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# DEEP FISSION, INC.

## Conceptual Design Review of the Deep Borehole Pressurized Water Reactor (DB-PWR)

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# 1.0 Introduction and Purpose

The purpose of this white paper is to introduce the conceptual design of the Deep Borehole Pressurized Water Reactor (DB-PWR), in support of a future Standard Design Approval (SDA) application. It provides a summary of the general plant design and operation as well as some of the relevant engineered safety features, the principal site, operating, and safety characteristics, along with the variety of engineered safety features which allow for the simple and safe operation of the DB-PWR. A very brief overview of major systems such as instrumentation, reactor control, power conversion, fuel handling, and cooling systems will be provided to give an initial conceptual design overview of the reactor.

Combined License (COL) applicants need to develop a detailed Final Safety Analysis Report (FSAR) with extended site-specific information such as the specific location of buildings and placement of systems. As Deep Fission intends to submit a Standard Design Approval (SDA) application, most site-specific information will not be included except as required by 10 CFR 52.47(a)(24) and 10 CFR 52.47(a)(25).

# 2.0 General Plant Description

## 2.1 Principal Site Characteristics

The Deep Borehole Pressurized Water Reactor (DB-PWR) fits in a 30-inch diameter cased borehole and operates at a depth of approximately 1 mile. This depth means that the pressure inside the reactor (160 atm) is in equilibrium with the ambient water pressure at that depth. Each reactor produces 30 megawatts thermal (30 MWt) of steam which, when, upon reaching the surface, is used to generate up to 10 megawatts of electric power (10 MWe). The reactor core and steam generator are at depth. The pressurizer is distributed along the borehole (pressure of water in a mile-tall vertical tube) with incremental control at the surface. The chemical and volume control system, boron system, and filters are located at the surface and connected to the core by vertical pressure tubes. These tubes also allow continuous sampling of the primary loop water.

The system is modular, so more power can be generated by adding more boreholes with separated reactors. This spacing would allow multiple reactors per acre with early geologic studies finding that most locations have suitable geology. A conceptual geologic profile is shown in Figure 1. It shows 5 different reactor configurations. On the left is a single borehole 5 MWe reactor; next is a single borehole 10 MWe reactor; next is a set of four 10 MWe borehole reactors at one location (a campus, factory, military base, or small community), a 100 MWe reactor, and finally a collection of 100 borehole reactors that deliver 1,000 MWe. The image is not to scale; not all boreholes are shown, and many boreholes could fit in an area of one acre.

The reactor is about 30 feet in height and 26 inches in diameter. Its major components at depth are shown in the reactor layout diagrams in Figure 2 and Figure 3. The reactor core consists of four 17x17 fuel assemblies of conventional pressurized water reactor (PWR) design, sitting in a 2x2 square array. The downcoming water flows in the lune-shaped gaps between this square array and the circulator shape of the reactor vessel; this water provides additional moderation of the reactor. The core sits under the steam generator and is connected to it by a region called the “neck.” In Figure 2, the neck is shown as short, but it can be made longer if desired. Control rods when withdrawn from the core move into guide tubes in the neck which extend into the steam generator if the neck is short.

The steam generator is a conventional design, similar to that used in geothermal plants. It consists of tubes carrying hot water from the core (the primary loop) past water in the secondary loop, which it heats and vaporizes. The pressurizer consists of small diameter tubes that rise from the primary loop to or near-to the Earth’s surface. These tubes provide a pressure at the bottom given by the hydrostatic height of the tubes, 1 atmosphere of pressure for every 10 meters of depth. The pressure in the tubes at the surface is close to ordinary atmospheric pressure, although it can be held slightly above one atmosphere to allow better control of the pressure in the core. These pressurizing tubes also allow for continuous sampling of the reactor coolant for indications of primary loop damage, such as corrosion or wear. These tubes also provide a means for a chemical and volume control system, including for boron injection and removal, for filtration of the primary coolant water, and for injection and dissolution of hydrogen gas into the primary loop.

The primary loop is expected to operate between 275°C and 315°C, similar to the range used in gigawatt-scale nuclear reactors. The secondary loop at depth is held at a much lower pressure, about 65 atm. Water at this pressure boils at 281°C. The steam is brought to the surface through an insulated pipe within the water-filled casing. A profile of the casing above the steam generator is shown in plan view in Figure 4. This casing also contains the return water pipe of the secondary loop, boron and hydrogen control tubes, power cables, and reactor lift cables. The pressure at the bottom of the secondary loop is controlled by varying the water level in the supply pipe. The hydrogen tube does not extend to the bottom but only to sufficient depth to assure ready dissolution of hydrogen gas.

