryocooler 104. The cryocooler 104 may be disposed partially outside of the outer vacuum chamber 106, in some embodiments. The cryocooler 104 may be vibrationally isolated from outer vacuum chamber 106 by a vibration isolation stage 105, which may include any suitable vibration isolation techniques as known in the art.

10 In some embodiments, the cryocooler 104 may be coupled to a cryocooler support 103. The cryocooler support 103 may be, for example, a compressor and/or compression system, in some embodiments. The cryocooler support 103 may include cooling members 103a, in some embodiments, configured to provide air-cooling to the dilution refrigerator 100. The cooling members 103a may be, as a non-limiting example, cooling fins, fans,
15 and/or heat pipes configured to remove waste heat generated by the cryocooler support 103 and/or the cryocooler 104.

 In some embodiments, the dilution refrigerator 100 may be disposed above a plenum (not pictured) disposed under a floor supporting the dilution refrigerator. The plenum may supply the cooling members 103a with air to provide air-cooling. In some
20 embodiments, the cooling members 103a may include inlets and/or louvers configured to draw in air from the plenum. Alternatively or additionally, in some embodiments, the dilution refrigerator 100 may be disposed in a facility including ductwork (not pictured) arranged to remove heat from the cooling members 103a, the cryocooler support 103, and/or the cryocooler 104 and to minimize vibrations experienced by the dilution
25 refrigerator 100.

 In some embodiments, the ^3He may be cooled to approximately 50K by a first stage 104a of a cryocooler 104. Thereafter, the ^3He may be cooled further to approximately 2-5K by a second stage 104b of the cryocooler 104. For example, the ^3He inlet 102a may be wound around the first stage 104a and/or the second stage 104b of the cryocooler 104 to
30 effect heat exchange between the ^3He and the cryocooler 104.

 In some embodiments, the ^3He may enter the innermost radiation shield 108c after being cooled by the cryocooler 104. The innermost radiation shield 108c may be mechanically decoupled from cryocooler 104 by a vibration isolation component 109. As a non-limiting example, in some embodiments, the vibration isolation component 109 may

be a copper braid, heat strap, or other hanging component configured to maintain thermal coupling between the innermost radiation shield 108c and cryocooler 104 while also mechanically decoupling the innermost radiation shield 108c from cryocooler 104.

In some embodiments, once inside the innermost radiation shield 108c, the ^3He may enter a first impedance stage 112. The first impedance stage 112 may be a Joule-Thomson expander configured to reduce the temperature of the ^3He . For example, in some embodiments, the ^3He may be at approximately 3-5K before entering the first impedance stage 112 and may be at approximately 1K after exiting the first impedance stage 112.

In some embodiments, the ^3He then moves into the still 114. The still may contain a mixture of liquid ^3He / ^4He that acts to cool the ^3He as it passes through the still 114. In some embodiments, the ^3He may be cooled to approximately 400-900mK by the still 114.

After exiting the still 114, the ^3He may flow through a second impedance stage 116 in some embodiments. The second impedance stage 116 may be configured to ensure that only liquid ^3He proceeds further downstream in the dilution refrigerator 100. The second impedance stage 116 may therefore reduce downstream cooling loads due to a latent heat of gaseous ^3He .

In some embodiments, the ^3He may then flow into a first heat exchanger 118. The first heat exchanger 118 may be a continuous heat exchanger. For example, the first heat exchanger 118 may be a counterflow (e.g., a tube-tube heat exchanger) or a cross-counterflow heat exchanger. The ^3He may be cooled by the first heat exchanger 118 to a temperature of approximately 20 mK.

In some embodiments, the ^3He enters discrete heat exchangers 120 after exiting the first heat exchanger 118. The discrete heat exchangers 120 may be formed of sintered nanoparticles (e.g., silver nanoparticles), in some embodiments. Alternatively or additionally, in some embodiments the discrete heat exchangers 120 may be formed of sintered nanowires, as described herein. The discrete heat exchangers 120 may be configured to further cool the ^3He to below approximately 20mK.

Thereafter, in some embodiments the ^3He is cooled to a final temperature in the mixing chamber 122. In the mixing chamber 122, ^3He atoms may be pumped from a concentrated phase into a dilute phase mixed with ^4He . This mixing causes further cooling of the ^3He . A sample plate (not pictured) may be thermally coupled to the mixing chamber 122 and configured to support a sample and/or quantum device at the mixing chamber temperature. The liquid ^3He may thereafter be pumped out back through the dilution refrigerator 100, exiting the outer vacuum chamber 106 through ^3He outlet 102b.

Following below are more detailed descriptions of various concepts related to, and embodiments of, techniques for implementing dynamic polarization drift correction for quantum telecommunications systems. It should be appreciated that various aspects described herein may be implemented in any of numerous ways. Examples of specific implementations are provided herein for illustrative purposes only. In addition, the various aspects described in the embodiments below may be used alone or in any combinations and are not limited to the combinations explicitly described herein.

II. Integrated Dilution Refrigerators

Conventional dilution refrigerator technology often requires large amounts of space to implement and expensive supporting infrastructure such as custom-built floating foundations to implement. These infrastructure requirements may reduce the scalability of quantum technologies that operate at low temperatures (e.g., liquid Helium temperatures). As a non-limiting example, the adoption of certain quantum computing technologies may be limited by the required use of dilution refrigerators. The inventors have thus recognized and appreciated that reducing the size and infrastructure requirements of dilution refrigerators may enable the scalability of quantum technologies. The inventors have further recognized that integrating dilution refrigerators with commercial computing infrastructure (e.g., commercial server infrastructure) can enable the scalability of dilution refrigerators and associated quantum technologies dependent on dilution refrigerators. Furthermore, such integrated dilution refrigerators may be more easily integrated into telecommunications networks, can use existing telecommunications heat removal architectures, and integrate with fiberoptic networks and systems.

FIGs. 2A and 2B are schematic diagrams of a dilution refrigerator 202 configured to be integrated with a server rack-type container 250, in accordance with some embodiments described herein. The server rack-type container 250 may include any generally rectangular housing configured to house at least a portion of the dilution refrigerator 202. In some embodiments, the server rack-type container may be configured to integrate with commercial server rack infrastructure. In some embodiments, the server rack-type container 250 may be a server rack. For example, the server rack-type container 250 may be a 19-inch (or any other suitable size) server rack.

In some embodiments, the server rack-type container 250 may include castors 252 configured to assist in transportation of the dilution refrigerator 202. In some embodiments, the castors 252 may be retractable such that the wheels of the castors 252

are not in contact with the floor supporting the dilution refrigerator 202 when the dilution refrigerator 202 is not being transported.

The dilution refrigerator 202 may be any suitable dilution refrigerator as described herein. For example, the dilution refrigerator 202, as shown in the examples of FIGs. 2A and 2B, may be oriented similar to dilution refrigerator 100 as described in connection with FIG. 1. The dilution refrigerator 202 may include an outer vacuum chamber 206 and inner radiation shields 202a-202e. Alternatively, in some embodiments, the dilution refrigerator 202 may be dilution refrigerator 400 as described in connection with FIG. 4 or dilution refrigerator 800 as described in connection with FIGs. 8A-8C.

As shown in the examples of FIGs. 2A and 2B, the server rack-type container 250 may support additional components external to the outer vacuum chamber 206 of dilution refrigerator 202. For example, the server rack-type container 250 may house compressors, pumps, and/or cooling equipment configured to support the operation of the dilution refrigerator 202. Alternatively, it should be appreciated that such external components may be housed in an adjacent (e.g., a different) server rack-type container than the dilution refrigerator 202, in some embodiments.

III. Distributed Cooling Systems

Dilution refrigerators generally include an integrated cryocooler (e.g., such as a pulse tube or a Gifford-McMahon cryocooler) to pre-cool ^3He gas below 5K. Conventionally, a dilution refrigerator is paired with at least one of these cryocoolers, and dilution refrigerators do not share cooling systems. Such small-scale dilution refrigeration systems typically rely on low-power cryocooling systems that are relatively inefficient (e.g., requiring more power for each Watt of cooling power at 4K) in comparison to larger, higher-power cryocooling systems. The inventors have recognized and appreciated that a single, high-efficiency cooling system may be thermally coupled to multiple cryogenic systems such as dilution refrigerators to distribute this first stage of cooling across multiple cryogenic systems. Such distributed cooling therefore allows for increased cooling efficiency across multiple cryogenic systems.

FIG. 3 is a schematic diagram of a distributed cooling system 300, in accordance with some embodiments described herein. The distributed cooling system 300 may include multiple housings 305. In some embodiments, the housings 305 may be server rack-type containers (e.g., server rack type-containers 250 as described herein). As shown in the example of FIG. 3, each housing 305 may contain a cooling system 310 or a cryogenic

device 320. It should be appreciated that cryogenic devices 320 and/or cooling systems 310 may be grouped within housings 305, in some embodiments.

In some embodiments, the cooling system 310 may be thermally coupled to multiple cryogenic devices 320. Cooling may be distributed to cryogenic devices 320 from cooling system 310 by cooling line 312. Additionally, heat may be returned from the cryogenic devices 320 to cooling system by return 314. In some embodiments, the cooling system 310 may cool cryogenic devices 320 to at least 5K (e.g., at or below 5K) as an initial cooling stage.

