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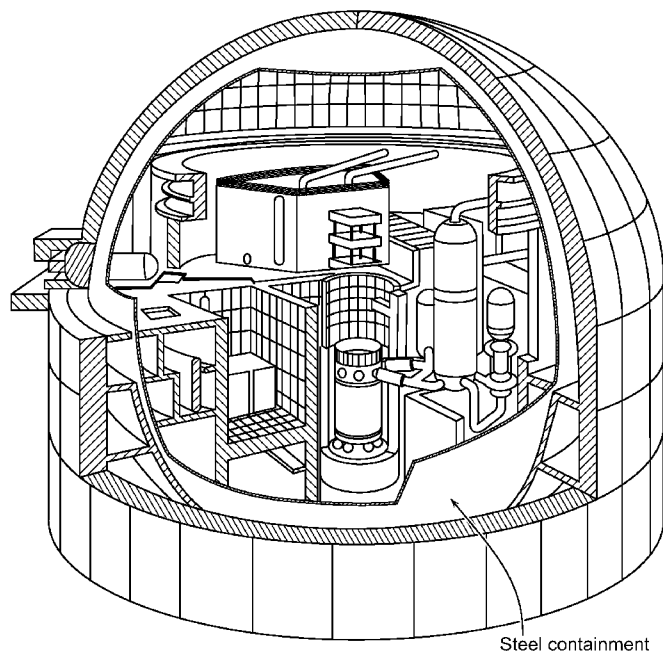


FIG. 1

(57) Abstract: A modular containment system to accommodate and hermetically contain salt and fission products in the event of a breach of a molten salt nuclear reactor is provided. The system can include a permanent housing, a containment module at least partially within the permanent housing that defines an interior cavity, a low friction mechanism provided between the permanent housing and the containment module, and a reactor vessel provided within the interior cavity. The system can also include at least one of a passive heat removal system at least partially provided within a wall of the containment module and a sacrificial layer within the interior cavity.



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## REACTOR MODULAR CONTAINMENT SYSTEM

### CROSS-REFERENCE TO RELATED APPLICATIONS

[0001] This application claims the benefit of U.S. Provisional Application No. 62/397,610, filed September 21, 2016, entitled “Reactor Modular Containment System,” the entirety of which is incorporated by reference.

### BACKGROUND

#### Field

[0002] Embodiments of the present disclosure relate generally to nuclear reactors, and, in particular, to containment modules for molten salt reactors configured to accommodate and hermetically contain a fuel salt composition and fission products in the event of a breach of the reactor

[0003] The global demand for energy has largely been fed by fossil fuels. This typically involves taking reduced carbon out of the Earth and burning it. However, those hydrocarbons are in limited supply and burning the hydrocarbons can produce carbon dioxide. According to the U.S. Environmental Protection Agency, more than 9 trillion metric tons of carbon are released into the atmosphere each year. Nuclear power is an appealing alternative to fossil fuels due to relative abundance of nuclear fuel and carbon-neutral energy production.

[0004] Light water reactors (LWRs) are the predominant commercial nuclear reactor for electricity production. LWRs have significant drawbacks, however. In one example LWRs can use solid fuels that have long radioactive half-lives. In another example, LWRs can utilize fuels in a relatively inefficient manner. As a result, LWRs can produce dangerous and long-lived waste products. Nuclear fuel can also be vulnerable to extreme accidents or proliferation (e.g., plutonium) to make nuclear weapons.

[0005] Molten salt reactors (MSRs) have been researched since the 1950s to improve on LWR technologies. MSRs are a class of nuclear fission reactors in which the primary coolant, or even the fuel itself, can be a molten salt mixture. In general, MSRs can provide energy more safely and cheaply than LWRs. As an example, MSRs can operate at relatively low pressures and they can be potentially less expensive and passively safer than LWRs.

Furthermore, compared to LWRs, MSRs can also provide advantages such as lower levelized cost on a per-kilowatt hour (kWh) basis, fuel and waste inventories of relatively benign composition, and more efficient fuel utilization.

### SUMMARY

[0006] Based on projected population growth, currently deployed energy technologies are not considered sufficient to meet rising energy demands of developed countries, let alone undeveloped and developing countries. MSRs represent a technology that can fill this gap. Unfortunately, since the 1970s, the United States and other nations have focused on development of LWRs instead of MSRs.

[0007] One of the main challenges in developing and maintaining nuclear reactors, including MSRs, is the containment of nuclear reaction products in the event of a nuclear reactor breach. In the event of a failure where the reactor vessel is breached, it is desirable to ensure fission product containment to inhibit radioactive particulates from entering the environment. It is also desirable to bring power back online as soon as possible.

[0008] Generally, containment barriers have been constructed in a permanent fashion, usually within a non-removable structure, such as those structures seen in FIGS. 1 and 2. Given past reactor accidents, reactor safety is in the public's mind as the world pursues new generation reactor technologies. Accordingly, it is desirable to devise a way to prevent contamination from releasing into the environment and to minimize power outages.

[0009] Embodiments of the present disclosure provide a nuclear reactor system and methods of using the same that can include a primary containment module within a modular containment system to accommodate and hermetically contain salt and fission products in the event of a reactor breach involving release of salt and subsequent damage to the reactor vessel which cannot be easily repaired. The presently disclosed modular containment system is capable of accommodating salt release, eliminating the possibility of re-criticality, and removing the heat generated due to decay. Also, this modular containment system allows for the entire containment module to be removed and another one installed in order to limit the duration of a power outage.

[0010] According to one embodiment, a modular containment system can include a permanent housing, a containment module at least partially within the permanent housing that

defines an interior cavity, a reactor vessel provided within the interior cavity, and a low friction mechanism provided in between the permanent housing and the primary containment module.

[0011] In another embodiment, the modular containment system can include a moderator layer.

[0012] In another embodiment, at least one of the permanent housing and the containment module can be formed from a concrete layer (e.g., reinforced or pre-stressed concrete). In another embodiment, both the permanent housing and the primary containment module can be formed from a concrete material.

[0013] Embodiments of the low friction mechanism can aid in the removal of the primary containment module from the permanent housing and can be provided in a variety of configurations. In one aspect, the low friction mechanism can be attached to only one of the containment module and the permanent housing. In another aspect, at least a portion of the low friction mechanism can have a curved shape (e.g., spherical). In one embodiment, the mechanism can include one or more substantially spherical structures.

[0014] In another embodiment, the modular containment system can also include a passive heat removal system at least partially provided within a wall of the containment module. The passive heat removal system can have a variety of configurations. In one aspect, the passive heat removal system can include a radiative heat removal structure that extends inward from the wall of the containment module into the interior cavity of the containment module. As an example, the radiative heat removal structure can include a set of fins. In another aspect, the passive heat removal system can include an embedded heat removal structure in which at least a portion of the embedded heat removal structure extends vertically through the wall of the containment module. A second portion of the embedded heat removal structure can extend into the interior cavity of the containment module, below the reactor vessel. In another embodiment, the heat removal system can include both the radiative heat removal structure and the embedded heat removal structure.

[0015] Embodiments of the moderator layer can have a variety of configurations. In one aspect, the moderator layer can be formed from graphite. In another aspect, the reactor vessel can be positioned on the moderator layer.

[0016] In another embodiment, the modular containment system can include a sacrificial layer within the interior cavity. The sacrificial layer can have a variety of configurations. In one aspect, the sacrificial layer can include at least one salt that is configured to melt upon contact with a salt (e.g., molten fuel salt that escapes from the reactor vessel). In another aspect, the sacrificial layer can be provided underneath the reactor vessel.

[0017] In another embodiment, a solid structure can be provided below the sacrificial layer.

[0018] In another embodiment, the modular containment system can include a sacrificial layer provided within the interior cavity and the second portion of the embedded heat removal structure can include an elevated portion located in a center of the interior cavity and at least partially within the sacrificial layer.

[0019] In embodiment, the sacrificial layer can include a top surface that forms a slope downward toward a center of the interior cavity. The slope can help to direct the melted sacrificial layer and the leaked fuel toward the elevate portion of the embedded heat removal structure in order to aid in the removal of heat.

#### **BRIEF DESCRIPTION OF THE DRAWINGS**

[0020] These and other features will be more readily understood from the following detailed description taken in conjunction with the accompanying drawings, in which:

[0021] FIG. 1 is a cut away view of a reactor system housed within a concrete and steel containment building.

[0022] FIG. 2 is a cut away view of a reactor system housed within a containment building.

[0023] FIG. 3 is a schematic diagram illustrating one exemplary embodiments of a molten salt nuclear reactor system.

[0024] FIG. 4 is a schematic diagram illustrating one exemplary embodiment of a fuel conditioning system of the molten salt nuclear reactor system of FIG. 3.

[0025] FIG. 5 is a schematic diagram illustrating one exemplary embodiment of a reactor of the molten salt nuclear reactor system of FIG. 3.

