



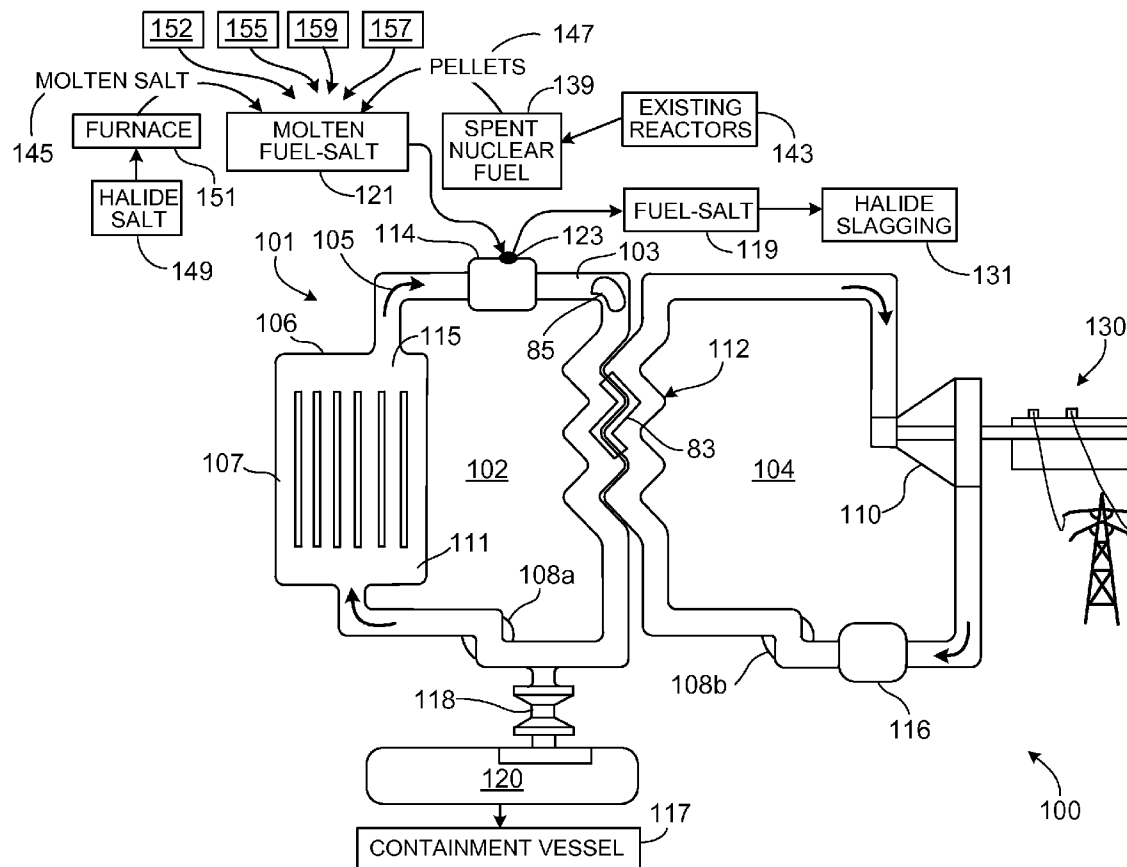
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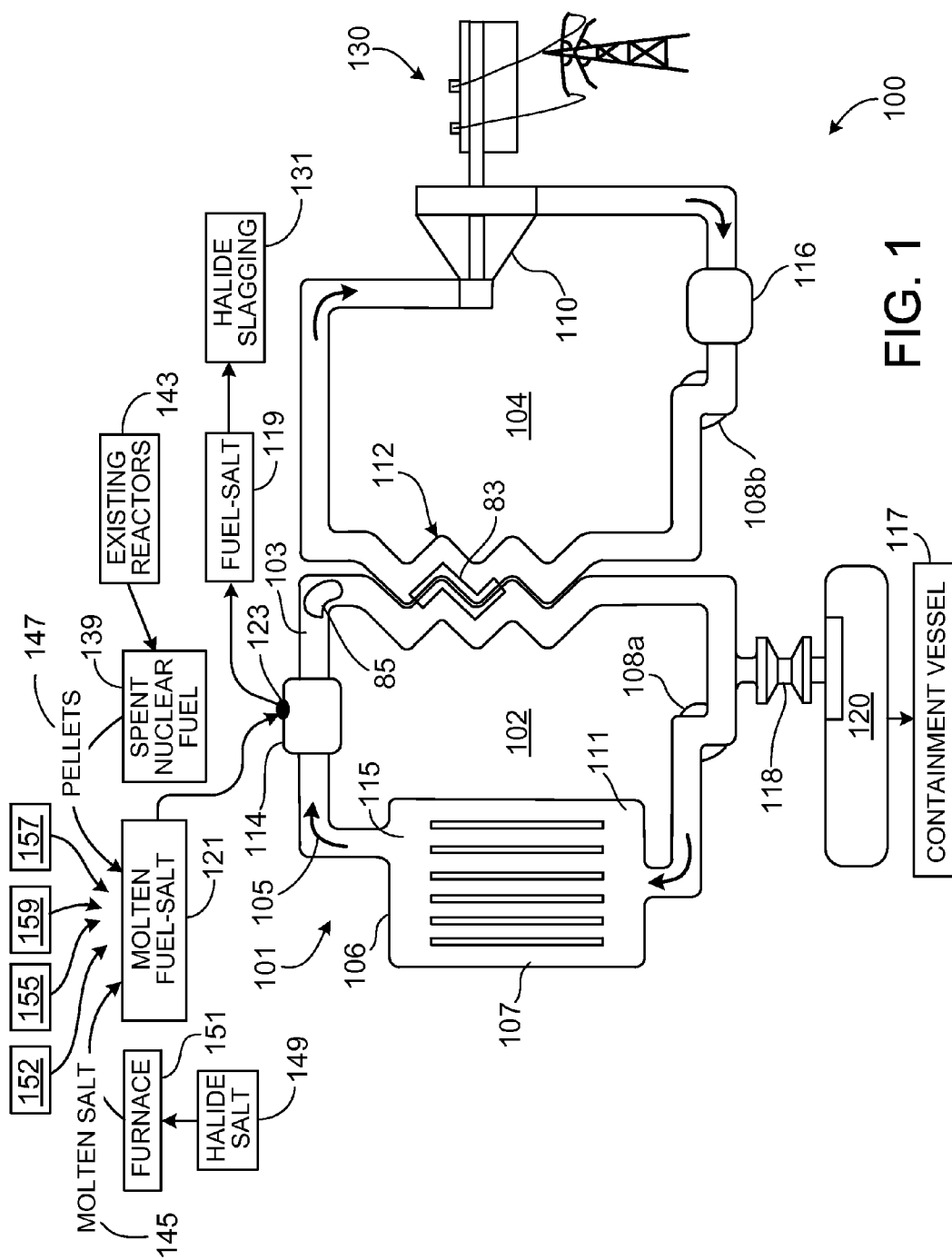
(19) **United States**(12) **Patent Application Publication**
Massie et al.(10) **Pub. No.: US 2013/0083878 A1**(43) **Pub. Date: Apr. 4, 2013**(54) **NUCLEAR REACTORS AND RELATED
METHODS AND APPARATUS***G21C 5/00* (2006.01)*G21C 3/54* (2006.01)*G21C 1/22* (2006.01)*G21C 1/04* (2006.01)(76) Inventors: **Mark Massie**, Cambridge, MA (US);
Leslie C. Dewan, Cambridge, MA (US)(52) **U.S. Cl.**USPC **376/110**; 376/359; 376/347; 376/458;
376/409; 376/264(21) Appl. No.: **13/251,717**(22) Filed: **Oct. 3, 2011****Publication Classification**(51) **Int. Cl.***H05H 3/06* (2006.01)*G21C 19/00* (2006.01)

(57)

ABSTRACT

Among other things, an apparatus includes a combination of a fissionable material, a molten salt, and a moderator material including one or more hydrides, one or more deuterides, or a combination of two or more of them.





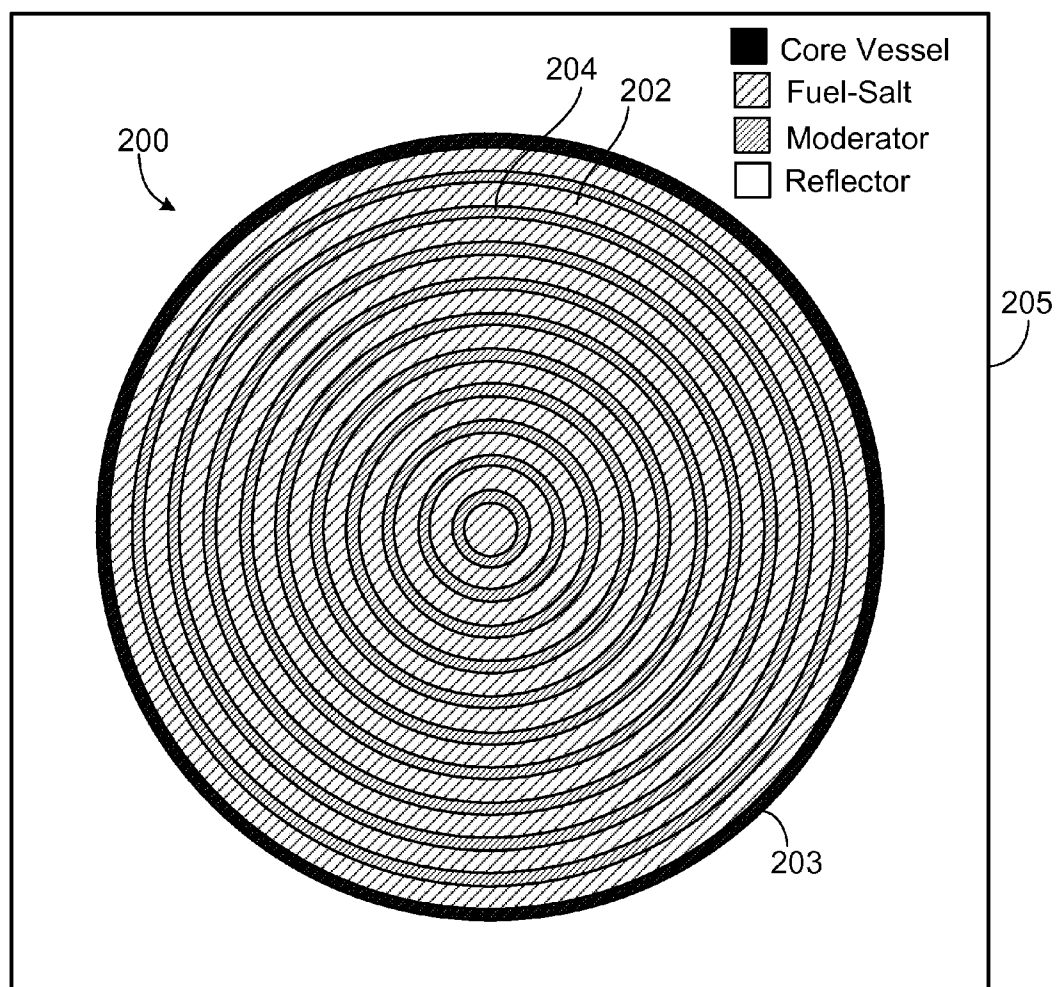
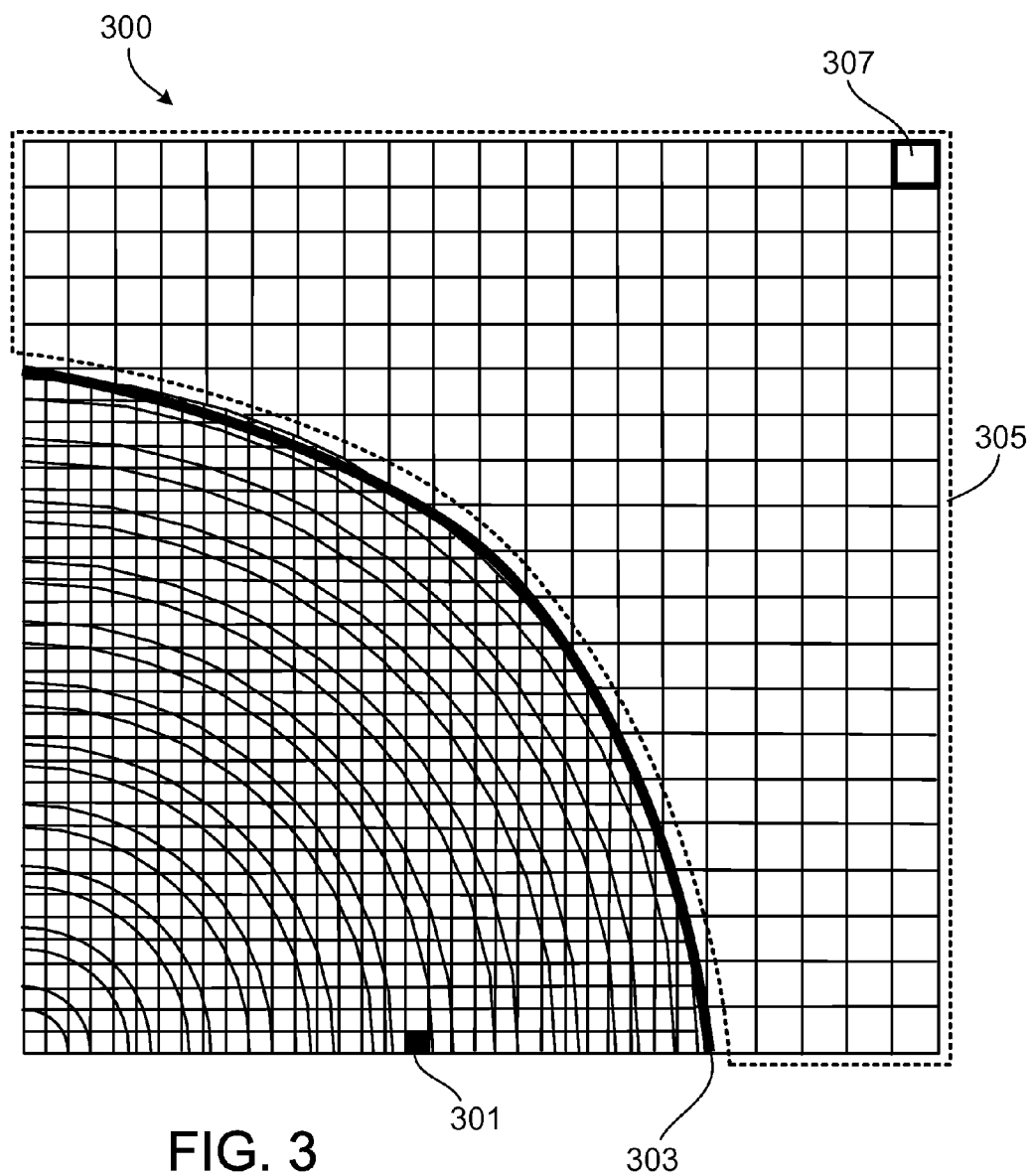


