

INTEGRATED DILUTION REFRIGERATORS

RELATED APPLICATIONS

5 This provisional application is related to U.S. Provisional Application No. 63/219,795 filed on July 8, 2021 and titled “INTEGRATED DILUTION REFRIGERATORS,” the contents of which are incorporated by reference herein in their entirety.

BACKGROUND

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

BRIEF DESCRIPTION OF DRAWINGS

15 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 with some embodiments described herein.

20 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 some embodiments described herein.

25 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.

30 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 film separation devices, in accordance with some embodiments described herein.

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

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

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

5 FIG. 7D includes images of different nanopellets 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.

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

FIG. 9A is a schematic diagram of another embodiment of a closed-cycle dilution refrigerator, in accordance with some embodiments described herein.

15 FIG. 9B is a close-up view of the schematic diagram of FIG. 9A showing a schematic diagram of a cooldown turbo charger device, in accordance with some embodiments described herein.

FIG. 9C is a close-up view of the schematic diagram of FIG. 9A showing a schematic diagram of helium cleaning devices, in accordance with some embodiments described herein.

20 FIG. 10A shows exemplary components of a removable dilution unit for the dilution refrigerator of FIG. 9A, in accordance with some embodiments described herein.

FIG. 10B shows a close-up view of a thermalization plate insert of the removable dilution unit of FIG. 10A, in accordance with some embodiments described herein.

25 FIG. 10C shows an exemplary implementation of a continuous heat exchanger 919 and discrete heat exchanger 120 of the dilution refrigerator of FIG. 9A, in accordance with some embodiments described herein.

FIG. 11A shows a side view of an exemplary implementation of the dilution refrigerator of FIG. 9A including elements configured to provide vibration isolation, in accordance with some embodiments described herein.

30 FIG. 11B shows an exemplary flexure configured to provide vibration isolation, in accordance with some embodiments described herein.

FIG. 12 shows a side view of an exemplary implementation of the dilution refrigerator of FIG. 9A including elements configured to provide tool-free assembly of the vacuum chamber and access to the experimental volume, in accordance with some embodiments described herein.

FIG. 13 shows another side view of an exemplary implementation of the dilution refrigerator of FIG. 9A including an external support rack and integrated lift configured to raise and lower portions of the vacuum chamber, in accordance with some embodiments described herein.

FIG. 14 shows an exterior view of a housing configured to support a dilution refrigerator, including an integrated desk and opening to an experimental volume of the dilution refrigerator, in accordance with some embodiments described herein.

FIG. 15 depicts, schematically, an illustrative computing device on which aspects of the technology described herein may be implemented.

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 3-5K. 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 also be, for example, a filter and mesh heat exchanger, in some embodiments.

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.

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, 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 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 and/or heat pipes (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 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 effect heat exchange between the ^3He and the cryocooler 104 and to provide vibrational isolation, in some embodiments.

5 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
10 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 and/or pressure of the ^3He . For example, in some embodiments, the ^3He may be at approximately 3-5K before entering
15 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.

20 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 .

25 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 and/or coflow heat exchanger. The ^3He may be cooled by the first heat exchanger 118 to a temperature of approximately 20 mK.

30 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 10-20mK.

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.

5 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
10 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
15 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
20 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.).

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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
30 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 with a lower pressure differential. Such a configuration can improve the 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.

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

Second sound is a quantum mechanical phenomenon present in superfluid helium that may be produced in a number of ways. For example, 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.

5 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, 10 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 15 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.) 20 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.

25 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, 30 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. Nanomaterial 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 should 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 nanomaterials with structures other than powder particulates, can provide advantages across all of the above-described criteria. Accordingly, the inventors have developed nanomaterial heat exchangers that provide efficient heat exchange via the nanomaterials' large surface area, high mechanical contact strength, and good neck growth between nanowires.

FIG. 7B shows an image of a nanomaterial comprising nanowires for use in a heat exchanger, FIG. 7C shows an image of a nanomaterial comprising nanoclusters for use in a heat exchanger, and FIG. 7D shows images of nanomaterials comprising different examples of nanopellet shapes for use in a heat exchanger, in accordance with some embodiments described herein. It should be appreciated that FIGs. 7B-7D show examples of nanomaterial shapes, but that embodiments of nanomaterial for use in a discrete heat exchanger are not so limited. For example, the nanomaterial may alternatively be a nanofoam, nanotube, and/or any other suitable nanoshape.

In some embodiments, such a nanomaterial-based heat exchanger may be formed by bonding the nanomaterial through sintering. For example, the nanomaterial may be formed as a chemical precipitate and/or by electronic deposition or electroplating techniques. A substrate with a rough surface (e.g., comprising nucleation sites) may be provided for the nanomaterial to be grown on or adhered to. In some embodiments, the heat exchanger may be produced under heat and/or compression. The nanomaterial may be held in compression during the sintering process to form the nanowire heat exchanger. In some embodiments, the substrate may be patterned with macroscopic structures (e.g., a lattice or series of posts). In some embodiments, the substrate may be a tube, and the nanomaterial may be adhered to the interior or exterior surface of the tube. In some embodiments, the substrate may be formed of a material with a lower thermal conductivity than the nanomaterial adhered to the substrate.

In some embodiments, the nanomaterial may be formed out of one of a selection of vacuum-compatible materials including but not limited to copper, silver, vacuum-compatible polymers, carbon, and/or carbon fiber. For example, the nanomaterial may be nanowires comprising 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 ^3He 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 .

IX. Dilution Refrigerator with Improved Cooldown

5 During initial cooldown, closed-cycle dilution refrigerators conventionally use an auxiliary compressor to cause the flow of warm helium, which initially resists such movement, and to pressurize the helium to reach the pressure needed to start isenthalpic expansion. These mechanical pumps are costly, prone to reliability issues, frequently leak, and can cause performance degradation over time. The inventors have recognized and
10 appreciated that, alternatively, helium may be pulsed through the dilution refrigerator during cooldown without the use of an auxiliary mechanical pump, enabling a faster and more efficient cooldown process.

FIG. 9A is a schematic diagram of another embodiment of a closed-cycle dilution refrigerator 900, in accordance with some embodiments described herein. The dilution
15 refrigerator 900 is similar to the dilution refrigerator 100 as described in connection with FIG. 1 herein but includes additional components. As compared to dilution refrigerator 100, the dilution refrigerator 900 additionally includes helium filters 922, a switching system 924, a cooldown turbo charger device 926, a bypass device 911a, and an additional continuous heat exchanger 919. It should be appreciated that one or more of these
20 additional components could also be integrated into the dilution refrigerator 100 in some embodiments.

FIG. 9B is a close-up view of the schematic diagram of FIG. 9A showing a schematic diagram of a cooldown turbo charger device 926, in accordance with some
25 embodiments described herein. The cooldown turbo charger device 926 includes a volume of a high surface-area material 926a, a heater 926b, and a valve 926c. The heater 926b and the valve 926c are communicatively coupled to a controller 928. The controller 928 may be, for example, a computer as described in connection with FIG. 15 herein.

In some embodiments, the high surface-area material 926a may be thermally coupled to a radiation shield. In the example of FIG. 9B, the high surface-area material
30 926a is thermally coupled to the radiation shield 108b, though it should be appreciated that the high surface-area material 926a could be thermally coupled to another radiation shield in some embodiments (e.g., radiation shield 108a). The high surface-area material 926a may comprise a material with a porous and/or textured surface such that helium adsorbs to the high surface-area material 926a during the cooldown process. For example, the high

surface-area material 926a may comprise activated charcoal or a metal powder (e.g., a copper or silver powder). In some embodiments, the valve 926c (e.g., a heat switch) may be opened (e.g., such that helium does not flow to the lower stages of the dilution refrigerator 900) based on pressure or temperature or in response to a signal generated by controller 928. While the valve 926c is opened, the helium may adsorb onto the high surface-area material 926a.

In some embodiments, after helium has adsorbed onto the high surface-area material 926a, the valve 926d (e.g., a heat switch) may be opened and the valve 926c may be closed in response to temperature, pressure, and/or a signal generated by controller 928. The heater 926b may also be caused, at a same or similar time, to heat the high surface-area material 926a in response to a signal generated by controller 928. For example, the heater 926b may be a resistive heater that is caused to heat the high surface-area material 926a by a flow of current through the heater 926b. In this way, the helium adsorbed to the high surface-area material 926a may act as a reserve that, when heated, is caused to be released from the high surface-area material 926a, increasing the pressure in the remainder of the helium intake path of the dilution refrigerator 900. This increase in pressure enables the start of isenthalpic expansion and speeds cooling of the dilution refrigerator 900.

In some embodiments, once the helium has been released from the high surface-area material 926a, the valve 926c may be opened and the heater 926b may be turned off by the controller 928, allowing new helium to adsorb to the high surface-area material 926a. The controller 928 may be configured to periodically (e.g., at regular time intervals, at irregular time intervals, at time intervals determined by the temperature of the experimental volume, at time intervals determined by the pressure of the experimental volume) open and/or close the valves 926c, 926d and operate the heater 926b to flush the helium intake path. In some embodiments, the controller 928 may be configured to “pulse” the helium from the high surface-area material 926a through the helium intake path, causing the dilution refrigerator to be cooled.

A. Helium Filtering

Contaminants in the helium flowing through the dilution refrigerator can clog the capillaries and lead to performance degradation or system failure. To reduce the risk of contaminants making their way into the system, helium is typically fed through an external ‘cleaning trap’ filled with liquid nitrogen before entering the dilution unit. These external traps must be refilled with liquid nitrogen at frequent intervals, which requires user

maintenance and interaction. The inventors have recognized and appreciated that passive helium filters, without the need for refilling of liquid nitrogen, can improve the user experience and reduce maintenance frequency of a dilution refrigeration system.

FIG. 9C is a close-up view of the schematic diagram of FIG. 9A showing a schematic diagram of helium cleaning devices 922, in accordance with some embodiments described herein. The helium cleaning devices 922 are coupled to the helium intake from pump system 102 by a switching system 924 that is external to the outer vacuum chamber 106. The switching system 924 includes one or more helium-compatible valves (e.g., three helium-compatible valves). The switching system 924 allows for switching of helium flow between each of the helium cleaning devices 922. In this manner, one helium cleaning device 922 may be used for actively filtering helium while the other may be cleaned (e.g., by heating and pumping out of impurities), enabling indefinite periods of operation of the dilution refrigerator 900.

In some embodiments, the helium cleaning devices 922 include a counter flow heat exchanger 922a, a trap 922b, and a gas gap heat exchanger 922c. The counter flow heat exchanger 922a and the gas gap heat exchanger 922c reduce the thermal load of the trap 922b and eliminate the use of cryogenic valves. The trap 922b may include, for example, a charcoal trap and/or another high surface-area material (e.g., a metal powder) configured to capture non-helium impurities in the dilution refrigerator 900.

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B. Diffusive Control of Helium Flow During Cooldown

During the initial cooldown of a dilution refrigerator, the helium flow rate is low due to the large impedance of the Joule-Thomson expanders in the system and the warm, low density, and viscous circulating helium. This reduced helium flow rate reduces the rate of cooling of the lower portions of the refrigerator. To combat this effect, a needle valve can be incorporated prior to the Joule-Thomson expander to reduce the impedance of the initially-warm gas. The inventors have recognized and appreciated that the helium flow rate may be improved without reliance on a mechanical component such as a needle valve.

Returning to FIG. 9A, the dilution refrigerator 900 may include a bypass device 911a, in some embodiments. The bypass device 911a may be disposed on a bypass line 911b that bypasses the Joule-Thomson expander 112. The bypass device 911a includes a sheet of a vacuum-compatible polymer material (e.g., Kapton, PEEK, mylar). At temperatures above approximately 150K, helium will diffuse easily through such a sheet

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of polymer. The bypass device 911a allows for the high impedance of the Joule-Thomson expander 112 to be circumvented when the helium is warm, thereby increasing the helium flow rate and rate of cooling of the dilution refrigerator 900. When the dilution refrigerator 900 has cooled sufficiently, the helium will no longer diffuse through the bypass device 911a and instead will flow through the Joule-Thomson expander 112.

C. Removable Dilution Unit and Heat Exchangers

The inventors have further recognized and appreciated that the user experience may be improved by allowing users to easily swap parts in and out of the dilution refrigerator 900 (e.g., for maintenance, to change the characteristics of the dilution refrigerator 900, and/or to upgrade the dilution refrigerator 900 as technological improvements are made). The inventors have accordingly developed a “swappable” dilution unit that is easily removed and replaced. FIG. 10A shows exemplary components of a removable dilution unit 1040 for the dilution refrigerator 900 of FIG. 9A, in accordance with some embodiments described herein.

In some embodiments, the removable dilution unit 1040 includes plates 1040a, 1040b, 1040c removably coupled to thermalization plates 1032, 1034, and 1036, respectively. As shown in the example of FIG. 10A, the plates 1040a, 1040b, and 1040c may be removably coupled using mechanical fasteners (e.g., bolts and/or screws). In some embodiments, the removable dilution unit 1040 further includes detachable connections above the still (e.g., flanges) to further simplify replacement of the removable dilution unit 1040.

FIG. 10B shows a close-up of a plate 1040b of the removable dilution unit of FIG. 10A, in accordance with some embodiments described herein. The plate 1040b includes an input (right) and an outlet (left, downward arrow) to allow helium to flow through the plate 1040b, in some embodiments.

In some embodiments, the plates 1040a, 1040b, and/or 1040c may include integrated heat exchangers. The integrated heat exchangers may be channels formed in the plates 1040a, 1040b, and/or 1040c. The channels may be configured to have a high surface area. By allowing helium to flow through the plates 1040a, 1040b, and 1040c, the helium’s rate of cooling may be increased. In some embodiments, the channels may be formed by machining and/or by additive fabrication techniques.