In some embodiments, the cryogenic devices 320 may include any suitable refrigeration system configured to reach temperatures at or below 5K. In some embodiments, cryogenic devices 320 may include one or more dilution refrigerators (e.g., dilution refrigerators 100, 202, 400, and/or 800 as described herein). Alternatively or additionally, it should be appreciated that cryogenic devices 320 may include cryogenic systems other than dilution refrigerators (e.g., microscopy systems, ^3He refrigeration systems, superconducting CMOS systems, etc.).

IV. Heat Sink Locations

For a closed-cycle dilution refrigerator (e.g., as described in connection with FIG. 1), prior to entering the still, the ^3He typically must pass through a first impedance stage to control the flow of ^3He . This first impedance stage typically acts as an independent refrigeration stage, known as a Joule-Thomson refrigerator, where the ^3He is cooled by isenthalpic expansion. In order to control the cooling power of the ^3He expansion, the pressure of the ^3He entering the impedance is typically raised by an external compressor prior to entering the first impedance stage. The inventors have recognized and appreciated, however, that reducing the temperature of the ^3He prior to entering the first impedance stage can achieve the same base temperature after the first impedance stage without the need for an additional compressor. Such a configuration can improve the Carnot efficiency of the dilution refrigerator and eliminate or reduce the need to pressurize the ^3He before the first impedance stage. Further, the inventors have recognized that the heat removed from the ^3He prior to the first impedance stage can be returned to the still, thereby eliminating or reducing the need for a supplemental heater within the still to raise the vapor pressure, and enabling evaporation, of the ^3He present in the still.

FIG. 4 is a schematic diagram of a dilution refrigerator 400 including a heat exchanger 422 configured to transfer heat from the incoming condensing line 102a to the

return helium mixture at a location above the first impedance stage 112, in accordance with some embodiments described herein. The heat exchanger 422 brings a cooler mixture from the first heat exchanger 118 above the still 114 to a point before the first impedance stage 112. The heat exchanger 422 then cools the ^3He in the condensing line 102a prior to the first impedance stage 112. Thereafter, the warmed mixture is transported to the still 114.

Cooling the incoming ^3He before it enters the first impedance stage 112 causes the first impedance stage 112 to output ^3He with a higher proportion of ^3He in the liquid state rather than in the vapor state. Thus, the first impedance stage 112 can be made more efficient by including the additional heat exchanger 422. Additionally, this improved efficiency eliminates or mitigates the need for supplemental pressure (e.g., an external compressor) and may lower the flow impedance of the circulating helium mixture. This is particularly important to reducing the complexity and size of smaller dilution refrigerators that include smaller (i.e., less powerful) pulse tubes or other cryocoolers.

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V. Second Sound $^3\text{He}/^4\text{He}$ Separation

Second sound is a quantum mechanical phenomenon present in superfluid helium. When a porous membrane is oscillated within a bath of fluid helium, the two-fluid model specifies that the superfluid helium moves through the membrane while non-superfluid components of the helium bath cannot pass through the porous membrane. In superfluid helium, this creates an enthalpy or temperature wave. Analogously in helium mixtures, the non-superfluid ^3He is pushed by the membrane while the superfluid ^4He remains stationary. The inventors have recognized and appreciated that this second sound phenomenon can be implemented within the still (e.g., still 114 as described herein) to improve ^3He evaporation at a lower temperature and to reduce a concentration of ^4He in the vapor above the still.

FIG. 5 is a schematic diagram of a still 500 including a device to separate ^3He and ^4He using second sound effects, in accordance with some embodiments described herein. The still 500 includes a stationary membrane 502 and a porous, movable membrane 504. The porous membrane 504 may be oscillated along the Z direction to create standing concentration waves of ^3He within the still so that there are regions 506 of lower ^3He concentration and regions 508 of high ^3He concentration. The standing wave may be tuned such that regions 508 of high ^3He concentration are disposed adjacent an outlet of the still, thereby allowing for improved ^3He purification.

VI. ^4He Separation

At low temperatures and pressures, ^4He forms a thick and mobile film that can move long distances across surfaces, including moving in a direction counter to the force of gravity. This helium creep can result in ^4He entering portions of a dilution refrigeration system where it is unwanted (e.g., in regions of purified ^3He). FIGs. 6A-6F are schematic diagrams of exemplary ^4He separation devices, in accordance with some embodiments described herein.

FIG. 6A illustrates a cooling stage 600 (e.g., a still, the mixing chamber, etc.) including a bath 602 of a dilute phase helium mixture (e.g., a $^3\text{He}/^4\text{He}$ mixture), in some embodiments. Helium-4 can creep up the ^3He outlet pipe and exit the cooling stage 600 unless a barrier 606 prevents the helium creep. In the example of FIG. 6A, barrier 606 comprises a right-angled surface configured to prevent helium from exiting the cooling stage 600 through the ^3He outlet.

Other embodiments of a barrier configured to prevent ^4He creep are shown in the examples of FIGs. 6B, 6C, 6D, and 6E. In the example of FIG. 6B, a ring 608 with a knife edge 609 is configured to prevent ^4He from exiting through the ^3He outlet. In some embodiments, the ring 608 may include a heating device (e.g., a resistive heater or any other suitable heater) configured to cause the creeping ^4He to leave the superfluid phase, thereby mitigating creep.

In the examples of FIGs. 6C, 6D, and 6E, vertical knife edges are used to prevent ^4He from exiting through the ^3He outlet. In some embodiments, and in the example of FIG. 6C, the knife edge 610 is on the exterior circumference of the outlet pipe. Alternatively, as shown in the example of FIG. 6D, the knife edge 611 may be beveled on the interior circumference of the outlet pipe. Further, as shown in the example of FIG. 6E, the knife edge 612 may be beveled on both the exterior and interior circumferences of the outlet pipe.

In some embodiments, and as shown in the example of FIG. 6F, the ^3He outlet may include a p-trap configured to collect ^4He 622 at a lower surface of the p-trap. The ^3He outlet may include a superleak 624 configured to allow superfluid ^4He to exit the p-trap, and a pump 626 (e.g., a fountain pump) may transport the ^4He away from the p-trap. In some embodiments, a further barrier 626 may be present on an interior surface of the outlet pipe. For example, the barrier 626 may be configured as a ring. In some embodiments, the barrier 626 may include a heating device to further prevent ^4He from exiting the ^3He outlet.

VII. Nanowire Heat Exchangers

The final heat exchanger in a dilution refrigerator prior to the mixing chamber (e.g., discrete heat exchangers 120 as described in connection with FIG. 1 herein) and the heat exchanger in the mixing chamber 122 are commonly made out of sintered silver or copper powder. An example of such sintered particulates are shown in FIG. 7A. To have efficient heat exchange at the sub-Kelvin temperatures, a number of factors must be true with regards to the heat exchanger materials. The heat exchange material must have a large surface area, provide high mechanical contact with the liquid helium, allow for good neck growth, and provide space inside the heat exchange material for the liquid helium to move through the heat exchanger.

The inventors have recognized and appreciated that nanowires, rather than powder particulates, can provide all of the above-described criteria. Accordingly, the inventors have developed nanowire heat exchangers that provide efficient heat exchange via the nanowires' large surface area, high mechanical contact strength, and good neck growth between nanowires. FIG. 7B shows an image of nanowires for use in a heat exchanger, in accordance with some embodiments described herein.

In some embodiments, such a nanowire-based heat exchanger may be formed by bonding the nanowires through sintering. For example, the heat exchanger may be produced under heat and compression. The nanowires may be held in compression during the sintering process to form the nanowire heat exchanger.

In some embodiments, the nanowires may be formed out of one of a selection of vacuum-compatible materials. For example, the nanowires may be at least one of copper nanowires, silver nanowires, polymer nanowires, carbon nanowires, and/or carbon fiber nanowires.

VIII. Inverted Dilution Refrigerators

Typically, dilution refrigerators are oriented such that warmer thermal stages are positioned towards the top of the system with the thermal stages getting increasingly colder as the ^3He progresses to the bottom of the dilution refrigerator. To date, there are no commercially available fridges oriented in an inverted fashion with the coldest stage disposed on top of the system (e.g., furthest from the floor). The inventors have recognized and appreciated that such an inverted geometry may simplify the operation and use of a dilution refrigerator by making the sample plate coupled to the mixing chamber more

accessible to a user. Accordingly, the inventors have developed an inverted dilution refrigerator as described herein.

FIG. 8A is a schematic diagram of an inverted dilution refrigerator 800, in accordance with some embodiments described herein. The inverted dilution refrigerator 800 includes a pump system 802 configured to circulate ^3He through the dilution refrigerator 800. The inverted dilution refrigerator 800 also may include a cryocooler 804. The cryocooler may be coupled to a cryocooler support (not pictured) as described in connection with cryocooler support 103 herein.

