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DRILLHOLE NUCLEAR REACTOR

Abstract

A nuclear reactor system includes a drillhole that extends from a terranean surface through one or more subterranean formations; a reactor core positioned in the drillhole, the reactor core comprising at least one nuclear fuel element; a primary coolant system configured to transport a primary fluid coolant between the reactor core and a heat exchanger; and a secondary coolant system thermally coupled to the primary coolant system with the heat exchanger and configured to transport a secondary fluid coolant between the heat exchanger and the terranean surface.

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Background/Summary

TECHNICAL BACKGROUND

[0001] This disclosure relates to systems and methods for generating power from a fission reactor formed by placing fissile material in a drillhole.

BACKGROUND

[0002] Highly radioactive material, such as radioactive waste, chemical waste, biologic waste, or other waste that is generally harmful to living creatures whether directly or indirectly, can be placed underground within (or outside of) canister systems. As an example, radioactive waste (also referred to as nuclear waste) can be stored in deep, human-unoccupiable drillholes that are formed from a terranean surface into one or more subterranean formations that are suitable to store such waste for years, decades, centuries, or longer. For instance, the human-unoccupiable drillholes (also called boreholes or wellbores) can be directional drillholes formed with conventional drilling equipment and include vertical, curved, and horizontal portions (including multilaterals in some cases). Alternatively, the human-unoccupiable drillholes can be substantially vertical or slanted (e.g., formed offset from substantially vertical). The isolation afforded by such boreholes suggests that they can be used, not only for the disposal of dangerous material, but as a site for the operation of a nuclear power plant.

SUMMARY

[0003] In an example implementation, a nuclear reactor system includes a drillhole that extends from a terranean surface through one or more subterranean formations; a reactor core positioned in the drillhole, the reactor core including at least one nuclear fuel element; a primary coolant system configured to transport a primary fluid coolant between the reactor core and a heat exchanger; and a secondary coolant system thermally coupled to the primary coolant system with the heat exchanger and configured to transport a secondary fluid coolant between the heat exchanger and the terranean surface.

[0004] In an aspect combinable with the example implementation, the at least one nuclear fuel element includes a fissile nuclear fuel element.

[0005] In another aspect combinable with any of the previous aspects, the fissile fuel element includes at least one of enriched uranium, plutonium, uranium or plutonium oxide, or a mixed oxide (MOX).

[0006] Another aspect combinable with any of the previous aspects includes at least one canister that at least partially encloses the at least one nuclear fuel element.

[0007] In another aspect combinable with any of the previous aspects, the canister includes a first opening at an uphole end of the canister and a second opening at a downhole end of the canister.

[0008] In another aspect combinable with any of the previous aspects, the primary coolant system is configured to transport the primary fluid coolant between the reactor core and the heat exchanger by at least one of natural circulation or pumping.

[0009] Another aspect combinable with any of the previous aspects includes one or more pumps configured to provide a force for transporting the primary fluid coolant between the reactor core and the heat exchanger.

[0010] In another aspect combinable with any of the previous aspects, the secondary coolant system is configured to transport the secondary fluid coolant between the heat exchanger and the terranean surface by natural circulation.

[0011] Another aspect combinable with any of the previous aspects includes one or more pumps

configured to provide a force for transporting the secondary fluid coolant between the heat exchanger and the terranean surface.

[0012] In another aspect combinable with any of the previous aspects, the primary fluid coolant includes water.

[0013] In another aspect combinable with any of the previous aspects, the secondary fluid coolant includes water.

[0014] In another aspect combinable with any of the previous aspects, the primary coolant system is fluidly isolated from the second coolant system.

[0015] In another aspect combinable with any of the previous aspects, the heat exchanger is configured to transfer heat from the primary fluid coolant in the primary coolant system to heat the secondary fluid coolant in the second coolant system to a higher temperature liquid phase or a gas phase.

[0016] Another aspect combinable with any of the previous aspects includes a power conversion system.

[0017] In another aspect combinable with any of the previous aspects, the power conversion system is located at or near the terranean surface.

[0018] In another aspect combinable with any of the previous aspects, the secondary fluid coolant includes a power conversion working fluid of the power conversion system.

[0019] In another aspect combinable with any of the previous aspects, the at least one nuclear fuel element is positioned at a first depth of the drillhole.

[0020] In another aspect combinable with any of the previous aspects, the first depth is up to 0.5 km from the terranean surface, 1.0 to 1.5 km from the terranean surface, or 1.5 km or greater from the terranean surface.

[0021] In another aspect combinable with any of the previous aspects, the heat exchanger includes a barrier configured to fluidly isolate the primary coolant system from the second coolant system, the barrier being positioned at a second depth of the drillhole, the second depth being less than the first depth.

[0022] Another aspect combinable with any of the previous aspects includes one or more pipes extending from the terranean surface to a third depth of the drillhole, the third depth being greater than the second depth.

[0023] In another aspect combinable with any of the previous aspects, the one or more pipes is configured to provide the primary fluid coolant to a region of the drillhole below the second depth.

[0024] In another aspect combinable with any of the previous aspects, the primary coolant system includes a first pipe having a diameter less than a diameter of the drillhole, the first pipe being positioned in the drillhole with an axis of the first pipe being approximately parallel to an axis of the drillhole, the reactor core being positioned inside the first pipe, the system including an annulus defined between the first pipe and the drillhole, the annulus including a flow circuit configured to convey the primary fluid coolant in a downhole direction to the reactor core.

[0025] In another aspect combinable with any of the previous aspects, the secondary coolant system includes a second pipe having a diameter less than the diameter of the drillhole, the second pipe being positioned in the drillhole with an axis of the second pipe being approximately parallel to the axis of the drillhole, the system including an annulus defined between the second pipe and the drillhole, the annulus including a flow circuit configured to convey the secondary fluid coolant in a downhole direction to the heat exchanger.

[0026] In another aspect combinable with any of the previous aspects, the secondary coolant system includes a first pipe having a diameter less than the diameter of the drillhole and configured to transport the secondary fluid coolant to the heat exchanger for heating; and a second pipe having a diameter less than the diameter of the drillhole and configured to transport heated secondary fluid coolant from the heat exchanger toward the terranean surface.

[0027] In another aspect combinable with any of the previous aspects, a diameter of the drillhole is

thirty-six inches or less.

[0028] In another aspect combinable with any of the previous aspects, a diameter of the drillhole is four inches or more.

[0029] In another aspect combinable with any of the previous aspects, the heat exchanger is positioned within a casing that is installed in the drillhole.

[0030] In another aspect combinable with any of the previous aspects, the primary coolant system includes at least one pipe installed external to the casing and to the heat exchanger, and the secondary coolant system includes at least another pipe installed external to the casing.

[0031] In another aspect combinable with any of the previous aspects, the casing is installed in the drillhole with a cement layer, and the heat exchanger is installed external to the cement layer.

[0032] In another aspect combinable with any of the previous aspects, the reactor core is controllable between a low power output and a maximum power output.

[0033] In another aspect combinable with any of the previous aspects, the reactor core is controllable with a fluid that includes a neutron absorber.

[0034] In another aspect combinable with any of the previous aspects, the neutron absorber is controllably added to the primary fluid coolant.

[0035] In another aspect combinable with any of the previous aspects, the reactor core is controllable with at least one control rod configured to move near or adjacent the at least one nuclear fuel element.

[0036] In another aspect combinable with any of the previous aspects, the reactor core is a first reactor core and the nuclear fuel element includes a first nuclear fuel element, the system including a second reactor core positioned in the drillhole, the second reactor core including at least one second nuclear fuel element.

[0037] In another aspect combinable with any of the previous aspects, the first and second reactor cores are individually controllable between a low power output and a maximum power output.

[0038] In another aspect combinable with any of the previous aspects, each of the first and second reactor cores is individually controllable with a fluid that includes a neutron absorber.

[0039] In another aspect combinable with any of the previous aspects, the fluid is individually transported to each of the first and second nuclear reactor cores through one or more tubes that extends from the terranean surface to the first and second nuclear reactor cores.