FIG. 2



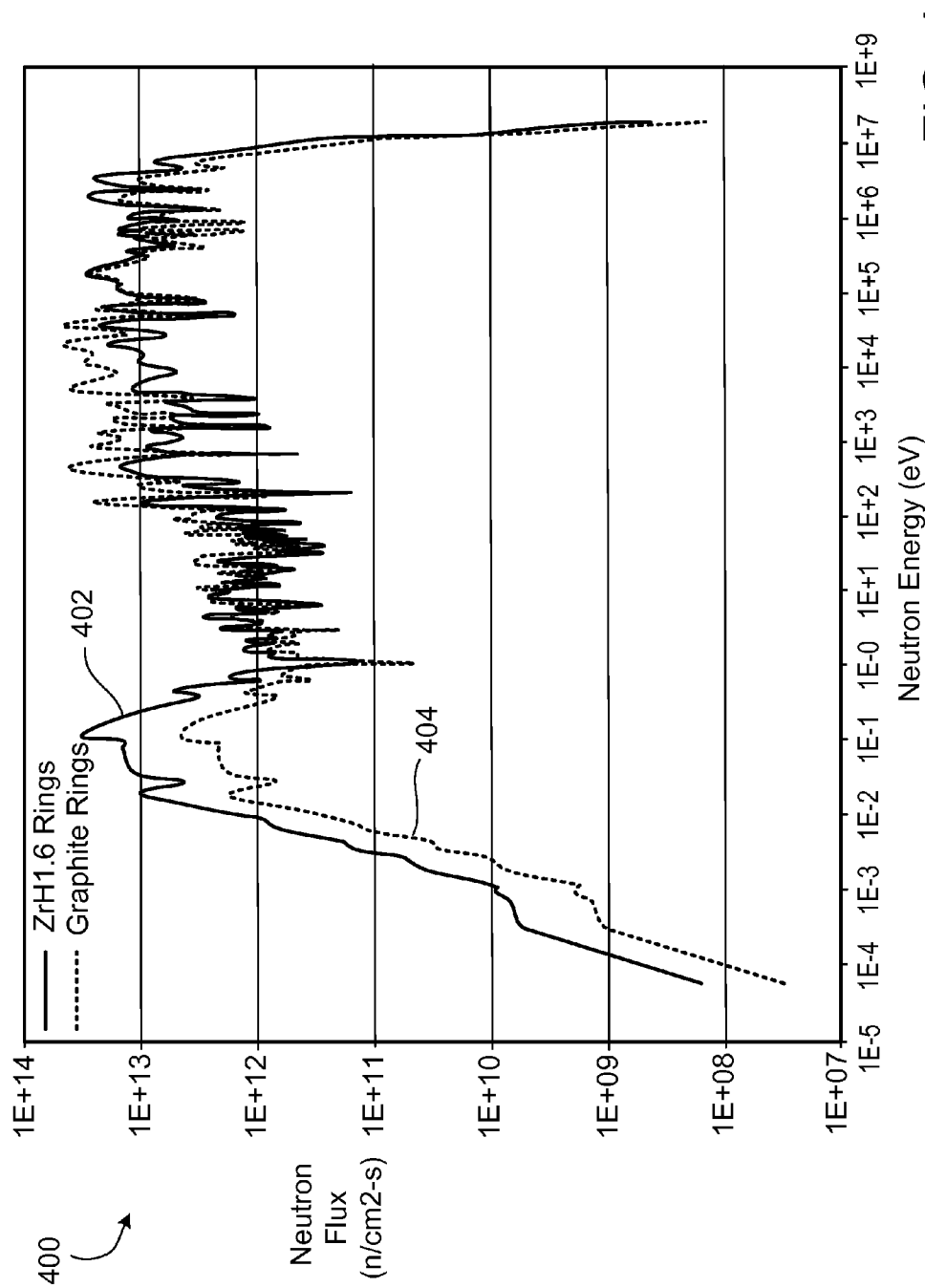


FIG. 4

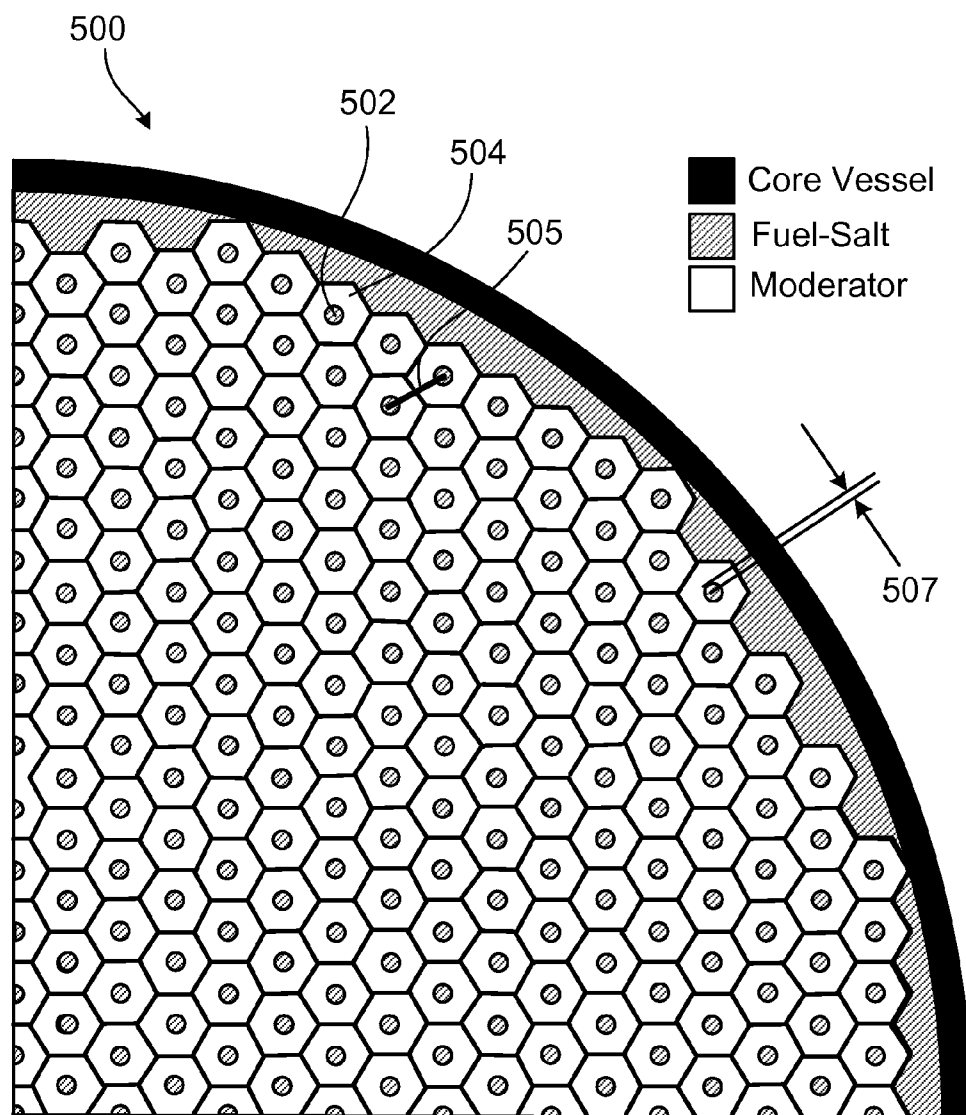


FIG. 5

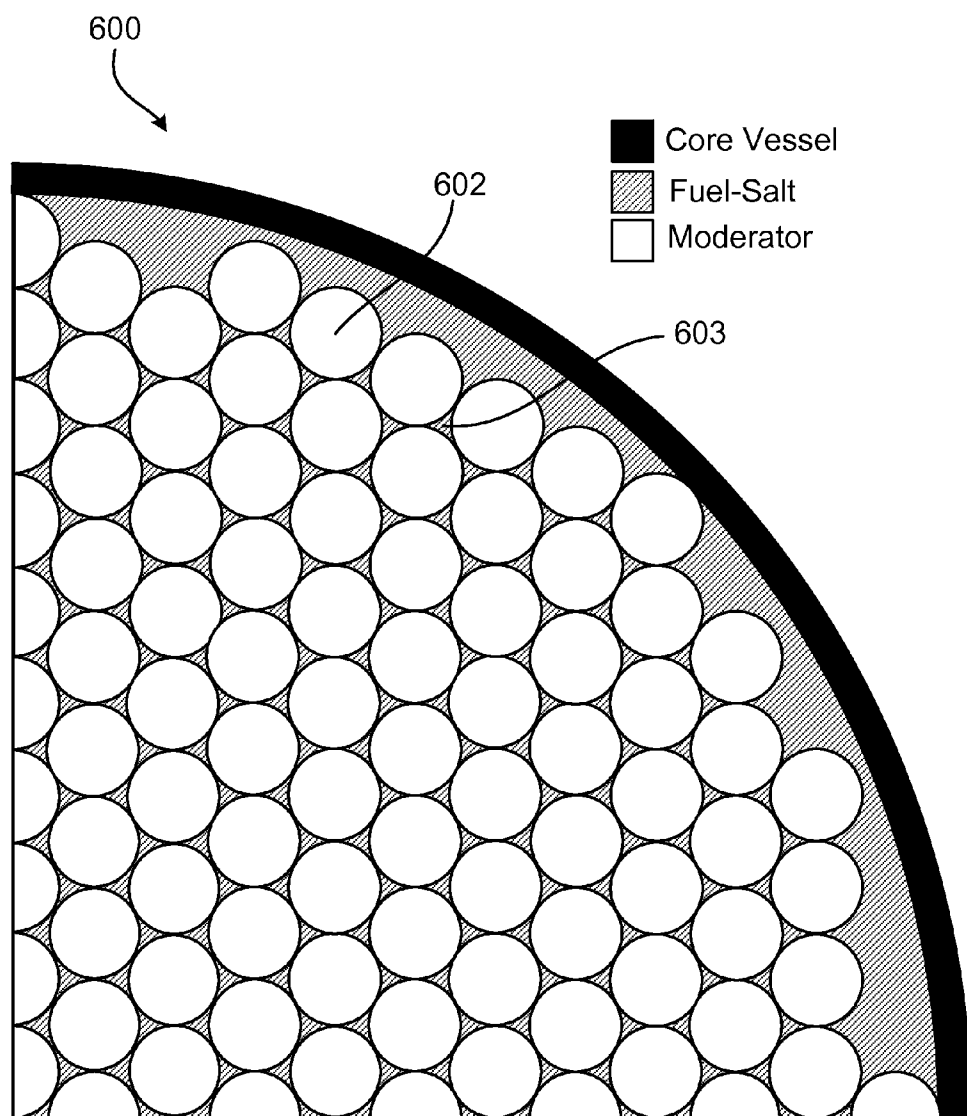


FIG. 6

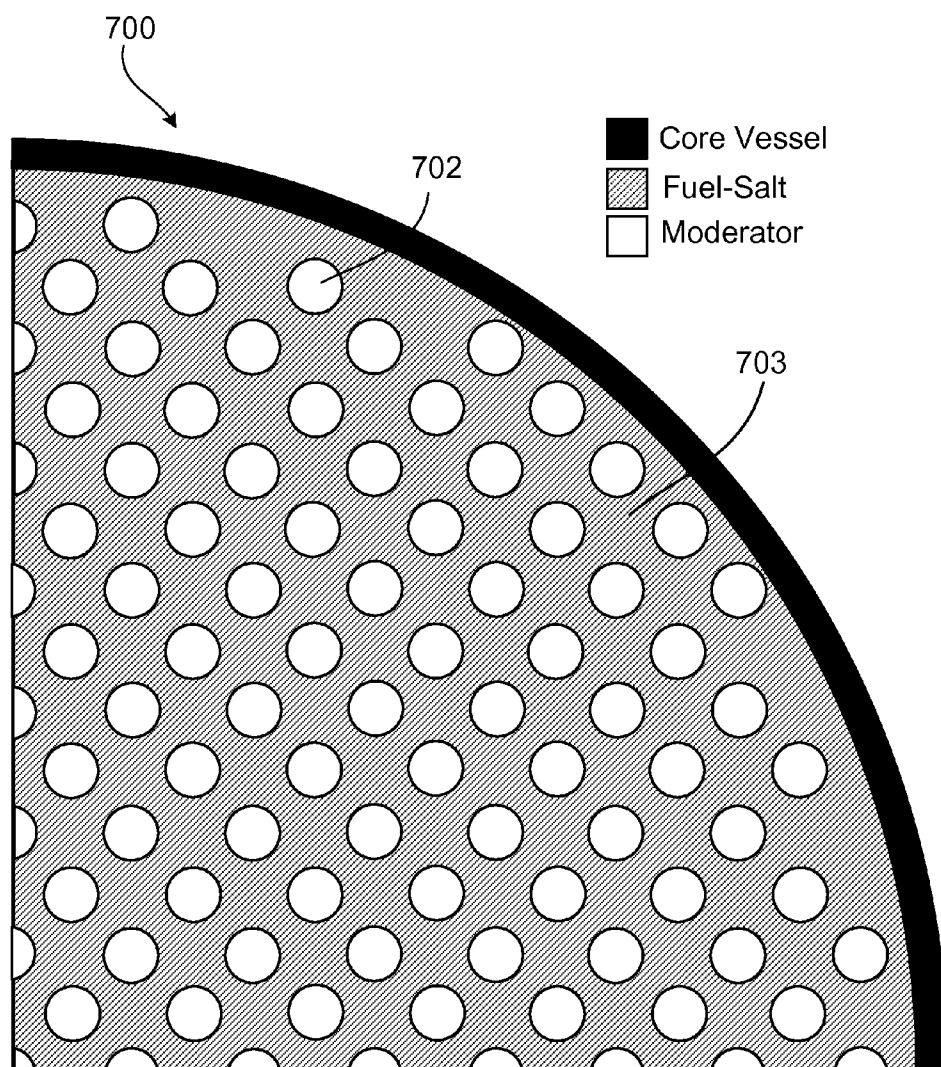


FIG. 7

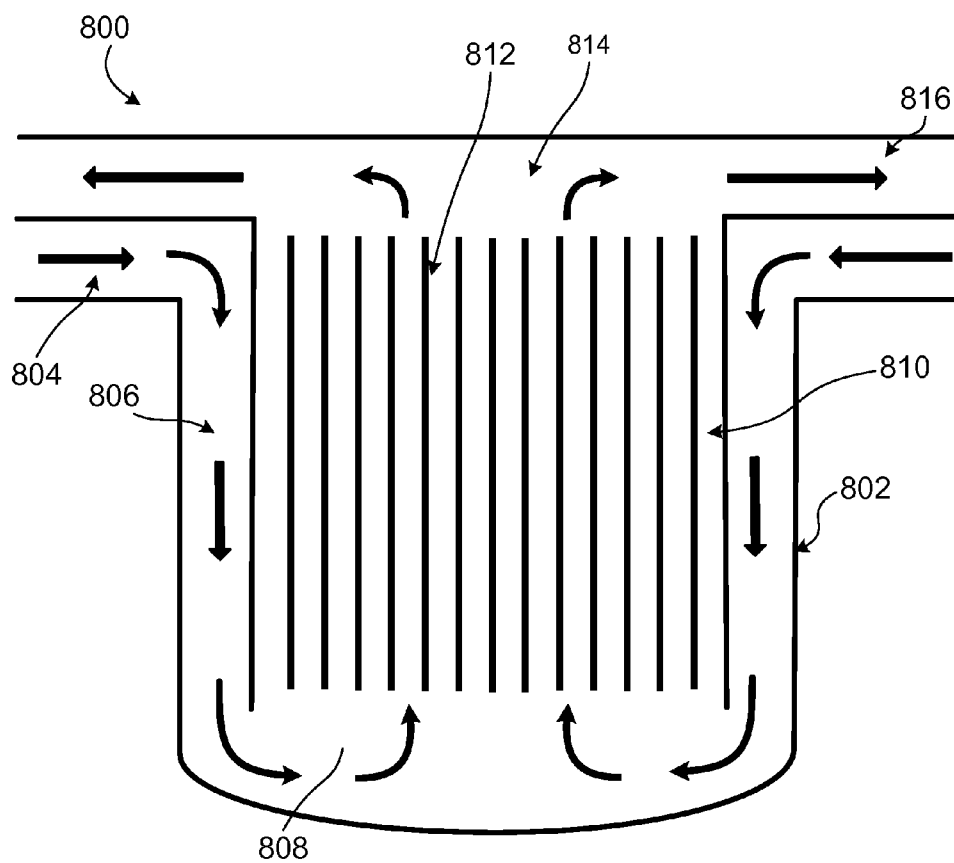


FIG. 8

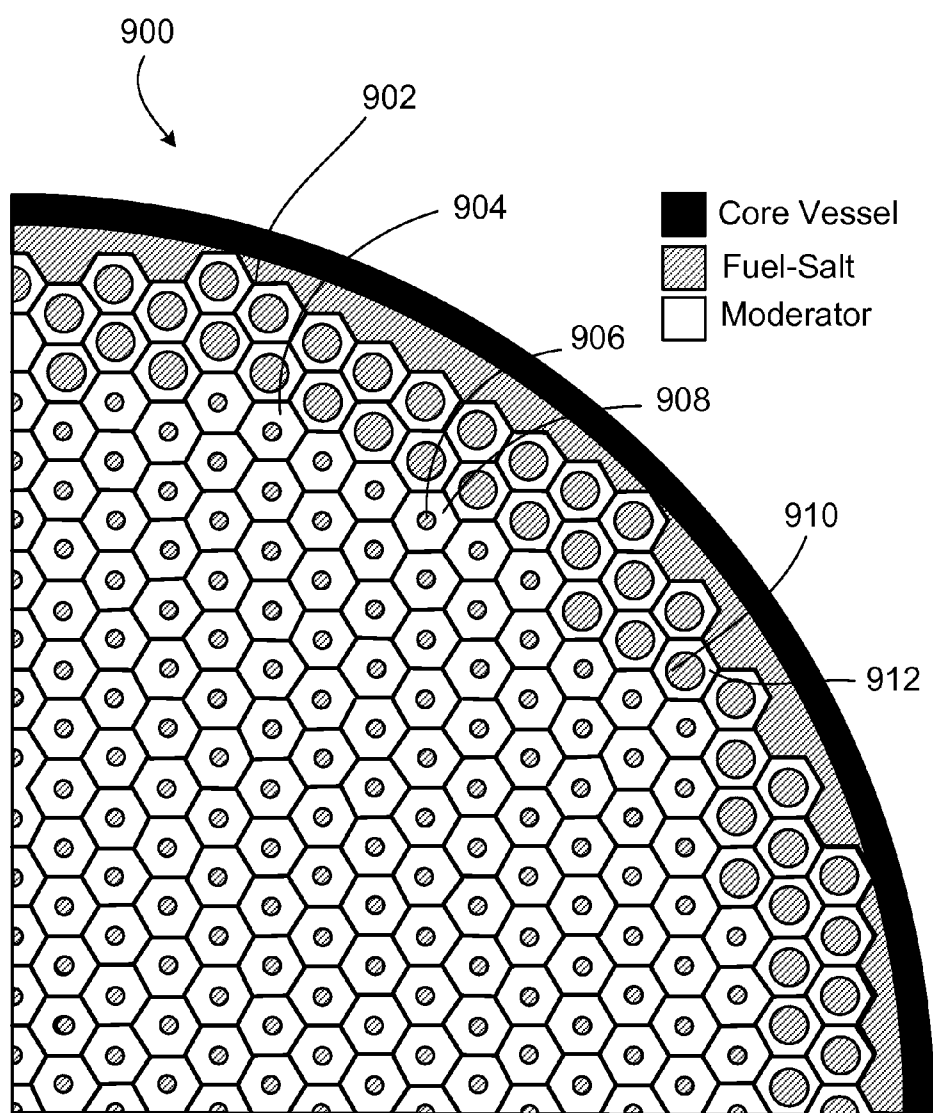


FIG. 9

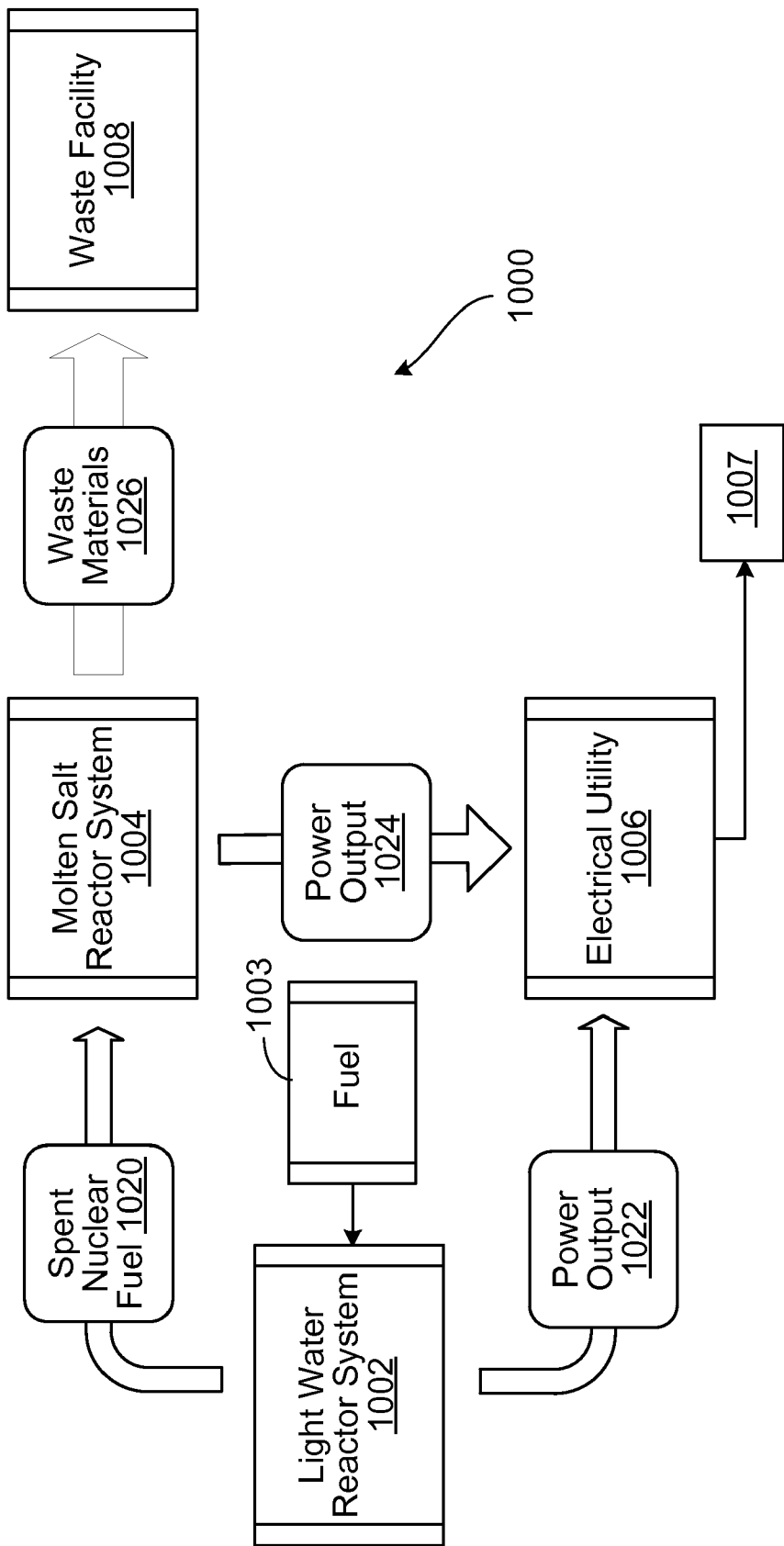


FIG. 10

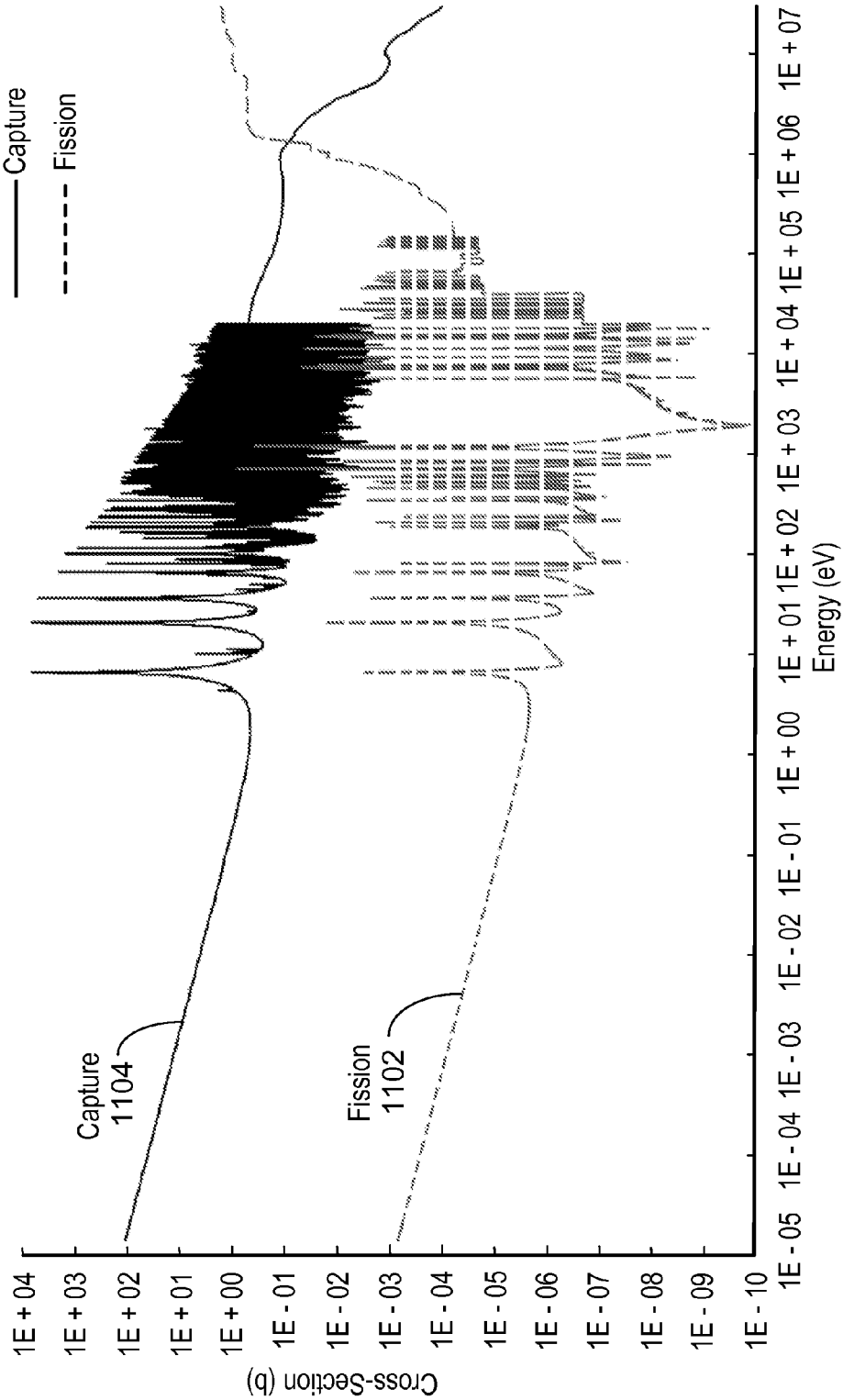


FIG. 11

NUCLEAR REACTORS AND RELATED METHODS AND APPARATUS

BACKGROUND

[0001] This description relates to nuclear reactors and related methods and apparatus.

[0002] A self-sustaining nuclear reaction in nuclear fuel within a reactor core can be used to generate heat and in turn electrical power. In typical molten salt reactors (sometimes called MSR's), the nuclear fuel is dissolved in a molten salt. In some proposed MSR's, the nuclear fuel would include actinides recovered from spent nuclear fuel (sometimes called SNF or simply spent fuel) of other reactors.

SUMMARY

[0003] Broadly, what we describe here is a nuclear reactor method and apparatus that uses molten salt and fissionable material that is typically at least partly spent fuel from another reactor, and a moderator chosen and structured to cause a critical reaction.

[0004] In general, in an aspect, an apparatus includes a fissionable material, a molten salt, and a moderator material including one or more hydrides, one or more deuterides, or a combination of them.

[0005] Implementations may include one or more of the following features. The moderator material includes a metal hydride. The moderator material includes a form of zirconium hydride. The moderator material includes $ZrH_{1.6}$. The moderator material includes a form of lithium hydride. The moderator material includes a form of yttrium hydride, for example, yttrium(II) hydride (YH_2), or yttrium(III) hydride (YH_3), or a combination of them. The moderator material includes a form of zirconium deuteride.

[0006] The fissionable material includes at least portions of spent nuclear fuel of a reactor. The fissionable material includes an entire spent nuclear fuel actinide vector. The fissionable material comprises unprocessed spent nuclear fuel. The fissionable material includes materials other than spent nuclear fuel. The fissionable material includes plutonium or uranium from decommissioned weapons. The fissionable material includes naturally occurring uranium. The fissionable material includes fresh fuel. The fissionable material includes depleted uranium. The fissionable material includes natural uranium, enriched uranium, depleted uranium, plutonium from spent nuclear fuel, plutonium down-blended from excess nuclear weapons materials, thorium and a fissile material, transuranic material, or a combination of any two or more of them. The fissionable material includes a fissile-to-fertile ratio in the range of 0.01-0.25. The fissionable material includes at least one of U-233, U-235, Pu-239, or Pu-241. The fissionable material also includes U-238. The fissionable material also includes thorium.

[0007] The molten salt includes a fluoride salt. The molten salt includes a chloride salt. The molten salt includes an iodide salt. The molten salt includes lithium fluoride. The lithium fluoride is enriched in its concentration of Li-7 (which has a lower thermal neutron capture cross section than Li-6). The solubility of actinides in the molten salt is sufficient to permit the fissionable material to become critical. The solubility of actinides in the molten salt is at least 0.3%. The solubility of actinides in the molten salt is at least 12%. The solubility of actinides in the molten salt is at least 20%. The molten salt includes essentially no beryllium. The molten salt

includes an amount of beryllium. The fissionable material is combined with the molten salt. The fissionable material and the molten salt are distinct from the moderator. The salt provides moderation.

[0008] In general, in an aspect, an apparatus includes a fissionable material including spent nuclear fuel of a reactor combined with a molten lithium fluoride salt that is essentially free of beryllium, and a zirconium hydride moderator that is distinct from the combined fissionable material and salt.

[0009] In general, in an aspect, a nuclear reaction moderator structure includes a hydride or deuteride and one or more passages for molten salt fuel to flow through or around the structure or both, the structure being configured so that the molten salt fuel is in a critical state while in the structure.

[0010] Implementations may include one or more of the following features. The moderator material includes a metal hydride. The moderator material includes a form of zirconium hydride. The moderator material includes $ZrH_{1.6}$. The moderator material includes a form of lithium hydride. The moderator material includes a form of yttrium hydride, for example, yttrium(II) hydride (YH_2), or yttrium(III) hydride (YH_3), or a combination of them. The moderator material comprises a form of zirconium deuteride.

[0011] There are at least two such passages. The plates are separated by the passages. There are at least two such passages in parallel. One or more of the passages are tubular. The structure includes three-dimensional discrete structural elements each of which has an extent in each of the three dimensions that is smaller than the extent of the structure. The discrete structural elements are arranged in the structure with the passage or passages between the discrete structures or within the discrete structures or both. The structure includes balls, or spheres, or pebbles, or a combination of any two or more of them, arranged in three dimensions. The structure includes an integral block of moderator material in which the passages are formed. The structure includes a set of discrete elements. The discrete elements are identical.

