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McIntyre et al.

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(54) **ACCELERATOR DRIVEN SUB-CRITICAL CORE**

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G21G 1/12 (2006.01)
G21G 1/08 (2006.01)

(52) **U.S. Cl.**
CPC ... ***G21G 1/12*** (2013.01); ***G21G 1/08*** (2013.01)
USPC **376/195**; 376/194; 376/190

(58) **Field of Classification Search**
CPC G21G 1/00
USPC 376/190, 194
See application file for complete search history.

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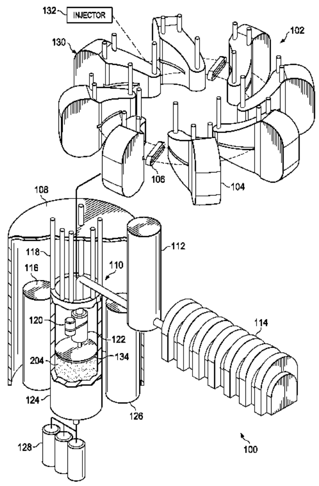
(57) **ABSTRACT**

Systems and methods for operating an accelerator driven sub-critical core. In one embodiment, a fission power generator includes a sub-critical core and a plurality of proton beam generators. Each of the proton beam generators is configured to concurrently provide a proton beam into a different area of the sub-critical core. Each proton beam scatters neutrons within the sub-critical core. The plurality of proton beam generators provides aggregate power to the sub-critical core, via the proton beams, to scatter neutrons sufficient to initiate fission in the sub-critical core.

14 Claims, 12 Drawing Sheets



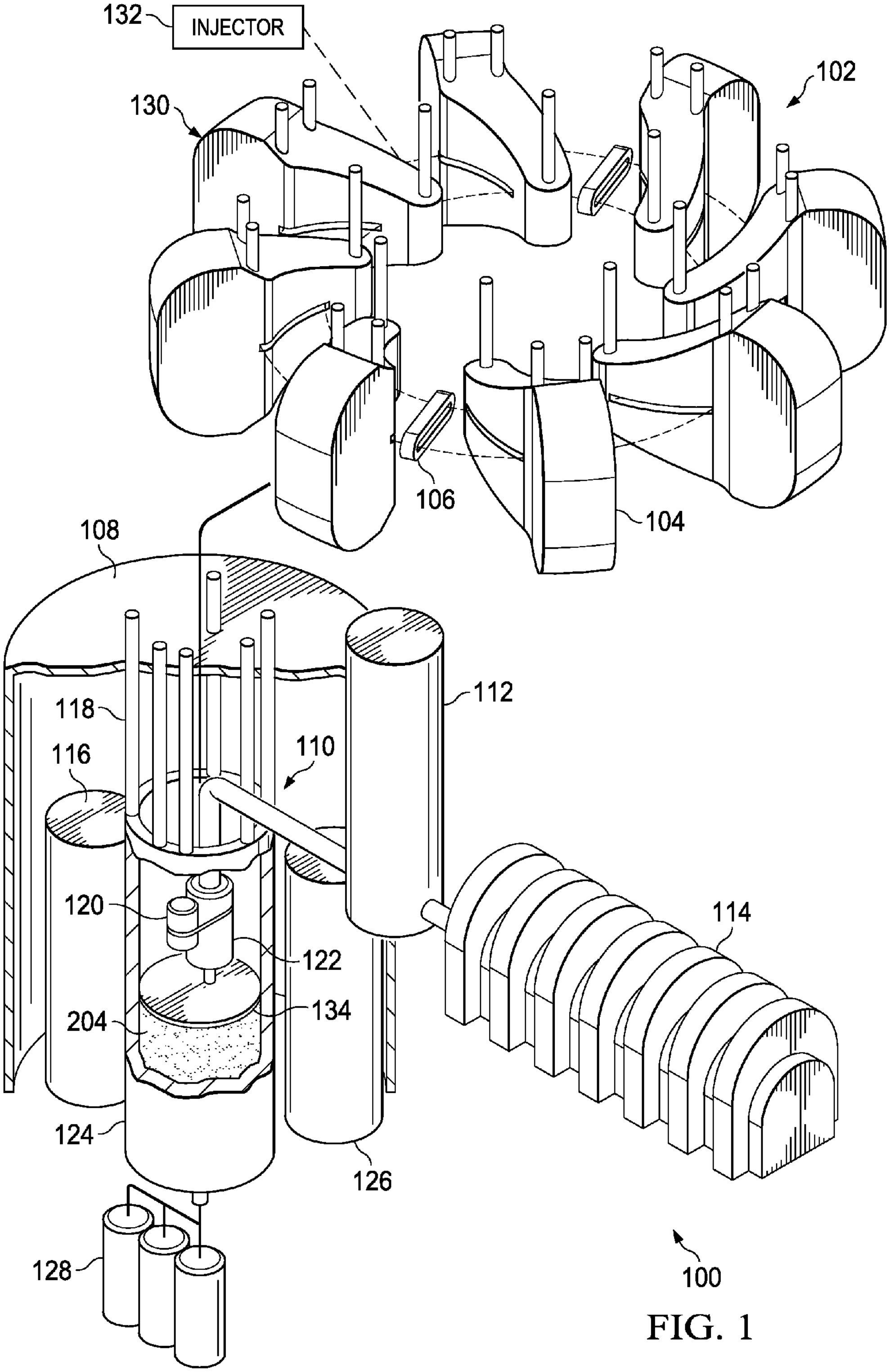

132
INJECTOR
130
102
106
104
108
112
118
110
116
120
122
204
134
114
124
126
128
100

FIG. 1

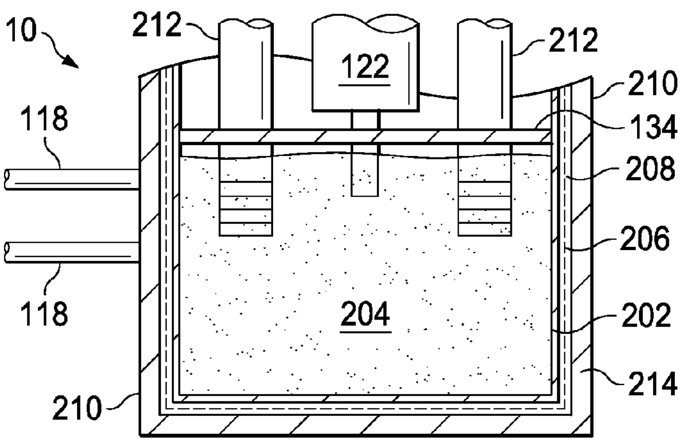

110
212
122
212
210
118
134
208
206
118
204
202
214
210

FIG. 2

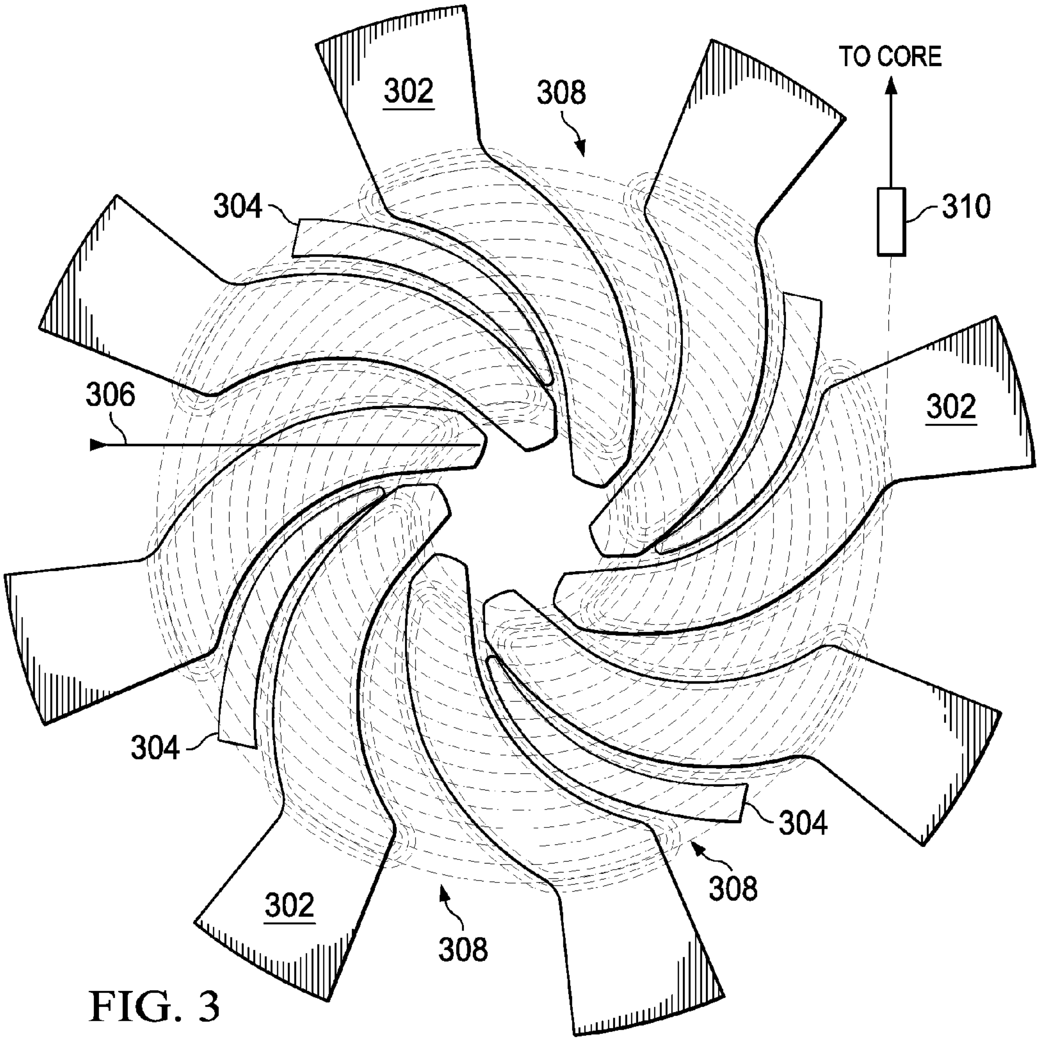

302
308
TO CORE
304
310
302
306
304
304
308
302
308

FIG. 3

FIG. 4

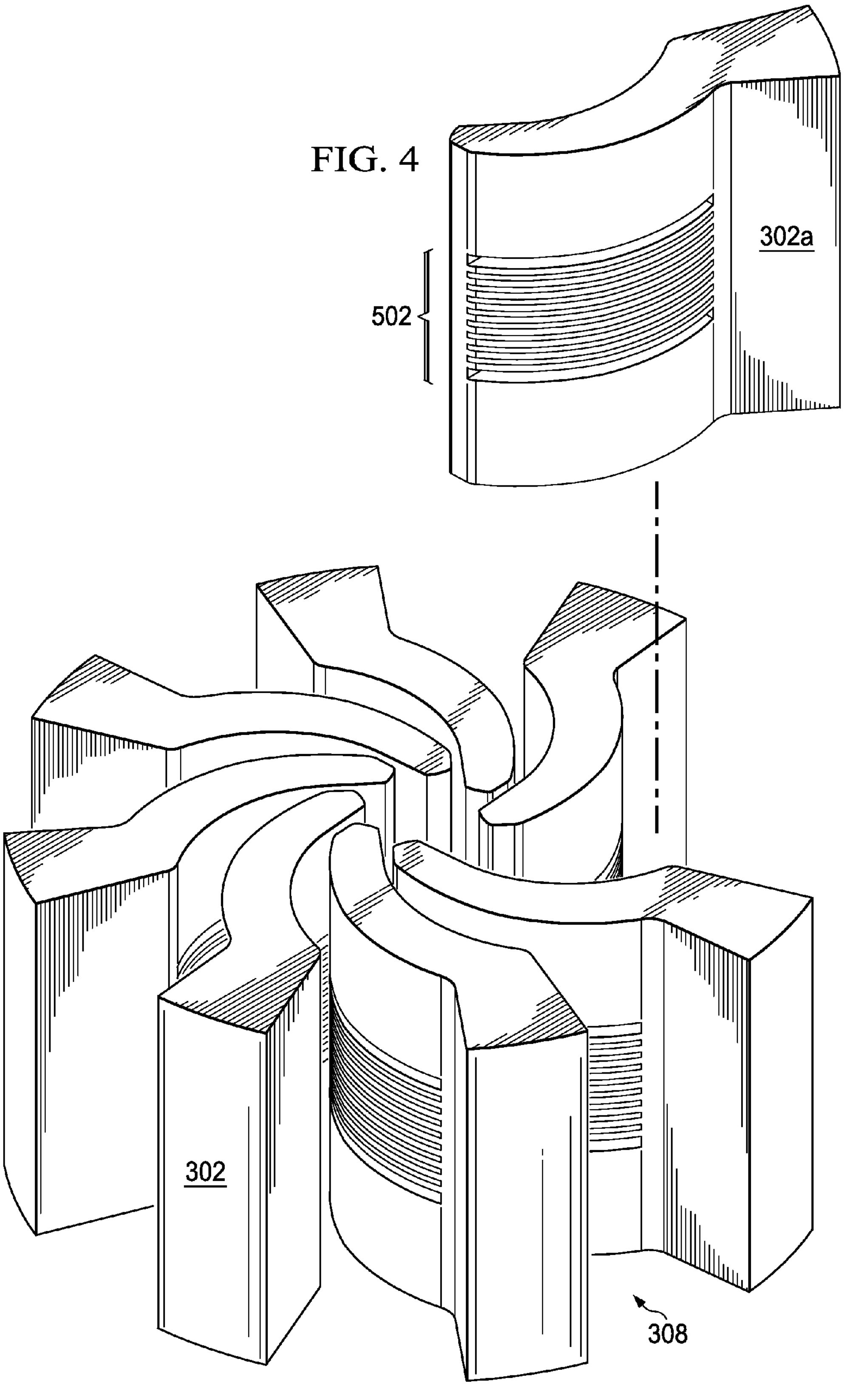
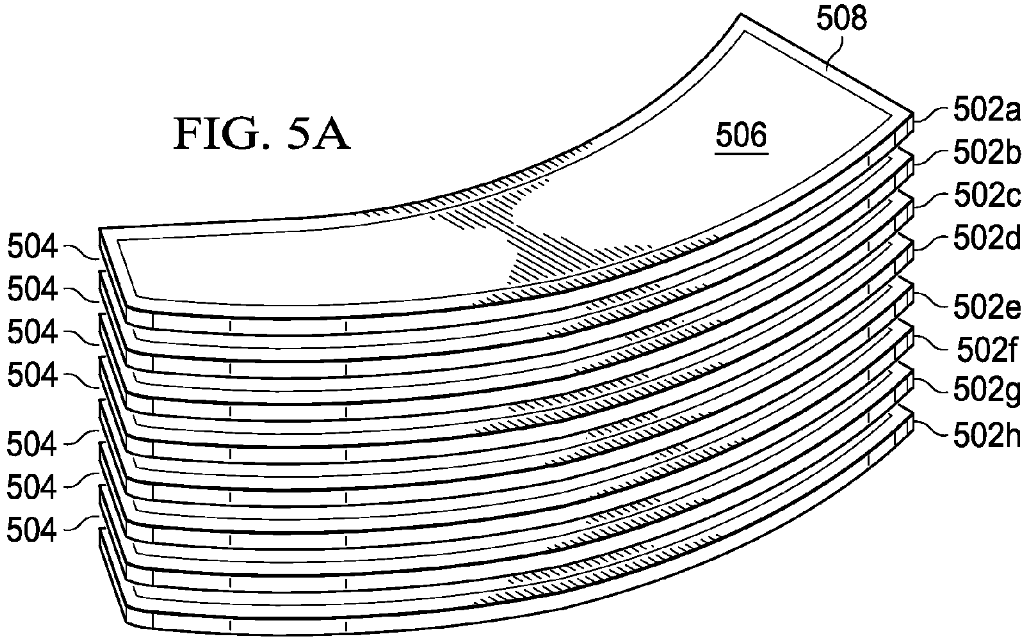


