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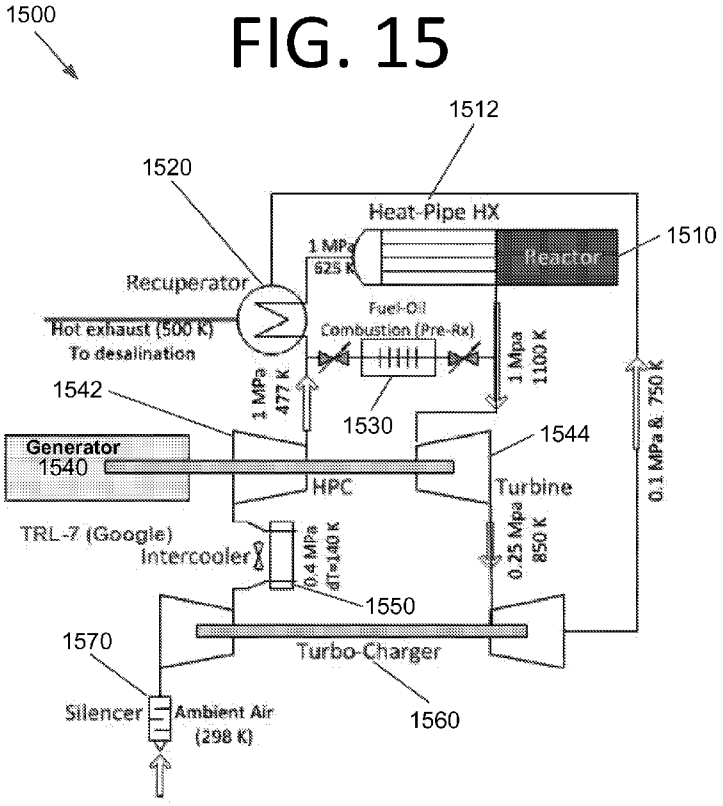
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[Continued on next page]

(54) Title: MOBILE HEAT PIPE COOLED FAST REACTOR SYSTEM

FIG. 15



(57) Abstract: A mobile heat pipe cooled fast nuclear reactor may be configured for transportation to remote locations and may be able to provide 0.5 to 2 megawatts of power. The mobile heat pipe cooled fast reactor may contain a plurality of heat pipes that are proximate to a plurality of fuel pins inside the reactor. The plurality of heat pipes may extend out of the reactor. The reactor may be configured to be placed in a standard shipping container, and may further be configured to be contained within a cask and attached to a skid for easier transportation.

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TITLE

MOBILE HEAT PIPE COOLED FAST REACTOR SYSTEM

CROSS REFERENCE TO RELATED APPLICATION

[0001] This application claims the benefit of U.S. Provisional Application Serial No. 61/816,060, filed on April 25, 2013. The subject matter of this earlier filed provisional patent application is hereby incorporated by reference in its entirety.

STATEMENT OF FEDERAL RIGHTS

[0002] The United States government has rights in this invention pursuant to Contract No. DE-AC52-06NA25396 between the United States Department of Energy and Los Alamos National Security, LLC for the operation of Los Alamos National Laboratory.

FIELD

[0003] The present invention generally relates to power systems, and more particularly, to a mobile heat pipe cooled fast reactor system.

BACKGROUND

[0004] Conventionally, diesel or gas-powered generator systems may be used to provide electricity to locations that do not have access to a reliable electrical grid, or where an electrical grid is unavailable. However, a significant issue with these

systems is that fuel must be transported to the location to supply the generator. This may require significant transportation resources and come at significant cost.

[0005] Nuclear reactors may be particularly useful for applications where power is needed for systems that are logistically remote from conventional fuel sources, such as systems deployed in the Arctic, a forward military base, or other geographically remote areas. However, conventional nuclear reactors tend to be large and require circulating coolant fluids. Accordingly, an improved reactor suited for deployment in remote environments may be beneficial.

SUMMARY

[0006] Certain embodiments of the present invention may provide solutions to the problems and needs in the art that have not yet been fully identified, appreciated, or solved by conventional reactor technologies. For example, some embodiments of the present invention pertain to heat pipe cooled reactor systems that are nearly solid state and have only a small amount of fluid. The reactor systems of some embodiments may be modular and configured to be transported in standard intermodal shipping containers, for example. Heat pipe reactors using alkali metal heat pipes, for example, may be particularly well suited for mobile/remote applications because they tend to be inherently simpler, smaller, and more reliable than "traditional" reactors that rely on pumping coolant through the reactor core.

[0007] In an embodiment, a system includes a plurality of heat pipes including coolant and a plurality of fuel pins containing nuclear fuel. The plurality of fuel pins are positioned proximate to the plurality of heat pipes. The heat pipes extend outward

from a reactor core through a block and are configured to transfer heat away from the reactor core.

[0008] In another embodiment, a system includes a mobile heat pipe cooled fast reactor and a cask housing the mobile heat pipe cooled fast reactor. The system also includes a skid including rollers or tires and a cradle operably attached to the skid. The cradle is configured to secure the cask in place to transport the mobile heat pipe cooled fast reactor using the skid.

[0009] In yet another embodiment, an apparatus includes a containment vessel surrounded by a neutron shield. The neutron shield is surrounded by an air gap. The apparatus also includes a gamma shield that defines an outer boundary of the air gap. The air gap provides cooling for the gamma shield. The apparatus further includes an outer wall that covers the gamma shield.

BRIEF DESCRIPTION OF THE DRAWINGS

[0010] For a proper understanding of the invention, reference should be made to the accompanying figures. These figures depict only some embodiments of the invention and are not limiting of the scope of the invention. Regarding the figures:

[0011] FIG. 1 illustrates a generic heat pipe, according to an embodiment of the present invention.

[0012] FIG. 2 illustrates a power system with closed loop CO_2 Brayton cycle power conversion, according to an embodiment of the present invention.

[0013] FIG. 3 illustrates a power system with air Brayton cycle power conversion, according to an embodiment of the present invention.

[0014] FIG. 4 illustrates an assembled core block with heat pipes, according to an embodiment of the present invention.

[0015] FIG. 5 illustrates reactor elevations for a closed loop CO_2 Brayton cycle system design, according to an embodiment of the present invention.

[0016] FIG. 6A is a cross-sectional view of a smaller version of a mobile heat pipe cooled fast reactor, according to an embodiment of the present invention.

[0017] FIG. 6B is a perspective cutaway view of the smaller version of the mobile heat pipe cooled fast reactor, according to an embodiment of the present invention.

[0018] FIG. 7A is a perspective cutaway view of a smaller version of a mobile heat pipe cooled fast reactor, according to an embodiment of the present invention.

[0019] FIG. 7B is a separated side cutaway view of the smaller version of the mobile heat pipe cooled fast reactor, according to an embodiment of the present invention.

[0020] FIG. 7C is a separated side cutaway view of the mobile heat pipe cooled fast reactor with perspective views of fuel pellets and a top view of the heat pipes and fuel pins, according to an embodiment of the present invention.

[0021] FIG. 8 illustrates a reactor core arrangement, according to an embodiment of the present invention.

[0022] FIG. 9 illustrates comparative turbine sizes for He and supercritical CO_2.

[0023] FIG. 10 is a side view of a mobile heat pipe cooled fast reactor with heat exchangers as they would be connected to the heat pipes, according to an embodiment of the present invention.

[0024] FIG. 11A illustrates a mobile reactor and one version of a transportation system, according to an embodiment of the present invention.

[0025] FIG. 11B illustrates a side view of the transportation cask and reactor of FIG. 11A, according to an embodiment of the present invention.

[0026] FIG. 12 is a perspective view of a truck and trailer configured to transport a mobile heat pipe cooled fast reactor, according to an embodiment of the present invention.

[0027] FIG. 13 is a photograph of a non-nuclear end-to-end 200 kW prototype testing the heat pipe concept, according to an embodiment of the present invention.

[0028] FIG. 14A is a photograph of a non-nuclear prototype core block, according to an embodiment of the present invention.

[0029] FIG. 14B is a virtual schematic of a non-nuclear prototype core block with a similar configuration to that shown in the core block of FIG. 14A, according to an embodiment of the present invention.

[0030] FIG. 15 is a schematic of a once-through air Brayton system, according to an embodiment of the present invention.

[0031] FIG. 16 illustrates a perspective cutaway view of a gas turbine.

[0032] FIG. 17 is a schematic diagram illustrating fuel resources and conventional diesel generators needed to achieve the power output of mobile heat pipe cooled fast reactor systems, according to an embodiment of the present invention.

[0033] FIG. 18 is a schematic diagram illustrating conventional solar equipment and fuel resources needed to achieve the power output of mobile heat pipe cooled fast reactor systems, according to an embodiment of the present invention.

DETAILED DESCRIPTION OF THE EMBODIMENTS

[0034] Some embodiments of the present invention pertain to a heat pipe cooled reactor power system that may be nearly solid state and have no circulating fluid. There are no pumps or valves in the vessel/core area like in a water or liquid metal cooled reactor. Also, other than control drums, moving parts could be limited to the power conversion system. Furthermore, high temperatures can be achieved, emergency decay heat removal can be made passive, and heat pipe reactors can generally work in any orientation. Heat pipe reactor systems in some embodiments may provide long term power in desired environments for five years or more.

[0035] Heat pipe reactors may have many advantages over conventional reactors. Their nearly solid state design and lack of circulating coolant fluid can significantly enhance safety and reliability of the reactor. Corrosion is less of an issue, and there is only a small amount of fluid that could spill, limited to the amount in the heat pipe. There are no positive void coefficients, which improves the nuclear safety case, and there is no high pressure (compared to a gas cooled reactor). Also, heat pipes increase the surface area for heat extraction and allow for multiple heat extraction systems. Some embodiments use either a carbon dioxide (CO_2) Brayton cycle power conversion system (air cooled) or a direct air Brayton cycle power conversion system.

[0036] Heat pipe reactors using alkali metal heat pipes, for example, are perfectly suited for mobile applications because their nature is inherently simpler, smaller, and more reliable than "traditional" reactors that rely on pumped coolant through the reactor core. Instead of the single point failure of a pumped loop reactor system, hundreds of heat pipes passively remove heat, including decay heat, from the core

using relatively simple and well-characterized physics. The heat pipes remove heat as liquid in the heat pipe is vaporized. These reliability and safety advantages are especially important for remote sites. The robust, solid-state characteristics of the core are also advantageous for potentially damaging transport conditions or perhaps hostile operating environments.

[0037] The use of heat pipes instead of liquid or gas coolants may lead to a lightweight and small design as compared to conventional reactors. For mobile reactor designs, these are generally desirable attributes. In addition, heat pipe reactors may operate at high temperature, which may allow for a smaller power conversion system. This is also generally desirable for a mobile reactor.

[0038] In some embodiments, the reactor and the power conversion system may fit into a standard intermodal shipping container that is 8 ft. × 8 ft. × 20 ft., for example. Some embodiments of the heat pipe cooled reactor may provide a safe and reliable power source of approximately 1 to 2 megawatts ("MW") of electric power and/or provide clean water via waste heat or reverse osmosis, although some embodiments are capable of achieving 5 MW thermal or more, and any desired power output may be achieved as a matter of design choice. The heat rejection system may fit into a separate container, and another container may be used for a control room. This may allow for rapid deployment of the reactor by government agencies, the military, or other entities to areas where logistics are a concern, such as disaster areas, remote locations, remote military sites, and in spacecraft. The opportunity cost of not having to ship fuel to the location may be a significant driver for the use of such reactor technology. This may also free up more cargo space for logistical purposes since

shipping fuel means not shipping other cargo, such as food, medicine, military equipment, etc.

[0039] For military applications in particular, sustainable energy at forward locations is generally a vital need. It typically takes approximately 7 gallons of fuel to supply one gallon to a fossil fuel generator. Furthermore, the majority of improvised explosive device ("IED") fatalities have occurred while protecting fuel convoys.

[0040] In some embodiments, a heat pipe reactor system may produce approximately 2 MW and weigh approximately 35 metric tons. Such embodiments may be transportable by air (e.g., by C-17 aircraft) and highway (e.g., by truck), allowing deployment to forward battlefield locations or other remote locations. These embodiments may enable savings of 92.5% of the fuel used at forward military bases, for example. An equivalent 2 MW fossil fuel generator would consume approximately 1.2 million gallons of JP8 fuel per year. An equivalent photovoltaic (PV) system and battery would weigh approximately 1,236 metric tons.

[0041] Such deployable embodiments may be configured to be "wheeled into" and "wheeled out of" a forward location. In certain embodiments, the entire system can be connected to generators and fully operable within 72 hours of arrival. Furthermore, such embodiments may be shut down, cooled, disconnected, and wheeled out in less than a week. The reactor is shut down by either turning control drums at the reactor core edge or by inserting a central control rod. The reactor core and other critical equipment may be housed in special armor, such as boron carbide, lead, and/or steel, for example. This armor may protect the reactor system from attacks, as well as shield personnel and equipment from core radiation during operation and transport.

[0042] FIG. 1 illustrates a heat pipe 100, according to an embodiment of the present invention. Heat pipes are passive heat removal devices that efficiently move thermal energy. Heat pipes are sealed tubes that contain a small amount of a volatile liquid (e.g., liquid potassium or sodium). The liquid is boiled at one end of the tube and the vapor travels to the other end of the tube where it condenses, depositing its heat of vaporization with a small attendant temperature change. The condensed liquid is then returned to the other end of the tube by means of a wick using capillary forces, drawing the condensate back toward the heated zone. The heat pipe wick shape imposes order on a saturated liquid by: (1) forming menisci between the condensate and the vapor; and (2) allowing the condensate to flow toward the heated zone. As such, a heat pipe, being isothermal, moves the working fluid for power conversion away from, and outside of, the core. Heat pipes also may extend the surface area available for heat transfer.

[0043] In conventional reactors, a single reactor coolant is typically the only mechanism for extracting heat from the reactor core. Safety is achieved by attempting to prevent the set of failures that could lose the fluid, cause the fluid not to circulate, or cause the fluid to lose its heat transfer capabilities (e.g., transition from nucleate to film boiling). Redundant equipment (pumps, electrical systems, etc.) or passive components are usually used to attempt to prevent failure.

[0044] However, in heat pipe reactors of some embodiments of the present invention, an array of heat pipes is used to remove heat from the reactor core using reliable and well-characterized physics (i.e., capillary action, boiling, and condensation). Typically, unless common cause failures dominate, the failure of

multiple heat pipes will be much lower than the failure rate associated with a conventional coolant system. Thus, traditional measures of safety could be an order of magnitude better in some embodiments.

[0045] In certain embodiments, the mobile heat pipe cooled fast reactor only consumes 5g of U^{235} per day (100 MW hours). The reactor also produces 1.7g of Pu^{239} per day (100 MW hours). After two years of operation, the Pu inventory would be approximately 1.2kg and the concentration would be ~0.01% (commercial spent fuel is ~1%). Extreme core radiation generally prevents access to the fuel.

[0046] In some embodiments, the only moving parts are control rods and power conversion. This makes such embodiments close to solid state. The feed mechanism for normal and emergency cooling could also be gravity fed. Assuming that there are no structural issues, this could improve reliability. It could also reduce maintenance costs and increase the ease of operation.

[0047] FIG. 2 illustrates a power system 200 with closed loop CO_2 Brayton cycle power conversion, according to an embodiment of the present invention. Power system 200 generally requires a heat rejection system, but tends to be more efficient than open air Brayton cycle systems. The pressure used in such systems may be moderate (e.g., 200 psi). Reactor 210 may have a solid core of stainless steel. While shown as a simulator here for testing purposes, in practical implementations, a real reactor would be used.