In some embodiments, the inverted dilution refrigerator 800 includes an outer vacuum chamber 806 and a series of inner radiation shields 808a-808c disposed inside of the outer vacuum chamber 806. The inverted dilution refrigerator 800 may include an opening 810 in the outer vacuum chamber 806 and/or through the inner radiation shields 808a-808c to provide ease of access to the coldest stage of the inverted dilution refrigerator 800. In some embodiments, the opening 810 may comprise hermetic seals and/or opening mechanisms (e.g., doors or other suitable mechanisms) that may withstand the vacuum within the outer vacuum chamber when the inverted dilution refrigerator 800 is in operation. It should be appreciated that opening 810 may be implemented in the other dilution refrigerators described herein (e.g., dilution refrigerator 100, 202, and/or 400).

In some embodiments, the inverted dilution refrigerator 800 includes a number of thermal stages disposed within the innermost radiation shield 808c. The thermal stages may be arranged with the coldest thermal stage, the mixing chamber 824, disposed above warmer thermal stages (e.g., the still, impedance stages, various heat exchangers, etc.).

In some embodiments, the inverted dilution refrigerator 800 includes a de-mixing chamber 822 coupled to the mixing chamber 824. The de-mixing chamber 822 may be connected to the mixing chamber 824 such that ^4He may be transported from the de-mixing chamber 822 to the mixing chamber 824 to provide additional cooling to the mixing chamber 824.

FIGs. 8B and 8C are schematic diagrams of exemplary internal components of an inverted dilution refrigerator, in accordance with some embodiments described herein. It should be appreciated that the exemplary components of FIGs. 8B and 8C could be implemented within inverted dilution refrigerator 800 of FIG. 8A (e.g., within the innermost radiation shield 808c).

As shown in the example of FIG. 8B, in some embodiments the inverted dilution refrigerator may include a ^4He line 826 configured to transport ^4He from the still to the

mixing chamber 824. In some embodiments, the ^4He line 826 may include a pump 828 configured to assist in the transportation of the ^4He to the mixing chamber 825. The pump 828 may be, for example, a fountain pump in some embodiments. Alternatively or additionally, the ^4He line 826 may include additional heat exchangers to cool the ^4He as it travels to the mixing chamber 824.

As shown in the example of FIG. 8C, in some embodiments, the inverted dilution refrigerator may include a heat exchange stage 830 configured to cool incoming ^3He prior to the first impedance stage. As should be appreciated from the description of FIG. 4, such a configuration may increase the efficiency of the first impedance stage and/or eliminate or reduce the need for pressurization of incoming ^3He .

Various aspects of the embodiments described above may be used alone, in combination, or in a variety of arrangements not specifically discussed in the embodiments described in the foregoing and is therefore not limited in its application to the details and arrangement of components set forth in the foregoing description or illustrated in the drawings. For example, aspects described in one embodiment may be combined in any manner with aspects described in other embodiments.

Use of ordinal terms such as “first,” “second,” “third,” etc., in the claims to modify a claim element does not by itself connote any priority, precedence, or order of one claim element over another or the temporal order in which acts of a method are performed, but are used merely as labels to distinguish one claim element having a certain name from another element having a same name (but for use of the ordinal term) to distinguish the claim elements.

Also, the phraseology and terminology used herein is for the purpose of description and should not be regarded as limiting. The use of “including,” “comprising,” “having,” “containing,” “involving,” and variations thereof herein, is meant to encompass the items listed thereafter and equivalents thereof as well as additional items.

The word “exemplary” is used herein to mean serving as an example, instance, or illustration. Any embodiment, implementation, process, feature, etc. described herein as exemplary should therefore be understood to be an illustrative example and should not be understood to be a preferred or advantageous example unless otherwise indicated.

Having thus described several aspects of at least one embodiment, it is to be appreciated that various alterations, modifications, and improvements will readily occur to those skilled in the art. Such alterations, modifications, and improvements are intended

to be part of this disclosure, and are intended to be within the spirit and scope of the principles described herein. Accordingly, the foregoing description and drawings are by way of example only.

What is claimed is:

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CLAIMS

- A1. A dilution refrigerator, comprising:
a closed-cycle refrigeration system; and
an air cooling system configured to remove heat from the closed-cycle
5 refrigeration system.
- A2. The dilution refrigerator of claim A1, wherein the closed-cycle refrigeration
system is configured to reach temperatures equal to or below 1 K.
- 10 A3. The dilution refrigerator of claim A1, wherein the dilution refrigerator comprises
an outer vacuum chamber, and the closed-cycle refrigeration system comprises:
a first refrigeration system disposed at least partially outside of the outer vacuum
chamber,
a second refrigeration system disposed at least partially outside of the outer
15 vacuum chamber and thermally coupled to the first refrigeration system; and
a sample plate thermally coupled to a coldest portion of the second refrigeration
system.
- A4. The dilution refrigerator of claim A3, wherein the first refrigeration system
20 comprises at least one compressor disposed outside of the outer vacuum chamber and at
least one thermal stage disposed inside of the outer vacuum chamber.
- A5. The dilution refrigerator of claim A4, wherein the at least one thermal stage
comprises a first thermal stage configured to reach a first temperature and a second
25 thermal stage configured to reach a second temperature lower than the first temperature,
and wherein the second refrigeration system is thermally coupled to the second thermal
stage of the first refrigeration system.
- A6. The dilution refrigerator of claim A5, wherein the first thermal stage is
30 configured to reach approximately 50K and the second thermal stage is configured to
reach approximately 4K.
- A7. The dilution refrigerator of claim A3, wherein the second refrigeration system
comprises:

at least one pump disposed outside of the outer vacuum chamber and configured to transport ^3He ; and

a plurality of thermal stages configured to remove heat from the transported ^3He .

- 5 A8. The dilution refrigerator of claim A4, wherein the air cooling system is configured to remove heat from the at least one compressor.

A9. The dilution refrigerator of claim A1, wherein the air cooling system comprises one or more of a fan, cooling fins, and/or heat pipes.

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A10. The dilution refrigerator of claim A8, wherein the air cooling system comprises inlets and/or louvers configured to draw in air from a plenum disposed under a floor supporting the dilution refrigerator.

- 15 A11. The dilution refrigerator of claim A8, wherein the dilution refrigerator is disposed in a room and the air cooling system comprises ductwork configured to remove heat from the first refrigeration system and to minimize vibrations experienced by the dilution refrigerator.

- 20 A12. The dilution refrigerator of claim A3, wherein the second refrigeration system comprises:

a still disposed inside of the outer vacuum chamber and comprising a helium mixture having a first temperature;

- 25 a continuous heat exchanger disposed inside of the outer vacuum chamber and having a range of temperatures along its length, wherein the range of temperatures consists of temperatures that are less than the first temperature; and

a heat exchange line configured to transfer a return helium mixture from the continuous heat exchanger to the still and to transfer heat from a condensing line entering the still to the return helium mixture.

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A13. The dilution refrigerator of claim A12, wherein the heat exchange line is further configured to decrease a temperature of helium in the condensing line at a point in the condensing line disposed before a Joule-Thomson expander.

A14. The dilution refrigerator of claim A9, wherein the heat exchange line is configured to maintain the helium mixture in the still at the first temperature.

A15. The dilution refrigerator of claim A12, wherein the heat exchange line comprises
5 one of a counterflow heat exchanger or a cross-counterflow heat exchanger.

A16. The dilution refrigerator of claim A3, wherein the second refrigeration system comprises:

a still disposed inside of the outer vacuum chamber, the still comprising:
10 a ^3He - ^4He mixture in a liquid phase; and
a porous membrane configured to oscillate within the still, creating a standing ^3He concentration wave within the ^3He - ^4He mixture, the standing ^3He concentration wave comprising regions of increased ^3He concentration and regions of decreased ^3He concentration.

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A17. The dilution refrigerator of claim A16, wherein the porous membrane is configured to oscillate such that a region of increased ^3He concentration is disposed at a liquid-vapor barrier within the still.

20 A18. The dilution refrigerator of claim A16, wherein oscillations of the porous membrane impart momentum to the ^3He causing the ^3He to move from a liquid phase to a vapor phase.

A19. The dilution refrigerator of claim A3, wherein the second refrigeration system
25 comprises:

a heat exchanger disposed inside of the outer vacuum chamber, the heat exchanger comprising nanowires.

A20. The dilution refrigerator of claim A19, wherein the nanowires comprise at least
30 one of copper nanowires, silver nanowires, gold nanowires, platinum nanowires, polymer nanowires, carbon nanowires, and/or carbon fiber nanowires.

A21. The dilution refrigerator of claim A20, wherein the heat exchanger is formed by sintering the nanowires.

B1. A dilution refrigerator, comprising:
an outer vacuum chamber configured to fit within a server rack-type container.

5 B2a. The dilution refrigerator of claim B1, wherein the server rack-type container is configured to integrate with commercial server rack infrastructure.

B2b. The dilution refrigerator of claim B1, wherein the server rack-type container is a 19-inch server rack.

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B3. The dilution refrigerator of claim B1, wherein the dilution refrigeration comprises a closed-cycle dilution refrigerator and further comprises:

a first refrigeration system disposed at least partially outside of the outer vacuum chamber,

15 a second refrigeration system disposed at least partially outside of the outer vacuum chamber and thermally coupled to the first refrigeration system; and

a sample plate thermally coupled to a coldest portion of the second refrigeration system.

20 B4. The dilution refrigerator of claim B3, wherein the first refrigeration system comprises at least one compressor disposed outside of the outer vacuum chamber and at least one thermal stage disposed inside of the outer vacuum chamber.