FIG. 5A


508
506
502a
502b
502c
502d
502e
502f
502g
502h
504
504
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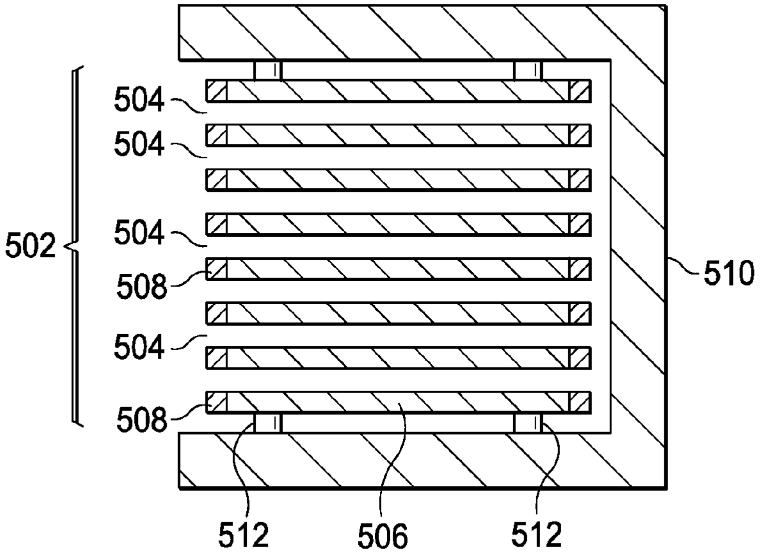
504

FIG. 5B


504
504
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504
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502
510
512
506
512