[0040] In another aspect combinable with any of the previous aspects, the neutron absorber is controllably added to the fluid.

[0041] In another aspect combinable with any of the previous aspects, each of the first and second reactor cores is individually controllable with respective first and second control rods that are moveable into or near the respective first and second nuclear reactor cores.

[0042] Another aspect combinable with any of the previous aspects includes one or more inverted cups positioned in the primary coolant system and within a flowpath of the primary fluid coolant.

[0043] In another aspect combinable with any of the previous aspects, the one or more inverted cups are coupled to a cladding of the at least one nuclear fuel element.

[0044] Another aspect combinable with any of the previous aspects includes a reflector configured to reflect neutrons generated in the reactor core without absorbing the neutrons.

[0045] In another aspect combinable with any of the previous aspects, the reflector includes at least one of beryllium, carbon, a beryllium alloy, or a carbon alloy.

[0046] In another aspect combinable with any of the previous aspects, a particular subterranean formation of the one or more subterranean formations that is adjacent the reactor core is configured to act as a reflector to reflect neutrons generated in the reactor core.

[0047] In another aspect combinable with any of the previous aspects, the casing is a material sufficient to act as a reflector to reflect neutrons generated in the reactor core.

[0048] In another aspect combinable with any of the previous aspects, the material of the casing includes at least one of carbon steel, stainless steel, ceramic, a plastic material, or fiberglass.

[0049] In another example implementation, a method of constructing a nuclear reactor system includes forming a drillhole from a terranean surface through one or more subterranean formation; moving at least one nuclear fuel element into the drillhole; positioning the at least one nuclear fuel element at a first depth of the drillhole; moving a heat exchanger into the drillhole, wherein the heat exchanger includes a fluid barrier; and positioning the heat exchanger in the drillhole with the fluid barrier being positioned at a second depth of the drillhole, the second depth being less than the first depth.

[0050] In an aspect combinable with the example implementation, the at least one nuclear fuel element includes a fissile nuclear fuel element.

[0051] Another aspect combinable with any of the previous aspects includes at least one canister that at least partially encloses the at least one nuclear fuel element.

[0052] In another aspect combinable with any of the previous aspects, the canister includes an opening at one or both ends, the method including positioning the canister in the drillhole with an opening facing a downhole direction.

[0053] Another aspect combinable with any of the previous aspects includes installing the power conversion system at or near the terranean surface.

[0054] Another aspect combinable with any of the previous aspects includes inserting one or more pipes extending from the terranean surface to a third depth of the drillhole, the third depth being greater than the second depth.

[0055] In another example implementation, a method includes identifying a nuclear reactor system that includes a drillhole that extends from a terranean surface through one or more subterranean formations; a reactor core positioned in the drillhole, the reactor core including at least one nuclear fuel element; a primary coolant system; and a secondary coolant system thermally coupled to the primary coolant system with a heat exchanger and configured to transport a secondary fluid coolant between the heat exchanger and the terranean surface. The method includes transporting a primary fluid coolant in the primary coolant system between the reactor core and the heat exchanger; transporting a secondary fluid coolant heated in the heat exchanger by the primary fluid coolant in the secondary coolant system between the heat exchanger and the terranean surface; and generating power with the heated secondary fluid coolant.

[0056] An aspect combinable with the example implementation includes transporting the primary fluid coolant into a region of the drillhole below a depth of a fluid barrier of the heat exchanger; and transporting the secondary fluid coolant into a region of the drillhole above the depth of the fluid barrier, wherein the fluid barrier fluidly isolates the primary fluid coolant from the second fluid coolant.

[0057] Another aspect combinable with any of the previous aspects includes transporting the primary fluid coolant into the drillhole through one or more pipes extending from the terranean surface to a depth of the drillhole that is deeper than the depth of the fluid barrier.

[0058] In another aspect combinable with any of the previous aspects, the primary and the secondary fluid coolants include water.

[0059] In another example implementation, a nuclear reactor system includes a first drillhole extending from a terranean surface through one or more subterranean formations; a reactor core positioned in the first drillhole, the reactor core including at least one nuclear fuel element; a second drillhole extending from the terranean surface through the one or more subterranean formations and separated from the first drillhole by a portion of a rock formation; a heat exchanger positioned in the second drillhole in thermal communication with the reactor core through the portion of the rock formation; and a coolant system thermally coupled to the heat exchanger and configured to transport a fluid coolant between the heat exchanger and the terranean surface.

[0060] In an aspect combinable with the example implementation, the at least one nuclear fuel element includes a fissile nuclear fuel element.

[0061] Another aspect combinable with any of the previous aspects includes at least one canister

that at least partially encloses the at least one nuclear fuel element.

[0062] In another aspect combinable with any of the previous aspects, the canister includes openings at axial ends of the canister.

[0063] In another aspect combinable with any of the previous aspects, the coolant system is configured to transport the fluid coolant between the heat exchanger and the terranean surface by natural circulation.

[0064] Another aspect combinable with any of the previous aspects includes one or more pumps configured to provide a force for transporting the fluid coolant between the heat exchanger and the terranean surface.

[0065] In another aspect combinable with any of the previous aspects, the fluid coolant includes water.

[0066] In another aspect combinable with any of the previous aspects, the heat exchanger is configured to transfer heat from the primary coolant system to the fluid coolant in the secondary coolant system.

[0067] Another aspect combinable with any of the previous aspects includes a power conversion system.

[0068] In another aspect combinable with any of the previous aspects, the power conversion system is located at the terranean surface.

[0069] In another aspect combinable with any of the previous aspects, the fluid coolant includes a power conversion working fluid of the power conversion system.

[0070] In another aspect combinable with any of the previous aspects, the at least one nuclear fuel element is positioned at a first depth of the first drillhole.

[0071] In another aspect combinable with any of the previous aspects, the first depth is less than 0.5 km from the terranean surface, 1.0-1.5 km from the terranean surface, or 1.5 km or greater from the terranean surface.

[0072] In another aspect combinable with any of the previous aspects, a diameter of the first drillhole is thirty-six inches or less.

[0073] In another aspect combinable with any of the previous aspects, a diameter of the first drillhole is four inches or more.

[0074] In another aspect combinable with any of the previous aspects, the reactor core is a first reactor core and the nuclear fuel element includes a first nuclear fuel element, the system including a second reactor core positioned in the first drillhole, the second reactor core including at least one second nuclear fuel element.

[0075] In another aspect combinable with any of the previous aspects, the first and second reactor cores are individually controllable between a low power output and a maximum power output.

[0076] In another aspect combinable with any of the previous aspects, each of the first and second reactor cores is individually controllable with a fluid that includes a neutron absorber.

[0077] In another aspect combinable with any of the previous aspects, the fluid is individually transported to each of the first and second nuclear reactor cores through one or more sets of tubes that extend from the terranean surface to the first and second nuclear reactor cores.

[0078] In another aspect combinable with any of the previous aspects, the neutron absorber is controllably added to the fluid.

[0079] In another aspect combinable with any of the previous aspects, each of the first and second reactor cores is individually controllable with a control rod assembly that is moveable into or near the respective first and second nuclear reactor cores.

[0080] The details of one or more implementations of the subject matter described in this disclosure are set forth in the accompanying drawings and the description below. Other features, aspects, and advantages of the subject matter will become apparent from the description, the drawings, and the claims.

Description

BRIEF DESCRIPTION OF THE DRAWINGS

[0081] FIGS. 1-3 are schematic diagrams of an example implementation of a drillhole (or borehole) nuclear reactor system according to the present disclosure.

[0082] FIG. 4 is a schematic diagram of another example implementation of a drillhole (or borehole) nuclear reactor system according to the present disclosure.

[0083] FIGS. 5A and 5B are schematic diagrams of another example implementation of a drillhole (or borehole) nuclear reactor system according to the present disclosure.

[0084] FIG. 6 is a schematic diagram of nuclear fuel element for a drillhole nuclear reactor system according to the present disclosure.