[0012] The structure has an entry end and an exit end, and the passage or passages extend from the entry end to the exit end. The structure includes rods. The rods include at least one of cylinders, annular rods, finned rods, helical rods, twisted helical rods, annular helical rods, annular twisted helical rod, rods with wire wrapped spacers, or annular rods with wire wrapped spacers, or a combination of two or more of them. The structure includes reactivity control elements that are movable relative to the structure.

[0013] In general, in an aspect, in a nuclear reactor, fissionable material and a molten salt flow past a moderator material that includes one or more hydrides, deuterides, or a combination of two or more of them.

[0014] Implementations may include one or more of the following features. The flowing of the fissionable material and the molten salt past the moderator material includes flowing the fissionable material and the molten salt as a mixture. The mixture flows through a fission product removal system. The fuel-salt mixture flows through a heat exchanger. The fissionable material includes an entire spent nuclear fuel actinide vector. The fissionable material comprises portions but not all of the actinides of spent nuclear fuel. The fissionable material comprises unprocessed spent nuclear fuel.

[0015] In general, in an aspect, a nuclear reactor moderator structure is formed of a moderator material that includes one

or more hydrides, deuterides, or a combination of them, and one or more passages for fissionable fuel to flow through the structure.

[0016] In general, in an aspect, a nuclear reactor includes a primary loop having a reactor core. The reactor core includes a moderator structure having a moderator material that includes one or more hydrides, deuterides, or a combination of them, and a pathway along which a fissionable material and molten salt can flow from an exit end of the moderator structure in a loop to an entrance end of the moderator structure.

[0017] Implementations may include one or more of the following features. The reactor includes a secondary loop and a heat exchanger to exchange heat between the primary loop and the secondary loop. The reactor includes an intermediate loop, a secondary loop, a heat exchanger to exchange heat between the primary loop and the intermediate loop, and an additional heat exchanger to exchange heat between the intermediate loop and the secondary loop. The reactor includes a freeze valve.

[0018] In general, in an aspect, a nuclear reactor is constructed by connecting a moderator structure, including a moderator material that includes one or more hydrides, deuterides, or a combination of them, to a pathway along which a fissionable material and molten salt can flow from an exit end of the moderator structure to an entrance end of the moderator structure, to form a primary loop.

[0019] In general, in an aspect, a nuclear reactor fuel includes spent fuel of a light water reactor in a molten salt in which solubility of actinides of the spent fuel, in the molten salt, is sufficient to permit the fissionable material to become critical.

[0020] Implementations may include one or more of the following features. The spent fuel includes an entire spent nuclear fuel actinide vector. The spent fuel comprises unprocessed spent nuclear fuel. The molten salt includes essentially no beryllium.

[0021] In general, in an aspect, a nuclear reaction fuel is formed by mixing spent fuel of a light water reactor with a molten salt; the solubility of actinides of the spent fuel, in the molten salt, is sufficient to permit the fissionable material to become critical. In some implementations, the spent fuel includes an entire spent nuclear fuel actinide vector; and the spent fuel comprises unprocessed spent nuclear fuel. The fissionable material comprises portions but not all of the actinides of spent nuclear fuel.

[0022] In general, in an aspect, a light water reactor is operated, spent nuclear fuel is recovered from the light water reactor, the recovered spent nuclear fuel is combined with molten salt, and a molten salt reactor is operated using the recovered spent nuclear fuel with molten salt.

[0023] Implementations may include one or more of the following features. The spent nuclear fuel comprises an entire spent nuclear fuel actinide vector. The spent nuclear fuel comprises unprocessed spent nuclear fuel. The fissionable material comprises portions but not all of the actinides of spent nuclear fuel.

[0024] In general, in an aspect, supplies of existing spent nuclear fuel are reduced by operating a molten salt nuclear reactor using, as fuel, spent nuclear fuel, without processing, from another reactor.

[0025] In general, in an aspect, electricity is generated using existing spent nuclear fuel by operating a molten salt nuclear reactor using, as fuel, spent nuclear fuel, without processing, from another reactor.

[0026] In general, in an aspect, supplies of nuclear weapons material are reduced by operating a molten salt nuclear reactor using, as fuel, spent nuclear fuel, without processing, from another reactor.

[0027] In general, in an aspect, supplies of existing spent nuclear fuel are reduced by operating a molten salt nuclear reactor using, as fuel, spent nuclear fuel, without processing, from another reactor.

[0028] Implementations may include one or more of the following features. The fluid includes a molten salt mixture.

[0029] In general, in an aspect, a combination of a reactor that includes nuclear fuel and a molten salt coolant that is distinct from the fuel, and moderator elements including one or more hydrides or deuterides.