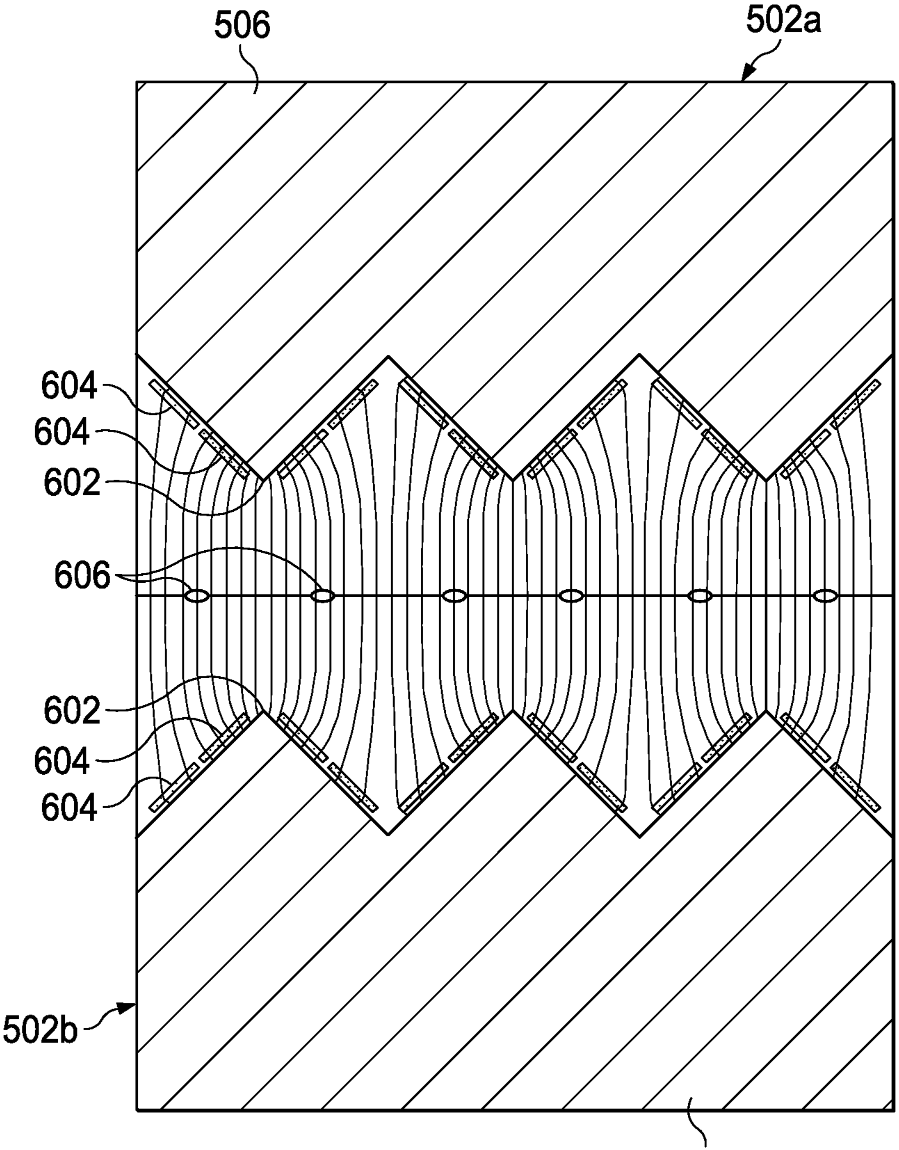

FIG. 6

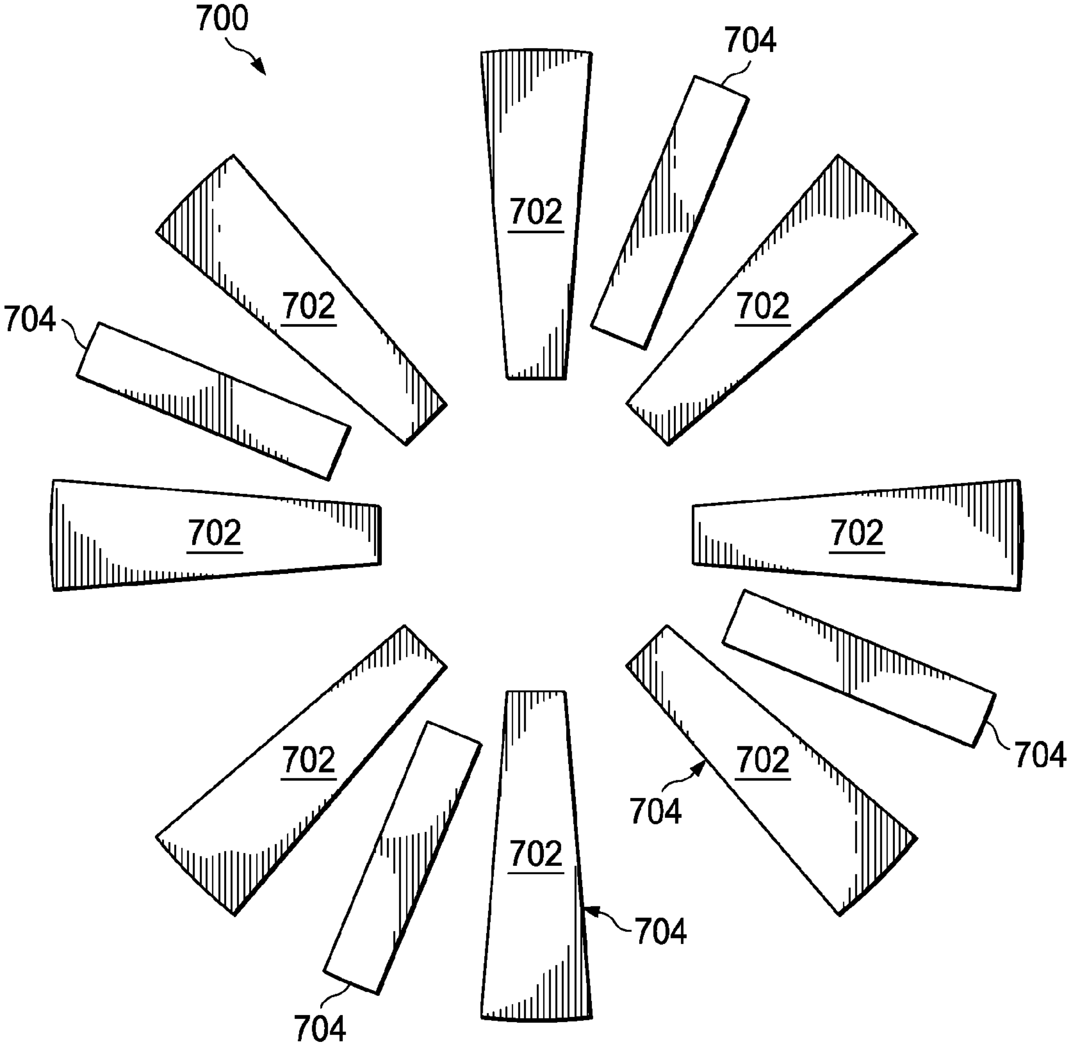

FIG. 7

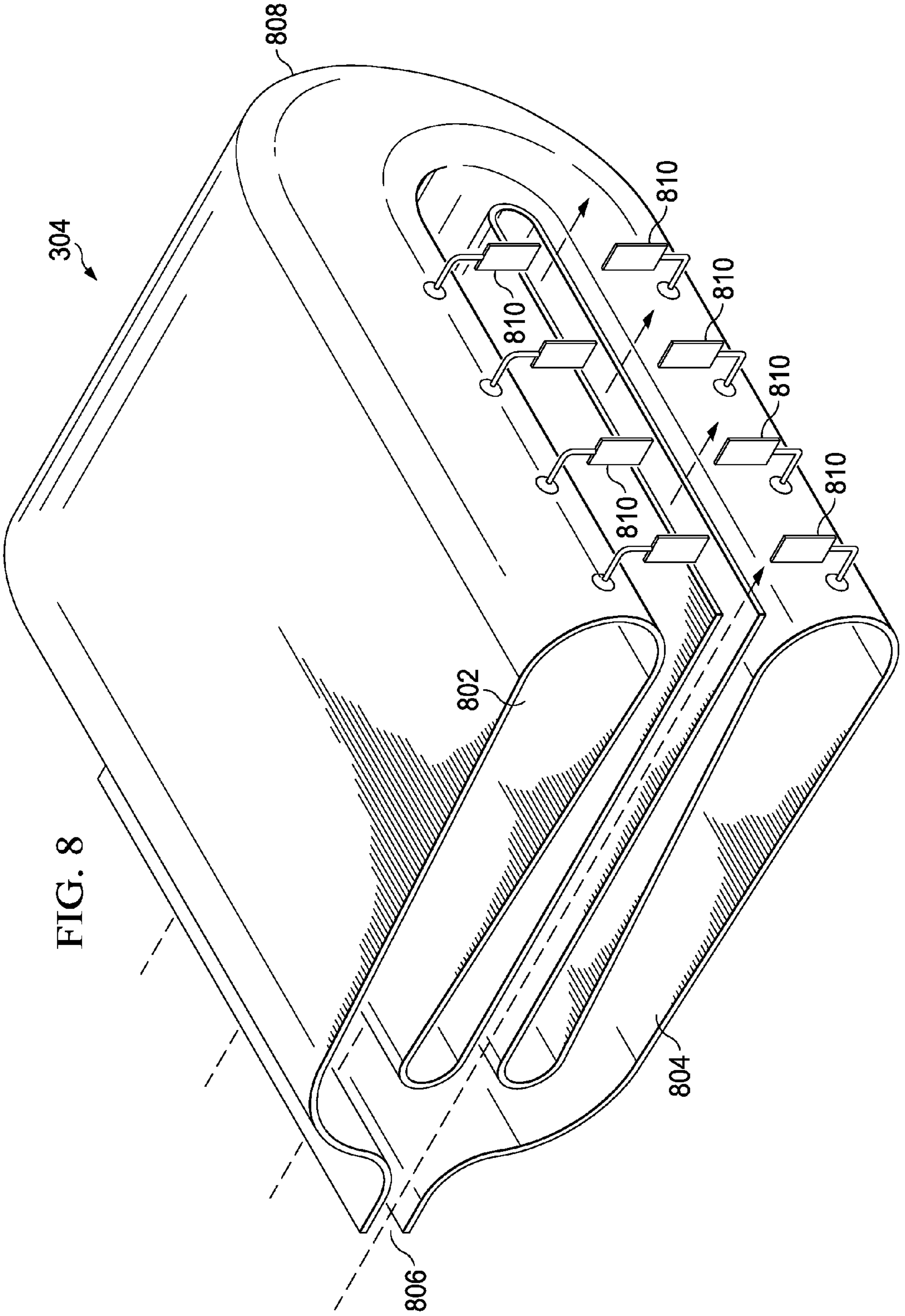

FIG. 8

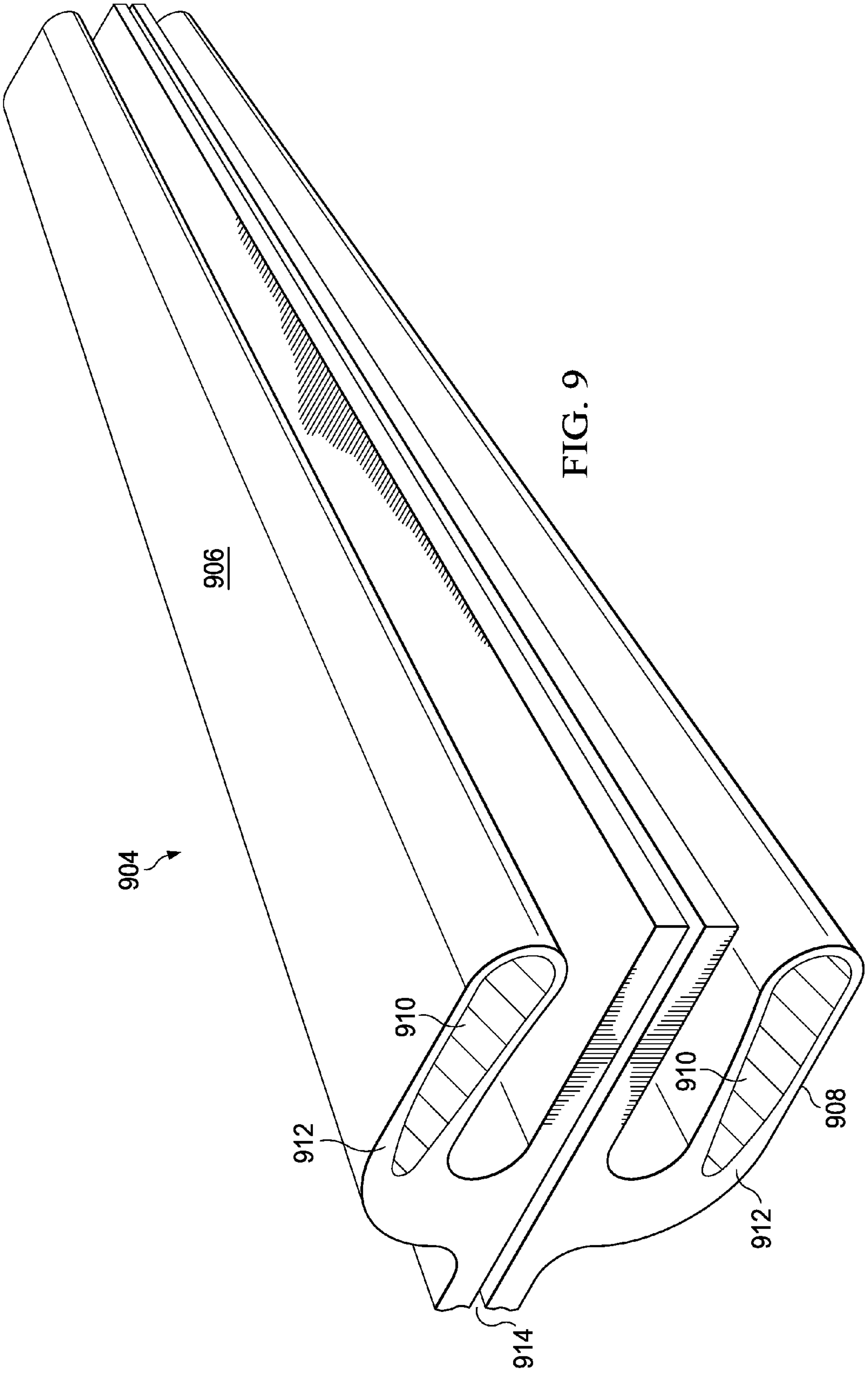

FIG. 9

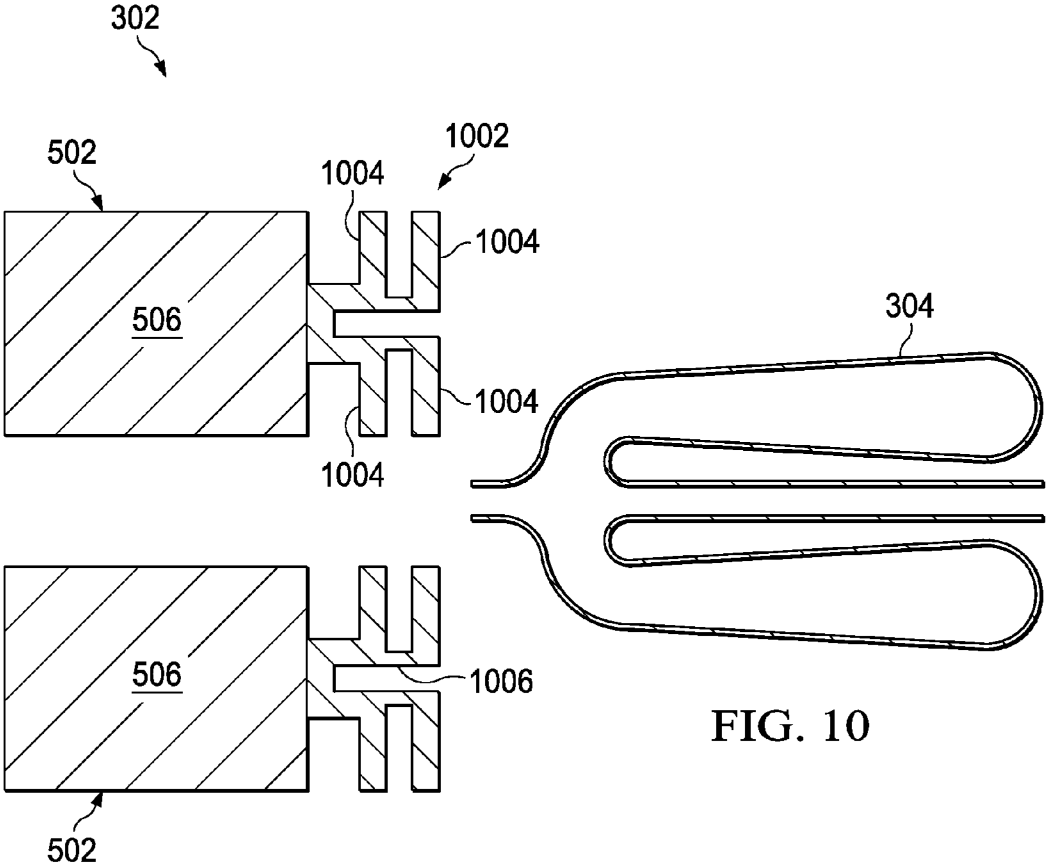

FIG. 10

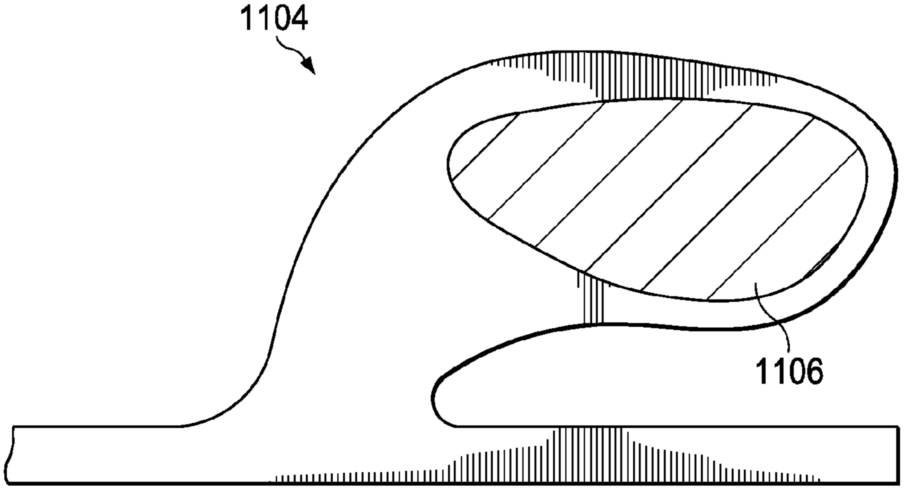

FIG. 11

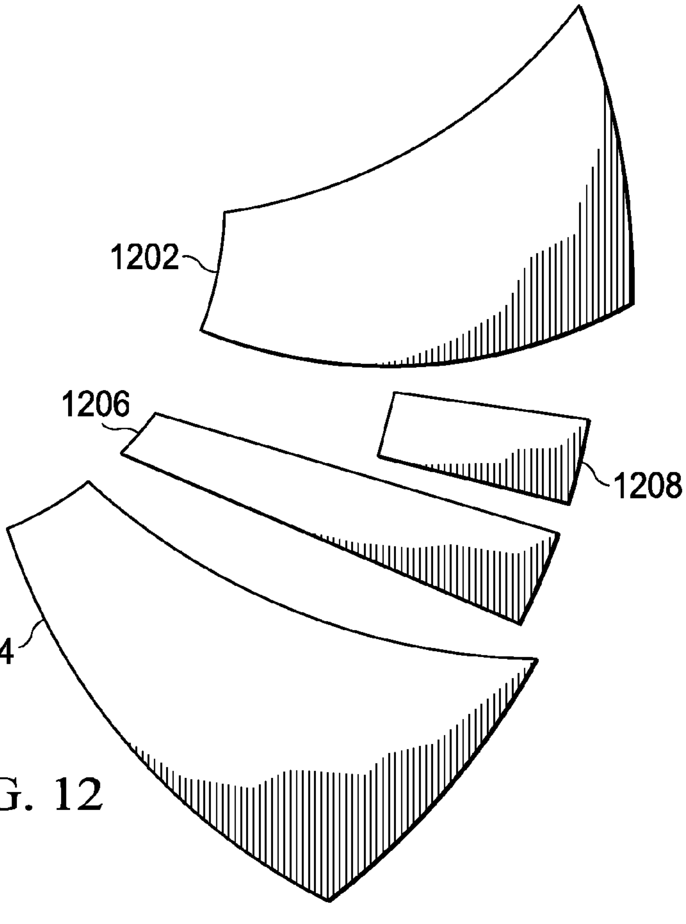

FIG. 12

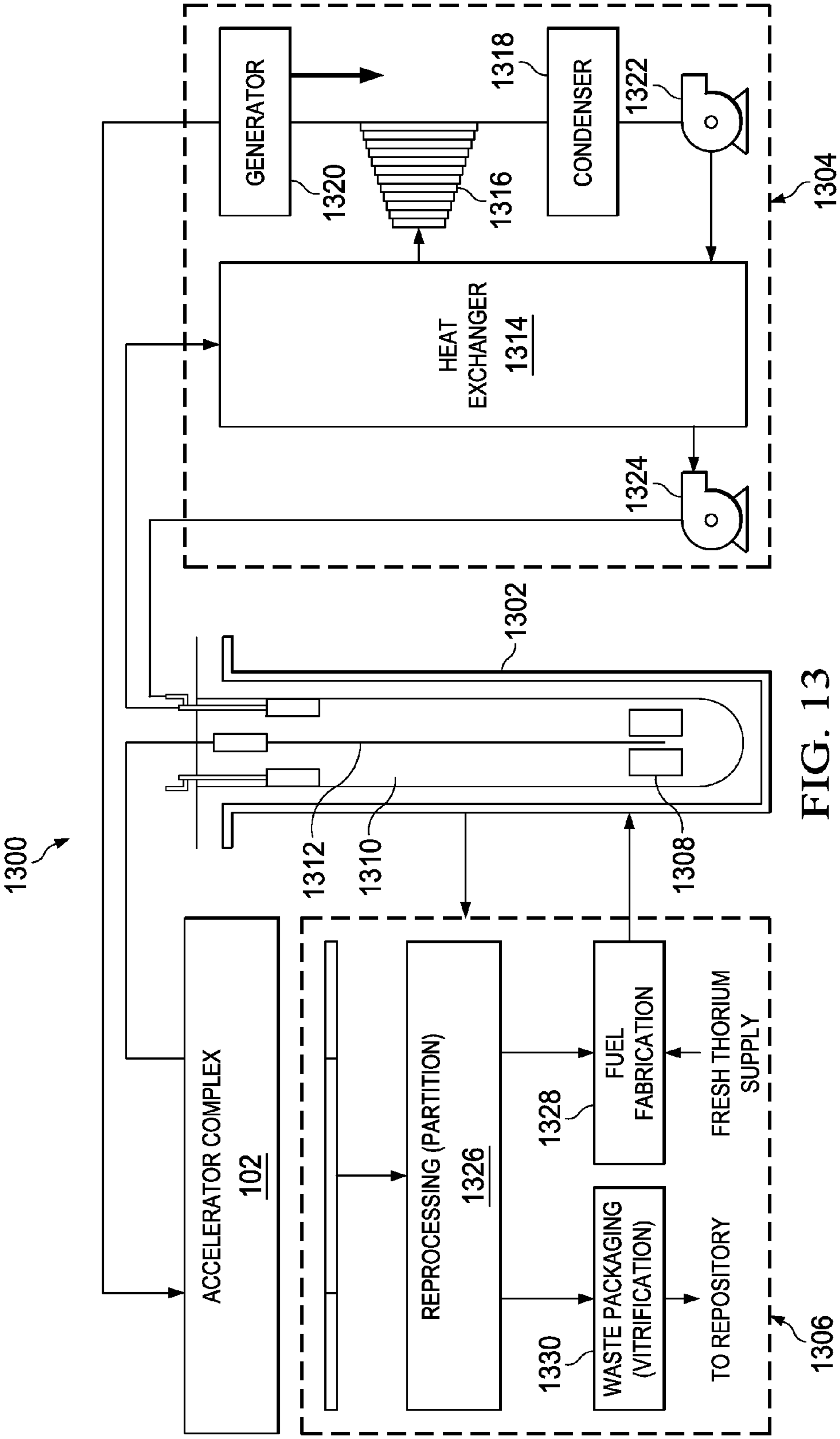
1300
ACCELERATOR COMPLEX
102
REPROCESSING (PARTITION)
1326
1328
FUEL FABRICATION
FRESH THORIUM SUPPLY
1330
WASTE PACKAGING (VITRIFICATION)
TO REPOSITORY
1306
1312
1310
1308
1302
1324
HEAT EXCHANGER
1314
GENERATOR
1320
1316
1318
CONDENSER
1322
1304