25 B5. The dilution refrigerator of claim B4, wherein the at least one thermal stage comprises a first thermal stage configured to reach a first temperature and a second thermal stage configured to reach a second temperature lower than the first temperature, and wherein the second refrigeration system is thermally coupled to the second thermal stage of the first refrigeration system.

30 B6. The dilution refrigerator of claim B5, wherein the first thermal stage is configured to reach approximately 50K and the second thermal stage is configured to reach approximately 5K.

B7. The dilution refrigerator of claim B3, wherein the second refrigeration system comprises:

at least one pump disposed outside of the outer vacuum chamber and configured to transport ^3He ; and

5 a plurality of thermal stages configured to remove heat from the transported ^3He .

B8. The dilution refrigerator of claim B3, wherein the first refrigeration system is disposed within the same server rack as the dilution refrigerator.

10 B9. The dilution refrigerator of claim B3, wherein the first refrigeration system is disposed within a different server rack than the outer vacuum chamber.

B10. The dilution refrigerator of claim B3, wherein the outer vacuum chamber comprises at least one substantially planar surface disposed within a plane perpendicular
15 to a plane of a floor supporting the dilution refrigerator.

B11. The dilution refrigerator of claim B10, wherein the outer vacuum chamber is generally shaped as a rectangular prism.

20 B12. The dilution refrigerator of claim B10, wherein a sample plate is accessible through one or more openings into the outer vacuum chamber.

B13. The dilution refrigerator of claim B12, wherein the one or more openings comprise hermetic openings.

25

B14. The dilution refrigerator of claim B12, wherein the one or more openings comprise hinged doors and/or removable panels.

B15. The dilution refrigerator of claim B1, further comprising a vibration reduction
30 system coupled to the outer vacuum chamber and configured to reduce vibrations transmitted to the dilution refrigerator.

B16. The dilution refrigerator of claim B15, wherein the vibration reduction system comprises at least one of a magnetic damping system, a mass and spring system, an air cushion system, sand, and/or pliable mats.

5 B17. The dilution refrigerator of claim B1, further comprising an acoustic damping system disposed within the server rack and configured to reduce acoustic vibrations transmitted to the dilution refrigerator.

B18. The dilution refrigerator of claim B17, wherein the acoustic damping system
10 comprises acoustic mufflers.

B19. The dilution refrigerator of claim B3, further comprising electromagnetic shielding coupled to the outer vacuum chamber and/or the second refrigeration system and configured to reduce electromagnetic noise transmitted to the cold head.

15 B20. The dilution refrigerator of claim B19, wherein the electromagnetic shielding comprises Mu-metal shielding and/or Helmholtz coils.

B21. The dilution refrigerator of claim B3, wherein the second refrigeration system is
20 disposed between the sample plate and a floor supporting the dilution refrigerator.

B22. The dilution refrigerator of claim B3, wherein the second refrigeration system comprises a series of thermal stages, and wherein a coldest thermal stage of the thermal stages is disposed above warmer thermal stages of the thermal stages such that the
25 coldest thermal stage is furthest from the floor.

B23. The dilution refrigerator of claim B16, wherein the second refrigeration system comprises a mixing chamber and a de-mixing chamber,
wherein the mixing chamber is disposed further from the floor than the de-mixing
30 chamber, and
the dilution refrigerator further comprises a fountain pump configured to transport ^4He from the de-mixing chamber to the mixing chamber.

B24. The dilution refrigerator of claim B23, wherein the dilution refrigerator further comprises a heat exchanger configured to cool ^4He as it is transported from the de-mixing chamber to the mixing chamber.

- 5 B25. The dilution refrigerator of claim B21, wherein the second refrigeration system comprises a still configured to provide cooling by distilling ^3He vapor from a ^3He - ^4He mixture, and

the still comprises a pumping port including a pipe entering the still from a surface of the still other than a surface of the still furthest from the floor.

10

B26. The dilution refrigerator of claim B21, wherein the pipe enters the still from a surface of the still closest to the floor.

- B27. The dilution refrigerator of claim B26, wherein the pipe is coupled to a trap, the
15 trap comprising a p-trap and a superleak configured to remove superfluid ^4He from the p-trap.

B28. The dilution refrigerator of claim B27, wherein the pipe comprises a physical barrier configured to prevent a liquid helium film from creeping into an outlet of the
20 pipe.

B29. The dilution refrigerator of claim B28, wherein the physical barrier comprises one or more knife edges on the outlet of the pipe.

- 25 B30. The dilution refrigerator of claim B28, wherein the physical barrier comprises a ring barrier on an exterior or interior surface of the pipe.

B31. The dilution refrigerator of claim B28, wherein the physical barrier further comprises a heater.

30

B25. The dilution refrigerator of claim B1, wherein the server rack comprises retractable wheels configured to, when extended, facilitate transportation of the server rack.

- C1. A distributed refrigeration system, comprising:
a pre-cooling system; and
one or more dilution refrigerators thermally coupled to the pre-cooling system.
- 5 C2. The distributed refrigeration system of claim C1, wherein the pre-cooling system is configured to provide a first cooling stage to the one or more dilution refrigerators, the first cooling stage having a temperature at or below 5 K.
- C3. The distributed refrigeration system of claim C1, wherein the one or more
10 dilution refrigerators comprise a first dilution refrigerator, the first dilution refrigerator configured to reach a temperature at or below 1 K.
- C4. The distributed refrigeration system of claim C1, wherein the distributed refrigeration system is configured to be integrated into one or more server racks.
15
- C5. The distributed refrigeration system of claim C4, wherein:
the pre-cooling system is integrated into a first server rack, and
the one or more dilution refrigerators comprise a first dilution refrigerator, the
first dilution refrigeration being integrated into a second server rack different than the
20 first server rack.