[0030] Implementations may include one or more of the following features. At least one of the hydrides comprises a metal hydride. The moderator elements comprise graphite in combination with the one or more hydrides.

[0031] In general, in an aspect, a combination of a reactor that includes a nuclear fuel in a sub-critical state and an accelerator driven source of neutrons in proximity to the nuclear fuel, and moderator elements comprising one or more hydrides or deuterides.

[0032] Implementations may include one or more of the following features. The accelerator driven source comprises a heavy metal target. The moderator elements are in proximity to the heavy metal target. The moderator elements are in proximity to the nuclear fuel. The fuel comprises thorium. The fuel comprises spent nuclear fuel. The fuel comprises transuranic materials from spent nuclear fuel. The fuel comprises minor actinides from spent nuclear fuel.

[0033] These and other aspects, features, and implementations, can be expressed as apparatus, methods, compositions, methods of doing business, means or steps for performing functions, and in other ways.

[0034] Other aspects, features, implementations, and advantages will become apparent from the following description, and from the claims.

DESCRIPTION

[0035] FIG. 1 is schematic diagram.

[0036] FIGS. 2, 5, 6, 7, 8, and 9 are sectional views of reactor cores.

[0037] FIG. 3 is a schematic diagram associate with a simulation.

[0038] FIG. 4 is a graph of neutron flux.

[0039] FIG. 10 is a flow chart.

[0040] FIG. 11 is a graph of cross sections.

[0041] Among other things, implementations of what we describe here hold promise for producing electricity safely at relatively low cost using the spent nuclear fuel (in some cases without further processing) from existing nuclear reactors and using elements of nuclear reactor technology that have been tried or are considered feasible. The nuclear reactor that we propose to use to generate the electricity renders the spent fuel into a state that is much less problematic from an environmental and disposal perspective—the nuclear reactions that occur in the reactor induce fission in the majority of the actinides comprising the spent fuel, reducing their radioactive half-lives. At least some implementations of what we describe here modify previously developed molten salt reactor technology to enable the use of spent fuel from other reactors.

[0042] In at least some of the implementations, an important feature of the modified molten salt reactor is that the molten fuel-salt mixture includes all of the material that is contained in the spent nuclear fuel. When we refer to spent fuel, SNF, or spent nuclear fuel, we mean all of the fuel material that is in a spent fuel assembly except for the cladding material, which is not technically part of the spent fuel. In effect, at least in some of the implementations, the reactor core uses all of the spent fuel without requiring any separation or other manipulation.

[0043] Also, in at least some of the implementations, an important feature is that a form of zirconium hydride (ZrH_x , where x may range from 1 to 4) is used as a moderator. In some cases, the zirconium hydride moderator is used as part of the elements that form a stationary reactor core. In some cases, the zirconium hydride moderator is used in movable moderator elements that can be inserted into and removed from the reactor core. In some cases, the zirconium hydride moderator is used in both the stationary reactor core and the moderator elements. The zirconium hydride can be more effective than other moderators in producing neutrons having appropriate energy levels to enable the spent fuel, which otherwise might be unable to do so, to become critical within the reactor core. In some cases, the fixed or moveable or both moderator elements can be one or more hydrides. In some cases, the elements can be one or more deuterides. In some cases, the elements can be a combination of hydrides or deuterides.

[0044] Although some of the implementations that we describe here contemplate combinations of molten salt reactors that use the spent fuel and highly effective moderators such as zirconium hydride, in some implementations, it may not be necessary to include all of these features together in a single facility.

[0045] FIG. 1 is a schematic diagram of an example nuclear reactor power plant 100 that includes a nuclear reactor core 106 in a primary loop 102. A molten (liquid) fuel-salt mixture 103 is circulated 105 continuously within the primary loop 102, including through the reactor core 106. The primary loop is charged with enough fuel-salt mixture to fill the loop, including the reactor core. The portion of the fuel-salt mixture that is in the reactor core at a given time is in a critical configuration, generating heat. (Fuel that has passed out of the reactor core and is in the rest of the loop is not in a critical configuration.) While the fuel-salt mixture is in this critical configuration in the reactor core, neutrons induce fission in the actinides, generating heat, and turning the actinides into fission products.

[0046] The salt (we sometimes use the simple word salt interchangeably with fuel-salt mixture or fuel) travels through the primary loop at a fast mass flow rate—in some implementations; this rate is approximately 800 kilograms per second. In some implementations, the rate could be higher than 800 kilograms per second or lower than 800 kilograms per second. The salt is moved quickly, because a large amount of heat is generated in the salt by the fissioning actinides in the reactor core 106, and the heat carried in this hot salt must be moved rapidly to the heat exchanger 112.

[0047] Because the salt is traveling so quickly, only a small fraction of the actinides are fissioned in the reactor core during each pass through the loop. The actinides, however, pass many times through the reactor core. In some cases, after 10 years' worth of passes through the reactor core, for

example, approximately 30% of a given initial amount of actinides may be turned into fission products.

[0048] The actinides dissolved in the fuel-salt mixture 103 can be a wide variety of actinides and combinations of actinides and can originate from a wide variety of sources and combinations of sources. In some implementations, for example, the actinides can be from spent nuclear fuel 139 generated by existing nuclear reactors 143. In some implementations, the actinides originate from decommissioned weapons 152 and include plutonium and/or uranium. In some examples, the sources can include natural uranium 155. In some examples, the sources can include depleted uranium 159 (left over from an enrichment process). In some examples, the sources can include fresh fuel 157 (which may encompass uranium enriched in U-235, or a mixture of fertile thorium and a fissile matter such as U-233, U-235, Pu-239, or Pu-241). In some examples, the sources can include a combination of any two or more of fresh fuel 157, decommissioned weapons plutonium or uranium 152, natural uranium 155, depleted uranium 159, or spent nuclear fuel 139.

[0049] The distribution of energy levels of neutrons in the reactor core affects the efficiency with which actinide fissioning occurs in the fuel-salt mixture in the core.

[0050] A cross section is a measure of the probability of a certain reaction occurring when a neutron interacts (e.g., collides) with a nucleus. For example, an absorption cross section measures the probability that a neutron will be absorbed by a nucleus of a particular isotope if it is incident upon that nucleus. Every isotope has a unique set of cross sections, which vary as a function of an incident neutron's kinetic energy.

[0051] The distribution of kinetic energies in a system's neutron population is represented, for example, by a neutron energy spectrum. Neutrons produced during a fission reaction have, on average, initial kinetic energies in the "fast" region of the neutron energy spectrum. Fast neutrons have kinetic energies greater than, for example, 10 keV. Epithermal neutrons have kinetic energies between, for example, 1 eV and 10 keV. Thermal neutrons have kinetic energies of, for example, approximately 0.025 eV. In the context of nuclear reactors, thermal neutrons more broadly refer to those with kinetic energies below, for example, 1 eV.

[0052] In some implementations, it is desirable for the reactor core (including the fuel-salt mixture in the core) to have a neutron energy spectrum comprising a large thermal neutron population, because in many cases thermal neutrons induce fission in actinides more readily than do fast neutrons. Decreasing the population of thermal neutrons in the reactor core reduces the rate of actinide fission in the reactor core.

[0053] The choice of salts to be used for the fuel-salt mixture depends, among other things, on the effect that the salt may have on the energy levels of neutrons within the mixture.

[0054] Several different factors should be taken into consideration when choosing a salt composition for a molten salt reactor. Important considerations are: the solubility of the heavy nuclei in the salt (generally, higher solubilities are better), neutron capture cross-section of the isotopes comprising the salt (generally, a lower capture cross-section is better), and moderating ability of the isotopes comprising the salt (generally, a higher moderating ability is better).

[0055] Heavy nuclide solubility depends on the chemical composition of the salt (e.g., lithium fluoride has a higher heavy nuclide solubility than potassium fluoride). In some implementations, preferred salt compositions are ones with

higher heavy nuclide solubilities. According to our analysis, several salt compositions (detailed in the following section) have heavy nuclide solubilities sufficiently high to allow the fuel-salt mixture in the reactor core to remain critical. How high the solubility needs to be depends on the fuel that is being used. In simulations based on a model with ten $\text{ZrH}_{1.6}$ rings (discussed in more detail later) and using fresh fuel enriched to 20% U-235, 0.35% heavy nuclide solubility was sufficient. A previously proposed molten salt breeder reactor design had planned to use a salt with 12% heavy nuclides. Using the entire spent fuel actinide vector in systems described here, we estimate a need for at least 20% solubility. All percentages are expressed in mol %.

[0056] The neutron capture cross section depends on the isotopic composition of the particular one or more species in the salt. Li-7 has a lower neutron capture cross section than Li-6, and is therefore likely to be a better lithium isotope for the lithium fluoride salt, when a lithium fluoride salt is being used). Chloride salts are, in general, expected to be less useful than fluoride salts because chlorine is comprised primarily of Cl-35, which has a high neutron capture cross section. As explained in subsequent sections, in the salts that are considered for use, the other component could advantageously include lighter elements such as lithium, which have a greater moderating ability than heavier elements such as chlorine.

[0057] In some implementations, the fuel-salt mixture **103** comprises a molten halide salt (e.g., $\text{LiF}-(\text{Heavy Nuclide})\text{F}_x$). In the preceding and subsequent chemical formulas, a heavy nuclide may be, for example, a lanthanide, or may be an actinide, or may be some combination of the two. There are at least three general classes of halide salts that can be used in molten salt reactors: chloride salts can be used, fluoride salts can be used, and iodide salts can be used, or a combination of any two or more of them can be used. In some implementations, there may be advantages to using fluoride salts in the nuclear reactor system **100**. (As mentioned earlier, for example, the isotope Cl-35, which has a natural abundance of 75.55% in naturally occurring chloride salts, has a high thermal neutron absorption cross section. A chloride salt, by contrast, therefore reduces the number of thermal neutrons in the reactor core's neutron energy spectrum.)

[0058] Suitable salt compositions may include each of the following taken individually, and combinations of any two or more of them: $\text{LiF}-(\text{Heavy Nuclide})\text{F}_x$, $\text{NaF}-\text{BeF}_2-(\text{Heavy Nuclide})\text{F}_x$, $\text{LiF}-\text{NaF}-(\text{Heavy Nuclide})\text{F}_x$, $\text{NaF}-\text{KF}-(\text{Heavy Nuclide})\text{F}_x$, and $\text{NaF}-\text{RbF}-(\text{Heavy Nuclide})\text{F}_x$. Example compositions using these species may include each of the following or combinations of any two or more of them: 8.5 mol % $(\text{Heavy Nuclide})\text{F}_x$ -34 mol % NaF -57.5 mol % BeF_2 , 12 mol % $(\text{Heavy Nuclide})\text{F}_x$ -76 mol % NaF -12 mol % BeF_2 , mol % $(\text{Heavy Nuclide})\text{F}_x$ -25 mol % NaF -60 mol % BeF_2 , 22 mol % $(\text{Heavy Nuclide})\text{F}_x$ -33 mol % LiF -45 mol % NaF , 22 mol % $(\text{Heavy Nuclide})\text{F}_x$ -78 mol % LiF , 25 mol % $(\text{Heavy Nuclide})\text{F}_x$ -48.2 mol % NaF -26.8 mol % KF , 27 mol % $(\text{Heavy Nuclide})\text{F}_x$ -53 mol % NaF -20 mol % RbF , 27.5 mol % $(\text{Heavy Nuclide})\text{F}_x$ -46.5 mol % NaF -26 mol % KF , and 30 mol % $(\text{Heavy Nuclide})\text{F}_x$ -50 mol % NaF -20 mol % KF .

[0059] Although a salt with a high heavy nuclide solubility is useful, considerations other than the heavy nuclide solubility should also be taken into account. The composition with the highest molar percentage of $(\text{Heavy Nuclide})\text{F}_x$ is not necessarily the most desirable. For example, 30 mol % $(\text{Heavy Nuclide})\text{F}_x$ -50 mol % NaF -20 mol % KF has a higher

heavy nuclide concentration than 22 mol % $(\text{Heavy Nuclide})\text{F}_x$ -78 mol % LiF , but the 22 mol % $(\text{Heavy Nuclide})\text{F}_x$ -78 mol % LiF may be better because the lithium in the second salt has a greater moderating ability than the sodium or potassium in the first salt. Lighter elements such as lithium have a greater moderating ability than heavier elements such as sodium.

[0060] In some implementations, the fuel-salt mixture **103** comprises a lithium fluoride salt containing dissolved heavy nuclides ($\text{LiF}-(\text{Heavy Nuclide})\text{F}_x$). In some implementations, a $\text{LiF}-(\text{Heavy Nuclide})\text{F}_x$ mixture can contain up to, for example, 22 mol % $(\text{Heavy Nuclide})\text{F}_x$. Lithium is a very light element and its moderating capability can make it neutronically advantageous for a thermal spectrum reactor. Li-7, in particular, has desirable neutronic properties. Li-6 has a significantly higher thermal neutron absorption cross section (941 barns) than Li-7 (0.045 barns). Neutron absorption by lithium decreases the reactor's reactivity because the neutrons absorbed by lithium are unavailable to split actinides. As such, in some implementations, the lithium in the salt can be enriched so that it has a high fraction of Li-7, which reduces the tendency of the fuel-salt mixture to absorb thermal neutrons.

[0061] In some implementations, beryllium can be added to molten halide salts to lower the salts' melting temperatures. In some implementations, the fuel-salt mixture **103** comprises a beryllium lithium fluoride salt containing dissolved heavy nuclei ($\text{LiF}-\text{BeF}_2-(\text{Heavy Nuclide})\text{F}_x$). The presence of beryllium in the fuel-salt mixture can, however, reduce the effectiveness of Li-7 enrichment, because Li-6 is produced in (n,α) reactions with Be-9. Therefore, in some implementations, no beryllium is added to the molten salt. In some implementations, a reduced amount of beryllium is added.

[0062] In addition, adding beryllium can decrease the solubility of actinides in the salt. Because there is less fissile material per kilogram of spent nuclear fuel than of fresh fuel, a higher actinide concentration may be required to make the nuclear reactor system **101** become critical. Removing BeF_2 entirely from the salt can increase the actinide solubility of the salt from 12.3% to 22%, enough to enable the fuel-salt mixture to reach criticality without first processing spent nuclear fuel to increase the fissile-to-fertile ratio (e.g., by removing uranium). In some implementations, the resulting increase in actinide solubility allows the nuclear reactor power plant **100** to use the entire spent nuclear fuel vector as fuel. In some implementations, a mixture of spent nuclear fuel, or portions of it, combined with other elements of fuel can also be used.

[0063] During operation, the fuel-salt mixture **103** fills the reactor core **106**. Some of the free neutrons from fission reactions in the reactor core **106** can induce fission in other fuel atoms in the reactor core **106**, and other neutrons from the fission reaction can be absorbed by non-fuel atoms or leak out of the reactor core **106**. The fuel-salt mixture in the reactor core can be in a critical or self-sustaining state when the number of neutrons being produced in the reactor core **106** is equal to or substantially equal to the number of neutrons being lost (e.g., through fission, absorption, or transport out of the system (e.g., "leakage")). When in a critical state, the nuclear reaction is self-sustaining.

[0064] In some instances, whether the fuel-salt mixture in the reactor core is in a critical state is primarily determined by three factors: the nuclear properties of the fuel-salt mixture, the properties of the materials used to fabricate the reactor core **106**, and the geometric arrangement of the fuel-salt mixture and the other materials in the reactor core. The com-

bination of these three factors primarily determines the distribution of neutrons in space and energy throughout the reactor core **106** and, thereby, the rate of the reactions occurring in the reactor core **106**. The reactor core **106** can be designed to keep the fuel-salt mixture in the reactor core in a critical state by arranging the mixture, the geometric arrangement, and the materials so that the rate of neutron production exactly or approximately equals the rate of neutron loss.

[0065] Generally, U-235 and Pu-239 have a larger fission cross section in the thermal neutron energy region than they do in the fast neutron energy region, that is, these nuclei are more easily fissioned by thermal neutrons than by fast neutrons.

[0066] Neutron capture is another possible nuclear reaction and may occur between U-238 and a neutron. In a neutron capture reaction, the nucleus absorbs a neutron that is incident upon it, but does not reemit that neutron or undergo fission.

[0067] In some instances, the most effective neutron energies for transmuting U-238 into Pu-239 are in the epithermal region. Pu-239, a fissile isotope, is produced when U-238 captures a neutron to become U-239, which beta decays into Np-239, which beta decays into Pu-239. The optimal energy range for converting U-238 into U-239 (and eventually into Pu-239) is determined by U-238's cross sections. In FIG. 11, the fission cross section of U-238 **1102** is lower than the capture cross section **1104** for all energies below about 1 MeV, meaning that a neutron with a kinetic energy below 1 MeV has a greater probability of being captured by U-238 than causing U-238 to fission. The probability of capturing a neutron relative to the probability of fissioning (the vertical distance between the two plots) is greatest in the range from approximately 5 eV to 10 KeV. This is a good range for converting U-238 into Pu-239.