FIG. 13

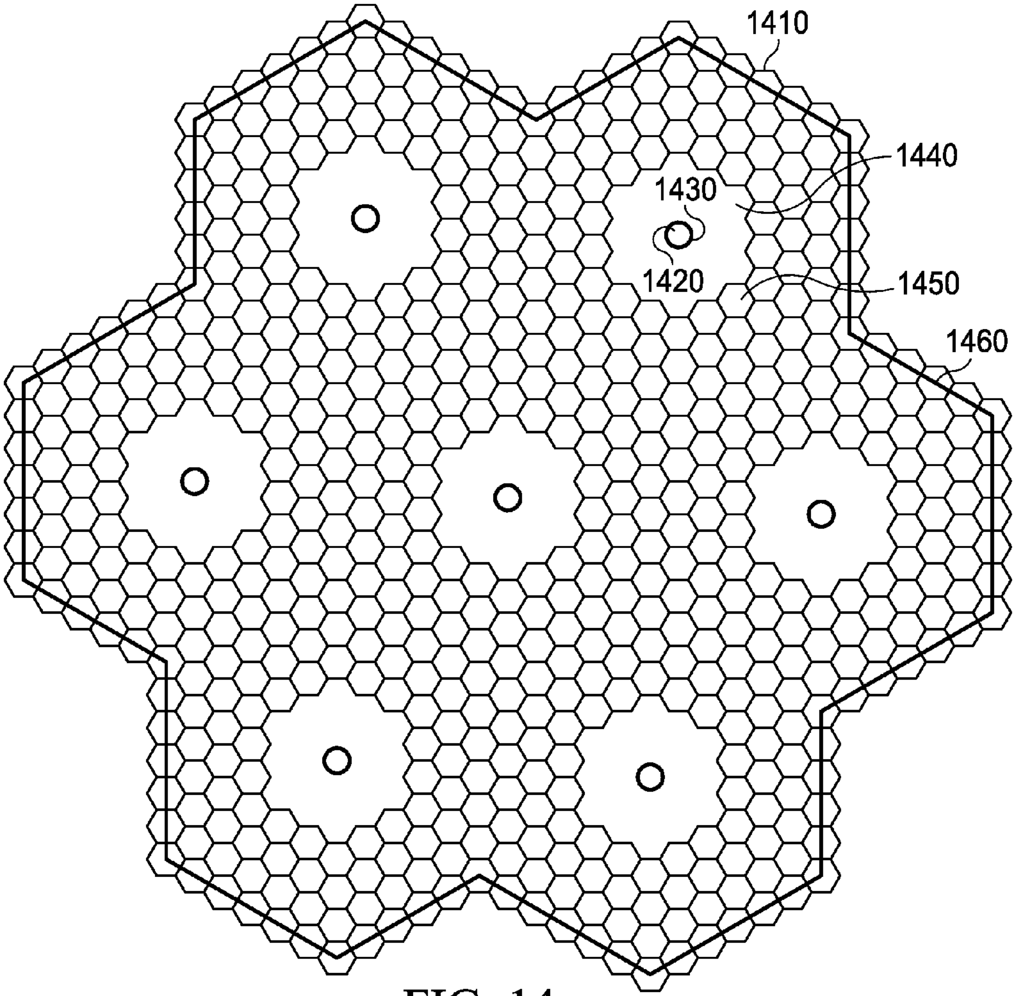

FIG. 14

ACCELERATOR DRIVEN SUB-CRITICAL CORE

CROSS-REFERENCE TO RELATED APPLICATION

The present application claims priority to U.S. Provisional Patent Application No. 61/378,741 filed on Aug. 31, 2010 entitled "Accelerator Driven Transmutation Fission Reactor and Method for Excitation and Control" which is hereby incorporated herein by reference in its entirety.

GOVERNMENT RIGHTS

This invention was made with Government support under the terms of Contract No. DE-FG03-95ER40924 awarded by the U.S. Department of Energy. The U.S. Government may have certain rights in this invention.

TECHNICAL FIELD

The present disclosure is generally related to nuclear power generation, and more specifically related to generation of nuclear power using an accelerator driven sub-critical core.

BACKGROUND

Generating power from nuclear fission utilizes a process in which fissionable nuclei of certain elements, for example uranium 235 (^{235}U), uranium 233 (^{233}U), or plutonium 239 (^{239}Pu) undergo spontaneous fission or fission stimulated by absorption of a neutron. During fission, a nucleus splits into two smaller nuclei and a number of free neutrons. Neutrons produced in a fission event typically have large kinetic energy, typically of order MeV, and are called fast neutrons. In a conventional nuclear reactor, a critical core typically includes fuel rods, or pins, containing fissionable nuclei. The fuel pins are arranged within a matrix of a material that decreases the kinetic energy of neutrons. This process is called moderation. A critical core is capable of self-sustained fission and is called a nuclear reactor.

Stimulated fission of a ^{235}U nucleus has maximum probability for an incident neutron of low energy, typically of order eV, called a thermal neutron . . . Reactors using ^{235}U fission utilize low-atomic-weight materials, such as water or carbon, as moderators because fast neutrons scattering from such light nuclei quickly lose kinetic energy and become available to stimulate fission. The fuel pins and moderator in a conventional ^{235}U-fueled core are arranged so as to sustain an equilibrium in which just enough neutrons are produced in fission to stimulate more fission. Such an arrangement is called a critical pile. The condition of equilibrium must be stabilized by insertion or removal of additional rods of a material whose nuclei have large probability to capture neutrons (control rods). The insertion and removal of control rods can thus be used to maintain the neutron gain, or criticality, of the pile at the precise value of one; this situation is called a critical reaction. If too many neutrons are absorbed, the rate of fission decreases exponentially with time and the core shuts down. If too few neutrons are absorbed, the rate of fission increases exponentially with time and the core explodes.

A critical fission core can be used to generate a large amount of heat, the heat used to generate steam, and the steam used to drive electric generators. Water-moderated ^{235}U-fueled fission reactors are commonly used to generate electric power.

In addition to stimulated fission, neutrons may be captured on certain heavy nuclei, for example uranium **238** (^{238}U) and thorium (^{232}Th), and through a sequence of such neutron capture and radioactive decay produce a fissionable nucleus such as ^{239}Pu (from ^{238}U) or ^{233}U (from ^{232}Th). This process is called breeding, and provides a mechanism by which the process of stimulated fission can actually produce additional fissionable nuclei within the core material

Breeding can also lead to the formation of yet-heavier elements, beyond plutonium in the periodic table. Such elements are called minor actinides. Examples of minor actinides include neptunium (Np) and americium (Am). The minor actinides present a significant problem for safety of nuclear power, because they are produced in significant quantity in thermal reactors and they are the only elements that have radioactive decay half-life greater than a century and less than a million years. For example americium (^{241}Am) has a half-life of 432 years; ^{243}AM has a half-life of 7,370 years. For that reason they present a serious problem for disposal of spent nuclear fuel.

SUMMARY

Systems and methods for operating an accelerator driven sub-critical core are disclosed herein. In one embodiment, a fission power generator includes a sub-critical core and a plurality of proton beam generators. Each of the proton beam generators is configured to concurrently provide a proton beam into a different area of the sub-critical core. Each proton beam scatters neutrons within the sub-critical core. The plurality of proton beam generators provides aggregate power to the sub-critical core, via the proton beams, to scatter neutrons sufficient to initiate fission in the sub-critical core.

In another embodiment, a method for reducing radioactive material includes injecting an externally produced minor actinide into a molten heavy salt eutectic core of a power generator. A plurality of proton beams is provided to the core. The minor actinide is split by fission in the molten heavy salt eutectic core.

In a further embodiment, a sub-critical nuclear power generation system includes a molten salt eutectic core. The molten salt eutectic core includes an inner core vessel, a molten mixture of fuel salt and carrier salt, and a plurality of spallation targets disposed within the molten salt eutectic core. Each spallation target is arranged to receive a different proton beam.

In yet another embodiment, a method for extending the life of a nuclear core includes providing a molten mixture of fuel salt and carrier salt in the core. A lanthanide extraction system is coupled to the core. The molten mixture is provided to the lanthanide extraction system as the core operates. Lanthanides are separated from the molten mixture in the lanthanide extraction system to generate a purified salt mixture as the core operates. The purified salt mixture is provided to the core.

BRIEF DESCRIPTION OF THE DRAWINGS

For a detailed description of exemplary embodiments of the invention, reference will now be made to the accompanying drawings, which may not be drawn to scale, and in which:

FIG. **1** shows a schematic diagram of a molten salt eutectic sub-critical core nuclear power generation system in accordance with various embodiments;

FIG. **2** shows a schematic diagram of the molten salt eutectic core in accordance with various embodiments;

FIG. **3** shows a top view of an isochronous cyclotron stack in accordance with various embodiments;

FIG. **4** shows a perspective view of a flux-coupled isochronous cyclotron stack in accordance with various embodiments;

FIG. **5**A shows a view coil assemblies of a sector magnet of a flux-coupled isochronous cyclotron in accordance with various embodiments;

FIG. **5**B shows a cross-section view of the coil assemblies of a sector magnet of a flux-coupled isochronous cyclotron in accordance with various embodiments;

FIG. **6** shows a cross-sectional view of a pair of coil assemblies **502** configured to produce alternating gradient quadrupole fields in accordance with various embodiments;

FIG. **7** shows a top view of a cyclotron stack including strong focusing in accordance with various embodiments;

FIG. **8** shows a schematic view of an RF cavity suitable for use a cyclotron stack in accordance with various embodiments;

FIG. **9** shows a schematic view of an alternative RF cavity suitable for use with a stacked cyclotron in accordance with various embodiments;

FIG. **10** shows a schematic view of a cross-section of an RF cavity **304** and associated magnetic shielding in accordance with various embodiments;

FIG. **11** shows a schematic view of an alternative RF cavity including a single RF chamber suitable for use with a stacked cyclotron in accordance with various embodiments;

FIG. **12** shows a schematic view of two RF cavities disposed between adjacent sector magnets in accordance with various embodiments;

FIG. **13** shows a schematic diagram of a fuel pin based sub-critical core nuclear power generation system in accordance with various embodiments; and

FIG. **14** illustrates overhead view of a proton beam distribution pattern in sub-critical nuclear core in accordance with various embodiments.

NOTATION AND NOMENCLATURE

Certain terms are used throughout the following description and claims to refer to particular system components. As one skilled in the art will appreciate, the same component may be referred to by different names. This document does not intend to distinguish between components that differ in name but not function. In the following discussion and in the claims, the terms "including" and "comprising" are used in an open-ended fashion, and thus should be interpreted to mean "including, but not limited to . . . " Also, the term "couple" or "couples" is intended to mean either an indirect or direct connection. Thus, if a first device couples to a second device, that connection may be through a direct connection, or through an indirect connection via other devices and connections. The recitation "based on" is intended to mean "based at least in part on." Therefore, if X is based on Y, X may be based on Y and any number of other factors.

DETAILED DESCRIPTION

The following discussion is directed to various embodiments of the invention. Although one or more of these embodiments may be preferred, the embodiments disclosed should not be interpreted, or otherwise used, as limiting the scope of the disclosure, including the claims. In addition, one skilled in the art will understand that the following description has broad application, and the discussion of any embodiment is meant only to be exemplary of that embodiment, and not intended to intimate that the scope of the disclosure, including the claims, is limited to that embodiment.

Power generation based on a critical fission core presents a number of challenges. The efficiency of systems employing a critical core is low. For example, only about 5% of the fertile fuel contained within a fuel pin may be consumed before accumulation of fission products makes the fuel pin unusable, necessitating premature replacement of the fuel pin. Thermal fission cores also produce significant quantities of minor actinides which remain radioactive for thousands of years. Such waste must be securely and safely stored. Further, the critical fission core is subject to catastrophic failure if core cooling or neutron gain is not carefully maintained.

Sub-critical cores contain fissionable fuel but they may be designed in a manner that they are incapable of a self-sustained fission chain reaction. In sub-critical cores, fission is initiated and maintained by introducing fast neutrons into the core from an outside source. A particle accelerator can be used to generate fast neutrons by spallation. Spallation is a process wherein a collision between particles, e.g., an accelerated proton and a target nucleus, results in the ejection of multiple particles (primarily fast neutrons) from the target nucleus. Thus, particle accelerator induced fission in a sub-critical core may be referred to as Accelerator Driven Sub-critical (ADS) fission.

ADS fission addresses at least some of the aforementioned challenges of critical fission cores. ADS fission is directly controlled by the particle beam. Thus, when the particle beam is disabled, ADS fission halts, providing direct control of the fission process. Furthermore, an ADS fission system may include sufficient thermal mass to preclude meltdown from radioactive heat after fission stops. ADS fission also provides greater flexibility for the composition and placement of fissile, fertile, or fission product waste within the core, and requires less enrichment of fissile content. ADS fission operates naturally in the fast neutron spectrum, rather than the thermal spectrum used by critical reactors. Use of fast-neutronics (i.e., neutron energies in the mega-electron-volt (MeV) range) provides an opportunity to burn minor actinide waste elements by fission in the core, thereby reducing the need for secure waste storage facilities and the attendant risks associated with waste and waste disposal.