DETAILED DESCRIPTION

[0085] A nuclear fission reactor is described. In general, nuclear fuel stored in canisters in a vertical, slanted, or directional drillhole creates an underground fission reactor to which a power system can be fluidly (e.g., gas, liquid, mixed-phase fluid) coupled to remove thermal energy from the drillhole to bring useful power to the surface or near surface. The reactor fits in a human-unoccupiable drillhole (or borehole) buried deeply in the ground. The example nuclear fission reactors according to the present disclosure can take advantage of the fact that the hydrostatic pressure of the brine in the rock is typically one atmosphere per ten meters. Thus, due to the depth at which nuclear fuel is stored in the drillhole, the nuclear reactor in a borehole at one kilometer (km) will have a pressure of one hundred atmospheres; at 1.5 km the pressure will be one hundred-fifty atmospheres, approximately equal to that of a pressurized water reactor (PWR).

[0086] At 150 atmospheres of pressure, water boils at about 325° C. Light water (H.sub.2O), heavy water (D.sub.2O), other materials containing hydrogen, or a combination can be used for a moderator (e.g., liquids and gases and reactor coolant). The moderator of a nuclear reactor is a substance that slows neutrons. In the example of a light water moderator, collisions between fast neutrons and hydrogen atoms of the water cause the fast neutrons to slow to lower speeds. At lower speeds, the neutrons are more susceptible to propagate a nuclear fission chain reaction.

[0087] Control of the rate of the chain reaction can be accomplished physically (such as adding or subtracting boron to the reactor core region) or automatically (such as inclusion of hydrogen-bearing materials in the moderator that reduce the moderation when the temperature rises). The accumulation of vapor from boiling can also be used to automatically reduce the moderator density and thus slow or stop the fission chain reaction if the reactor grows too hot. Thus, the reactor can self-control, without external intervention (e.g., control rods), to keep reactor temperature at or below the boiling point. A heat exchanger in the borehole serves to heat a separate reservoir of water that circulates to the surface, thus bringing heat, uncontaminated by radioisotopes, to the surface. Sides of the borehole (or in some aspects, a drillhole casing) can function to bring lower pressure water to the heat exchanger, where it can boil, to deliver power to the surface in the form of steam. Because the reactor is below millions to billions tons of rock, the reactor can be installed in the borehole without a separately installed or conventional containment building. Further, because the reactor is in a geologic formation in which the ambient water or brine pressure is comparable to that in a pressurized water reactor (PWR) or boiling water reactor (BWR), no thick-walled pressure vessel is needed.

[0088] For example, the present disclosure describes one or more fuel assemblies similar in configuration and size to those of a PWR or BWR fuel assembly placed near the bottom of a vertical borehole (e.g., 1.5 km deep borehole). The assembly is surrounded by “water” (e.g., water or water with additives such as soluble neutron poisons), to make the fissile fuel (e.g., uranium with greater than 0.7% uranium-235 (U-235), or which contains plutonium-239 (Pu-239), or which contains both uranium and plutonium) undergo a fission chain reaction. In other embodiments,

other materials such as graphite or uranium-zirconium hydride, can be used as a moderator. In some embodiments, a combination of moderators can be used, such as graphite and water.

[0089] In some aspects, the fuel assemblies are placed inside canisters that have open bottoms and tops. In example embodiments, if the water in the fuel assembly boils (that is, if the fuel rises above 325° C. for a reactor at a depth of 1.5 km) then gas will accumulate in void collectors, and the fission chain reaction will reduce, until the temperature lowers. Thus, the temperature of the reactor can be self-regulated at or about 325° C. The temperature can be regulated at lower temperatures at lesser depths, and at higher temperatures at greater depths.

[0090] Above the reactor in the borehole is a heat exchanger that removes heat from the reactor. In this embodiment, the heat exchanger also isolates the water (e.g., as a primary coolant) from a flow of water (e.g., as a secondary coolant) that is brought to the surface to carry the heat upward. The heat can be carried from the fuel to the heat exchanger using a pump or using natural circulation from heat-driven convection. The light water that brings the heat to the surface can do so using natural circulation, or by being actively pumped. The secondary water can be kept pressurized so that the water reaches the surface as hot water, or the water can be allowed to boil in the heat exchanger and come to the surface as steam.

[0091] Fresh (non-saline) water can be used as the fluid that carries the heat to the surface or near surface, but other fluids can also be used, such as brine, hydrocarbons, or gas such as helium or nitrogen. If a gas is used, then the gas conveyance pipe can be surrounded by a fluid filled pipe (containing, for example, fresh water) that provides emergency core cooling for the reactor. Otherwise, if water is used as the secondary fluid, then this water can also serve as a source for an emergency core cooling system (ECCS).

[0092] The upward flowing hot fluid can be partially isolated from the surrounding rock, and from the downward flowing cool water, by insulators. The rock formations surrounding the hot upward flowing pipe can also serve as an insulator. As the temperature of this rock rises, the rate of heat flow from the upward flown hot pipe into the surrounding rock will diminish, and thus the rock, once heated, serves as an insulator.

[0093] A diagram of an example reactor system **100** is shown in FIGS. **1** to **3**. FIG. **1** is an overview of a borehole nuclear reactor system for the embodiment of a vertical borehole. In this embodiment, only one hole is depicted, and it contains only one fuel assembly. In other embodiments, multiple fuel assemblies can be placed in a drillhole, either vertically arranged, or spread though branches in the borehole. Further, multiple drillholes can be used to increase the total power delivered to the surface or near surface. In addition, once the fuel in a borehole reactor is depleted, it can be removed, or, in the preferred implementation, left it place, covered with sand or other support, and a second nuclear reactor placed above it. FIG. **2** shows the reactor section of the borehole nuclear reactor system. FIG. **3** shows an example heat exchange section of the borehole nuclear reactor system. The dashed line **110** represents the same level, or depth, in FIGS. **1** to **3**. All materials in the reactor can be designed for low corrosion. One method of doing this is to include anti-corrosion materials in the fluids. Another is to make the pipes and other parts from low or non-corrosion materials including plastics. A third is to coat the metal surfaces with anti-corrosive materials, including quartz and diamond. Other methods can be evident to an engineer practiced in the anti-corrosion field.

[0094] Ultimately, when the reactor fuel is spent, the fuel can be removed from the drillhole, or left at depth, with the drillhole sealed (e.g., with a drillhole plug or otherwise). The casing to the surface can be left in place or cut and pulled out. The fuel might never be removed from the borehole **115**. In some cases, the fuel can be disposed in the borehole **115** by sealing the borehole **115** above the reactor when the fuel is spent. Such borehole disposal offers very high levels of safety. The reactor system **100** may be less expensive to build and operate compared to a standard BWR or PWR reactor. Thus, in some examples, the fission chain reaction can be designed to burn more slowly. The reactor system **100** can thus operate for long periods of time, e.g., thirty to sixty

years or longer, with need for no or few replacements of the nuclear fuel. In addition, fuel that is more highly enriched than typically used in a commercial nuclear reactor (e.g., about 4%) can be used to extend the working lifetime of the borehole reactor, that is, the time that it can deliver useful power without requiring the use of additional fuel. One example of such fuel is high assay low enriched uranium (HALEU) which is typically enriched to almost 20% U-235. Another example embodiment is that when the fuel has become sufficiently spent, that is the amount of fissionable material such as U-235 has been significantly reduced, that instead of removing the fuel assembly, it can be left in place, and a new fuel assembly put in position closer to the access hole. Doing this allows the highly radioactive spent fuel to remain safely at depth, where it will eventually be disposed by the action of sealing the borehole above the new fuel assembly (i.e., at a location in the borehole that is closer to the surface than the new fuel assembly). The reactor system **100** can be used to provide heat in the form of hot water, steam **106**, and/or by using a power conversion system, e.g., generator **102**. The generator **102** can be, for example, a turbine or thermocouple stack or other heat-driven generator. The heat can also be used for commercial purposes (such as heating buildings or for heat-intensive industry) without conversion to electricity. [0095] FIG. **1** is an overview of a borehole nuclear reactor system **100**. FIG. **1** includes a reference arrow **105** defining uphole and downhole directions. This figure shows a vertical borehole, but the borehole can be directionally drilled into a slanted or near-horizontal or other configuration. A generator **102** is located at a ground surface **104**. A vertical borehole **115** descends to a depth of approximately one-half kilometer (km) or greater (e.g., 1.0 km or greater, 1.5 km or greater, 2.0 km or greater, or other predetermined depth). The borehole **115** includes a casing **216** that can be made to adhere to the borehole wall, e.g., by being cemented with cement **214** to the borehole wall. [0096] In some aspects, a gap can also be left between the casing and the borehole wall, so that water that typically fills this gap will boil and become steam, and that steam can help to provide insulation reducing subsequent heat flow into the rock. The borehole **115** can be narrow, e.g., four to thirty-six inches in diameter.