[0026] FIG. 6 is a schematic diagram depicting a modular containment system compatible with the systems and reactor of FIGS 3-5.

[0027] It can be noted that the drawings can be not necessarily to scale. The drawings can be intended to depict only typical aspects of the subject matter disclosed herein, and therefore should not be considered as limiting the scope of the disclosure. It is also to be understood that bends or turns can be at any angle or can be curved. Alternatively, various bends and angles can be removed such that the material follows a straight path at that point.

[0028] For a thorough understanding of the present disclosure, reference should be made to the following detailed description, including the appended claims, in connection with the above-described drawings. Although the present disclosure can be described in connection with exemplary embodiments, the disclosure can be not intended to be limited to the specific forms set forth herein. It can be understood that various omissions and substitutions of equivalents can be contemplated as circumstances can suggest or render expedient.

### **DETAILED DESCRIPTION**

[0029] Embodiments of the present disclosure provide a modular containment system for containing salt and fission products in the event of a breach of the reactor vessel. The system involves the use of a primary containment module to hermetically seal the reactor vessel in the event of an accident and to allow for the removal of the vessel from a permanent housing with the aid of a low friction mechanism.

[0030] In one embodiment, the presently disclosed system is configured for use with a fast-spectrum molten-salt reactor (FS-MSR). FS-MSRs are a class of nuclear reactor in which a fission chain reaction can be sustained by fast neutrons, as opposed to slow or thermal, neutrons used in a thermal reactor. Thus, FS-MSRs can also be referred to interchangeably as "fast neutron reactors" or simply "fast reactors." The term "thermal" in this context refers to thermal equilibrium with the medium the neutrons interact with, such as the reactor's fuel, moderator and structure. Thermal neutrons have much lower energy than the fast neutrons initially produced by fission, and thermal reactors rely on a neutron moderator for reducing the speed of neutrons so as to make them capable of sustaining a nuclear chain reaction. The moderator slows neutrons until they approach the average kinetic

energy of the surrounding particles (i.e., reducing the speed of the neutrons to low-velocity thermal neutrons), thereby remaining uncharged and allowing them to penetrate deeper in the target element and close to the nuclei. Fast reactors, however, do not require a neutron moderator, but must rather use fuel that is relatively rich in fissile material when compared to that required for a thermal reactor.

[0031] FIG. 3 schematically illustrates a nuclear thermal generator plant system 100. As shown, the system 100 includes a reactor system 102 and a secondary system 104. The reactor system 102 includes a primary heat exchanger 106 connected to a reactor 110 having a reactor core 112 configured to receive a fuel salt composition 114. The reactor system 102 also includes a reactivity control system 116 and a fuel conditioning system 120, each connected to the reactor 110.

[0032] The system 100 can be configured to generate electrical energy from fission of the fuel salt composition 114 in a molten state. In certain embodiments, the fuel salt composition 114 can include a carrier salt and a fuel salt. As an example, components of the fuel salt composition 114 can be in the form of one or more chloride salts, fluoride salts, and mixtures of one or more chloride and fluoride salts.

[0033] Embodiments of the fuel salt can include fissile materials, fertile materials, and combinations thereof. Examples of fissile materials can include, but are not limited to, thorium (Th), protactinium (Pa), uranium (U), neptunium (Np), plutonium (Pu), americium (Am), curium (Cm), and any combination thereof. In certain embodiments, the fissile materials can include one or more of the following isotopes, in any combination: Th-225, Th-227, Th-229, Pa-228, Pa-230, Pa-232, U-231, U-233, U-235, Np-234, Np-236, Np-238, Pu-237, Pu-239, Pu-241, Am-240, Am-242, Am-244, Cm-243, Cm-245, and Cm-247. Examples of fertile materials can include, but are not limited to,  $^{232}\text{ThCl}_4$ ,  $^{238}\text{UCl}_3$  and  $^{238}\text{UCl}_4$ .

[0034] In an embodiment, the fuel salt composition 114 can include one or more chloride salts and the system 100 can be referred to as a molten chloride fast reactor (MCFR). As an example, the carrier salt can include a chloride salt of an alkali or alkaline earth metal and the fuel salt can include a chloride salt of at least one actinide. In another non-limiting example, the fuel salt composition 114 can include a fuel salt containing one or more of  $^{233}\text{UCl}_3$ ,  $^{235}\text{UCl}_3$ ,  $^{233}\text{UCl}_4$ ,  $^{235}\text{UCl}_4$ , and  $^{239}\text{PuCl}_3$ ; and a carrier salt including one or more of sodium

chloride (NaCl), potassium chloride (KCl), and calcium chloride (CaCl<sub>2</sub>). In another embodiment, the fuel salt composition 114 can include at least NaCl as the carrier salt and UCl<sub>3</sub> as the fuel salt.

[0035] In an embodiment, fuel salt can have a concentration selected from about 1 mole % to about 90 mole % of the fuel salt composition 114. In further embodiments, the fuel salt composition 114 can have a melting temperature that is greater than or equal to about 300°C. In additional embodiments, the melting temperature of the fuel salt composition can be selected from about 325°C to about 475°C.

[0036] Further embodiments of fuel salt compositions suitable for use with the system 100 are discussed in greater detail in U.S. Provisional Patent Application No. 62/340,754, filed on May 24, 2016, entitled “Chloride and Fluoride Salt Composition For Molten Salt Reactor,” U.S. Provisional Application No. 62/340,762 filed on May 24, 2016, entitled “Salt Composition With Phase Modifiers For Molten Salt Reactor,” U.S. Provisional Application No. 62/269,525, filed on December 18, 2015, entitled “Salt Composition for Molten Salt Reactor,” and U.S. Application No. 15/380,473, filed on December 15, 2016, entitled “Salt Compositions for Molten Salt Reactors,” each of which is hereby incorporated by reference in its entirety.

[0037] Upon absorbing neutrons, nuclear fission can be initiated and sustained in the fuel salt composition 114 by chain-reaction within the reactor 110, generating heat that elevates the temperature of the fuel salt composition 114 (e.g., to about 650°C or about 1,200°F). The heated fuel salt composition 114 can be transported from the reactor core 112 to the primary heat exchanger 106 via a primary fluid loop 122 via a pump, discussed in greater detail below. The primary heat exchanger 106 can be configured to transfer heat generated by nuclear fission occurring in the fuel salt composition 114.

[0038] In general, fluids of three types can be contained in and/or circulated through the system 100, namely fuel, coolant, and moderator (e.g., any substance that slows neutrons). Various fluids can perform one or more of the fuel, coolant, and moderator functions simultaneously. One or more fluids, including more than one fluid of each functional type, can be contained within or circulated through the reactor core 112. Examples of fluids contained within or circulated through the reactor core 112 can include, but are not limited to, liquid metals, molten salts, supercritical H<sub>2</sub>O, supercritical CO<sub>2</sub>, and supercritical N<sub>2</sub>O.

[0039] The transfer of heat from the fuel salt composition 114 can be realized in various ways. For example, the primary heat exchanger 106 can include a pipe 124 and a secondary fluid 126. The molten fuel salt composition 114 can travel through the pipe 124, while the secondary fluid 126 (e.g., a coolant) can surround the pipe 124 and absorb heat from the fuel salt composition 114. Upon heat transfer, the temperature of the fuel salt composition 114 in the primary heat exchanger 106 can be reduced and fuel salt composition 114 can be subsequently transported from the primary heat exchanger 106 back to the reactor core 112.

[0040] The primary heat exchanger 106 can be provided in a variety of configurations. In various embodiments, the primary heat exchanger 106 can be either internal or external to a reactor vessel (not shown) that contains the reactor core 112. In additional embodiments, the system 100 can be configured such that primary heat exchange (e.g., heat exchange from the molten fuel salt composition 114 to a different fluid) can occur both internally and externally to the reactor 110. In other embodiments, the system 100 can be provided such that the functions of nuclear fission and primary heat exchange can be integral to the reactor core 112. That is, heat exchange fluids can be passed through the reactor core 112.

[0041] The secondary system 104 can also include a secondary heat exchanger 130 configured to transfer heat from the secondary fluid 126 to a tertiary fluid 132 (e.g., water). As shown in FIG. 1, the secondary fluid 126 is received from primary heat exchanger 106 via fluid loop 134 and circulated through secondary heat exchanger 130 via a pipe 136.

[0042] Additionally or alternatively, in another embodiment (not shown), heat exchange can occur within the reactor core prior to heat exchange within the secondary heat exchanger. As an example, heat from the fuel salt composition can pass to a solid moderator, then to a liquid coolant circulating through the reactor. Subsequently, the liquid coolant circulating through the reactor system can be transported to the secondary heat exchanger. As required by basic thermodynamics, after one or more stages of exchange, heat can be finally delivered to an ultimate heat sink, e.g., the overall environment (not shown).