In some embodiments, the dilution unit 1040 may include additional heat exchangers. FIG. 10C shows an exemplary implementation of a continuous heat exchanger

919 and discrete heat exchanger 120 (e.g., as described in connection with FIGs. 7A-7D herein) of the dilution refrigerator of FIG. 9A, in accordance with some embodiments described herein. The continuous heat exchanger 919 is disposed below the thermalization plate 1034. The thermalization plate 1034 may be an intermediate cold plate (ICP) configured to be cooled to a temperature of approximately 100mK. While continuous heat exchangers are more efficient than discrete heat exchangers, they become less efficient below approximately 80mK. Adding a short continuous heat exchanger 919 below the ICP 1034 may enable the ICP to operate with more cooling power at a higher temperature during cooldown.

In some embodiments, the dilution refrigerator 900 may further include combined gas gap and superconducting heat switches between thermal stages of the dilution refrigerator 900. The example of FIG. 10C shows such a combined gas gap and superconducting heat switch 1050 thermally coupled between thermalization plates 1032 and 1036. Refrigeration cycles in cryogenic coolers typically use a method to control the flow of heat throughout the system. This control may be achieved with a superconductor, gas gap, or other mechanisms to make or break a thermal connection between components within the system (i.e., heat switches). One common type of heat switch, a gas gap, typically comprises two high surface area objects with a small gap between them that is filled with a gas. As the system falls below a certain temperature, the conductive gas is adsorbed onto surface area in the heat switch, creating a vacuum and reducing heat transfer between the surfaces. Another common type of heat switch is a superconducting switch where a material passes through a superconducting transition and reduces thermal conductivity. The combined gas gap and superconducting heat switches 1050 include both a superconducting material (e.g., aluminum, titanium) that becomes superconducting at a temperature higher than a target temperature of the thermalization plate to which it is thermally coupled and a gas gap heat switch.

D. Vibration Isolation

Many experiments conducted at sub-Kelvin temperatures are sensitive to vibrational noise both from the surrounding environment and the cooling system pumps and components. Additionally, at sub-Kelvin temperatures, vibration can be a source of heat load on the dilution refrigerator. The inventors have recognized and appreciated that improved vibration isolation can improve the cooling power and other performance characteristics (e.g., magnetic flux disruption) of a dilution refrigerator.

FIG. 11A shows a side view of an exemplary implementation of the dilution refrigerator of FIG. 9A including elements configured to provide vibration isolation, and FIG. 11B shows an exemplary flexure 1142 configured to provide vibration isolation, in accordance with some embodiments described herein. The vibration isolation elements 1140 are configured to suspend the thermal stages below the innermost radiation shield 108c from the upper interior surface of the vacuum chamber 106. This independent suspension of the lower thermal stages vibrationally isolates them from the radiation shields 108a, 108b, thereby improving the vibration isolation of the lower thermal stages. In some embodiments, the vibration isolation elements 1140 include one or more springs 1142 and one or more connectors 1144 (e.g., rods or other connection mechanisms). The springs 1142 may be leaf suspension springs, in some embodiments, and the connectors 1144 may be configured to have a low spring constant (e.g., comprising spring steel).

E. Tool-Free Assembly and Integrated Lift

FIG. 12 shows a side view of an exemplary implementation of the dilution refrigerator 900 including elements configured to provide tool-free assembly of the vacuum chamber and access to the experimental volume, in accordance with some embodiments described herein. As shown in the example of FIG. 12, the vacuum chamber includes three sections, a first section (top), a second section suspended from the first section (middle), and a third section (bottom) suspended from the second section. It should be appreciated that the technology described herein is not limited to three sections, and that a vacuum chamber may have one, two, four, or five sections, in some embodiments.

In some embodiments, the vacuum chamber may include an opening to provide access to the experimental volume within the dilution refrigerator 900. The opening may be sealed by a door 1260, as shown in the example of FIG. 12. The door may be sealed, for example, using a hinge or clamp that may be manually engaged and disengaged.

In some embodiments, the three sections of the vacuum chamber are coupled to one another by integrated clamps and/or cams 1250. These integrated cams comprise handles that enable a user to unclamp the sections of the vacuum chamber from one another without the use of any tools. To ensure a proper seal between the three sections of the vacuum chamber, a rubber O-ring, copper or indium gasket, or other compressive layer may be included between the three sections of the vacuum chamber.

In some embodiments, the three sections of the vacuum chamber may be removed either in full or partially. For example, the three sections of the vacuum chamber may

comprise removable panels (e.g., side panels, panels attached to a frame, etc.), in some embodiments.

In some embodiments, the dilution refrigerator 900 may be supported by an external support rack. The external support rack may include an integrated lift configured to support the three sections of the vacuum chamber during assembly and/or maintenance of the dilution refrigerator 900. FIG. 13 shows another side view of an exemplary implementation of the dilution refrigerator 900 including an external support rack and integrated lift 1372 configured to raise and lower sections 106a, 106b, and 106c of the vacuum chamber, in accordance with some embodiments described herein. The external support rack may be a server-rack enclosure (e.g., compatible with 19-inch server racks), in some embodiments. The integrated lift 1372 may be removably coupled to the external support rack (e.g., slidably removable from the external support rack) to provide extra space to the user (e.g., during maintenance). In some embodiments, the integrated lift 1372 may be operated manually (e.g., using screws and/or cables). In some embodiments, the integrated lift 1372 may be operated using an electronically-operated machine (e.g., pneumatic or hydraulic devices).

G. External Housing

FIG. 14 shows an exterior view of a housing 1400 configured to support a dilution refrigerator, including an integrated desk and opening to an experimental volume of the dilution refrigerator, in accordance with some embodiments described herein. The housing 1400 may house, for example, dilution refrigerators 100 and/or 900 as described herein.

In some embodiments, the housing 1400 includes an integrated horizontal surface 1480. For example, the integrated horizontal surface 1480 may be used as a desk or support surface when the user interacts with the dilution refrigerator. The integrated horizontal surface 1480 may be configured to be stowed by folding (as shown in the example of FIG. 14) or sliding away when not in use. In some embodiments, the housing 1400 may further include one or more storage locations (e.g., drawers, shelves) for the storage of related parts and/or tools for maintenance of the dilution refrigerator.

In some embodiments, the housing 1400 may further include a door 1490 providing access to the experimental volume of the dilution refrigerator. For example, the door 1490 may open to provide access to the experimental volume through the vacuum chamber exterior and the radiation shields inside of the vacuum chamber. In some embodiments, the vacuum chamber exterior and/or the radiation shields may be coupled to the door 1490

such that when a user opens the door 1490, they open the vacuum chamber exterior and/or the radiation shields. In some embodiments, the radiation shields may alternatively be slidably and/or hingedly movable such that the user may move the radiation shields such that they no longer block access to the experimental volume as needed.

5 In some embodiments, the housing 1400 may further be configured to perform sound dampening. For example, the housing 1400 may include sound dampening materials to perform passive sound dampening. Alternatively or additionally, the housing 1400 may include audio equipment (e.g., speakers) configured to provide active sound dampening through the emission of destructive interference of the sounds generated by functional
10 components of the system.

 In the embodiment shown in FIG. 15, the computer 1500 includes a processing unit 1501 having one or more processors and a non-transitory computer-readable storage medium 1502 that may include, for example, volatile and/or non-volatile memory. The
15 memory 1502 may store one or more instructions to program the processing unit 1501 to perform any of the functions described herein. The computer 1500 may also include other types of non-transitory computer-readable medium, such as storage 1505 (e.g., one or more disk drives) in addition to the system memory 1502. The storage 1505 may also store one or more application programs and/or resources used by application programs (e.g.,
20 software libraries), which may be loaded into the memory 1502.

 The computer 1500 may have one or more input devices and/or output devices, such as devices 1506 and 1507 illustrated in FIG. 15. These devices can be used, among other things, to present a user interface. Examples of output devices that can be used to provide a user interface include printers or display screens for visual presentation of output
25 and speakers or other sound generating devices for audible presentation of output. Examples of input devices that can be used for a user interface include keyboards and pointing devices, such as mice, touch pads, and digitizing tablets. As another example, the input devices 1507 may include a microphone for capturing audio signals, and the output devices 1506 may include a display screen for visually rendering, and/or a speaker
30 for audibly rendering, recognized text.

 As shown in FIG. 15, the computer 1500 may also comprise one or more network interfaces (e.g., the network interface 1510) to enable communication via various networks (e.g., the network 1520). Examples of networks include a local area network or a wide area network, such as an enterprise network or the Internet. Such networks may be based

on any suitable technology and may operate according to any suitable protocol and may include wireless networks, wired networks or fiber optic networks. Such networks may include analog and/or digital networks.

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:

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 and/or heat pipes 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.

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

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

10 a still disposed inside of the outer vacuum chamber, the still comprising:
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
15 regions of decreased ^3He concentration.

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.

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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.

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

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

30 A20. The dilution refrigerator of claim A19, wherein the nanomaterial comprises at least one of nanowires, nanofoams, nanopellets, and/or nanotubes.

A21. The dilution refrigerator of claim A19, wherein the nanomaterial comprises nanowires. comprise at least one of copper nanowires, silver nanowires, gold nanowires,

platinum nanowires, polymer nanowires, carbon nanowires, and/or carbon fiber nanowires.

5 A22. The dilution refrigerator of claim A20, wherein the heat exchanger is formed by sintering the nanomaterial.

A23. The dilution refrigerator of claim A20, wherein the nanomaterial is formed by in situ material growth.

10 A24. The dilution refrigerator of claim A20, wherein the heat exchanger is formed by etching.

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

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

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

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

25 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 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.

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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.

5 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.

10 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.

15 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

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.

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

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

30 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.

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

5 B15. The dilution refrigerator of claim B1, further comprising a vibration reduction 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
10 comprises at least one of a magnetic damping system, a mass and spring system, an air cushion system, sand, and/or pliable mats.

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

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

20 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.

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

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

30 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 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 chamber, and

5 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-

10 mixing chamber to the mixing chamber.

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

15 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.

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

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

25 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 pipe.

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

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.

5 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.
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- 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.

D1. A dilution refrigerator, comprising:

a first thermal stage configured to be cooled to a first temperature;

a second thermal stage configured to be cooled to a second temperature lower than the first temperature;

5 a high-surface area material thermally coupled to the first thermal stage and configured to cause helium to adsorb to the high-surface area material during a cooldown cycle of the dilution refrigerator; and

at least one heater thermally coupled to the high-surface area material and configured to cause the adsorbed helium to release from the high-surface area material

10 and to be cooled by moving from the first thermal stage to the second thermal stage.

D2. The dilution refrigerator of claim D1, further comprising:

a helium intake path disposed between a helium inlet and the second thermal stage, the high-surface area material being disposed along the helium intake path

15 between the helium inlet and the second thermal stage; and

at least one valve disposed along the helium intake path between the helium inlet and the high-surface area material and configured to, when closed, cause the adsorbed helium to be moved from the first thermal stage to the second thermal stage.

20 D3. The dilution refrigerator of claim D1, wherein:

the first thermal stage is configured to reach approximately 50K; and

the second thermal stage is configured to reach approximately 4K.

D4. The dilution refrigerator of claim D1, wherein the high-surface area material

25 comprises one of activated charcoal or a metal powder.

D5. The dilution refrigerator of claim D1, further comprising:

a non-transitory computer-readable memory comprising computer-readable instructions; and

30 a control system comprising one or more computer processors coupled to the non-transitory computer-readable memory, the control system configured to execute the instructions to cause the control system to, during a cooldown process:

control the at least one valve disposed along the helium intake path to open and close; and

operate the at least one heater to heat the high-surface area material.

D6. The dilution refrigerator of claim D5, wherein the control system is further configured to, at both a first point in time and a second point in time after the first point in time:

control the at least one valve disposed along the helium intake path to open and close; and

operate the at least one heater to heat the high-surface area material.

D7. The dilution refrigerator of claim D2, wherein the first thermal stage and the second thermal stage are disposed within a vacuum chamber, and the dilution refrigerator further comprises:

a first helium filter disposed within the vacuum chamber and between the helium inlet and the first thermal stage;

a second helium filter disposed within the vacuum chamber and between the helium inlet and the first thermal stage; and

at least one valve disposed external to the vacuum chamber and configured to switch a flow of helium along the helium intake path between the first and second helium filters.

D8. The dilution refrigerator of claim D7, wherein the first helium filter and/or the second helium filter comprise a charcoal trap.

D9. The dilution refrigerator of claim D7, further comprising:

a first gas gap heat exchanger disposed between the first helium filter and the first thermal stage; and

a second gas gap heat exchanger disposed between the second helium filter and the first thermal stage.

D10. The dilution refrigerator of claim D7, further comprising:

a first counterflow heat exchanger disposed between the first helium filter and the helium inlet; and

a second counterflow heat exchanger disposed between the second helium filter and the helium inlet.

D11. The dilution refrigerator of claim D1, further comprising:

an experimental volume configured to be cooled to a third temperature lower than the second temperature; and

5 a discrete heat exchanger disposed between the second thermal stage and the experimental volume, the discrete heat exchanger comprising a nanomaterial.

D12. The dilution refrigerator of claim D11, wherein the nanomaterial comprises at least one of nanowires, nanofoams, nanopellets, and/or nanotubes.

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D13. The dilution refrigerator of claim D12, wherein the nanomaterial comprises nanowires. comprise at least one of copper nanowires, silver nanowires, gold nanowires, platinum nanowires, polymer nanowires, carbon nanowires, and/or carbon fiber nanowires.