[0097] At the bottom of the borehole **115**, nuclear fuel is held in a reactor **130** including one or more fuel assemblies (or rods) **218**. Details of the reactor **130** are described with reference to FIG. **2**. In some examples, the reactor **130** includes an individual fuel element, or fuel rod **218**. The reactor **130** is surrounded by a moderator. In some examples, the moderator is water. The reactor section is isolated from the surface **104** by a heat exchanger **120** and a pressure equalizer barrier **212** (shown in FIG. **3**). The water serves as both coolant and moderator. The water flows by natural circulation to the heat exchanger **120** above the reactor **130** through hot water pipe **205**.

[0098] An insulated pipe **208** is positioned in the borehole **115**. During operation, water **108** flows downward outside of the pipe **208**. The secondary water **108** is heated by the primary water as the secondary water **108** passes through the heat exchanger **120**. The heated water, or steam **106**, then flows upward inside the pipe **208**. The pipe **208** thus carries heat generated by the reactor **130** to the surface **104**.

[0099] Many methods can be used to cause the fuel to become critical, that is, to undergo a sustained chain reaction. One method to accomplish this can be to use a “neutron reflector”, a material that has low neutron absorption properties, and which can scatter the neutrons that are leaving the reactor region back into it. In some instances, the neutron reflector is made of graphite (carbon) or beryllium. These materials can also serve to help moderate the neutrons.

[0100] Referring to FIG. **3**, the heat exchanger **120** is depicted in a simplified schematic. Any appropriate heat exchanger system can be used for removing heat from the reactor **130**. The primary water is fluidly isolated from the secondary water by a barrier, e.g., pressure equalizer barrier **212**. The pressure equalizer can be omitted if it is desired to maintain the secondary water at a lower pressure to facilitate boiling. The barrier is positioned above the region of the system **100** in which heavy water flows, and in which the reactor **130** is located.

[0101] The system **100** includes primary water supply and drain pipes **201** and **202**, respectively.

The primary fluid supply and drain pipes **201**, **202** can be used to replace the primary fluid (or part of it) and also to provide pressure control for the reactor **130**. In some implementations, two small pipes, e.g., water supply and drain pipes **201**, **202**, penetrate the pressure equalizer barrier **212**. The pipes **201**, **202** can be used to partially replace or remove the primary water near the reactor. For example, the primary water, which might initially contain dissolved boron salts, can be replaced with fresh water, brine, or water with additional boron salts (material that quenches the fission chain reaction).

[0102] The use of boiling (creation of gas) to reduce reactivity and thus control the chain reaction is called a “negative void coefficient.” Other methods to control the reactivity are well-known in the reactor design community. They include use of neutron reflectors and absorbers with efficiency that is temperature dependent. In addition to these passive (not moving) methods, control rods can be inserted into or near the reactor. These can be controlled from the surface, or they can automatically move into the reactor region when the temperature rises. Such movement can be controlled by using materials with a temperature coefficient of expansion large enough to allow a mechanism to move the control rods. Such mechanisms are found, for example, in bimetallic thermometers in which relatively small expansion can be used to drive a readout needle over a large distance.

[0103] The pipes **201**, **202** can provide control of the content of the fluid in the reactor (for example, channeling the boron concentration), and they can also provide pressure stability. In another configuration, there can be a second pipe that goes from the reactor region to the surface to provide pressure stability. For example, when bubbles form, the space taken by the bubbles pushes water up the pipe instead of causing reactor pressure to increase. Such a pipe need not circulate water; the pipe allows enough flow upward to prevent an increase in pressure in the reactor section. The fission chain reaction can be turned off, if desired, by pumping out, e.g., pure primary water and replacing that water with water containing a neutron poison (that is, a material that absorbs neutrons), or high pressure gas such as argon or nitrogen.

[0104] The pressure equalizer barrier **212** between the primary water and secondary water provides an alternative (to the pipe described in the prior paragraph) or redundant method to control the pressure in the reactor. The barrier **212** can also be placed between the primary water and the brine from the local rock formation, to maintain the pressure of the primary system as equal to or approximately equal to that of the host rock formation. The barrier **212** can be formed from a flexible material that bends when the pressures are unequal, for example, in the form of a bellows. In another instance, the barrier **212** can be a tube with a non-circular cross section that compresses or becomes more circular depending on the pressure difference inside and outside of the tube. In some examples, the pressure equalizer barrier **212** can be composed of a permeable material, such as sandstone or sand that allows flow whenever the pressures are unequal across the barrier. Although a permeable plug could allow some mixing between the moderating material (such as heavy water) and either the rock brine or the heat extraction fluid (secondary water), under normal operations the amount of mixing will be small. The mixed water can be replaced in the reactor by using the primary drain and supply pipes **201**, **202**. The primary drain and supply pipes **201**, **202** can be filled with water near the bottom, and include a moveable plug part way up, with other water filling above the movable plug.

[0105] The hydrostatic weight of the water in the pipes **201**, **202** can supply about one hundred atmospheres of pressure. The pressure can be controlled in several ways. The top of the water pipes **201**, **202** can have gas at the top that allows the water to flow up the pipe (if bubbles are produced in the reactor) without significantly increasing the pressure in the reactor **130**. The pressure of the water will be equal to the hydrostatic pressure of water at the bottom of the pipes **201**, **202** which (if they go to the surface **104**) can be fifty to one hundred-fifty atmospheres or more.

[0106] The water pipes **201**, **202** can be used for an emergency replacement of the moderator, if there is a desire to turn off the nuclear reactor **130**, or for replacement by neutron-poisoned water.

Thus, the waterpipes **201**, **202** can function as reactivity control mechanisms for the reactor. In some examples, control rods can be included in the reactor **130**. Any appropriate method of controlling reactivity of the reactor **130** can be implemented.

[0107] In FIG. 2, the fuel, e.g., fuel rods **218**, is held inside a canister **220**. The bottom and the top of the canister **220** are left open to provide a pathway for the primary coolant loop **213**. If the fuel overheats, that is, rises in temperature sufficiently to boil the water in the primary loop (which, at PWR pressures, occurs at a temperature of 250 to 325° C.) then the bubbles, or vapor **206**, will reduce the density of the moderator near the fuel rods **218**, and reducing the rate of the fission chain reaction. Thus, the formation of bubbles provides “negative feedback” to control and stop a power production overrun. Thus, the bubble capture mechanism provides “negative feedback” to control and stop a power production overrun.

[0108] To enhance the negative temperature coefficient from voids, inverted cups or tubes can be placed in the reactor to trap bubbles. These inverted cups can also be elongated in shape, like conventional “test tubes,” to provide more gas accumulation capability. The cups can be made of a thermally-conductive metal such as zircoloy to assure that they can transfer heat from the fuel rods to the part of the liquid coolant.

[0109] The flow of the secondary coolant fluid can be provided by a pump or by natural circulation. If the pump fails, or is turned off, then the circulation of the secondary water will be reduced, and more of the heat will be transferred to the secondary water and then to the surrounding rock **222**. In some examples, the secondary water can be a power conversion working fluid of a power conversion system. For example, the secondary water, when heated to steam **106** by the heat exchanger **120**, can be used as a power conversion working fluid for a steam turbine generator, e.g., generator **102**.

