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(54) SYSTEMS FOR MOLTEN SALT REACTOR FUEL-SALT PREPARATION

SYSTEME ZUR HERSTELLUNG VON BRENNSTOFFSALZEN FÜR SCHMELZSALZREAKTOREN

SYSTÈMES DE PRÉPARATION DE SEL DE COMBUSTIBLE DE RÉACTEUR À SEL FONDU

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Description

TECHNOLOGICAL FIELD

[0001] The present disclosure relates generally to methods and systems for processing pelletized-form light water reactor spent nuclear fuel into fluoride-based or chloride-based molten salt reactor fuel.

BACKGROUND

[0002] Nuclear fuel that has been irradiated in a nuclear reactor is generally referred to as spent nuclear fuel. Such spent nuclear fuel is generally not reused or recycled but instead is most often stored onsite in specially-design pools in the vicinity of the nuclear reactor in which such nuclear fuel was used. Aged spent nuclear fuel, having undergone significant decay so that it doesn't produce significant heat, may also be stored in dry casks on pads at the reactor site in which it was produced, at decommissioned reactor sites, and/or at other approved sites pending disposal at a permanent disposal facility.

[0003] According to the U.S. Energy Information Administration, as of 2013, there were more than 70,000 metric tons of spent nuclear fuel stored at sites within the United States (https://www.eia.gov/nuclear/spent_fuel/). Such spent nuclear fuel will be lethal to humans for thousands of years, requiring its storage meet stringent requirements and close monitoring. Further, while spent nuclear fuel storage has proven to be reasonably safe to date, the risk remains that a large fire, explosion, terrorist attack, plane crash, or accident could occur that damages a spent fuel pool and/or dry cask storage of such spent fuel.

[0004] Therefore, it would be desirable to have a system, apparatus and/or method that takes into account at least some of the issues discussed above, as well as possibly other issues, and yields an improved solution.

[0005] CA 755 544 A describes chemical reprocessing of spent or irradiated material removed from a nuclear chain fission reactor. JP H09 138295 A describes a method and device for converting spent nuclear fuel into chloride. WO 2017/158335 A1 describes a method of reprocessing spent nuclear fuel. RU 2 371 792 C2 describes a method and plant for recycling of spent nuclear fuel. WO 97/47015 A1 describes an apparatus and method is described for transmuting higher actinides, plutonium and selected fission products in a liquid-fuel subcritical assembly.

BRIEF SUMMARY

[0006] Provided is a system according to claim 1.

[0007] Preferred embodiments are defined in dependent claims 2-12.

[0008] The features, functions and advantages discussed herein may be achieved independently in various exemplary implementations or may be combined in yet other exemplary implementations further details of which may be seen with reference to the following description and drawings.

BRIEF DESCRIPTION OF THE DRAWINGS

[0009] Reference will now be made to the accompanying drawings, which are not necessarily drawn to scale, and wherein:

FIG. 1 schematically illustrates methods and systems according to exemplary implementations of the present disclosure for use in processing spent nuclear fuel into molten salt reactor fuel, and more specifically, a fluoride-based salt fuel for a thermal molten salt reactor (TMSR);

FIG. 2 schematically illustrates methods and systems according to an exemplary implementation of the present disclosure for use of a molten salt preparation in processing spent nuclear fuel into chloride fuel salt, and more specifically, the receiving of pellet-form spent fuel, which has been milled to pulverized-granulated form and
uranium/plutonium oxide reduction tank, wherein the purpose is to remove oxygen and prevent production of other oxides, results in the removal of oxygen as water and conversion of generated hydrogen to water, obviating the need for using costly catalysts or chemicals not readily available, and upon oxygen and hydrogen being removed from the fuel salt, substantially the only byproduct is water;

FIG.3 schematically illustrates the mixing and adjustment tank, illustrates methods and systems according to exemplary implementations of the present disclosure for use of a molten salt sampling, adjustment, and certification, in processing spent nuclear fuel into chloride fuel salt;

FIG. 4 schematically illustrates in plan view an exemplary methods and implementations of the present disclosure for use of a molten salt preparation in processing spent nuclear fuel into chloride fuel salt, and more specifically, typical separation for operation and critical-safe parallel arrangements of molten salt spent fuel oxide reduction and mixing tanks, including oxide reduction tanks and mixing and adjustment tanks and their relative orientation and physical separation, and physical separation by neutron absorbing panels to ensure subcriticality between parallel arrangements of oxide reduction tanks, and the same neutron absorbing panels between parallel arrangements of mixing tanks to ensure subcriticality, and including an oxide reduction tank discharge header discharges to the mixing and adjustment tank without using nozzles;

FIG. 5 schematically illustrates methods and systems according to exemplary implementations of the present disclosure for use of a molten salt preparation in

processing spent nuclear fuel into chloride fuel salt, and more specifically, salt mold cooling trays;

FIG. 6 schematically illustrates methods and systems according to exemplary implementations of the present disclosure for use of a molten salt preparation in processing spent nuclear fuel into chloride fuel salt, and more specifically, a salt mold cooling tray, including a top cover, cooling molds, and heating and cooling coils;

FIG. 7 schematically illustrates a method and system according to an exemplary implementation of a system 100, which is not part of the present invention, including, a process for thermal molten salt reactor (TMSR) fuel-salt preparation:

FIG. 8 schematically illustrates a method and system according to an exemplary implementation of the present disclosure, including, a process for fast molten salt reactor (FMSR) fuel-salt preparation;

FIG. 9 schematically illustrates methods and systems according to an exemplary implementation of the present disclosure for use of a molten salt preparation in processing spent nuclear fuel into chloride fuel salt; and

FIG. 10 schematically illustrates a site on which components of a system according to an example implementation of the present disclosure may be located.

DETAILED DESCRIPTION

[0010] Some implementations of the present disclosure will now be described more fully hereinafter with reference to the accompanying drawings, in which some, but not all variations of the disclosure are shown. Indeed, variations of the disclosure may be embodied in many different forms and should not be construed as limited to the examples set forth herein; rather, these are provided so that this disclosure will be thorough and complete and will fully convey the scope of the disclosure to those skilled in the art.

[0011] As used herein,"and/or" means any one or more of the items in the list joined by "and/or." As an example,"x and/or" means an element of the three-element set, e.g., [(x), (y), (x, y)]. Additionally, as used herein, the terms"exemplary" and"example" mean in context as serving as a non-limiting example, instance, illustration, or circumstance.

[0012] Moreover, as used herein, the term"for example," or,"e.g.," introduces a list of one or more non-limiting examples, instances, illustrations, or circumstances.

[0013] Exemplary implementations in accordance with the present disclosure are described with reference to systems and/or methods, such as in the context of processing spent nuclear fuel. Further, for example, reference is made herein to values of or

relationships between components, parameters, properties, variables or the like. These and other similar values or relationships are absolute or approximate to account for variations that may occur, such as those due to engineering tolerances or the like. Like reference numerals refer to like elements throughout.

[0014] Of note are the disclosures set forth in Conversion of Oxide to Metal or Chloride , by Sakamura, et ah, Organization Central Research Institute of the Electric Power Industry (CRIEPI), Japan, and Effect of Melt Composition on the Reaction of Uranium Dioxide with Hydrogen Chloride in Molten Alkali Chlorides, by Volkovich, et ah, Ural State Technical University, Russia.

[0015] Further of importance are the following documents: Processing of Used Nuclear Fuel , World Nuclear Association, (updated June 2018), https://world-nuclear.org/information-library/nuclear-fuel-cycle/fuel-recycling/processing-of-used-nuclear-fuel.aspx); Recycling Nuclear Fuel: The French Do It, Why Can't Ouif December 28, 2007, The Heritage Foundation (https://www.heritage.org/environment/ commentary/recycling-nuclear-fuel -the-french-do-it-why-cant-oui; Recycling Process of Defective Aged Uranium Dioxide Pellets , Fatah Mernache, et al, published online Aug.12 , 2015, Journal of Nuclear Science and Technology, Vol 53, Issue 6; Engineering Design of a Voloxidizer with a Double Reactor for the Hull Separation of Spent Nuclear Fuel Rods , Young-Hwan Kim, et al Korea Atomic Energy Research Institute, Science and

[0016] Technology of Nuclear Installations, Vol 2017, Article ID 985; Oxidation of U02 Fuel Pellets in Air At 503 and 543 K Studied Using X Ray Photoelectron Spectroscopy and X Ray Diffraction, P.A. Tempest et al, Journal of Nuclear Materials Feb 1988; The High Burnup Structure in Nuclear Fuel, Vincenzo V. Rondinella et al, European Commission, Joint Research Centre, Institute for Transuranium Elements Germany, Materials Today, Dec 2010, Vol 13, No 12; Uranium Tetrafluoride, IBILABS International Bio-Analytical Industries, Inc. August 7, 2016; Uranium Tetrafluoride, Wikipedia Ref Journal of the American Chemical Society, 1969; Hydrofluoric Acid Corrosion Study of High-Alloy Materials, P.E. Osborne et al, ORNL, UT Battelle, LLC for DOE, August 2002; and "Inconel 600", Spec sheet FSA, Shanghai Fengqu Superalloy Co, Ltd. March 13, 2019.

[0017] Further of importance are , the following patent documents: GB 803258; GB 1171257; GB 2536857; JP 11231091; KR 20060035917A; KR 20090089091 A; KR 2009010 109237A; KR 20090109238A; KR 20110034347A; US 2013/0266112A1; WO 2017/158335A1; US 2011/0286570A1; US 9767926; US 4062923; and US 6251310. Further it is referred to the documents: "Economic

[0018] Analysis on Direct Use of Spent Pressurized Water Reactor Fuel in CANDU Reactors - I:DUPIC Fuel Fabrication Cost, by Hangbox Choi, Won Li Ko, and Myung Seung Yang, Korea Atomic Energy Research Institute, Nuclear Technology , Vol. 134, May 2001; Proceedings of the 16th International Conference on Nuclear Engineering ICONE 16, 2006/2008 "Second Generation Experimental Equipment Design to Support Veloxidation

Testing At INL"; World Journal of Nuclear Science and Technology , 2015 "Reduction Kinetics of Uranium Tri oxide to Uranium Dioxide Using Hydrogen." Briefly, FIGs. 1 and 7 illustrate an exemplary implementation of a system including one or more processes for thermal molten salt reactor (TMSR) fuel-salt preparation, and FIG. 8 illustrates another exemplary implementation of the present disclosure, namely, a system including one or more processes for fast molten salt reactor (FMSR) fuel-salt preparation.

[0019] Methods and Systems for Calciner Fluoride Fuel Salt Preparation, which are not part of the present invention ("Option A") FIGs. 1 and 7 illustrate an exemplary implementation of a system 100, which is not part of the present invention, for calciner fluoride fuel salt preparation in the production of thermal molten salt reactor fuel salt. An externally heated and cooled calciner apparatus provides for a continuous process for converting spent fuel UO2 pellets (which have been previously removed from the fuel cladding) at elevated temperatures to ETricrystals/powder using a rotating cylinder through which the pellets advance, and using a counter-flow of oxygen (via the center of an axial support tube of an integrated helical auger) for oxidizing, then reducing in a concurrent flow of hydrogen gas, then fluorinating in a concurrent flow of HF gas (the gasses being introduced via the central pipes contained in the axis of the calciner.)

[0020] The calciner apparatus has sealing mechanisms at both ends to prevent any of the gases or particulates from entering the surrounding facility's atmosphere. The pellets are loaded through these sealing mechanisms at one end of the calciner apparatus, and the UF4 continuously exits through such sealing mechanisms at the other end of the calciner apparatus.