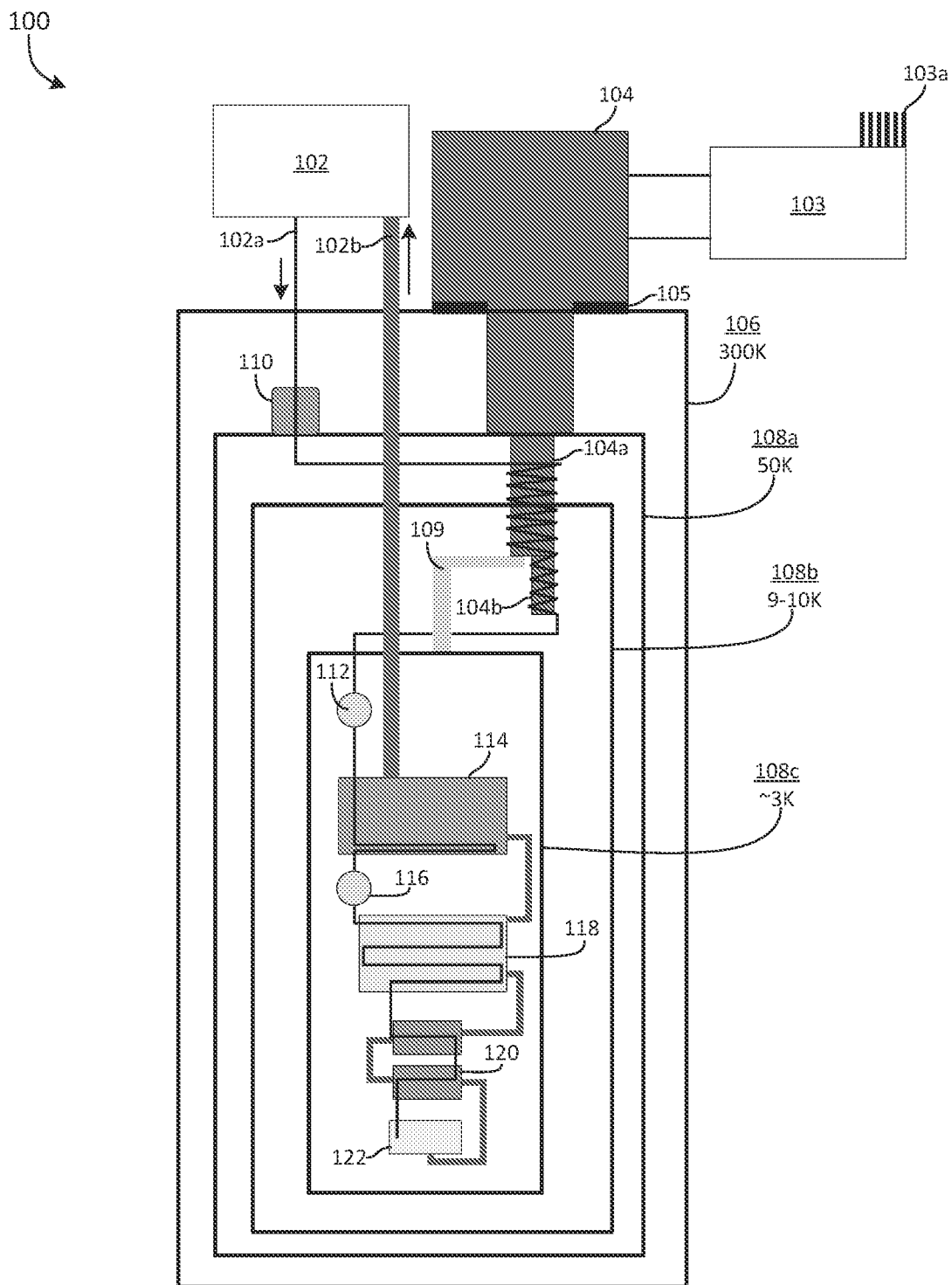


FIG. 1

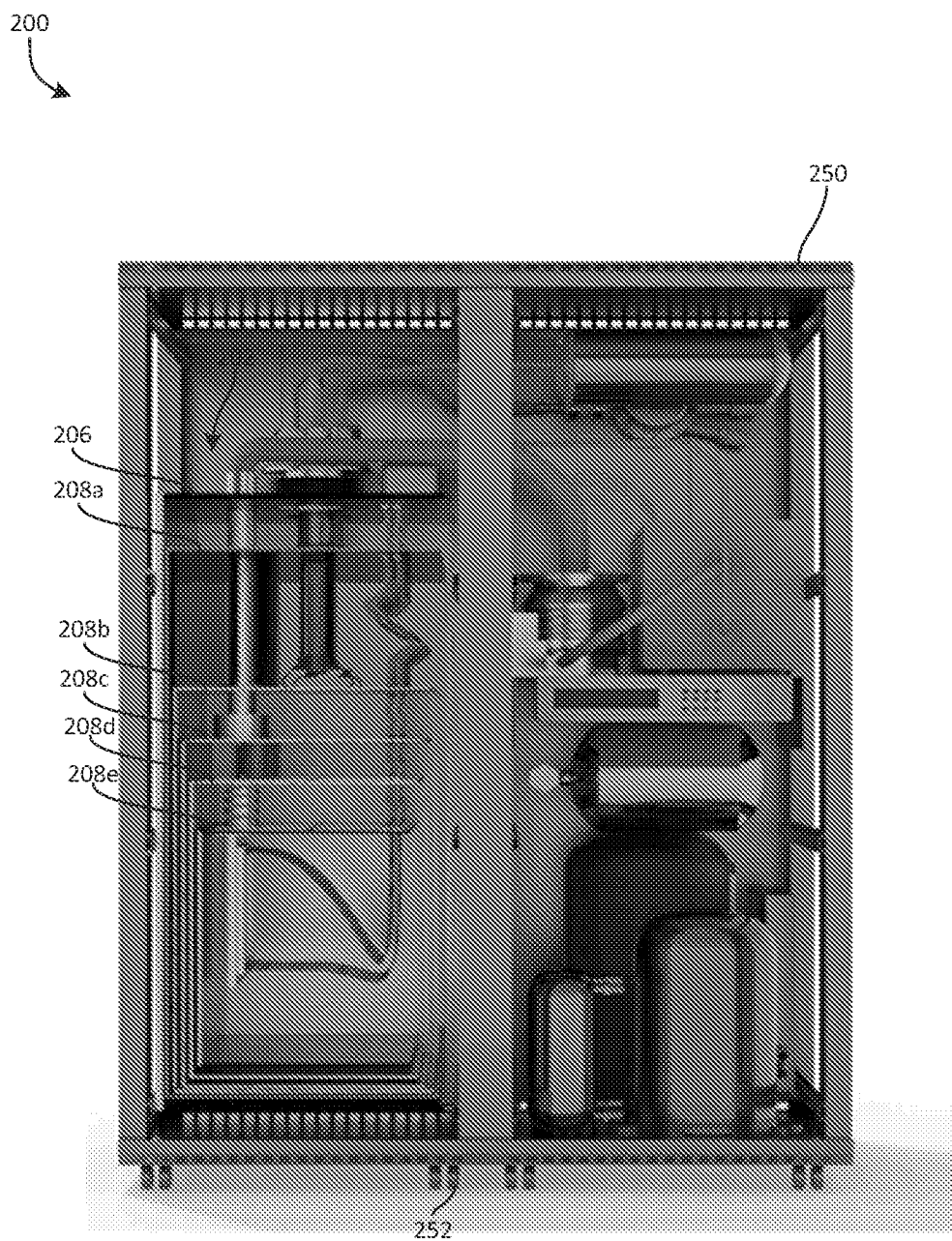


FIG. 2A

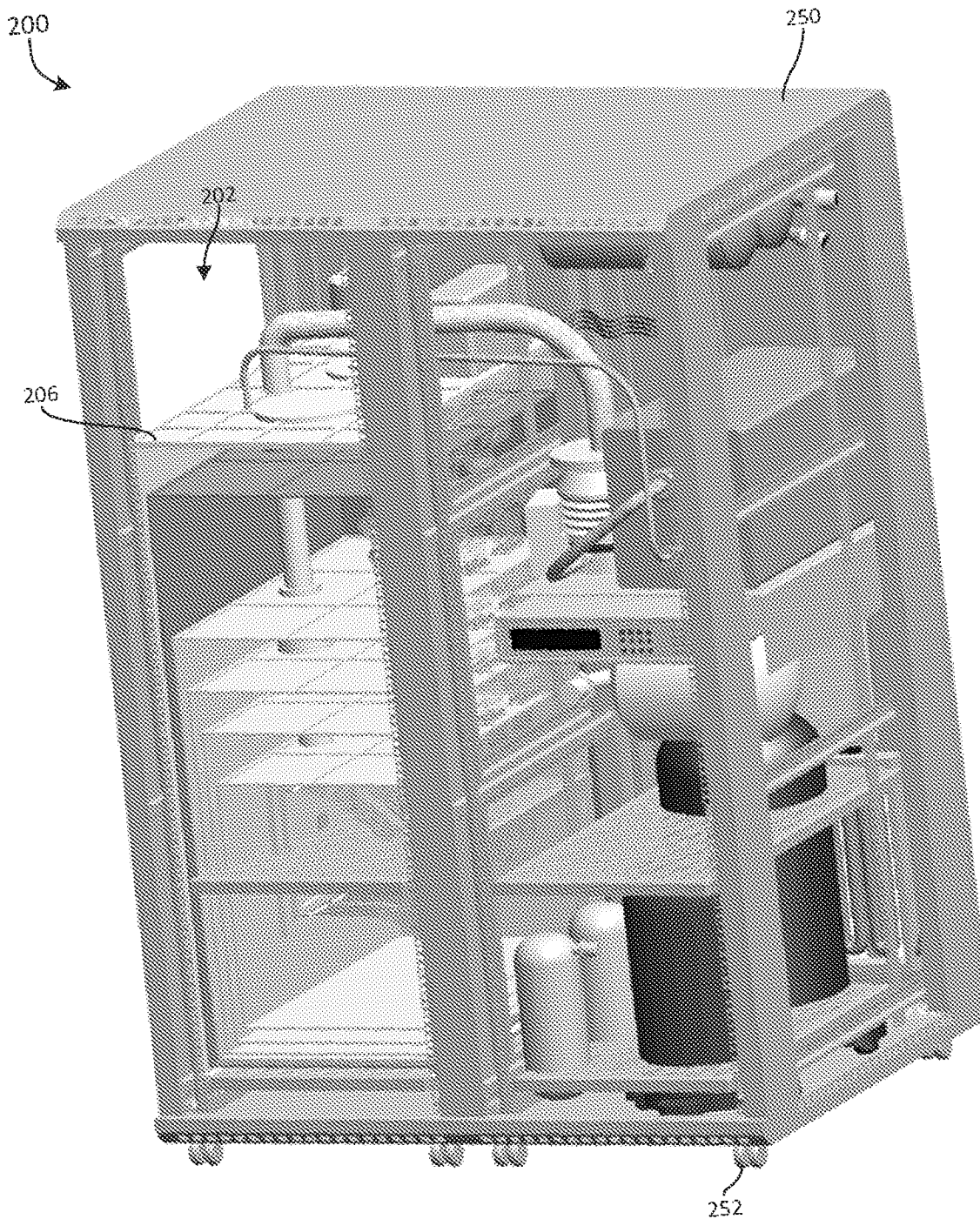


FIG. 2B

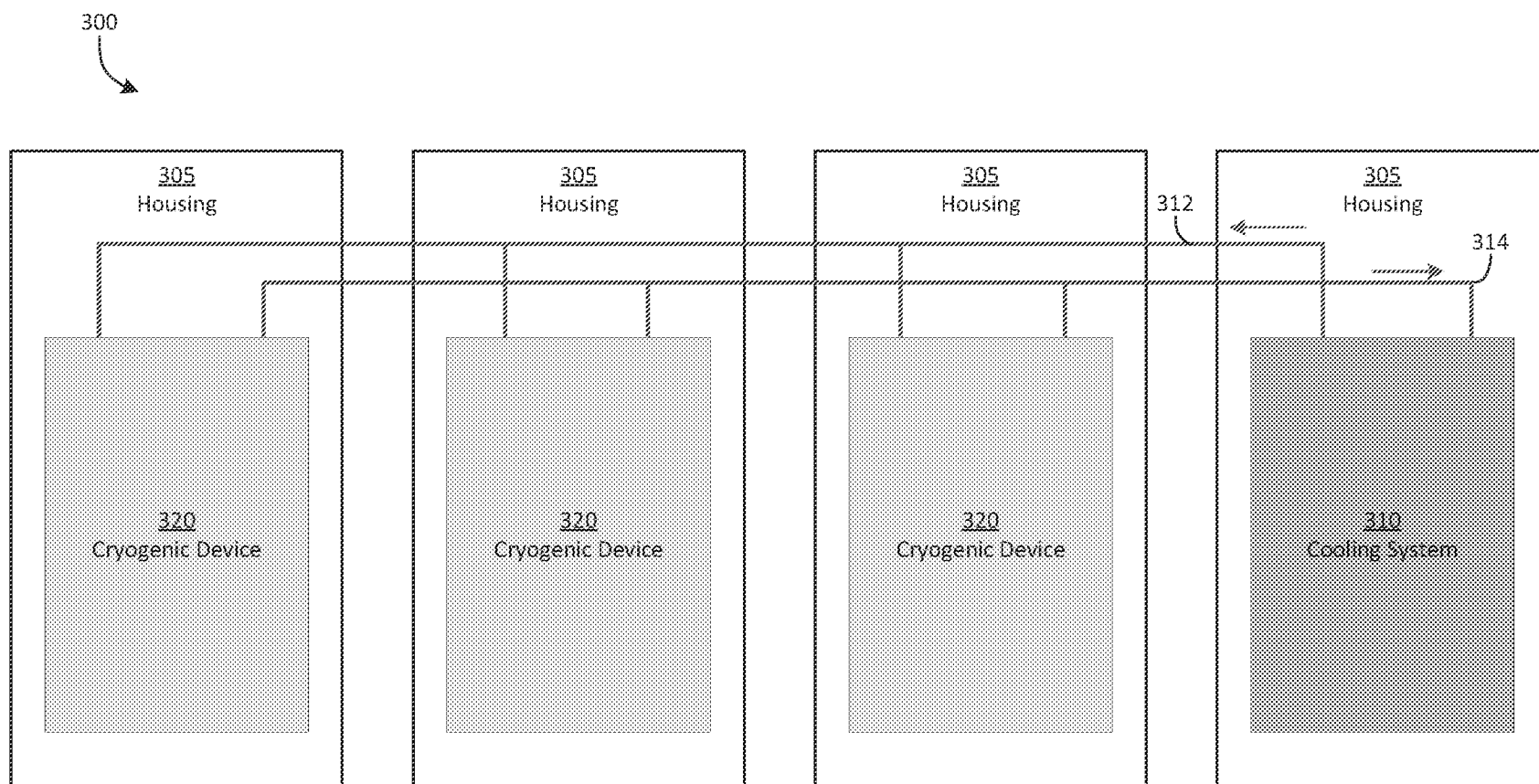


FIG.3