[0110] The design in FIG. 3 shows the pipe **208** that brings the hot water **106** (or steam **106**) to the surface **104** as being insulated with an insulator **204**. Insulation can be added to various parts of the system **100** to improve efficiency. In another embodiment, the hot H₂O pipe **208** can be used for cool water supply, and the cool water pipe **201** can be for hot water return. In this alternate embodiment, as well as in the embodiment shown in the figures, insulation between the outer pipe **201** and the casing and rock might be reduced or omitted. Doing this can cause the rock surrounding the casing to either warm or cool, respectively, although that can take longer to take place. Similarly, if insulation is used between that pipe and the casing, the temperature of the rock can still change with time since the insulator is not perfect. In these embodiments, the temperature of the rock will eventually be close to that of the pipe, and when this happens, the rock itself serves as an effective insulator against future loss of energy through the rock.

[0111] Various embodiments that are exemplified in FIGS. 1-3 can be implemented in accordance with the present disclosure. In some examples, carbon (e.g., low boron graphite) can be added to the design to provide a component of the moderator that will not boil and also operate as a neutron reflector to increase the reactivity. A hydrogen-bearing compound such as uranium-beryllium-hydride can be added because it gives a very strong negative temperature coefficient. The enrichment of the fuel can be as low as natural uranium (0.7%), at approximately the level typically used in a PWR (4.5%), as high as enrichment levels used in many “fourth generation” nuclear reactors (19.9%), or higher.

[0112] Any appropriate type of pressure equalizer can be used. Any appropriate type of heat exchanger can be used. In some examples, the concrete, or cement **214**, between the casing **216** and the borehole wall can be omitted. Casing centralizers can be used to provide stability of the pipes.

[0113] The secondary water brought to the surface **104** can be kept pressurized, so it reaches the surface **104** as a liquid, or the secondary water can be allowed to boil in the heat exchanger, so the secondary water arrives at the surface **104** as steam **106**.

[0114] Other forms of fuel and moderators can be used, including TRISO fuel and pebble fuel (typically containing TRISO in larger pellets), and molten salt or molten metal containing fissile

material. The reactor system **100** can use a heat pipe in the vertical section to bring the heat to the surface **104**. This can similarly allow the water to boil at depth. In an implementation including a heat pipe, pressure for the secondary water can be supplied by the secondary water pipes.

[0115] Other aspects of example embodiments according to the present disclosure can include one or more other features. For example, a turbine to generate electricity can be placed inside the borehole **115** to extract energy while keeping most of the borehole pressurized. The borehole **115** can be slanted or otherwise directionally drilled, rather than vertical. There are many more variations that are evident to someone practiced in the field of hydrology, heat transfer, and nuclear power.

[0116] The reactor system **100** can be designed to deliver a low level of power (e.g., heat, electrical power) for a short period or for an extended period (thirty to sixty years or more) by using control rods and neutron poisons to reduce the rate of fission reactors while keeping the reactor critical. The power delivered can also be extended by use of more highly enriched fuel, or by using multiple fuel assemblies or inserting new reactors in the same hole once the fissile fuel in the previous reactor has become depleted. At the end of that period, the spent fuel can be recovered. However, this design offers the option of leaving the spent fuel at depth and sealing the reactor. The borehole **115**, in appropriate geologies (e.g., low permeability rock, no deep aquifers, little vertical flow of brine within the rock) can offer high levels of protection to humans at the surface **104** for a million years or longer.

[0117] The hot water (or steam **106**) that reaches the surface **104** can be used directly for heat, or to produce electricity using a steam turbine, thermopile, or other electric generator, e.g., generator **102**. The steam **106** can also be used to run engines for other uses such as manufacturing. The ability to be local, or modular, the borehole nuclear reactor heat can be usefully used, for example, to heat a large building, campus, or to provide energy for a factory. In this aspect, the system **100** has an advantage over larger plants that must be located far from where the power is used.

[0118] The system **100** can also be used for military operations, in which a borehole of suitable size is dug in a few days, and a pre-fabricated reactor is lowered into the borehole. For military use, the depth of the reactor offers a very high level of military “hardness,” that is, invulnerability to attack by missile, drone, bomb, or terrorist attack. If it is necessary to abandon the reactor, the vertical access hole can easily be destroyed by inserting explosives. Further, at an end of life of system **100** (e.g., when the fissile material is no longer capable of sustaining a nuclear reaction as desired), the reactor portion and heat exchanger of the system **100** can be removed or may be allowed to remain in the borehole **115**, which can be appropriately sealed to store the fissile material therein (permanently or temporarily).

[0119] The pressure equalizer barrier (**212** in FIG. **3**) or any direct interface between primary and secondary circulation systems, can also serve as a safety mechanism. It can be made in such a way that it will be opened if the pressure difference grows larger than a critical and undesired level, for example, if the reactor fluid boils too vigorously to be equalized by the plug or by the pipes **201** and **202**. If that happens, then the hot reactor fluid will rise past this plug, and cool water from above the plug will flow down. This process provides “emergency core cooling system” (ECCS) as is required for PWR reactors under present code. This ECC is provided passively, that is, unlike the ECCS at many PWRs, it does not require outside power to be supplied to surround the reactor with cool water, but is gravity driven.

[0120] There are many variants on the idea of putting a nuclear reactor in a borehole.

[0121] For example, two holes can be drilled that converge just above the heat exchanger. In this embodiment the hot water can come to the surface from the second hole, and the first hole can be used to supply cold water, provide a path for the replacement water supply, provide a pathway for control of control rods (which can be operated electrically with an underground motor or by cables that rise to the surface or near surface). The separation of the two holes allows rock to serve as the insulator between the cold and hot water. Bringing two holes together at depth is a technology that

is within the state-of-the-art of current drilling practice. In another embodiment, three holes are dug, one of relatively large diameter to emplace the fuel assembly and heat exchanger, a second to provide a path for the hot water to come to the surface, and a third to provide pressure a pathway for injection and removal of fluids into the reactor region. Those fluids might include water or a fluid carrying neutron absorbing poisons. The supplementary holes (all but the one that allows for placement of the fuel and the heat exchanger) need not be wide in diameter, but can be between 2-inches and 10-inches in diameter, enabling them to be constructed at relatively low cost. Additional boreholes that intersect the main large-diameter borehole are also possible, and can serve to improve the efficiency or safety of the borehole reactor.

[0122] FIG. 4 shows another example implementation of a drillhole (or borehole) nuclear reactor system **400** according to the present disclosure. Borehole nuclear reactor system **400** is a variation of system **100**, as the same or substantially similar components as shown in FIG. 1 are included in FIG. 4, but nuclear fuel that generates heat is disposed of or otherwise positioned in a waste drillhole **401** that is separated from a heat exchanger borehole **415** by the rock formation **406**. Therefore, the heat exchanger **120** (as described previously) is positioned in a separate borehole than the reactor **130** that includes, for example, one or more waste canisters **402** that enclose nuclear waste **404** (together which form the reactor **130**). The nuclear waste **404** in canisters **402** are positioned in waste drillhole **401**, which is formed from the ground surface **104** into one or more subterranean formations including rock formation **406**. The waste drillhole **401** is shown as a vertical drillhole (e.g., wellbore or borehole) but can be directional, slanted, horizontal, or a combination thereof. Details of the reactor **130** are described with reference to FIG. 2.

[0123] FIG. 4 includes reference arrow **105** defining uphole and downhole directions. This figure shows a vertical heat exchanger (HX) borehole **415**, but the borehole **415** can be directionally drilled into a slanted or near-horizontal or other configuration. The generator **102** is located at the ground surface **104**. The HX borehole **415** can descend to a depth of approximately one half kilometer (km) or greater (e.g., 1.0 km or greater, 1.5 km or greater, 2.0 km or greater, or other predetermined depth). The HX borehole **415** can include a casing that can be made to adhere to the borehole wall, e.g., by being cemented with cement to the borehole wall. The HX borehole **415** can be narrow, e.g., four to thirty-six inches in diameter.