[0021] In some aspects, for example, the system 100 process begins with spent fuel pellets being recovered from fuel rod cladding (not shown) and fed into a rotating calciner, generally, 106. In an exemplary implementation, two calciners, one for each of two lines, could be used. As shown in FIG. 1, an axial cross-section of a calciner 106 depicts the construction thereof and the gas flow therethrough, shown by arrows 112. The direction of process flow through the calciner, is from left to right as indicated by arrows, in the axial-cross section. Sealed entries and exits to and from the calciner prevent gases escaping outside the system, while allowing entry of spent fuel pellets and exit of fluoride salt. (See U.S. Patent No. 7,824,640, to Pitts). All gases used and recycled in the calciner will be filtered to exclude unwanted elements and particles from exiting with the product. (See U.S.

[0022] Patent No. 4,666,684, to Pitts). Proceeding through the calciner 106, there are three process subdivisions designated by three radial cross-sections, or zones, generally 106 A, 106B, and 106C, (FIG. 1) showing the particular gas flow of each section and desired product.

[0023] Excess gases leave the calciner 106 by negative pressure to external filters (not shown). The externally-heated calciner rotates slowly, heating pellets to approximately 500°C for a period of time, which in one non-limiting example could be approximately 1 to 3 hours. Section 106 A includes a fixed integral helical auger, the direction of rotation being indicated, as viewed in the direction of gas flow from right to left in FIG. 1.

[0024] Calciner 106 dimensions, in one non-limiting example, could be approximately 15 to 30 inches in outside diameter, and axial section
A could be approximately 3.048 to 6.096 m (10 to 20 feet) in length. Axial sections 106B and 106C, in one non-limiting example, could be approximately 1.524 to 3.048 m (to 10 feet) in length each. Sensors, which in some non-limiting examples may be embedded or attached wireless micro-sensors, generally 114, are shown in the calciner casing 116 and serve to monitor process parameters such as temperatures, pressures, material and added constituents flow rates, radiation, gases, and/or other measurable process details.

[0025] One center conduit, or pipe, 118 extends the entire length of the calciner 106, which has a plug in the mid length of the pipe to prevent the mixing of the oxygen and hydrogen gasses. Oxygen (an oxidizing agent) enters at the left (as shown in FIG. 1), as pellets enter the calciner 106, and the oxygen exits from the pipe 118 into the
calciner interior 120, starting the oxidation of pellets. Curved arrows 112 on the axial section 106 A indicate oxygen flow from the pipe 118 to the calciner interior 120. Spent fuel pellets, generally 124, are indicated in section 106A at the helical auger 126 as are also mixing vanes 128. During this part of the process in calciner 106, UO2 (uranium dioxide) spent fuel pellets are oxidized to various oxides of uranium, which causes the pellets to disintegrate because of expansion during oxidation. All other constituents of spent fuel are contained and oxidized in this section.

[0026] A smaller center pipe 130 enters from the right end of calciner 106 and does not penetrate the full length of the calciner, but instead terminates at the start of axial section B. A baffle 131 will be used to reduce the mixing of the oxidizing gas and the reducing gas, at the appropriate spot axially, in the calciner, but will still allow advancement of the product through the calciner. (See U.S. Patent No. 3,969,477), One non-limiting exemplary location of baffle 131 is shown in FIG. 1. Baffle 131 is between the oxygen flow and the hydrogen gas flow in the calciner 106. The center pipe 130 supplies hydrogen gas for the second part of the process that takes place in the calciner 106, as shown by curved arrows 112 indicating outflow into the calciner main volume. The hydrogen gas is a reducing agent and flows from the center pipe 130 into the calciner interior 120, in section 106B. During this part of the process, various oxides of uranium are reduced to UO2, and the consistency of the spent fuel pellets has been changed from a generally pellet form to coarse powder, shown
in section 106B at the helical auger 126 and mixing vanes

128. Virtually the only effluent is water vapor, which is condensed during filtration of the recirculating gasses. All other constituents of spent fuel are contained and reduced during this part of the process.

[0027] The final process converts UO2 to UF4 (uranium tetrafluoride). Hydrogen gas continues to flow through the smaller center pipe exiting into the calciner section 106B, as described previously; then, HF (hydrogen fluoride) gas enters into the larger annular pipe 118 at the right end of the calciner 106 as shown in FIG. 1, and exits into the main interior, or, body, 120 of the calciner 106 at the beginning of axial

section 106C, with arrows 132 indicating direction of flow. During this part of the process, uranium and virtually all other constituents in the spent fuel, fission products, rare earths, and actinides are all substantially fluoridated. The resultant coarse
powder product is shown in cross-section 106C at the helical auger and mixing vanes 128.

[0028] Design and construction of the calciner apparatus 106 may include any suitable manufacturing techniques, including without limitation, application of 3D printing in order to use heat and corrosion resistant materials to create a durable internal design of calciner 106.

[0029] Calciner 106 includes instruments and sensors for the measurement of pressure, temperature, gas concentration, gas flow, and material flow, which can be accomplished by many, perhaps hundreds, of wireless imbedded micro sensors 114, which are monitored in real-time by computer systems and artificial intelligence applications to maintain safety of operation and to provide continuous improvement of the process. The sensors 114 may be built into the calciner apparatus 106 during the 3D printing process.

[0030] The calciner apparatus 106 keeps radioactive particles contained to prevent contamination of the surrounding facility, and calciner apparatus 106 generally produces only relatively small volumes of condensed liquid waste water, which will require specialized disposal. Operation of calciner apparatus 106 is more easily automated for operation on a 24/7 basis and is potentially less-expensive to operate over its lifetime than other types of processing. The design of the process using calciner apparatus 106 is scalable for increased capacity, as well as lending itself to be standardized for
replication, so that multiple units can be used for backup purposes and/or to increase facility capacity. The conversion gases used in calciner apparatus 106 are carried by inert gases such as helium or argon, which are recycled. Water vapor generated during processing is condensed and removed from the process on a continuous basis. Gases exit

[0031] the calciner apparatus 106 at each of the sealed ends to the filtering and replenishment equipment. The recirculated gases are filtered to remove elements not desired in the end product.

[0032] During the first stage of this process, as shown in section 106A of FIG.1, the pellets 124 are exposed to a counter-flow of oxidizing gas, shown by arrow 125, such as oxygen, to covert the U02 to various combinations of higher oxides of uranium, which increases the volume of the pellets up to 30%, potentially causing them to fracture. As shown in the section 106 A, the motion of the rotating cylinder 138, integral helical auger 128 blades, with small shelves, or ledges, 140 to lift the pellets 124, provides friction between the pellets, and small impact forces experienced by the pellets hasten the oxidation process, which itself expands and fragments the pellets 124 further. This ultimately results in powdered oxides of uranium. The diameter of the calciner 106, in one exemplary implementation, could be in the range of approximately 38.1-76.2 cm (15-30 inches).

[0033] The second stage 106B of the calciner 106 process is to the right of a closure 127 in conduit 118 (FIG. 1) and exposes the oxide powders of uranium to a flow of reducing gas such as hydrogen, converting the various uranium oxide powders to UO2. FIG. 1 shows the designs of section 106B, helical auger 128, and the axial gas supply
channel 130.

[0034] The third stage 106C of the calciner 106 process shown in section 106C exposes the UO2 powder to fluoridizing gaseous HF, which produces UF4 in a crystalline/powder
form for use in lithium fluoride molten salt-based reactors, for example. Section 106C shows the auger 128 and central path of the HF gas. Such Yh and HF gases then exit conduit 119 to filtering, which includes condensing and removing of the water vapor formed during the reduction and fluorination operations.

[0035] The UF4 exits the process in a manner which prevents leaking of gases to the atmosphere. A mechanism will be provided to seal the end of the calciner, so that the gases generated will be contained, and the product will exit cooled and ready for the next operation. The product is sampled, tested, and certified for shipment. The UF4 is automatically placed in containers, which are automatically sealed and cooled, and then stored for delivery to the customer. (In order to provide more uniform particle sizes than can perhaps be produced in the calciner 106, as the product exits the calciner 106, a subsequent milling operation for milling to powder to desired specifications may be used.) The third stage of the process shown in section 106C exposes the UO2 powder to fluoridizing gaseous HF, which produces UF4 in a crystalline/powder form for use in lithium fluoride salt-based reactors, for example. Section 106C shows the auger 128 and central path of the HF gas.

[0036] In an exemplary implementation of the present disclosure, a method is illustrated in FIG. 7 for producing fuel for a thermal molten salt reactor, the implementation of the method including:

a. providing fuel assemblies containing an array of fuel tubes are aligned horizontally on the rod puller disassembly table 270 (FIG. 9), and fuel pellets are removed from tubes;

b. processing the spent fuel pellets and fuel pieces into a fluoride salt by ultimate oxidation, reduction and fluorination of uranium and its associated fuel constituents; and c. filtering (including condensing and removing) the water vapor formed during the reduction and fluorination operations.

[0037] Another exemplary implementation of such method could include, if desired and as shown in FIG. 7, fluorinating the U235-enriched granular spent fuel salt or plutonium in a calciner rotary kiln or fluidized bed, and if additionally desired, enriching the granular spent fuel salt with U235.

[0038] In an exemplary implementation, because both the reduction of the oxides of uranium to uranium dioxide and the conversion of uranium dioxide to uranium tetrafluoride are exothermic, the calciner includes both external heating and cooling apparatus (not shown) over most of its length.

[0039] In an exemplary implementation, the temperature of conversion of uranium dioxide to uranium tetrafluoride in HF gas is to be maintained above 400 deg C during and after the conversion is completed, to prevent the undesired formation of volatile uranium hexafluoride, which will occur if it is cooled below 400 deg C in the presence of HF gas. Therefore, the uranium tetrafluoride must exit through the sealed end of the calciner above 400 deg C and then cooled to ambient temperature. This requires a counter flow of argon in the exit sealing mechanism of the calciner as cooling proceeds. Toward this end, the sealing and transfer mechanism for the fuel product is to be configured with sufficient cooling capacity. The calciner is configured to reduce the likelihood of the oxygen and hydrogen used in processing from being too close together in the oxidation and reduction steps in the calciner. Although at least one baffle 131 is used, it may be desirable to use multiple baffles, with the introduction of positive pressure inert gasses such as argon, between them, to prevent the mixing of oxygen and hydrogen during the process. Such inert gas can be introduced into the calciner through a pipe (not shown) placed axially in the auger 126, extending from the entrance end of the calciner to the baffle area.

[0040] In exemplary implementation, Option A may include, if desired, the spent nuclear fuel being generally permanently stored, then processed into spent fuel salt, and the spent fuel salt used in a thermal molten salt reactor, all on a single site having a secured perimeter.

[0041] Non-limiting example approximate temperatures, times, gas concentrations, materials used to construct the apparatus, and other parameters which are expected to be used are shown in the drawings.

Methods and Systems for Chloride Fuel Salt Preparation ("Option B")

[0042] FIGs. 2-7 and 9 illustrate an exemplary implementation of a system 200 according to the invention, for chloride fuel salt preparation in the production of fast molten salt reactor fuel salt.