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D14. The dilution refrigerator of claim D11, wherein the discrete heat exchanger is formed by sintering the nanomaterial.

D15. The dilution refrigerator of claim D1, further comprising:

20 an experimental volume configured to be cooled to a third temperature lower than the second temperature; and

a dilution unit disposed between the second thermal stage and the experimental volume, the dilution unit being detachably coupled to one or more structures disposed between the second thermal stage and the experimental volume.

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D16. The dilution refrigerator of claim D15, wherein the dilution unit is coupled to one or more thermalization plates, the one or more thermalization plates being detachably coupled to the one or more structures disposed between the second thermal stage and the experimental volume.

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D17. The dilution refrigerator of claim D15, wherein the dilution unit comprises a premeasured gas mixture of ^3He and ^4He .

D18. The dilution refrigerator of claim D16, wherein the one or more thermalization plates include integrated heat exchangers.

5 D19. The dilution refrigerator of claim D18, wherein the integrated heat exchangers comprise channels formed in the one or more thermalization plates through which a helium fluid flows during operation of the dilution refrigerator.

D20. The dilution refrigerator of claim D19, wherein the channels are formed by one of machining and/or additive manufacturing.

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D21. The dilution refrigerator of claim D1, further comprising:

an experimental volume configured to be cooled to a third temperature lower than the second temperature;

15 an intermediate cold plate disposed between the experimental volume and the second thermal stage, the intermediate cold plate configured to be cooled to a fourth temperature between the second and third temperatures; and

a continuous heat exchanger disposed between the intermediate cold plate and the experimental volume.

20 D22. The dilution refrigerator of claim D21, further comprising:

a discrete heat exchanger disposed between the continuous heat exchanger and the experimental volume.

D23. The dilution refrigerator of claim D1, further comprising:

25 an experimental volume configured to be cooled to a third temperature lower than the second temperature;

a Joule-Thomson expander disposed between the second thermal stage and the experimental volume; and

30 a bypass disposed between the second thermal stage and the experimental volume, the bypass configured to allow helium to bypass the Joule-Thomson expander when the helium is warmer than 150K.

D24. The dilution refrigerator of claim D23, wherein the bypass comprises a polymer configured to allow helium to diffuse through the polymer when the helium is warmer than 150K.

- 5 D25. The dilution refrigerator of claim D1, further comprising:
an experimental volume configured to be cooled to a third temperature lower than the second temperature;
thermalization plates disposed between the experimental volume and the second thermal stage; and
10 a gas gap heat switch disposed between the experimental volume and at least one of the thermalization plates, the gas gap heat switch comprising a material configured to transition to a superconducting state below a fourth temperature.

15 D26. The dilution refrigerator of claim D25, wherein the fourth temperature is between the second and third temperatures.

- D27. The dilution refrigerator of claim D1, further comprising:
a vacuum chamber housing the first and second thermal stages;
a first suspension system coupled between an interior surface of the vacuum
20 chamber and the first thermal stage; and
a second suspension system coupled between the interior surface of the vacuum chamber and the second thermal stage.

25 D28. The dilution refrigerator of claim D27, wherein the first and second suspension system comprise one or more of springs and/or rods.

- D29. The dilution refrigerator of claim D1, further comprising:
an experimental volume configured to be cooled to a third temperature lower than the second temperature;
30 a vacuum chamber housing the first thermal stage, the second thermal stage, and the experimental volume, wherein the vacuum chamber comprises an opening providing access to the experimental volume from an exterior of the vacuum chamber.

D30. The dilution refrigerator of claim D29, wherein the opening comprises a door.

D31. The dilution refrigerator of claim D29, wherein the vacuum chamber comprises:
a first section; and

5 a second section suspended from the first section; and
wherein the first section is coupled to the second section by integrated clamps
and/or cams.

D32. The dilution refrigerator of claim D31, wherein the first and/or second section of
the vacuum chamber are configured to be partially and/or fully removed from the
10 dilution refrigerator to provide access to at least the first and/or second thermal stages.

D33. The dilution refrigerator of claim D32, wherein the first and/or second section
comprise multiple removable panels.

15 D34. The dilution refrigerator of claim D31, further comprising:
an external system configured to lift and/or lower the first and/or second sections of the
vacuum chamber.

D35. The dilution refrigerator of claim D34, wherein the external system comprises
20 pneumatic or hydraulic devices.

D36. The dilution refrigerator of claim D34, wherein the external system is integrated
into a server-rack enclosure.

25 D37. The dilution refrigerator of claim D36, wherein the external system is removably
coupled to the server-rack enclosure.

D38. The dilution refrigerator of claim D1, further comprising:
a vacuum chamber housing the first and second thermal stages; and
30 a system disposed in the vacuum chamber, the system configured to slide the first
and second thermal stages horizontally out from the vacuum chamber.

D39. The dilution refrigerator of claim D38, wherein the system comprises one of rails,
rollers, and/or detachable flanges.

D40. A dilution refrigerator system comprising:
a dilution refrigerator of any one of claims D1-D39; and
an external housing, wherein the external housing comprises a door providing
5 access to the experimental volume of the dilution refrigerator.

D41. The dilution refrigerator system of claim D40, wherein one or more radiation
shields of the dilution refrigerator are coupled to the door of the external housing.

10 D42. The dilution refrigerator system of claim D40, wherein one or more radiation
shields of the dilution refrigerator may be slidably and/or hingedly moveable to provide
access to the experimental volume.

D43. The dilution refrigerator system of claim D40, wherein the external housing
15 further comprises an integrated horizontal surface.

D44. The dilution refrigerator system of claim D43, wherein the integrated horizontal
surface may be stowed as a part of the external housing.

20 D45. The dilution refrigerator system of claim D40, wherein the external housing
further comprises one or more storage locations configured to store tools and/or parts.