[0048] Uranium dioxide (UO_2) or UN fuel, or any other suitable fissile material, may be used as a fuel source in holes in the core surrounded by an inert gas such as helium. In some embodiments, the nuclear fuel material may be hundreds of times

less hazardous than material that is regularly shipped around the globe every day, such as highly toxic MOX spent fuel. Heat pipes 222 extend through rector 210 and heat exchangers 220, and may include any suitable coolant material, such as sodium or potassium. Heat pipes 222 may connect to several heat exchangers. One heat exchanger may be used for heating a working fluid (gas) and one or two other heat exchangers may be used for decay heat removal. A typical Brayton power conversion system compresses the working fluid (such as CO_2) using compressor 230, then passes it through the heat exchanger before releasing the gas through a turbine 232 to do work (e.g., to make electricity via generator 240) and then passing the working fluid through a heat rejection system 250 to complete the thermodynamic cycle.

[0049] FIG. 3 illustrates a power system 300 with air Brayton cycle power conversion, according to an embodiment of the present invention. Power system 300 generally does not require a heat rejection system, but tends to be less efficient than a closed loop CO_2 Brayton cycle system. In an open air Brayton cycle, air is the working fluid and it is released into the environment instead of be cooled and recycled through the system as in a closed loop CO_2 Brayton cycle.

[0050] FIG. 4 illustrates an assembled core block with heat pipes 400, according to an embodiment of the present invention. Assembled core block with heat pipes 400 includes upper heat pipe tubes 410 that are welded to block 420 via weld joint 430. The block holds the heat pipes and fuel pins in place and allows for heat to be transferred between the heat pipes and fuel pins. Fuel 440 is positioned between the heat pipe tubes below block 420. This allows the heat pipe tubes to transfer heat derived from the fuel for external use.

[0051] FIG. 5 illustrates reactor elevations 500 for heat pipes and fuel in the reactor core, according to an embodiment of the present invention. The elevations are given taking into account the lengths of the core reflector in the fuel pin, the fuel in the fuel pin, the fission gas plenum in the fuel pin, the shielding outside the core, the location of the lower heat exchanger for decay heat removal, and the location of the upper heat exchanger for the power conversion working fluid.

[0052] FIG. 6A is a cross-sectional view of a smaller version of the mobile heat pipe cooled fast reactor 600, according to an embodiment of the present invention. Reactor 600 includes a core block 610 that houses heat pipes 620 and fuel pins 630. A reflector 640 surrounds core block 610 and scatters neutrons and gamma radiation that escapes from the core. Rotating core control drums 650 and B_4C crescents 660 are used to provide reactivity control for the reactor. In some embodiments, all of control drums 650 may be moved individually to near-equal positions (i.e., all drums are at the same or a similar angle). Even if several of control drums 650 do not rotate to their respective positions, the core will still be subcritical in many embodiments.

[0053] FIG. 6B is a perspective cutaway view of a smaller version of the mobile heat pipe cooled fast reactor 600, according to an embodiment of the present invention. Such a reactor may produce 250 kW of power and be suitable for a myriad of applications, including terrestrial and space applications.

[0054] FIG. 7A is a perspective cutaway view of a mobile heat pipe cooled fast reactor 700, according to an embodiment of the present invention. A heat pipe array 710 includes a plurality of heat pipes 720. Fuel pins 730 are placed adjacent to heat pipes 720 such that heat pipes 720 can transfer heat from fuel pins 730. An axial

reflector 740 scatters neutron and gamma radiation. A fission gas plenum 750 is used for containing fission gas release as the core fissions. Such embodiments may use proven UO_2 fuel (19% enriched) and may have a steel monolith core (not shown). Passive coupling may be used for heat pipes 720 with no moving parts. Reactor 700 may be housed in an armored and shielded cask (not shown), as shown in more detail below.

[0055] FIG. 7B is a separated side cutaway view of mobile heat pipe cooled fast reactor 700, according to an embodiment of the present invention. A heat pipe wall 722 surrounds each of heat pipes 720 showing how the heat pipes would be welded to the solid metal block core. Fuel pellets 732 include radioactive material such as UO_2 that serves as fissile material for reactor 700.

[0056] FIG. 7C is a separated side cutaway view of mobile heat pipe cooled fast reactor 700 with perspective views of fuel pellets 732 and a top view of heat pipes 720 and fuel pins 730, according to an embodiment of the present invention. Dime-sized nuclear pellets 732 are stacked in the monolith in this embodiment. The core monolith in this embodiment has openings for fuel pins 730 and heat pipes 720, and may further conduct heat from fuel pins 730 to heat pipes 720. Heat pipes 720 passively transport heat generated in the core to turbine fluid, for example, to facilitate power generation.

[0057] FIG. 8 illustrates a reactor core arrangement 800, according to an embodiment of the present invention. Heat pipes 810 (shown slightly larger) are located proximate to fuel pins 820. Corner heat pipes 810 are adjacent to one fuel pin 820, side heat pipes 810 are adjacent to three fuel pins 820, and inner heat pipes 820 are surrounded by six fuel pins 820. In this embodiment, there are 2,112 fuel pins 820

and 1,224 heat pipes 810. Each fuel pin 820 has a diameter of 1.425 cm and each heat pipe 810 has a diameter of 1.575 cm. However, any number and arrangement of heat pipes and fuel pins may be used, depending on the application. As can be seen, the core consists of six thermally and mechanically independent segments 830, although any number of segments may be used.

[0058] The number of heat pipes in a reactor block can be a potential impediment to scaling a heat pipe reactor. Depending on the type of working fluid and the heat pipe design, most heat pipes have a limit on heat throughput per heat pipe. Given this limit, the larger the reactor, the more heat pipes that are typically required. However, there is a limit on the practical number of heat pipes that could be realistically manufactured into a solid block core.

[0059] Limits on the number of heat pipes can be overcome by breaking the core into smaller segments. A heat pipe reactor can be broken into segments that are mechanically and thermally isolated, but are neutronically connected. An example of this configuration is shown in segments 830 of FIG. 8. By limiting the segments to a size corresponding the perceived level of manufacturability, the reactor core can be scaled to the size needed for various applications. In other words, more segments can be used to generate more power.

[0060] Some embodiments use a CO_2 Brayton cycle power system instead of a Rankin cycle system. Some of the advantages of this configuration are that it tends to be smaller and lighter and more heat is produced (~600°C in come embodiments), leading to a higher efficiency system with the potential for process heat applications. Also, there is less heat to reject.

[0061] CO_2 also has favorable properties for a Brayton system. The relatively high molecular weight is better for low power Brayton cycle heat engines. Also, low c_p/c_v (1.2) leads to low pumping power. Further, better performance than a HeXe mixture at similar molecular weight may be realized.

[0062] FIG. 9 illustrates comparative turbine sizes 900 for He and supercritical CO_2. As can be seen, steam turbine 910 is the largest and produces 250 MW using 55 stages. He turbine 920 produces 333 MW using 17 stages, and the size is reduced to approximately 5 m. Supercritical CO_2 turbine 930 is smaller still and produces 450 MW using only 4 stages.

[0063] FIG. 10 is a side view of a mobile heat pipe cooled fast reactor 1000, according to an embodiment of the present invention. Reactor 1000 includes potassium filled heat pipes 1010 with a steel casing. An Al_2O_3 reflector 1020 surrounds a monolith core 1030 and reflects neutron and gamma radiation. A primary heat exchanger 1040 exchanges heat from nuclear reactions and a decay heat exchanger 1050 exchanges heat from decay of the fuel material.

[0064] FIG. 11A illustrates a mobile reactor and transportation system 1100, according to an embodiment of the present invention. In this embodiment, a cask 110 containing a mobile reactor is secured to a skid with rollers/tires 1150, but a train car, truck, container, or any other transportation mechanism may be used in other embodiments. Cask 1110 with the mobile reactor inside weighs about 35-45 tons loaded, holds three tons of fuel in five tons of steel monolith, and is approximately 12 feet long with a 6 foot diameter. Cask 1110 is designed to be robust, and the boron carbide shield (see FIG. 11B) also acts as armor.

[0065] Two impact absorbers 1120 are at either end of cask 1110. Openings 1122 are provided for shield cooling flow and also for airflow through the core in case of an emergency. Impact absorbers 1120 may include a steel shell filled with soft wood, ridged foam, honeycombed material. A cradle 1130 attaches cask 1110 to skid 1150 and a personnel barrier 1140 protects workers from exposure to a high dose of radiation. Personnel barrier 1140 may be stuffed with locally fabricated shielding (ALARA) in some embodiments.

[0066] FIG. 11B illustrates a side view of cask and reactor 1160 of FIG. 11A, according to an embodiment of the present invention. A ¼ inch thick stainless steel outer wall 1161 contains the reactor. A four inch thick lead gamma shield 1162 deflects gamma radiation. A 1-2 inch air gap 1163 provides shield cooling for lead gamma shield 1162 and six inch thick B_4C neutron shield 1164. A 1-2 inch stainless steel containment vessel 1165 separates the inner reactor from the cask.

[0067] For the mobile embodiment depicted in FIGS. 11A and 11B, a power output of 0.5 to 2 MW may be realized. Power conversion may be accomplished by coupling the reactor to a conventional power conversion system. Heat rejection may be accomplished using air or waste heat may be used for other missions. The reactor may be controlled remotely or locally. Self-regulation may be provided for power output. Embodiments may be reliable and safe, with three independent means of removing decay heat and two independent means of shutdown. The heat pipe cooled core may have no active components, passive heat removal may occur following shutdown, and a large heat capacity may be achieved.

[0068] FIG. 12 is a perspective view of a truck and trailer 1200 configured to transport a mobile heat pipe cooled fast reactor 1210, according to an embodiment of the present invention. Reactor 1210 is contained within cask 1220, and may generate 0.5-5 MW, depending on the configuration. Cask 1220 may be an armored, shielded, and certified transport cask.

[0069] FIG. 13 is a photograph of a non-nuclear end-to-end 200 kW prototype 1300 testing the heat pipe concept, according to an embodiment of the present invention. Prototype 1300 has a similar heat pipe and fuel pin configuration to that shown in FIG. 7B, for example. The reflectors are Al_2O_3 in prototype 1300. This photograph is of a prototype of a simulated nuclear reactor core that uses electricity to simulate nuclear power. Complex electronics are used to simulate reactor physics feedback mechanisms during operation of the prototype. The prototype allows the simulation of the reactor to power conversion components without using an actual reactor undergoing fission.

[0070] FIG. 14A is a photograph of a non-nuclear prototype core block 1400, according to an embodiment of the present invention. Electric heaters were used to heat core block 1400 to temperatures that were routinely in excess of 1,200 K. The components that were fabricated and tested included heat pipes, heat exchangers, and structural elements. These components were tested for over 4,000 hours to demonstrate proof of concept.

[0071] FIG. 14B is a virtual schematic of a non-nuclear prototype core block 1410 with a similar configuration to that shown in core block 1400 of FIG. 14A, according to an embodiment of the present invention. A plate 1420 holds heat pipes 1440 in

place. Heat pipes 1440 contain a liquid metal such as sodium or potassium. Heat pipes 1440 are heated electrically to simulate nuclear fission. The heat from heat pipes 1440 is then delivered to heat exchangers 1430 in the same fashion that a nuclear heated core block would.

[0072] FIG. 15 is a schematic of a once-through air Brayton system 1500, according to an embodiment of the present invention. Fuel oil powered Brayton systems are conventionally available, and the system can be used before the nuclear reactor system arrives to provide power. The flow of system 1500 can be realigned upon arrival of mobile heat pipe cooled fast reactor 1510. Reactor 1510 includes heat pipes that are in contact with or sufficiently proximate to a heat pipe heat exchanger 1512 that is heated by reactor 1510 via the heat pipes. Heat is transferred via a working fluid (e.g., air, carbon dioxide, etc.) contained in a series of pipes. In this embodiment, a working fluid is heated via heat exchanger 1512 to approximately 1100 Kelvin (K) at a pressure of one megapascal (MPa), and the working fluid is provided to a turbine 1544 to do work. The working fluid is supplied to the "combustor" of turbine 1544 and powers turbine 1544 in a similar manner to burning fossil fuel. In some embodiments, if reactor 1510 is not present or otherwise is not working, a series of valves (not shown) may be turned in turbine 1544 to enable turbine 1544 to operate by combusting fossil fuel. Turbine 1544 and a high pressure compressor (HPC) 1542 are connected to, and drive, a generator 1540 to produce electricity.

[0073] After exiting turbine 1544, the pressure and temperature in the working fluid have been reduced to approximately 0.25 MPa and 850 K, respectively. The fluid then drives a turbocharger 1560 that accepts ambient air at approximately 298 K

via a silencer 1570. The turbocharger includes an intercooler 1550 and feeds air to HPC 1542. Air provided from intercooler 1550 is at a pressure of approximately 0.4 MPA and the temperature is reduced by approximately 140 K, significantly increasing the density of the air.

[0074] Air leaving HPC 1542 is at approximately one MPa and 477K, and working fluid leaving turbocharger 1560 is at approximately 0.1 MPa and 750 K. The air and working fluid are then fed into a recuperator 1520, which is a heat exchanger configured to remove heat from the air and working fluid. Hot exhaust from recuperator 1520 at approximately 500 K is provided to a destination to be used for desalination. Working fluid at approximately one MPa and 625 K is then fed back into heat exchanger 1512 to be heated and cycle back though system 1500. The air may also be used to perform fuel-oil combustion via a combustion engine 1530 when reactor is 1510 is not connected. Alternatively, combustion engine 1530 may be used to supplement the heat generation of reactor 1510 in some embodiments.

[0075] In reactor mode, system 1500 may be altered to allow air to be compressed, heated by the heat pipes coming out of the core of reactor 1510, and then be directed to turbine 1544 in place of air heated by natural gas or diesel fuel via combustion engine 1530, for example. The design changes allow for alternate piping connections that allow reactor 1510 to be attached to system 1500.

[0076] FIG. 16 illustrates a perspective cutaway view of a gas turbine 1600. Gas turbine 1600 may be connected by an on-site operator to a heated air outlet from a mobile heat pipe cooled fast reactor, for example. This realigns the gas turbine to reactor mode, where fossil fuel is not required for its operation. In many embodiments,

the generator, regulator, and programmable logic controller (PLC) need not be redesigned.

[0077] FIG. 17 is a schematic diagram 1700 illustrating fuel resources and conventional diesel generators needed to achieve the power output of mobile heat pipe cooled fast reactor systems, according to an embodiment of the present invention. In this example, the power requirements are 6 MW. In order to achieve this power output using conventional MEP-011E diesel generators, 30 generators are required, having a pad area of 5,000 square feet. Further, a weekly convoy of six tanker trucks providing 66,000 gallons of fuel is needed to run the generators.

[0078] However, a mobile heat pipe cooled fast reactor solution only requires three 2 MW reactors, having a pad area of 2,000 square feet. Thus, not only is the need for refueling eliminated, but the space required to deploy the reactors is significantly less than with a diesel generator solution. Furthermore, a smaller size of the power generator site provides a smaller target size to enemy combatants, making the reactors harder to hit with mortars, for example. Further, even if hit, the reactors may be armored as discussed above.

[0079] FIG. 18 is a schematic diagram 1800 illustrating conventional solar equipment and fuel resources needed to achieve the power output of mobile heat pipe cooled fast reactor systems, according to an embodiment of the present invention. Solar power does not have 100% availability, i.e., it only works well when there is little or no cloud cover. As such, solar systems require a greater level of generating capacity to offset the lack of energy when the sun is not available. However, nuclear

reactors can run 100% of the time, and thus, require less installed capacity relative to solar systems.