[0068] The thermal and epithermal neutron spectra needed by some implementations can be achieved by introducing moderating materials. In some implementations, the moderating materials can, for example, be introduced in the reactor core elements. In some implementations, the moderating materials can be inserted into and removed from the reactor core **106**. In some implementations, a combination of the two can be used. In some implementations, the moderating elements shift the neutron spectra to more have more useful characteristics, by, for example, reducing the energies of neutrons in the fuel-salt mixture.

[0069] The moderating efficiency, η_{mod} , of a material is defined as the mean logarithmic reduction of neutron energy per collision, ξ , multiplied by the macroscopic scattering cross section Σ_s , divided by the macroscopic absorption cross section Σ_a , as presented in equations 1.1 and 1.2.

$$\xi = \ln \frac{E_0}{E} = 1 + \frac{(A-1)^2}{2A} \ln \left(\frac{A-1}{A+1} \right) \quad [1.1]$$

$$\eta_{mod} = \frac{\xi \Sigma_s}{\Sigma_a} \quad [1.2]$$

[0070] In equation 1.1, E_0 is the kinetic energy of the neutron before the collision with the nucleus, E is the kinetic energy of the neutron after the collision with the nucleus, and A is the atomic mass of the nucleus.

[0071] As indicated by equation 1.1, neutrons typically lose a smaller fraction of their kinetic energy when they scatter off nuclei with a larger atomic mass. Conversely, neutrons typi-

cally lose a larger fraction of their kinetic energy when they scatter off nuclei with a smaller atomic mass (e.g., carbon, hydrogen, lithium). A low atomic mass of the nuclei means that a neutron needs to undergo fewer collisions with the moderator to slow down to a particular energy.

[0072] Every time a neutron collides with a nucleus, there is a finite probability that the neutron will be captured by that nucleus. Typically, neutron capture in a non-fuel material like a moderator should be minimized because it cannot result in fission. To reduce neutron capture, a moderator with a higher moderating efficiency should be one that has a low capture cross section and a low atomic mass. A low capture cross section means that, for every collision with the moderator, there is a low probability the neutron will be captured.

[0073] The reactor cores of some nuclear reactor systems use graphite as a moderator. In some implementations, the reactor core **106** uses a moderator material that has a higher moderating effectiveness than does graphite alone.

[0074] In some implementations, a form of zirconium hydride (e.g., $ZrH_{1.6}$) can be used as a moderator in the reactor core **106** instead of, or in some implementations in addition to, graphite. $ZrH_{1.6}$ is a crystalline form of zirconium hydride, with face-centered cubic symmetry. There are other phases of zirconium hydride (ZrH_x , where x can range from 1 to 4) and the physical properties of zirconium hydride vary among the other phases. In some implementations, the zirconium hydride moderator could be in the form of a solid single crystal. In some implementations, a powdered form of zirconium hydride, comprising smaller crystals could be used. In some implementations, smaller crystals could be formed into solid shapes (using, for example, one or any combination of the following processes: sintering the crystals, binding the crystals together using a binder such as coal tar, or any other suitable process).

[0075] Zirconium hydride has a greater moderating ability than graphite because it has a high density of hydrogen nuclei. The hydrogen nuclei in zirconium hydride are approximately 12 times lighter than the carbon nuclei in graphite. Following equation 1.1, a neutron typically requires fewer collisions with zirconium hydride to reach thermal energies than it does with graphite. In some implementations, using zirconium hydride rather than graphite alone in the reactor core **106** can increase the number of neutrons in the epithermal and thermal energy ranges.

[0076] The use of zirconium hydride as a moderator can also provide the benefit of increasing the rate at which U-238 is transmuted into Pu-239. This increase can allow the nuclear reactor system **101** to operate as a so-called converter reactor by producing fissile Pu-239 at the same or substantially the same rate as fissile and fissionable actinides are consumed. Although minor actinides—e.g., actinide elements other than uranium or plutonium—are more easily fissioned with fast neutrons, they can still be fissioned in such implementations using the neutron spectrum that would be present in reactor core **106**.

[0077] Other types of moderators individually and in combination can be used as a moderator in the stationary reactor core **106**, or in the movable moderating elements, or in both of them. For example, any suitable combinations of any two or more of graphite, zirconium hydride, zirconium deuteride, or other moderator materials can be used.

[0078] In some implementations, the moderator material has a high density of light atomic nuclei (e.g., hydrogen, deuterium, lithium, etc., individually or in any combinations

of any two or more of them). The concentration of hydrogen in ZrH is 1.6 hydrogen atoms per zirconium atom. Additional or other materials, or combinations of them, with similar or higher densities of hydrogen can be used as a moderator material. Other moderator materials may include any of the following individually or in any combination: other metal hydrides, metal deuterides, and low atomic mass materials in solid form (e.g. solid lithium). In some implementations, zirconium deuteride may be more effective than zirconium hydride because deuterium has a much smaller neutron absorption cross section than hydrogen. Specifically, our computer simulations show the following materials to be effective moderators in our reactor core design: zirconium hydride ($\text{ZrH}_{1.6}$ and ZrH_2), yttrium(II) hydride (YH_2), yttrium(III) hydride (YH_3), and lithium hydride (LiH). Those materials could be used individually or in any combination of two or more of them.

[0079] In some implementations, the level of reactivity in the reactor core **106** can be controlled using one or more movable moderating elements, for example moderator rods. The moderating elements can alter the thermal and epithermal neutron spectra by being inserted into and removed from the reactor core **106**. In some implementations, these moderating materials may be in the form of rods, blocks, plates, or other configurations, used individually or in any combination.

[0080] The moderating rods can be made of zirconium hydride, zirconium deuteride, graphite, used individually, or any other suitable material or combination of materials. The rods may be of a wide variety of shapes, sizes, and configurations, and can have a wide variety of approaches for their insertion into and removal from the reactor core.

[0081] In the context of reactivity control, in some implementations, a moderating rod can mean an element made of moderating material that can be inserted or withdrawn from the reactor core. In some implementations, the moderator rods can be movable relative to the reactor core vessel **106** so that the moderator rods can be fully or partially withdrawn from the reactor core **106**. In some examples, the nuclear reactor system **101** is subcritical when the moderator rods are partially or fully withdrawn from the reactor core **106**. Reactivity is increased by partially or fully inserting moderator rods until the reactor becomes critical. The reactor can be shut down by withdrawing the moderator rods.

[0082] In some implementations, the use of zirconium hydride (and possibly other hydrides and deuterides) as a moderator material can allow the nuclear reactor system **101** to operate entirely on spent nuclear fuel. In some implementations, the use of such materials can allow the nuclear reactor system **101** to operate partially on spent nuclear fuel. In some implementations, zirconium hydride could be used to make, for example, a more efficient thorium molten salt reactor. In some implementations, the use of zirconium hydride could make a thorium molten salt reactor more neutronically efficient because the moderating effectiveness of zirconium hydride is greater than that of graphite. The use of zirconium hydride in a thorium reactor—a reactor that transmutes thorium into fissile U-233—could reduce the required amount of fuel, could improve fuel utilization, could reduce the required size of the reactor core, or could achieve a combination of them.

[0083] In some implementations, it is desirable to surround the moderating material with a material that is more resistant to chemical corrosion than the moderating material is, e.g.,

using either a graphite or a silicon carbide composite (or a combination of them) cladding on a zirconium hydride moderator rod. Including such a cladding reduces the likelihood of corrosion-induced degradation of the moderating material. In various implementations, the cladding material can have a low neutron absorption cross section, can be a neutron moderator, or can have a combination of these and other properties. In some examples, the cladding can be provided on parts of the reactor core. In some examples, the cladding can be provided on parts of the moderator rods. In some examples, the cladding can be provided on both.

[0084] In some implementations, differential swelling or shrinkage of materials comprising the reactor core **106** can occur. For example, zirconium hydride, graphite, or other moderator materials in the reactor core **106** will be subject to large neutron fluxes, which can lead to volumetric swelling or shrinkage. In cases in which both graphite and zirconium hydride are used in the reactor core **106**, the graphite and the zirconium hydride could experience significantly different amounts of volumetric swelling or shrinkage. In some implementations, gaps can be provided at the interfaces of the graphite and zirconium hydride to prevent (or reduce the tendency of) such swelling or shrinkage from cracking the graphite cladding and exposing the zirconium hydride directly to the fuel-salt mixture.

[0085] In some implementations, the reactor core **106** can be designed with gaps at the interfaces between different types of materials, for example, to protect against damage caused by differential swelling or shrinkage. In some implementations, the gaps could be filled with an inert gas, e.g., helium, to reduce chemical interactions between the materials.

[0086] Alternatively or in addition to movable moderating elements, movable control rods can be used in reactor core **106** in some instances. Control rods can remove neutrons from the system by capturing neutrons that are incident upon them. For example, control rods that are used on solid-fuel reactors, or other types of control rods, or combinations of them, can be used. Reactivity can be increased by withdrawing the control rods from the reactor core **106**. Reactivity can be decreased by inserting the control rods in the reactor core **106**.

[0087] In some implementations, the same or a similar effect can be achieved in some cases using a reflector control system. In some examples, both a reflector system and control rods could be used. In some examples of reflector control systems, movable sheets of either absorbing or of a moderating material (or a combination of them) can reside between an interior region of the reactor core **106** and a reflector about the interior region. The sheets can be manipulated (e.g., raised, lowered, rotated, or otherwise manipulated) to increase or decrease the amount of neutrons reflected into the interior region of the reactor core **106**. The reflector **205** may be inside the reactor vessel **203**, outside the reactor vessel, or both.

[0088] In some implementations, in combination with or in replacement of the techniques described above, reactivity can be controlled by adjusting the rate at which additional fuel is added to the fuel-salt mixture in the primary loop **102**. In some cases, reactivity can be controlled by adjusting the rate at which waste materials are removed from the fuel-salt mixture in the primary loop **102**. In some implementations a combination of the rate of adding fuel and the rate of removing waste can be used. As fuel is consumed in the reactor core, the reactivity of the fuel-salt mixture decreases. Eventually,

without adding fuel or removing waste, or both, the fuel-salt mixture would no longer be critical, and the generation of heat would stop. By adding fuel and removing waste at appropriate rates, the reactivity can be maintained at a suitable level.

[0089] In some implementations, the fissile-to-fertile ratio may be too low to remain critical over time. In such instances, in addition to or in replacement of the techniques described above, reactivity may be controlled by partially or fully inserting or removing solid fuel elements. Inserting a solid fuel element that has a higher fissile concentration than the fuel-salt mixture may increase reactivity in the reactor. Conversely, removing such an element would reduce the reactivity of the reactor system. Such solid fuel elements may take the form of one of oxide fuel rods such as those used in conventional reactors, or metallic fuel rods, or plates of metallic fuel, or pebbles containing fissionable material, or a combination of any two or more of those. The fissionable fuel may comprise any one or a combination of any two or more of enriched uranium (up to 20% U-235), or depleted uranium, or natural uranium, or actinide material from spent fuel, or weapons material, or thorium and a fissile material, or any combination of these with any other fissionable material.

[0090] In some instances, a solid fuel element may comprise pellets of fissionable material surrounded by a cladding material. In various implementations, the cladding material may comprise a metal or metal alloy similar to or the same as those used in conventional reactors, or a metal or metal alloy such as Hastelloy that is resistant to corrosion in molten salts, or any other suitable metal or metal alloy, or a moderating material such as graphite, or zirconium hydride, or yttrium hydride, or any combination of two or more of those.

[0091] In some instances, solid fuel elements may be fully inserted at all times during operation and may be replaced, periodically or otherwise, as they are in conventional reactors. In such implementations, the solid fuel elements may provide more reactivity than the fuel-salt mixture alone. This would allow a reactor to operate with a fuel-salt mixture that has a lower concentration of heavy nuclei, allow a reactor to operate with a fuel-salt mixture with a lower fissile-to-fertile ratio, or allow higher burnup—a measure of how much fuel material has undergone fission—of the fuel in the fuel-salt mixture, or any combination of these.

[0092] In some instances, solid fuel elements removed from a molten salt reactor may contain large amounts of long-lived heavy nuclei, similar to those found in spent fuel from conventional reactors. In some implementations, these used fuel elements could then be mixed with a molten salt for use as a fuel-salt in a molten salt reactor. In some cases, these used fuel elements could be put in temporary storage or sent to a permanent disposal facility.

[0093] If an important objective of operating molten salt reactors is reducing spent fuel inventories, the use of molten salt reactors that include solid fuel elements may still be advantageous if more actinide waste is destroyed than is produced by such reactors. If the primary objective is electricity production, the amount of actinide waste produced may be of lesser concern.

[0094] FIG. 2 is a schematic cross-sectional diagram of an example reactor core configuration **200** used in numerical simulations. The numerical simulations were used to test the ability to reach criticality in a molten salt reactor using only spent nuclear fuel dissolved in a molten lithium fluoride salt as fuel. The numerical simulations used the SCALE code

system developed by Oak Ridge National Laboratory. In the implementation shown in FIG. 2, the reactor core was modeled as a series of ten concentric moderator cylinders (which we sometimes refer to as rings) **204** at equal radial spacings, a core vessel **203** made of Hastelloy, and a fuel-salt mixture **202** in the gaps between the moderator rings. (FIG. 2 also shows a reflector **205**.) Concentric rings were used in the numerical simulations for ease of computer modeling. A wide variety of other types of reactor core configurations may be advantageous or optimal in various contexts.

[0095] The cylinders in the simulations were 3 meters tall.

[0096] In the numerical simulations, the Hastelloy core vessel was 5 cm thick and had an inner radius of 1.5 meters. Each of the ten concentric zirconium hydride rings was 5 cm thick.

[0097] The LiF-(Heavy Nuclide) F_x fuel-salt mixture was located in the 9 cm gaps between the zirconium hydride rings and between the outermost moderator ring and the vessel wall. The vessel is surrounded by a neutron reflector **205**. In this simulation, the reflector was zirconium hydride ($ZrH_{1.6}$). Additional or other reflectors (e.g., graphite or zirconium deuteride), individually or in combinations, can be used.

[0098] Table 1 shows the material data used in the numerical simulations.

TABLE 1

Fuel-Salt Mixture	
LiF (mol %)	78
(Heavy Nuclide) F_x (mol %)	22
Density (g/cm ³)	3.89
Li-7 Enrichment	99.99%
Zirconium Hydride	
Zr-90 (wt %)	51.79
Zr-91 (wt %)	11.29
Zr-92 (wt %)	17.26
Zr-94 (wt %)	17.49
H-1 (wt %)	2.16
Density (g/cm ³)	5.66
Hastelloy	
C (wt %)	0.06
Co (wt %)	0.25
Cr (wt %)	7.00
Mo (wt %)	16.50
W (wt %)	0.20
Cu (wt %)	0.10
Fe (wt %)	3.00
Mn (wt %)	0.40
Si (wt %)	0.25
B (wt %)	0.01
Ni (wt %)	72.23
Density (g/cm ³)	8.86

[0099] (In the discussion that follows, the references to simulation tools are to elements of the Oak Ridge National Laboratory, “SCALE: A Modular Code System for Performing Standardized Computer Analyses for Licensing Evaluations,” (2009).) The isotopic composition of spent nuclear fuel from an example light water reactor was calculated with the ORIGEN-ARP graphical user interface, which is a SCALE analytical sequence that solves for time-dependent material concentrations using the ORIGEN-S depletion code and pre-computed cross section sets for common reactor designs. In this case, a Westinghouse 17×17 assembly normalized to 1 metric ton of uranium with an initial enrichment of 4.2% was depleted to 50 GWd/MTHM (gigawatt-days per metric ton of heavy metal) and the isotopic concentrations

from the ORIGEN output file were used to calculate the weight percent (wt %) for each actinide isotope (fission products were discarded) in the spent fuel. Table 2 shows the isotopic composition of the spent nuclear fuel used for numerical simulations.

TABLE 2

Isotope	wt %
U-234	1.84E-02
U-235	7.46E-01
U-236	6.05E-01
U-238	9.73E+01
Np-237	7.59E-02
Pu-236	1.00E-10
Pu-238	3.50E-02
Pu-239	6.33E-01
Pu-240	3.10E-01
Pu-241	1.41E-01
Pu-242	9.61E-02
Am-241	4.50E-02
Am-242	1.38E-04
Am-243	2.61E-02
Cm-242	1.41E-06
Cm-243	7.40E-05
Cm-244	8.80E-03
Cm-245	5.23E-04
Cm-246	6.76E-05
Cm-247	1.07E-06
Cm-248	7.74E-08
Bk-249	1.00E-10
Cf-249	1.08E-09
Cf-250	3.51E-10
Cf-251	1.85E-10
Cf-252	3.41E-11

[0100] The TRITON-NEWT sequence in SCALE was used to analyze the core model shown in FIG. 2 and described above. Within this sequence, the TRITON control module is used to call, in order, the functional modules BONAMI, WORKER, CENTRM, PMC, and NEWT. BONAMI performs Bondarenko calculations on master library cross sections to account for energy self-shielding effects; WORKER formats and passes data between other modules; CENTRM uses both pointwise and multigroup nuclear data to compute a continuous energy neutron flux by solving the Boltzmann transport equation using discrete ordinates; PMC takes the continuous energy neutron flux from CENTRM and calculates group-averaged cross sections; and NEWT performs a 2D discrete ordinates calculation to determine the multiplication factor for the system. An axial buckling correction is then applied to account for axial neutron leakage.