[0043] Heat received from the fuel salt composition 114 can be used to generate power (e.g., electric power) using any suitable technology. For example, when the tertiary fluid 132 in the secondary heat exchanger 130 is water, it can be heated to a steam and transported to a turbine 140 by a fluid loop 142. The turbine 140 can be turned by the steam and drive an electrical generator 144 to produce electricity. Steam from the turbine 140 can be conditioned

by an ancillary gear 146 (e.g., a compressor, a heat sink, a pre-cooler, and a recuperator) and it can be transported back to the secondary heat exchanger 130 through the fluid loop 142.

[0044] Additionally, or alternatively, the heat received from the fuel salt composition 114 can be used in other applications such as nuclear propulsion (e.g., marine propulsion), desalination, domestic or industrial heating, hydrogen production, or combinations thereof.

[0045] Embodiments of the reactivity control system 116 can include one or more fluid reservoirs in fluid communication with the reactor 110. The fluid reservoirs can contain an inert gas (e.g., argon) or a non-reactive liquid (e.g., a liquid metal). A selected amount of fluid can be transported from the fluid reservoirs to the reactor 110 to control reactivity.

[0046] The fuel conditioning system 120 can be configured to remove at least a portion of fission products generated in the fuel salt composition 114 during nuclear fission. In general, during the operation of the system 100 to generate power, fission products (e.g., radioactive noble metals and/or radioactive noble gases) can be generated in the fuel salt composition 114. Non-limiting embodiments of fission products can include, but are not limited to, one or more of the following, in any combination: rubidium (Rb), strontium (Sr), cesium (Cs), barium (Ba), lanthanides, palladium (Pd), ruthenium (Ru), silver (Ag), molybdenum (Mo), niobium (Nb), antimony (Sb), technetium (Tc), xenon (Xe), and krypton (Kr).

[0047] Buildup of fission products in the fuel salt composition 114 can impede or interfere with the nuclear fission in the reactor core 112 by poisoning the nuclear fission. For example, xenon-135 and samarium-149 can have a high neutron absorption capacity and they can lower the reactivity of the fuel salt composition 114. Fission products can also reduce the useful lifetime of the system 100 by clogging or corroding components, such as heat exchangers or piping. Therefore, it can be desirable to keep concentrations of fission products in the fuel salt composition 114 below certain thresholds to maintain proper functioning of the system 100.

[0048] This goal can be accomplished by the fuel conditioning system 120. As an example, the fuel salt composition 114 can be transported from the reactor core 112 to the fuel conditioning system 120, which can process the molten fuel salt composition 114 and allow the reactor 110 to function without loss of efficiency or degradation of components due to development of fission products. As shown in FIG. 3, the fuel conditioning system 120 can

be contained within the reactor system 102 along with the reactor 110 and the primary heat exchanger 106. However, in alternative embodiments (not shown), at least one of the primary heat exchanger and the fuel-conditioning system can be located external to the reactor system.

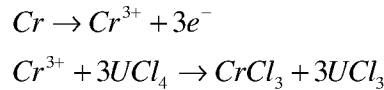
[0049] FIG. 4 illustrates the fuel conditioning system 120 in greater detail. During normal operation of the reactor system 102, the fuel salt composition 114 can be circulated continuously or near-continuously from the reactor core 112 through one or more of functional sub-units of the fuel conditioning system 120 via fluid loop 146 by a pump 150. As discussed below, examples of the sub-units can include, but are not limited to, a corrosion reduction unit 152, a mechanical separation unit 154, and a chemical exchange unit 156. The fuel conditioning system 120 can also include a tank 160 for storage(e.g., excess fuel salt composition 114 and/or substances removed from the fuel salt composition 114).

[0050] In an embodiment, the corrosion reduction unit 152 can be configured to inhibit or mitigate corrosion of components of the system 100 by the fuel salt composition 114. At least a portion of the reactor core 112 can be constructed of metallic alloy including one or more of the following elements: iron (Fe), nickel (Ni), chromium (Cr), manganese (Mn), carbon (C), silicon (Si), niobium (Nb), titanium (Ti), vanadium (V), phosphorus (P), sulfur (S), molybdenum (Mo), nitrogen (N), cermet alloys, stainless steels (austenitic stainless steels), zirconium alloys, or tungsten alloys, and variants thereof.

[0051] During operation of the system 100, the fuel salt composition 114 can be transported from the reactor core 112 to the corrosion reduction unit 152 and from the corrosion reduction unit 152 back to the reactor core 112. Transportation of the fuel salt composition 114 at a variably adjustable flow rate can be driven by the pump 150. The corrosion reduction unit 152 can be configured to process the fuel salt composition 114 to maintain an oxidation reduction (redox) ratio,  $E(o)/E(r)$ , of the fuel salt composition 114 in the reactor core 112 (and elsewhere throughout the system 100) at a substantially constant level, where  $E(o)$  is an element (E) at a higher oxidation state (o) and  $E(r)$  is that element (E) at a lower oxidation state (r).

[0052] In one embodiment, the element (E) can be an actinide (e.g., uranium, U),  $E(o)$  can be U(IV) and  $E(r)$  can be U(III). In this embodiment, U(IV) can be in the form of uranium tetrachloride ( $UCl_4$ ), U(III) can be in the form of uranium trichloride ( $UCl_3$ ), and the redox

ratio can be a ratio E(o)/E(r) of  $UCl_4/UCl_3$ . Although  $UCl_4$  can corrode the reactor core 112 by oxidizing chromium according to:



the existence of  $UCl_4$  can reduce the melting point of the molten fuel salt composition 114. Therefore, the level of the redox ratio,  $UCl_4/UCl_3$ , can be selected based on at least one of a desired corrosion reduction and a desired melting point of the fuel salt composition 114. For example, the redox ratio can be substantially constant and selected between about 1/50 to about 1/2000. More specifically, the redox ratio can be at a substantially constant level of about 1/2000.

[0053] The mechanical separation unit 154 can be configured to remove at least part of insoluble fission products and/or dissolved gas fission products from the fuel salt composition 114. Examples of insoluble fission products can include one or more of the following in any combination: krypton (Kr), xenon (Xe), palladium (Pd), ruthenium (Ru), silver (Ag), molybdenum (Mo), niobium (Nb), antimony (Sb), and technetium (Tc). Examples of gas fission products can include one or more of xenon (Xe) and krypton (Kr). As an example, the mechanical separation unit 154 can generate a froth from the fuel salt composition 114 that includes the insoluble fission products and/or the dissolved gas fission products. The dissolved gas fission products can be removed from the froth, and at least a portion of the insoluble fission products can be removed by filtration.

[0054] The chemical exchange unit 156 can be configured to remove at least a portion of the soluble fission products dissolved in the fuel salt composition 114. Examples of the soluble fission products can include one or more of the following, in any combination: rubidium (Rb), strontium (Sr), cesium (Cs), barium (Ba), and lanthanides. The removal of soluble fission products can be realized through various mechanisms.

[0055] Comprehensive lists of fission products applicable to various embodiments to the present disclosure are provided below. A person skilled in the art will appreciate that these lists are illustrative and not meant to be exhaustive.

[0056] Fission products sufficiently noble to maintain a reduced and insoluble state in the fuel salt composition 114 can include, but are not limited to:

- Germanium - 72, 73, 74, 76
- Arsenic - 75
- Selenium - 77, 78, 79, 80, 82
- Yttrium - 89
- Zirconium - 90 to 96
- Niobium - 95
- Molybdenum - 95, 97, 98, 100
- Technetium - 99
- Ruthenium - 101 to 106
- Rhodium - 103
- Palladium - 105 to 110
- Silver - 109
- Cadmium - 111 to 116
- Indium - 115
- Tin - 117 to 126
- Antimony - 121, 123, 124, 125
- Tellurium - 125 to 132

[0057] Fission products that can form gaseous products at the typical operating temperature of can include, but are not limited to:

- Bromine - 81
- Iodine - 127, 129, 131
- Xenon - 131 to 136
- Krypton - 83, 84, 85, 86

[0058] Fission products that can remain as chloride compounds in the molten fuel salt, in addition to actinide chlorides (Th, Pa, U, Np, Pu, Am, Cm) and carrier salt chlorides (Na, K, Ca), can include, but are not limited to:

- Rubidium - 85, 87
- Strontium - 88, 89, 90
- Cesium - 133, 134, 135, 137
- Barium - 138, 139, 140
- Lanthanides

- Lanthanum - 139
- Cerium - 140 to 144
- Praseodymium - 141, 143
- Neodymium - 142 to 146, 148, 150
- Promethium – 147
- Samarium - 149, 151, 152, 154
- Europium - 153, 154, 155, 156
- Gadolinium - 155 to 160
- Terbium - 159, 161
- Dysprosium - 161

[0059] FIG. 5 schematically illustrates a cross-sectional view of the reactor 110 in greater detail. As shown, the reactor 110 includes a primary vessel 300 and a secondary vessel 400 surrounding the primary vessel 300. The primary vessel 300 can have a primary vessel wall 302 including an outer surface 304 and the inner surface 306. The primary vessel wall 302 can be composed of one or more layers of different materials. The secondary vessel 400 includes a secondary vessel wall 402 having an outer surface 404 and an inner surface 406.