[0080] It will be readily understood that the components of various embodiments of the present invention, as generally described and illustrated in the figures herein, may be arranged and designed in a wide variety of different configurations. Thus, the detailed description of the embodiments of the systems, apparatuses, methods, and computer programs of the present invention, as represented in the attached figures, is not intended to limit the scope of the invention as claimed, but is merely representative of selected embodiments of the invention.

[0081] The features, structures, or characteristics of the invention described throughout this specification may be combined in any suitable manner in one or more embodiments. For example, reference throughout this specification to "certain embodiments," "some embodiments," or similar language means that a particular feature, structure, or characteristic described in connection with the embodiment is included in at least one embodiment of the present invention. Thus, appearances of the phrases "in certain embodiments," "in some embodiment," "in other embodiments," or similar language throughout this specification do not necessarily all refer to the same group of embodiments and the described features, structures, or characteristics may be combined in any suitable manner in one or more embodiments.

[0082] It should be noted that reference throughout this specification to features, advantages, or similar language does not imply that all of the features and advantages that may be realized with the present invention should be or are in any single embodiment of the invention. Rather, language referring to the features and

advantages is understood to mean that a specific feature, advantage, or characteristic described in connection with an embodiment is included in at least one embodiment of the present invention. Thus, discussion of the features and advantages, and similar language, throughout this specification may, but do not necessarily, refer to the same embodiment.

[0083] Furthermore, the described features, advantages, and characteristics of the invention may be combined in any suitable manner in one or more embodiments. One skilled in the relevant art will recognize that the invention can be practiced without one or more of the specific features or advantages of a particular embodiment. In other instances, additional features and advantages may be recognized in certain embodiments that may not be present in all embodiments of the invention.

[0084] One having ordinary skill in the art will readily understand that the invention as discussed above may be practiced with steps in a different order, and/or with hardware elements in configurations that are different than those which are disclosed. Therefore, although the invention has been described based upon these embodiments, it would be apparent to those of skill in the art that certain modifications, variations, and alternative constructions would be apparent, while remaining within the spirit and scope of the invention. In order to determine the metes and bounds of the invention, therefore, reference should be made to the appended claims.

CLAIMS

1. A system, comprising:

a plurality of heat pipes comprising coolant; and

a plurality of fuel pins containing nuclear fuel, the plurality of fuel pins positioned proximate to the plurality of heat pipes, wherein

the heat pipes extend outward from a reactor core through a block and are configured to transfer heat away from the reactor core.

2. The system of claim 1, wherein each of the plurality of heat pipes comprises:

a sealed tube comprising volatile liquid; and

a wick that uses capillary forces to draw condensate of the volatile liquid back toward the reactor core, wherein

a shape of the wick imposes order on the volatile liquid by forming menisci between the condensate and the vapor and allowing the condensate to flow toward the reactor core.

3. The system of claim 2, wherein the volatile liquid comprises potassium or sodium.

4. The system of claim 1, further comprising:

a plurality of control drums and a reflector.

5. The system of claim 1, further comprising:

a primary heat exchanger configured to recover heat from nuclear reactions; and

a decay heat exchanger configured to recover heat from nuclear decay.

6. The system of claim 5, further comprising:

a Brayton cycle power conversion system configured to:

compress a working fluid using a compressor,

pass the working fluid through at least one of the primary and decay heat exchangers, and

release the working fluid through a turbine to do work.

7. The system of claim 1, wherein the reactor core comprises a plurality of separate, thermally and mechanically isolated, but neutronically connected, sections.

8. The system of claim 1, wherein there are more fuel pins than heat pipes.

9. The system of claim 8, wherein there are two fuel pins for every heat pipe.

10. The system of claim 1, wherein each fuel pin comprises:

nuclear fuel;

an upper and lower axial reflector positioned above and below the nuclear fuel, respectively, the axial reflectors configured to scatter neutron and gamma radiation; and

a fission gas plenum positioned below the lower axial reflector.

11. The system of claim 1, further comprising:

an Al_2O_3 reflector that surrounds the reactor core.

12. The system of claim 1, further wherein the plurality of heat pipes, the plurality of fuel pins, and the reactor core are part of a mobile heat pipe cooled fast reactor.

13. The system of claim 12, further comprising:

a combustion engine; and

a turbine configured to receive, and be driven by, a working fluid heated by the mobile heat pipe cooled fast reactor and the combustion engine, wherein

the system is configured to drive the turbine via the mobile heat pipe cooled fast reactor when the mobile heat pipe cooled fast reactor is connected, and via the combustion engine when the mobile heat pipe cooled fast reactor is not connected.

14. The system of claim 13, wherein the turbine is configured to be driven by working fluid heated by both the mobile heat pipe cooled fast reactor and the combustion engine.

15. A system, comprising:

a mobile heat pipe cooled fast reactor;

a cask housing the mobile heat pipe cooled fast reactor;

a skid comprising rollers or tires; and

a cradle operably attached to the skid, wherein

the cradle is configured to secure the cask in place to transport the mobile heat pipe cooled fast reactor using the skid.

16. The system of claim 15, further comprising:

a pair of impact absorbers configured to cover ends of the cask.

17. The system of claim 16, wherein the impact absorbers comprise a plurality of openings configured to provide shield cooling flow.

18. The system of claim 15, further comprising:

a personnel barrier that at least partially surrounds the cask and is configured to shield personnel from radiation.

19. An apparatus, comprising:

a containment vessel surrounded by a neutron shield, the neutron shield surrounded by an air gap;

a gamma shield that defines an outer boundary of the air gap, the air gap providing cooling for the gamma shield; and

an outer wall that covers the gamma shield.

20. The apparatus of claim 19, wherein the apparatus is configured to be transported by aircraft, by truck, or both.

100

FIG. 1

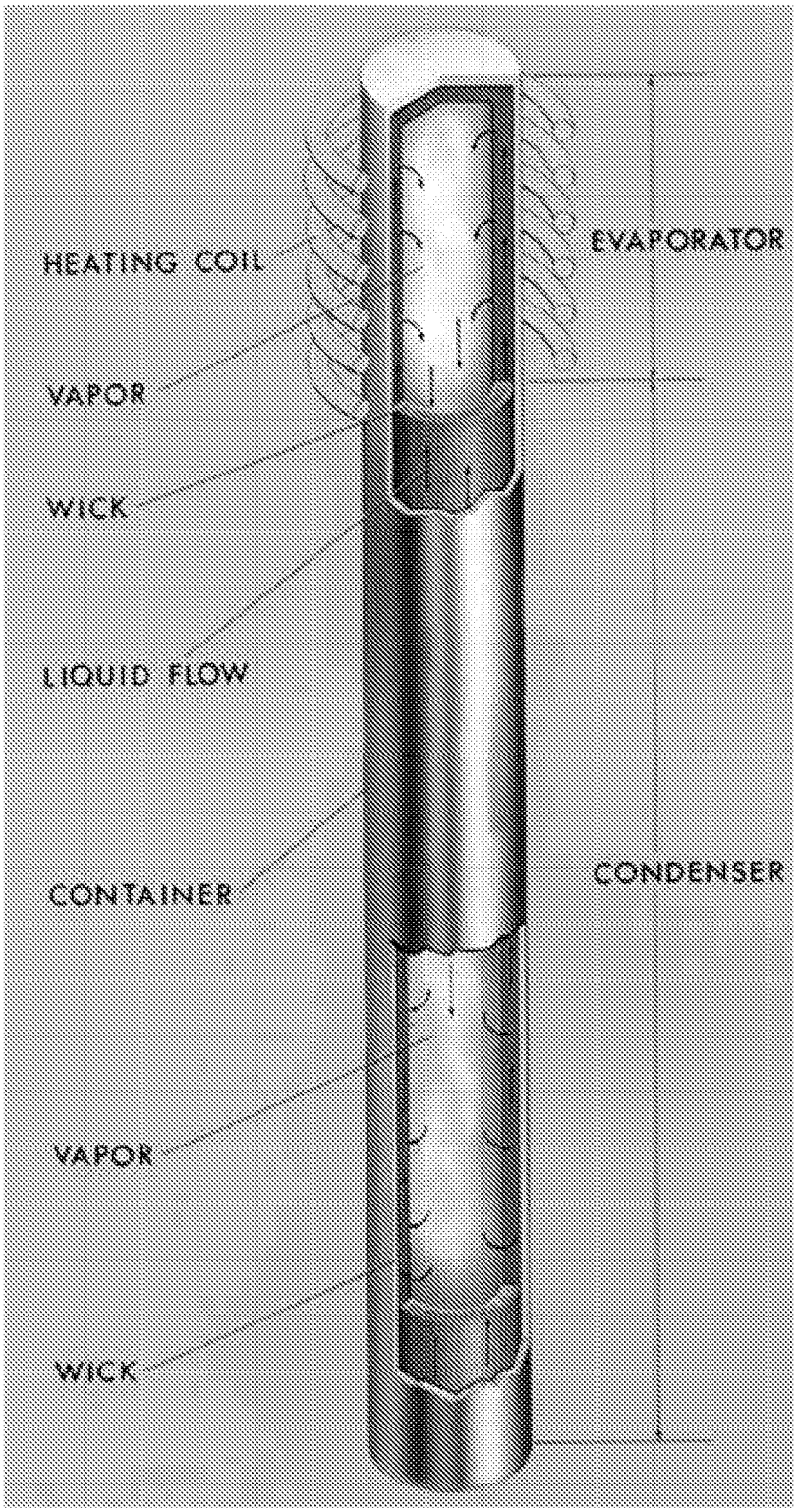

HEATING COIL
VAPOR
WICK
LIQUID FLOW
CONTAINER
VAPOR
WICK
EVAPORATOR
CONDENSER

FIG. 2

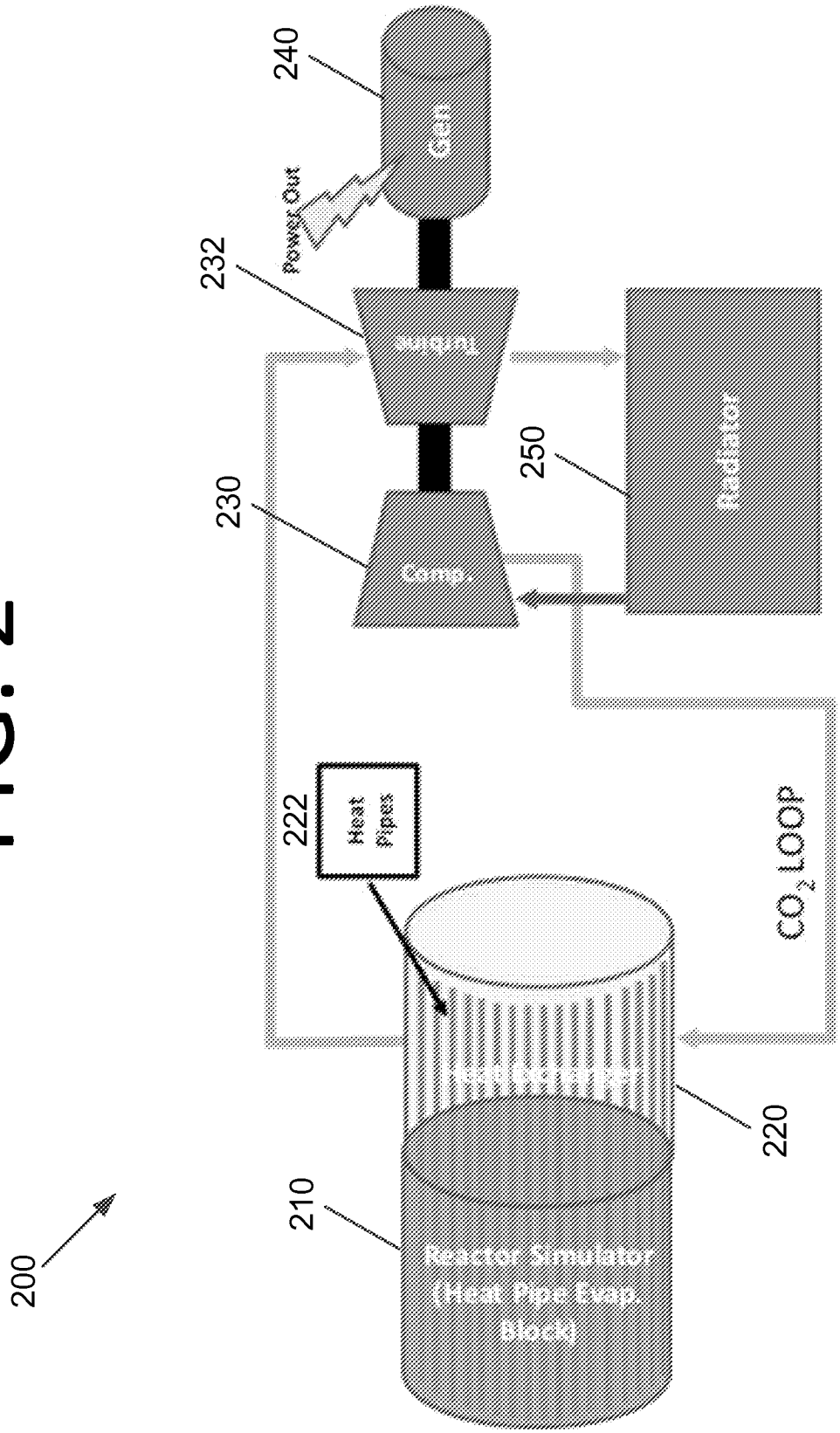

200
210
Reactor Simulator (Heat Pipe Evap. Block)
220
222
Heat Pipes
CO_2 LOOP
230
Comp.
250
Radiator
232
Turbine
240
Gen
Power Out