[0043] The process 200 begins after the spent fuel pellets 124 recovered from cladding in a manner as discussed above, being fed into a ball mill 202 (FIG. 9), and pulverized to a granular form. Gases are recovered from the initial disassembly, from the ball mill 202, and from one or more enclosed conveyors (not shown), routing granulated spent fuel to the (FIG. 2) oxide reduction tanks 210. The oxide reduction tanks are the first tanks in line of the process 200 to treat granular/pulverized spent nuclear fuel. Spent fuel is reduced using a strong reducing agent, preferably a chloride-containing reducing agent, such as anhydrous hydrogen chloride (AHC1) addition through a tank sparger 212 at the bottom of the tank 210. A small excess of chloride with molten chloride fuel salt ensures enough free chloride to produce chloride salt fuel. The process produces water vapor and hydrogen which are continuously removed by blower extraction and condensation, and. Glow plugs (not shown) ensure hydrogen gas is burned to water product. This process completes the goal of removing oxygen from all oxides in the salt fuel. Automated and dip sampling configuration, and density probes, while provided, are not shown. Gases are collected into a fluidized bed (not shown) for chlorination and recycling back into the main process. Raw granulated spent fuel is routed from the ball mills 202 by the enclosed conveyor to parallel oxide reduction tanks 210 containing molten salt. Granulated spent fuel is conveyed in a closed system, to the oxide reduction tank hopper 216.

[0044] A tank 220 containing molten chloride salt maintained, in one non-limiting example, at approximately (30-50) degrees C (80-120 degrees F) above the melting point of the halide salt (molten alkali or alkali earth chloride) melting point estimated to be 500 C (930 F). The melting point of the molten salt is variable with the amount and consistency of alkali and alkali -earth chlorides, and with the amount of spent fuel added to the mix. Nominal density of spent fuel salt chloride is expected to be 3.0 g/cc, depending on concentration (mol%). It is anticipated salt fuel for the fast molten salt reactor will require significant enrichment. This enrichment will be performed with addition of U235, Pu239, or MOX fuel. At an estimated beginning 30 mol% uranium chloride and plutonium-chloride, the balance being fission product chlorides and actinide chlorides (5-10) mol%, the remaining mix contains free molten salt at (60-65) mole%.

[0045] FIG. 3 shows the fuel salt mixing and adjustment tank 220, second in line of an exemplary implementation of the process, receives fuel salt in a hopper 221 from the oxide reduction tank 210. Both tanks 210, 220 (FIG. 2 and 3) have automated sampling, and pump

recirculation distribution headers (not shown) internal to the tanks. Tanks 210, 220 (FIG. 3) are sized and configured to prevent a criticality (critical-safe) in the tank as pulverized spent fuel is added and enriched with U235, Pu239, or MOX fuel, to high assay low enriched uranium (HA-LEU) at less than approximately 20% enrichment. Both tanks 210, 220 have the capability to receive salt, spent fuel, or enrichments; however, tank 220 will normally receive only salt replenishment as needed. The enrichment is necessitated in fueling and operation of a fast molten salt reactor. Tanks 210 and 220, in one nonlimiting example, have approximate estimated dimensions of 10 feet in height by 16 feet front to
back and 10 inches wide and is capable of processing approximately 1000 gallons. Tanks 220, in one exemplary implementation, are constructed integrally with an outside tank (not shown) having leak detection between the inside and outside tanks. Outside tank dimensions allow for insulation, multiple electric heater access points, recessed instrument enclosures, and accesses to each.

[0046] The tanks 210, 220 are instrumented with dip sample points (not shown) for automatic and/or manual sampling and analysis. This capability confirms independent on line sampling that a receiving-mixing tank's contents are fully chlorinated to the extent possible (uranium, fission products, lanthanides, and actinides), i.e., substantially the entire inventory of spent nuclear fuel nuclides. A density probe 22 land manual liquid density measurement generated therefrom confirm whether the spent fuel salt density is at the expected density nominally (3.0-4.0) g/cm^3 (kg/m^3), molten alkali or alkali earth chloride density, no other content, is approximately (1.6 g/cm^3). The contents of the oxide reduction tank 210 (FIG. 2), and mixing and adjustment tank 220 will be processed further when sample analyses are confirmed. It is estimated reaction processing time is in an exemplary implementation 8 hours, including enrichment and sample confirmation, for the oxide reduction tank 210, and 4 hours for the mixing and adjustment tank 220. Full range gamma and neutron nuclear instruments, generally 224, provide continuous monitoring, trending, and alarming (counts/second) and rate of change. In one implementation, oxide reduction tank 210 size and configuration require four equally spaced instruments over the height and depth of each tank. A blower and chiller 226 combination removes water from tank 210. An anhydrous hydrogen chloride cylinder and compressor, generally 228, supply sparger arrangement 212. Salt mixers (e.g., screw-type mixers) 222 set at different depths, and front to back of the tank, ensure sufficient mixing of each tank. Additionally, FIG. 2 is an exemplary implementation wherein tank screw pump 218 is shown. Tank screw pump 218 is connected to tank 210 via conduit 210A, and an inlet valve 218A is provided proximate the inlet of pump, and an outlet valve 218B is provided proximate the outlet of pump 218. A conduit 218C connects valve 218B to a discharge valve 219 and to a tank pump recirculation isolation valve 229 connected to molten fuel salt mixing tank 220.

[0047] In an exemplary implementation shown in FIG. 3, a tank screw pump 218 is connected to tank 220 via conduit 220A, and an inlet valve 218A is provided proximate the inlet of pump, and an outlet valve 218B is provided proximate the outlet of pump 218. A conduit 218C connects valve 218B to a tank header valve 217and to a tank pump recirculation isolation valve 225.

[0048] In FIG.4, a representation of tanks 220 containing molten salt spent fuel are shown in a plan view in a side-by-side relationship, and, as in the case of all the drawings herein, are not shown to scale. This view represents the general size and configuration for both the oxide reduction tanks 210 (side by side) and mixing and adjustment tanks 220 (side by side). More specifically, FIG. 4 shows an implementation wherein six tanks 220 are shown. Accompanying apparatus and equipment and configurations used in connection with the tanks 220, are not shown.

[0049] In the basic process flow (FIG. 9), it could be considered that the first oxide reduction tank 210 would pump out to the first mixing and adjustment tank, the second oxide tank, the second mixing tank, and continue this sequence until all oxide reduction tanks have pumped out to their respective mixing and adjustment tank. The tanks, FIG. 4, also include the tank pump discharge header and nozzles, which are only located on the mixing and adjustment tank 220 pump out header. Spaced between tanks are encased boron slabs, or, dividers, or encasements, 230. Boron encasements 230 positioned between all fuel salt tanks 220 prevent nuclear criticality communication between the array of oxide reduction tanks in close proximity, and between the array of mixing and adjustment tanks in close proximity. Each group is considered herein as one subcritical assembly group, generally 266. Boron dividers 230 are backup defense in depth against possible criticality.

[0050] In an exemplary implementation, equipment is selected for durability and reliability. Two channels of electric"jacketed heaters" (not shown) are fitted to piping, valves and pumps ensure salt fuel in piping and equipment is of a high enough temperature to remain liquid and will flow. The heater channels are monitored, alarmed, and component failure identified if such a failure occurs. If sections of piping are allowed to cool where molten salt is solidified, heaters can be activated to re-melt the fuel salt.

[0051] Instrumentation and automated functions are fully alarmed and continuously communicated to a control center. Diagnostic protocols help operators identify system interruptions or points requiring repair. All components on tanks and transfer piping are preferably accessible and capable of remote repair after steps are taken to isolate failed components from the system. Multiple independent receiving-mixing tanks and transfer equipment ensures a continuous supply of fuel salt in operation, including in the event of a system failure.

[0052] In an exemplary implementation, fuel salt pre-

paration is begun with introduction of chloride salts of alkali metals or alkaline earth metals (e.g., NaCl, KC1, MgCh, CaCb), typically in crystalline form, and usually a mixture of two or more salts to a tank. Heaters (e.g., electrical heating elements) 231 are energized to melt the salt to molten state and maintain temperature well above melting point. Pulverized-granulated spent nuclear fuel is taken from the ball mill 202 and carried by enclosed conveyor to the tank hopper 223 and deposited via hopper isolation valve 227 into the oxide reduction tank, and open isolation valve 227 (FIG. 2). Spent fuel addition, regulated by limiting size and speed of the enclosed conveyor, ensures tank temperature is maintained within predetermined specifications and sufficient mixing and reaction of tank contents occurs. All mixers and the tank pump are turned on to initiate mixing, recirculation by pumping, and consistency of fuel salt in the tank and pump discharge lines. In an exemplary implementation, tank size and screw pump capacity are regulated to allow 4-6 hours for mixing and sampling, density recording and analysis before a tank is ready to be discharged.

[0053] Figures 5 and 6 show an exemplary implementation in plan and elevational views of a molten fuel salt collection tray, generally 240, consisting of the tray cover 254, fuel salt collection molds 256 atop heating and cooling elements 242, in a generally

[0054] checkerboard pattern of heating elements 234A and cooling elements 234B. Insulation between elements along the sides and bottom of the tray prevents solidification during pouring and minimizes cooling time after solidification. More specifically, FIG. 5 is a plan view of salt mold cooling tray 240 with the tray cover and cooling molds removed.

[0055] In an exemplary implementation, salt mold cooling trays 240 (FIG. 9) are positioned and held in a stacked array of 8-10 trays, with spacing between the trays being sufficient to allow for removal of the cooling molds and cover as one assembly. Stacked arrays are tracked together by a revolving drive (not shown) which moves one stacked and cooled array group, to the ball mill feed table 250. At the table 250, the one-piece molds of each tray, in a particular group, are removed and upended or overturned to deposit solid "bars" of fuel salt. Each tray's mold is removed and returned to its position before the next mold is removed. After an entire array group has been emptied, it is returned in turn to be refilled with molten salt. Tray molds can be a non-stick surface, with salt fuel contraction during cooling, thereby facilitating solid salt fuel removal. The metal molds may be connected side-to-side and laterally supported to ensure tray strength and versatility. Solid salt"bars" are gathered to the side of the turning table and are generally organized lengthwise on a moving conveyor and fed into 2-3 coarse ball mills 202A (FIG. 9).

[0056] Product fuel salt from the ball mill is further conveyed to a fine mill, such as a Fitzmill 252 for sizing, sampling, certification, and packaging for protection against environmental conditions. More specifically, FIG. 6 illustrates a salt mold cooling tray front view, including top cover 254, cooling molds 256, heating and cooling elements 234A, 234B, which, in one implementation, could be coils.

[0057] In an alternate implementation, molten salt fuel may be stored as a contiguous solid in canisters and subcritical arrays. This process involves preparation of chloride fuel salt in the aforementioned receiving and mixing tanks 220, sampling and certification of tanks, and transfer by screw pump to a"critical safe" steel canister (not shown), set aside for cooling. Canisters are transported and stored, in "critical safe" arrays. Facilities using "solid salt" canisters are equipped to remotely handle and inductively heat each canister to form liquid fuel salt for addition to their molten salt reactors.

[0058] In FIG. 4, molten salt spent fuel receiving and mixing tanks 220 are shown in a side-by-side representative top view, but not to scale. More specifically, FIG. 4 shows an implementation wherein six receiving-mixing tanks 220 are side-by-side, including a tank pump discharge header, generally 260, and encased boron encasements 230 (sized for inner tank side dimension area). Boron encasements 230 provide structural stability and protection from damage and are positioned between fuel salt tanks 220 to prevent nuclear criticality communication between tanks in a given array of tanks in close proximity, such array being considered herein as one subcritical assembly group, generally 266. Boron dividers 230 are backup defense, in depth, against possible criticality.