[0060] The primary vessel 300 can form part of a heat removal system. When the primary vessel 300 and the secondary vessel 400 are assembled with one another as shown in FIG. 5, the outer surface 304 of the primary vessel wall 302 faces the inner surface 406 of the secondary vessel 400 and a gap is formed between the primary vessel wall 302 and the secondary vessel wall 402. In the gap, heat can be drawn in a direction away from the reactor 110 to prevent the temperature within the reactor 110 from rising to unacceptable levels.

[0061] As shown, the reactor 110 can include the reactor core 112, which can be configured to contain the nuclear fuel components where the nuclear reactions take place and the heat is generated. The reactor core 112 can further include one or more neutron reflectors 312 to elastically scatter neutrons during a fission reaction. In some embodiments, a control rod 314 can be lowered into the reactor core 310 to help initiate nuclear fission. In some embodiments, the reactor 110 can also include a neutron absorber 316 configured to function to confine fission products within the reactor 110.

[0062] FIG. 5 also shows the reactor 110 including one or more heat exchangers 318. During use, one or more pumps 320 can circulate the molten fuel salt composition 114 along

paths within the primary vessel 300, as indicated by arrows 322a-322e. For example, the molten fuel salt composition 114 can be pumped through and out of the heat exchangers 318, indicated by arrow 322a, at which point the molten fuel salt composition 114 flows through a channel defined between the inner surface 306 of the primary vessel wall 302 and the neutron reflector 312, indicated by arrow 322b. The molten fuel salt composition 114 can then flow into and through the reactor core 112, indicated by arrows 322c and 322d, respectively. Subsequently, the molten fuel salt composition 114 can flow through a channel 324 before returning to the heat exchangers 318, indicated by arrow 322e.

[0063] In the event of a breach in the reactor 110 (e.g., a break through the primary vessel 300 and the secondary vessel 400), salt and fission products can potentially exit the reactor 110. Accordingly, as illustrated in FIG. 6 in accordance with one embodiment, the reactor 110 can be provided within a removable primary containment module for hermetically containing salt and fission products.

[0064] Generally, the modular containment system 600 can include a permanent housing 405, a primary containment module 415 at least partially within the permanent housing 405, and a low friction mechanism 410 provided between the permanent housing 405 and the primary containment module 415. As discussed in greater detail below, the primary containment module 415 can provide a sealed interior cavity for containing a reactor vessel 435 (e.g., reactor 110) and any leakage that may occur due to a leak or breach in the reactor vessel 435. Furthermore, unlike previous containment structures, the primary containment module 415 is configured to be removable. In certain embodiments, it can be configured for removal from of the permanent housing 405 using, for example, a crane (not shown). In this manner, when the primary containment module 415 is damaged, it can be removed and replaced with a new module within the permanent housing 405.

[0065] The permanent housing 405 can be made of a material capable of withstanding prolonged exposure to nuclear environments. In an embodiment, the material can also be capable of withstanding the effects of earthquakes without the loss of function or threat to public safety. This is especially important in the wake of the Fukushima nuclear reactor event, which was caused by an earthquake and subsequent tsunami. Suitable materials can include, but are not limited to, reinforced concrete (concrete including reinforcing bars, or "rebars") or pre-stressed concrete (concrete including high strength steel pre-stressing tendons) or other similar materials. In one embodiment, an interior surface of the permanent

housing 405 can be lined with a steel liner (not shown), such as a carbon steel liner, to aid in the provision of a leak tight environment.

[0066] The primary containment module 415 can include a side wall or side walls, a bottom, and a top. The primary containment module 415 can only have one side wall if the primary containment module 415 is substantially cylindrical in shape. The primary containment module 415 can have more than one side wall if it is not cylindrical in shape, but instead contains two or more side walls meeting one another at angles. Like the permanent housing 405, the primary containment module 415 can also be made of a material capable of withstanding prolonged exposure to nuclear environments as well as the effects of earthquakes, such as pre-stressed concrete. The primary containment module 415 can also include a liner, such as a steel liner for example.

[0067] In further embodiments, the primary containment module 415 can be configured to provide a hermetically sealed environment for containing the reactor vessel 435. Thus all seams and points of entry for various connections and structures within the walls of the primary containment module 415 can be sealed.

[0068] The primary containment module 415 can also include at least a portion of its top 416 that can be removed to access the reactor vessel 435 and other contents therein. Accordingly, a seal can be provided at all junctures where there is a break in the material of the primary containment module 415, such as at line 417 in FIG. 6, which allows for removal of the top 416.

[0069] In certain embodiments, at least a portion of the modular containment system can be installed underground. Accordingly, the top of the primary containment module can be approximately at ground level for access and removal. In other embodiments, at least a portion of the modular containment system can be installed above ground. So configured, the top of the primary containment module can be above ground level.

[0070] The low friction mechanism 410 can be configured to aid in the removal of the primary containment module 415 from the permanent housing 405. The low friction mechanism 410 can be made of any material that can withstand nuclear reactor environments, yet provide a low friction surface. Additionally, the material can provide protection to one or both of the permanent housing 405 and the primary containment module

415 as the containment is being lifted out of or lowered into the permanent housing 405. For example, if being lifted by a crane, it is possible that the primary containment module 415 is not lifted out of the permanent housing in a perfect vertical straight line. It is also possible that the primary containment module 415 could sway back and forth as it is being lifted. Thus, the low friction mechanism 410 can provide protection from possible damage in the event that the primary containment module 415 contacts the permanent housing 405 as it is being lifted. Accordingly, the material could include metal materials capable of withstanding nuclear reactor environments, providing a low coefficient of friction, and providing protection/shock absorption properties. The material can also include coatings to impart a low coefficient of friction, such as a chromium carbide and/or nickel aluminide coating.

[0071] The low friction mechanism 410 can also include one or more structures located between the permanent housing 405 and the primary containment module 415. In certain embodiments, at least one structure, or a portion of at least one structure, can be located between the permanent housing 405 and the primary containment module 415 on two opposing sides of the containing module and at the bottom of the primary containment module 415. The structure(s) can be any shape, such as, but not limited to, a square, rectangular, oval, elliptical, cylindrical, conical, sinusoidal and spherical shape. In certain embodiments, the shape of the structures is one that makes contact with the surface of the primary containment module 415 in a tangential manner, such as a structure having a curved surface. As shown in FIG. 6, the shape of the structures forming the low friction mechanism 410 can include one or more substantially spherical structures.

[0072] Embodiments of the structure(s) of the low friction mechanism 410 can be anchored in place by attachment to at least one of the permanent housing 405 or the primary containment module 415. In one example, the structures can all be anchored to the permanent housing 405. In another example, the structures can all be anchored to the primary containment module 415. In another embodiment, the structure(s) can each be in contact with both the primary containment module 415 and permanent housing 405. In another embodiment, the structure(s) of the low friction mechanism 410 can each be separated from at least one of the primary containment module 415 or the permanent housing 405, such that only one or the other is in contact with each of the structures.

[0073] In the event of a nuclear reactor shut down, although not on a large scale, nuclear fission still occurs and decay heat is produced from the delayed decay of fission products.

Failure to remove decay heat may cause the reactor core temperature to rise. Accordingly, it can be desirable to ensure substantially consistent removal of heat from the reactor core, which can be done, in part, through a passive heat removal system 420. The passive heat removal system 420 can be embedded within the primary containment module 415 and it can be configured to facilitate radiative and conductive removal of heat. The passive heat removal system 420 of the present disclosure does not require a power source to function as intended. Accordingly, the heat removal system 420 can draw decay heat released by the molten fuel salt composition 114 following shutdown of nuclear fission within the reactor vessel 435, thereby reducing the temperature in the reactor vessel 435.

[0074] The heat removal system 420 can include a radiative heat removal structure. As an example, the heat removal system 420 can include a set of fins 422 that extend inward from the wall of the primary containment module 415 and into the interior cavity containing the reactor vessel 435. As shown in FIG. 6, the set of fins 422 protrude through the walls of the primary containment module 415 and into the interior cavity of the primary containment module 415. Voids can be included between adjacent fins 422, such that the fins 422 and voids are arranged in an alternating pattern. Alternately or additionally, the fins 422 can crisscross one another. The fins 422 can extend along the entire circumference of the interior surface of the walls of the primary containment module 415, or they may only extend along a portion of the circumference. The physical dimensions of the fins 422, the number of fins 422 and the orientation of the fins 422 can all affect the amount of heat removal that can be achieved. Accordingly, any one parameter or combination of parameters can be modified to produce the desired amount of heat removal.