FIG. 3

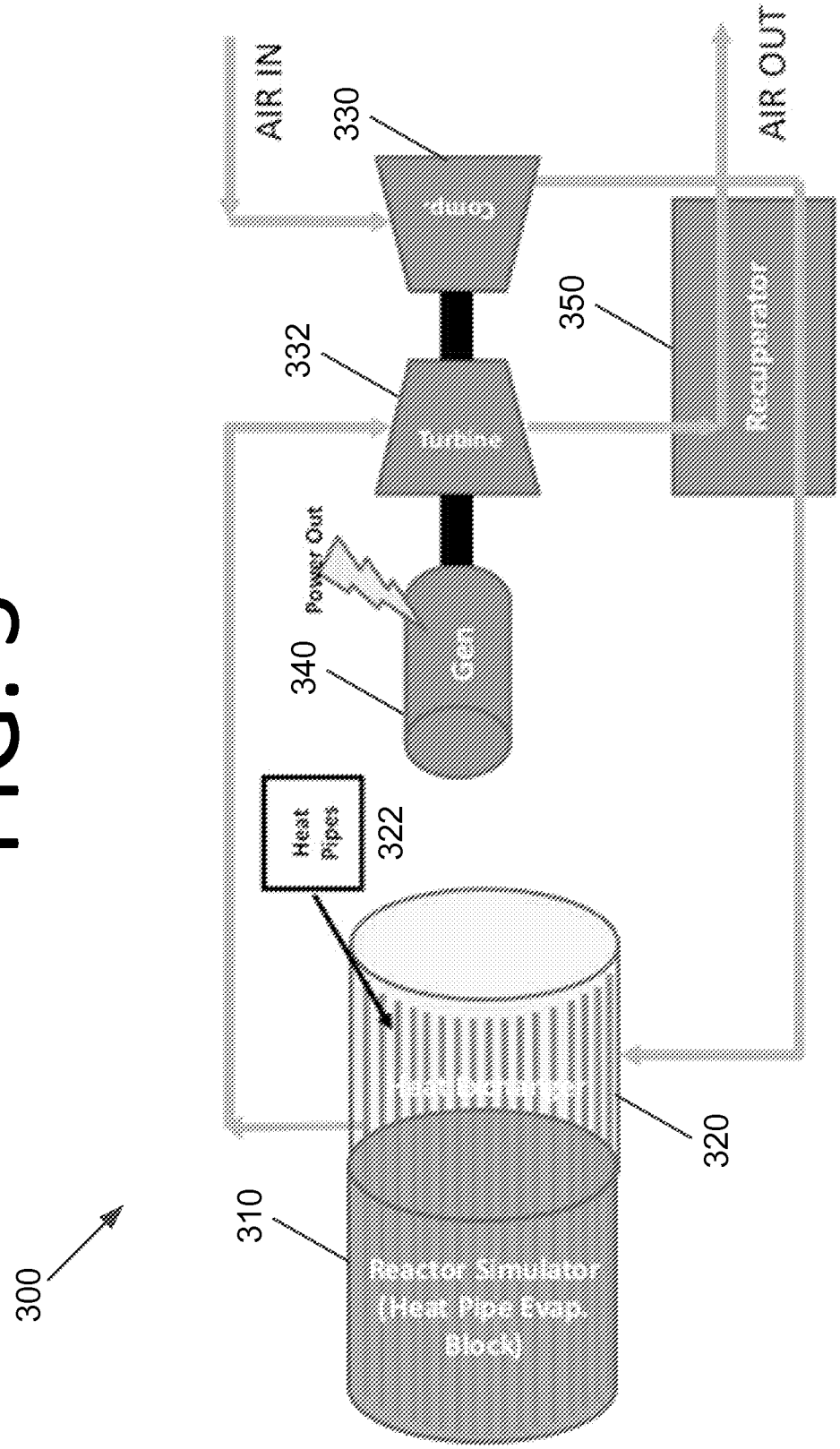
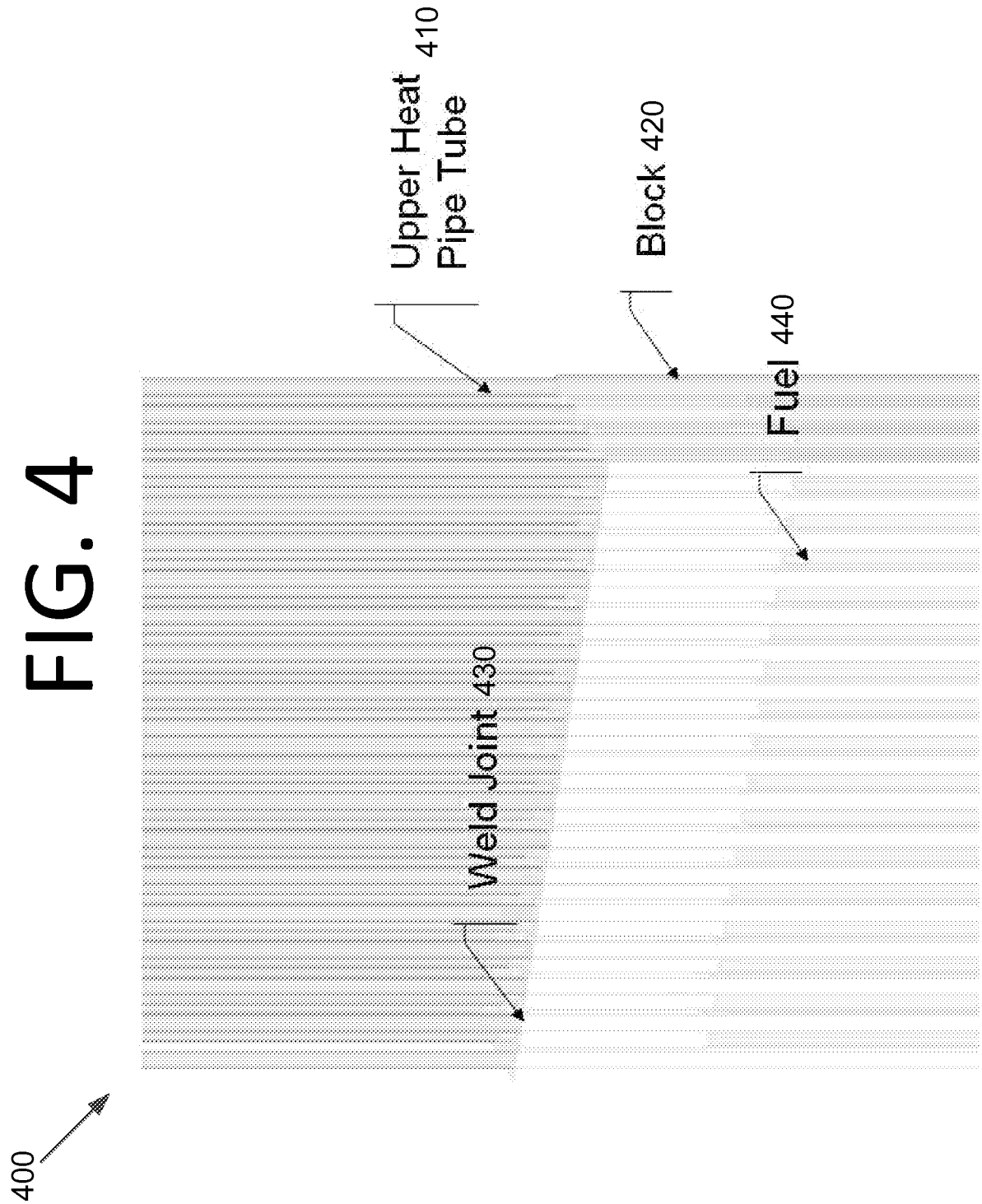

AIR IN
AIR OUT
330
Comp
332
Turbine
350
Recuperator
Power Out
340
Gen
Heat Pipes
322
320
310
Reactor Simulator (Heat Pipe Evap. Block)
300

FIG. 4


400
Upper Heat Pipe Tube 410
Block 420
Fuel 440
Weld Joint 430

500

FIG. 5

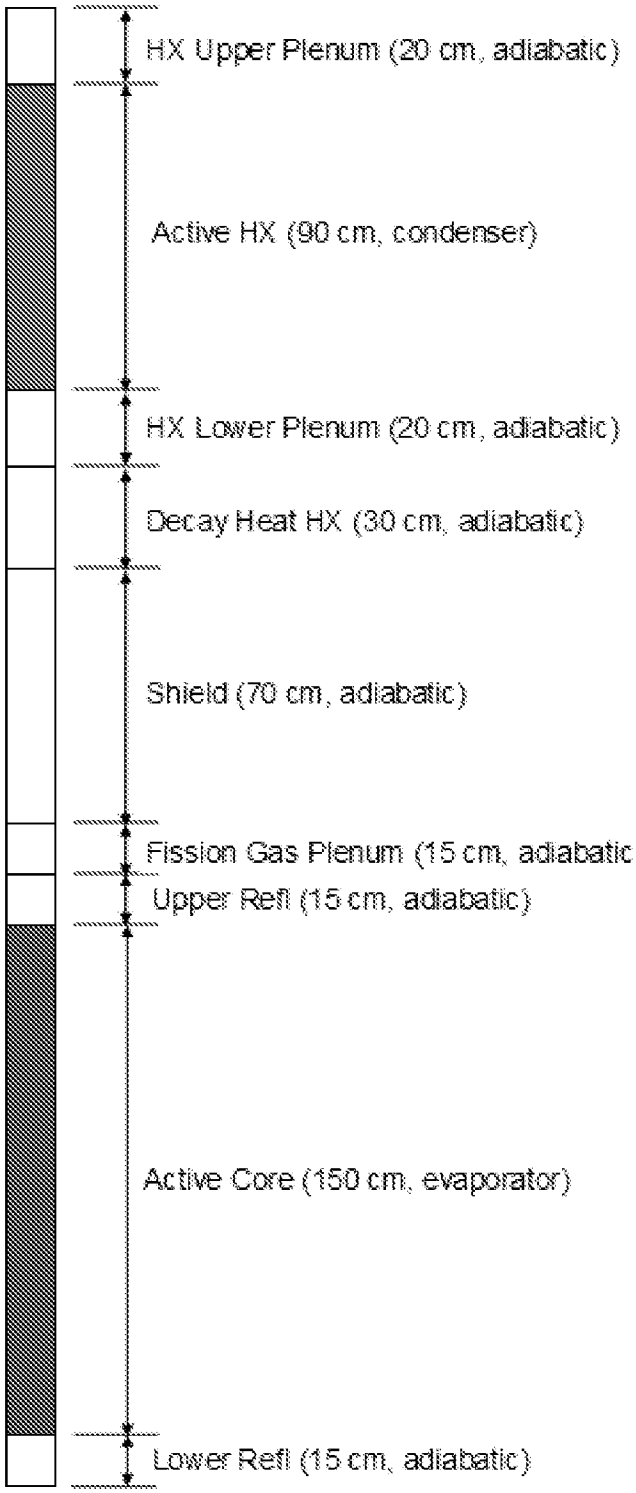
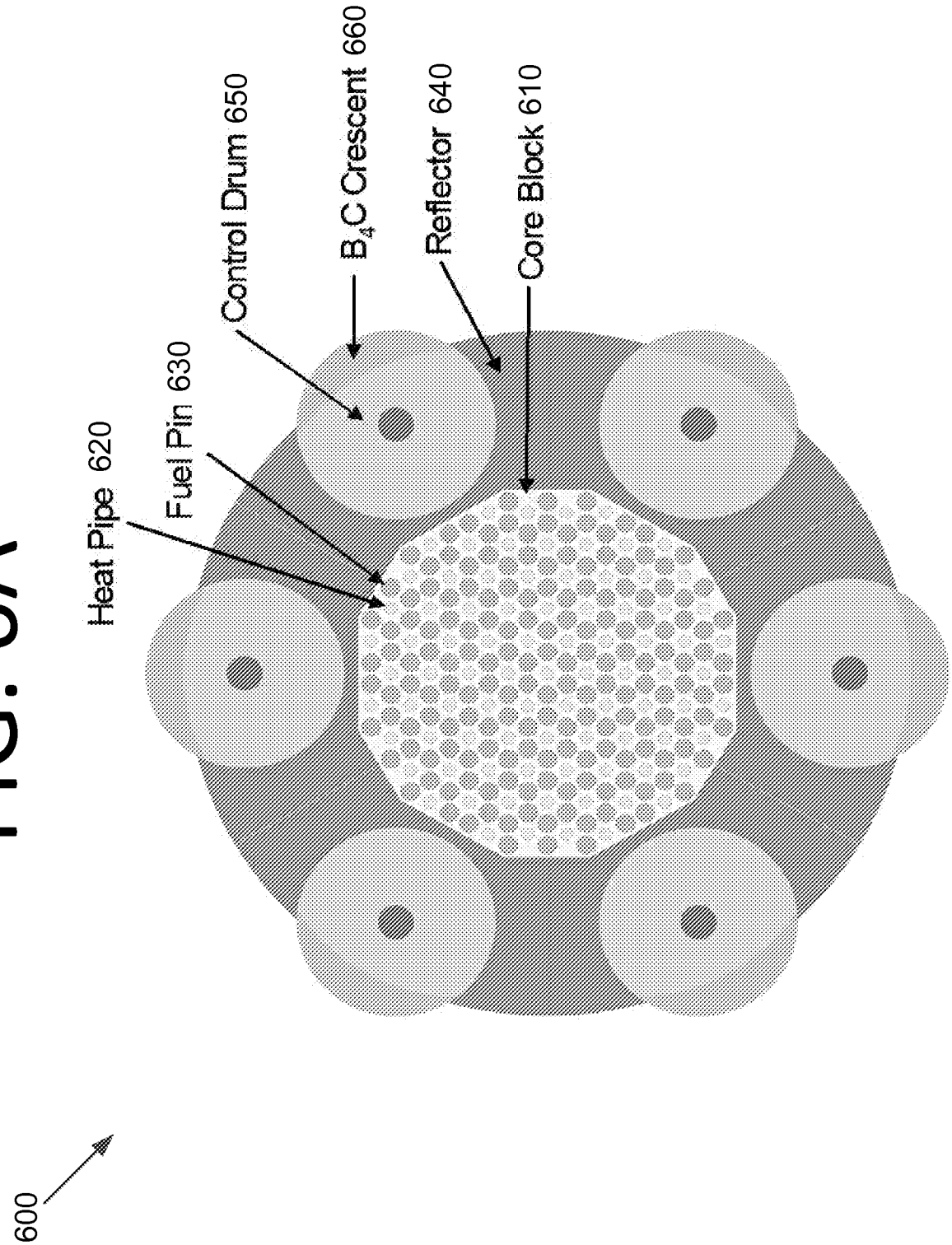
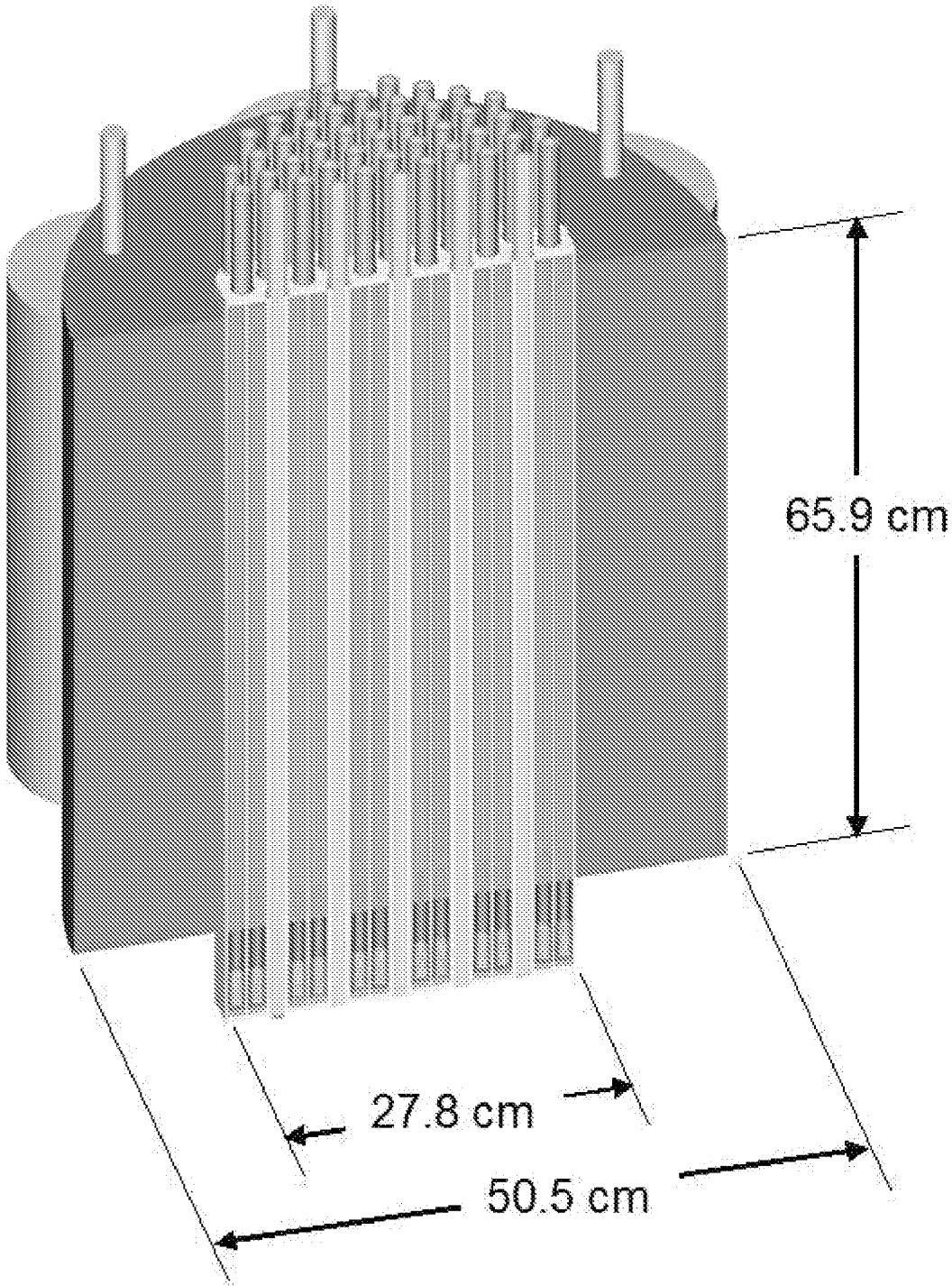