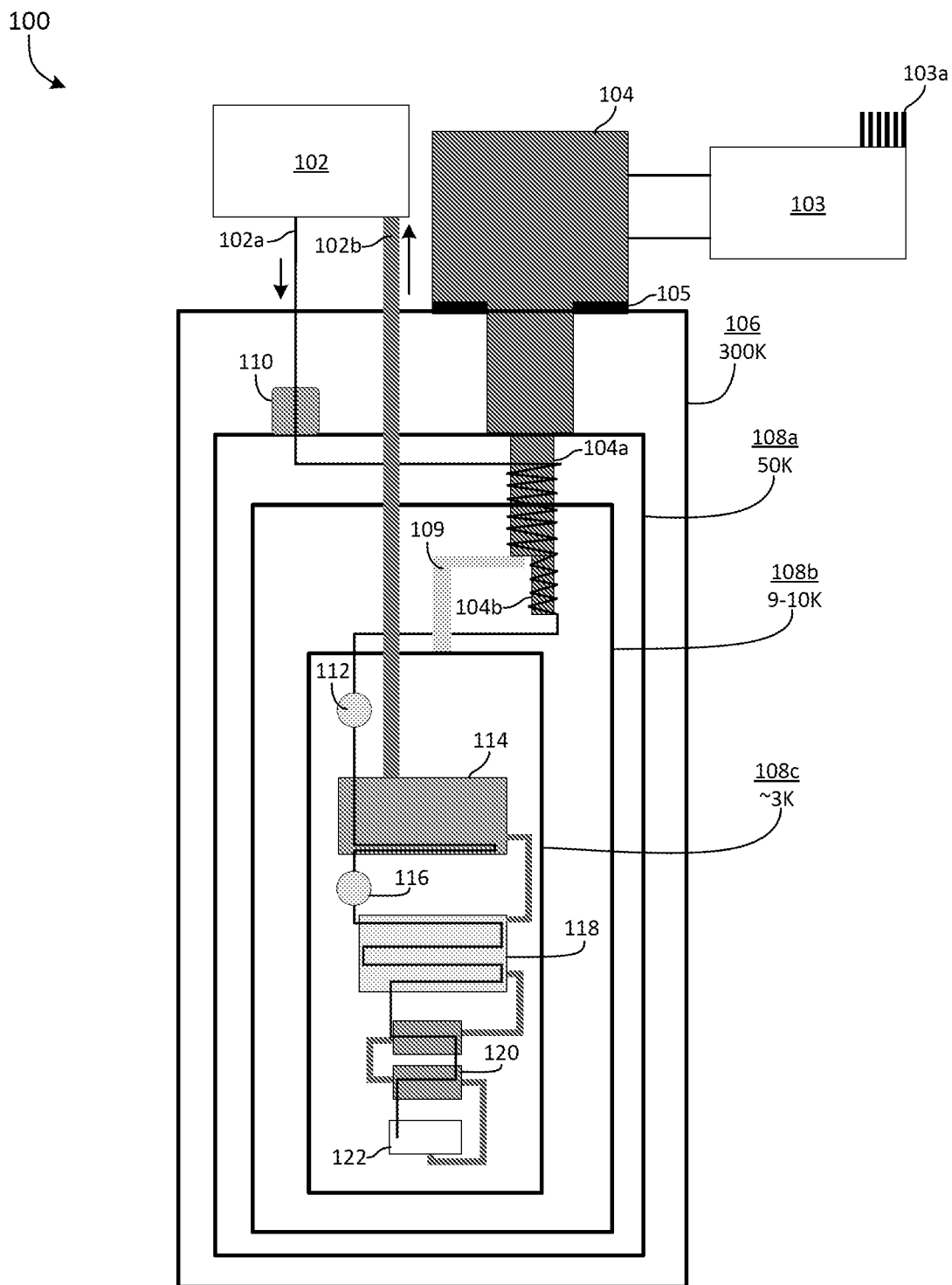


FIG. 1

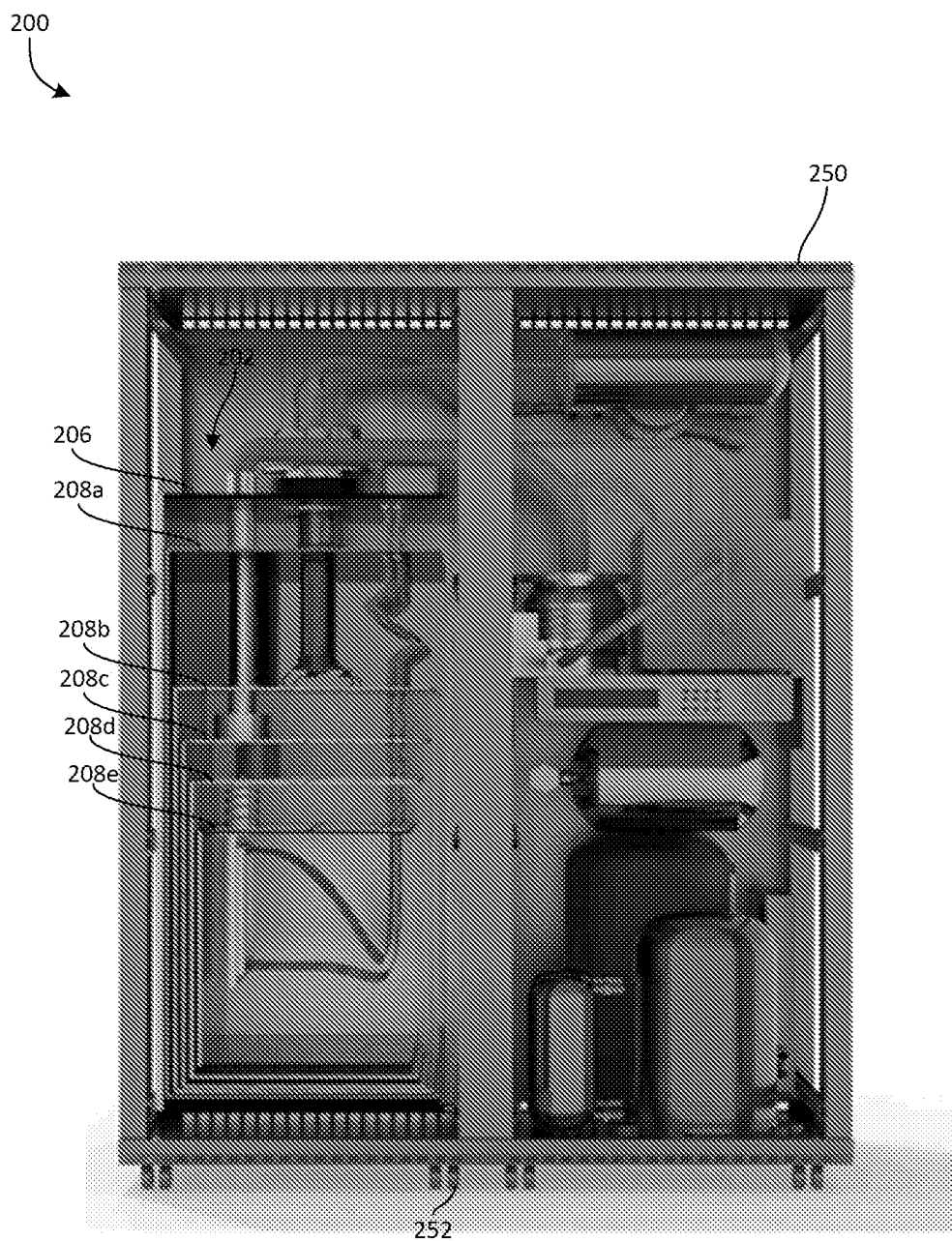


FIG. 2A

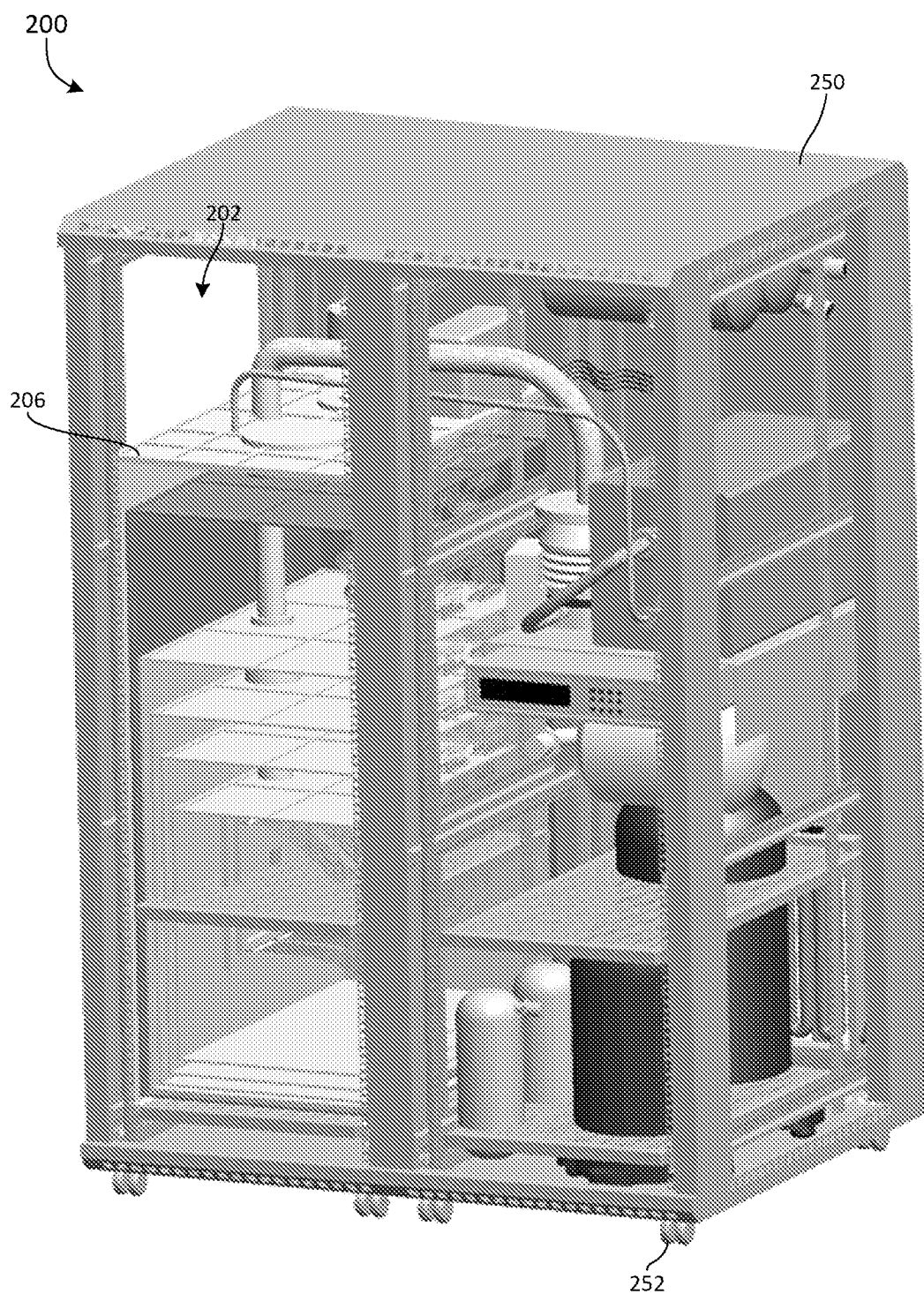


FIG. 2B

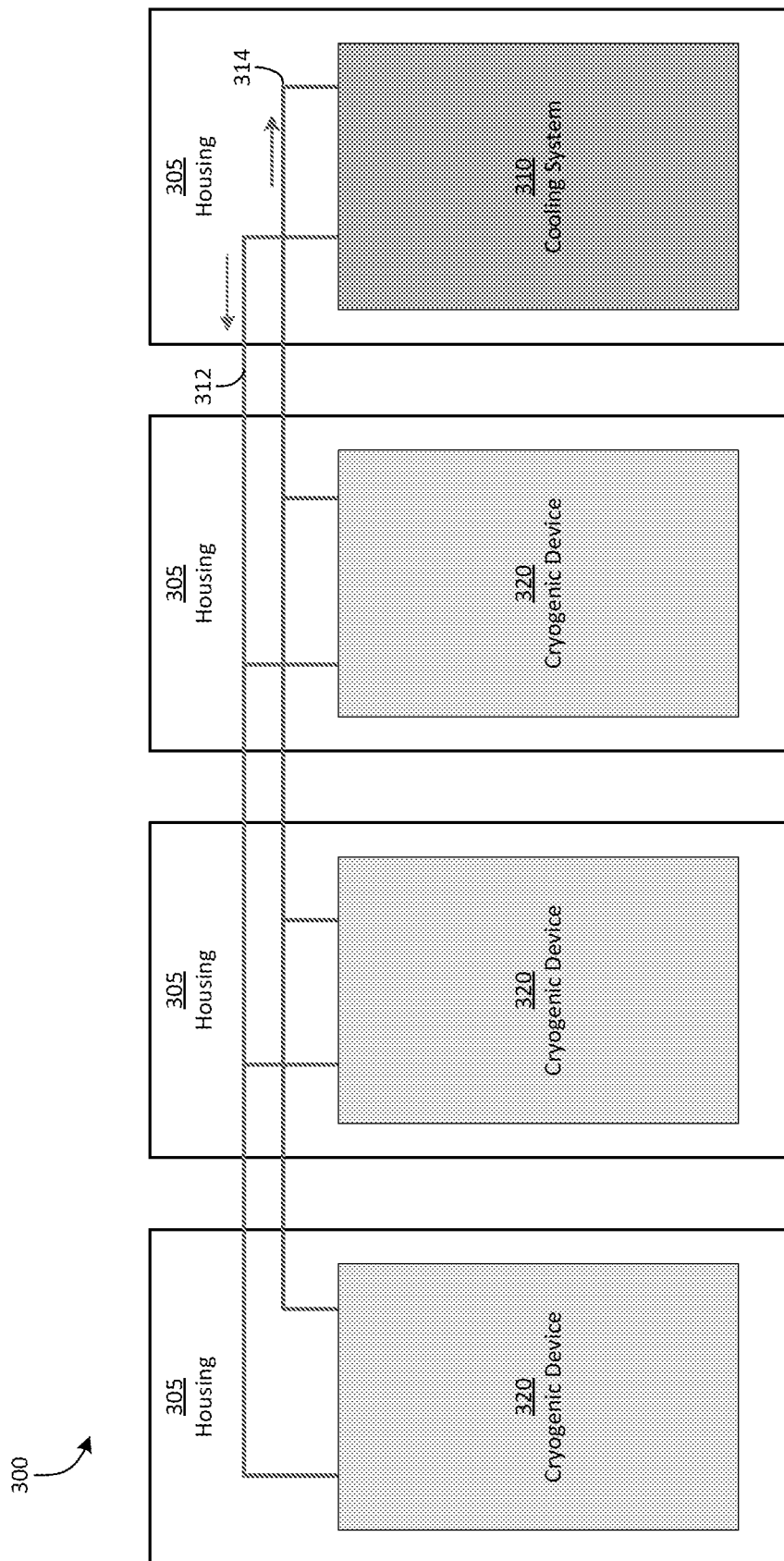


FIG. 3

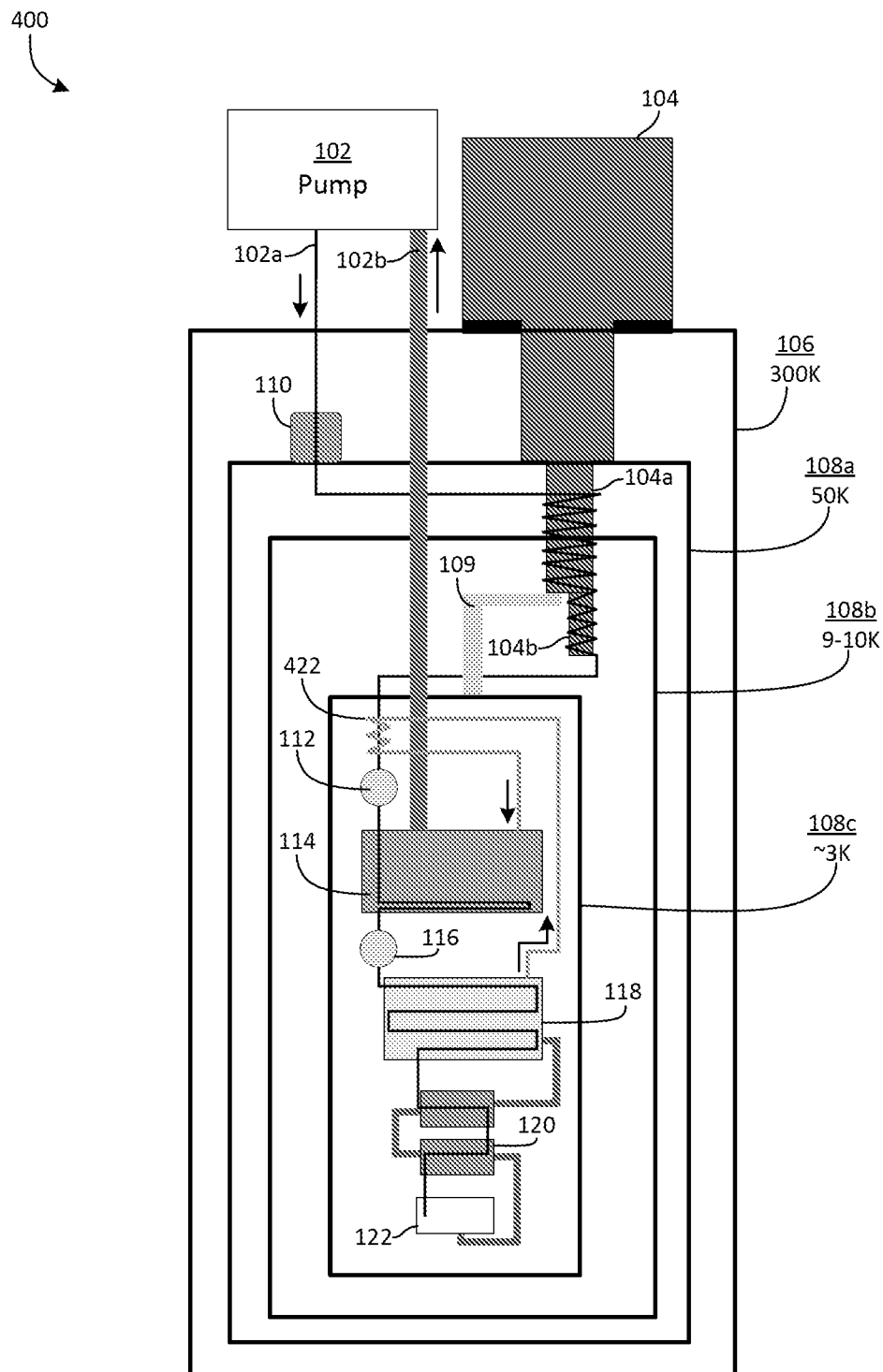


FIG. 4

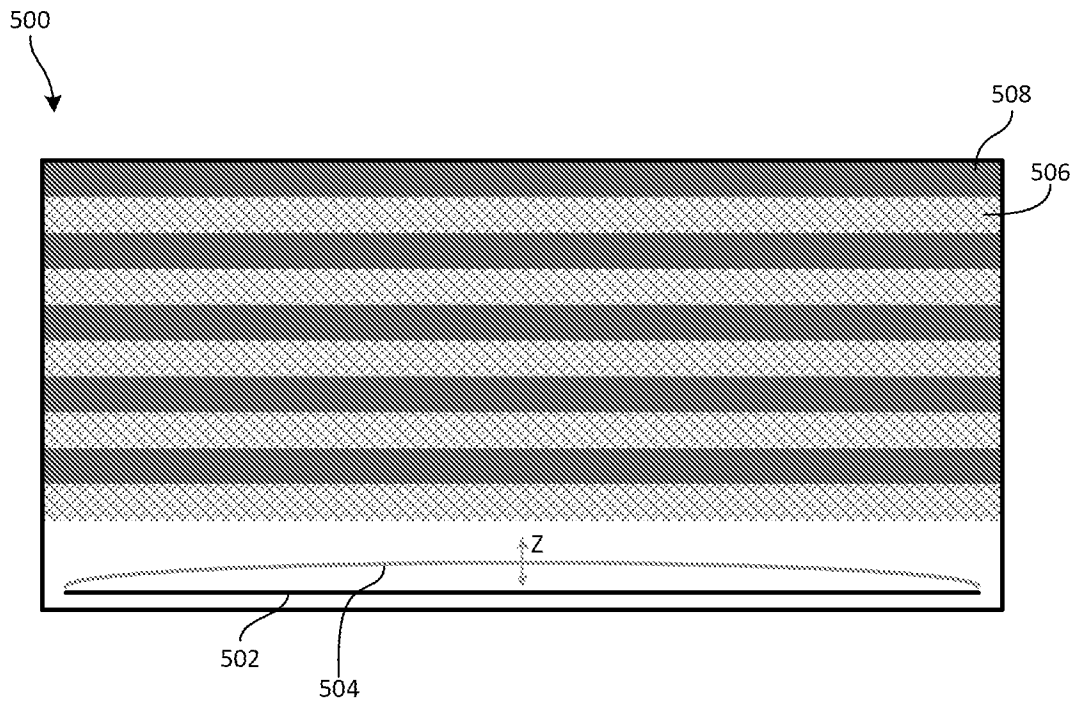


FIG. 5