[0075] The heat removal system 420 can also include an embedded heat removal structure 421. A first portion of the embedded heat removal structure 421 can extend through at least a portion of the walls of the primary containment module 415. As shown, the first portion of the embedded heat removal structure 421 extends from a point within the top 416 of the primary containment module 415. The embedded heat removal structure 421 can also include a second portion that extends along the vertical axis and inward along a substantially horizontal axis through the interior of the primary containment module 415, above the interior surface of the bottom of the primary containment module 415, and forms an elevated portion 423 in the center of the primary containment module 415 (e.g., at about a center of the diameter of the primary containment module 415).

[0076] The passive heat removal system 420 can include of one or more layers having different materials. One layer can include, for example, a high nickel alloy such as HASTELLOY<sup>®</sup> N, molybdenum alloy TZM (titanium-zirconium-molybdenum), and 316FR steel. A second layer can optionally include, for example, a steel composition, such as austenitic steel or a high-CR martensitic steel HT-9.

[0077] Embodiments of the modular containment system 600 can optionally include a moderator layer 425. The moderator layer 425 can be configured to block at least a portion of radiation in the event of a nuclear reactor leak or total failure.

[0078] In one embodiment, the reactor vessel 435 can be positioned upon the moderator layer 425. The reactor vessel 435 can be secured in place by one or more of a variety of mechanisms. For example, the moderator layer 425 can include a depression area dimensioned to receive at least a portion of a bottom of the reactor vessel 435. Alternatively or additionally, the moderator layer 425 can include one or more holes or openings which are configured to receive anchor pins extending down from the bottom of the reactor vessel 435 and which serve to hold the reactor vessel 435 in place upon the moderator layer 425.

[0079] In one embodiment, the moderator layer 425 can be formed from a material having a mass that is comparable to or slightly greater than the mass of a neutron. In this configuration, when a neutron collides with the moderator layer 425, the neutron will lose energy and slow down. In one embodiment, the moderator layer 425 can be formed from carbon (e.g., graphite).

[0080] A sacrificial layer 430 including a salt can also be provided. The sacrificial layer 430 can be configured to further absorb radiation and inhibit flow of the molten fuel salt composition 114 that leaks out of the reactor vessel 435 in the event of a breach. Upon reaching the sacrificial layer 430, the molten fuel salt composition 114 can melt the sacrificial layer 430, diluting the molten fuel salt composition 114, and increasing heat conductivity. The diluted molten fuel salt composition 114 can then be cooled down by the passive heat removal system 420 running through the sacrificial layer 430, as shown in FIG. 6. The sacrificial layer 430 can include, but is not limited to, salts of one or more of the following: boron, xenon, cadmium, hafnium, gadolinium, cobalt, samarium, titanium,

dysprosium, erbium, europium, molybdenum, magnesium, zirconium, scandium, manganese, aluminum, vanadium, chromium, silver, and ytterbium.

[0081] In one aspect, the sacrificial layer comprises a top surface that forms a slope downward toward the center of the interior cavity. The slope can help to direct the melted sacrificial layer 430 and the leaked molten fuel toward the elevated portion 423 of the embedded heat removal structure 421 in order to aid in the removal of heat.

[0082] In another embodiment, the moderator layer 425 can include moderator materials such as those discussed above in combination with a sacrificial salt. The sacrificial salt can be a salt that can be present in the sacrificial layer 430. Accordingly, in certain embodiments, the moderator layer 425 can comprise both graphite and a sacrificial salt.

[0083] The modular containment system 600 can also include a refractory solid structure 440. The refractory solid structure 440 can include those materials indicated to be suitable for the primary containment module 415 and the permanent housing 405, such as pre-stressed concrete.

[0084] The refractory solid structure 440 can have a variety of configurations. As shown in FIG. 6, the refractory solid structure 440 can be positioned underneath the sacrificial layer 430. The sacrificial layer 430 can be applied to the top surface of a possible refractory solid structure 440. A top surface of the refractory solid structure 440 can be contoured to allow for the above-described slope of the sacrificial layer 430, as shown in FIG. 6. In another non-limiting embodiment, the top surface of the refractory solid structure can be substantially horizontal, with the thickness of the sacrificial layer varying to provide for the above-described slope (not shown). Other configurations can also be provided that will allow for the slope of the top surface of the sacrificial layer.

[0085] The modular containment system 600 can also include a number of connectors/disconnects to allow for the connection and disconnection of various components, which can facilitate the removal and replacement the reactor vessel 435. For example, as shown in FIG. 6, connectors 424 can be provided to allow for connection of the passive heat removal system 420 to other areas within the reactor system 102. Disconnects 437 and 439 can also be provided for a secondary heat transport system 436 and electricity 438, respectively.

[0086] In order to facilitate removal of the primary containment module 415, a handle 445 and attachment mechanism 448 are provided. The handle 445 and attachment mechanism 448 are configured to allow a crane or similar piece of machinery to connect to the attachment mechanism 448 and lift the primary containment module 415 out of the permanent housing 405.

[0087] Furthermore, as discussed previously, at least a part of the top portion 416 of the primary containment module 415 can be removed to allow for access to and removal of the reactor vessel 435. In the embodiment shown in FIG. 6, the top portion 416 of the primary containment module 415, delineated by lines 417, is removable. It is also contemplated that a smaller part of the top portion 416 can be removable. However, the opening created should be at least slightly bigger in diameter than the diameter of the reactor vessel 435.

[0088] All references cited throughout this application, for example patent documents including issued or granted patents or equivalents, patent application publications, and non-patent literature documents or other source material, are hereby incorporated by reference herein in their entireties, as though individually incorporated by reference.

[0089] When a Markush group, or other grouping is used herein, all individual members of the group and all combinations and sub-combinations possible of the group are intended to be individually included in the disclosure.

[0090] When a compound is described herein such that a particular isomer, enantiomer, or diastereomer of the compound is not specified, for example, in a formula or in a chemical name, that description is intended to include each isomers and enantiomer of the compound described individual or in any combination. Additionally, unless otherwise specified, all isotopic variants of compounds disclosed herein are intended to be encompassed by the disclosure. For example, it will be understood that any one or more hydrogens in a molecule disclosed can be replaced with deuterium or tritium. Isotopic variants of a molecule are generally useful as standards in assays for the molecule and in chemical and biological research related to the molecule or its use. Methods for making such isotopic variants are known in the art. Specific names of compounds are intended to be exemplary, as it is known that one of ordinary skill in the art can name the same compounds differently.

[0091] As used herein, and in the appended claims, the singular forms “a,” “an,” and “the” include plural reference unless the context clearly dictates otherwise. Thus, for example, reference to “a cell” includes a plurality of such cells and equivalents thereof known to those skilled in the art, and so forth. Additionally, the terms “a” (or “an”), “one or more” and “at least one” can be used interchangeably herein.

[0092] As used herein, the term “comprising” is synonymous with “including,” “having,” “containing,” and “characterized by” and each can be used interchangeably. Each of these terms is further inclusive or open-ended and do not exclude additional, unrecited elements or method steps.

[0093] As used herein, the term “consisting of” excludes any element, step, or ingredient not specified in the claim element.

[0094] As used herein, the term “consisting essentially of” does not exclude materials or steps that do not materially affect the basic and novel characteristics of the claim. In each instance herein any of the terms “comprising”, “consisting essentially of,” and “consisting of” may be replaced with either of the other two terms.

[0095] The embodiments illustratively described herein suitably may be practiced in the absence of any element or elements, limitation or limitations which is not specifically disclosed herein.

[0096] The expression “of any of claims XX-YY” (where XX and YY refer to claim numbers) is intended to provide a multiple dependent claim in the alternative form and in some embodiments can be interchangeable with the expression “as in any one of claims XX-YY.”

[0097] Unless defined otherwise, all technical and scientific terms used herein have the same meanings as commonly understood by one of ordinary skill in the art to which the disclosed embodiments belong.

[0098] Whenever a range is given in the specification, for example, a temperature range, a time range, a composition range, or a concentration range, all intermediate ranges and sub-ranges, as well, as all individual values included in the ranges given, are intended to be included in the disclosure. As used herein, ranges specifically include the values provided

as endpoint values of the range. For example, a range of 1 to 100 specifically includes the end point values of 1 and 100. It will be understood that any subranges or individual values in a range or sub-range that are included in the description herein can be excluded from the claims herein.

[0099] In the descriptions above and in the claims, phrases such as “at least one of” or “one or more of” may occur followed by a conjunctive list of elements or features. The term “and/or” may also occur in a list of two or more elements or features. Unless otherwise implicitly or explicitly contradicted by the context in which it is used, such a phrase is intended to mean any of the listed elements or features individually or any of the recited elements or features in combination with any of the other recited elements or features. For example, the phrases “at least one of A and B;” “one or more of A and B;” and “A and/or B” are each intended to mean “A alone, B alone, or A and B together.” A similar interpretation is also intended for lists including three or more items. For example, the phrases “at least one of A, B, and C;” “one or more of A, B, and C;” and “A, B, and/or C” are each intended to mean “A alone, B alone, C alone, A and B together, A and C together, B and C together, or A and B and C together.” In addition, use of the term “based on,” above and in the claims is intended to mean, “based at least in part on,” such that an unrecited feature or element is also permissible.