HX Upper Plenum (20 cm, adiabatic)
Active HX (90 cm, condenser)
HX Lower Plenum (20 cm, adiabatic)
Decay Heat HX (30 cm, adiabatic)
Shield (70 cm, adiabatic)
Fission Gas Plenum (15 cm, adiabatic
Upper Refl (15 cm, adiabatic)
Active Core (150 cm, evaporator)
Lower Refl (15 cm, adiabatic)

FIG. 6A


Heat Pipe 620
Fuel Pin 630
Control Drum 650
B_4C Crescent 660
Reflector 640
Core Block 610
600

600

FIG. 6B



700

FIG. 7A

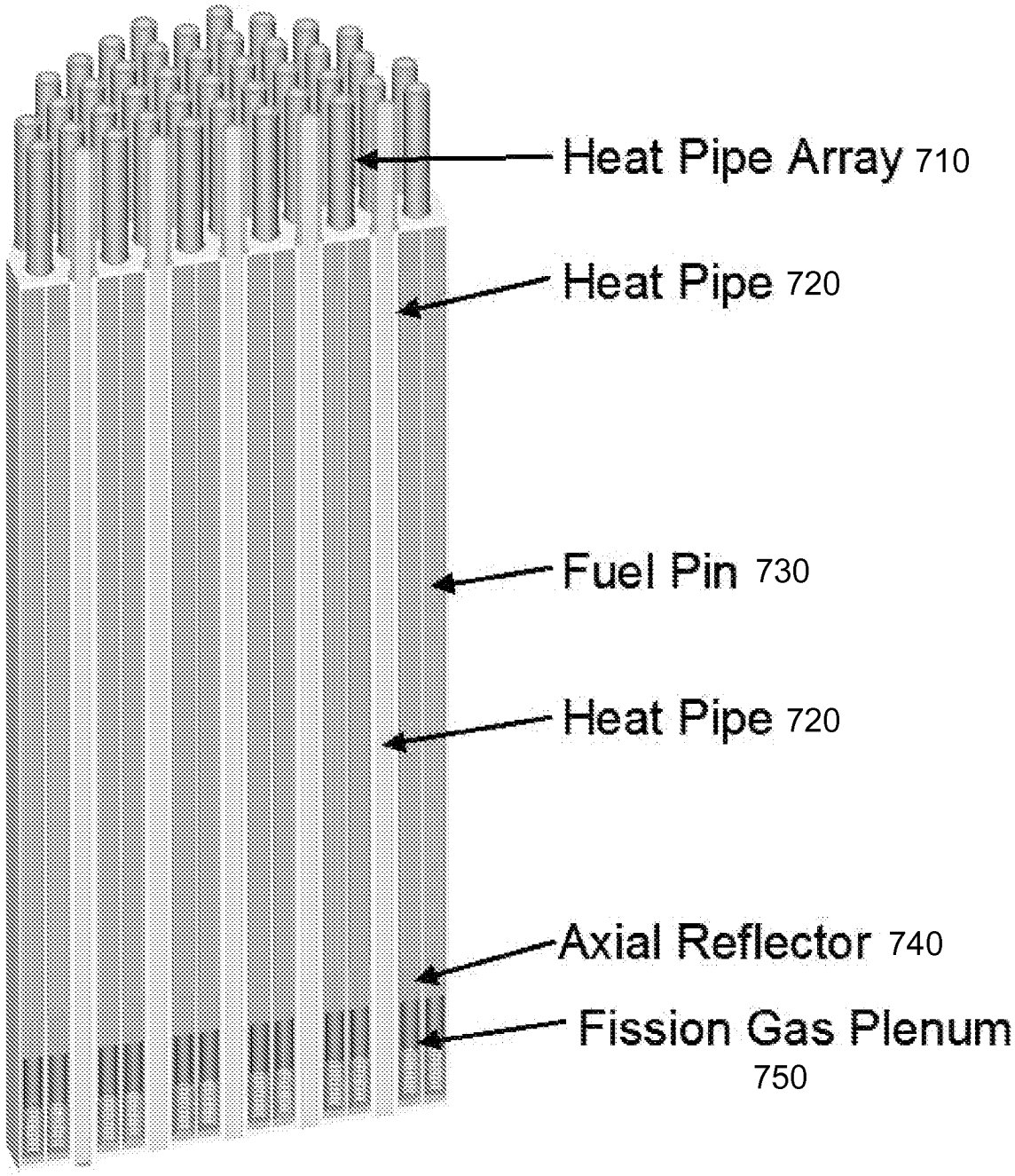

Heat Pipe Array 710
Heat Pipe 720
Fuel Pin 730
Heat Pipe 720
Axial Reflector 740
Fission Gas Plenum
750

FIG. 7B

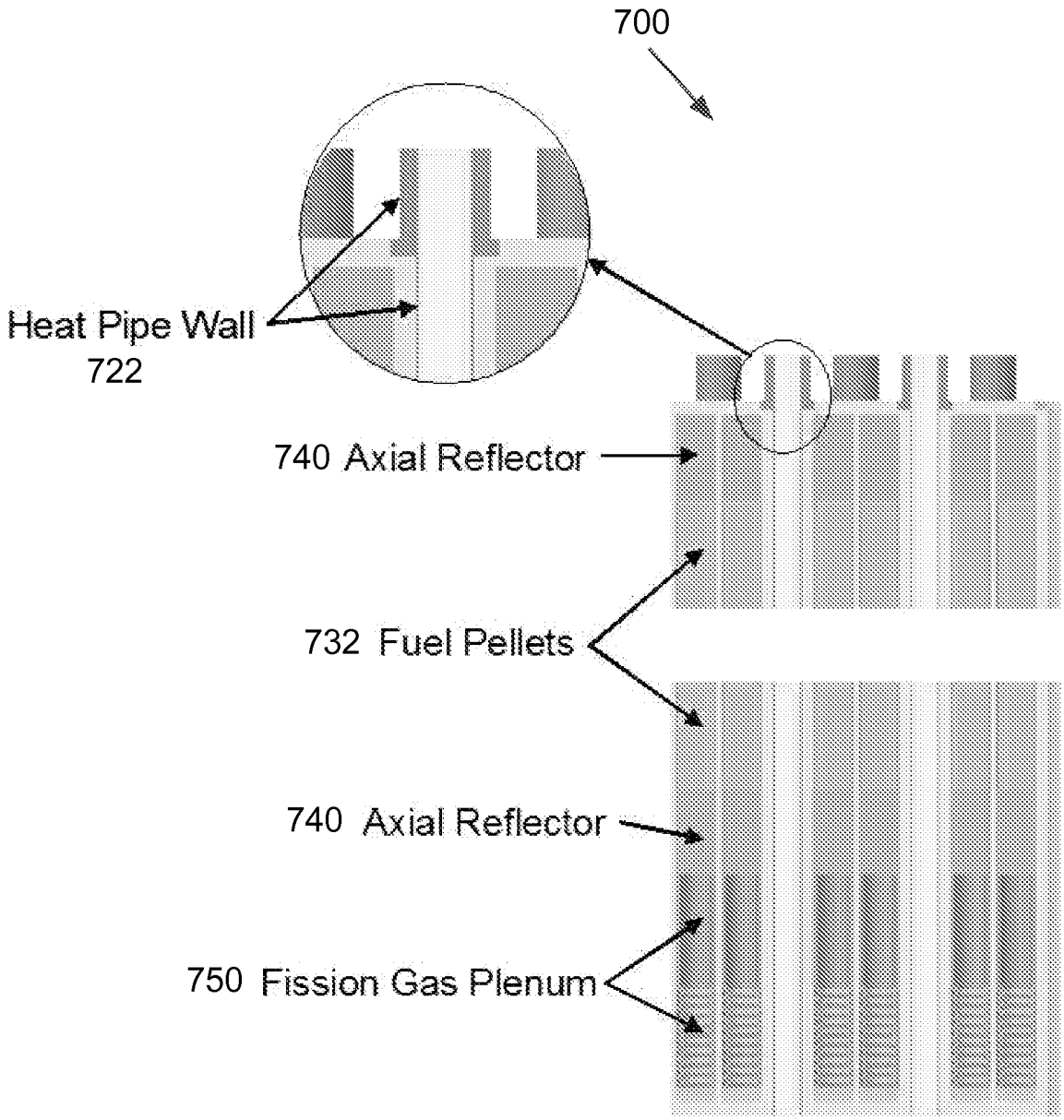

700
Heat Pipe Wall
722
740 Axial Reflector
732 Fuel Pellets
740 Axial Reflector
750 Fission Gas Plenum

FIG. 7C

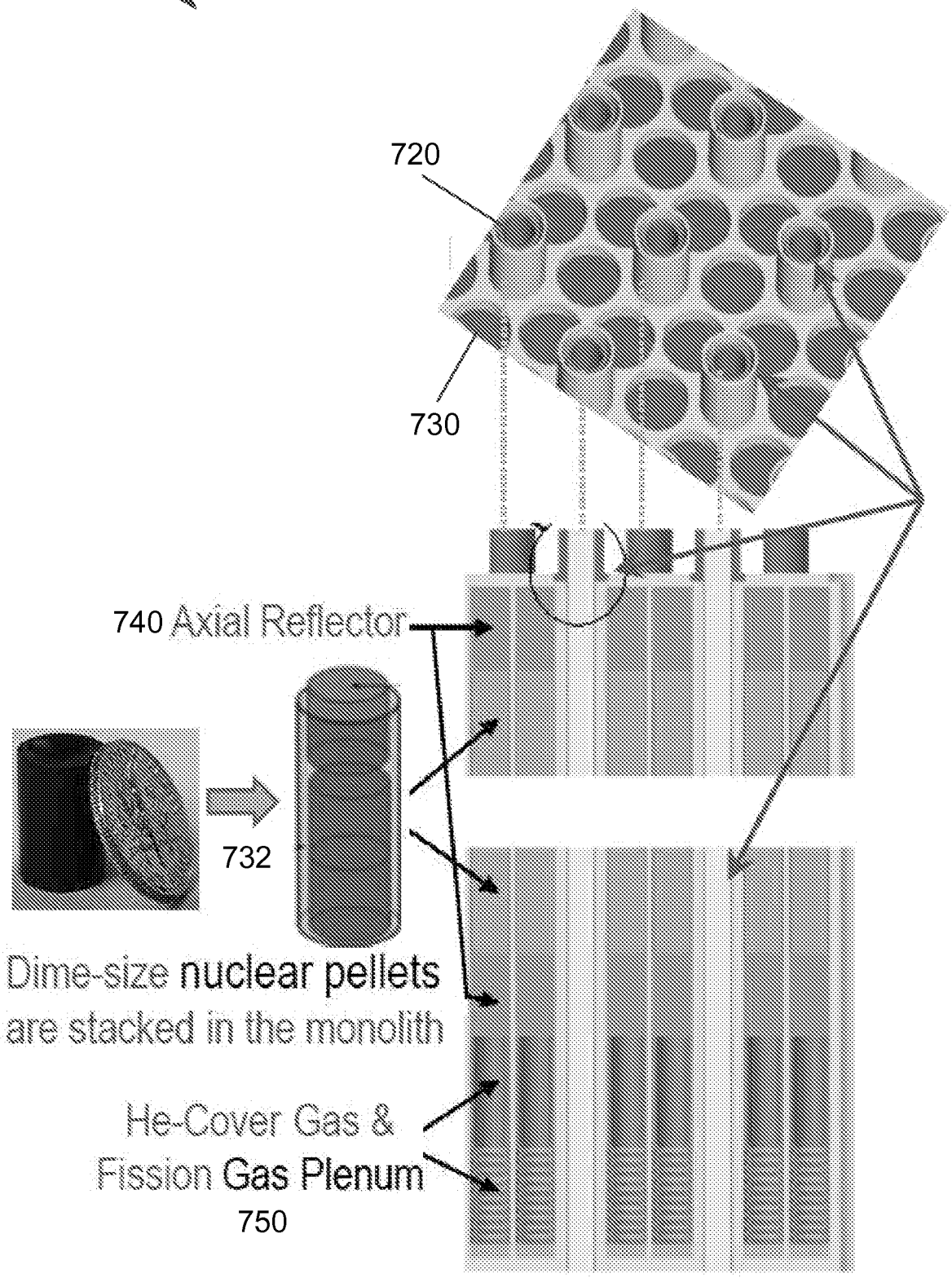

700
720
730
740 Axial Reflector
732
Dime-size nuclear pellets
are stacked in the monolith
He-Cover Gas &
Fission Gas Plenum
750