[0101] FIG. 3 is a diagram of a computational mesh **300** used in the numerical simulations. Only one fourth (a quadrant) of the reactor core was modeled to reduce computational time. The resulting multiplication factor is not affected because of the symmetry of the reactor core. As shown in FIG. 3, the circular region bounded by the outer edge **303** of the vessel was divided into a thirty-by-thirty mesh **301**; the reflector region **305**, which fills the remaining area of the 210 cm by 210 cm system, was divided into a twenty-by-twenty mesh **307**. Reflective boundary conditions were used on the bottom and left sides and vacuum boundary conditions were used on the top and right sides. For the axial buckling calculation, the active core height was set to 300 cm with no reflection on either side. The axial buckling correction used here assumes vacuum boundary conditions on the top and

bottom of the active core region. An eighth-order quadrature set was used in the NEWT discrete-ordinates transport calculation.

[0102] According to the numerical simulations, a multiplication factor (ratio of neutron production to loss) of 1.043 was calculated. This value indicates that there is more than enough reactivity to achieve criticality using the entire spent nuclear fuel actinide vector as fuel, without processing to enhance the actinide vector (e.g., without removing some or all of the uranium).

[0103] The numerical simulations used here can be modified to include higher fidelity neutronics calculations, optimized or improved material configurations, a complete three-dimensional model that accounts for reflectivity above and below the reactor core, and other modifications. Such modifications could potentially result in numerical simulations that indicate significantly higher excess reactivity.

[0104] As mentioned earlier, in some implementations, a moderator material (e.g., zirconium hydride and others mentioned) may be incompatible with the fuel-salt mixture in the reactor core. In some implementations, a clad material can be used between the moderator material and the fuel-salt mixture. Graphite is compatible with some types of molten salt and is also a neutron moderator. The numerical simulations using zirconium hydride as a moderator material were modified and repeated with the faces on both sides of each zirconium hydride ring replaced with graphite. The numerical simulations used 1 cm graphite cladding on both sides of each zirconium hydride ring. As such, each ring was composed of 1 cm of graphite, 3 cm of zirconium hydride, and another 1 cm of graphite. The numerical simulation showed that this modification does not severely reduce reactivity. The multiplication factor for this modified system was 1.01, which is a reduction of 0.03 due to the addition of the graphite cladding.

[0105] In some cases, in which corrosion processes are slow, at least compared with some operational aspects of the nuclear reactor system **101**, preventing contact between the fuel-salt mixture and a potentially incompatible moderator material can be accomplished with thin cladding (e.g., a few millimeters thick graphite cladding). In some implementations, materials such as silicon carbide crystals or SiC—SiC composites or combinations of them could be used.

[0106] In some implementations, cladding materials could have one or any combination of two or more of the following properties: resistance to corrosion in molten halide salts, low neutron cross sections, and ability to retain their mechanical and material integrity at the reactor's steady-state operating temperatures and pressures. It can be desirable to keep the cladding material as thin as possible, because a thinner layer of cladding material absorbs fewer neutrons. Depending on the material used, the cladding thickness will likely range from approximately one millimeter to one centimeter.

[0107] To illustrate the differences in the neutron energy spectrum caused by using zirconium hydride as a moderator instead of graphite, the same numerical simulation was repeated using graphite rings instead of zirconium hydride rings. FIG. 4 is a diagram **400** showing plots of the simulated neutron energy spectra in the two different reactor cores. The plot labeled “ZrH1.6 Rings” **402** in the diagram **400** is based on numerical simulations of the reactor core configuration shown in FIG. 2, which includes zirconium hydride moderator material. The plot labeled “Graphite Rings” **404** in the diagram **400** is based on numerical simulations of the reactor core configuration shown in FIG. 2, with graphite moderator

material substituted for the zirconium hydride moderator material shown in FIG. 2. The plots shown in the diagram 400 are the full-core neutron energy spectra for both numerical simulations. The total neutron flux was normalized to 1×10^{15} n/cm²-s in both numerical simulations.

[0108] A comparison of the plots shown in the diagram 400 illustrates, by way of example, some of the advantages of using zirconium hydride as a moderator. As shown in the diagram 400, the numerical simulations indicate that use of zirconium hydride moderator material resulted in approximately ten times more neutrons in the thermal range than in a graphite moderated system. According to the numerical simulations, the multiplication factor for the graphite moderated system was 0.358, which is significantly below criticality, whereas the multiplication factor for the zirconium hydride moderated system was 1.043, which is above criticality.

[0109] The reactor core design used in the numerical simulations illustrates, by way of example, some performance aspects of zirconium hydride as a moderator material. These performance aspects, or additional or different operational parameters, can be achieved by using other reactor core designs. In various implementations, there are almost limitless ways to arrange the materials (e.g., the hydride or deuteride moderator, fuel-salt mixture, and Hastelloy vessel).

[0110] One design parameter for achieving a critical reactor is the fuel-to-moderator ratio, expressed as a ratio of the volume of the fuel to the volume of the moderator, which is independent of the geometric arrangement of materials. An optimal, improved, or otherwise preferred fuel-to-moderator ratio value could potentially be identified, and such a value may guide the overall core design.

[0111] The six-factor formula (equation 1.3) describes the factors used to determine the reactivity (and therefore the criticality) of a nuclear reactor system.

$$k = \eta f p \epsilon P_{FNL} P_{TNL} \quad [1.3]$$

[0112] In equation 1.3, k is termed the “neutron multiplication factor” and may also be defined as the number of neutrons in one generation divided by the number of neutrons in the preceding generation. η is termed the “reproduction factor” and is defined as the number of neutrons produced by fission per absorption event in the fuel. f is termed the “thermal utilization factor” and is defined as the probability that, for a given neutron absorption event, the neutron absorption occurs in the actinide material. p is termed the “resonance escape probability” and is defined as the fraction of fission neutrons that make the energy transition from fast to thermal without being absorbed. ϵ is termed the “fast fission factor” and is defined as the ratio of the total number of fission neutrons divided by the number of fission neutrons produced by thermal fissions. P_{FNL} is termed the “fast non-leakage probability” and is defined as the probability that a fast neutron will not leak out of the system. P_{TNL} is termed the “thermal non-leakage probability” and is defined as the probability that a thermal neutron will not leak out of the system. In general, systems with a high surface area to volume ratio have higher P_{FNL} and P_{TNL} .

[0113] If k is less than 1, the system is defined as subcritical. A subcritical system cannot sustain a nuclear reaction. If k equals 1, the system is defined as critical. A critical system is in a steady state, and the number of neutrons produced exactly equals the number of neutrons lost. If k is greater than 1, the

system is defined as supercritical. In a supercritical system, the number of neutrons produced by fission events increases exponentially.

[0114] The reactivity, ρ , of a nuclear reactor is defined as the reactor’s divergence from a critical state, and is given by equation 1.4.

$$\rho = (k-1)/k \quad [1.4]$$

[0115] FIGS. 1, 2, 5, 6, 7, 8, and 9 show possible reactor core configurations and features for various implementations. A wide variety of these and other reactor core configurations and features, and combinations of them, can be used.

[0116] FIG. 5 is a cross-sectional view of an example prism configuration 500 for a reactor core. In some implementations of the prism configuration, the fuel-salt mixture flows (perpendicularly to the plane of the paper) through tubular channels 502 in either hexagonal blocks, square blocks, triangular blocks, or other-shaped blocks 504 (or combinations of any two of them) of moderating material.

[0117] An example of a prism core configuration 500 with a channel pitch 505—the distance between the center of one channel and the center of an adjacent channel—of 1.26 cm, a channel radius of 0.500 cm 507, and a length of 300 cm was modeled with SCALE. The multiplication factor, k , for this system was 1.0489.

[0118] In one instance of the reactor core, in which the diameter is 300 centimeters and the height is 300 centimeters, the volume is approximately 21.2 cubic meters. In this implementation, approximately 30,000 of these hexagonal channels are in the reactor core. In some useful implementations, the open volume of the reactor core (i.e., the volume not occupied by some combination of moderators, cladding, moderator rods, or control rods) is filled entirely with the fuel-salt mixture. The volume and surface area to volume ratio affects the P_{FNL} and P_{TNL} terms of the six-factor formula, as described in a preceding section, and in turn affects the criticality. In general, the varying of the core geometry changes the terms in the six-factor formula.

[0119] In the example illustrated in FIG. 5, each of the hexagonal blocks 504 contains one tubular channel 502. In some implementations, each hexagonal block 504 may contain more than one tubular channel 502. In some implementations, large blocks of moderating material may contain many tubular channels 502. In some implementations, combinations of two or more of such types of hexagonal blocks could be used.

[0120] The example reactor core configuration (FIG. 2) used in the numerical simulations described above uses a manifold configuration. In implementations that include the manifold configuration, the fuel-salt mixture flows through the reactor core from one end 111 (FIG. 1) to the other end 115 (FIG. 1) in the regions (gaps) 202 between plates 204 of moderating material. The plates 204 can include sections of moderating material in any suitable shape. A manifold configuration can incorporate curved plates (for example, as shown in FIG. 2), or flat plates, or a combination of these and any of a wide variety of other types of plate geometries.

[0121] In some implementations, the plates can be grouped together in moderator assemblies. In some implementations, multiple assemblies can be aggregated in a single reactor core. In some aspects, such moderator assemblies can be similar to the fuel assemblies used in solid-fueled reactors.

[0122] FIG. 6 shows a cross-sectional view of an example pebble configuration 600 for stationary (but not permanent)

moderator elements of a reactor core. In some implementations of such a pebble configuration, the fuel-salt mixture flows through gaps **603** around pebbles **602** of moderating material as it traverses the reactor core from one end to the other. The pebbles **602** can be spherical (as shown in FIG. 6) or any other suitable (for example, non-regular) geometry, or a combination of spherical and non-spherical. One example of a pebble core configuration **600** was modeled using SCALE. In this simulation, spherical pebbles (packed such that their centers form a regular rectangular grid with spacing between the center points equal to the diameter of the spheres, unlike FIG. 6. This is known as a “square pitch.”) with radii of 4 cm resulted in a multiplication factor of 1.0327.

[0123] FIG. 7 shows a cross-section of an example rod configuration **700** for stationary moderator elements of a reactor core. In implementations of the rod configuration **700**, the fuel-salt mixture flows through the gaps **703** around rods **702** of moderating material. The rods **702** can be simple cylinders, or the rods **702** can have another shape. In a single reactor core, sets of rods having different shapes can also be used. For example, the rods **702** can be any one of annular rods; or finned rods; or helical rods; or twisted helical rods; or annular helical rods; or annular twisted helical rods; or closely packed rods with wire-wrap spacers; or closely packed annular rods with wire-wrap spacers, or other types of rods; or can be any combination of two or more of such shapes. One example of a rod core configuration **700**, in which the radius of a rod was 0.5075 cm and the rod pitch—the distance between the center of one rod and the center of an adjacent rod—was 1.26 cm, was modeled with SCALE. The multiplication factor for this system was 1.0223.

[0124] In some implementations, the rods can each include a hollow inner channel. These rods are called annular rods. The fuel-salt mixture, or possibly a coolant fluid to regulate the temperature of the moderator, can flow through the hollow inner channel of the rods. One instance of an annular rod core configuration, with fuel-salt flowing through a channel within each moderating rod as well as flowing through the spaces outside of the rods, was modeled with SCALE. The inner radius of each rod was 0.05 cm, the outer radius of each rod was 0.53 cm, and the rod pitch was 1.26 cm. The multiplication factor for this system was 1.0235. In the modeled case, the fuel-salt mixture flows both inside and outside the annular rod. In examples in which the fuel salt flows on the outside and a different, non-radioactive coolant on the inside of each rod, the purpose of the non-radioactive coolant would be to keep the annular rod from overheating. Such an approach could be used if the annular rod were made of a material that could not be allowed to get hotter than a certain maximum temperature.

[0125] In a given reactor core, it would also be possible to use any combination of two or more of plate elements, pebble elements, and rod elements, and even other kinds of elements and combinations of them. Among the principles that could govern the geometric configuration and selection of the elements would be that the reactor core has a low surface area to volume ratio, to keep the P_{TNL} and P_{FNL} terms of the six-factor formula as high as possible.

[0126] FIG. 8 is a side sectional view of an example reactor core **800** that includes an implementation of a downcomer **802**. The downcomer **802** in this example forms a cylindrical channel or sleeve around the reactor core and allows the fuel-salt mixture to enter and flow through the reactor core. FIG. 8 shows the general direction of flow through the reactor

core **800**. The fuel-salt mixture enters the reactor core through an inlet region **804** and flows through a cylindrical flow passage **806** of the downcomer **802** into a lower plenum **808**. From the lower plenum **808**, the fuel-salt mixture flows through the driver region **810** into an upper region **814**. From the upper region **814**, the fuel-salt mixture flows out of the reactor core through the outlet region **816**.

[0127] In some implementations, the driver region can be defined as the portion of the reactor core that is not the downcomer. In some configurations, instead of using a downcomer, the fuel-salt mixture directly enters the reactor core at the bottom of the reactor core and flows out of the top of the reactor core. In some configurations, instead of using a downcomer, the fuel-salt mixture directly enters the reactor core at the side of the reactor core and flows out of the other side of the reactor core.

[0128] In some implementations, the driver region **810** includes stationary moderator elements **812** comprising moderator material. The downcomer **802** can expose the fuel-salt mixture to neutrons that might otherwise leak out of the core. As such, use of a downcomer **802** can reduce leakage and thereby increase the rate of transmutation of fertile nuclei into fissile nuclei. The downcomer **802** can include moderating material. A downcomer **802** can be used with any of the example core configurations that we have described, and others.

[0129] FIG. 8 shows the downcomer **802** surrounding the driver region **810**. In some implementations, a reactor core can include a downcomer having another configuration. For example, a reactor core can include a downcomer in the center of the reactor core. In such examples, the incoming fuel-salt mixture can flow through the downcomer in the center of the reactor core and then flow through the active region where most of the heat is generated. A wide variety of other configurations would be possible for the downcomer in order to trap neutrons that may leak out of the core (to increase the P_{TNL} and P_{FNL} terms of the six-factor formula). For example, the wider the downcomer is, the fewer neutrons that are lost, but the more salt that must be in the reactor.

[0130] FIG. 9 is a diagram of an example reactor core **900** that includes an implementation of a blanket region **902**. A blanket region **902** can be used with any of the reactor core configurations that we have described, and others. In some implementations, the blanket region **902** is generally cylindrical and surrounds an interior region **904** of the reactor core. In some implementations, the blanket region **902** and the interior region **904** have different fuel-to-moderator ratios. The fuel-to-moderator ratio in the different regions can be tuned, for example, to increase the fertile-to-fissile transmutation. In some implementations, there may be multiple zones, having different respective fuel-to-moderator ratios. One such example is a core with relatively low moderation in the central zone, an intermediate zone with somewhat higher moderation, and an outer zone with the highest moderation. This would allow the neutron spectrum to remain fast in the central region, and become more thermalized in the radial direction.

[0131] In the example shown in FIG. 9, the fuel-to-moderator ratio is higher in the blanket region **902** than in the interior region **904**. In the interior region **904**, the fuel-salt mixture flows through channels **906** in blocks **908** of moderator material. In the blanket region **902**, the fuel-salt mixture flows through different size (in this case, larger) channels **910** in blocks **912** of moderator material. In some implemen-

tations, the interior region can have a higher fuel-to-moderator ratio than the blanket region.

[0132] A wide variety of configurations, sizes, and shapes of the plates, the assemblies of plates, and the aggregations of plate assemblies (which we broadly can call the geometry of the moderator plates) would be possible. As one simple example, plates or groups of plates can be twisted, for example, to improve thermal-hydraulic characteristics of the reactor core, or for other purposes. The relationships between criticality (and other figures of merit for the reactor core) and a wide variety of parameters associated with the geometry of the moderator plates (and temperature, etc.) are complex and typically not susceptible to being expressed in explicit formulas. Computer simulations can be used to identify feasible and advantageous geometries of the moderator plates.

[0133] Fluoride salts have a high volumetric heat capacity relative to some other reactor coolants, as shown in Table 3 below.

TABLE 3

Relative heat-transport capabilities of coolants to transport 1000 MWt with a 100 C. rise in coolant temperature				
	Water	Sodium	Helium	Liquid Salt
Pressure, MPa	15.5	0.69	7.07	0.69
Outlet Temperature, C.	320	545	1000	1000
Velocity, m/s (ft/s)	6 (20)	6 (20)	75 (250)	6 (20)
Number of 1-m-diameter pipes required to transport 1000 MWt	0.6	2.0	12.3	0.5

(Source: C. W. Forsberg, "Thermal- and Fast-Spectrum Molten Salt Reactors for Actinide burning and Fuel Production," GenIV Whitepaper, United States Department of Energy, (2007)).

[0134] Because of this high heat capacity, the components of the primary loop **102** (e.g., the piping, the valves, and the heat exchanger, putting aside the reactor core) can have smaller internal diameters than those used in a system with other coolants, because the amount of heat that can be carried by the fuel-salt mixture from the reactor core to the heat exchanger is high per unit volume.