[0100] The terms and expressions which have been employed herein are used as terms of description and not of limitation, and there is no intention in the use of such terms and expressions of excluding any equivalents of the features shown and described or portions thereof, but it is recognized that various modifications are possible within the scope of the claimed embodiments. Thus, it should be understood that although the present application may include discussion of preferred embodiments, exemplary embodiments and optional features, modification and variation of the concepts herein disclosed may be resorted to by those skilled in the art. Such modifications and variations are considered to be within the scope of the disclosed embodiments, as defined by the appended claims. The specific embodiments provided herein are examples of useful embodiments of the present disclosure and it will be apparent to one skilled in the art that they may be carried out using a large number of variations of the devices, device components, and methods steps set forth in the present description. As will be obvious to one of skill in the art, methods

and devices useful for the present methods can include a large number of optional compositions and processing elements and steps.

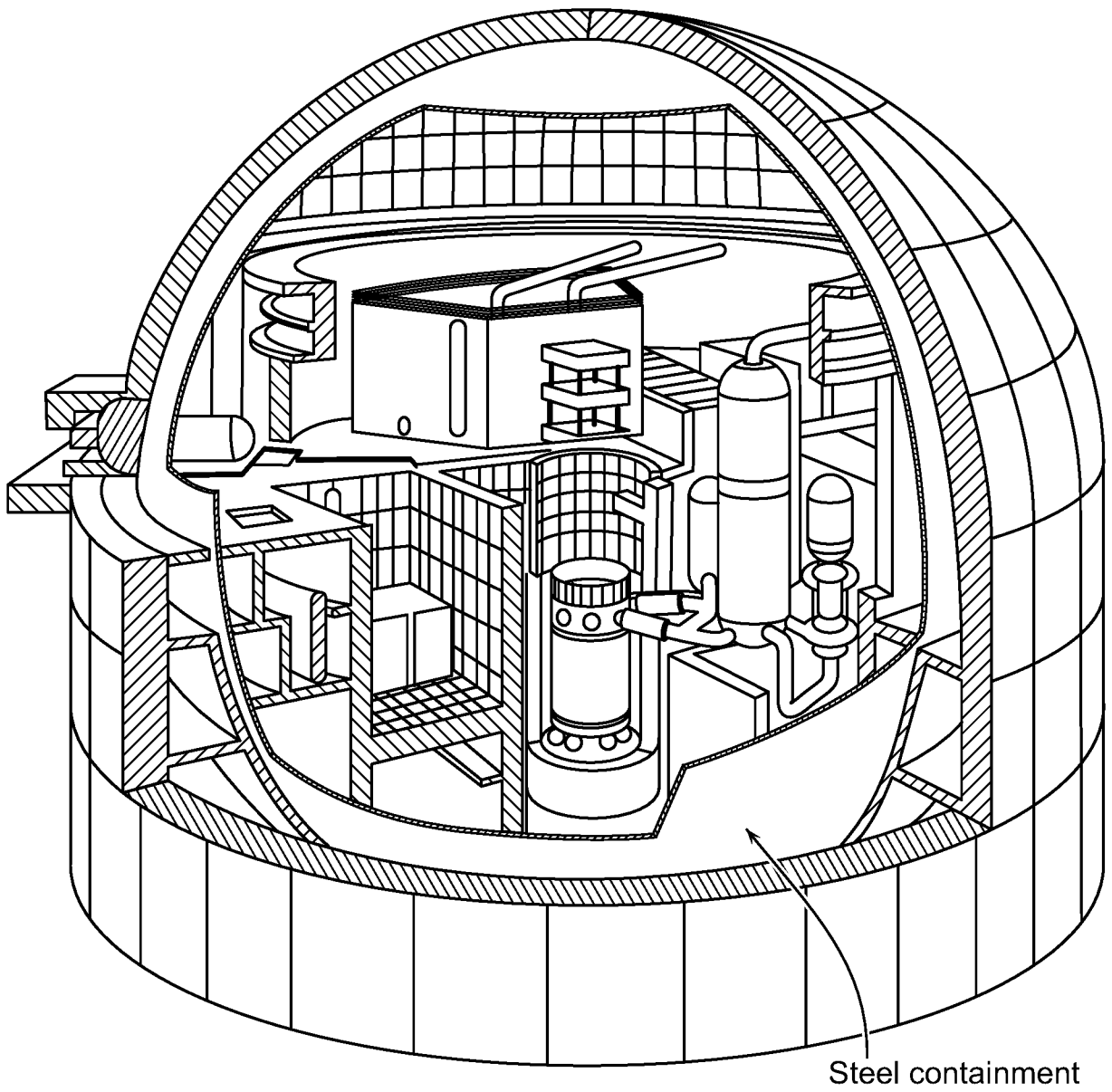
[0101] The disclosed subject matter can be embodied in other specific forms without departing from the spirit or essential characteristics thereof. The foregoing embodiments are therefore to be considered in all respects illustrative rather than limiting on the subject matter described herein.

## CLAIMS

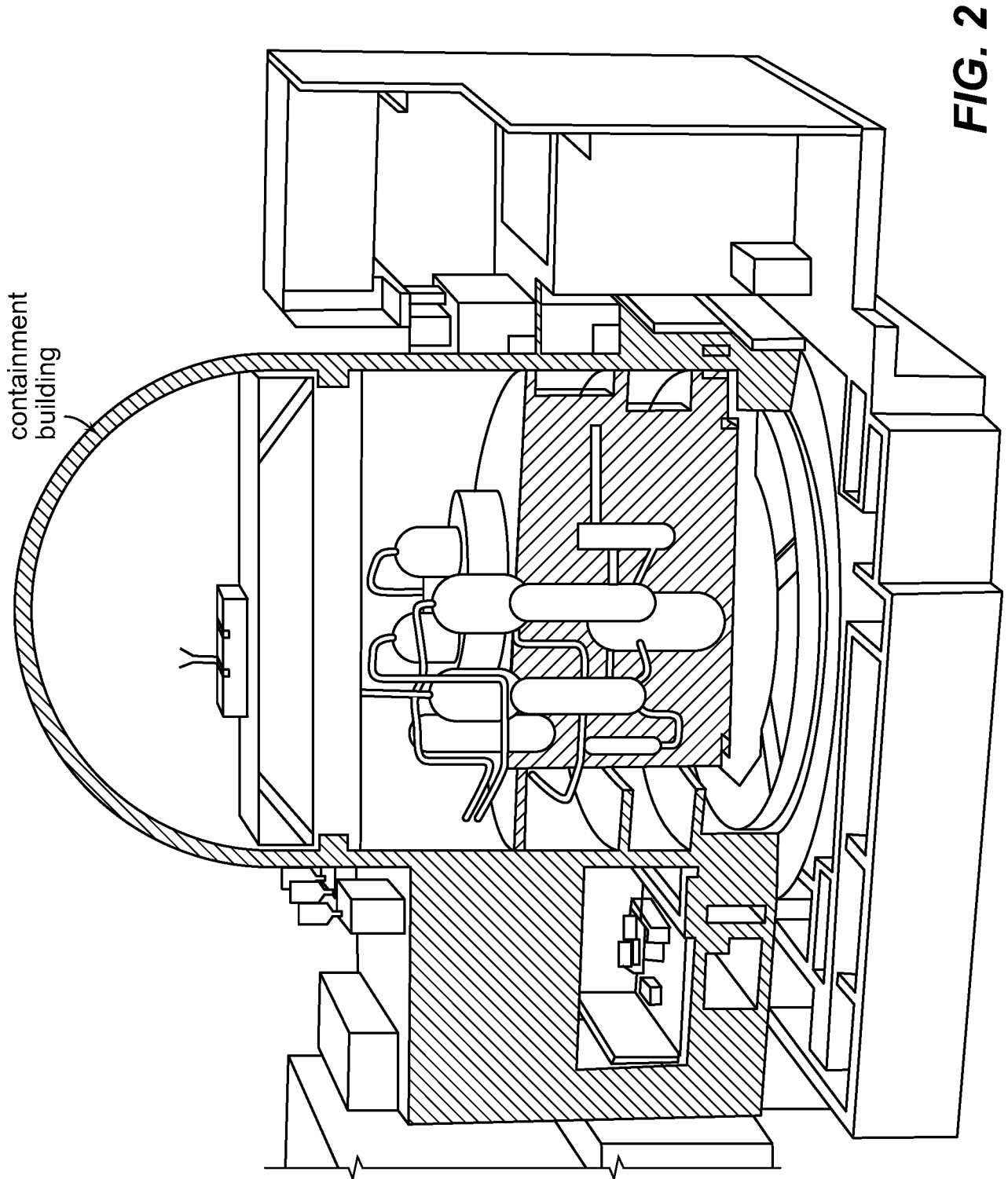
1. A modular containment system comprising:
  - a permanent housing;
  - a containment module at least partially within the permanent housing and defining an interior cavity;
  - a low friction mechanism provided in between the permanent housing and the containment module; and
  - a reactor vessel provided within the interior cavity of the containment module.
2. The modular containment system of claim 1, wherein the modular containment system further comprises a moderator layer.
3. The modular containment system of claim 1, wherein the permanent housing comprises a concrete material.
4. The modular containment system of claim 1, wherein the containment module comprises a concrete material.
5. The modular containment system of claim 1, wherein the low friction mechanism is attached to only one of the containment module or the permanent housing.
6. The modular containment system of claim 1, wherein at least a portion of the low friction mechanism has a curved shape.
7. The modular containment system of claim 6, wherein the low friction mechanism comprises one or more substantially spherical structures.
8. The modular containment system of claim 1, further comprising a passive heat removal system at least partially provided within a wall of the containment module.
9. The modular containment system of claim 8, wherein the passive heat removal system comprises a radiative heat removal structure that extends inward from the wall of the containment module into the interior cavity of the containment module.
10. The modular containment system of claim 9, wherein the radiative heat removal structure comprises a set of fins.