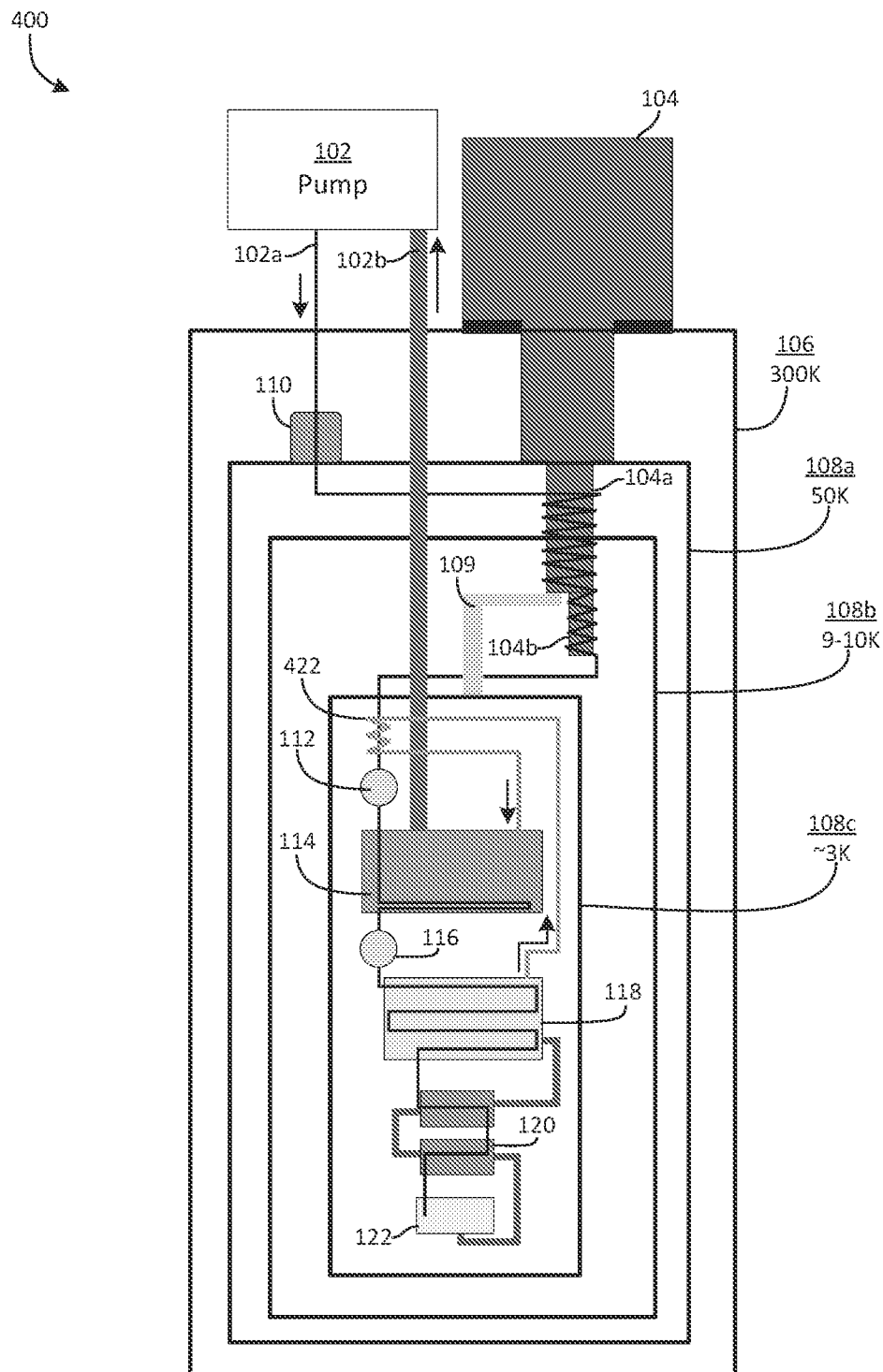


FIG. 4

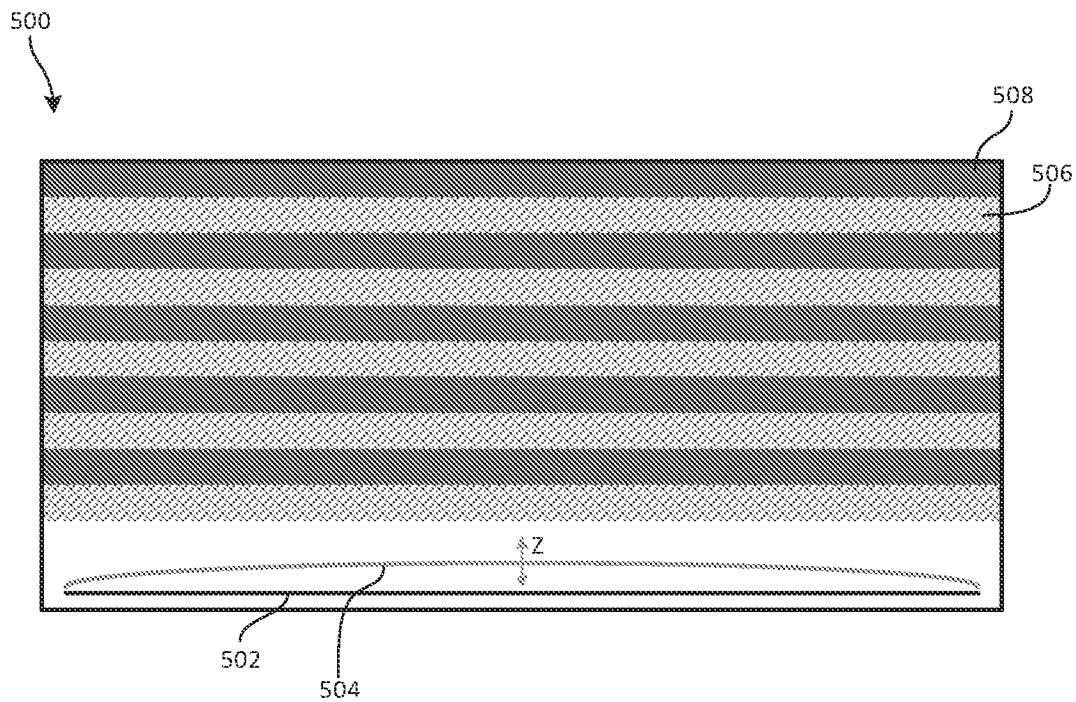


FIG. 5

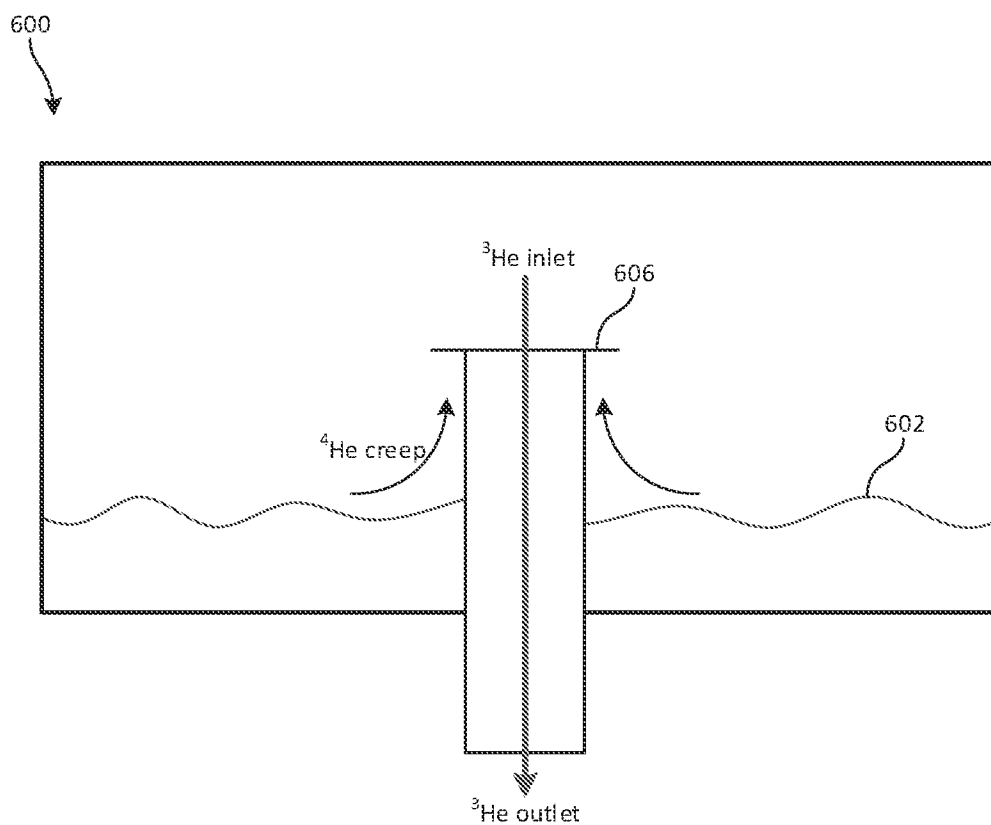


FIG. 6A

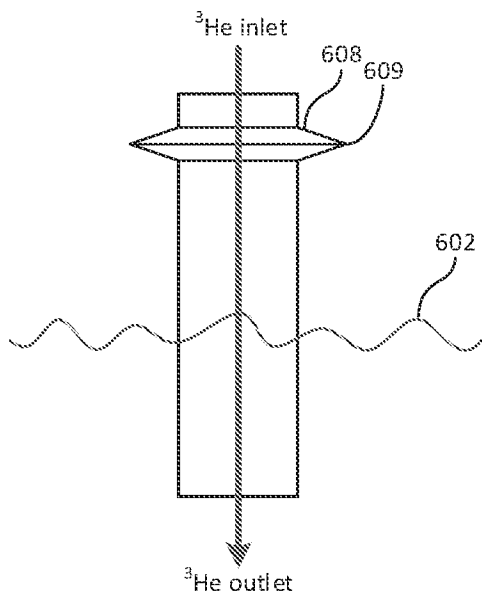


FIG. 6B