[0124] At the bottom of the HX borehole **415**, nuclear fuel is held in a reactor **130** including one or more fuel assemblies. A pipe **208** (insulated or uninsulated) is positioned in the HX borehole **415**. During operation, secondary water **108** flows downward outside of the pipe **208**. The water **108** is heated (by heat that is transferred to the primary water from the nuclear waste **404** of the reactor **130** through the rock formation **406**) as the secondary water **108** passes through the heat exchanger **120**. The heated secondary water, or steam **106**, then flows upward inside the pipe **208**. The pipe **208** thus carries heat generated by the reactor **130** (in the separate, waste drillhole **401**) to the surface **104**.

[0125] Other variations on the disclosed implementations are also contemplated by the present disclosure. For example, a heat exchanger of a borehole nuclear reactor system, such as heat exchanger **120**, can be positioned external to a casing in a borehole, such as between the casing and a rock formation. In some aspects, in such an implementation, cold water can be transported through a pipe external to the casing (e.g., within the rock formation, a cement layer that attaches the casing to the rock formation, or between the rock formation and the casing). The cold water is heated by the external heat exchanger into hot water or steam and brought to the surface **104** or near surface **104** where the heat can be used in the generator **102**.

[0126] As another variation, a reactor for a borehole nuclear reactor system (such as reactor **130**) can be split into or include multiple, independently-controllable reactors. For example, multiple reactors **130** within a reactor region can be operated simultaneously to provide maximum power, or individual reactors **130** can be periodically shut down or reduced in heat power output when less generated power is needed or desired. The control of each reactor **130** (of multiple reactors **130**)

can be accomplished by, for example, putting a strong neutron absorber in a vicinity or one or more of the multiple reactors **130**. This can be done, for example, by having tubing or pipes that extend from the one or more reactors **130** to the surface **104**. If the tubes are filled with water, then a particular reactor **130** will produce maximum power. If filled with a fluid containing a strong neutron absorber, such as boron or cadmium or their salts, then the reactivity of the particular reactor **130** can be reduced. A set of tubes (supply and return fluids) could be installed and provided for each reactor **130** of multiple reactors **130**.

[0127] In some aspects, control of one or more of the multiple reactors **130** can be accomplished with control rods (e.g., solid control containing boron or cadmium or their salts) that are controllably moveable into and out of individual reactors **130**. The controllable movement of the control rods can be performed mechanically or hydraulically, such as by using fluids in pipes that are controlled at or near the surface **104**.

[0128] FIGS. **5A** and **5B** are schematic diagrams of another example implementation of a drillhole (or borehole) nuclear reactor system **500** according to the present disclosure. System **500** is similar in some or most aspects to the drillhole nuclear reactor system **100** and shown with more detail. FIG. **5A** shows a heat exchanger portion **501** of the system **500**, while FIG. **5B** shows a nuclear reactor portion **503** of the system **500** (that is downhole of the heat exchanger portion **501**). The heat exchanger portion **501** is positioned or installed in a borehole **505** that is formed from a terranean surface into a subterranean formation **502**. In some aspects, the subterranean formation **502** can serve to moderate and reflect neutrons back into the nuclear reactor section **503** during a fission reaction generated therein.

[0129] In this example, the borehole **505** includes a casing **504** (that includes optional perforations **508**) that is cemented into the borehole **505** with cement **506**. In example implementations, the heat exchanger portion **501** if installed in a borehole **505** that is approximately 18 inches in diameter, and the portion **501** is approximately 40 feet in length.

[0130] As shown in FIG. **5A**, the heat exchanger portion **501** includes a primary fluid flowpath **524** that includes a riser section **526** (within riser **595**) and downcomer sections **528** (between the riser **595**). The riser section **526** turns to the downcomer sections **528** at a closed end of the primary fluid flowpath **524** at or near an uphole end of the heat exchanger portion **501**. In some aspects, an insulating layer **534** is installed between the riser section **526** and the downcomer sections **528**. In combination, the riser section **526** and the downcomer sections **528** (i.e., the primary fluid flowpath **524**) form at least a part of a closed-circuit for circulating (e.g., naturally or by convection or both) a primary fluid coolant therewithin between the nuclear reactor portion **503** and the heat exchanger portion **501**. The primary fluid coolant can be water (e.g., heavy water, light water, or other water-based liquid with additives).

[0131] As further shown in FIG. **5A**, the heat exchanger portion **501** includes a secondary fluid flowpath **523** that includes downflow sections **512** and upflow sections **518**. Generally, the downflow sections **512** extend downhole in the borehole **505** from at or near a generator and condenser at the terranean surface until they turn at closed ends into the upflow sections **518**, which also extend to the generator at the terranean surface. In some aspects, an insulating layer **522** is installed between the downflow sections **512** and the upflow sections **518**. In combination, the downflow sections **512** and the upflow sections **518** (i.e., the secondary fluid flowpath **523**) form at least a part of a closed-circuit for circulating (e.g., forcibly, naturally or by convection or a combination thereof) a secondary fluid coolant therewithin between the heat exchanger portion **501** and the generator at the terranean surface. As shown, the secondary fluid flowpath **523** and the primary fluid flowpath **524** are in thermal communication such that heat can be transferred from the primary fluid coolant to the secondary fluid coolant (as explained in more detail later), but the fluid flowpaths are fluidly decoupled so that mixing of the primary and secondary fluid coolants does not occur within the heat exchanger portion **501**. The secondary fluid coolant can be light water other water-based liquid with additives.

[0132] Turning now to FIG. 5B, this figure shows the nuclear reactor portion **503** of the system **500**. As shown, a reactor vessel **590** is installed in the borehole **505** (and likely within a brine **580** that fills the borehole **505**). The reactor vessel **590** at least partially encloses a core **560** (defined by a core reflector **562**) that includes nuclear fuel elements **570** and a control rod system **550** (that can be controlled from, e.g., the terranean surface). The downcomer sections **528** extend downhole into the core **560** at an outer circumference of the core vessel **562** until, at a closed, downhole end of the reactor vessel **590**, they turn to meet the riser section **526** within the core **560** at the nuclear fuel elements **570**. In some aspects, the core vessel **562** can comprise a neutron reflector surface that faces the nuclear fuel elements **570**, as well as an insulating material that provides thermal separation between the downcomer sections **528** and the core **560**. The nuclear reactor portion **503** can be, e.g., approximately 14-28 feet in length.

[0133] In some aspects, the core reflector **562** can be made of a material sufficient to reflect neutrons without absorbing the neutrons, such as, for example, carbon, beryllium (or any of their alloys). In some aspects, the subterranean formation **502** can act as a reflector or moderator of neutrons based on its geological properties. Thus, in combination, the core reflector **562** (if provided) and the formation **502** can operate in combination to contribute to the reactivity of the nuclear reactor portion **503**. Additionally, or alternatively, the casing **504** can be made of a material sufficient to reflect neutrons without absorbing the neutrons (or otherwise act to increase reactivity), such as, for example, carbon steel or stainless steel. The casing **504** can also be made of a material such as ceramic, a plastic material, or fiberglass,

[0134] In some aspects, there can be one, some, or many nuclear fuel elements **570**. For example, a nuclear fuel element can be a nuclear fuel assembly rod (e.g., with a cladding that holds nuclear fuel pellets, such as shown in FIG. 6). In some aspects, a nuclear fuel element can nuclear fuel (e.g., one or more nuclear fuel assemblies) enclosed in a canister. In some aspects, a nuclear fuel element can be another form of fissile material, such as TRISO fuel, metallic uranium or plutonium, oxides of uranium or plutonium, or mixtures of uranium and plutonium oxides (MOX).