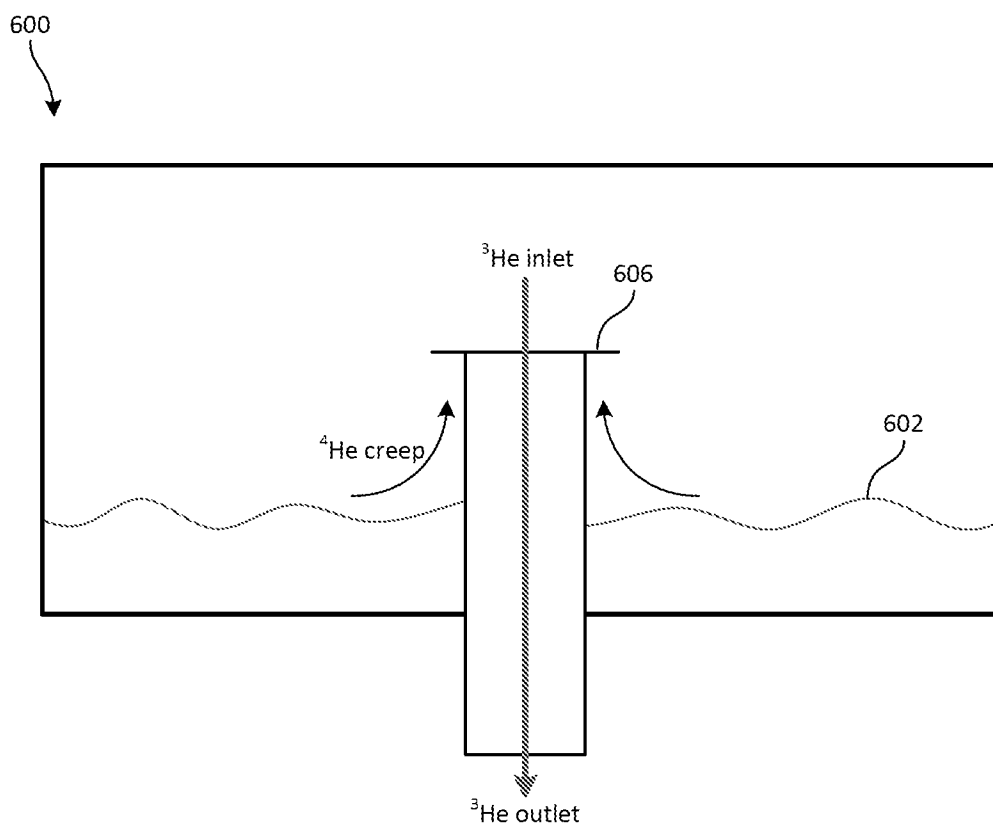


FIG. 6A

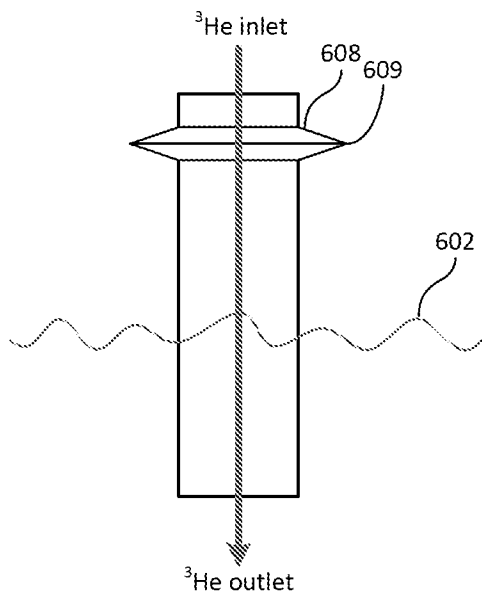


FIG. 6B

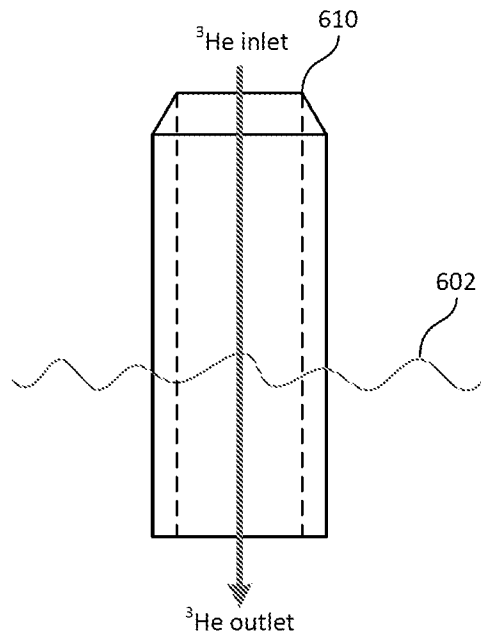


FIG. 6C

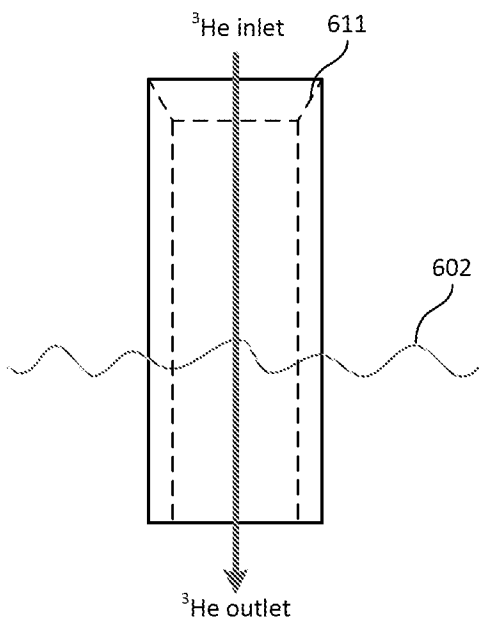


FIG. 6D

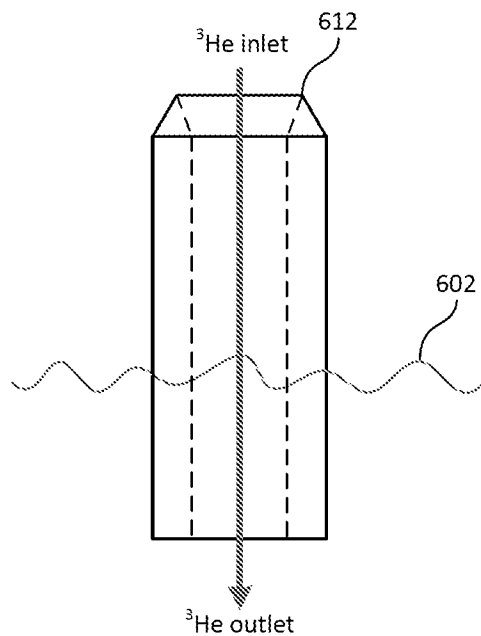


FIG. 6E

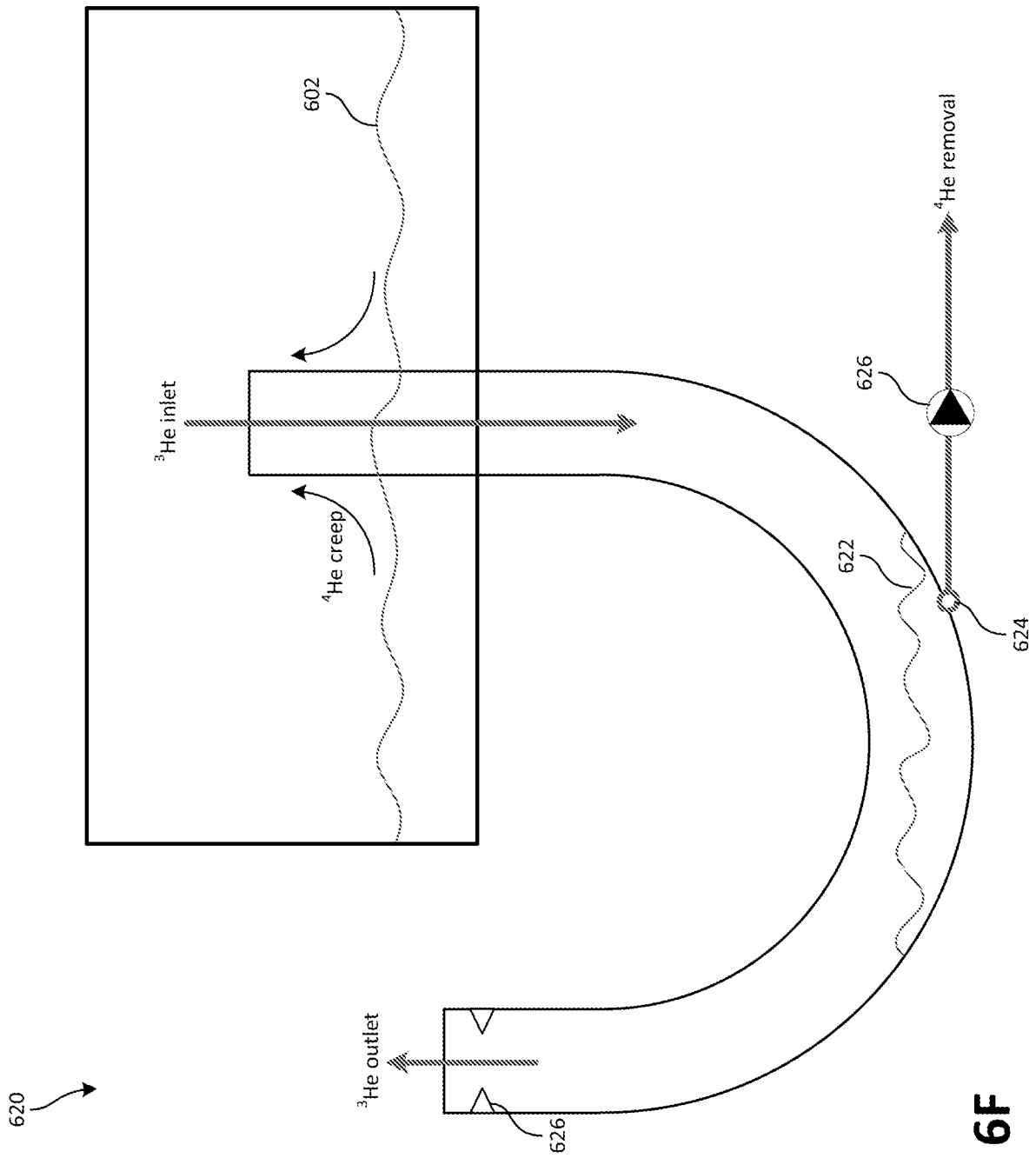


FIG. 6F

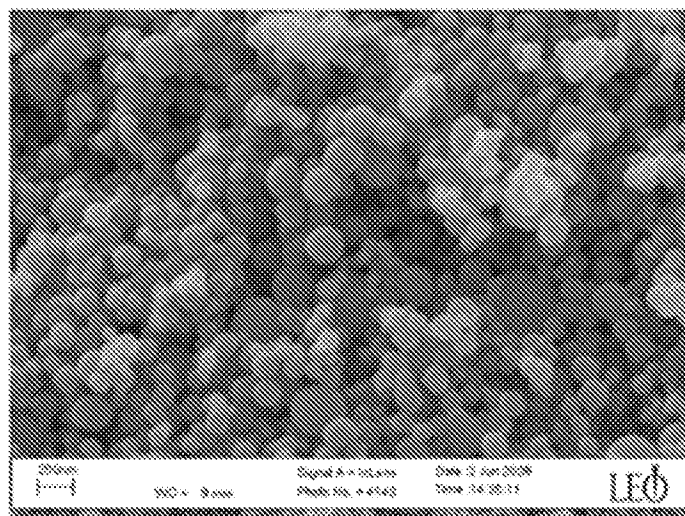