FIG. 8

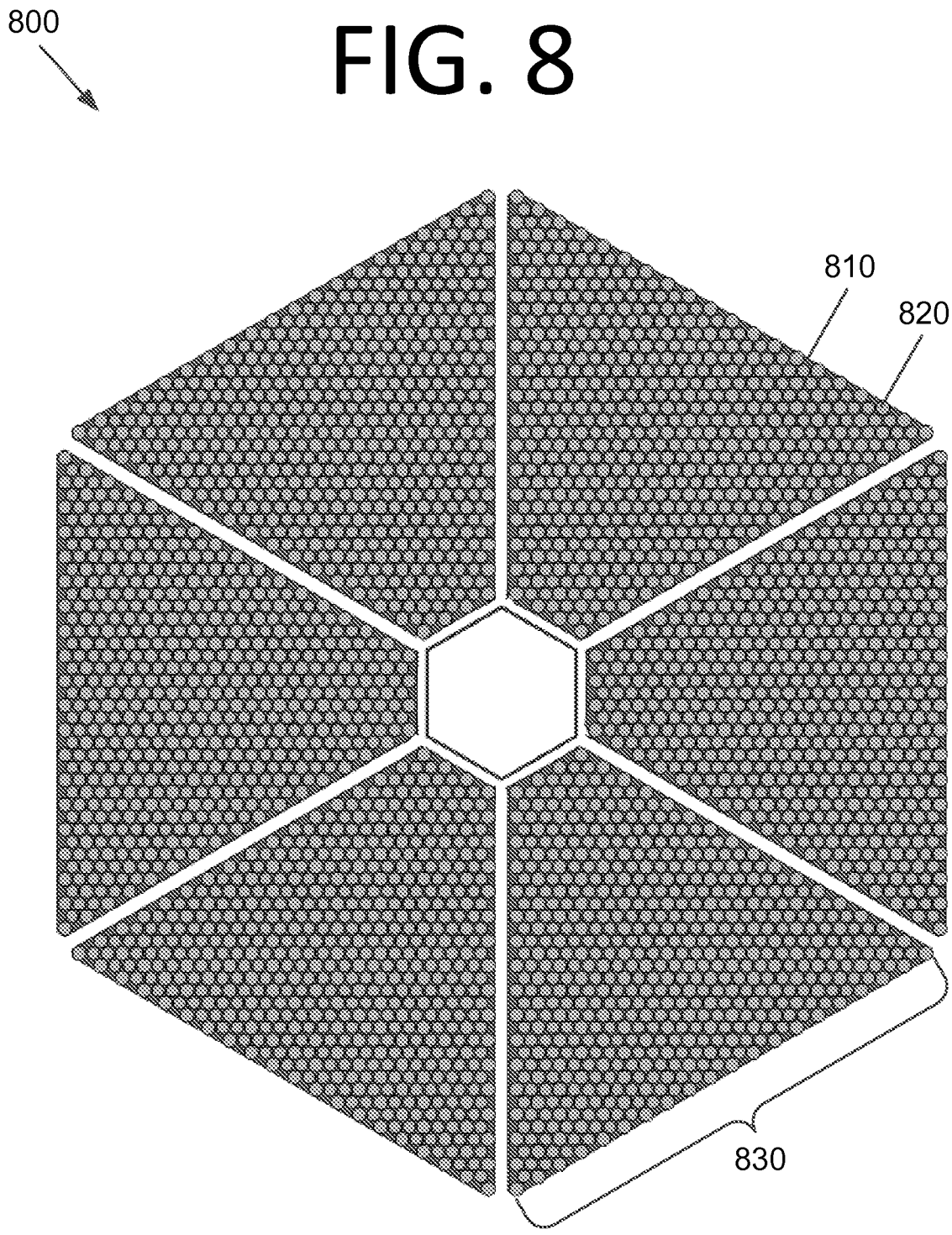
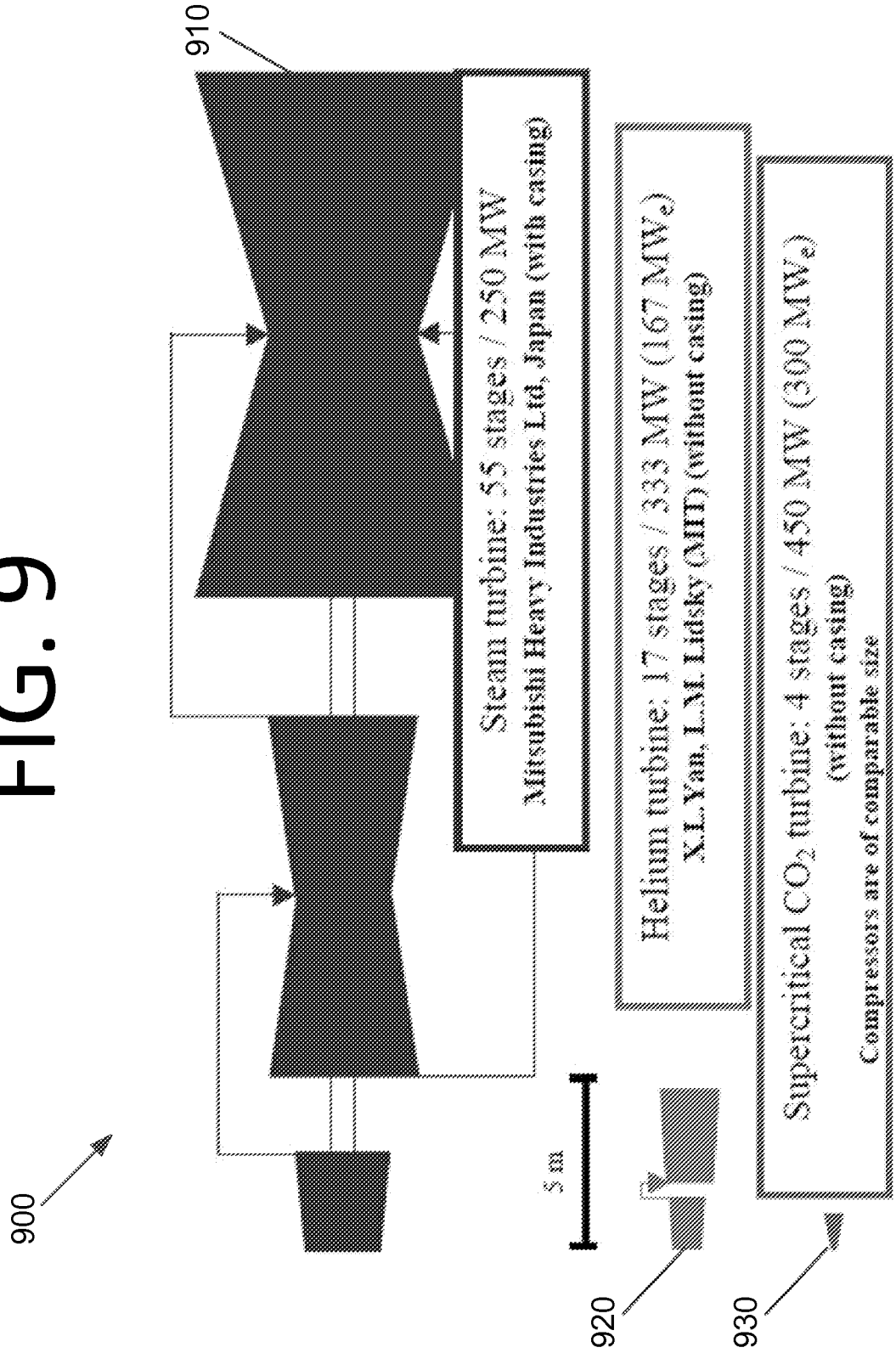


FIG. 9



Related Art

FIG. 10

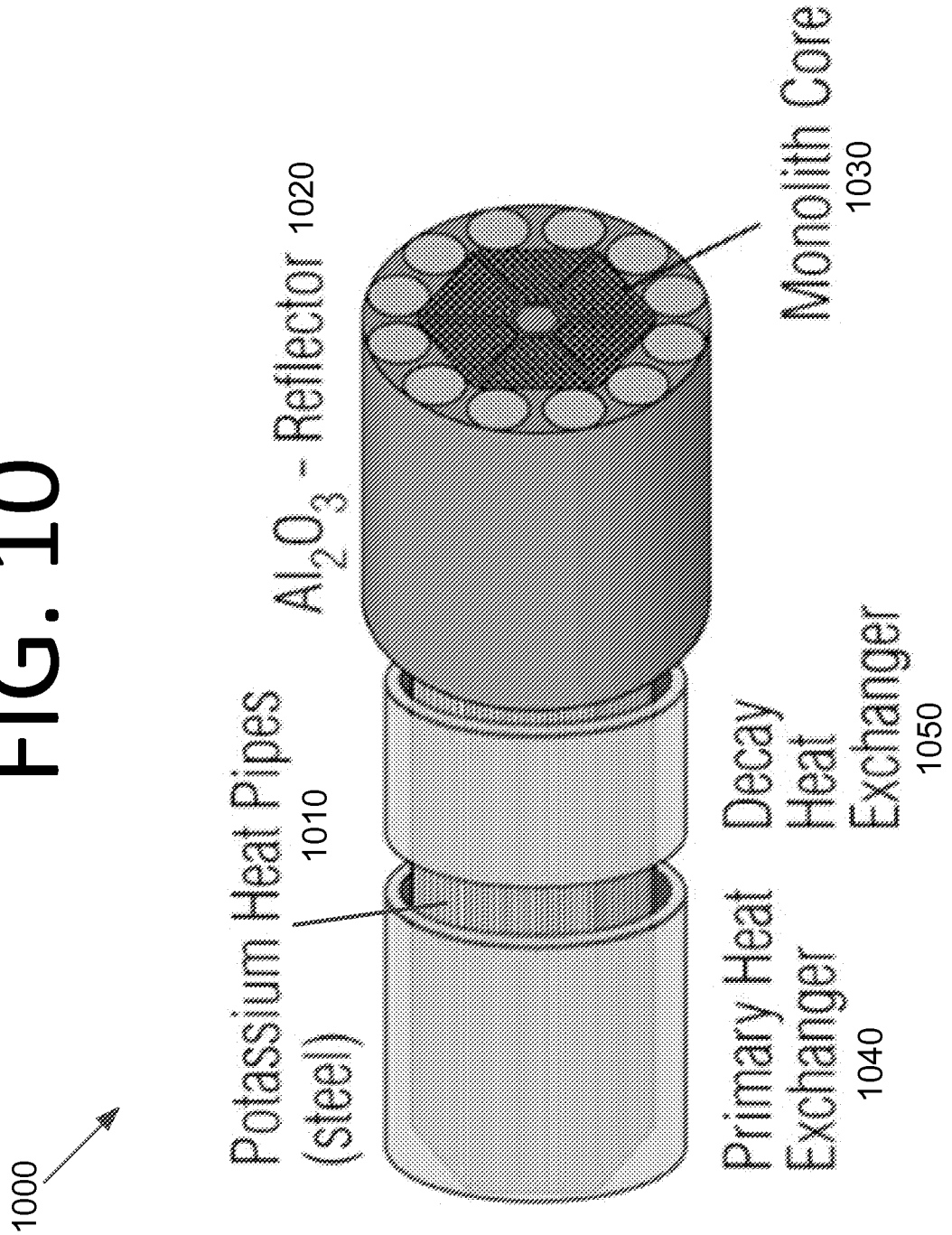

1000
Potassium Heat Pipes (steel) 1010
Al_2O_3 - Reflector 1020
Monolith Core 1030
Primary Heat Exchanger 1040
Decay Heat Exchanger 1050