[0135] The nuclear reactor system **101** can provide safety advantages. The physics of designs such as those described in the previous sections give them many safety features that reduce the likelihood of certain accident scenarios. For example, reactivity in the reactor core **106** could potentially be increased by accidental moderator rod ejection or control rod ejection. If such a reactivity increase (whatever the cause) results in a supercritical system, the temperature in the reactor core and primary loop would rise rapidly. One or more features can be incorporated in the reactor core **106** to compensate for unintended reactivity increases.

[0136] For example, the fuel-salt mixture has a positive temperature expansion coefficient. Therefore, when the temperature of the fuel-salt mixture increases, the salt expands and the fuel density decreases, leading automatically to a drop in reactivity. This expansion can also force some of the fuel-salt mixture out of the reactor core **106**, and the decreased amount of fuel in the core can lower reactivity.

[0137] In cases in which the reactor core **106** operates with a large fraction of U-238 in the fuel, the Doppler broadening effect also can cause a drop in reactivity. This effect can occur when the large thermal resonance of U-238 expands with increasing temperature. Neutron absorption rates increase in the wider U-238 resonance and neutron concentrations below

the resonance decline, leading to lower thermal and total fission reaction rates and decreased reactivity. In addition to or in place of these passive safety features, control rods or shutdown rods can be inserted and moderator rod can be removed, or a combination of them can be controlled, to shut down the chain reaction, for example, within a few seconds.

[0138] The nuclear reactor system **101** can also provide additional safety advantages. Some nuclear reactors rely on operator action, external electric power, or active safety systems to prevent damage in accident scenarios. For example, some nuclear reactor systems continuously pump coolant over the reactor core to prevent a meltdown. In such conventional nuclear reactor systems, the pumps operate on an external power supply that is separate from the reactor itself. Backup power systems (e.g., large diesel generators and batteries) are used in such nuclear power systems to ensure a constant supply of electricity to the pumps. However, it is possible that all of the backup systems in such conventional nuclear reactors can fail at once (e.g., due to a common cause).

[0139] Although, in some implementations, the nuclear reactor system **101** can incorporate one or a combination of two or more of such active safety features, the nuclear reactor system **101** can also or instead provide safety without reliance on such features. For example, the nuclear reactor system **101** can provide passive safety without reliance on active safety measures. Passively safe nuclear reactors do not require operator action or electrical power to shut down safely, for example, in an emergency or under other conditions. The fuel-salt mixture in the nuclear reactor system **101** does not require additional coolant. If the nuclear reactor system **101** loses external power, the fuel-salt mixture flows out of the reactor core through freeze valves **118** into the auxiliary containment subsystem **120**.

[0140] In some implementations, the nuclear reactor system **101** can provide environmental advantages. Spent nuclear fuel from some reactors includes two broad classes of materials: actinides and fission products. Many of the fission products in the waste produced by some reactors have short radioactive half-lives and have significant radioactivity for only a few hundred years. Many of the actinides in the waste produced by some reactors can be significantly radioactive for upwards of 100,000 years.

[0141] The nuclear reactor system **101** can use as fuel the actinides in the spent nuclear fuel from other reactors. By inducing fission in the actinides in the spent nuclear fuel from other reactors, the majority of the waste produced by the nuclear reactor system **101** is composed of fission products. The longer the spent nuclear fuel is held in the nuclear reactor primary loop, the greater the percentage of actinides that can be turned into fission products. As such, the nuclear reactor system **101** can reduce the levels of radioactive materials having longer half-lives that otherwise exist in spent nuclear fuel, and thereby reduce the radioactive lifetime of waste produced by other nuclear reactor systems (e.g., to hundreds of years), thereby decreasing the need for permanent nuclear waste repositories (e.g., Yucca Mountain). The fission products that have shorter half-lives can be safely stored above ground until their radioactivity has decayed to insignificant levels.

[0142] In some implementations, the nuclear reactor system **101** can provide advantages in power production. In some implementations, the nuclear reactor power plant system **100** can convert the high-level nuclear waste produced by conven-

tional nuclear reactors into a substantial supply of electrical power. For example, while some nuclear reactor systems utilize only about 3% of the potential fission energy in a given amount of uranium, the nuclear reactor system **101** can utilize more of the remaining energy in some instances. The longer the spent nuclear fuel is held in the nuclear reactor, the greater the percentage of the remaining energy can be utilized. As an illustrative example, substantial deployment of the nuclear reactor system **101** could potentially use existing stockpiles of nuclear waste to satisfy the world's electricity needs for several decades.

[0143] As shown in FIG. 1, a fission product removal **114** component of the primary loop **102** can incorporate a wide variety of systems, components, and techniques. Fission products are produced continuously in the nuclear reactor system **101**, as actinides are split. Such fission products can act as neutron poisons in the reactor core **106**. Such fission products can be removed from the fuel-salt mixture by a halide slugging process. Halide slugging has been used at an industrial scale for decades as a batch process. The halide slugging process can ensure that the reactor remains critical in some cases.

[0144] In some implementations, the fission product removal component **114** comprises a port **123** in the primary loop piping that allows for the removal of a batch **119** of molten fuel-salt mixture. In some implementations, this fuel-salt mixture is then processed using halide slugging **131**. In some cases, fresh fuel-salt mixture **121** is then added to the primary loop through, for example, the same port to make up the volume of the removed salt. In some implementations, the halide slugging process can be automated, for example, to make it an in-line unit in the nuclear reactor system **101**. In such implementations, the molten fuel-salt mixture, as it flows through the piping of the primary loop, passes through the fission product removal component **114**, where the halide slugging process occurs. Other arrangements would also be possible for removing the waste and recharging the primary loop.

[0145] In some implementations, one or more freeze valves can control fluid flow between the primary loop **102** and an auxiliary containment subsystem **120**. In some examples, these freeze valves are made of a halide salt that is actively and continuously cooled so that the salt is in solid form, allowing them to remain closed during normal operation. In the event of an accident scenario that results in a loss of offsite or backup power supplies, the freeze valves will no longer be actively cooled. When the halide salt comprising the freeze valve is no longer actively cooled, the salt melts and the valve opens, allowing the fuel-salt mixture to flow out of the primary loop **102** into a passively cooled storage tank **117** of the auxiliary containment subsystem **120**.

[0146] In some implementations, the freeze valves **118** and the passively cooled storage tank **117** can use a wide variety of components, materials, and techniques to provide auxiliary containment of the fuel-salt mixture from the primary loop **102**. In some implementations, the auxiliary containment subsystem **120** itself includes a containment vessel **117** that can safely store the fuel-salt mixture from primary loop **120**. The geometry of the containment vessel **117** is such that the fuel-salt mixture contained in the containment vessel cannot achieve criticality. For example, the containment vessel **117** could be constructed such that the fuel-salt mixture flowing into it has a large surface area to volume ratio. The fuel-salt

mixture in a non-critical configuration can remain cool due to, e.g., natural convection and conduction, without requiring further active cooling.

[0147] Any suitable piping can be used for primary loop **102**. The piping of primary loop **102** carries the molten fuel-salt mixture. In the primary loop **102**, heat is produced in the reactor core **106** when actinides undergo fission following neutron bombardment. The photons, neutrons, and smaller nuclei produced in the nuclear reaction can deposit energy in the fuel-salt mixture **103**, heating it. The fuel-salt mixture carries the heat out of the reactor core **106**. For example, the pumps **108a** move the fuel-salt mixture through the piping of primary loop **102** through the reactor core **106** to the heat exchanger **112**.

[0148] In some implementations, the piping of the primary loop **102** can be resistant to both corrosion damage from molten halide salts and radiation damage from nuclear reactions. In some cases, corrosion can be reduced or minimized in alloys that have a high nickel content, such as Hastelloy-N or Hastelloy-X. These alloys can operate at temperatures up to 704° C. For systems using higher system temperatures, SiC—SiC composites or carbon-carbon composites or a combination of them can be used for the piping, valves, and heat exchangers of the primary loop. In some implementations, it is possible to hold the fuel-salt mixture contained in the primary loop **102** at approximately atmospheric pressure. Holding the system at approximately atmospheric pressure reduces the mechanical stress to which the system is subjected.

[0149] In some implementations, the heat exchanger **112** can include a wide variety of structures, components or subsystems to transfer heat energy between the primary loop **102** and the secondary loop **104**. In some implementations, the heat exchanger **112** transfers heat energy from the primary loop **102** to the secondary loop **104**, and the secondary loop **104** runs helium gas through a regular gas turbine system in a Brayton cycle. Some types of heat exchangers (e.g., those developed by the aircraft industry) contain buffer gas zones **83** to better separate gases that may diffuse across the heat exchanger. Such a buffer gas zone can be used in the nuclear reactor system **101** to reduce tritium migration from the primary loop **102** to the secondary loop **104**.

[0150] In some implementations, noble metals can be collected in the primary loop **102** by replaceable high surface area metal sponges **85**. The use of such materials can reduce the degree to which noble metals plate on surfaces in contact with the molten fuel-salt mixture. It is desirable to reduce such plating because noble metals' plating onto the heat exchanger **112** can change its heat transfer properties.

[0151] In some implementations, the nuclear reactor system **101** can include an intermediate loop that contains a non-radioactive molten salt or any other suitable working fluid. The intermediate loop can be held at a pressure slightly higher than that of primary loop **102**. As such, if there were a leak between the intermediate loop and the primary loop, the pressure difference can prevent the radioactive fuel-salt mixture from entering the intermediate loop.

[0152] In some implementations, the secondary loop will contain a suitable working fluid, such as helium, carbon dioxide, or steam, or a combination of two or more of them, that will not be corrosive, as a molten halide salt would be, nor contain radioactive materials. Because the secondary loop will not be subjected to significant corrosion or radiation damage, there is more leeway in choosing materials for the

secondary loop piping than for the primary loop piping. The secondary loop piping may be constructed of a suitable material such as stainless steel.

[0153] The Brayton cycle can use helium, carbon dioxide, or another suitable fluid. In some implementations, the secondary loop **104** can use a steam cycle such as a Rankine cycle, or a combined cycle, which incorporates an assembly of heat engines that use the same source of heat. A Rankine cycle is a method of converting heat into mechanical work that is commonly used in coal, natural gas, oil, and nuclear power plants. A Brayton cycle is an alternative method of a method of converting heat into mechanical work, which also relies on a hot, compressed working fluid such as helium or carbon dioxide. The helium Brayton cycle has the advantage that, in some instances, tritium can be scrubbed (removed) from helium more easily than it can be scrubbed from water. The Brayton cycle may also operate at higher temperatures, which allows for greater thermodynamic efficiency when converting heat to mechanical work. Additional or different factors may be considered in selecting a thermodynamic cycle for the secondary loop **104**. Use of open-cycle Brayton turbines is well-established in aircraft and in natural gas power plants. Closed-cycle helium Brayton turbines have been demonstrated at the lab scale.

[0154] In some implementations, it would be possible to use the high-temperature process heat produced by the reactor directly. This high-temperature process heat could be used, for example, in hydrogen production, or water desalinization, or district heating, or any combination of two or more of them.

[0155] In some implementations, a tritium scrubber component **116** of the secondary loop **104** can incorporate a wide variety of systems, components, and techniques. In a molten salt reactor, tritium can be mobile. For example, the tritium can diffuse readily through the fuel-salt mixture and across the heat exchanger **112** into the secondary loop **104**. Such tritium can be scrubbed (e.g., continually, periodically, or otherwise) from the secondary loop **104**, for example, to prevent the release of tritium into the environment.

[0156] In some implementations, the nuclear reactor system **101** receives spent nuclear fuel **139** from another nuclear reactor system **143**. For example, spent nuclear fuel pellets **147** from another nuclear reactor system can be separated from the metal cladding. The pellets can then be dissolved in a molten halide salt **145** for charging the primary loop. In some cases, the spent nuclear fuel can be manipulated in a variety of ways before being combined with the molten fluoride salt. For example, the fuel assembly can be mechanically chopped and shaken to separate the bulk of the spent fuel from the metal cladding. After the bulk of the metal cladding is separated from the spent fuel, some residual metal cladding may remain on the separated fuel. Then, a suitable solvent can be applied to dissolve either the fuel, the cladding, or both. The fuel and cladding materials may be separated more easily when they are in a dissolved state.

[0157] In some implementations, the molten fuel-salt mixture is formed using a halide salt **149** (e.g., LiF) that does not yet contain any radioactive material. The halide salt is placed in a mixing vessel and heated until molten in a furnace **151**. When the salt is molten, the spent nuclear fuel pellets **147** are added to the molten salt, and the components are mixed until the actinides from the spent fuel pellets are dissolved in the salt to form the fuel-salt mixture. The fuel-salt mixture is then added to the primary loop through the port on the side of the

primary loop. In some implementations, computer simulations can determine the actinide and fission product concentrations in the fuel-salt mixture following the fuel-salt mixture's addition to the primary loop. These computer simulations can, in turn, be used to predict the neutron energy spectrum in the reactor core **106**. In some cases, following these computer simulations, the loading and unloading cycles of fuel in the reactor can be regulated to ensure an optimal neutron spectrum in the reactor core **106**.

[0158] In some implementations, the fuel used in the fuel salt mixture can include spent nuclear fuel from other reactors, as we have mentioned. The spent nuclear fuel is typically available in assemblies, which have been removed from an existing reactor **143**, and include hollow casings (cladding) of another material that are filled with the spent nuclear fuel in the form of pellets. In some implementations, the assemblies would be altered by removing the cladding to expose the spent fuel pellets. When we speak of unprocessed spent nuclear fuel, however, we do not consider the removal of the cladding to be processing of the spent nuclear fuel. When we say that the spent nuclear fuel is unprocessed we mean that nothing has been done (for example, chemically or reactively, or by way of separation) to change the composition of the spent nuclear fuel that was inside the casing. In some implementations this entire unprocessed spent nuclear fuel vector is used in the reactor. In some implementations, chemical, reactive, or separation processing can be applied to the spent nuclear fuel before it is used in the reactor. For example, we may remove the fission products from the spent nuclear fuel. Removing fission products from the spent nuclear fuel does not change the actinide vector of the spent nuclear fuel. In some cases, either the entire unprocessed spent nuclear fuel vector, or the entire actinide vector, or the actinide vector following additional such processing (such as removal of U-238) can be mixed with other sources of actinides as we discuss elsewhere, in a variety of proportions or mixtures. Thus, the spent nuclear fuel that comes out of the reactor has a small fraction of fission products and a large fraction of actinides. "Unprocessed" spent nuclear fuel has none of these fission products or actinides removed. If the fission products (but not the actinides) are removed, what remains is an "entire spent fuel actinide vector." If some of the actinides (for example, U-238) are removed, what remains can be called processed fuel that contains at least portions of the spent nuclear fuel from a reactor. You can then take any one of these three (unprocessed fuel, the entire spent fuel actinide vector, or processed fuel), or combinations of any two or more them) and also can mix them with other sources of actinides.

[0159] FIG. **10** is a flow diagram showing an example process **1000** for processing nuclear materials. The example process **1000** includes operations performed by multiple entities. In particular, as shown in FIG. **10**, aspects of the example process **1000** can be performed by the operators of a light water reactor system **1002**, a molten salt reactor system **1004**, an electrical utility **1006**, and a waste facility **1008**. In some implementations, the process **1000** can include additional or different operations that are performed by the entities shown or by different types of entities.

[0160] In some implementations, the light water reactor system **1002** can include a typical light water nuclear reactor or a different type of nuclear reactor system. The light water reactor system **1002** receives nuclear fuel **1003** and generates power by a reaction of the nuclear fuel. The output power **1022** from the reaction of the nuclear fuel can be converted

and delivered to the electrical utility **1006**. The electrical utility **1006** can distribute the output power **1022** to consumption sites **1007** as electricity. For example, the electrical utility **1006** may use a power grid to distribute electrical power. In some cases, the electrical utility **1006** can convert, condition, or otherwise modify the output power **1022** to an appropriate format for distribution to the grid.

[0161] The light water reactor system **1002** produces spent nuclear fuel **1020** as a byproduct of the nuclear reaction that generates the output power **1022**. In some implementations, the spent nuclear fuel **1020** from the light water reactor system **1002** can be transferred to the molten salt reactor system **1004**. In some implementations, as explained earlier, the molten salt reactor system **1004** operates entirely on the spent nuclear fuel **1020** without further manipulation except removal from any cladding. For example, the molten salt reactor system **1004** can use spent nuclear fuel having substantially the material composition of the waste material produced by the light water nuclear reactor system **1002**. In some implementations, the molten salt reactor system **1004** can receive additional or different types of materials, including additional or different types of fuel. For example, the molten salt reactor system **1004** can receive fuel materials from nuclear weapon stockpiles, or nuclear waste storage facilities, or a combination of these and other sources, as mentioned earlier. In some implementations, fresh nuclear fuel can be combined in various proportions with spent nuclear fuel.