FIG. 7A

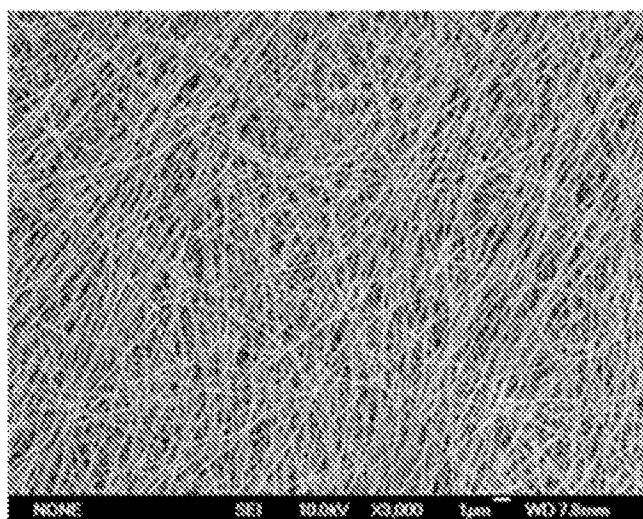


FIG. 7B

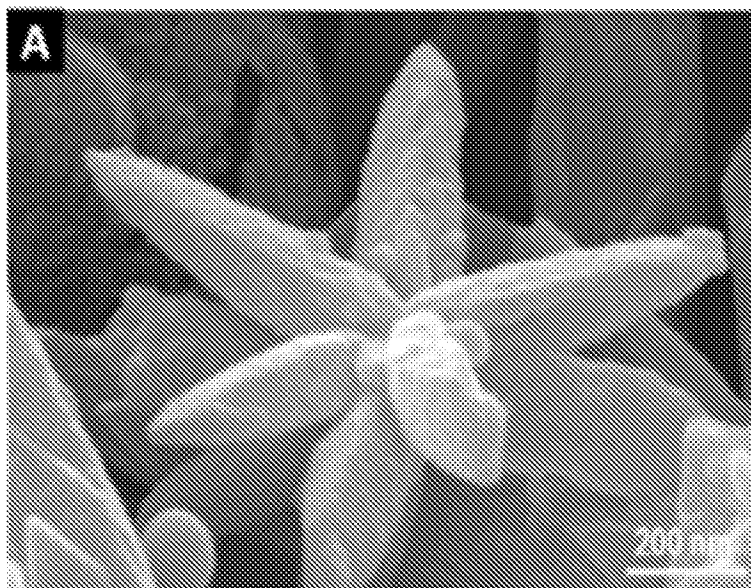


FIG. 7C

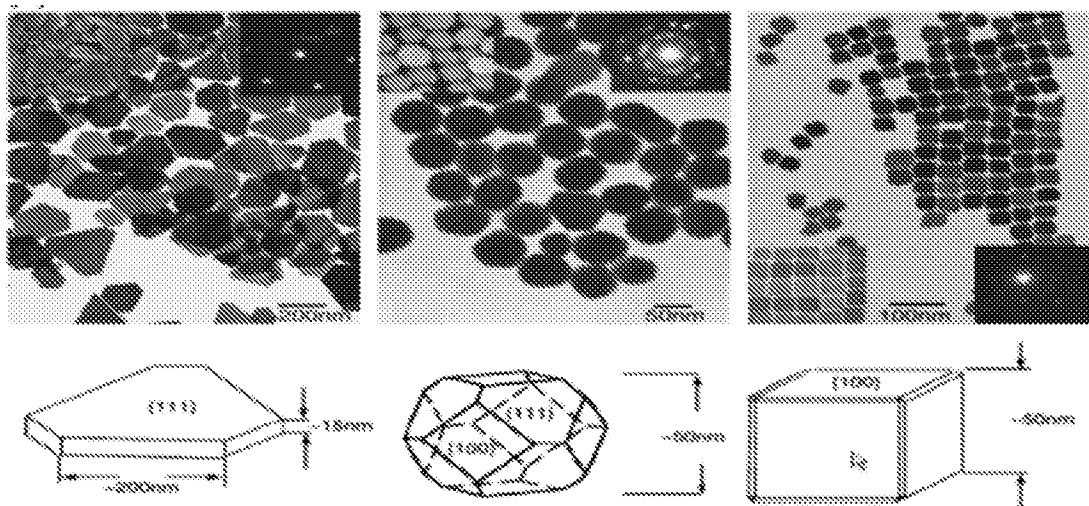


FIG. 7D

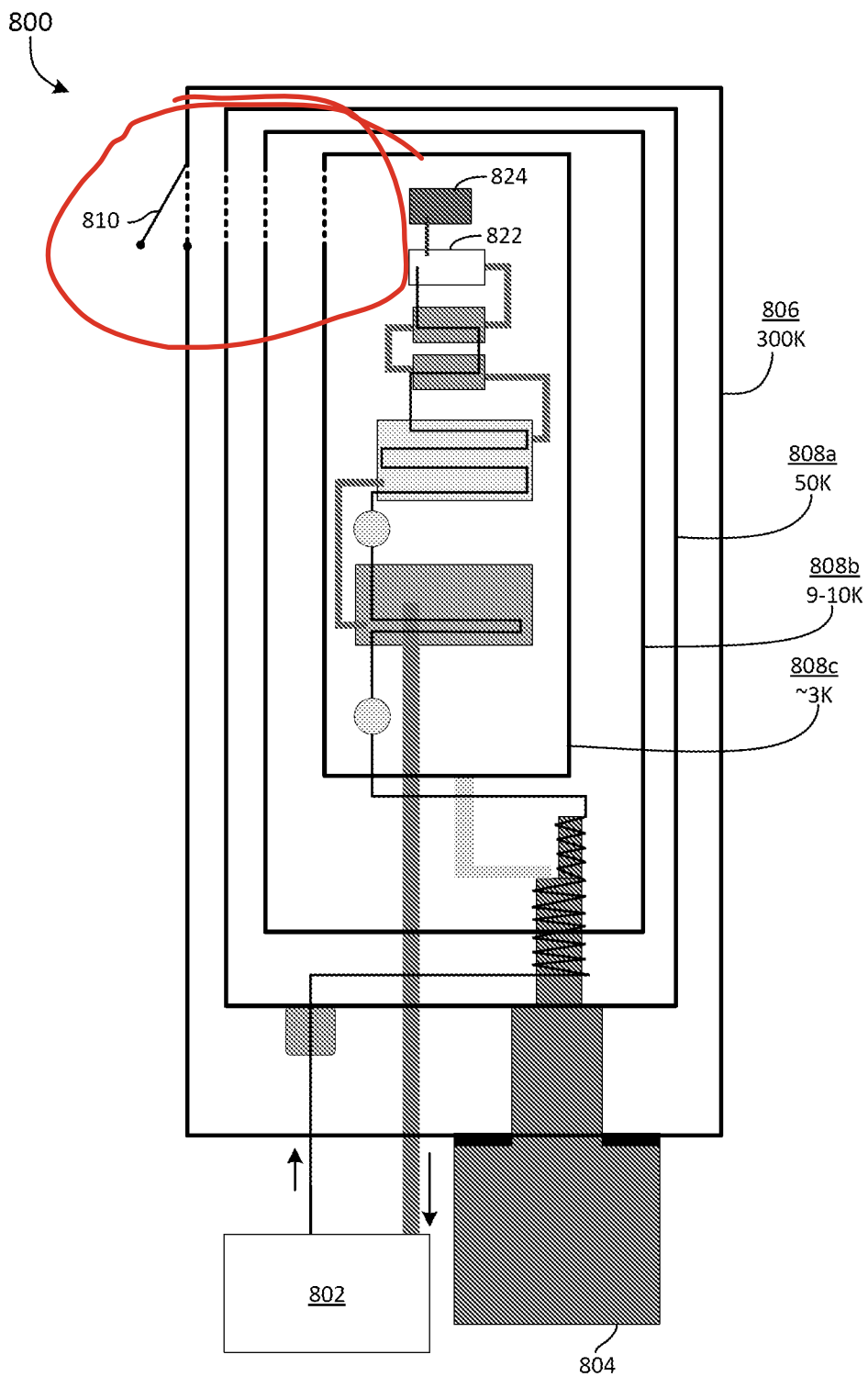


FIG. 8A

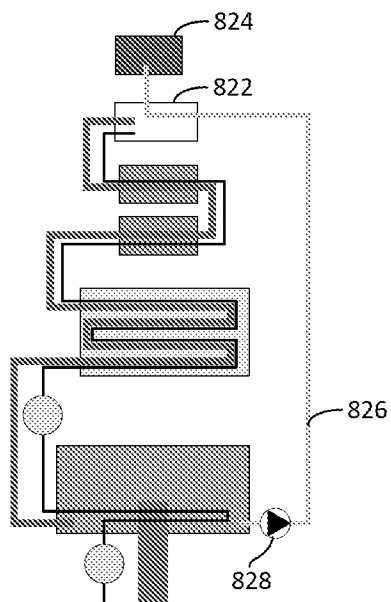


FIG. 8B

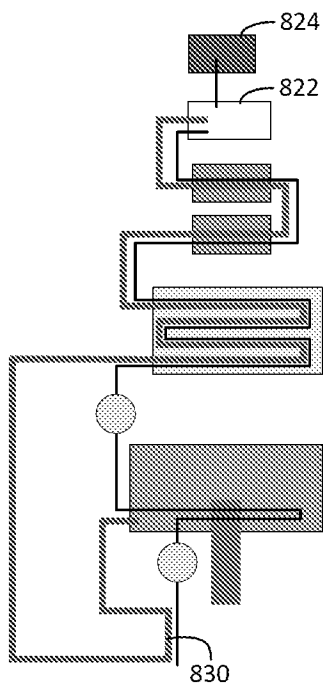