FIG. 11A

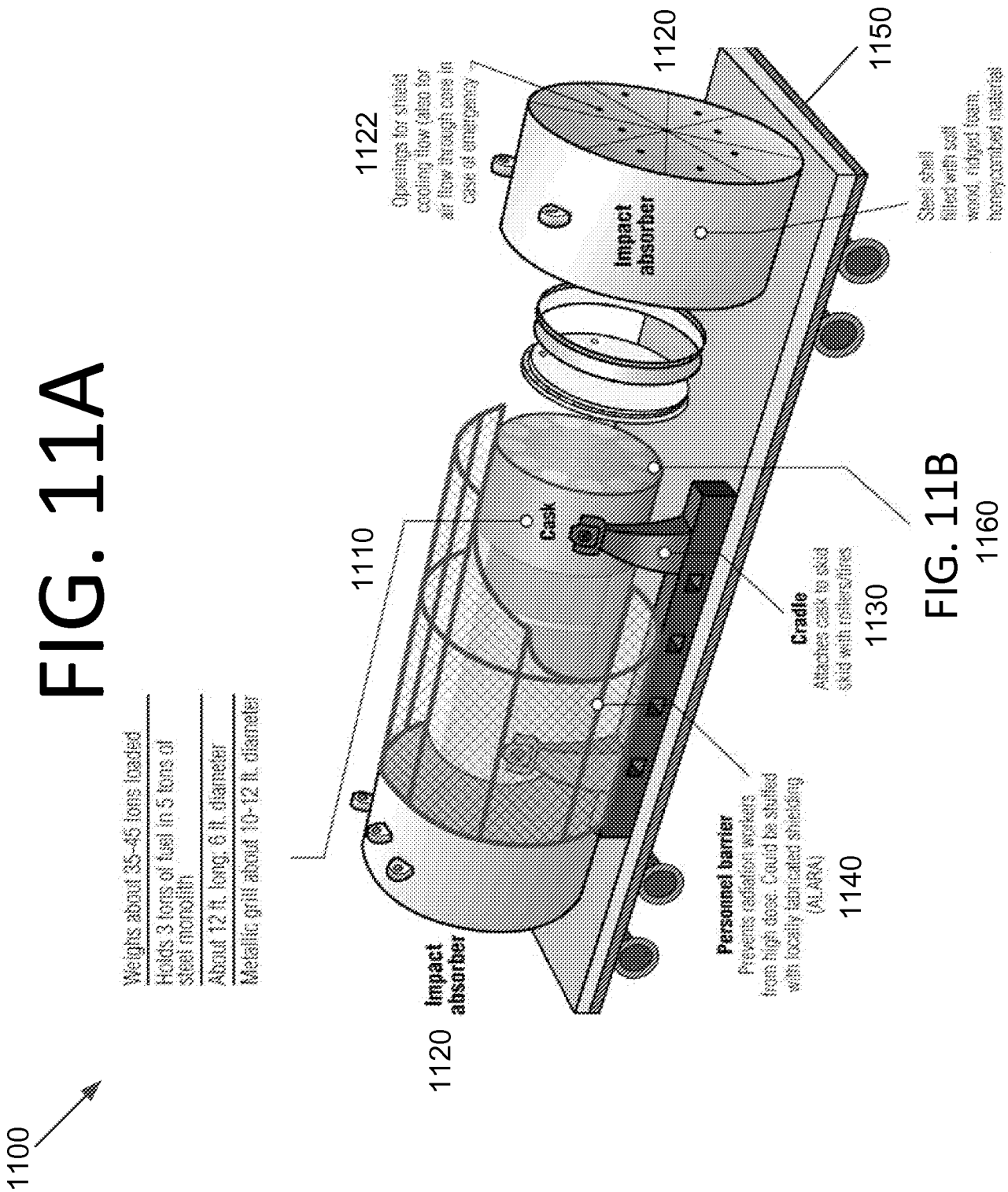


FIG. 11B

FIG. 11B

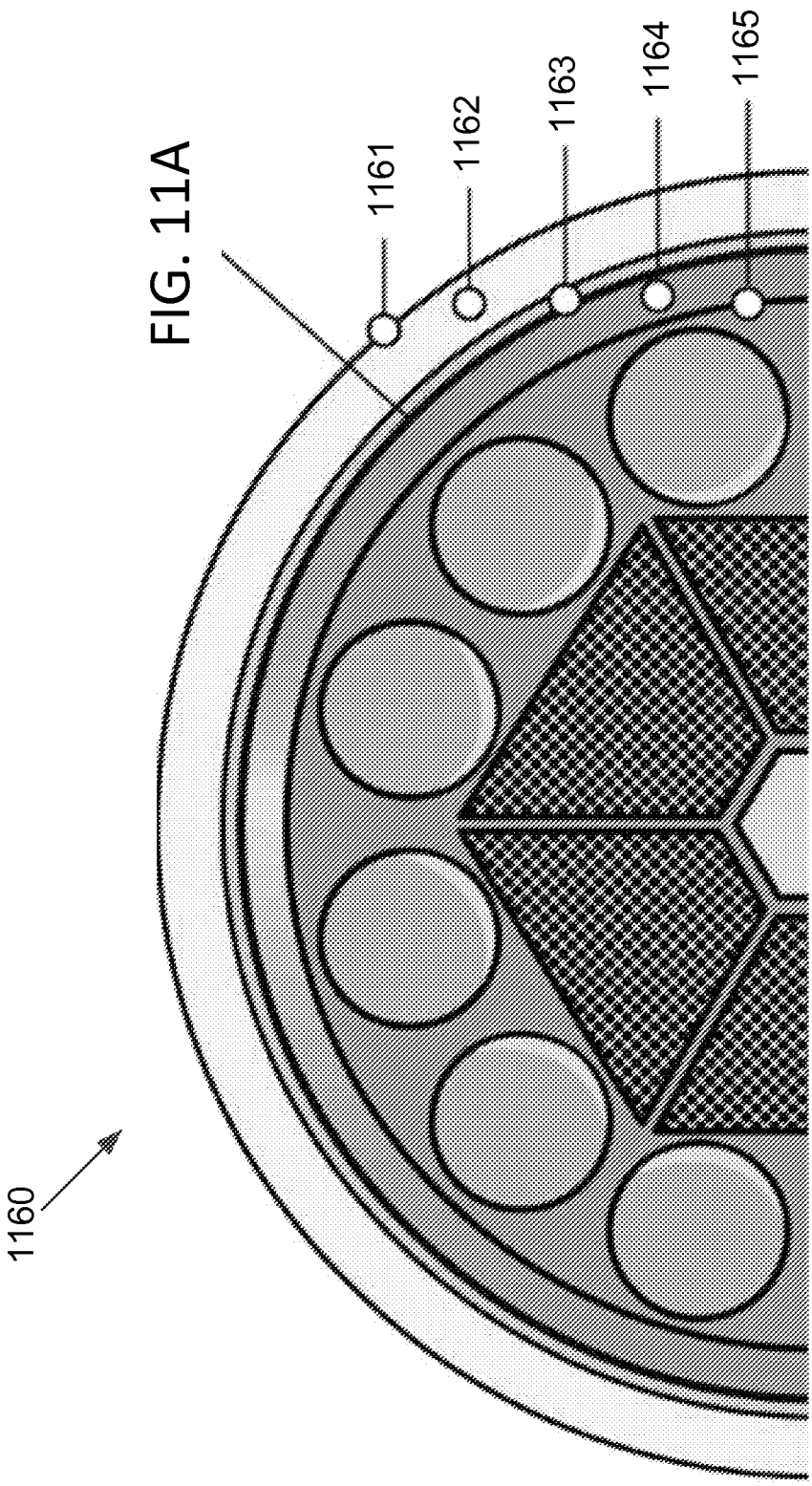


FIG. 12

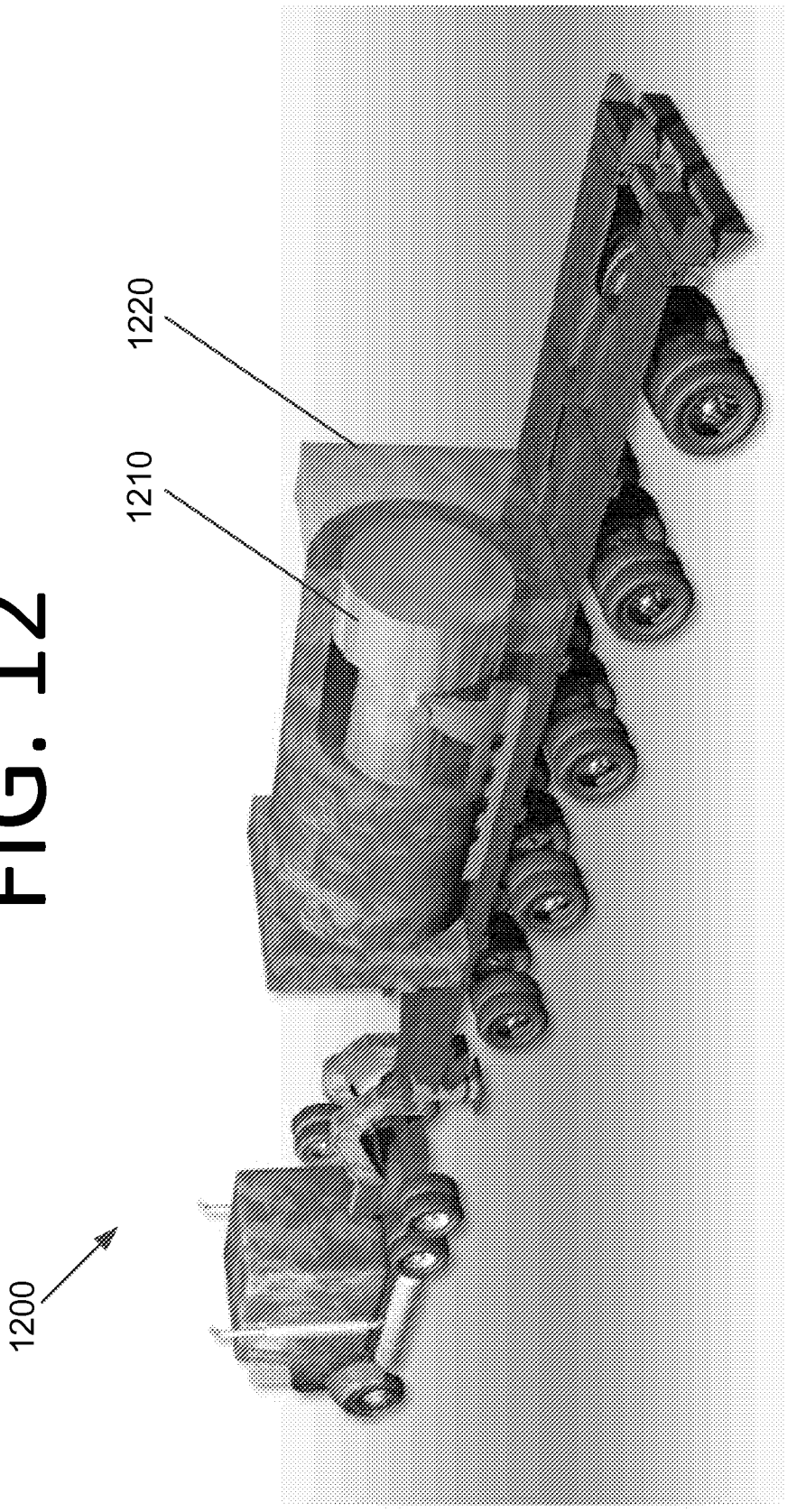


FIG. 13

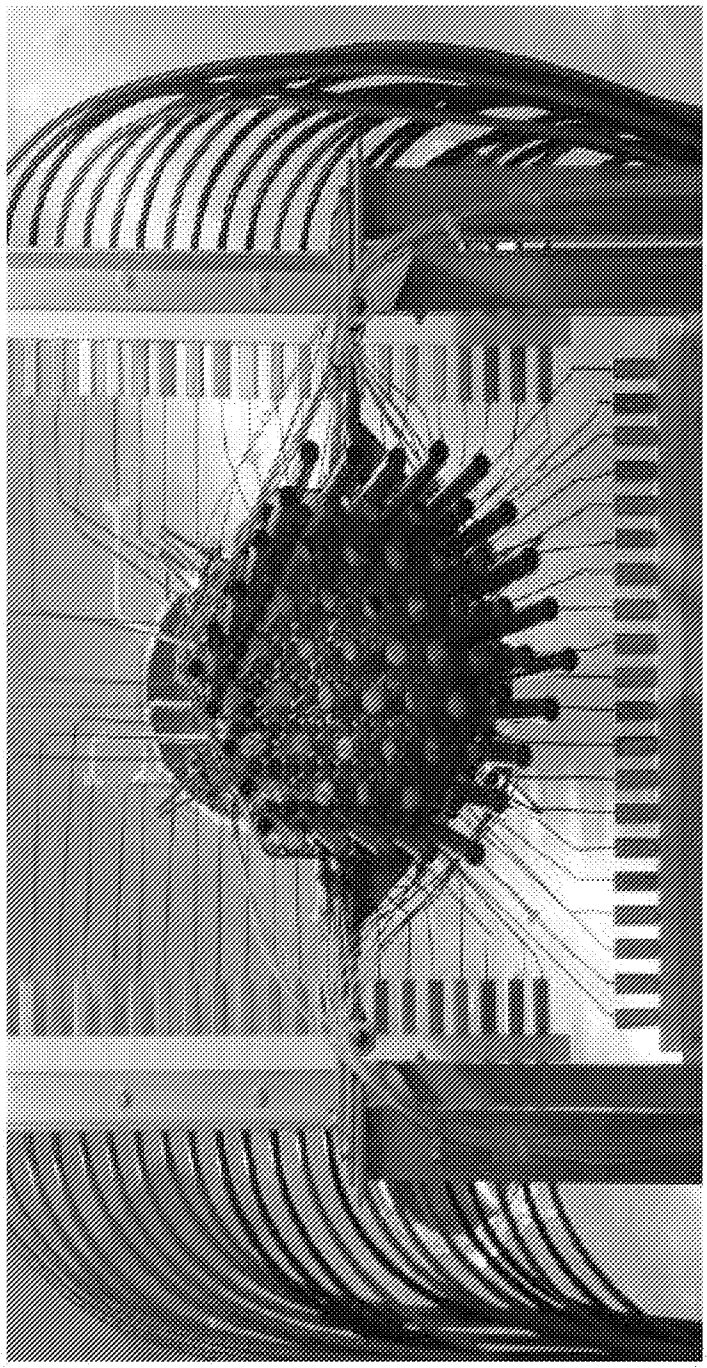


FIG. 14A

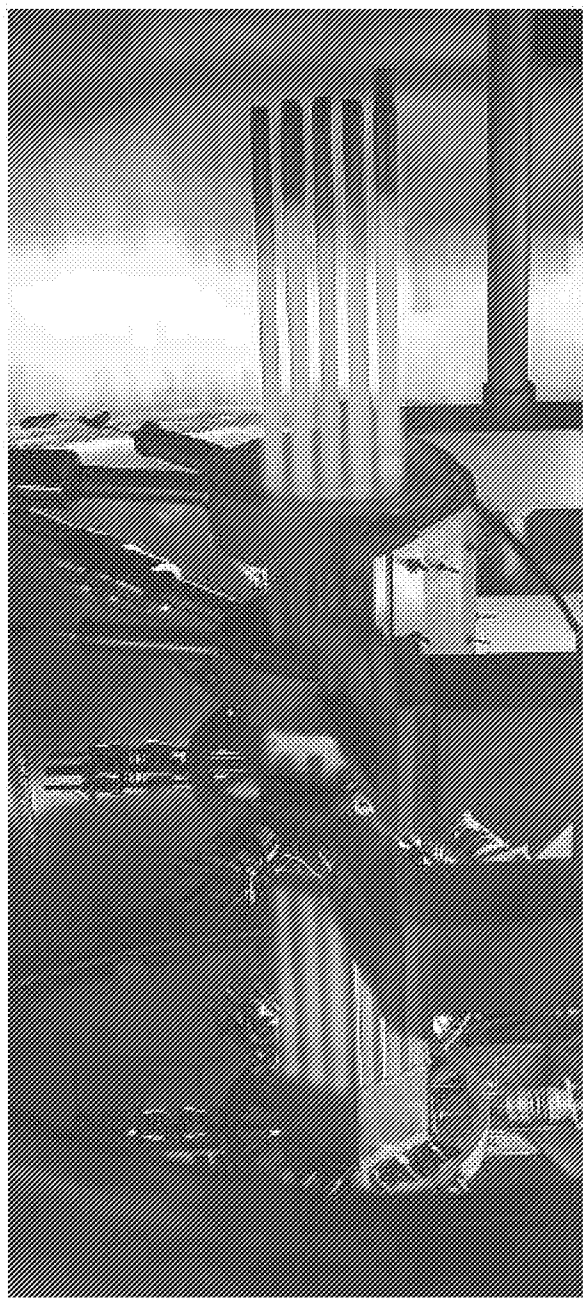


FIG. 14B

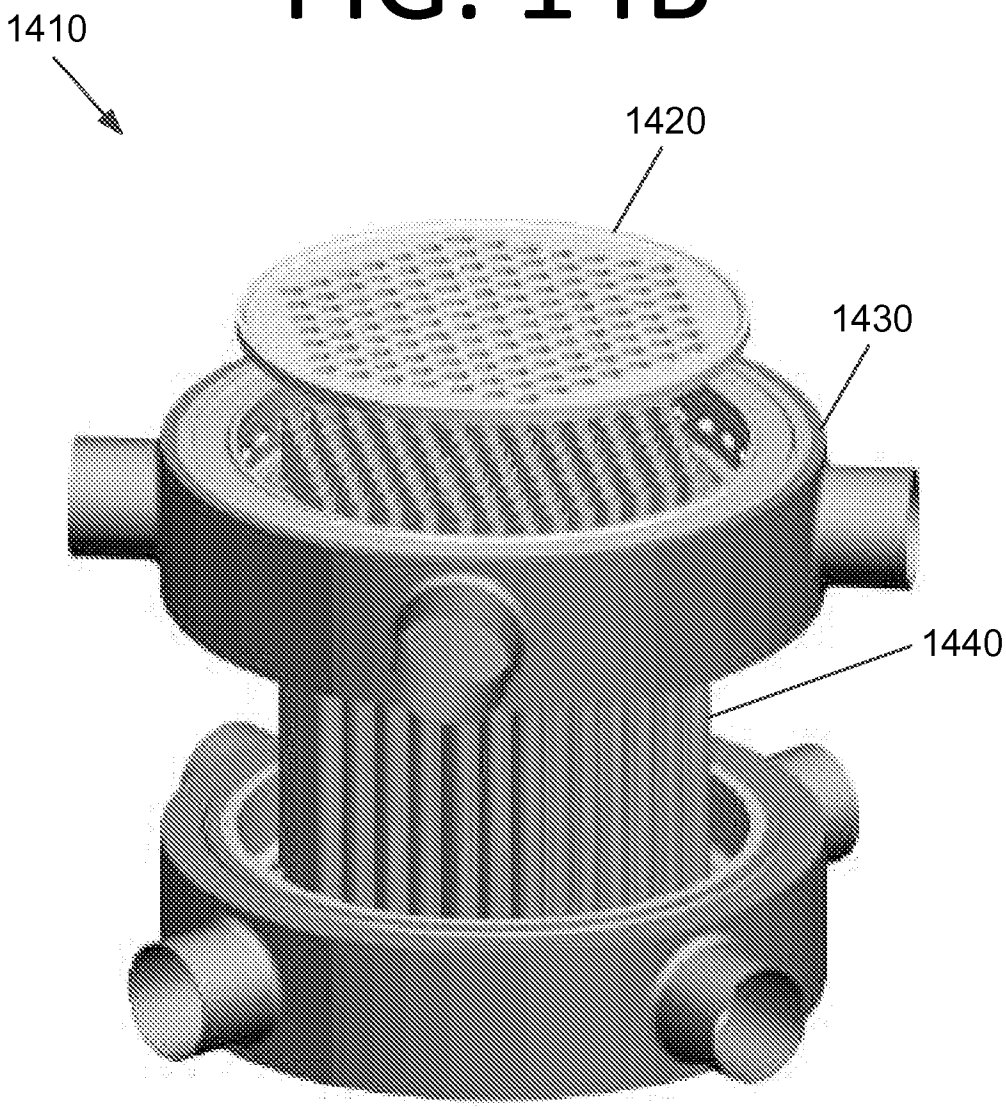
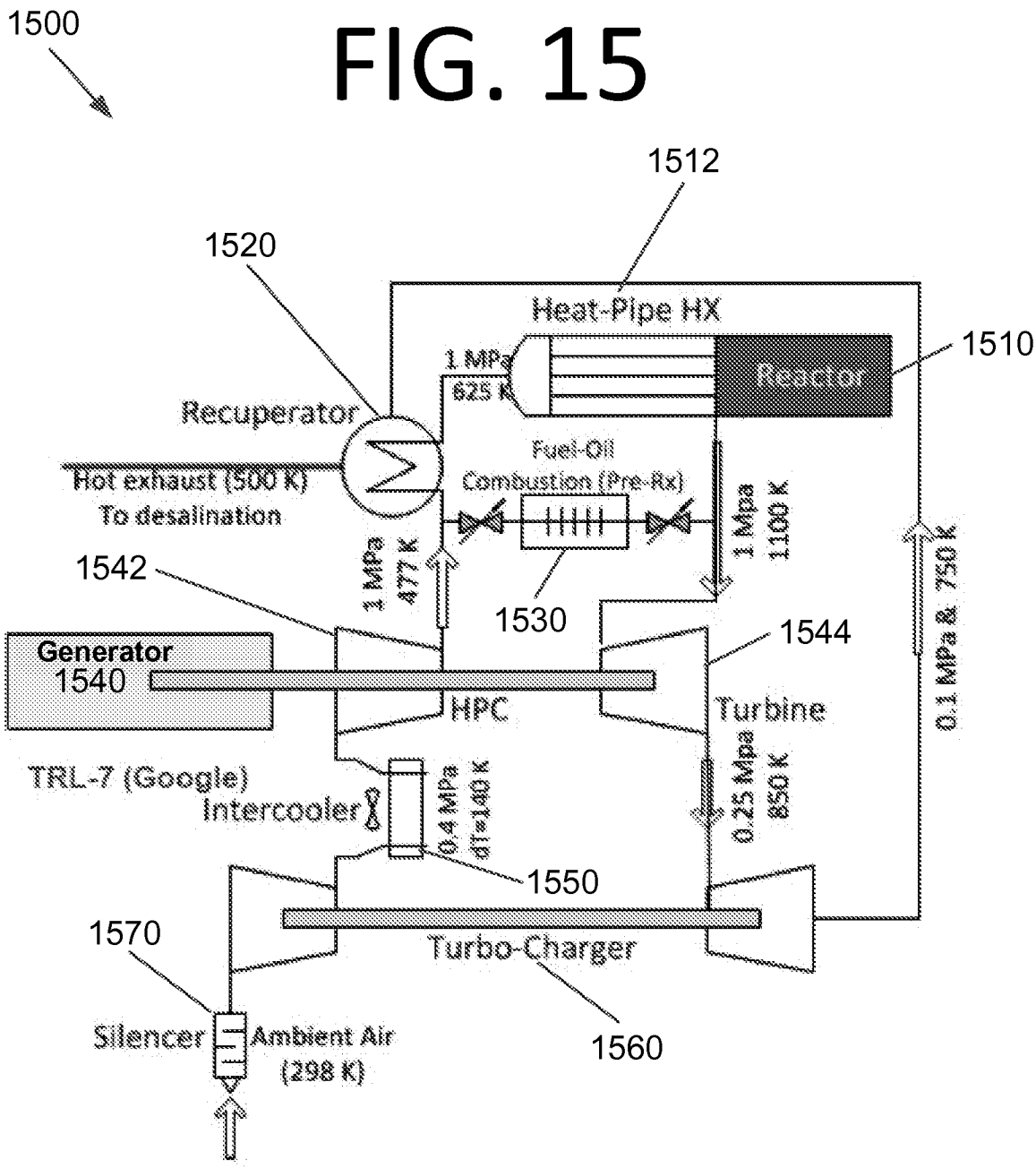
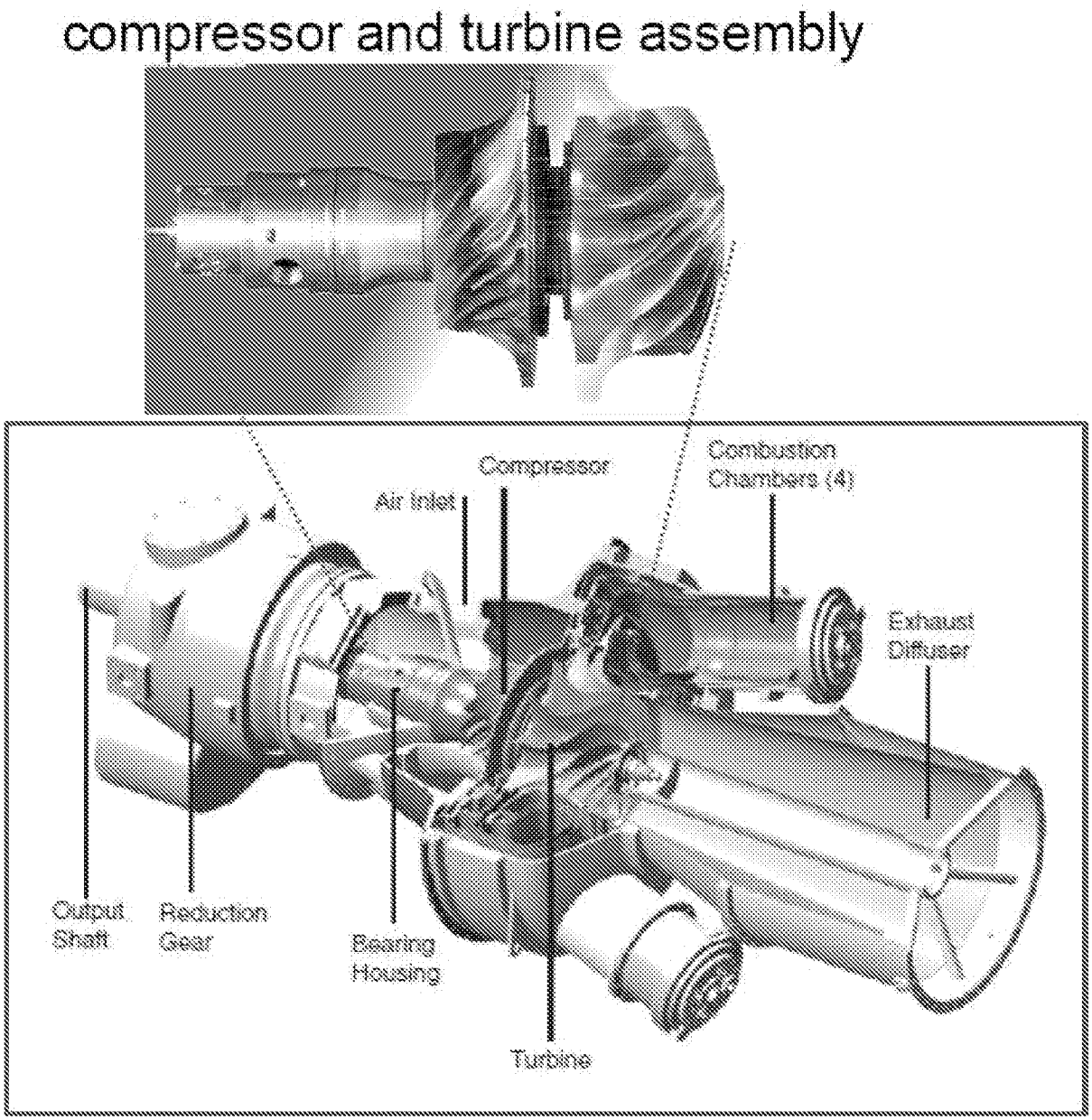


FIG. 15


1500
1512
1520
Heat-Pipe HX
1510
1 MPa
625 K
Reactor
Recuperator
Fuel-Oil
Combustion (Pre-Rx)
Hot exhaust (500 K)
To desalination
1 MPa
477 K
1 Mpa
1100 K
1542
1530
1544
Generator
1540
HPC
Turbine
0.1 MPa & 750 K
TRL-7 (Google)
Intercooler
0.4 MPa
dT=140 K
0.25 Mpa
850 K
1550
1570
Turbo-Charger
Silencer