[0059] As shown in an exemplary implementation in FIG. 2, the oxide reduction tank is the first tank in the process, wherein a system and process are illustrated which reduces uranium and plutonium oxides to chlorides. After this process, the contents of the reduction tank 210 are pumped over to the mixing and adjustment tank. In one

[0060] implementation, an isolation valve is provided on the loading hopper. In an exemplary implementation wherein only chloride salts are desired, the salts are prepared in the oxide reduction tank, and, then pulverized, granulated spent fuel is added to the oxide reduction tank, the temperature increase is noted, and oxide reduction is begun by the sparging action of anhydrous hydrogen chloride. After an allowance of time necessary for mixing and water and hydrogen gas removal, toward complete reduction, the contents are pumped to the mixing and adjustment tank for final analysis, certification, and then pumped over to cooling trays. The teaching of the present disclosure includes reducing all oxides, removing oxygen entirely and preventing production of other oxides, ensures an authentic chloride salt fuel, when oxygen is removed from the fuel salt. The result is that substantially the only byproduct from this implementation of the present disclosure is
water, which is collected for sampling and released.

[0061] In an exemplary implementation, which is not part of the present invention, a method is illustrated in

FIG. 8 for producing fuel for a fast molten salt reactor, the implementation of the method including:

a. providing fuel assemblies, removing fuel pellets containing uranium and all spent fuel constituents, from the fuel assemblies;
b. granulating the fuel pellets in a semi-voided atmosphere using a ball mill, roller mill, or chopping mill, for process feed to the chlorination process;
c. processing the granular spent fuel salt into chloride salt by ultimate reduction and chlorination of the uranium and associated fuel constituents chloride salt solution, by anhydrous hydrogen chloride (AHC1);
d. enriching the granular spent fuel salt with U235, Pu239, or MOX;
e. chlorinating the enriched granular spent fuel salt to yield molten chloride salt fuel using AHC1 halide salt reduction;
f. analyzing, adjusting, and certifying the molten chloride salt fuel for end use in a molten salt reactor;
g. pumping the molten chloride salt fuel to stacked arrays of cooling trays or canisters and cooling the molten chloride salt fuel to yield solid salt fuel bars, sticks, or canister solid form; and
h. milling the solidified molten chloride salt fuel to predetermined specifications for the fast molten salt reactor.

[0062] In exemplary implementations, Option B may include, if desired, the spent nuclear fuel being generally permanently stored, then processed into spent fuel salt, and the spent fuel salt used in a fast molten salt reactor, all on a single site having a secured perimeter.

[0063] Non-limiting example approximate temperatures, times, gas concentrations, materials used to construct the apparatus, and other parameters which are expected to be used are shown in the drawings.

[0064] FIG. 10 schematically illustrates a site on which components of a system 1000 according to an example implementation of the present disclosure may be located. The system 1000 may include a site 1002 within a secured perimeter 1004, and a limited-access facility 1006 on the site 1002. As described above, the system 1000 may include a number of components 1008, and at least some of these components 1008 of the system 1000 may be located within the limited-access facility 1006. The system 1000 may also include a spent nuclear fuel storage facility 1010 located on the site, and a molten salt reactor 1012 located on the site 1002.

[0065] The invention is defined in the appended claims.

Claims

1. A system (200) for processing spent nuclear fuel from fuel assemblies having fuel tubes with fuel pellets into molten salt reactor fuel, the system comprising components including at least:

a first mill (202) configured to granulate the spent nuclear fuel in a semi-voided atmosphere into granular spent fuel;
an oxide reduction tank (210) configured for chlorinating and processing the granular spent fuel into chloride salt by ultimate reduction and chlorination, which includes reacting the spent fuel with anhydrous hydrogen chloride (AHCI) in the oxide reduction tank (210), wherein hydrogen is produced, and wherein the system (200) is adapted to convert the hydrogen to water, and to continuously remove the water from the oxide reduction tank (210); the oxide reduction tank (210) being configured for enriching the granular spent fuel salt;
a salt immersion bath for chlorinating the enriched granular fuel salt with AHCI to yield molten chloride fuel salt for a fast molten salt reactor;
a pump configured to pump the molten chloride salt fuel to cooling trays or canisters configured to cool the molten chloride salt fuel to yield solid salt fuel bars, sticks, or canister solid forms; and
a second mill configured to mill the solidified molten chloride salt fuel to predetermined specifications for a fast molten salt reactor.
characterized in that:
the system (200) comprises a fluidized bed for collecting spent fuel gases and converting the spent fuel gases to chlorinated fuel salts.

2. The system (200) according to claim 1, further comprising a chemical reactor configured to receive spent fuel gases and to convert the spent fuel gases to chlorinated fuel salts.

3. The system (200) according to claim 1, wherein the first mill is a ball mill, a roller mill, or a chopping mill.

4. The system (200) according to claim 1, wherein the oxide reduction tank (210) is for enriching the granular spent fuel salt with one or more of uranium-235 (U235), plutonium-239 (Pu239), or mixed oxide (MOX).

5. The system (200) according to any previous claim, comprising a plurality of oxide reduction tanks, wherein the plurality of oxide reduction tanks are side-by-side and encased by boron encasements.

6. The system (200) according to any previous claim, comprising a rod puller disassembly table for receiving an array of fuel tubes aligned horizontally thereon.

7. The system (200) according to claim 6, comprising a

laser for removing the spent fuel pellets by laser slitting of the fuel tubes, opening the tubes, and removing the spent fuel pellets.

8. The system (200) according to any previous claim, wherein the cooling trays or canisters are stacked arrays and are cooled by chilled water, and wherein the stacked arrays of cooling trays or canisters are configured with multiple parallel and separate rows, each surrounded by cooling coils.

9. The system (200) according to any previous claim, wherein the pump is configured to pump the molten chloride salt fuel into individual storage canisters, and wherein the individual storage canisters are inductively heated to liquid.

10. The system (200) according to any previous claim, wherein the second mill comprises a ball mill and optionally, a fine mill.

11. The system (200) according to any previous claim, comprising two channels of electric jacketed heaters fitted to piping, valves and pumps to ensure salt fuel in piping and equipment is of a high enough temperature to remain liquid and will flow.

12. The system (200) of any previous claim, further comprising:

a site within a secured perimeter;
a limited-access facility on the site;
the components of the system being located within the limited-access facility;
a spent nuclear fuel storage facility located on the site; and
a molten salt reactor located on the site.

Patentansprüche

1. System (200) zur Verarbeitung von gebrauchtem Kernbrennstoff von Brennstoffbaugruppen mit Brennstoffrohren mit Brennstoffpellets zu Flüssigsalzreaktorbrennstoff, wobei das System Komponenten umfasst, die wenigstens enthalten:

eine erste Mühle (202), gestaltet zum Granulieren des gebrauchten Kernbrennstoffs in einer halbleeren Atmosphäre zu granulatförmigem gebrauchtem Brennstoff;
einen Oxidreduktionstank (210), gestaltet zum Chlorieren und Verarbeiten des granulatförmigen gebrauchten Brennstoffs zu Chloridsalz durch höchste Reduktion und Chlorierung, umfassend Umsetzen des gebrauchten Brennstoffs mit wasserfreiem Chlorwasserstoff (AHCl) in dem Oxidreduktionstank (210), wobei Wasserstoff erzeugt wird,
und wobei das System (200) dafür ausgelegt ist, den Wasserstoff in Wasser umzuwandeln und das Wasser kontinuierlich aus dem Oxidreduktionstank (210) zu entfernen; wobei der Oxidreduktionstank (210) dafür gestaltet ist, das granulatförmige gebrauchte Brennstoffsalz anzureichern;
ein Salztauchbad zum Chlorieren des angereicherten geanulatförmigen Brennstoffsalzes mit AHCl, um geschmolzenes Chlorid-Brennstoffsalz für einen schnellen Flüssigsalzreaktor zu ergeben;
eine Pumpe, dafür gestaltet, den geschmolzenen Chloridsalz-Brennstoff zu Kühlwannen oder -kanistern zu pumpen, die dafür gestaltet sind, den geschmolzenen Chloridsalz-Brennstoff abzukühlen, um feste Salz-Brennstoffblöcke, -stäbe oder feste Kanisterformen zu erhalten; und
eine zweite Mühle, dafür gestaltet, den erstarrten geschmolzenen Chloridsalz-Brennstoff auf vorgegebene Spezifikationen für einen schnellen Flüssigsalzreaktor zu mahlen,
dadurch gekennzeichnet, dass:
das System (200) ein Fließbett zum Sammeln von gebrauchten Brennstoffgasen und Umwandeln der gebrauchten Brennstoffgase in chlorierte Brennstoffsalze umfasst.

2. System (200) nach Anspruch 1, ferner umfassend einen chemischen Reaktor, der dafür gestaltet ist, gebrauchte Brennstoffgase aufzunehmen und die gebrauchten Brennstoffgase in chlorierte Brennstoffgase umzuwandeln.

3. System (200) nach Anspruch 1, wobei die erste Mühle eine Kugelmühle, eine Walzenmühle oder eine Hackmühle ist.

4. System (200) nach Anspruch 1, wobei der Oxidreduktionstank (210) zum Anreichern des granulatförmigen gebrauchten Brennstoffsalzes mit einem oder mehreren von Uran-235 (U235), Plutonium-239 (Pu239) oder Mischoxid (MOX) ist.

5. System (200) nach einem der vorstehenden Ansprüche, umfassend eine Vielzahl von Oxidreduktionstanks, wobei die Vielzahl von Oxidreduktionstanks Seite an Seite angeordnet und von Borumhüllungen umhüllt sind.

6. System (200) nach einem der vorstehenden Ansprüche, umfassend einen Stababzieh-Demontagetisch um Aufnehmen einer Anordnung von Brennstoffrohren, die horizontal darauf ausgerichtet sind.

7. System (200) nach Anspruch 6, umfassend einen Laser zum Entfernen der gebrauchten Brennstoff-

pellets durch Laserschlitzen der Brennstoffrohre, Öffnen der Rohre und Entfernen der gebrauchten Brennstoffpellets.

8. System (200) nach einem der vorstehenden Ansprüche, wobei die Kühlwannen oder -kanister gestapelte Anordnungen sind und durch gekühltes Wasser gekühlt werden, und wobei die gestapelten Anordnungen von Kühlwannen oder -kanistern in mehreren parallelen und getrennten Reihen gestaltet sind, die jeweils von Kühlschlangen umgeben sind.

9. System (200) nach einem der vorstehenden Ansprüche, wobei die Pumpe dafür gestaltet ist, den geschmolzenen Chloridsalz-Brennstoff in einzelne Vorratskanister zu pumpen, und wobei die einzelnen Vorratskanister einzeln auf Flüssigkeit erhitzt werden.

10. System (200) nach einem der vorstehenden Ansprüche, wobei die zweite Mühle eine Kugelmühle und gegebenenfalls eine Feinmühle umfasst.

11. System (200) nach einem der vorstehenden Ansprüche, umfassend zwei Kanäle von elektrischen Mantelheizern, die an Rohrleitungen, Ventile und Pumpen angepasst sind, um zu gewährleisten, dass Salzbrennstoff in Rohrleitungen und Ausrüstung eine ausreichend hohe Temperatur aufweist, um flüssig zu bleiben, und fließen wird.