In practice, ADS fission systems are not without difficulties. In order to drive a ~GW_e ADS fission core, a continuous-wave (CW) proton beam of >700 MeV and ~10 megawatts (MW) beam power may be required. No conventional proton accelerator has yet achieved that performance, and accelerator system cost and reliability remain particular concerns. Beam reliability is particularly problematic in cores based upon the use of fuel pins because it can cause thermal shock and cracking of fuel pins.

All particle accelerators are prone to periodic beam interruptions. As noted above, fission stops with the proton beam. When fission stops, fuel pin temperature drops. The fuel pins are encased in a cladding material, such as zircaloy. Changes in temperature can thermally shock the fuel pin cladding, inducing fatigue and/or cracking that necessitate fuel pin replacement.

Finally, if the neutrons produced by spallation are produced as a line source in the center of a sub-critical core, fission products accumulating in fuel pins closest to the spallation source will block neutron propagation to the more distant fuel pins. As a consequence, fission occurs predominantly in the portion of the core nearest the spallation source, and the core must be periodically rebalanced by changing the positioning of the fuel pins. Access to the fuel pins for rebalancing presents undesirable security concerns.

Embodiments of the ADS fission systems of the present disclosure include features that overcome the deficiencies of critical cores and of conventional ADS systems which employ a single proton beam. Embodiments include multiple proton beam sources and multiple spallation targets. By incorporating multiple beams, embodiments generate the high beam power required to induce fission for power generation while also providing redundancy that enables core operation during beam interruption. Further, by dispersing the spallation targets about the core, core efficiency is enhanced and the need to reshuffle the fuel pins is reduced in those embodiments employing fuel pins.

Some embodiments of the ADS fission system disclosed herein include a molten salt eutectic rather than fuel pins and moderator. The molten salt eutectic includes a mixture of fuel salt and carrier salt. In a molten salt eutectic core, there is no fuel pin cladding and no concerns related to cladding. The molten salt core provides a number of additional advantages over a core employing fuel pins. As explained above, an ADS core using fast neutronics can burn long-lived radioactive waste. The molten salt core provides fast neutronics and advantageously allows waste produced by conventional cores to be added to the fuel salt and destroyed. Thus, the molten salt core disclosed herein provides a means for destroying minor actinide waste produced by other sources, such as critical fission cores. The molten salt core can also be fueled with spent nuclear fuel in which fission products have accumulated to a degree that the fuel can no longer be used to generate fission in a critical fission core.

The molten salt core allows for isolation and removal of fission products that absorb neutrons from the salt. Thus, embodiments are very efficient, allowing for complete or nearly complete consumption of all fertile fuel in the core. Furthermore, embodiments of the molten salt core herein disclosed provide fail-safe heat transfer. The core cannot melt through its containment even with a complete loss of power and coolant.

FIG. **1** shows a molten salt eutectic sub-critical core nuclear power generation system **100** in accordance with various embodiments. The power generation system **100** includes a molten salt core **110**, a particle accelerator complex **102**, one or more primary heat exchangers **122**, one or more secondary heat exchangers **112**, and at least one turbine generator **114**. Molten salt from or in the core **110** transfers heat to molten sodium, non-fuel salt, or another secondary fluid that is suitable to transport heat, in the primary heat exchanger **122**. The heated fluid flows from the primary heat exchanger **122** to the secondary heat exchanger **112**. In the secondary heat exchanger **112**, heat provided by the fluid is used to generate steam, or another suitable pressurized fluid, that drives the turbine generator **114** to generate electrical power. The primary and secondary heat exchangers **122**, **112** may be tube-and-shell heat exchangers as known in the art. Though only a single turbine generator **114** is shown, in practice, the system **100** may include more than one turbine generator **114**.

The power generation system **100** also includes a containment vessel **108**, one or more lanthanide stills **120**, a primary vessel **124**, a set of conductive heat pipes **118**, a lanthanide storage vessel **116**, a volatile fission fragment storage vessel **126**, and dump tanks **128**. The lanthanide stills **120** and at least some portions of the primary heat exchangers **112** are contained within the primary vessel **124**. The heat pipes **118** extend from the primary vessel **124** to a thermal sink. The primary vessel **124**, lanthanide storage vessel **116**, and volatile fission fragment storage vessel **126** are disposed within the containment vessel **108**.

In some embodiments, the primary heat exchanger **122** is completely contained within the primary vessel **124** at a position above a neutron reflector **134**. In such embodiments, the molten salt **204** is isolated within the primary vessel **124**. The flow of the molten salt **204** to the primary heat exchanger **122** is sustained by at least one pump and connecting pipes that transfer molten salt **204** from a plenum disposed at the upper levels of the molten salt **204** to an inlet of the primary heat exchanger **122**. Embodiments of the primary heat exchanger **122** may transfer 400 MW of heat and be no more than about 2.5 meters in height, providing sufficient space to accommodate three or more particle beams entering the top of the primary vessel **124**.

The secondary fluid is circulated through the secondary tubing manifolds of the primary heat exchanger **122** by at least one pump and pipes connected to the secondary heat exchanger **112**. Cooled molten salt **204** may flow from an outlet of the primary heat exchanger **122** to a cylindrical plenum shell forming an annulus just inside the side wall of the primary vessel **124**. By directing the flow of cooled molten salt **214** downward along the side walls of the primary vessel **214**, the surface temperature and corrosion of the side walls is reduced, thereby increasing the operating life of the primary vessel **124** (e.g., to up to 100 years).

FIG. **2** shows a schematic diagram of the sub-critical molten salt eutectic core **110** and portions of the primary vessel **124** in accordance with various embodiments. The primary vessel **124** includes an inner core vessel **202** and an outer core vessel **210**. The inner core vessel **202** contains the molten salt eutectic **204**. The outer core vessel **210** is disposed about the inner core vessel **202**, and separated from the inner core by space **208** and multi-layer radiant heat shield **206**. The outer core vessel **210** includes a reflector **214** that contains neutrons within the core **110**, thereby minimizing core leakage. The reflector may include lead. In some embodiments, the outer core vessel **210** may include a lead filled stainless steel shell, and the walls of the outer core vessel **210** may be approximately 0.8 meters thick. The neutron shield **134** is disposed above the molten salt **204** to isolate components, such as the primary heat exchanger **122** and lanthanide still **120**, from the core neutronics. The neutron shield **134** may also comprise lead. By positioning the primary heat exchanger **112** and other components above the molten salt **204** and the neutron reflector **134**, embodiments avoid neutron damage to the heat exchanger **122** shell and tubing caused by fast neutrons, and avoid capture of fast neutrons by the metal of the primary of heat exchanger **122** that may soften the neutron spectrum of the core **110**.

Some embodiments of the core **110** generate approximately 400 megawatts (MW) of heat, and the molten salt has a temperature of 600°-800° C. while the outer core vessel **210** operates at about room temperature. The space **208** between the inner core vessel **202** and the outer core vessel **210** is void of fluid (in a state of vacuum) when the core **110** is operating. The vacuum and the multi-layer heat shield **206** serve to inhibit conduction and/or radiation of heat from the inner core vessel **202** to the outer core vessel **210**. In some embodiments, the vacuum and the multi-layer heat shield **206** limit the heat transferred from the inner core vessel **202** to the outer core vessel **210** to less than about 1 MW.

The space **208** also serves as a component of a safety subsystem of the system **100**. Under conditions in which heat transfer from the molten salt **204** is inhibited, for example, a failure of the heat exchangers **122**, **112**, the space **208** may be filled with a fluid that facilitates conduction of heat from the inner core vessel **202** to the outer core vessel **210**. Such a condition may occur, for example, if power is lost to the heat exchangers **122**, **112**. Under such conditions, fission and heating caused by fission are discontinued, but decay of fission products within the molten salt **204** continues to generate heat in the core **110** for a time. In some embodiments of the system **100**, heat conduction between the core vessels **202** and **210** is provided by filling the space **208** with helium gas. The helium may be at atmospheric pressure. Thus, embodiments of the system **100** may include a helium source activated manually or automatically to fill the space **208** when thermal energy is to be conducted from the inner core vessel **202** to the outer core vessel **210**. In other embodiments another thermally conductive fluid may be used in place of or in addition to helium.

The heat conducted to the outer core vessel **210** through the space **208** is absorbed, in large part, by the lead core of the outer vessel **210**. A set of passive heat pipes **118** are connected to the outer core vessel **210**. The conductive heat pipes **118** may be fluid filled and operate to conduct heat away from the outer core vessel **210** to heat dissipation structures, such as radiator panels or a geothermal heat sink. Because the molten salt **204** is in direct and constant contact with the surface of the inner core vessel **202**, heat transfer from the salt **204** to the inner core vessel **202** is uninhibited. Thus, the molten salt eutectic **204** in combination with the described heat transfer features greatly enhance overall safety of the system **100** relative to conventional critical cores by making core meltdown extremely unlikely or impossible.

The molten salt eutectic **204** contained within the inner core vessel **202** includes a carrier salt and a fuel salt. The carrier salt may be NaCl and/or another suitable heavy salt. Some embodiments may use lithium salts or potassium salts. The carrier salt features relatively heavy atomic weight nuclides that contribute to the fast neutronics of the core **110** by maintaining neutron energy in the MeV range as neutrons collide with the carrier salt nuclei. In contrast, light salts and other light materials cause reduction of neutron energy on collision. The fuel salt may be, for example, a uranium salt including the same halide (chlorine, fluorine, bromine, etc.) as the carrier salt (e.g., uranium trichloride).

The neutron gain of the molten salt **204** is less than one (between 0.85 and 0.97 for example), and the salt mixture is consequently incapable of self-sustained fission. In the molten salt core **110**, and other embodiments of a sub-critical core disclosed herein, the neutrons required to initiate and sustain fission are provided via spallation. The core **110** includes an array of spallation targets **212**. Each spallation target **212** includes one or more metal plates. The metal plates are formed of a tough and ductile material, such as tungsten, and may be about 1 centimeter thick or more. A beam of energetic protons is guided to each spallation target **212**, via an evacuated vacuum tube, from the particle accelerator complex **102**. Assuming proton energy of about 800 mega-electron volts (MeV), each proton liberates approximately twenty neutrons. The liberated neutrons collide with the nuclei of the fuel salt to initiate fission.

The spallation targets **212** are arranged symmetrically around the center of the inner core vessel **202** in a roughly circular pattern (e.g., see FIG. **14** for an exemplary arrangement of seven spallation targets). In some embodiments, the pattern may have a radius that is approximately ⅓ of the radius of the inner core vessel **202**. Each spallation target **212** is driven with a proton beam generated by a different particle accelerator of the accelerator complex **102**. By providing multiple spallation targets **212**, each driven by a different proton beam, embodiments of the system **100** allow the core **110** to be driven with high aggregate beam power while employing accelerators that provide modest beam power. The multiple targets **212** and associated accelerators of the accelerator complex **102** also provide a level of redundancy, wherein failure of one accelerator does not shut down the core **110**. Instead, embodiments of the system **100** can continue to operate, at a reduced power level, when one or more particle accelerators are inoperative. Furthermore, by distributing spallation neutrons evenly through the molten salt **204**, the multiple proton beams enhance the efficiency of the core **110**.

The fast neutronics provided by the heavy molten salt **204** allows the core **110** to breed fuel from non-fissile materials such as thorium, uranium **238** (^{238}U), etc. Via the process of transmutation wherein non-fissile nuclei capture neutrons in the core **110** and undergo radioactive decay, non-fissile materials can be transmuted into fissile materials such as uranium **233** or plutonium **239**. For example, the fuel cycle for ^{238}U involves transmuting ^{238}U to ^{239}U by neutron capture followed by beta decay to neptunium and plutonium **239**.

The ultra-fast neutronics of the molten salt **204** also allows for fission of long-lived waste isotopes that are generated in the core **110**. Waste materials (e.g., minor actinides, such as americium) having long half-lives (e.g., 1-10,000 years), that are bred in the core **110** will capture thermal neutrons, but are split by the fast neutrons of the core **110**. Consequently, such waste materials do not accumulate in the core **110** over time, but rather settle at a low equilibrium level. Because the core **110** is configured to maintain an equilibrium level of minor actinides, the core **110** can be used to consume waste actinides produced by conventional cores, thereby reducing or eliminating the need to store the actinides and the attendant security concerns. Minor actinides or other waste generated by a conventional core can be periodically added to the molten salt **204** and consumed. Thus, the core **110** provides a method for destroying dangerous waste that would otherwise require secure storage.

Spent nuclear fuel contains a large quantity of the fertile nuclide ^{238}U, modest quantities of the fissile nuclides ^{235}U and ^{239}PU, and a significant quantity of minor actinides. The power generation system **100** can be used to maintain an equilibrium in which the fertile nuclide ^{238}U is transmuted into the fissile isotope ^{239}PU, and the ^{239}PU is fissioned, so that the inventory of ^{239}PU remains roughly constant while the ^{238}U is consumed. This equilibrium is called isobreeding, and makes it possible for the power generation system **100** to extract most of the available energy from the spent nuclear fuel.

The process of transmutation also breeds a portion of the ^{238}U into heavier nuclides, including the minor actinides. In the fast neutronics of the molten salt **204** the probability for fission of the minor actinides is as great as the probability for breeding them, so the inventory of minor actinides does not continue to increase during the isobreeding cycle but reaches and remains at an equilibrium inventory.

In order to optimize destruction of minor actinides, some embodiments of the molten salt core **110** use thorium as the fertile nuclide in the molten salt **204**. The low atomic weight of thorium maximizes the number of neutron captures required to breed minor actinides. The stable nuclide ^{232}Th is 9 atomic mass units lighter than the minor actinide ^{241}Am, and so it requires the capture of 9 fast neutrons in order to breed ^{232}Th into ^{241}Am, whereas it requires only **3** neutron captures to breed ^{238}U into ^{241}Am. For this reason, a thorium-fueled power generation system **100** has a much smaller equilibrium inventory of minor actinides than a uranium fueled system, and therefore may be used as an incinerator for minor actinides that had been produced in the operation of conventional fission power plants. For example, use of thorium rather than uranium in the molten salt **204** may reduce minor actinide inventory in the core **110** by a factor of 10^4. Minor actinides from spent nuclear fuel may be separated chemically, and the separated minor actinides added periodically to the fuel salt **204** of an operating power generation system **100**. The added minor actinides are consumed by fission, and the inventory of minor actinides would return to its equilibrium value, essentially without limit.