[0135] As shown in FIGS. 5A and 5B, pressure control tubes **510** extend within the borehole **505** through the heat exchanger portion **501** and into the nuclear reactor portion **503**. In some aspects, the pressure control tubes **510** allow pressure control of the fluid in the reactor system **500** and the insertion and removal of a primary reactor coolant fluid. In the case of pressure control, the tubes **510** allow the operator to set the pressure in the primary reactor loop to be close to the pressure of the brine **580** in the subterranean formation **502**, thereby allowing the use of thinner and less expensive metal for the reactor vessel **595**.

[0136] In an example operation of the borehole nuclear reactor system **500**, the nuclear reactor portion **503** operates to heat (and re-heat, once cooled) a cool primary fluid coolant **532** that circulates (e.g., naturally, by convention, or both) from the heat exchanger portion **501** and into the core **560** through the downcomer sections **528**. As the cool primary fluid coolant **532** rises through the core **560** and through nuclear fuel elements **570**, the nuclear fuel elements **570** heat the cool primary fluid coolant **532** into hot primary fluid coolant **530** that enters the riser **595** and into the riser section **526**

[0137] The hot primary fluid coolant **530** flows through the riser **595** and the riser section **526** and into the heat exchanger portion **501** of the system **500**. The hot primary fluid coolant **530** turns into the downcomer sections **528** at the closed end of the primary fluid coolant flowpath **524**, and begins to transfer heat to a rising secondary fluid coolant **516** that circulates in the upflow sections **518** of the secondary fluid coolant flowpath **523**. As heat is transferred, the rising secondary fluid coolant **516** can remain in liquid form or phase change (at least partially) to gas form in order to form steam **520** that, eventually, rises to the generator at the terranean surface.

[0138] The steam **520** that is used in the generator, generally, changes phase back to liquid and circulates through the downflow sections **512** as cold secondary fluid coolant **514**. The cold secondary fluid coolant **514** circulates through the downflow sections **512** and into the upflow

sections **518** within the secondary fluid coolant flowpath **523**, where it is heated to the rising secondary fluid coolant **516**.

[0139] This process repeats as the nuclear reactor portion **503** (and/or the generator) is in operation. In the case of, e.g., an uncontrolled fission reaction that occurs in the nuclear reactor section **503**, or in order to abate a controlled fission reaction, the control rod assembly **550** can be operated (e.g., inserted into the core **560**) to stop or reduce the nuclear fission reaction of the nuclear fuel elements **570**.

[0140] Although a particular type of nuclear reactor is shown in the nuclear reactor portion **503**, (enriched uranium, plutonium, their oxides, or mixed oxides) the present disclosure contemplates that many forms of nuclear reactors can be used with fissile materials that forms the nuclear fuel elements **570**. For example, molten salt reactors, molten metal reactors, TRIGA reactors, TRISO fuel reactors, boiling water reactors, high temperature gas cooled reactors, or another kind of 4th generation reactors that can be installed in a human-unoccupiable borehole (such as borehole **505**) are all contemplated by the present disclosure.

[0141] Furthermore, although a single nuclear reactor portion **503** is shown in FIG. 5B, there can be multiple nuclear reactor portions **503** (as well as multiple heat exchanger portions **501**) installed in the borehole **505**, whether within a single vertical borehole or multiple, slant or lateral boreholes from the borehole **505**. Moreover, additional systems found in standard reactors, such as filtration systems, can be readily added to the reactors described here.

[0142] FIG. 6 is a schematic diagram of nuclear fuel element **600** (fuel “rod” or “pin”) for a drillhole nuclear reactor system according to the present disclosure. This figure explicitly shows one implementation of the void collectors described previously. As shown in this example, nuclear fuel element **600** includes multiple fissionable nuclear fuel pellets **604** (or other, discretized form of fissionable nuclear fuel) within a cladding **602** (e.g., a metallic or other material that is in the form of a tube, such as zircaloy or an aluminum alloy). In some aspects, the nuclear fuel element **600** represents a nuclear fuel rod (of which many make up a nuclear fuel assembly within a support structure).

[0143] As shown in this example, multiple cups **606** are installed or attached to (or integral with) the cladding **602**. Each cup **606** is inverted such that the cup **606** includes a closed end **608** and an open end **610**. When installed in the nuclear reactor portion of a drillhole nuclear reactor system, the closed ends **608** face an uphole direction, while the open ends **610** face a downhole direction. Thus, the open ends **610** face (and receive) a flow of a primary fluid coolant in an uphole direction, through a core of the reactor, and into a riser of the reactor.

[0144] In some aspects, the cups **606** act as bubble catchers during operation of the nuclear reactor section. For example, the cups **606** can operate to accumulate primary fluid coolant in the form of vapor if the primary fluid coolant boils. In some aspects, the cups **606** can be formed such that they have small aspect ratios (e.g., the cup diameter is less, and perhaps much less, than a cup length). It is expected that many of the voids that are “captured” by the cups **606** will be generated inside the cups **606** but remain there instead of rising upward.

[0145] When the primary fluid coolant temperature drops, the vapor within the cups **606** will drop and convert back to liquid phase. Thus, the cups **606** can act to provide or enhance a negative temperature coefficient to the reactivity of the nuclear reactor portion of the drillhole nuclear reactor system.

[0146] Although the cups **606** are shown as cylinders, other shapes that have similar functionality can be used. The cups **606** can have good thermal contact with the cladding **602**, so that they do not reduce the cooling of the cladding **602** by the primary fluid coolant. In some aspects they will enhance this cooling by providing additional surface area for the cladding.

[0147] While this specification contains many specific implementation details, these should not be construed as limitations on the scope of any inventions or of what may be claimed, but rather as descriptions of features specific to particular implementations of particular inventions. Certain

features that are described in this specification in the context of separate implementations can also be implemented in combination in a single implementation. Conversely, various features that are described in the context of a single implementation can also be implemented in multiple implementations separately or in any suitable subcombination. Moreover, although features may be described above as acting in certain combinations and even initially claimed as such, one or more features from a claimed combination can in some cases be excised from the combination, and the claimed combination may be directed to a subcombination or variation of a subcombination.

[0148] Similarly, while operations are depicted in the drawings in a particular order, this should not be understood as requiring that such operations be performed in the particular order shown or in sequential order, or that all illustrated operations be performed, to achieve desirable results. In certain circumstances, multitasking and parallel processing may be advantageous. Moreover, the separation of various system components in the implementations described above should not be understood as requiring such separation in all implementations, and it should be understood that the described program components and systems can generally be integrated together in a single software product or packaged into multiple software products.

[0149] A number of implementations have been described. Nevertheless, it will be understood that various modifications may be made without departing from the spirit and scope of the disclosure. For example, example operations, methods, or processes described herein may include more steps or fewer steps than those described. Further, the steps in such example operations, methods, or processes may be performed in different successions than that described or illustrated in the figures. Accordingly, other implementations are within the scope of the following claims.

Claims

1. A nuclear reactor system, comprising: a drillhole that extends from a terranean surface through one or more subterranean formations; at least one reactor core positioned in the drillhole, the at least one reactor core comprising at least one nuclear fuel element; a primary coolant system configured to transport a primary fluid coolant between the at least one reactor core and a heat exchanger; and a secondary coolant system thermally coupled to the primary coolant system with the heat exchanger and configured to transport a secondary fluid coolant between the heat exchanger and the terranean surface.
2. The nuclear reactor system of claim 1, wherein the at least one nuclear fuel element comprises a fissile nuclear fuel element.
3. The nuclear reactor system of claim 2, wherein the fissile fuel element comprises at least one of enriched uranium, plutonium, uranium or plutonium oxide, or a mixed oxide (MOX).
4. The nuclear reactor system of claim 1, comprising at least one canister that at least partially encloses the at least one nuclear fuel element.
5. The nuclear reactor system of claim 4, wherein the canister includes a first opening an uphole end of the canister and a second opening at a downhole end of the canister.
6. The nuclear reactor system of claim 1, wherein the primary coolant system is configured to transport the primary fluid coolant between the at least one reactor core and the heat exchanger by at least one of natural circulation or pumping.
7. The nuclear reactor system of claim 1, comprising one or more pumps configured to provide a force for transporting the primary fluid coolant between the at least one reactor core and the heat exchanger.
8. The nuclear reactor system of claim 1, wherein the secondary coolant system is configured to transport the secondary fluid coolant between the heat exchanger and the terranean surface by natural circulation.
9. The nuclear reactor system of claim 1, comprising one or more pumps configured to provide a force for transporting the secondary fluid coolant between the heat exchanger and the terranean

surface.