12. System (200) nach einem der vorstehenden Ansprüche, ferner umfassend:

einen Standort innerhalb eines gesicherten Bereichs;
eine Anlage mit Zugangsbeschränkung an dem Standort;
wobei die Komponenten des Systems innerhalb der Anlage mit Zugangsbeschränkung angeordnet sind;
eine Lageranlage für gebrauchten Kernbrennstoff, die an dem Standort angeordnet ist; und
einen Flüssigsalzreaktor, der an dem Standort angeordnet ist.

Revendications

1. Système (200) pour le traitement de combustible nucléaire usagé à partir d'assemblages de combustible ayant des tubes de combustible avec des pastilles de combustible dans un combustible de réacteur à sel fondu, le système comprenant des composants comprenant au moins :

un premier broyeur (202) configuré pour granuler le combustible nucléaire usagé dans une atmosphère semi-vide en un combustible usagé granulaire ;
un réservoir de réduction d'oxyde (210) configuré pour chlorer et traiter le combustible usagé granulaire en sel de chlorure par réduction ultime et chloration, qui comprend la mise en réaction du combustible usagé avec du chlorure d'hydrogène anhydre (AHCl) dans le réservoir de réduction d'oxyde (210), dans lequel de l'hydrogène est produit, et dans lequel le système (200) est conçu pour convertir l'hydrogène en eau, et pour éliminer de manière continue l'eau du réservoir de réduction d'oxyde (210) ; le réservoir de réduction d'oxyde (210) étant configuré pour enrichir le sel de combustible usagé granulaire ;
un bain d'immersion de sel pour chlorer le sel de combustible granulaire enrichi avec AHCl pour produire du sel de combustible de chlorure fondu pour un réacteur à sel fondu rapide ;
une pompe configurée pour pomper le combustible de sel de chlorure fondu dans des plateaux ou des conteneurs de refroidissement configurés pour refroidir le combustible de sel de chlorure fondu pour produire des formes solides de barres, de bâtons ou de conteneurs de combustible de sel solide ; et
un deuxième broyeur configuré pour broyer le combustible de sel de chlorure fondu solidifié jusqu'à des spécifications prédéterminées pour un réacteur à sel fondu rapide,
caractérisé en ce que :
le système (200) comprend un lit fluidisé pour collecter des gaz de combustible usagé et convertir les gaz de combustible usagé en sels de combustible chlorés.

2. Système (200) selon la revendication 1, comprenant en outre un réacteur chimique configuré pour recevoir des gaz de combustible usagé et pour convertir les gaz de combustible usagé en sels de combustible chlorés.

3. Système (200) selon la revendication 1, le premier broyeur étant un broyeur à billes, un broyeur à rouleaux ou un broyeur à hacher.

4. Système (200) selon la revendication 1, le réservoir de réduction d'oxyde (210) étant pour l'enrichissement du sel de combustible usagé granulaire avec l'un ou plusieurs parmi l'uranium-235 (U235), le plutonium-239 (Pu239) ou un oxyde mixte (MOX).

5. Système (200) selon une quelconque revendication précédente, comprenant une pluralité de réservoirs de réduction d'oxyde, la pluralité de réservoirs de réduction d'oxyde étant côte à côte et encastrés par des coffrages de bore.

6. Système (200) selon une quelconque revendication précédente, comprenant une table de désassemblage pour le tirage des barres pour recevoir un réseau de tubes de combustible alignés horizontalement sur celle-ci.

7. Système (200) selon la revendication 6, comprenant un laser pour éliminer les pastilles de combustible usagé par découpe au laser des tubes de combustible, ouverture des tubes et élimination des pastilles de combustible usagé.

8. Système (200) selon une quelconque revendication précédente, les plateaux ou conteneurs de refroidissement étant des réseaux empilés et étant refroidis par de l'eau réfrigérée, et les réseaux empilés de plateaux ou conteneurs de refroidissement étant configurés avec des rangées parallèles et distinctes, chacune entourée par des bobines de refroidissement.

9. Système (200) selon une quelconque revendication précédente, la pompe étant configurée pour pomper le combustible de sel de chlorure fondu dans des conteneurs de stockage individuel, et les conteneurs de stockage individuel étant chauffés par induction à un liquide.

10. Système (200) selon une quelconque revendication précédente, le deuxième broyeur comprenant un broyeur à billes et éventuellement, un broyeur fin.

11. Système (200) selon une quelconque revendication précédente, comprenant deux canaux de chauffages gainés électriques montés sur la tuyauterie, des vannes et des pompes pour garantir qu'un combustible de sel dans la tuyauterie et les appareils soit d'une température suffisamment élevée pour rester liquides et qu'il s'écoulera.

12. Système (200) selon une quelconque revendication précédente, comprenant en outre :

un site dans un périmètre sécurisé ;
une installation à accès limité sur le site ;
les composants du système étant situés dans l'installation à accès limité ;
une installation de stockage de combustible nucléaire usagé située sur le site ; et
un réacteur à sel fondu situé sur le site.

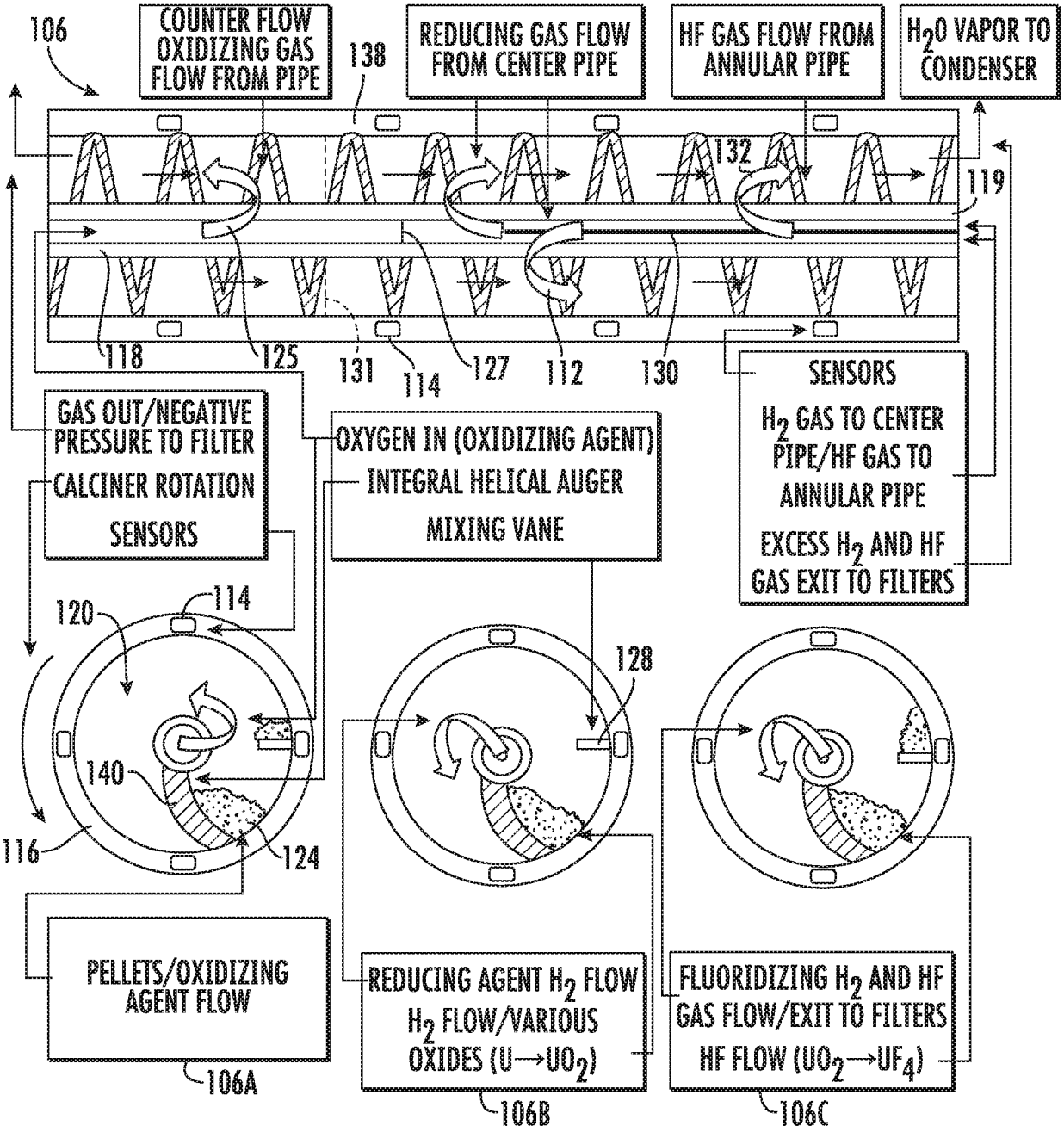
106
COUNTER FLOW OXIDIZING GAS FLOW FROM PIPE
138
REDUCING GAS FLOW FROM CENTER PIPE
HF GAS FLOW FROM ANNULAR PIPE
H_2O VAPOR TO CONDENSER
132
119
118
125
131
114
127
112
130
SENSORS
H_2 GAS TO CENTER PIPE/HF GAS TO ANNULAR PIPE
EXCESS H_2 AND HF GAS EXIT TO FILTERS
GAS OUT/NEGATIVE PRESSURE TO FILTER
CALCINER ROTATION SENSORS
OXYGEN IN (OXIDIZING AGENT)
INTEGRAL HELICAL AUGER MIXING VANE
120
114
128
140
116
124
PELLETS/OXIDIZING AGENT FLOW
106A
REDUCING AGENT H_2 FLOW
H_2 FLOW/VARIOUS OXIDES ($U \rightarrow UO_2$)
106B
FLUORIDIZING H_2 AND HF GAS FLOW/EXIT TO FILTERS
HF FLOW ($UO_2 \rightarrow UF_4$)
106C