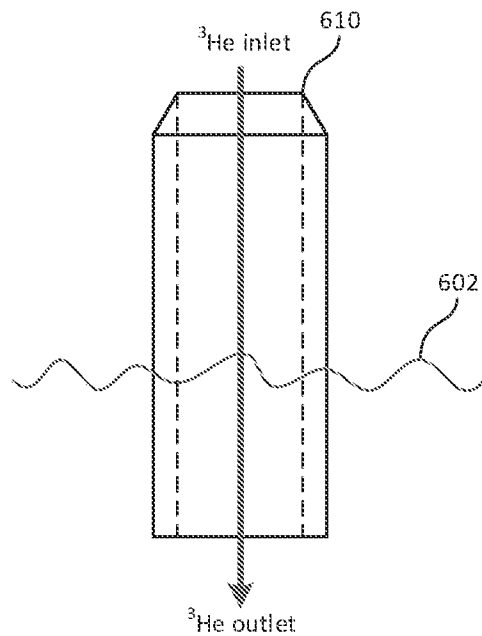


FIG. 6C

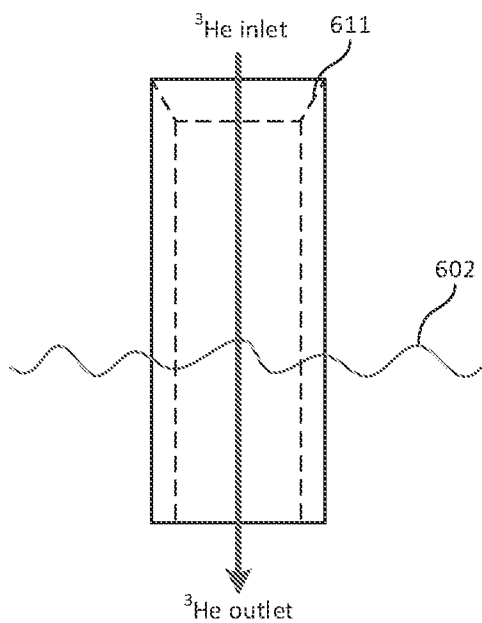


FIG. 6D

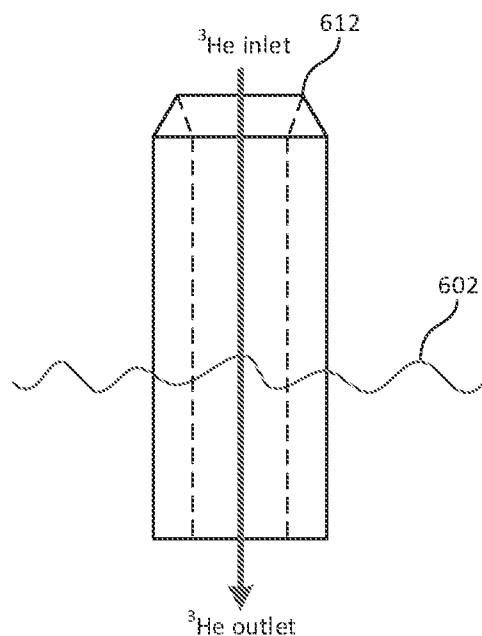


FIG. 6E

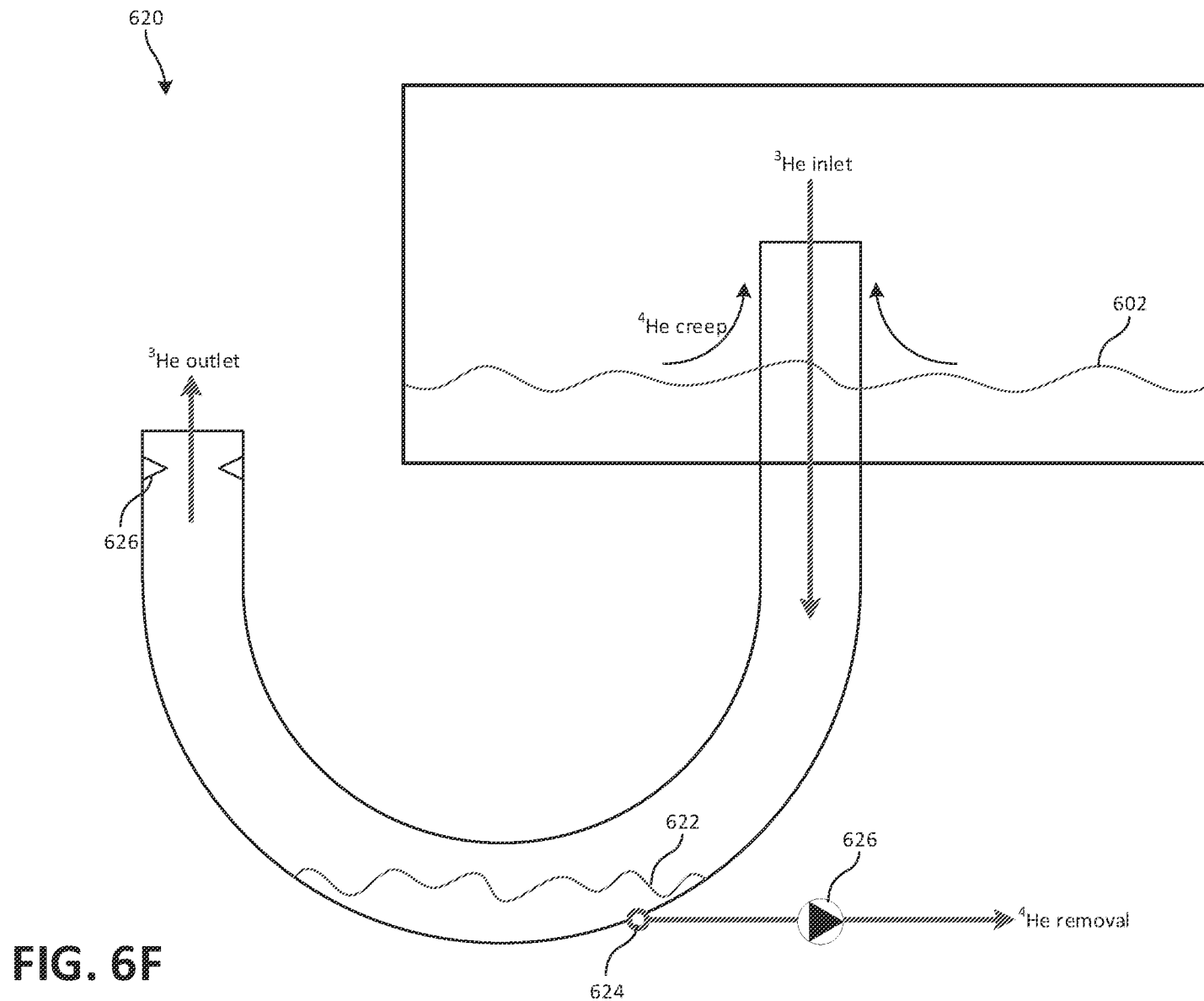
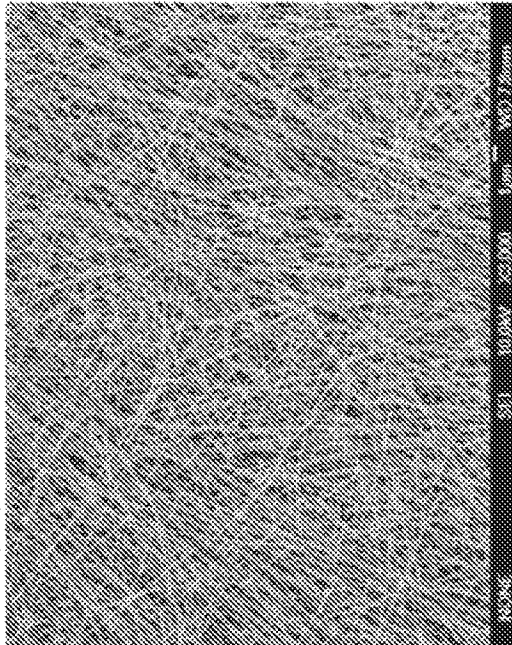