11. The modular containment system of claim 8, wherein the passive heat removal system comprises an embedded heat removal structure in which at least a portion of the embedded heat removal structure extends vertically through the wall of the containment module.
12. The modular containment system of claim 11, wherein a second portion of the embedded heat removal structure extends into the interior cavity of the containment module below the reactor vessel.
13. The modular containment system of claim 2, wherein the moderator layer comprises graphite.
14. The modular containment system of claim 2, wherein the reactor vessel is positioned on the moderator layer.
15. The modular containment system of claim 1, further comprising a sacrificial layer provided within the interior cavity.
16. The modular containment system of claim 15, wherein the sacrificial layer comprises at least one salt that is configured to melt upon contact with a molten fuel salt composition.
17. The modular containment system of claim 15, wherein the sacrificial layer is provided underneath the reactor vessel.
18. The modular containment system of claim 17, further comprising a solid structure provided below the sacrificial layer.
19. The modular containment system of claim 12, further comprising a sacrificial layer provided within the interior cavity, wherein the second portion of the embedded heat removal structure comprises an elevated portion located at about a center of the interior cavity and at least partially within the sacrificial layer.
20. The modular containment system of claim 19, wherein the sacrificial layer comprises a top surface that forms a slope downward toward the center of the interior cavity.

1/6



**FIG. 1**



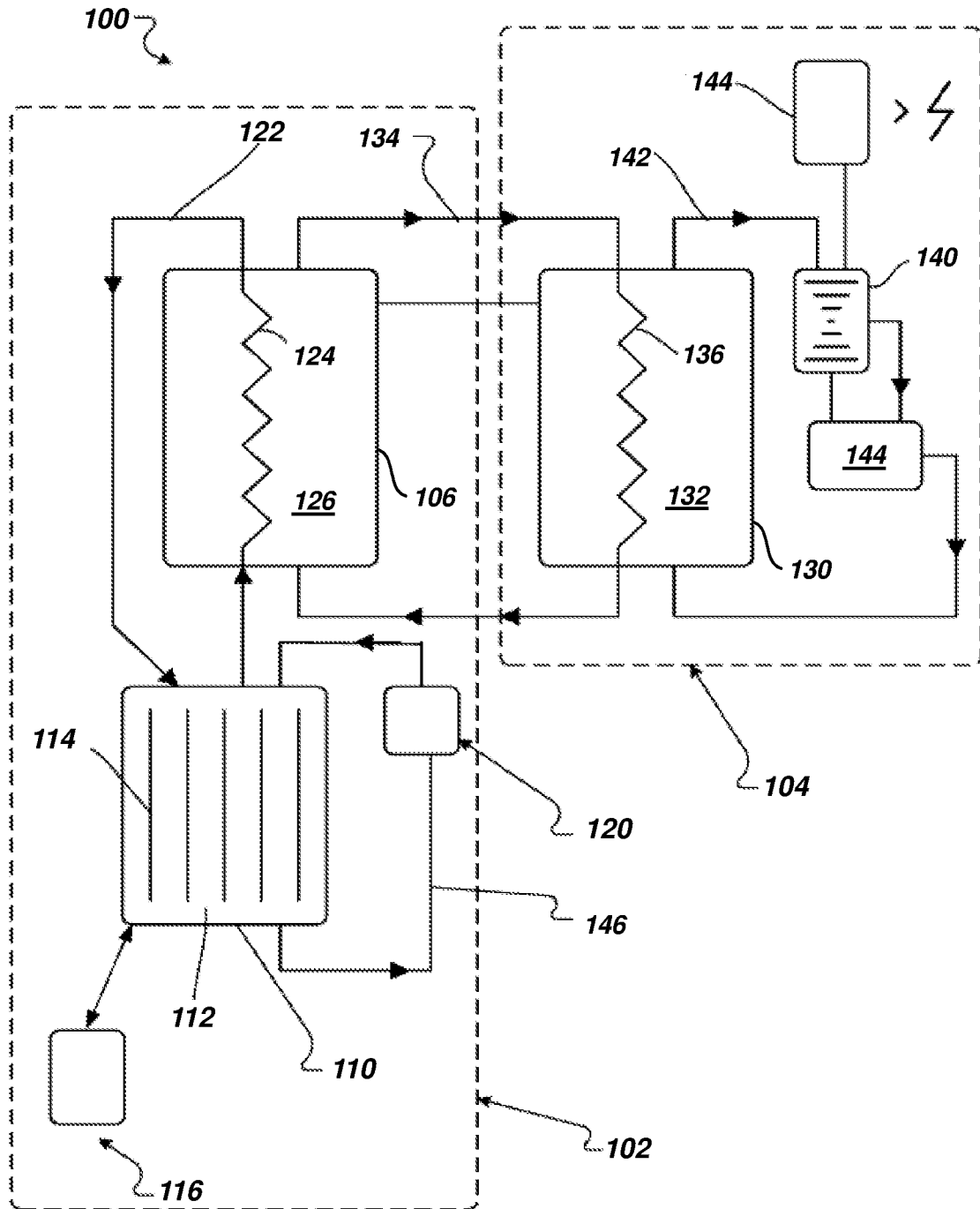


FIG. 3

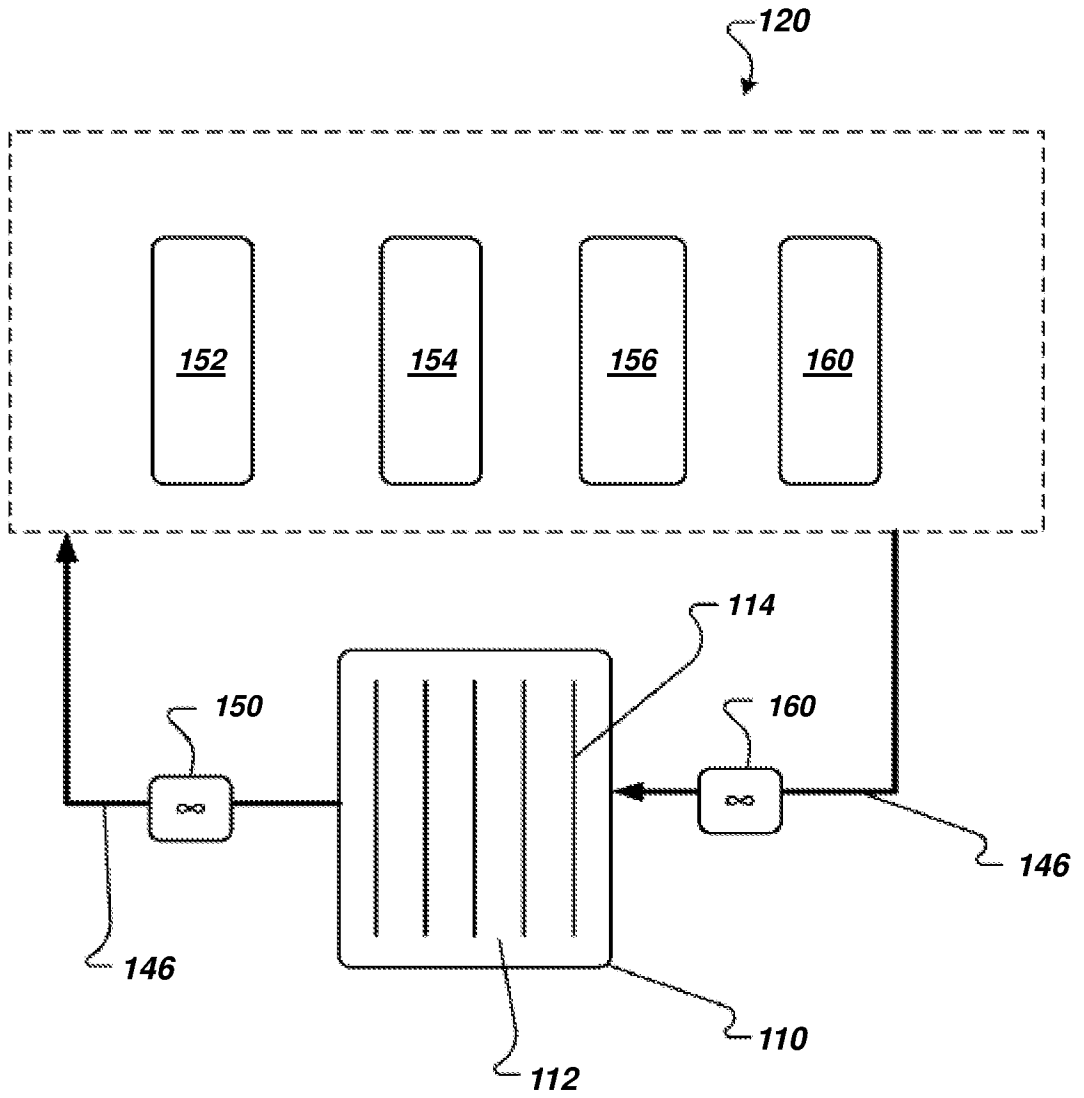


FIG. 4

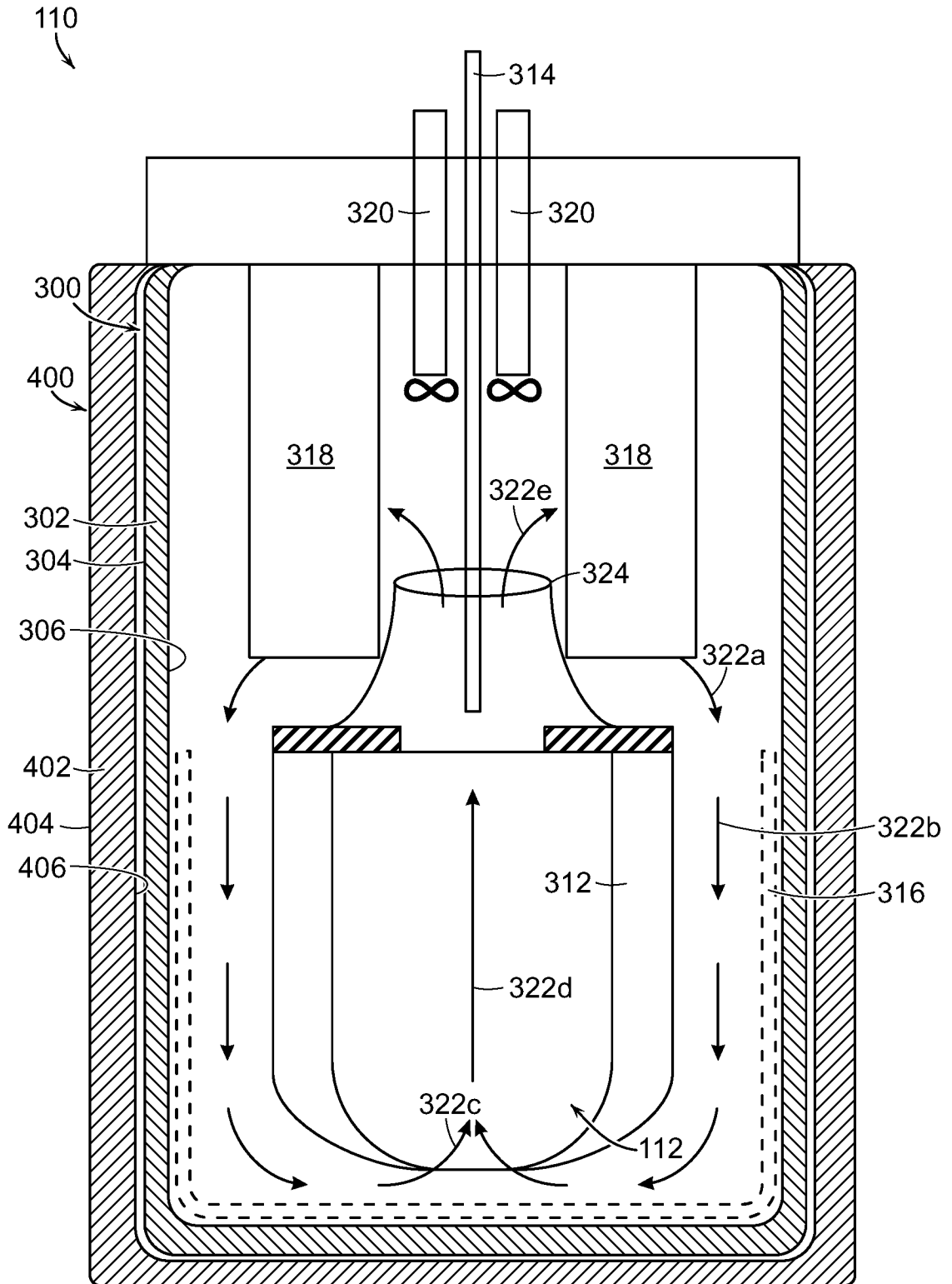


FIG. 5

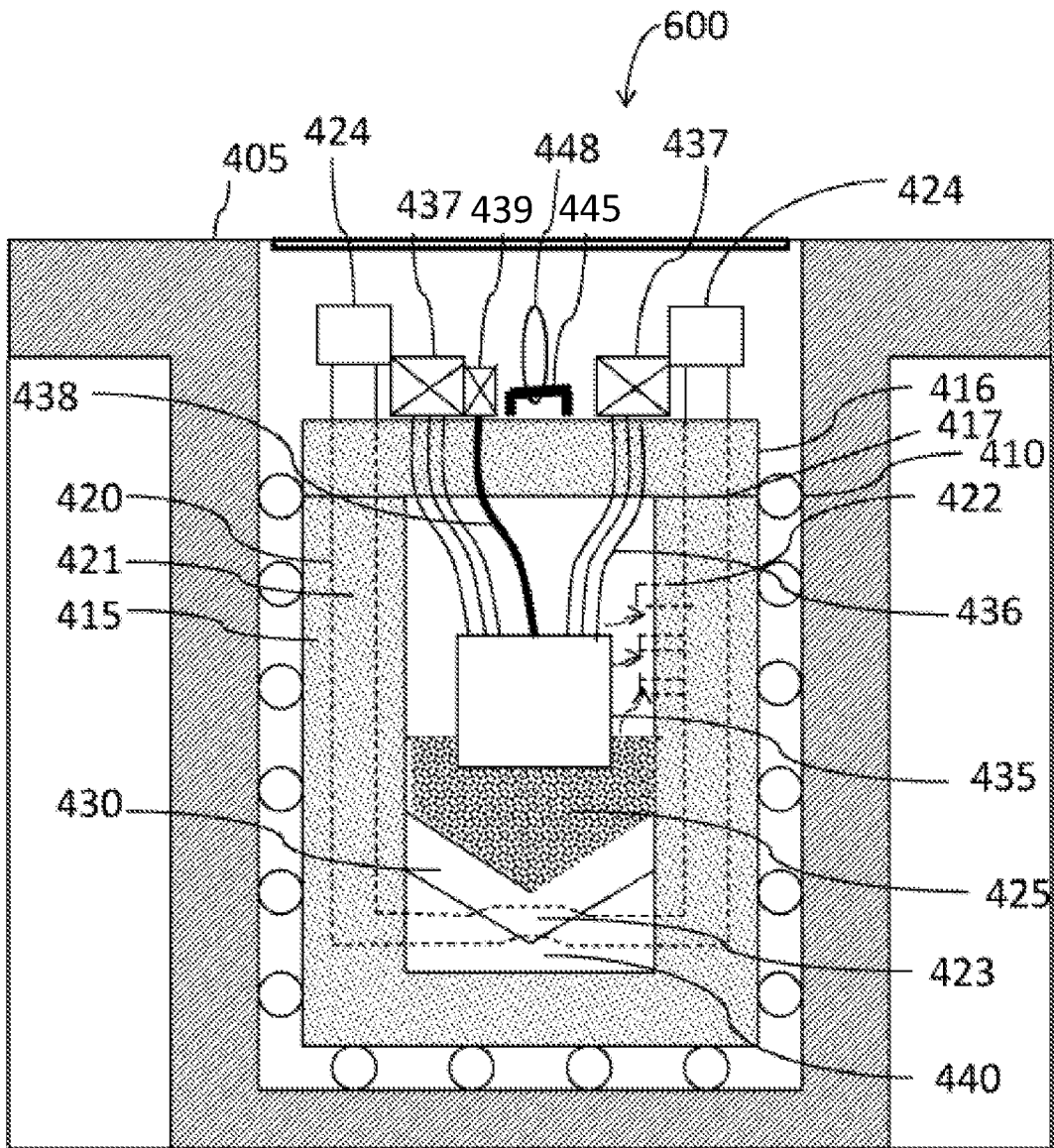


FIG. 6