FIG. 1

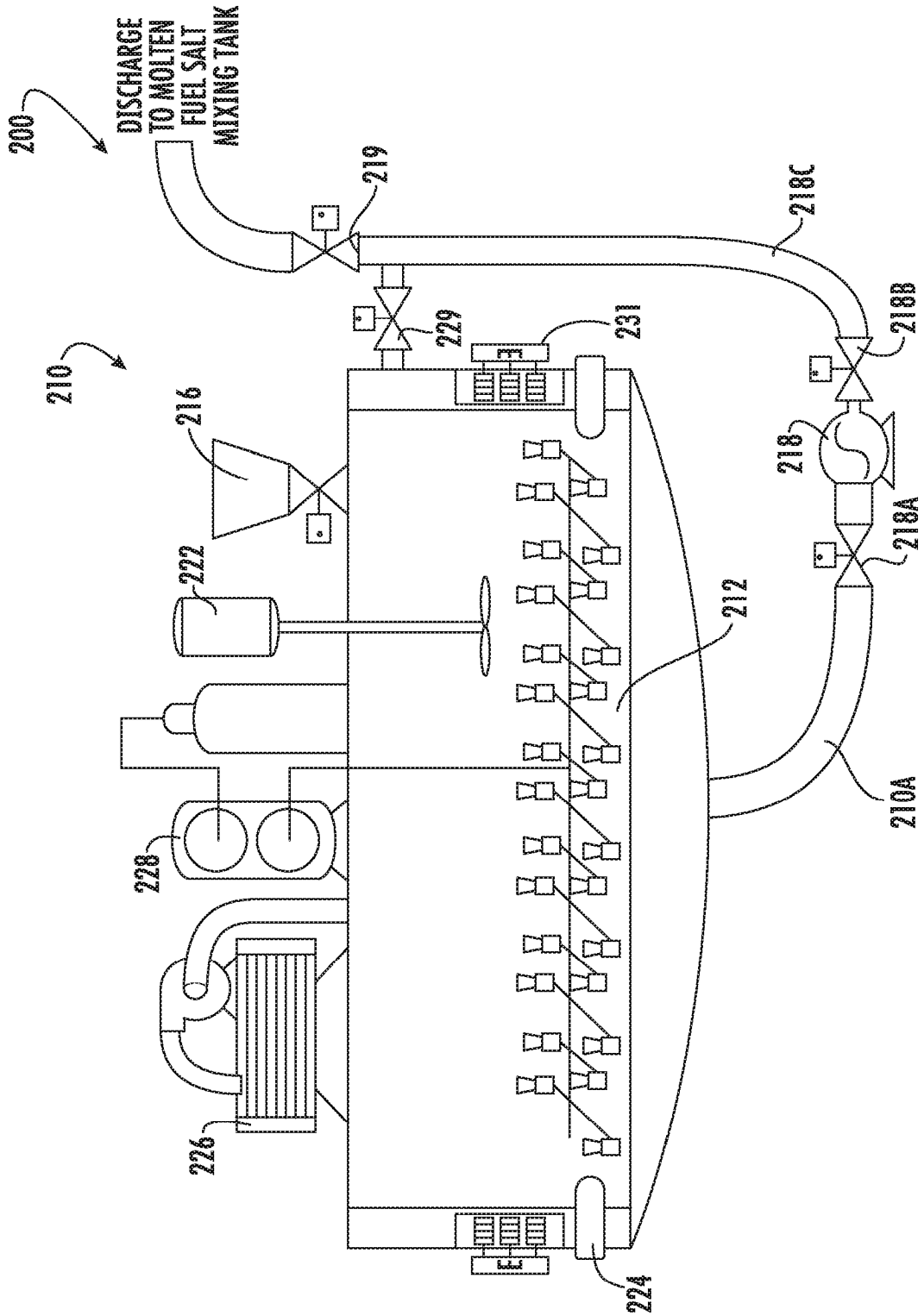
200
DISCHARGE TO MOLTEN FUEL SALT MIXING TANK
219
218C
229
231
218B
210
216
218
222
218A
212
228
210A
226
224

FIG. 2

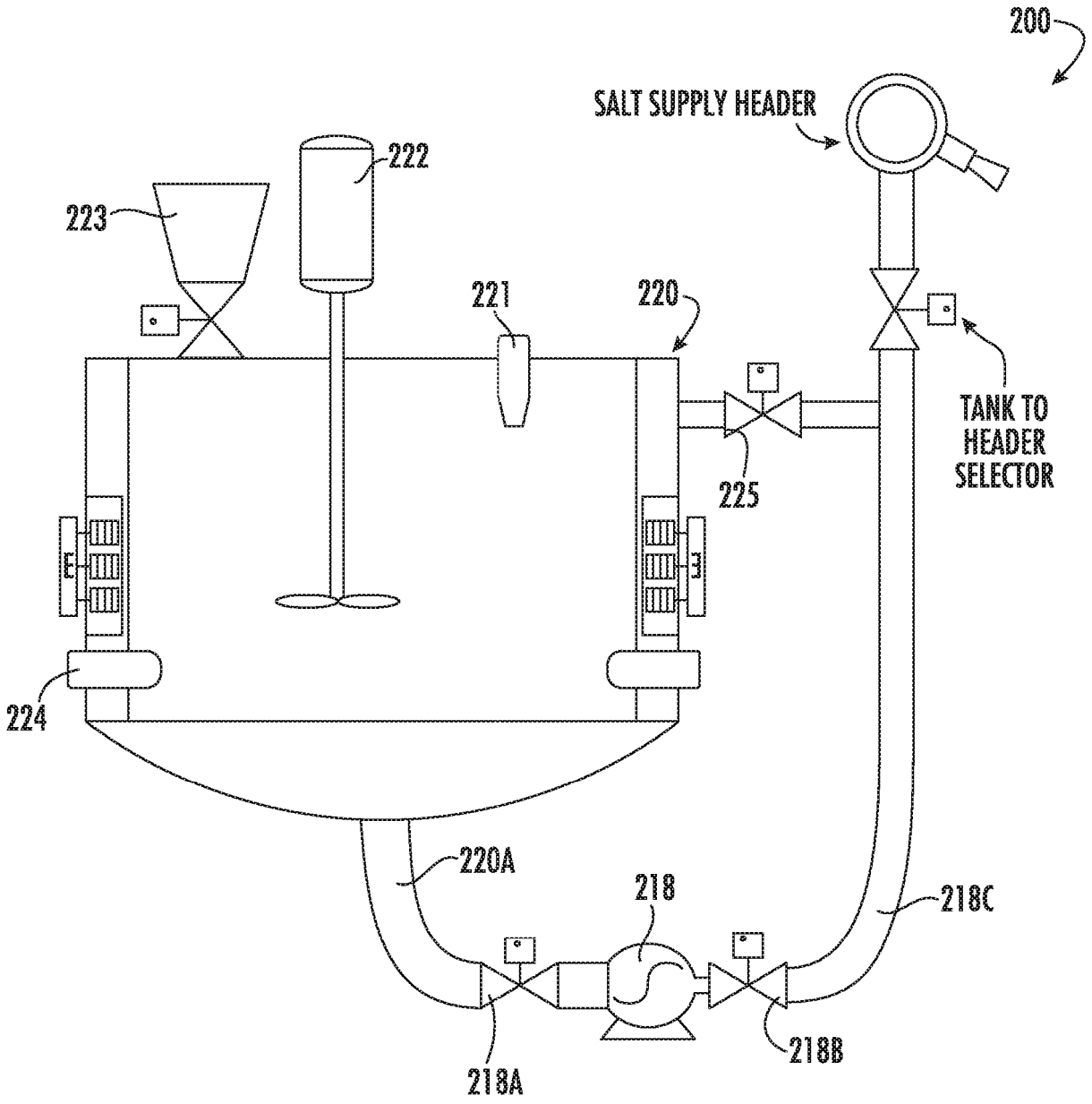
200
SALT SUPPLY HEADER
222
223
221
220
TANK TO
HEADER
SELECTOR
225
224
220A
218
218C
218A
218B

FIG. 3

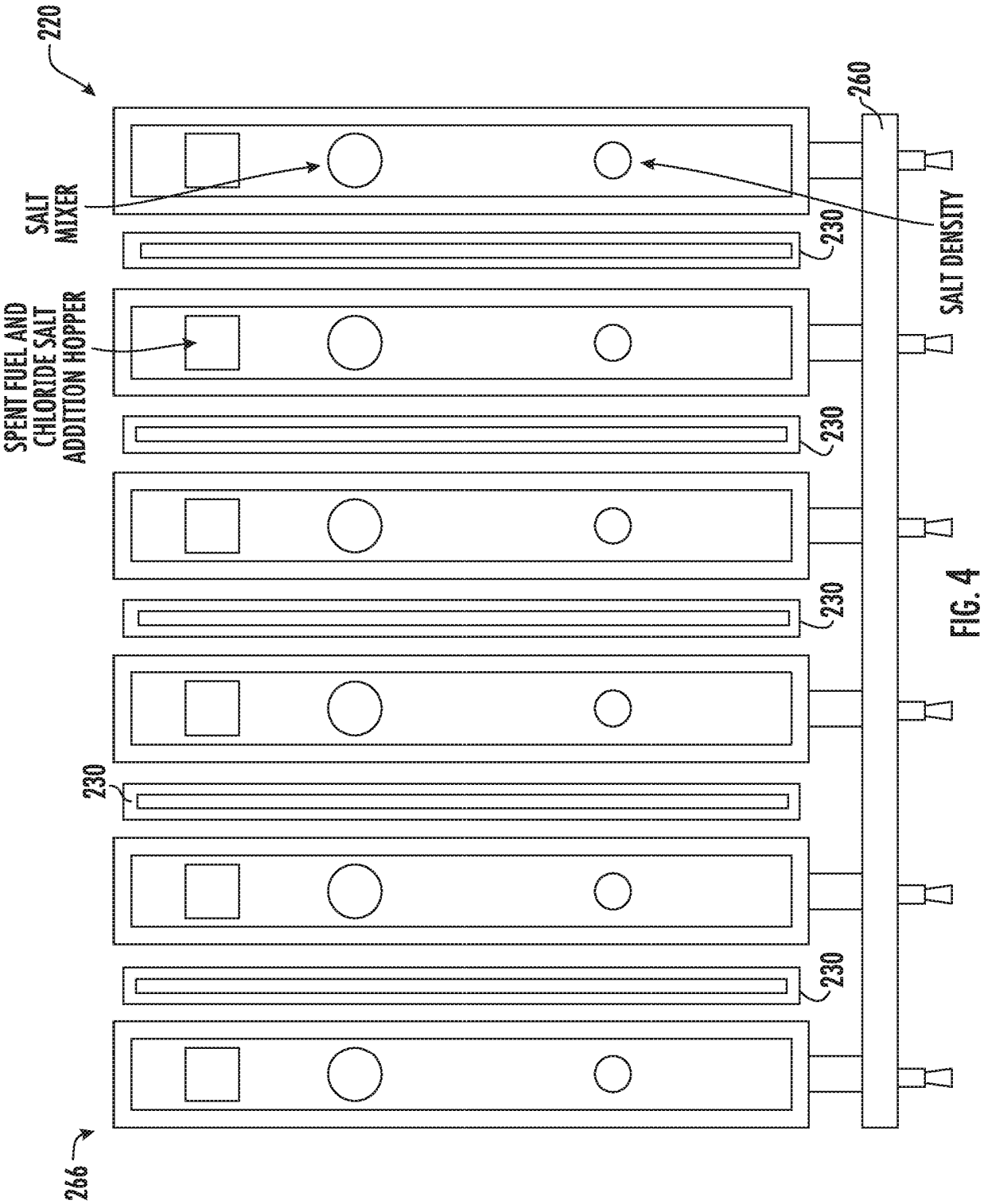
220
SALT MIXER
SPENT FUEL AND CHLORIDE SALT ADDITION HOPPER
230
230
230
230
230
260
SALT DENSITY
266