FIG. 8C

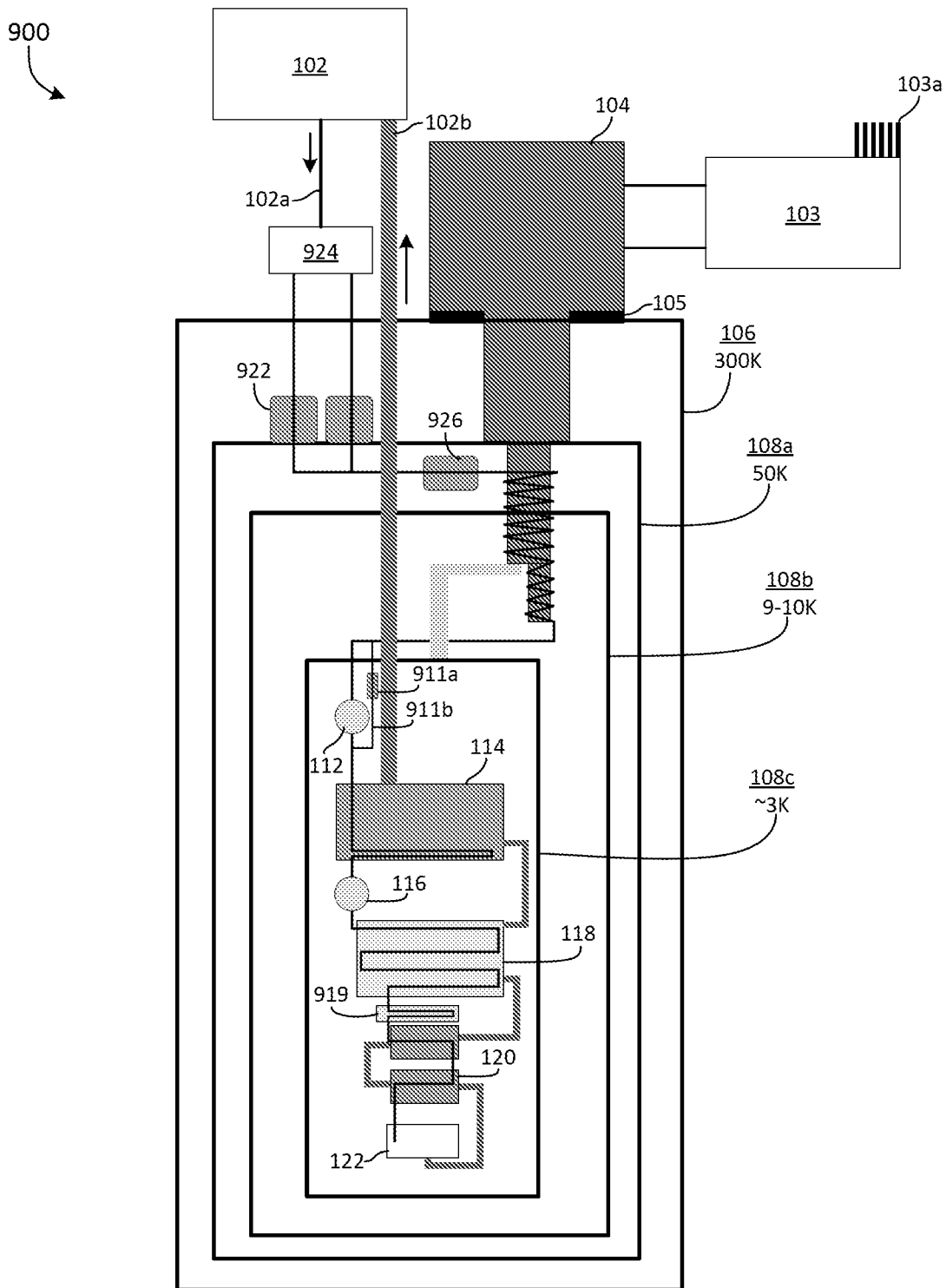


FIG. 9A

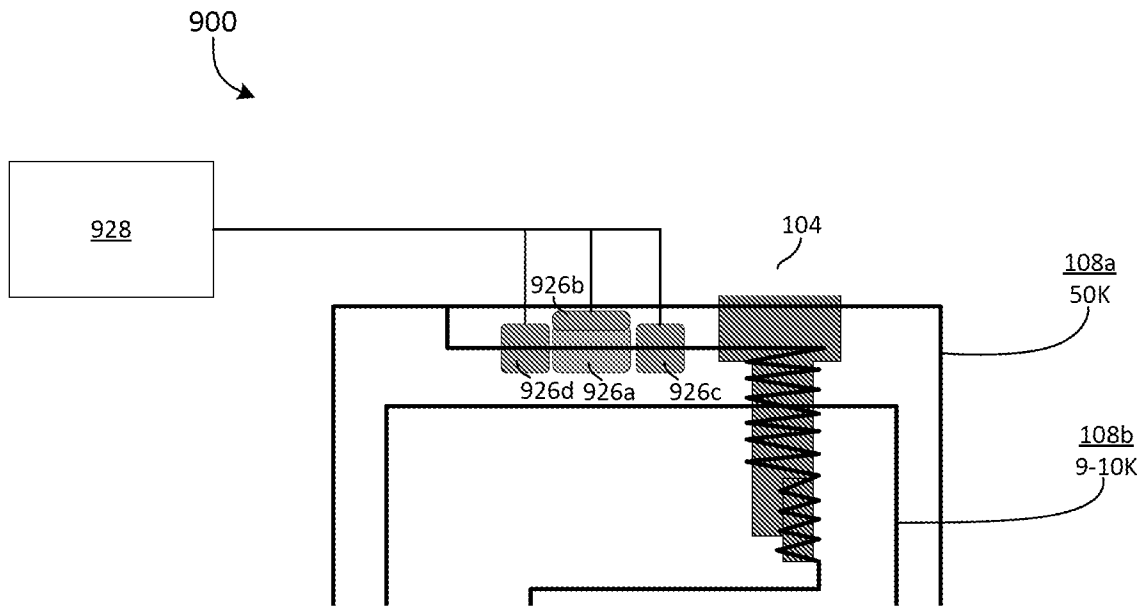


FIG. 9B

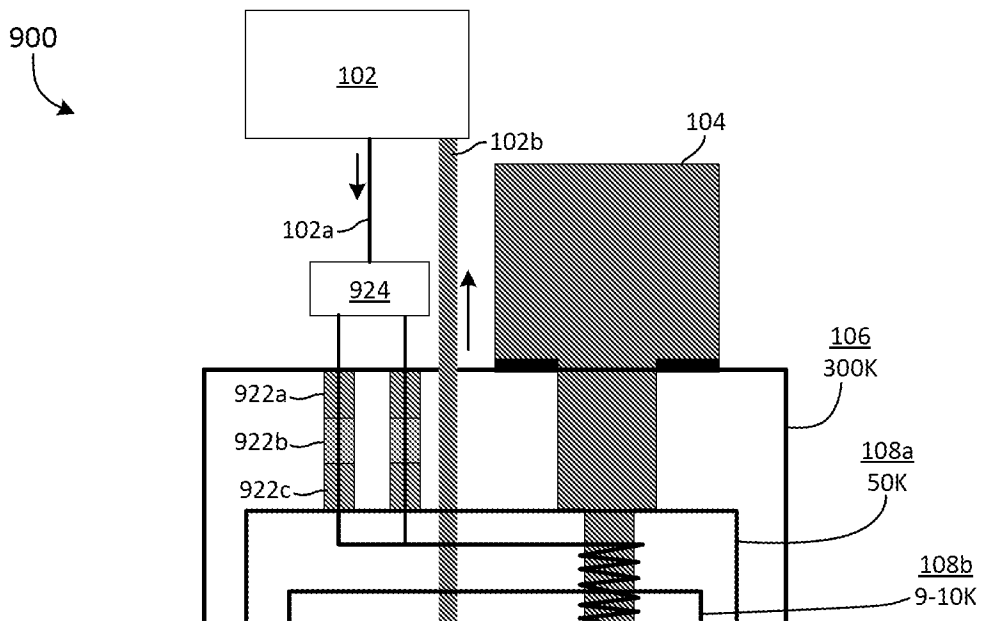


FIG. 9C

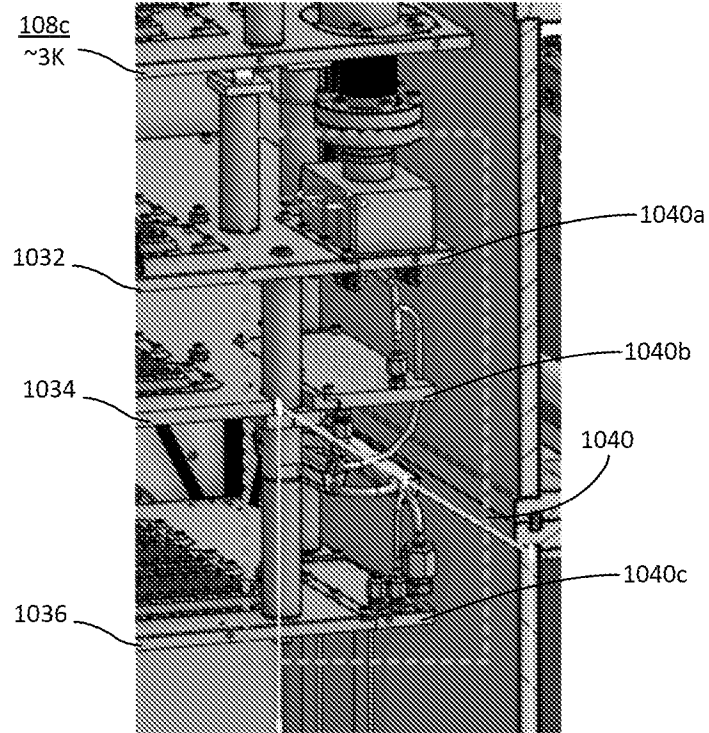


FIG. 10A

1040b

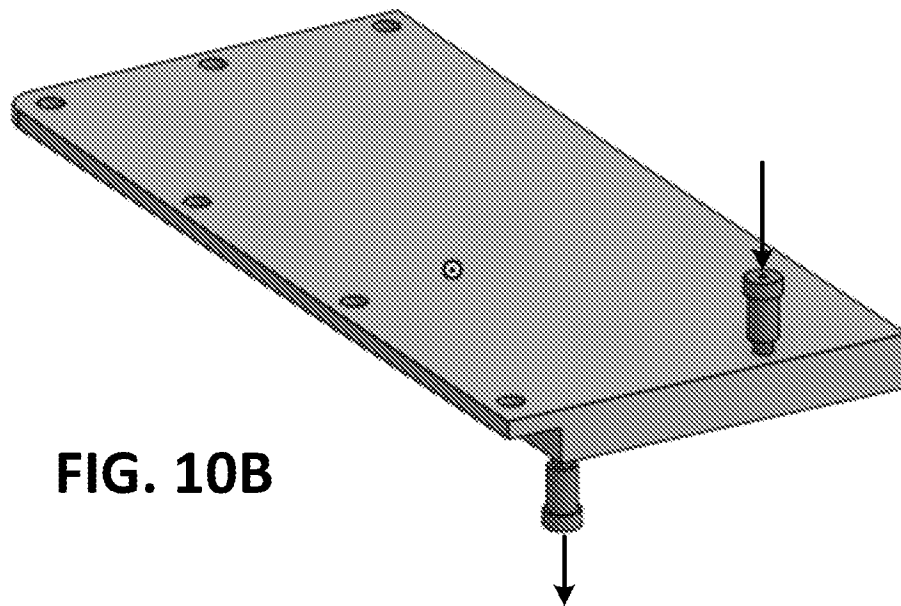


FIG. 10B

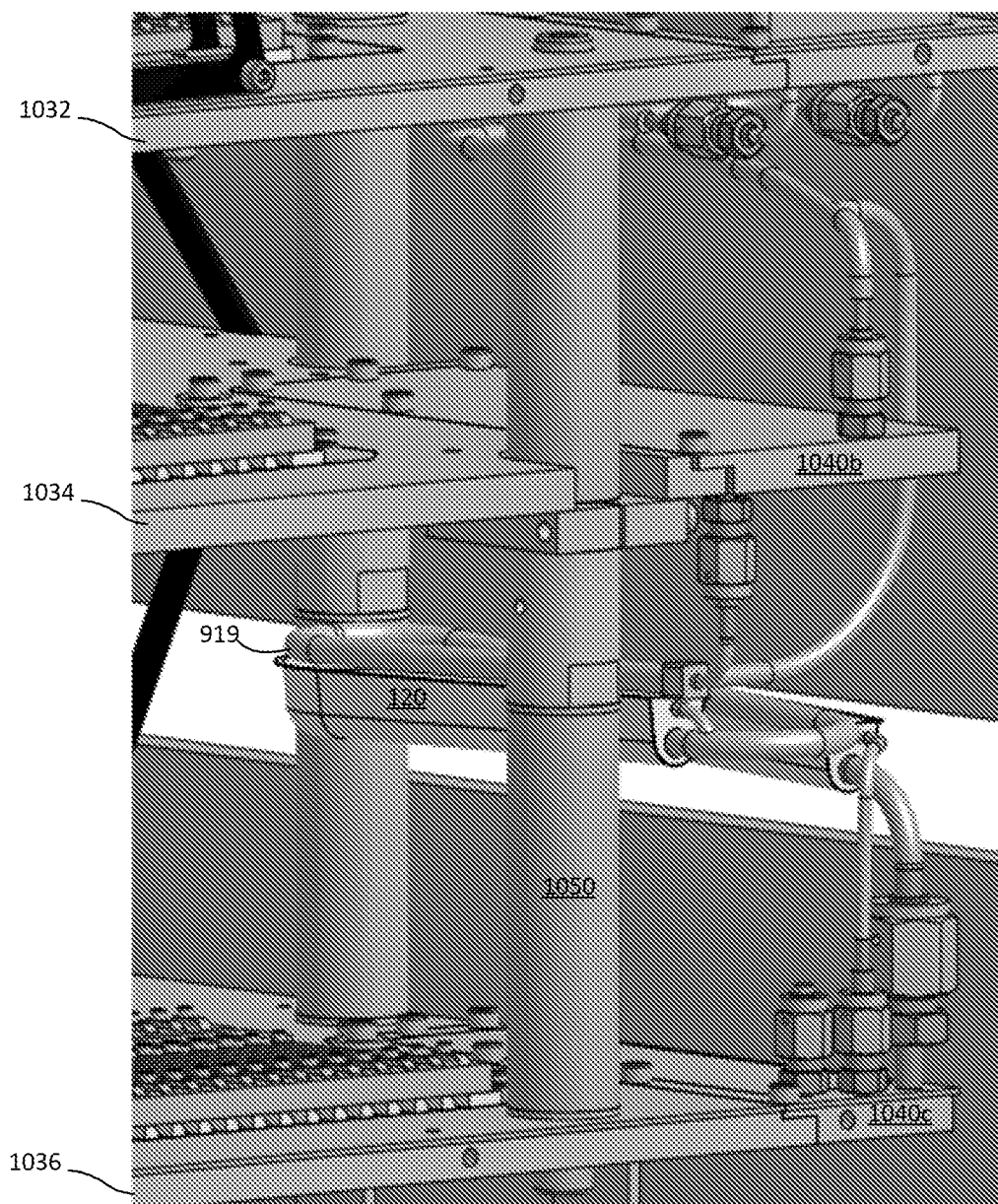