Ambient Air
(298 K)
1560

1600

FIG. 16



Related Art

FIG. 17

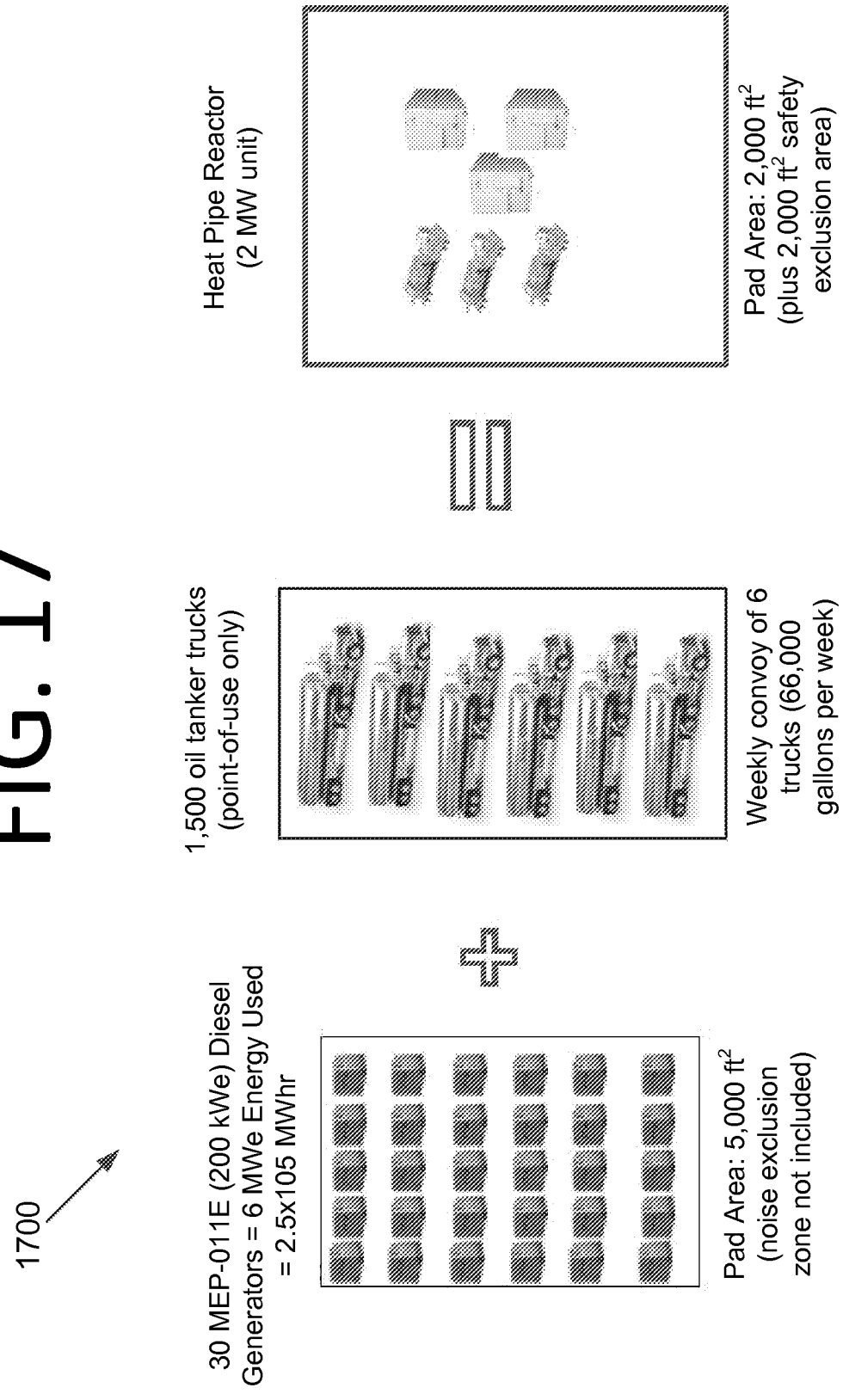
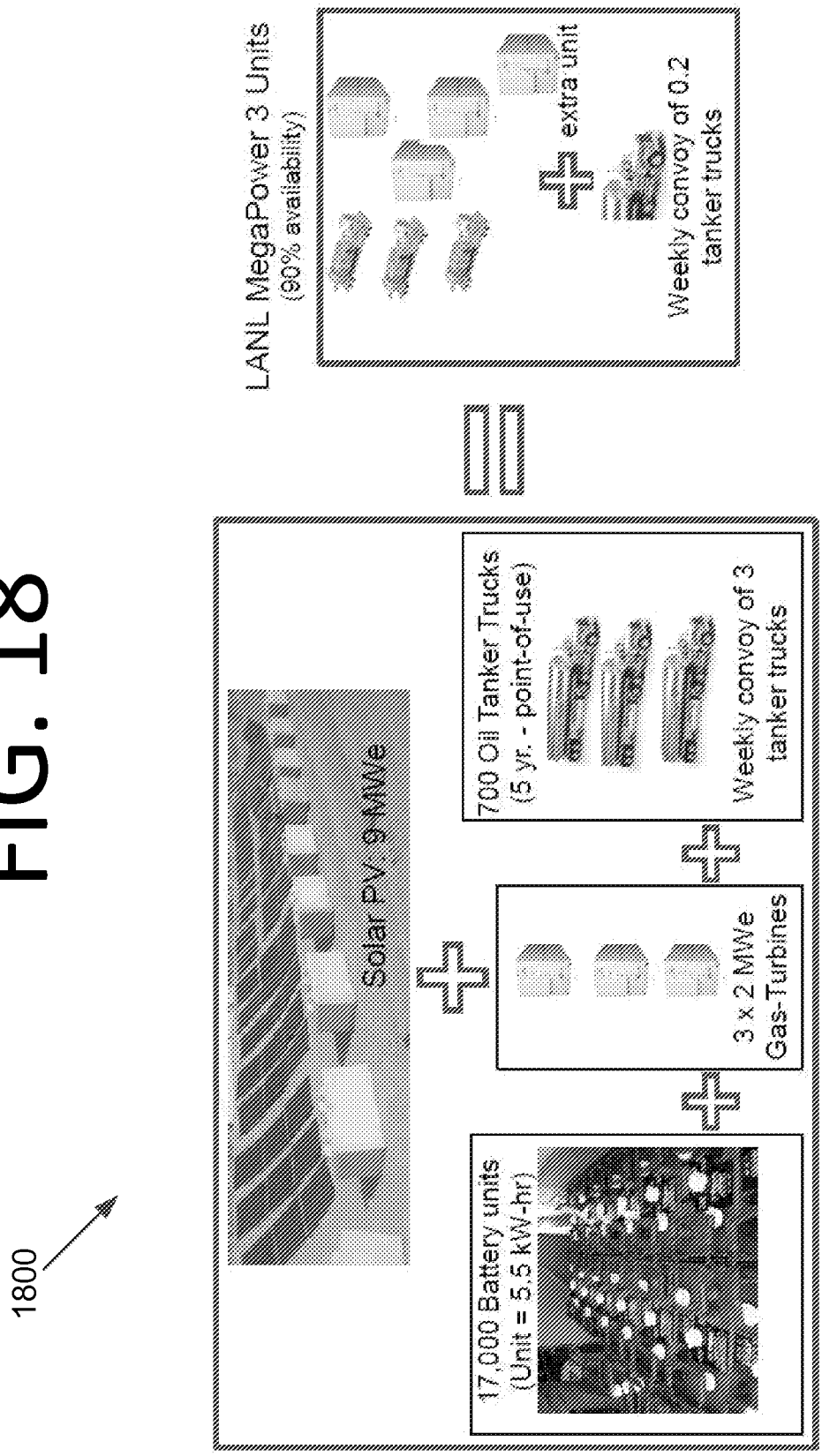

1700
30 MEP-011E (200 kWe) Diesel Generators = 6 MWe Energy Used = 2.5x105 MWhr
Pad Area: 5,000 ft2 (noise exclusion zone not included)
1,500 oil tanker trucks (point-of-use only)
Weekly convoy of 6 trucks (66,000 gallons per week)
Heat Pipe Reactor (2 MW unit)
Pad Area: 2,000 ft2 (plus 2,000 ft2 safety exclusion area)

FIG. 18


1800
Solar PV 9 MWe
17,000 Battery units
(Unit = 5.5 kW-hr)
3 x 2 MWe
Gas-Turbines
700 Oil Tanker Trucks
(5 yr. - point-of-use)
Weekly convoy of 3
tanker trucks
LANL MegaPower 3 Units
(90% availability)
extra unit
Weekly convoy of 0.2
tanker trucks