FIG. 4

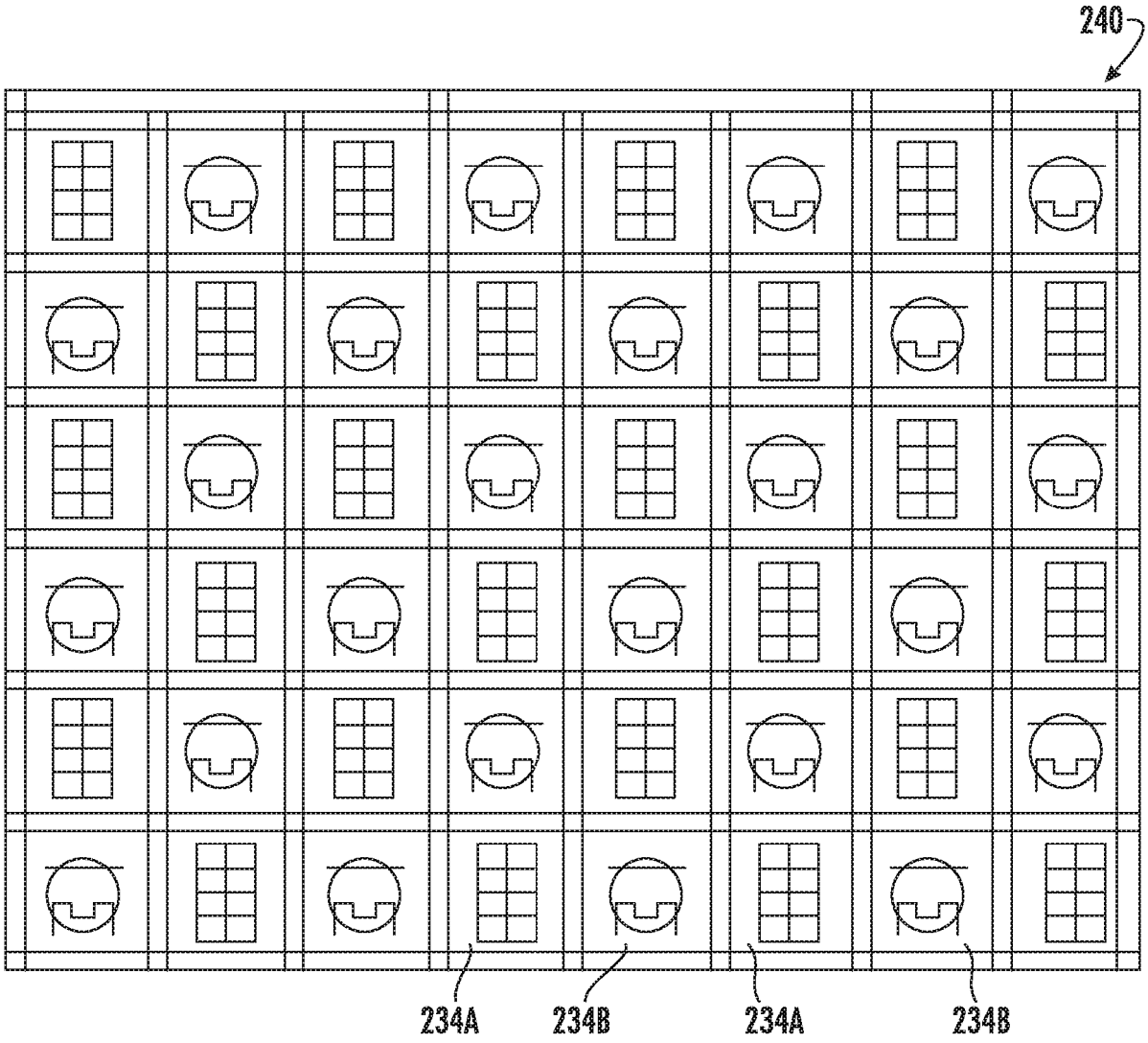

FIG. 5

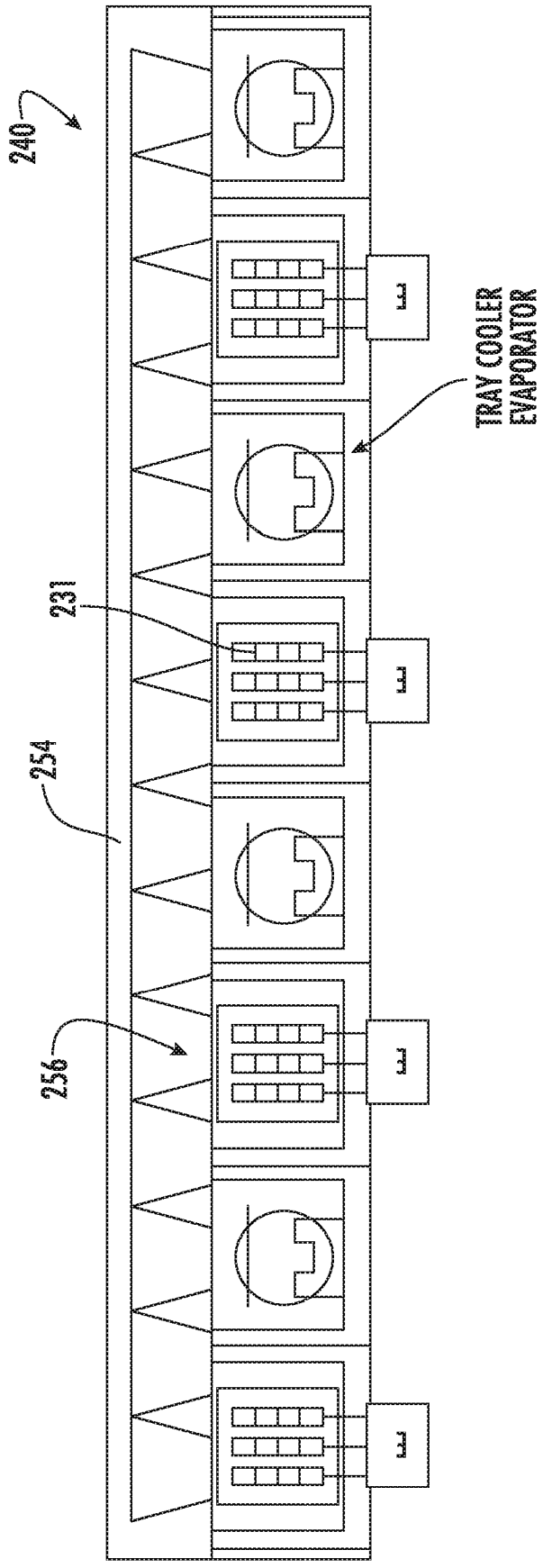

FIG. 6

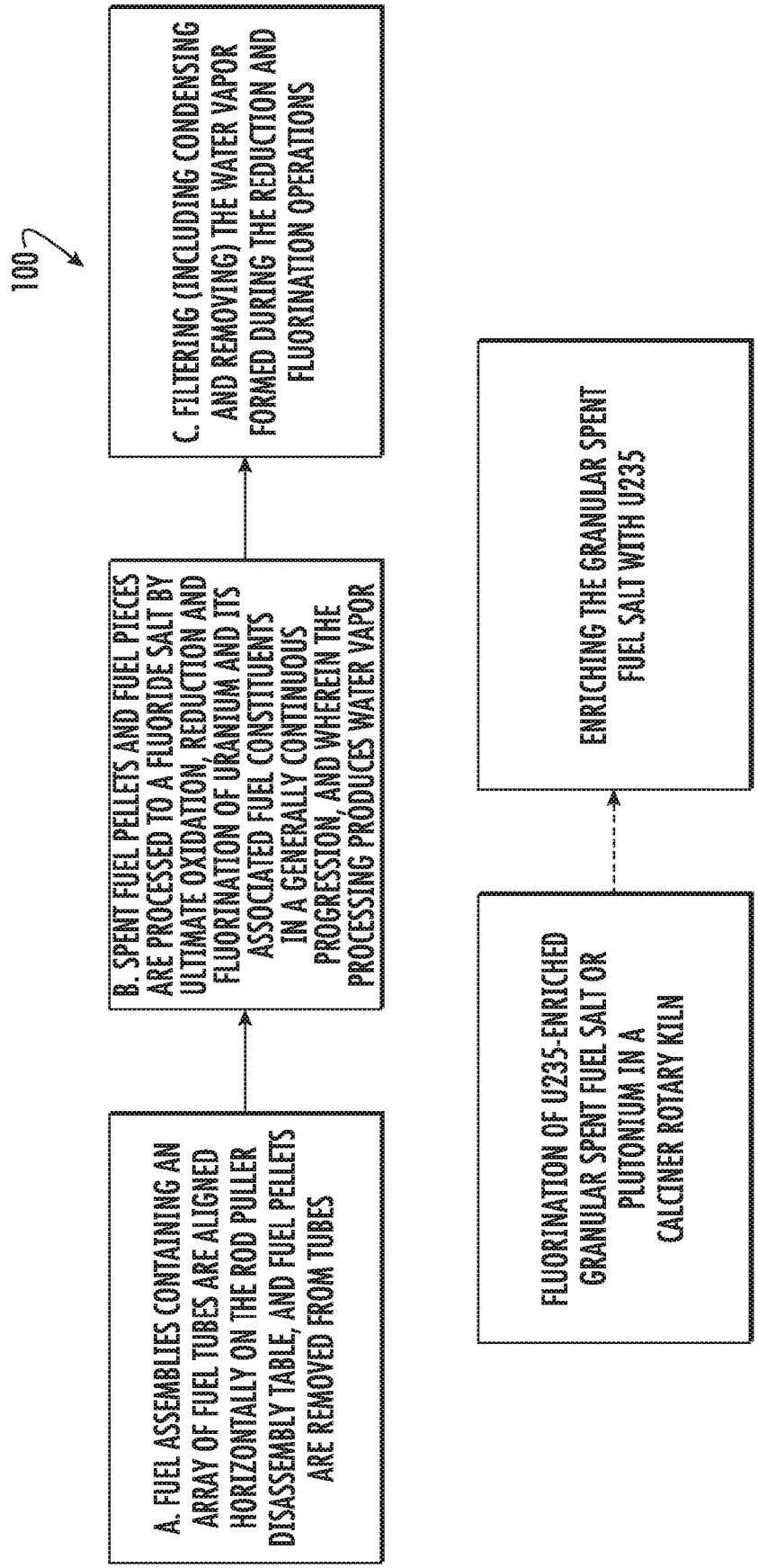
100
A. FUEL ASSEMBLIES CONTAINING AN ARRAY OF FUEL TUBES ARE ALIGNED HORIZONTALLY ON THE ROD PULLER DISASSEMBLY TABLE, AND FUEL PELLETS ARE REMOVED FROM TUBES
B. SPENT FUEL PELLETS AND FUEL PIECES ARE PROCESSED TO A FLUORIDE SALT BY ULTIMATE OXIDATION, REDUCTION AND FLUORINATION OF URANIUM AND ITS ASSOCIATED FUEL CONSTITUENTS IN A GENERALLY CONTINUOUS PROGRESSION, AND WHEREIN THE PROCESSING PRODUCES WATER VAPOR
C. FILTERING (INCLUDING CONDENSING AND REMOVING) THE WATER VAPOR FORMED DURING THE REDUCTION AND FLUORINATION OPERATIONS
FLUORINATION OF U235-ENRICHED GRANULAR SPENT FUEL SALT OR PLUTONIUM IN A CALCINER ROTARY KILN
ENRICHING THE GRANULAR SPENT FUEL SALT WITH U235