In some embodiments of the core **110**, spent fuel pins may be disposed in the molten salt **204** to raise the initial neutron gain of the core **110**. Over time, isobreeding raises the neutron gain of the molten salt **204** to a level sufficient to provide high core efficiency. Initially, however, the solubility of fuel salt (e.g. UCI_3) in the carrier salt may limit the molten salt **204** to a relatively low neutron gain (e.g., 0.7), which corresponding limits the initial efficiency of the core **110**. The initial neutron gain of the molten salt **204** may be enhanced by addition of enriched uranium to the molten salt **204**. Unfortunately, enriched uranium may raise security concerns. Therefore, the core **110** may advantageously include spent fuel pin assemblies removed from a conventional thermal core to raise the initial neutron gain of the core **110**. The spent fuel pin assemblies may be symmetrically arranged in the core **110**. For example, the spent fuel pin assemblies may be disposed about the perimeter of the primary vessel **122** in cooled molten salt **204** flowing in the annulus formed between the wall of the primary vessel **124** and the cylindrical plenum shell coupled to the output of the primary heat exchanger **122**. By inclusion of the spent fuel pin assemblies, embodiments of the core **110** may raise initial neutron gain to about 0.95 or higher without use of enriched uranium.

In some embodiments of the core **110**, fuel salt extracted from spent nuclear fuel provides fissile content sufficient for efficient operation of the core **110** from startup. In such embodiments, enrichment may not be required. An embodiment of the core **110** may include about 30 tons of uranium in the molten salt **204** and may generate 400 MW of continuously for 100 years or more. The uranium and other fertile and fissile components of the molten salt **204** may be extracted from spent nuclear fuel generated by a conventional reactor. The spent fuel produced by a conventional reactor may require removal and replacement at about five year intervals. The spent fuel contains about 80 tons of uranium and 328 kilograms of ^{239}PU, and may be processed using the Experimental Breeder Reactor-II (EBR2) reprocessing technology to generate the fuel salt used by the core **110**.

EBR2 reprocessing extracts the fuel from the fuel assemblies of spent nuclear into molten salt, and then deposits metallic uranium by electro-separation leaving all other components in the salt. Thirty tons of spent nuclear fuel may be processed through only the first stage of the EBR2 process to produce salt containing all the uranium and transuranic waste (TRU) of the spent fuel. The salt extracted from the thirty tons of spent fuel contains about 123 kg of ^{239}PU. Another 420 tons of spent fuel may be processed through the full EBR2 process to extract the spent fuel into salt followed by separation of metallic uranium from TRU salt. The remnant salt contains about 4590 kilograms of ^{239}PU. The remnant salt may be combined with the salt produced from the initial 30 tons of spent fuel to produce the fuel salt for the core **110**. The fuel salt produced by combining the salts includes about 4.71 tons of ^{239}PU and 30 tons of uranium, corresponding to a fissile content of about 13%. The remaining 415 tons of metallic uranium is available for other uses.

The amount of spent fuel reprocessed as described above is equivalent to about six five-year fuel cycles of a conventional reactor, and such amount may be available at any number of nuclear power generation sites. Consequently, an instance of the power generation system **100** may be co-located with a conventional reactor that provides the fuel for the core **110**.

Returning again to FIG. **1**, the power generation system **100** is configured to purify the molten salt **204** as the system **100** operates. The lanthanide stills **120** disposed in the primary vessel **124** extract lanthanides from the molten salt **204** while the core **110** is in operation. The extracted lanthanides are stored in the lanthanide storage vessel **116**. Lanthanides are fission products that build up the molten salt **204** during system operation. The lanthanides have relatively large cross sections for absorbing the neutrons propagating within the core **110**. Consequently, the build-up of lanthanides in the molten salt **204** makes neutrons unavailable for fission, and is therefore detrimental to the efficiency of the core **110**. In conventional critical cores, the build-up of lanthanides in the fuel pins necessitates shuffling and/or premature replacement of the pins.

Embodiments of the power generation system **100** maintain high efficiency by extracting lanthanides from the molten salt **204** while the core **110** operates. The vapor pressure versus temperature of the lanthanides is about 100 times lower than that of the fuel salts (actinides). Consequently, the fuel salts can be separated from the lanthanides via heating and distillation in the lanthanide stills **120**. The lanthanide stills **120** include heating elements that heat the molten salt **204** to a temperature that vaporizes the fuel and carrier salts, leaving the lanthanides. The vaporized salts are condensed using cooled molten salt **204** and returned to the core **110**. The lanthanides are accumulated and stored in the lanthanide storage vessel **116** for removal when the core **110** removed from service. Removal of lanthanides from the molten salt **204** improves the efficiency of the core **110**, and extends the useful life of the core **110** by allowing for the fuel salt to be more completely consumed. Furthermore, the extracted lanthanides are valuable rare-earth elements that can be recycled to produce various products.

Some lanthanide stills **120** employed in the system **100** utilize a batch distillation process. In the batch process, a quantity of molten salt **204** is processed at a periodic interval. Other embodiments of the lanthanide stills **120** employ a continuous distillation process. In the continuous process, molten salt **204** is constantly refined.

Some embodiments of the system **100** include one or more cryotraps for removing volatiles (such as krypton and xenon) created in the core **110**. Gases are condensed in the cryotraps and stored in the volatile fission fragment storage vessel **126** for removal when the core is decommissioned. Some embodiments of the system **100** provide a stream of inert gas, such as helium, in the inner core vessel **202** to sweep volatiles into the cryotraps for extraction.

As explained above, each spallation target **212** of the core **110** is associated with a proton beam generated by the accelerator complex **102**. The accelerator complex **102** includes a plurality of particle accelerators to generate the proton beams. For example, the accelerator complex **102** may include a different particle accelerator for each spallation target **212**. Some embodiments of the accelerator complex **102** include isochronous cyclotrons serving as the particle accelerators.

The accelerator complex **102** also includes an injector **132**. The injector **132** may produce a single proton beam or multiple proton beams. In some embodiments, the injector **132** may produce proton beams at kinetic energy in the range from 70 MeV to 200 MeV traveling at approximately one-third the speed of light. The cyclotron stack **130** may accelerate the proton beams before they reach the spallation targets **212**. In some embodiments, each proton beam generated by an isochronous cyclotron of the accelerator complex **102** may produce an average of about 2 milliamps of current and 700 MeV. The protons beams provided to the core **110** may, in aggregate, provide about 10 MW or more of beam energy.

The isochronous cyclotrons of the accelerator complex **102** may be arranged as a cyclotron stack **130**. The cyclotrons of the cyclotron stack **130** are independently operating isochronous cyclotrons, and are arranged in a flux-coupled vertical stack with minimal separation between cyclotrons. The vertical stacking allows the multiple cyclotrons to share a footprint approximately corresponding to that of a single cyclotron. Thus, embodiments of the accelerator complex **102** consume less space and are more economical than a corresponding number of convention particle accelerators. The cyclotrons share magnetic flux return while other subsystems (RF cavities, insertion, extraction, etc.) are independent, allowing continued operation of one cyclotron if another cyclotron fails.

Each cyclotron of cyclotron stack **130** generates one of the multiple proton beams used to drive the fission in core **110**. Cumulatively, the accelerated beams from cyclotron stack **130** provide the beam current and/or energy to stimulate fission. Because no single beam is required to produce the desired amount of beam current and/or energy, core **110** may continue to operate even after one or more of the cyclotrons cease to operate. Moreover, using multiple proton beams alleviates the need to design a particle accelerator capable of producing a single beam with the desired level of beam current and energy.

As discussed in more detail below, the cyclotron stack **130** includes a magnetic ring containing a plurality of similar sector magnets, RF accelerating cavities, injection accelerator and injection channel, extraction channel, and beam transport to an injection channel on the core **110**. The sector magnets and RF cavities of cyclotron stack **130** operate to accelerate the proton beams provided from injector **132**. As the proton beams circle the cyclotron stack **130** they gain speed and energy causing the protons in the proton beam to move in a spiral pattern. As the protons reach their desired energy, they are ejected from cyclotron stack **130** and directed to core **110** of system **100** to initiate fission.

FIG. **3** shows a top view of the isochronous cyclotron stack **130** in accordance with various embodiments. The cyclotron stack **130** includes a plurality (e.g., seven) vertically stacked cyclotrons. Each cyclotron may be able to receive a low energy proton beam **306** in a circular orbit in the inner radial region of the cyclotron which is accelerated before being directed to the core **110**. The proton beam within each cyclotron may circulate in a relatively flat cylindrical vacuum tank enclosed within the gaps **308** of a symmetrical arrangement of magnetic dipole sector magnets **302**. The multiple sector magnets **302**, in conjunction with multiple RF cavities **304** arranged in gaps **308** between the sector magnets **302**, accelerate the proton beams **306** received from the injector **132**. Each cyclotron of the cyclotron stack **130** may include fewer RF cavities **304** than sector magnets **302**. In some embodiments, the sector magnets **302** may comprise superferric fields in which the magnetic field produced is limited to less than what would saturate the steel in its flux return (e.g., approximately 1.8 T). The RF frequency of operation of the RF cavities **304** may be based on the revolution frequency of the proton beam in the cyclotron (e.g., about 50 MHz which corresponds to harmonic **8** of the revolution frequency in 1.8 Tesla guide field). In some embodiments, the RF cavities **304** may be superconducting RF cavities or dielectric-loaded superconducting RF cavities. In certain embodiments, the RF cavities **304** may be configured as a half-wave structure or as a shorted transmission line. The RF cavities **304** occupy less space than conventional RF cavities.

As each proton bunch gains kinetic energy it spirals towards the outer radial region of cyclotron stack **130**. The pole geometry of sector magnets **302** may be designed so that the average bending field yields a constant orbit frequency even as the proton energy becomes comparable to its rest mass energy. This may allow synchronism with the RF field to be maintained. In some embodiments, an extraction septum electrode **310** may be situated to outwardly deflect the outermost proton orbit so that it can be extracted into a beam transport line coupled to the core **110**.

The frequency of the RF field generated by the RF cavities **304** may be synchronous with an integral harmonic of the orbit frequency of the protons, thereby accelerating the protons by the cavity voltage V on each revolution of the proton orbit. In certain embodiments, the spiraling orbits of the accelerating protons may be spaced so as to increase the efficiency of extraction of a high-current beam at, for example, 800 MeV. In some embodiments, this spacing may be facilitated by providing a relatively high RF voltage V (e.g., a total of 1 MeV energy gain per turn of orbit). The spacing may be further facilitated by using a relatively low magnetic field (e.g., less than 1.8T) so the radial separation from a given energy gain per turn is maximized.

FIG. **4** is a perspective view of the flux-coupled isochronous cyclotron stack **130** in accordance with particular embodiments. Sector magnet **302**A is shown in isolation. The cyclotron stack **130** includes seven isochronous cyclotrons arranged in a vertical stack. Other embodiment of the cyclotron stack **103** may include a different number of cyclotrons. The proton beams of each cyclotron orbit in an aperture formed by adjacent pairs of the coil assemblies **502**.

FIG. **5**A shows a perspective view of coil assemblies **502** of the sector magnet **302** in accordance with various embodiments. FIG. **5**B shows a cross-sectional view of coil assemblies **502** of the sector magnet **302** in accordance with various embodiments. Sector magnet **302** includes a plurality of coil assemblies **502** (shown as **502**A-H) which are supported in a vertical stack with vacuum gaps **504** between adjacent pairs of coil assemblies **502**. The magnetic field for each cyclotron is generated by an adjacent pair of coil assemblies **502**. Each coil assembly **502** consists of one or more superconducting windings **508** bonded to a magnetically permeable steel flux plate **506**. In some embodiments, the superconducting windings may be niobium-titanium alloy. The vacuum gap **504** between each adjacent pair of coil assemblies **502** constitutes the aperture through which one proton beam circulates as it is accelerated in the respective cyclotron. The sector magnets **302** include eight coil assemblies **502** defining seven apertures (i.e., seven isochronous cyclotrons). The entire stack of coil assemblies **502** for sector magnet **302** is supported within the aperture of a C-shaped flux return **510** made of magnetically permeable steel. Magnetic flux passes from one gap **504** to the next and is returned through the single C-shaped room-temperature steel flux return **510** facilitated by flux plate **506**. In some embodiments, coil assemblies **502** may be maintained at the cryogenic temperature of liquid helium, while the surrounding C-shaped flux return **510** is maintained at room temperature.

In certain embodiments, there may be a balancing of the Lorentz forces that are generated by the action on each coil assembly **502** by the magnetic field generated by all other elements. The balancing may be attained by appropriate design of the geometry of the superconducting winding assembly **508** and the succession of vacuum gaps **504** between them in the stack. This may have the benefit that the

Lorentz forces, which can be immense in comparison to the gravitational weight of the segments, are held in balance one with the next. For example, the Lorentz forces from coil assembly **502**C pulling up on coil assembly **502**D may be approximately equal to the Lorentz forces from coil assembly **502**E pulling down on coil assembly **502**D. This balance may be attained with relatively little or no impact upon the magnetic field distribution in gaps **504**. The tension support members **512** that support the stack of cryogenically cooled coil assemblies **502** within the room-temperature flux return **510** therefore may only need to support the gravitational weight of the elements, and not the much larger Lorentz forces. This may allow for the support of the huge Lorentz forces with a structure that would not be a thermal short between the 4K coil assembly and the warm-iron flux return. This benefit permits design of tension supports **512** allowing a reasonable minimum of conductive heat load through the supports **512**.

In some embodiments of the sector magnets **302**, the coil assemblies **502** are configured to produce alternating gradient quadrupole fields. The coil assemblies **502** generate an array of quadrupoles, one quadrupole centered on the equilibrium orbit of each consecutive beam orbit. The quadrupoles focus the proton beam to direct the beam along the equilibrium orbit of each turn in the cyclotron. By directing beam orbits in this manner, embodiments of the accelerator stack **130** require less calibration, setup, and maintenance than other cyclotrons, have larger acceptance of the beam phase space, and permit acceleration of larger beam current with smaller losses, making embodiments more suitable for industrial use.