FIG. 10C

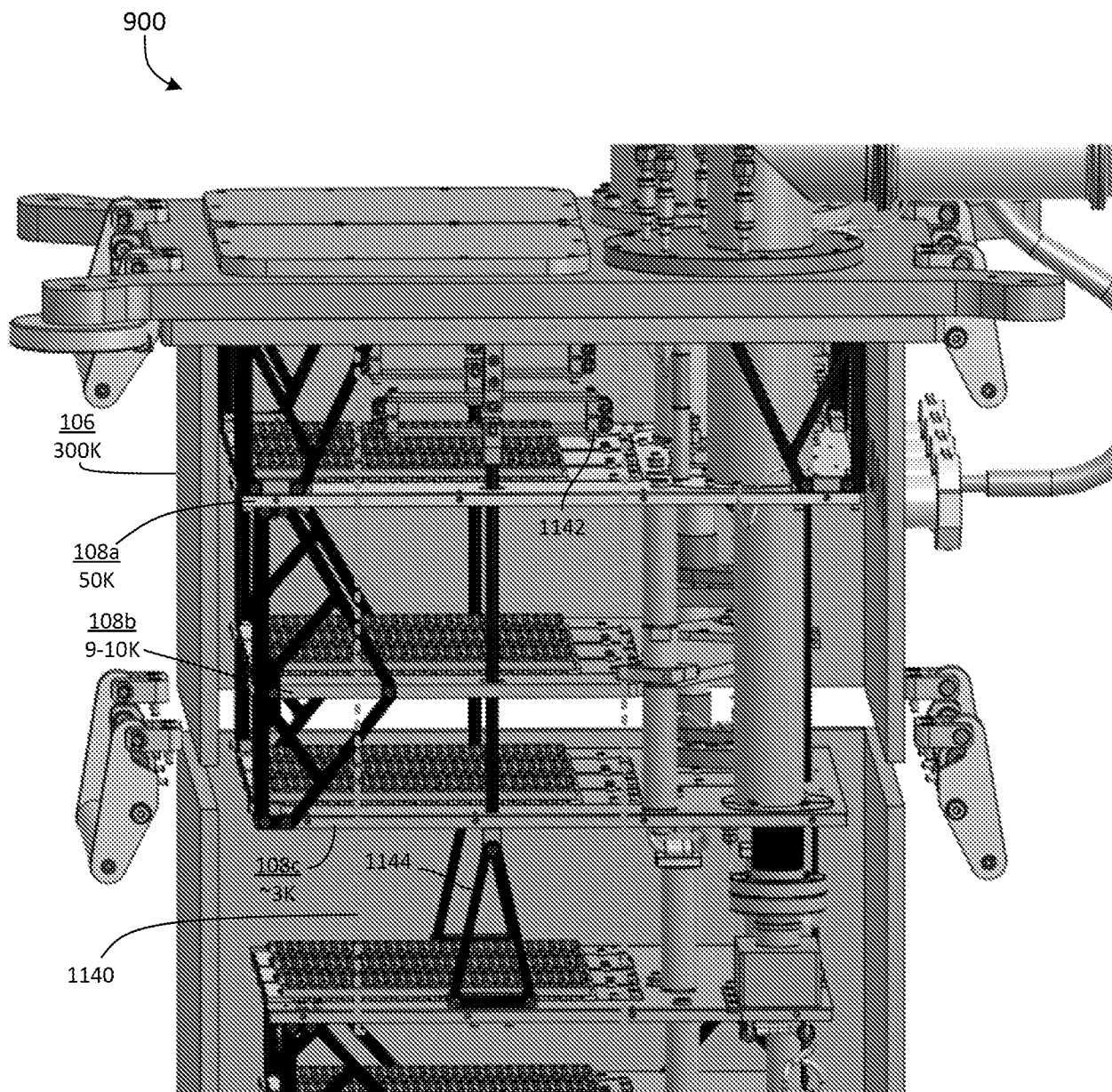


FIG. 11A

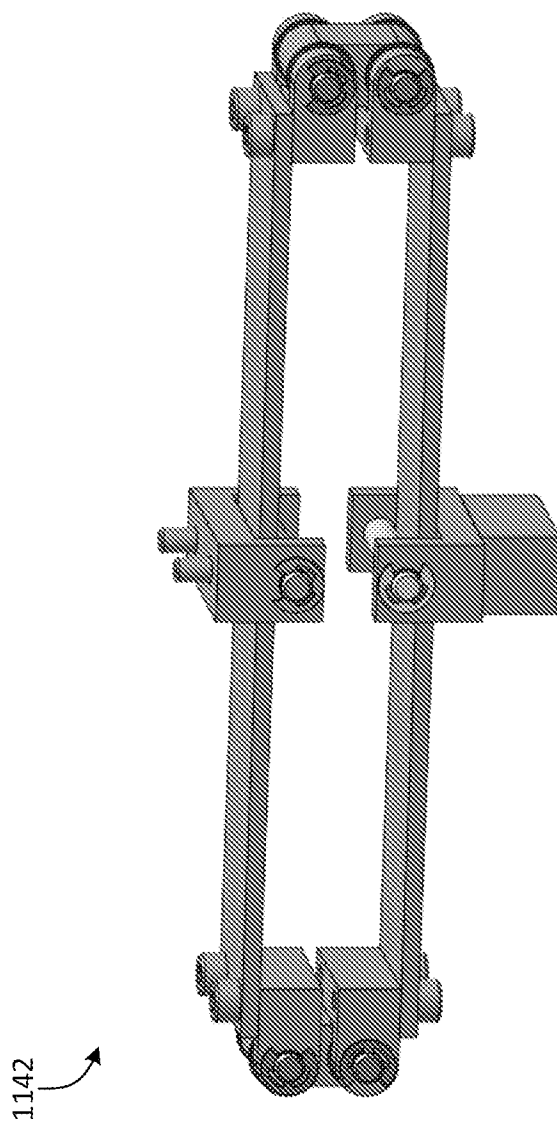


FIG. 11B

900

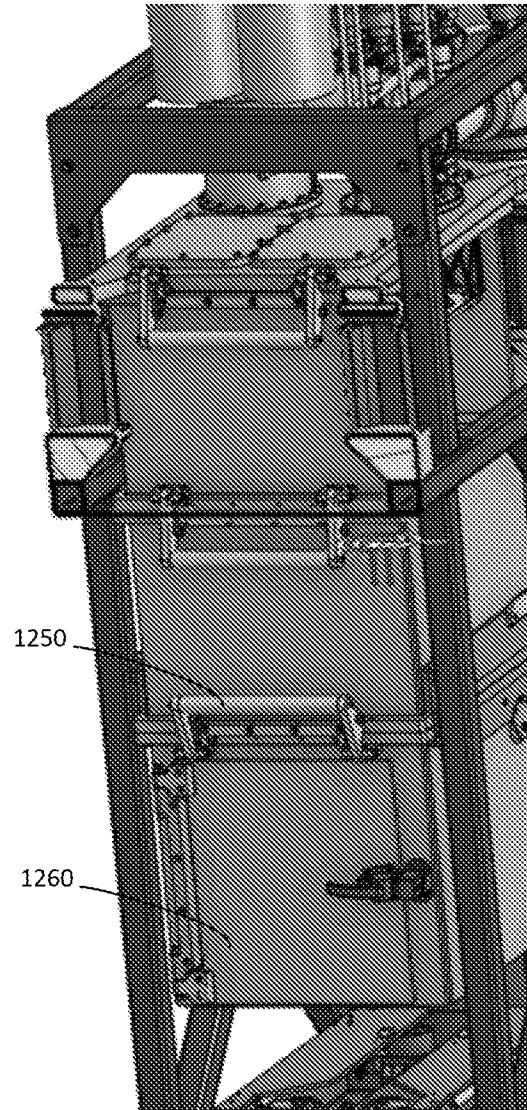


FIG. 12

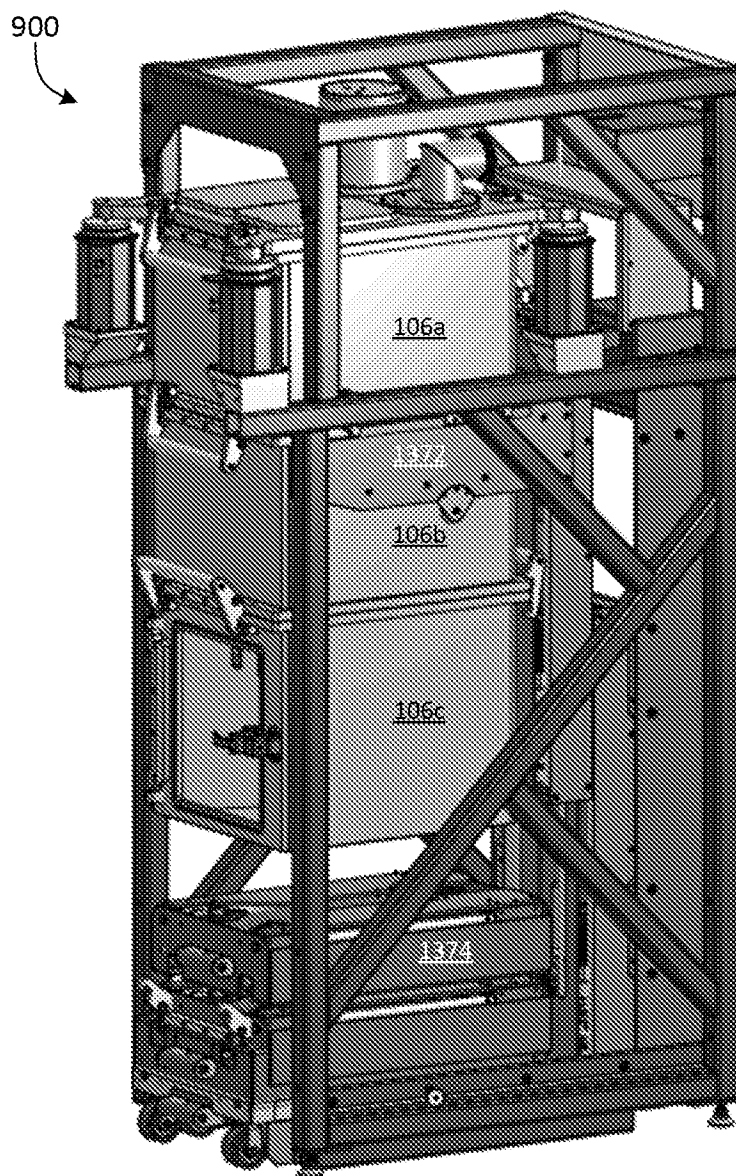


FIG. 13

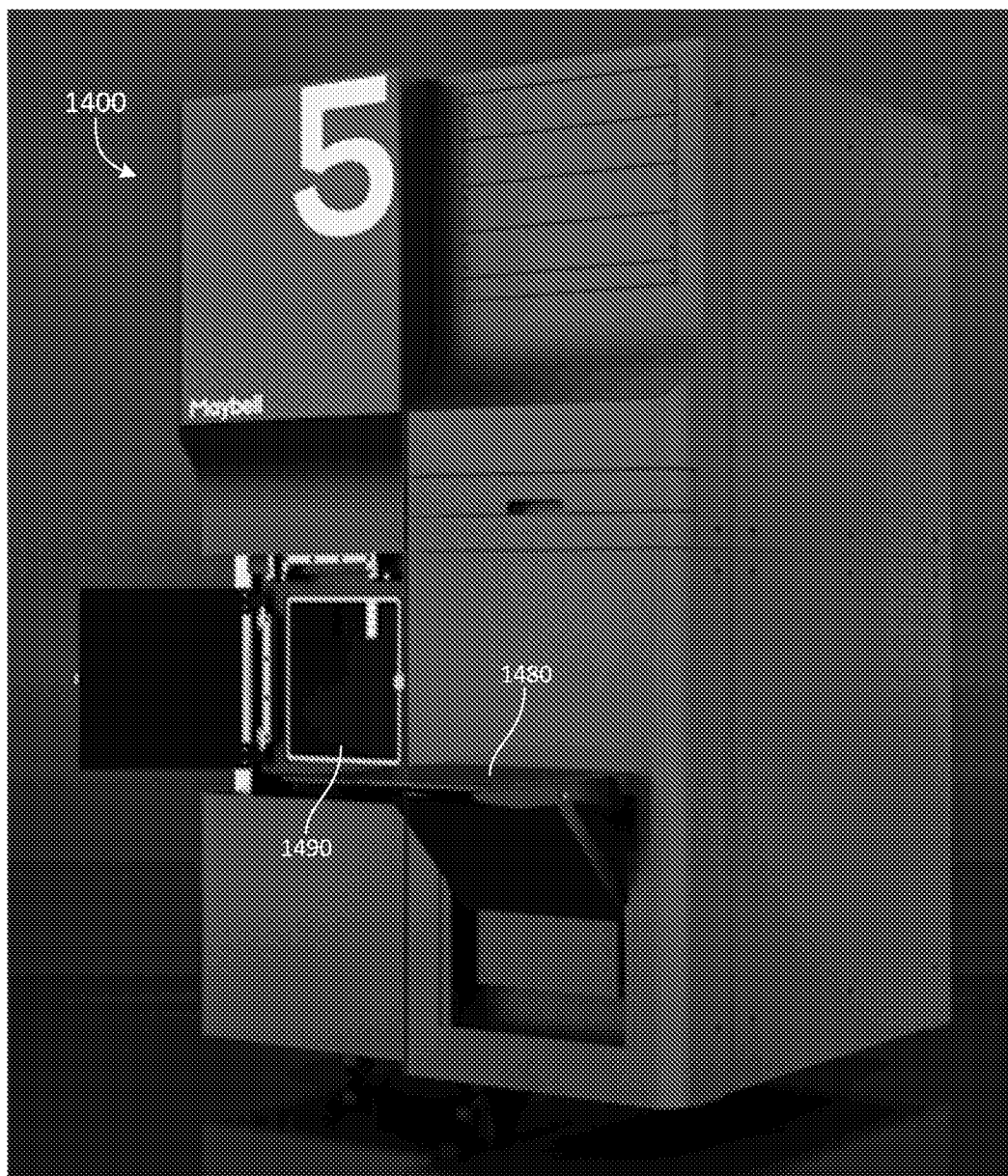


FIG. 14

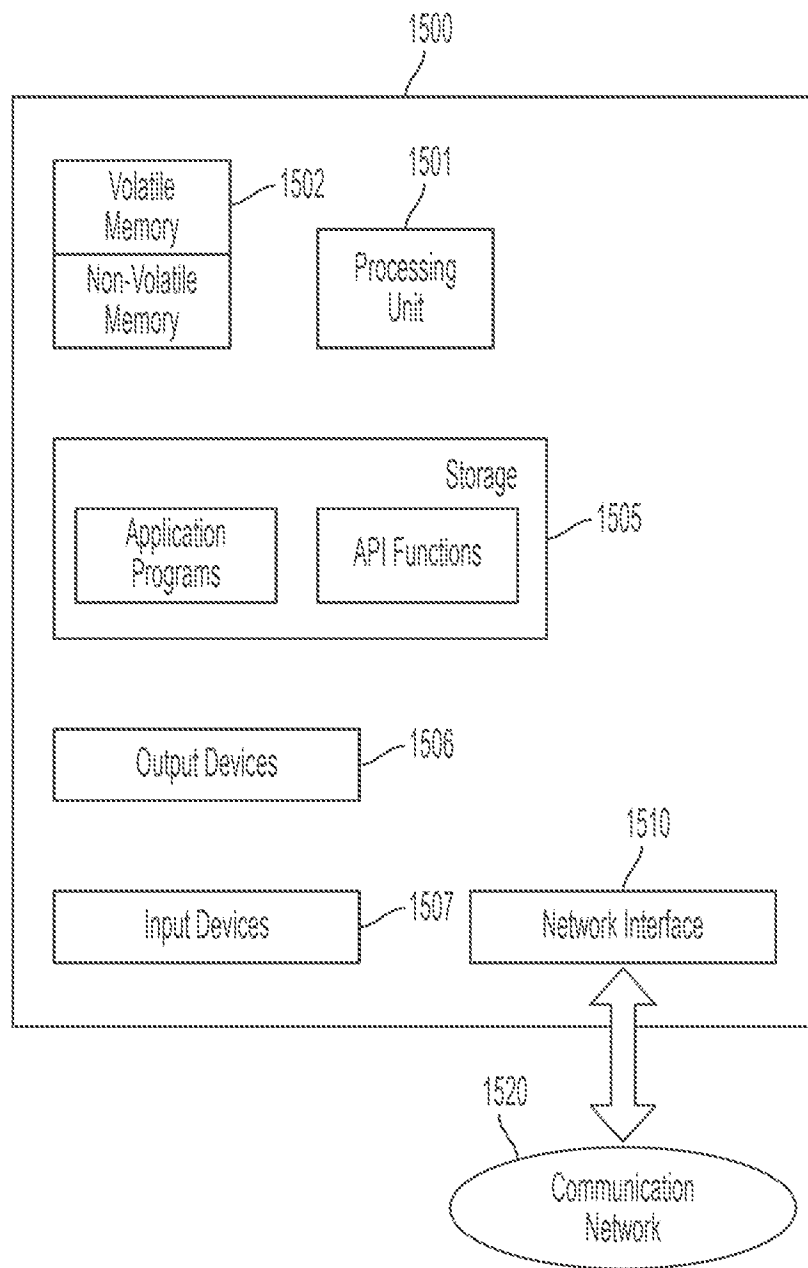


FIG. 15