FIG. 7

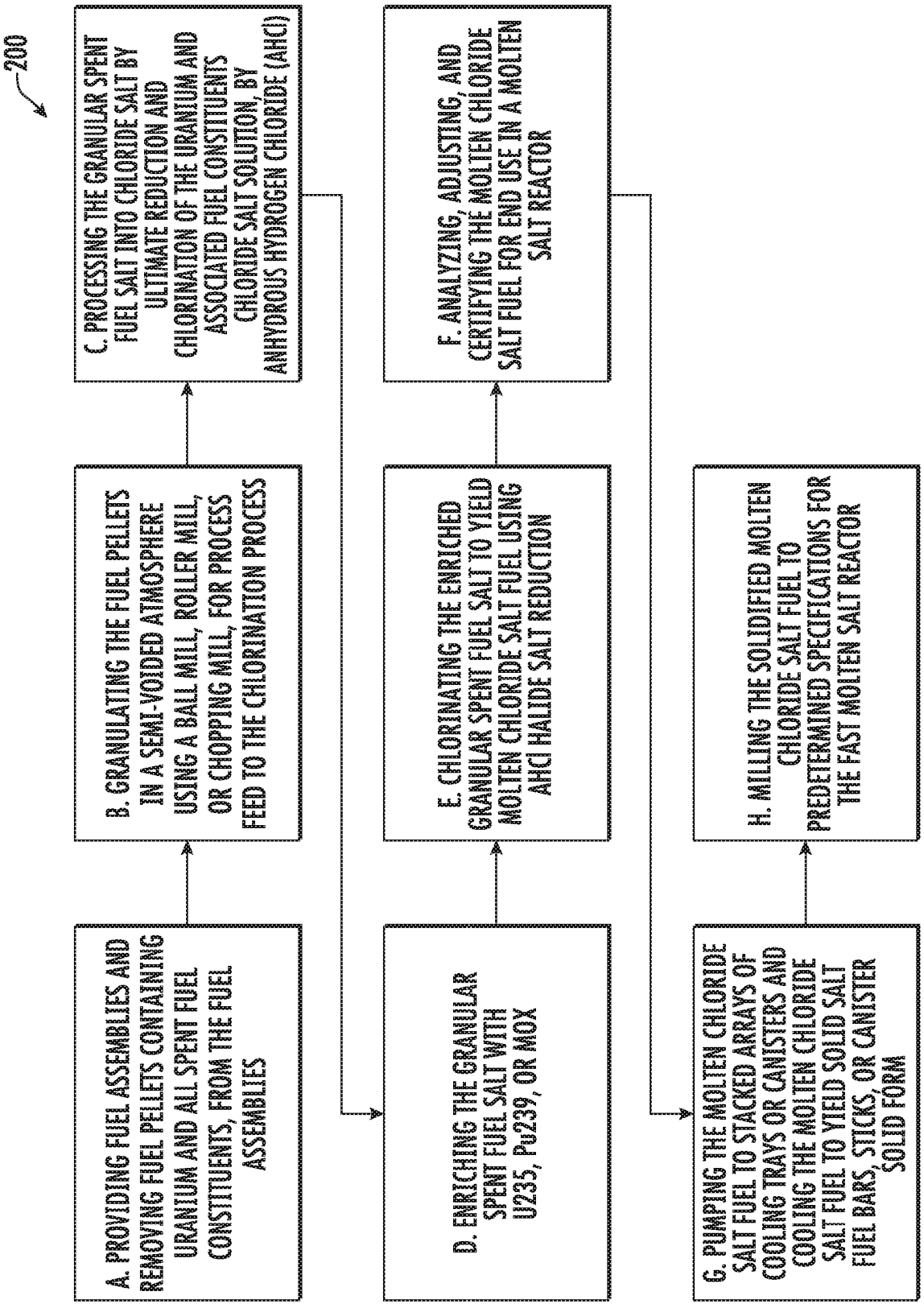
200
A. PROVIDING FUEL ASSEMBLIES AND REMOVING FUEL PELLETS CONTAINING URANIUM AND ALL SPENT FUEL CONSTITUENTS, FROM THE FUEL ASSEMBLIES
B. GRANULATING THE FUEL PELLETS IN A SEMI-VOIDED ATMOSPHERE USING A BALL MILL, ROLLER MILL, OR CHOPPING MILL, FOR PROCESS FEED TO THE CHLORINATION PROCESS
C. PROCESSING THE GRANULAR SPENT FUEL SALT INTO CHLORIDE SALT BY ULTIMATE REDUCTION AND CHLORINATION OF THE URANIUM AND ASSOCIATED FUEL CONSTITUENTS CHLORIDE SALT SOLUTION, BY ANHYDROUS HYDROGEN CHLORIDE (AHCl)
D. ENRICHING THE GRANULAR SPENT FUEL SALT WITH U235, Pu239, OR MOX
E. CHLORINATING THE ENRICHED GRANULAR SPENT FUEL SALT TO YIELD MOLTEN CHLORIDE SALT FUEL USING AHCl HALIDE SALT REDUCTION
F. ANALYZING, ADJUSTING, AND CERTIFYING THE MOLTEN CHLORIDE SALT FUEL FOR END USE IN A MOLTEN SALT REACTOR
G. PUMPING THE MOLTEN CHLORIDE SALT FUEL TO STACKED ARRAYS OF COOLING TRAYS OR CANISTERS AND COOLING THE MOLTEN CHLORIDE SALT FUEL TO YIELD SOLID SALT FUEL BARS, STICKS, OR CANISTER SOLID FORM
H. MILLING THE SOLIDIFIED MOLTEN CHLORIDE SALT FUEL TO PREDETERMINED SPECIFICATIONS FOR THE FAST MOLTEN SALT REACTOR

FIG. 8

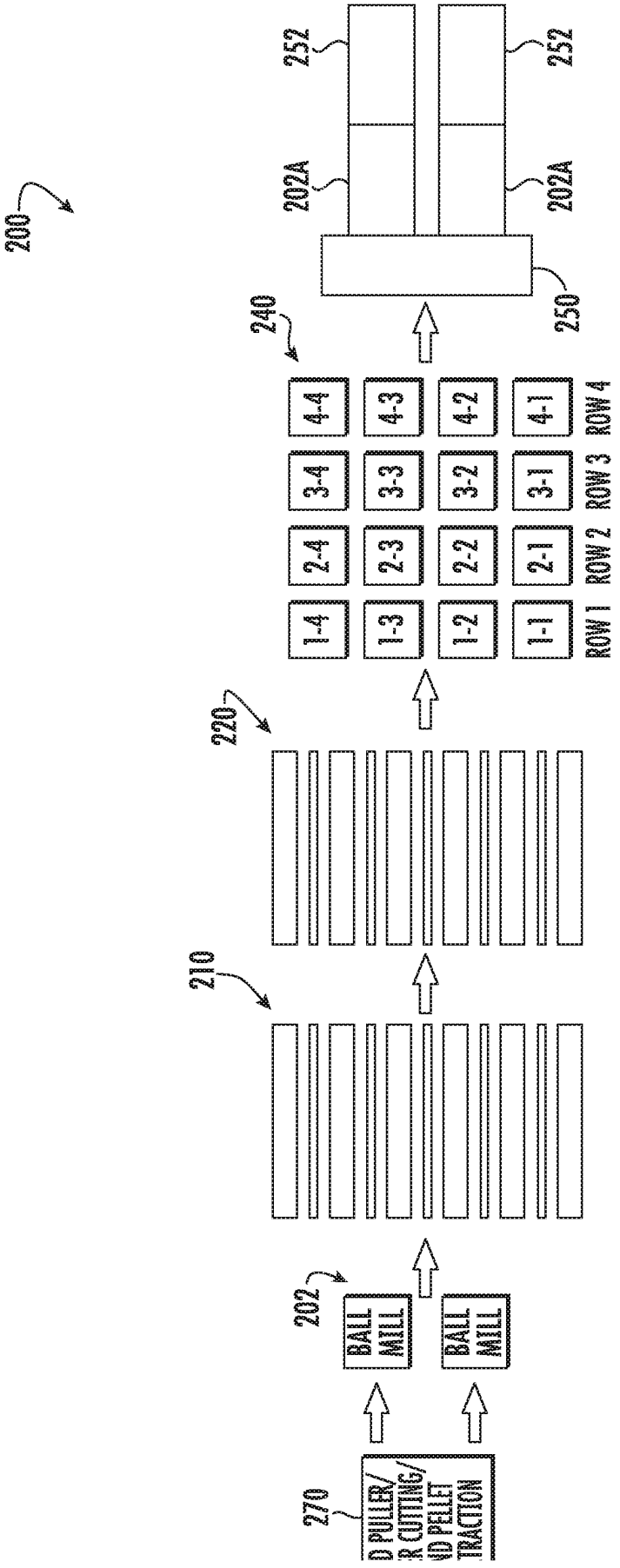
200
252
252
202A
202A
250
240
4-4
4-3
4-2
4-1
3-4
3-3
3-2
3-1
2-4
2-3
2-2
2-1
1-4
1-3
1-2
1-1
ROW 1
ROW 2
ROW 3
ROW 4
220
210
202
BALL MILL
BALL MILL
270
D PULLER/
R CUTTING/
ID PELLET
TRACTION

FIG. 9

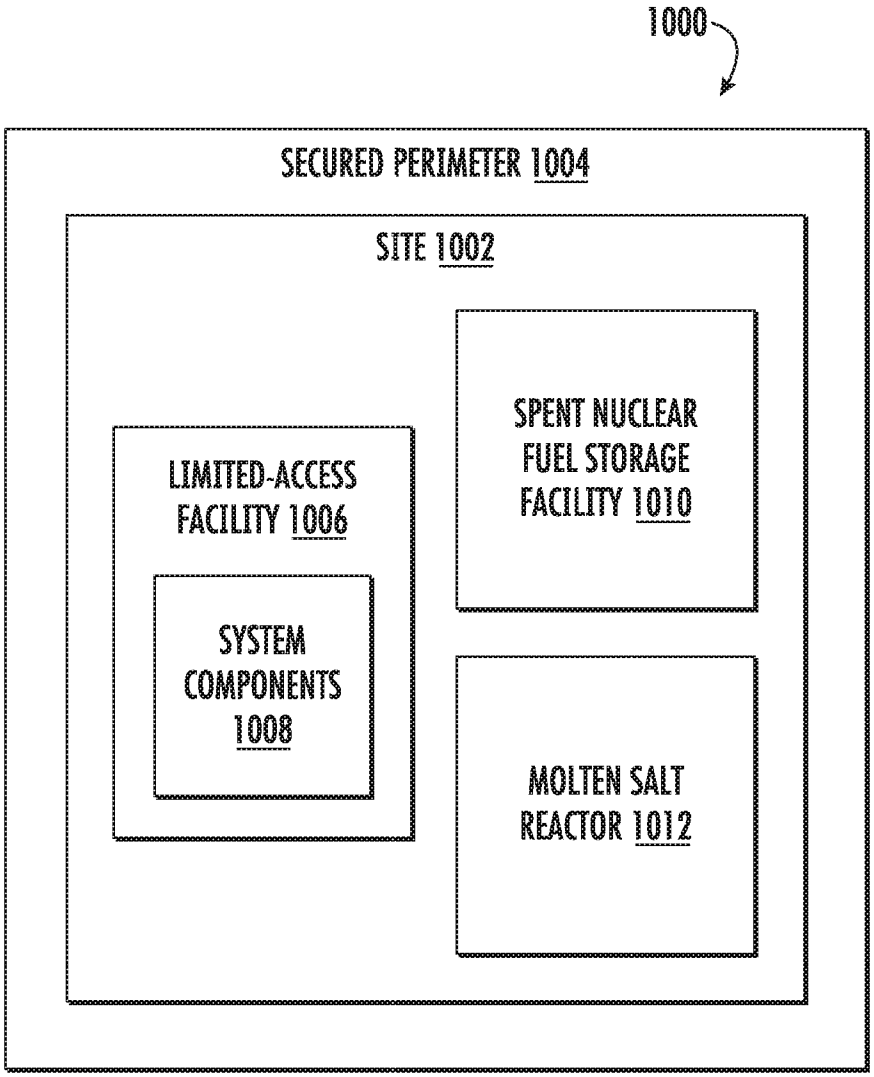
1000
SECURED PERIMETER 1004
SITE 1002
SPENT NUCLEAR FUEL STORAGE FACILITY 1010
LIMITED-ACCESS FACILITY 1006
SYSTEM COMPONENTS 1008
MOLTEN SALT REACTOR 1012

FIG. 10

REFERENCES CITED IN THE DESCRIPTION

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