FIG. **6** shows a cross-sectional view of a pair of coil assemblies **502** configured to produce alternating gradient quadrupole fields. In some embodiments of the coil assembly **502**, the face of the coil assembly **502** includes a set of triangular or sawtooth ridges **602** that produce the quadrupoles defining the orbits **606** of the proton beam. In other embodiments, the face of the coil assembly **502** includes pole-face winding **604** that that produce the quadrupoles. Yet other embodiments include ridges **602** and pole-face windings **604**. Other embodiments of the coil assembly **502** may include different shaped ridges and produce a different field, e.g., an octupole field. The ridges **602** and/or pole face windings **604** may be curved to form arcs corresponding to the desired beam orbits of the cyclotron.

FIG. **6** also shows magnetic field distribution in the gap between coil assemblies **502** equipped with both a ridged steel surface **602** and pole-face windings **604**, driven by the main dipole winding for a 1.7 T dipole field. The quadrupole gradient produced by the ridges **802** alone is G ~1.5 T/m. The quadrupole gradient produced by the pole face winding **604** alone, excited with 1000 A/mm^2 in a 1 mm thick winding, is G~1 T/m. The quadrupole gradient produced by the combination of ridges **602** and windings **604** together is G~2.5 T/m, corresponding to a focal length for focusing the proton beam, as it passes through the sector dipole, of

$$f[m] = \frac{.3G[T/m]l[m]}{p[\mathrm{GeV}/c]}.$$

In the mid-range of the cyclotron orbits:

$$l \cong 1 \text{ m}, \; p = \sqrt{2T/m} = .9 \text{ GeV}/c,$$

$$p = \sqrt{2T/m} = \frac{.9\mathrm{GeV}}{c}, \text{ and } f = 0.8 \text{ m}.$$

Some embodiments of the accelerator stack **130** configure the quadrupoles on successive sector magnets **302** to have alternating-sign gradient for each orbit; this produces a focus/defocus (FODO) alternating-gradient focal channel with transport beta function comparable to the focal length β~f, and betatron tunes ~2πR/β~10. Thus, embodiments of the accelerator stack **130** produce strong-focusing transport of the proton beam within the orbits of the each isochronous cyclotron using the pole-face quadrupoles described above.

The strong-focusing beam transport provides embodiments of the accelerator stack **130** with a number of advantages. By controlling the betatron tune, embodiments can make the tuning the same for all orbits, and can be used to select a tuning value that avoids fractional resonances and coupling resonances. Because the transverse size of the beam is inversely proportional to β, the beam size may be reduced by a factor of two or more compared to a conventional weak-focusing transport. Furthermore, while in a conventional isochronous cyclotron the sector magnets must be curved as spirals to produce vertical focusing in the fringe fields, embodiments of the accelerator stack **130** provide ample focusing the pole face method disclosed above and may employ uncurved sector magnets. This is advantageous because it simplifies location of the RF cavities in the spaces between sector magnets. FIG. **7** shows a top view of a cyclotron stack **700** including pole faces configured to generate a quadrupole gradient as described above. The sector magnets **702** include uncurved sides **704** that facilitate placement of the RF cavities **704**. The cyclotron stack **700** may be substituted for the cyclotron stack **130** in embodiments of the accelerator complex **102**.

The cyclotron stack **130** arranges a plurality of cyclotrons in close proximity to one another. For example, cyclotron spacing in the sector magnet **302** may be approximately 0.35 meters or less. Embodiments of the cyclotron stack **130** include RF cavities **304** configured to operate within such dimensions. FIG. **8** shows a schematic diagram of a cutaway side view of an RF cavity **304** suitable for use with the cyclotron stack **130** in accordance with various embodiments. The RF cavity **304** comprises two RF chambers **802** and **804**. RF chambers **802**, **804** may be arranged symmetrically above and below the acceleration gap **806**. RF chambers **802**, **804** may be oriented parallel to the acceleration gap **806** (disposed in horizontal planes or planes parallel to the orbitary plane of the cyclotron) as shown. This arrangement may produce a symmetric pattern of accelerating electric fields in the region traversed by the proton beam. Such an above/below configuration may allow the half-wave or shorted stub-line geometry to be terminated at the innermost and outermost extent of the radial region bracketed by the cavity **304**.

The RF cavity **304** is continuous and wraps on itself at both the inner (not shown) and outer end **808**) of the cavity **304** to reduce or eliminate coupling to longitudinal modes for which the electric field is oriented to point towards or away from the center of the cyclotron. RF signal is coupled to the cavity **304** at points **810** at the far end of the chambers **802**, **804**. The system **100** may include solid state power amplifiers to drive the RF signal to the RF cavity **304**. For example, one or more solid state RF power amplifier may be configured to drive RF signal to each point **810**. The multiple power amplifiers provide redundancy and allow the cavity **302** to continue to operate should one or more power amplifiers fail. Multiple amplifiers may be used to introduce RF power in the same distribution in radius as the distribution of power that is delivered by the cavity to the successive orbits of proton beam, so that the currents on the cavity walls flow purely in the desired accelerating mode.

The walls of RF cavity **304** may be made from a superconducting material, such as niobium or other suitable superconductor, and refrigerated to a temperature suitable for superconducting operation. The RF cavity **304** may operate at the 4^{th} or 6^{th} harmonic of the revolution frequency of the protons' orbit through the cyclotron. In some embodiments, the RF cavity **304** may be capable of 1 MV accelerating voltage and excellent mode stability.

FIG. **9** shows another embodiment of an RF cavity **904** suitable for use with the accelerator stack **130**. The alternate cavity **904** includes horizontal chambers **906**, **908**. In certain embodiments, the RF cavity **904** may comprise a shorted transmission line containing a high-permittivity dielectric slab **910**. In some embodiments, the dielectric slab **910** may comprise rutile (α-phase Ti_2O_3) or another suitable material. The walls **912** of RF cavity **904** may be made from a superconducting material, such as niobium or other suitable superconductor. In some embodiments, the surface field may be kept within breakdown limits by providing slot space between the superconducting walls of RF cavity **904** and dielectric slab **910**, and by tapering the width of the slot space so that the electric field in the slot space is made approximately constant throughout RF cavity **904**.

In certain embodiments, the predominant share of RF losses may occur in dielectric slab **910**. Maintaining dielectric slab **910** at a higher operating temperature than that of the superconducting walls **912** may improve the Carnot-cycle efficiency with which the heat from RF losses may be pumped to room temperature. In some embodiments, dielectric slab **910** within RF cavity **904** may be suspended clear of the walls **912** within the above-mentioned slot space. The walls **912** and dielectric slab **910** may be refrigerated at different temperatures. For example, the walls **912** may be refrigerated at approximately 4 K (the temperature of liquid helium, needed to sustain superconducting operation) and dielectric slab **910** at 20 K (using LNe coolant) or 80 K (using LN_2 coolant) to minimize loss tangent of the dielectric **910**. Other, more advanced superconducting materials, such as Nb3Sn, may be used as a surface coating on the inner surface of the niobium cavity. This may permit operation at a higher temperature than with pure niobium, such as 8-12 K. The increase in temperature may improve the Carnot-cycle efficiency with which the heat from RF losses may be pumped to room temperature.

In some embodiments, RF cavity **904** may comprise a pattern of azimuthally oriented slots in the superconducting walls **912** to mode-lock the cavity **904** so that the fields and currents within the RF cavity **904** are maintained in the mode appropriate for its acceleration of proton bunches circulating in the beam. This form of mode selection may permit stabilization of the cavity **904** against distortions in the fields that would arise from beam loading, from power coupling, and/or from termination of the cavity structure at the outermost and innermost radial extent of each RF cavity **904**.

The height of the dielectric **910** may be determined using the equation

$$f = \frac{0.5 \cdot c}{\sqrt{\varepsilon} \cdot L}.$$

If it is assumed that the relative permittivity $\in$ of the material is 125 (the average value for rutile at room temperature), the target frequency f is 48 MHz, and the speed of light c is 3×10^8, then the height L of the dielectric is:

$$L = \frac{0.5 \cdot 3\times10^8}{\sqrt{125} \cdot 32\times10^6} = 0.42 \text{ m.}$$

For more complicated geometries, it may be suitable to use numerical methods to determine the height of the dielectric. Increasing the length of RF cavity **904** may reduce the amount of dielectric used, increase the insulating gap, and reduce the peak field in the structure.

Dielectric **910** may be recessed within RF chamber so that there is no line of sight from the proton beam as it passes through acceleration gap **914** (e.g., non-linear dynamical effects, inverse Cerenkov, etc). This may help to prevent a variety of secondary field interactions and charging phenomena that can limit high-current operation. In some embodiments, dielectric **910** may be separated from the walls of RF cavity **904** by a vacuum gap for thermal isolation. In particular embodiments, dielectric **910** may be supported in RF chambers **906**, **908** via a pattern of rutile tubes that pass through cut-off holes in the walls of RF cavity **904**. The rutile tubes may then be refrigerated with a forced flow of liquid nitrogen at 80K. This may allow for approximately 1 MV of accelerating voltage. In some embodiments, dielectric **910** may comprise fusion-bonded bricks wherein milled side faces form LN_2 coolant slots.

In certain instances, the geometric factor of RF chambers **906**, **908** may be 4.25 W as determined from the equation

$$G = \frac{\omega E}{\frac{1}{2}\int H^2 ds}.$$

Because the operating frequency may be low and the surface resistance may be scaled as a square of the frequency, the surface resistance of the niobium at 4.2 K is determined by residual resistance of the bulk niobium, which for cavity-grade niobium is less than 10 nΩ. The power dissipated on the niobium walls, at 4.2 K, 48 MHz, may be about 10 nW. The integral $\int H^2 ds$ is 2.1 A^2/m (for 25.2 V across gap), corresponding to a wall dissipation of 33 W/m in the niobium for the full-geometry cavity. For a stack of 5 cyclotrons, each containing four 5-m-long cavities, this would constitute a cryogenic heat load of 3.5 kW at 4.2 K, equivalent to a mains power requirement of approximately 3 MW for refrigeration.

The Q-value of the cavity **904** may be about 3.3×10^7, with losses of 33 W/m (at 4.2K) for the superconducting walls **912** of RF chamber **908**, **906** and 1.2 kW/m (at 77K) for dielectric **910**. In some embodiments the shunt impedance of the dielectric-loaded shorted-stub cavity **904** may be

$$R_{sh} = V^2/P_{diss} = 803 \text{ MW.}$$

Losses from the walls **912** of RF cavity **904** may be about 250 W/m. Radiation heat load from a warmer dielectric may bring another 11 W/m. The total heat load on liquid helium refrigeration system may be about 261 W/m. In certain instances, a magnetic field on the walls of RF cavity **904** may be approximately 16000e.

In some embodiments, rectangular slots may be integrated into dielectric **910** to provide cooling. Dielectric **910** may be assembled from identical square-cross-section dielectric bricks in which one side face may be milled to form a rectangular pocket. The bricks may be fusion-bonded to seal the pocket channels so that they provide flow channels for coolant to flow. The brick size may provide sufficient surface heat transfer to keep within the 1 W/cm^2 limit that is typical for the transfer to liquid coolant to avoid boiling.

In some embodiments, the thickness of dielectric **910** may be tapered. This may help to maintain a roughly constant electric field level along acceleration gap **914**. Accelerating voltage with no phase shift is defined as

$$V_{acc} = \int_{-x_0}^{x_0} E_{gap}(x) \cdot \cos\left(\frac{\omega \cdot x}{v}\right) dx,$$

where w is an angular frequency, v is a speed of the particle and x_0 is half the width of the accelerating gap, with maximum E field at x=0.

In particular embodiments, the ends of RF cavity **904** may be terminated by continuing the superconducting walls around a U-turn beyond the region traversed by the proton beams. This may connect one cyclotron layer to the next. Another method for terminating the ends of RF cavity **904** may be to continue the superconducting wall of RF chambers **906**, **908** without continuing dielectric **910**. The superconducting wall **912** may extend with a logarithmic taper of the inner vertical separation. In both methods the magnetic fields can be maintained with little perturbation over the portion of acceleration gap **914** traversed by the proton beams.

FIG. **10** shows a cross-sectional view of an RF cavity **304** and associated magnetic shielding **1002** in accordance with various embodiments. The accelerator complex **102** includes magnetic shielding **1002** disposed between each RF cavity **304** and adjacent sector magnet **302** in accordance with various embodiments. The arrangement of coil assemblies **502** produces a pattern of magnetic flux that primarily flows between adjacent coil assemblies **502**. However, some of the magnetic flux may fringe into the regions flanking the sector magnet **302**. The RF cavity **304** is positioned between sector magnets **302**. The magnetic shielding **1002** shields the RF cavity **304** from the magnetic field produced by the coil assemblies **502** thereby preventing the magnetic field from saturating the superconductor of the cavity **304** and rendering the cavity **304** inoperable.

The magnetic shielding **1002** includes a plurality of metal plates **1004**. The metal plates **1004** may be made from permeable steel, or from high-permeability alloy. Each plate **1004** extends vertically nearly to the plane of beam orbits, and is disposed to intercept fringe flux and conduct the flux back to the flux plate **506**, thereby closing the flux path. Each plate **1004** connects to a horizontal plate segment that connects from the end of the plate farthest from the beam plane to the side wall of the flux plate **506**. By creating a low-reluctance path for fringing magnetic flux, the level of flux reaching the cavity **304** is greatly reduced. A succession of multiple plates **1004** may be placed in this manner, with a gap space between successive plates **1004**, to optimize shielding of the fringe field. For, example two plates **1004**, may be disposed with suitable gapping, as shown in FIG. **10**, that reduce the fringe of a 1.8 Tesla (T) sector magnet **302** to less than 10 mT at the cavity **304**.