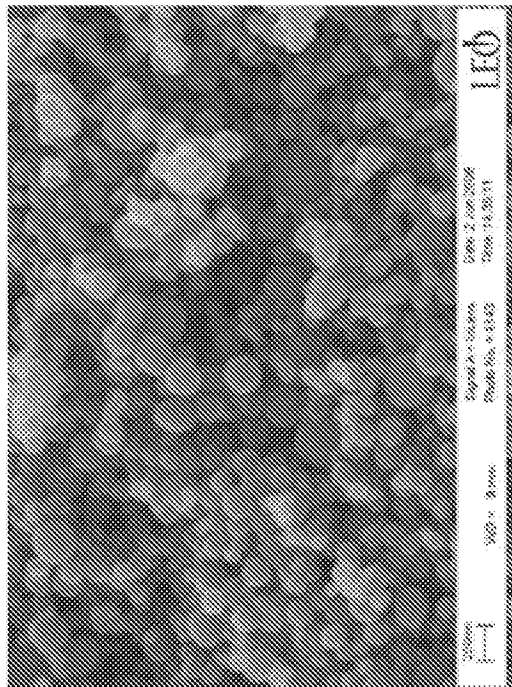


FIG. 6F



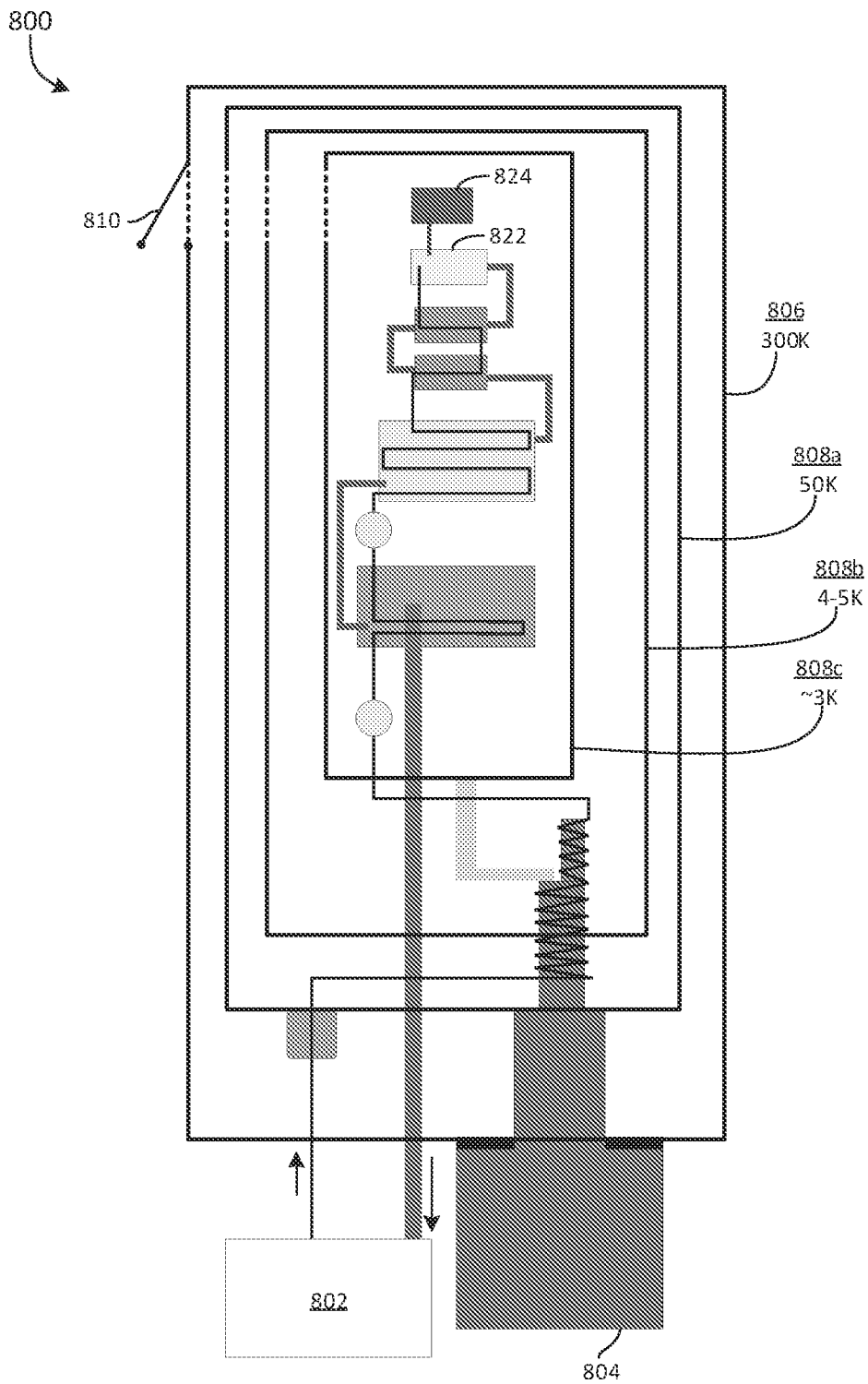


FIG. 8A

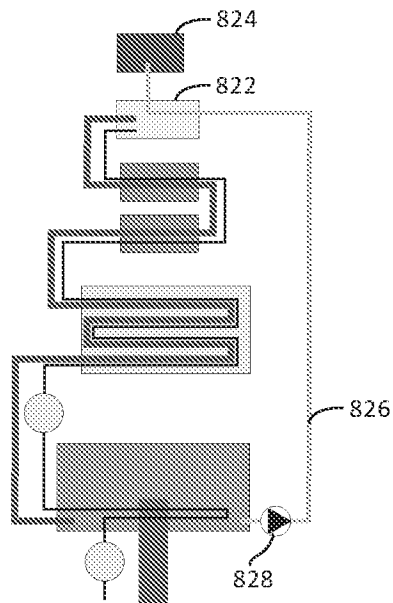


FIG. 8B

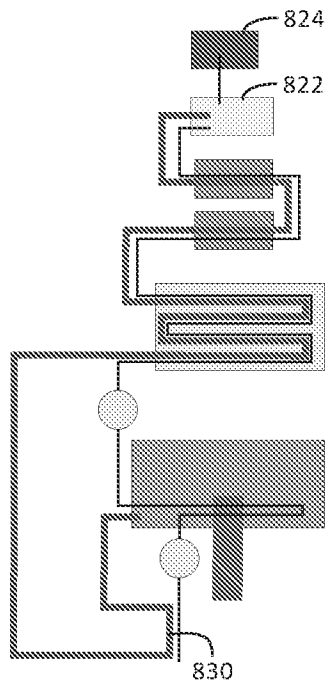


FIG. 8C