[0162] In some implementations, the molten salt reactor system **1004** can include the nuclear reactor system **101** of FIG. 1 or another type of nuclear reactor system configured to burn the spent nuclear fuel **1020**. The molten salt reactor system **1004** can be co-located with the light water reactor system **1002**, or with the waste facility **1008**, or with a combination of any two or more of these and other types of systems and facilities. The molten salt reactor system **1004** generates power by a reaction of the spent nuclear fuel material mixed with a molten salt material. The output power **1024** from the reaction of the fuel-salt mixture can be converted and output to the electrical utility **1006**. The electrical utility **1006** can distribute the output power **1024** to consumption sites **1007** in the form of electricity. In some cases, the electrical utility **1006** can convert, condition, or otherwise modify the output power **1024** to an appropriate format for distribution to the grid.

[0163] The molten salt reactor system **1004** produces waste material **1026** as a byproduct of the nuclear reaction that generates the output power **1024**. In some implementations, the waste material **1026** from the molten salt reactor system **1004** can be transferred to the waste facility **1008**. The waste facility **1008** can process, store, or otherwise manage the waste material **1026** produced by the molten salt reactor **1004**. In some implementations, the waste material **1026** includes a significantly lower level of long-radioactive-half-life materials than the spent nuclear fuel **1020**. For example, the molten salt reactor system **1004** may produce waste materials that primarily include fission products that have short half-lives, as compared to actinides.

[0164] Other implementations are within the scope of the following claims.

[0165] For example, in some cases, the actions recited in the claims can be performed in a different order and still achieve desirable results. In addition, the processes depicted in the accompanying figures do not necessarily require the particular order shown, or sequential order, to achieve desir-

able results. In some cases we have described individual or multiple devices for elements for systems for performing various functions. In many cases, references to the singular should be interpreted as references to the plural and conversely.

[0166] In some implementations of the system and techniques that we have described here, the operators of the molten salt reactors will be electric utility companies. An electric utility that operates a molten salt reactor may own the molten salt reactor or may lease it from another entity. If a utility owns and operates the molten salt reactor, it will likely finance the construction of the molten salt reactor. If the molten salt reactor is leased to the operator, the manufacturer of the molten salt reactor will likely finance the construction.

[0167] In some implementations, an electric utility company may operate light water reactors, which produce spent nuclear fuel that could then be used as fuel for the molten salt reactors, or the utility may be paid to take spent nuclear fuel from another entity and use that spent nuclear fuel as fuel for the molten salt reactors. In some implementations, it is envisioned that spent nuclear fuel will be processed (e.g., removed from its cladding) at the molten salt reactor site and it is likely that the utility that operates the molten salt reactors will also process the spent nuclear fuel. In this case, the utility company would purchase halide salt from a salt producer and then mix the halide salt with processed spent nuclear fuel to create the fuel-salt mixture for use in a molten salt reactor. Alternatively, a separate company may be paid by a utility or government agency to take spent nuclear fuel, mix this spent nuclear fuel with a halide salt purchased from a salt producer, and then sell the fuel-salt mixture to molten salt reactor operators.

[0168] In some examples, the waste produced by the molten salt reactors will be taken, for a fee, by a governmental agency that oversees permanent waste disposal. This waste would be processed (e.g. vitrified) into a waste-form suitable for placement in a long-term disposal facility. If immediate disposal is unavailable (as is presently the case in all countries), the waste may be stored on site until long-term storage becomes available, or it may be taken, for a fee, by a government agency or third party for short-term storage until long-term storage becomes available.

[0169] The same concepts of using hydrides or deuterides, such as metal hydrides, as moderating material, which we described in the context of a molten salt reactor, may be applied, for example, in molten salt cooled reactors or in accelerator driven systems. Molten salt cooled reactors use distinct fuel and coolants, whereas molten salt reactors use fuel that is mixed with the coolant. Molten salt cooled reactors can have fuel elements that are of essentially any shape; likely shapes are rods or pebbles. The salt coolant, which contains no fuel material, flows around these fuel elements. Previous molten salt cooled reactor designs have proposed using graphite as a moderator. These designs could be altered to use hydride or deuteride moderators, for example, metal hydride moderators, in place of, or in addition to, graphite moderators. Metal hydride moderators for use in molten salt cooled reactors may take any of the forms described above for use in molten salt reactors.

[0170] Another potential application of hydride or deuteride moderators is in an accelerator driven systems (ADS). In ADS, neutrons are produced through a process known as spallation when a proton beam from a high energy accelerator is directed at a heavy metal target. When the heavy metal

target is surrounded by nuclear fuel, the spallation neutrons can induce fission in the nuclear fuel, which in turn produces even more neutrons.

[0171] Because the nuclear fuel is in a subcritical configuration, a nuclear chain reaction cannot be sustained without the spallation neutrons produced by the accelerator. This means the reactor may be shut down by simply turning off the accelerator. Such a system is called an accelerator driven system.

[0172] ADSs can be used to destroy actinide waste (e.g. spent nuclear fuel from conventional reactors, depleted uranium, excess weapons material). A hydride or deuteride (e.g., metal hydride) moderator may be useful, as it would slow down the high energy spallation neutrons to energies that are more efficient for transmuting or fissioning the surrounding actinide fuel. Thorium fuelled ADSs have also been proposed. Such systems use spallation neutrons and subsequent fission neutrons to convert thorium-232 into protactinium-233, which quickly decays to fissile uranium-233. The transmutation of thorium-232 into uranium-233 is most efficient with thermal neutrons. Hydride or deuteride moderators could be used in such a thorium fuelled ADS to soften the neutron energy spectrum to allow more efficient breeding of U-233 from thorium.

[0173] For both types of ADSs, it may be advantageous to place hydride or deuteride moderators around the heavy metal target to reduce the energy of the spallation neutrons. Especially in the thorium fuelled ADS, it may be advantageous to include such moderators not just around the target, but also in the surrounding nuclear fuel zone, as the entire system requires a soft neutron spectrum for optimal U-233 production.

1. An apparatus comprising:
 - a fissionable material,
 - a molten salt, and
 - a moderator material comprising one or more hydrides, one or more deuterides, or a combination of two or more of them.
2. The apparatus of claim 1 in which the moderator material comprises a metal hydride.
3. The apparatus of claim 1 in which the moderator material comprises a form of zirconium hydride.
4. The apparatus of claim 3 in which the moderator material comprises $ZrH_{1.6}$.
5. The apparatus of claim 1 in which the moderator material comprises a form of lithium hydride.
6. The apparatus of claim 1 in which the moderator material comprises a form of yttrium hydride.
7. The apparatus of claim 6 in which the form comprises yttrium(II) hydride (YH_2).
8. The apparatus of claim 6 in which the form comprises yttrium(III) hydride (YH_3).
9. The apparatus of claim 1 in which the moderator material comprises a form of zirconium deuteride.
10. The apparatus of claim 1 in which the fissionable material comprises at least portions of spent nuclear fuel of a reactor.
11. The apparatus of claim 1 in which the fissionable material comprises an entire spent nuclear fuel actinide vector.
12. The apparatus of claim 1 in which the fissionable material comprises unprocessed spent nuclear fuel.
13. The apparatus of claim 1 in which the fissionable material comprises other than spent nuclear fuel.

14. The apparatus of claim 1 in which the fissionable material comprises plutonium from decommissioned weapons.

15. The apparatus of claim 1 in which the fissionable material comprises uranium from decommissioned weapons.

16. The apparatus of claim 1 in which the fissionable material comprises naturally occurring uranium.

17. The apparatus of claim 1 in which the fissionable material comprises fresh fuel.

18. The apparatus of claim 1 in which the fissionable material comprises depleted uranium.

19. The apparatus of claim 1 in which the fissionable material comprises natural uranium, enriched uranium, depleted uranium, plutonium or uranium from spent nuclear fuel, plutonium down-blended from excess nuclear weapons materials, thorium and a fissile material, transuranic material, or a combination of any two or more of them.

20. The apparatus of claim 1 in which the fissionable material comprises a fissile-to-fertile ratio in the range of 0.01-0.25.

21. The apparatus of claim 1 in which the fissionable material comprises at least one of U-233, U-235, Pu-239, or Pu-241.

22. The apparatus of claim 21 in which the fissionable material also comprises U-238.

23. The apparatus of claim 21 in which the fissionable material also comprises thorium.

24. The apparatus of claim 1 in which the molten salt comprises a fluoride salt.

25. The apparatus of claim 1 in which the molten salt comprises a chloride salt.

26. The apparatus of claim 1 in which the molten salt comprises an iodide salt.

27. The apparatus of claim 1 in which the molten salt comprises lithium fluoride.

28. The apparatus of claim 27 in which the lithium fluoride is enriched in its concentration of Li-7.

29. The apparatus of claim 1 in which solubility of actinides in the molten salt is sufficient to permit the fissionable material to become critical.

30. The apparatus of claim 29 in which the solubility of actinides in the molten salt is at least 0.3%.

31. The apparatus of claim 29 in which solubility of actinides in the molten salt is at least 12%.

32. The apparatus of claim 29 in which solubility of actinides in the molten salt is at least 20%.

33. The apparatus of claim 1 in which the molten salt comprises essentially no beryllium.

34. The apparatus of claim 1 in which the molten salt comprises an amount of beryllium.

35. The apparatus of claim 1 in which the fissionable material is combined with the molten salt.

36. The apparatus of claim 1 in which the fissionable material and the molten salt are distinct from the moderator.

37. The apparatus of claim 36 in which the molten salt provides some moderation.

38. An apparatus comprising:

- a fissionable material comprising spent nuclear fuel of a reactor combined with a molten lithium fluoride salt that is essentially free of beryllium, and
- a zirconium hydride moderator that is distinct from the combined fissionable material and salt.

39. A nuclear reaction moderator structure comprising a hydride or deuteride and one or more passages for molten salt fuel to flow through the structure or around the structure or

both, the structure being configured so that the molten salt fuel is in a critical state while in the structure.

40. The structure of claim 39 in which the moderator material comprises a metal hydride.

41. The apparatus of claim 39 in which the moderator material comprises a form of zirconium hydride.

42. The structure of claim 41 in which the moderator material comprises $ZrH_{1.6}$.

43. The apparatus of claim 39 in which the moderator material comprises a form of lithium hydride.

44. The apparatus of claim 39 in which the moderator material comprises a form of yttrium hydride.

45. The apparatus of claim 44 in which the form comprises yttrium(II) hydride (YH_2).

46. The apparatus of claim 44 in which the form comprises yttrium(III) hydride (YH_3).

47. The apparatus of claim 39 in which the moderator material comprises a form of zirconium deuteride.

48. The structure of claim 39 comprising at least two such passages.

49. The structure of claim 39 comprising plates separated by the passages.

50. The structure of claim 39 comprising at least two such passages in parallel.

51. The structure of claim 39 in which the one or more passages are tubular.

52. The structure of claim 39 extending in each of three dimensions and comprising three-dimensional discrete structural elements each of which has an extent in each of the three dimensions that is smaller than the extent of the structure, the discrete structural elements being arranged in the structure with the passage or passages between the discrete structures or within the discrete structures or both.

53. The structure of claim 39 comprising balls, or spheres, or pebbles, or a combination of any two or more of them, arranged in three dimensions.

54. The structure of claim 39 comprising an integral block of moderator material in which the passages are formed.

55. The structure of claim 39 comprising a set of discrete elements.

56. The structure of claim 55 in which the discrete elements are identical.

57. The structure of claim 39 having an entry end and an exit end and in which the passage or passages extend from the entry end to the exit end.

58. The structure of claim 39 comprising rods.

59. The structure of claim 58 in which the rods comprise at least one of cylinders, annular rods, finned rods, helical rods, twisted helical rods, annular helical rods, annular twisted helical rod, rods with wire wrapped spacers, or annular rods with wire wrapped spacers, or a combination of two or more of them.

60. The structure of claim 39 comprising reactivity control elements that are movable relative to the structure.

61. A method comprising:

in a nuclear reactor, flowing fissionable material and a molten salt past a moderator material that comprises one or more hydrides, deuterides, or a combination of two or more of them.

62. The method of claim 61 in which flowing the fissionable material and the molten salt past the moderator material comprises flowing a fuel-salt mixture through a reactor core, the fuel-salt mixture comprising the fissionable material and the molten salt.

63. The method of claim 62 comprising flowing the fuel-salt mixture through a fission product removal system.

64. The method of claim 62 comprising flowing the fuel-salt mixture through a heat exchanger.

65. The method of claim 61 in which the fissionable material comprises an entire spent nuclear fuel actinide vector.

66. The method of claim 61 in which the fissionable material comprises portions but not all of the actinides of spent nuclear fuel.

67. The apparatus of claim 61 in which the fissionable material comprises unprocessed spent nuclear fuel.

68. A method comprising forming a nuclear reactor moderator structure comprising a moderator material that comprises one or more hydrides, deuterides, or a combination of them, and one or more passages for fissionable fuel to flow through the structure.

69. A nuclear reactor comprising:

a primary loop comprising:

a reactor core comprising a moderator structure comprising a moderator material that comprises one or more hydrides, deuterides, or a combination of them, and

a pathway along which a fissionable material and molten salt can flow from an exit end of the moderator structure in a loop to an entrance end of the moderator structure.

70. The reactor of claim 69 comprising a secondary loop and a heat exchanger to exchange heat between the primary loop and the secondary loop.

71. The reactor of claim 69 comprising an intermediate loop, a secondary loop, a heat exchanger to exchange heat between the primary loop and the intermediate loop, and an additional heat exchanger to exchange heat between the intermediate loop and the secondary loop.

72. The reactor of claim 69 also comprising a freeze valve.

73. A method comprising:

constructing a nuclear reactor by connecting a moderator structure, comprising a moderator material that comprises one or more hydrides, deuterides, or a combination of them, to a pathway along which a fissionable material and molten salt can flow from an exit end of the moderator structure to an entrance end of the moderator structure, to form a primary loop.

74. A nuclear reactor fuel comprising:

spent fuel of a light water reactor in a molten salt in which solubility of heavy nuclides of the spent fuel, in the molten salt, is sufficient to permit the fissionable material to become critical.

75. The apparatus of claim 74 in which the spent fuel comprises an entire spent nuclear fuel actinide vector.

76. The apparatus of claim 74 in which the spent fuel comprises unprocessed spent nuclear fuel.

77. The apparatus of claim 74 in which the molten salt comprises essentially no beryllium.

78. A method comprising forming a nuclear reactor fuel, the method comprising mixing spent fuel of a light water reactor with a molten salt in which solubility of actinides of the spent fuel, in the molten salt, is sufficient to permit the fissionable material to become critical.

79. The method of claim 78 in which the spent fuel comprises an entire spent nuclear fuel actinide vector.

80. The method of claim 78 in which the spent fuel comprises unprocessed spent nuclear fuel.

81. The method of claim **78** in which the fissionable material comprises portions but not all of the actinides of spent nuclear fuel.

82. A method comprising:
operating a light water reactor,
recovering spent nuclear fuel from the light water reactor,
combining the recovered spent nuclear fuel with molten salt, and
operating a molten salt reactor using the recovered spent nuclear fuel with molten salt.

83. The method of claim **82** in which the spent nuclear fuel comprises an entire spent nuclear fuel actinide vector.

84. The method of claim **82** in which the spent nuclear fuel comprises unprocessed spent nuclear fuel.

85. The method of claim **82** in which the fissionable material comprises portions but not all of the actinides of spent nuclear fuel.

86. A method comprising reducing supplies of existing spent nuclear fuel by operating a molten salt nuclear reactor using, as fuel, spent nuclear fuel, from another reactor.

87. A method comprising generating electricity using existing spent nuclear fuel by operating a molten salt nuclear reactor using, as fuel, spent nuclear fuel, from another reactor.

88. A method comprising reducing supplies of nuclear weapons material by operating a molten salt nuclear reactor using, as fuel, spent nuclear fuel, from another reactor.

89. A method comprising reducing supplies of existing depleted uranium by operating a molten salt nuclear reactor using, as fuel, spent nuclear fuel, from another reactor.

90. A method comprising:
receiving a fluid in a reactor core, the fluid having a fissile-to-fertile ratio similar to the fissile-to-fertile ratio of spent nuclear fuel from a light water nuclear reactor.

91. The method of claim **90** in which the fluid comprises a molten salt mixture.

92. An apparatus comprising
a reactor comprising nuclear fuel and a molten salt coolant that is distinct from the fuel, and
moderator elements comprising one or more hydrides or deuterides.

93. The apparatus of claim **92** in which at least one of the hydrides comprises a metal hydride.

94. The apparatus of claim **92** in which the moderator elements comprise graphite in combination with the one or more hydrides.

95. An apparatus comprising
a reactor comprising a nuclear fuel in a sub-critical state and an accelerator driven source of neutrons in proximity to the nuclear fuel, and
moderator elements comprising one or more hydrides or deuterides.

96. The apparatus of claim **95** in which the accelerator driven source comprises a heavy metal target.

97. The apparatus of claim **96** in which the moderator elements are in proximity to the heavy metal target.

98. The apparatus of claim **95** in which the moderator elements are in proximity to the nuclear fuel.

99. The apparatus of claim **95** in which the fuel comprises thorium.

100. The apparatus of claim **95** in which the fuel comprises spent nuclear fuel.

101. The apparatus of claim **95** in which the fuel comprises transuranic material from spent nuclear fuel.

102. The apparatus of claim **95** in which the fuel comprises minor actinide material from spent nuclear fuel.

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