10. The nuclear reactor system of claim 1, wherein the primary fluid coolant comprises water.
11. The nuclear reactor system of claim 1, wherein the secondary fluid coolant comprises water.
12. The nuclear reactor system of claim 1, wherein the primary coolant system is fluidly isolated from the second coolant system.
13. The nuclear reactor system of claim 1, wherein the heat exchanger is configured to transfer heat from the primary fluid coolant in the primary coolant system to heat the secondary fluid coolant in the second coolant system to a higher temperature liquid phase or a gas phase.
14. The nuclear reactor system of claim 1, comprising a power conversion system.
15. The nuclear reactor system of claim 14, wherein the power conversion system is located at or near the terranean surface.
16. The nuclear reactor system of claim 14, wherein the secondary fluid coolant comprises a power conversion working fluid of the power conversion system.
17. The nuclear reactor system of claim 1, wherein the at least one nuclear fuel element is positioned at a first depth of the drillhole.
18. The nuclear reactor system of claim 17, wherein the first depth is: up to 0.5 km from the terranean surface, 1.0 to 1.5 km from the terranean surface, or 1.5 km or greater from the terranean surface.
19. The nuclear reactor system of claim 16, wherein the heat exchanger includes a barrier configured to fluidly isolate the primary coolant system from the second coolant system, the barrier being positioned at a second depth of the drillhole, the second depth being less than the first depth.
20. The nuclear reactor system of claim 19, comprising one or more pipes extending from the terranean surface to a third depth of the drillhole, the third depth being greater than the second depth.
21. The nuclear reactor system of claim 20, wherein the one or more pipes is configured to provide the primary fluid coolant to a region of the drillhole below the second depth.
22. The nuclear reactor system of claim 1, wherein the primary coolant system comprises a first pipe having a diameter less than a diameter of the drillhole, the first pipe being positioned in the drillhole with an axis of the first pipe being approximately parallel to an axis of the drillhole, the reactor core being positioned inside the first pipe, the system comprising an annulus defined between the first pipe and the drillhole, the annulus comprising a flow circuit configured to convey the primary fluid coolant in a downhole direction to the reactor core.
23. The nuclear reactor system of claim 22, wherein the secondary coolant system comprises a second pipe having a diameter less than the diameter of the drillhole, the second pipe being positioned in the drillhole with an axis of the second pipe being approximately parallel to the axis of the drillhole, the system comprising an annulus defined between the second pipe and the drillhole, the annulus comprising a flow circuit configured to convey the secondary fluid coolant in a downhole direction to the heat exchanger.
24. The nuclear reactor system of claim 13, wherein the secondary coolant system comprises: a first pipe having a diameter less than the diameter of the drillhole and configured to transport the secondary fluid coolant to the heat exchanger for heating; and a second pipe having a diameter less than the diameter of the drillhole and configured to transport heated secondary fluid coolant from the heat exchanger toward the terranean surface.
25. The nuclear reactor system of claim 1, wherein a diameter of the drillhole is thirty-six inches or less.
26. The nuclear reactor system of claim 1, wherein a diameter of the drillhole is four inches or more.
27. The nuclear reactor system of claim 1, wherein the heat exchanger is positioned within a casing that is installed in the drillhole.
28. The nuclear reactor system of claim 27, wherein the primary coolant system comprises at least

one pipe installed external to the casing and to the heat exchanger, and the secondary coolant system comprises at least another pipe installed external to the casing.

29. The nuclear reactor system of claim 27, wherein the casing is installed in the drillhole with a cement layer, and the heat exchanger is installed external to the cement layer.

30. The nuclear reactor system of claim 1, wherein the at least one reactor core is controllable between a low power output and a maximum power output.

31. The nuclear reactor system of claim 30, wherein the at least one reactor core is controllable with a fluid that comprises a neutron absorber.

32. The nuclear reactor system of claim 31, wherein the neutron absorber is controllably added to the primary fluid coolant.

33. The nuclear reactor system of claim 30, wherein the at least one reactor core is controllable with at least one control rod configured to move near or adjacent the at least one nuclear fuel element.

34. The nuclear reactor system of claim 1, wherein the at least one reactor core comprises a first reactor core and the nuclear fuel element comprises a first nuclear fuel element, the system comprising a second reactor core positioned in the drillhole, the second reactor core comprising at least one second nuclear fuel element.

35. The nuclear reactor system of claim 34, wherein the first and second reactor cores are individually controllable between a low power output and a maximum power output.

36. The nuclear reactor system of claim 34, wherein each of the first and second reactor cores is individually controllable with a fluid that comprises a neutron absorber.

37. The nuclear reactor system of claim 36, wherein the fluid is individually transported to each of the first and second nuclear reactor cores through one or more tubes that extends from the terranean surface to the first and second nuclear reactor cores.

38. The nuclear reactor system of claim 37, wherein the neutron absorber is controllably added to the fluid.

39. The nuclear reactor system of claim 34, wherein each of the first and second reactor cores is individually controllable with respective first and second control rods that are moveable into or near the respective first and second nuclear reactor cores.

40. The nuclear reactor system of claim 1, comprising one or more inverted cups positioned in the primary coolant system and within a flowpath of the primary fluid coolant.

41. The nuclear reactor system of claim 40, wherein the one or more inverted cups are coupled to a cladding of the at least one nuclear fuel element.

42. The nuclear reactor system of claim 1, comprising a reflector configured to reflect neutrons generated in the at least one reactor core without absorbing the neutrons.

43. The nuclear reactor system of claim 42, wherein the reflector comprises at least one of beryllium, carbon, a beryllium alloy, or a carbon alloy.

44. The nuclear reactor system of claim 1, wherein a particular subterranean formation of the one or more subterranean formations that is adjacent the at least one reactor core is configured to act as a reflector to reflect neutrons generated in the at least one reactor core.

45. The nuclear reactor system of claim 27, wherein the casing is comprised of a material sufficient to act as a reflector to reflect neutrons generated in the at least one reactor core.

46. The nuclear reactor system of claim 27, wherein the material of the casing comprises at least one of carbon steel, stainless steel, ceramic, a plastic material, or fiberglass.

47. (canceled)

48. (canceled)

49. (canceled)

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51. (canceled)

52. (canceled)

53. A method, comprising: identifying a nuclear reactor system that comprises: a drillhole that extends from a terranean surface through one or more subterranean formations; at least one reactor core positioned in the drillhole, the at least one reactor core comprising at least one nuclear fuel element; a primary coolant system; and a secondary coolant system thermally coupled to the primary coolant system with a heat exchanger and configured to transport a secondary fluid coolant between the heat exchanger and the terranean surface; transporting a primary fluid coolant in the primary coolant system between the at least one reactor core and the heat exchanger; transporting a secondary fluid coolant heated in the heat exchanger by the primary fluid coolant in the secondary coolant system between the heat exchanger and the terranean surface; and generating power with the heated secondary fluid coolant.

54. The method of claim 53, comprising: transporting the primary fluid coolant into a region of the drillhole below a depth of a fluid barrier of the heat exchanger; and transporting the secondary fluid coolant into a region of the drillhole above the depth of the fluid barrier, wherein the fluid barrier fluidly isolates the primary fluid coolant from the second fluid coolant.

55. The method of claim 54, comprising transporting the primary fluid coolant into the drillhole through one or more pipes extending from the terranean surface to a depth of the drillhole that is deeper than the depth of the fluid barrier.

56. The method of claim 53, wherein the primary and the secondary fluid coolants comprise water.

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78. (canceled)