FIG. **11** shows an alternative RF cavity **1104** including a single RF chamber **1106** suitable for use with the accelerator stack **130** in accordance with various embodiments. While having only a single RF chamber **1106**, the RF cavity **1104** is substantially similar to the RF cavity **904** described above in other respects. Embodiments of the accelerator stack **130** may include one or more of the RF cavity **304**, **904**, and/or **1104** in any combination.

Some embodiments of the stacked cyclotron **130** may include multiple RF cavities arranged in series between the sector magnets **302**. FIG. **12** shows a pair of sector magnets **1202**, **1204** and a pair of RF cavities **1206**, **1208** disposed between the sector magnets **1202**, **1204**. The sector magnets **1202** are equivalent to the sector magnet **302** and the RF cavities **1206**, **1208** may be any of RF cavities **304**, **808**, and/or **1104**. Outer RF cavity **1208** may be in the outer region where the gap between sector magnets **1202** and **1204** may be greater as they extend radically out from a center of a stacked cyclotron **130**. Outer RF cavity **1208** may provide additional energy gain per turn. The additional energy gain per turn may provide additional spacing between successive orbits, facilitating low-loss extraction of the beam at its maximum energy.

FIG. **13** shows a fuel pin based sub-critical core nuclear power generation system **1300** in accordance with various embodiments. The fuel pin based sub-critical core nuclear power generation system **1300** includes the accelerator complex **102** described above, a fuel pin based sub-critical core **1302**, power generation **1304**, and fuel processing complex **1306**. The core **1302** includes fuel pins **1308** that may include thorium. Like the molten salt eutectic system **100** described above, the system **1300** can generate power using thorium-cycle fission. In thorium-cycle fission, thorium (^{232}Th) is transmuted to ^{233}U for fission. The thorium nucleus is not subject to fission, but it will readily capture a fast neutron, becoming the radioactive isotope ^{233}Th. The ^{233}Th nucleus decays twice to form the fissionable isotope ^{233}U. In some embodiments, the same process of transmutation that creates the ^{233}U may also transmute fission products generated in the core **1302**, limiting the accumulation of long-lived waste isotopes in the core **1302**.

Transmutation of ^{232}Th and stimulation of ^{233}U uses fast neutronics. To achieve fast neutronics, the core **1302** uses a large-atomic-weight material (e.g., molten lead, metal, salt, etc.) as moderator. The heavy moderator, like the heavy carrier salt of the salt **204** described above, allows an energetic (fast) neutron to lose only a small fraction of its energy with each collision or scatter with a moderator nucleus. Thus, the energy of the neutron decreases slowly as it diffuses and scatters within the core **1302**. Each neutron thereby retains sufficient energy to have maximum probability to capture on and transmute a ^{232}Th nucleus, or alternatively to stimulate fission of a ^{233}U nucleus previously produced through transmutation.

The accelerator complex **102** generates and injects multiple (e.g., 3 or more) beams of energetic protons into the core **1302** that, via spallation, provide some of the neutrons needed to sustain fission. When a proton scatters on a nucleus in the moderator (e.g., a lead nucleus), multiple energetic neutrons are released. The cumulative energy of the multiple proton beams provides neutrons sufficient for fuel transmutation, and sustaining fission in the sub-critical core **1302**. Furthermore, because a large-atomic-weight material (e.g., lead) is used as the moderator, the moderator has a relatively large heat capacity and may prevent the core **1302** from heating to a dangerous temperature if the heat transfer systems fail when the core **1302** is shut down.

Heat from the fission may be transferred via convection through the molten column **1310** (e.g., molten lead) of the core **1302** to heat exchanger **1314** located above core **1302**. Heat exchanger **1314** transfers the heat from the molten lead to steam which is used to drive steam powered turbine **1316** which, along with generator **1320**, generates electricity. As the temperature is increased the thermal efficiency for driving turbine **1316** may improve.

Pumps **1322**, **1324** may facilitate movement of the water and molten lead. In particular, pump **1324** may pump the cooled molten lead back to the bottom of core **1302** to close the heat transfer cycle. Condenser **1318** may take the steam that drives turbine **1316** and condense it back into a liquid. Pump **1322** may pump the liquid from condenser **1318** back to heat exchanger **1314** to be converted back into steam.

FIG. **14** illustrates a block diagram of an overhead view of a proton beam distribution pattern in the core **1302** in accordance with various embodiments. The thorium fuel of core **1302** is contained in fuel pins **1308** that are assembled into bundles **1450**. The space between the fuel pins is filled with a molten material, such as lead. An additional layer **1460** of molten metal along the outermost radius of core **1302** serves as a neutron reflector. In the depicted embodiment, core **1302** is driven by seven proton beams **1420** distributed equidistant from one another. The distribution of proton beams **1420** may help to maintain the generation of spallation neutrons with a flux that may be approximately homogeneous throughout the region of core **1302** containing thorium fuel. In some embodiments, beams **1420** may, cumulatively, provide approximately 15 MW of continuous beam power of protons (e.g., corresponding to approximately 12 mA of current at 800 MeV of kinetic energy).

Each proton beam **1420** is directed from a cyclotron of the cyclotron stack **130** to a different one of spallation zones **1440** within core **1302** through respective evacuated tubes, proton beam injection channels **1430**. Each proton beam injection channel **1430** may be arranged parallel to the vertical axis of core **1302** (e.g., perpendicular to the top surface of core **1302**) and may stop at core **1302** or extend, either fully or partially, through the core **1302**. Proton beam injection channels **1430** may be disposed in a symmetric pattern within core **1302**. This arrangement may have the effect of approximating a volumetric feed of neutrons throughout the core **1302**. This may be done with a pattern of 3 beams for an approximately 0.5 giga-watt (GW) core, a pattern of 7 beams (6-on-1) for an approximately 1.2 GW core, or a larger multiplicity of beams for a yet higher power core. In addition, the use of multiple beams **1420** may reduce the attenuation of neutrons in the outer regions of core **1302**, allowing the power density of core **1302** to remain relatively flat through a prolonged period of operation. In some embodiments, the fuel pin bundles **1450** may be used continuously (e.g., without being reshuffled) during the prolonged period of operation.

Proton beams **1420**, injected into each proton beam injection channel **1430**, may be scanned by one or more steering elements so that the protons within proton beams **1420** strike the side walls of proton beam injection channels **1430** with an approximately tangential orientation. In some embodiments, mercury vapor based high-power targeting may be used. A mercury vapor target may give optimum targeting for high-power proton or ion beams, yet the target would be a Hg vapor column that is continuously being condensed and re-circulated so that there is nothing that can be destroyed or radiation-damaged. For example, a liquid mercury target may be produced as the beam enters a 'fountain' flow of liquid mercury. The liquid column may be disrupted by the liquid flow, but recovers shortly thereafter so that a subsequent bunch can be targeted. Particular embodiments may comprise a high-density column of mercury vapor. The metal mercury has the unique property that it is liquid at room temperature and also has large vapor pressure at moderate temperature.

When a proton strikes the tube wall it passes into the spallation zone **1440** and produces a sequence of nuclear scatterings that yield a longitudinally distributed flux of spallation neutrons around each proton beam **1420**. A proton having approximately 800 MeV of kinetic energy may produce approximately twenty fast neutrons through spallation. The spallation neutrons gradually lose energy by elastic collisions with lead nuclei. As the spallation neutrons pass through fuel pins bundles **1450** they can be captured by ^{232}Th nuclei to transform them into the heavier isotope ^{233}Th.

Spallation zone **1440** may comprise a molten metal, such as lead. In certain embodiments, core **1302** may be immersed in a bath of molten metal (e.g., lead). The molten metal may fill spallation zones **1440** and serve as a spallation target, a fast neutron moderator, and a medium for convective heat transfer. In some embodiments, a molten salt slurry may be used instead of molten lead or molten metal.

Evenly distributing the proton beams may increase the efficiency with which the fuel rods **1308** in the core **1302** are consumed. In particular, because fission products have a relatively high probability of capturing fast neutrons, fission products tend to accumulate near the region where a proton beam **1420** is injected thereby reducing the neutron flux that can reach further from the point of injection. This effectively turns-off the core **1302** in regions distant from the point of injection. The symmetric pattern of injection employed in system **1300** may provide a volumetric feed of spallation neutrons which is not significantly modified by shadowing. Thus allowing for power distribution to remain nearly uniform throughout core **1302** and the overall power generation to be maintained at a nearly constant level over a multi-year period of operation. In some embodiments, core **1302** may be operated for up to ten years without accessing core **1302** or shuffling the fuel rods **1308** within core **1302**.

At high temperatures molten lead may be chemically active. For example, it may migrate along grain boundaries in steel and other metals. This may lead to corroding of the weak-link attachment between grains so that the metal becomes brittle and subject to fatigue, swelling, and stress cracking. Some embodiments of the fuel rods **1308**, or other components of the core **1302**, may include a cladding material such as a metal-matrix composite (MMC), in which filaments of ceramic are embedded within a high-strength matrix metal. Certain embodiments may include forming the MMC by coating the ceramic fibers with a nanolayer of titanium. Titanium readily bonds to most ceramics at high temperature, diffusing the titanium into the surface layer of ceramic. This may grade the composition and with it the temperature coefficient (tempco) of expansion (tempco mismatch, a major problem for metal-ceramic bonds). The titanium surfaced fiber may be coated with a nanolayer of the desired matrix metal. The two coatings and the diffusion may be applied under high vacuum, without breaking to air between coatings. The titanium may serve as adhesion layer and also to grade tempco.

The core **1302** may be designed so that it remains safe to restart after an extended down-time. During operation of core **1302** there may be an inventory of the intermediary isotope ^{233}Pa. ^{233}Pa may be formed after neutron capture on ^{232}Th and subsequent rapid beta decay. ^{233}Pa has a one-month half-life for its beta decay into the ^{233}U that is the fissile fuel. Thus, if the proton beams fail or are shut-off (and with them the fission reaction), the inventory of ^{233}Pa continues to beta-decay into ^{233}U over the following months. When core **1302** is restarted it may have more ^{233}U than it did when the proton beams were shut-off. This may shift the criticality of the core **1302** by up to 2%. Certain embodiments may be designed with that consideration in mind and may thus limit the choice of criticality in designing the core (e.g., it may be designed so that it is impossible for it to go critical under any circumstance.

As fission proceeds in the core **1302**, fuel is consumed. Consequently, the core **1302** may periodically be reloaded with fresh fuel. The fresh fuel may include fresh thorium and actinides which are combined in a fuel fabrication block **1328**. The fresh fuel is loaded into core **1302** while the spent fuel is removed. The spent fuel is removed from the core **1302** is sent to a reprocessing block **1326** which removes the fission fragments and sends them to waste packaging **1330** while the actinides are separated and sent to the fuel fabrication **1328** to be combined with the fresh thorium. The waste packaging of the fission fragments is then sent to a repository for storage.

The above discussion is meant to be illustrative of the principles and various embodiments of the present invention. Numerous variations and modifications will become apparent to those skilled in the art once the above disclosure is fully appreciated. It is intended that the following claims be interpreted to embrace all such variations and modifications.

What is claimed is:

1. A fission power generator, comprising:

a sub-critical core, and

a plurality of proton beam generators, each of the proton beam generators configured to concurrently provide a proton beam into a different area of the sub-critical core;

wherein each proton beam scatters neutrons within the sub-critical core, and the plurality of proton beam generators provide aggregate power to the sub-critical core, via the proton beams, to scatter neutrons sufficient to initiate fission in the sub-critical core;

wherein the proton beam generators are isochronous cyclotrons, each of the cyclotrons comprising folded radio frequency cavities each cavity comprising a horizontal lobe disposed above a proton beam aperture and a horizontal lobe disposed below the proton beam aperture, wherein each lobe extends lengthwise along an orbital plane of the cyclotron.

2. The fission power generator of claim **1**, wherein the cyclotrons are configured to share a flux return in a sector magnet flux-coupled stack.

3. The fission power generator of claim **2**, wherein a beam aperture of the sector magnet flux-coupled stack comprises pole faces having ridges aligned in curvature of beam travel, the ridges producing at least a quadrupole gradient that focuses a proton beam passing through the aperture.

4. The fission power generator of claim **3**, wherein each ridge comprises faces and each face comprises superconducting windings that produce at least a quadrupole gradient that focuses the proton beam passing through the aperture.

5. The fission power generator of claim **2**, wherein a beam aperture of the sector magnet flux-coupled stack comprises pole faces having windings that produce at least a quadrupole gradient that focuses a proton beam passing through the aperture.

6. The fission power generator of claim **2**, wherein the longitudinal sides of the sector magnet flux coupled stack are flat.

7. The fission power generator of claim **1**, wherein the sub-critical core comprises a molten mixture of fuel salt and heavy carrier salt.

8. The fission power generator of claim **7**, further comprising:

a core vessel; and

a containment vessel;

wherein the core vessel comprises:

- an inner vessel that contains the molten mixture;
- a lead outer vessel disposed about the inner vessel; and
- a multi-layer heat shield disposed between the inner vessel and the outer vessel.

9. The fission power generator of claim **8**, wherein a space between the inner vessel and the outer vessel comprises helium while configured to conduct heat from the inner vessel to the outer vessel, and comprises vacuum while configured to inhibit heat conduction from the inner vessel to the outer vessel.

10. The fission power generator of claim **8**, further comprising a lanthanide distillation system disposed within the containment vessel, wherein, during power generator operation, the lanthanide distillation system extracts lanthanides from the molten mixture, and stores the lanthanides in a lanthanide storage vessel.

11. The fission power generator of claim **8**, further comprising heat pipes coupled to the outer vessel, the heat pipes configured to conduct heat away from the outer vessel.

12. The fission power generator of claim **8**, further comprising a cryotrap disposed within the containment vessel, wherein the cryotrap configured to extract volatiles the sub-critical core.

13. The fission power generator of claim **1**, further comprising a plurality of spallation targets disposed within the sub-critical core, wherein at least one spallation target receives protons from each of the proton beam generators, and ejects neutrons based on the received protons.

14. The fission power generator of claim **1**, wherein each proton beam comprises at least 700 megaelectronvolts of energy and the plurality of proton beams comprises at least 10 megawatts of power.

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