Flow in the primary loop is driven by natural convection. Flow in the secondary loop is controlled by pumps at the surface that feed water into the down-flowing steam generator supply pipe. The current reactor design has no moving parts at depth other than the control rods, which are moved by electric pulses acting on permanent magnets on the rods. If electric power fails, the rods will be drawn by gravity into the reactor core.

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The DB-PWR concept leverages geology and depth, not only for pressure, containment, and security, but also for the ultimate heat sink, the host rock of the formation. There is an emergency core cooling system (ECCS) in the mile of water in the borehole that sits above the reactor. There is added safety from the fact that there is no ready supply of gas to displace the reactor water. If it should boil, and the pressure from the mile of water is maintained, then the density of the steam produced is sufficiently high (about 160 atmospheres) to provide high heat removal to the surrounding rock.

The casing is a steel pipe that strengthens the borehole, holds water, and contains the secondary system cold water delivery and steam return, the electrical control wires, the sampling/pressurizer tubes, and the reactor support cables.

It is ambiguous whether the borehole and casing should be considered part of the nominal reactor building. It would not be normal architectural usage to do so, but if the reactor building is defined as the structure that contains the reactor, then it would be called a subsurface reactor building. The surface reactor structure contains:

- Access to the borehole;
- A section just below the surface (the Basement) for examining the reactor if it is brought to the surface for visual and/or X-ray and/or gamma ray tomography inspection;
- A pipe and pump system that provides water for the secondary loop;
- A steam pipe that conveys steam from depth to a steam turbine;
- Two small (1-inch diameter) tubes that are used to
    - sample primary water during operation,
    - allow adjustment of the pressure of the primary loop,
    - allow injection of boron and its removal by dilution and filtering, and
    - provide a Chemical, Volume, and Pressure Control System (CVPCS);
- Cables that provide electric power for control rod support and movement; and
- Cables that provide power and return signals for monitoring devices, such as:
    - temperature sensors,
    - radiation sensors,
    - N-16 gamma sensor,
    - pressure sensors,
    - acoustic monitors, and
    - video imaging above the radiation zone; and
    - cables that can be used to lower or lift the reactor.

A detailed design of the surface reactor building is under development. The method of raising and lowering the reactor from depth may be incompatible with the concept of a closed surface reactor building but could involve the use of an overhead crane or a coiled tubing system brought to the site when necessary. The implications of raising the reactor on the concept of a closed surface reactor building are still to be determined.

The Control Room may be located near the wellhead and includes sensor displays, boron system control, secondary loop water level adjustments, and steam turbine and electric generator controls.

The DB-PWR concept is that the reactor will be stored in place as the initial waste heat is dissipated to the host rock. When that has happened, there are two choices:

- It can be stored in that mile deep location until a disposal method is chosen.
- It can be lowered into a storage region that had been pre-drilled prior to the original emplacement of the reactor. The secondary loop can be cut or otherwise detached above the heat exchanger and the pipes removed. The reactor and steam generator can be lowered into the storage area and covered for permanent disposal.

Since the secondary loop water comes to the surface, and could be radioactive, a low-level radioactive storage area could be included. The storage area could consist of small tanks (several cubic meters) placed underground adjacent to the reactor borehole.

Alternately, the above ground facilities could have handling systems to remove radioactive spent reactors. The fuel could remain in the reactor canister and either shipped to a disposal facility or placed in on-site storage.

The cooling tower is located adjacent to the turbine generator. For the DB-PWR, the cooling tower is expected to be about the size and shape of a shipping container but may be larger if it serves multiple reactors.

## 2.2 Fluid Flow Description

The secondary loop consists of

- a water delivery pipe;
- a means of controlling the pressure of the delivered water;
- a steam generator at depth;
- an insulated steam pipe that carries the steam to the surface piping;
- a drier;
- an electric power generator;
- piping to take low temperature steam for other use, such as industrial or combined heat and power;
- a condenser; and
- a pump and control system to deliver the cooled water to the downflowing pipe.

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The secondary loop begins at the steam generator (immediately above the reactor at depth) where cool water, returning from the turbine and entering the condenser at the surface, is converted to steam. The rising steam and the returning cool water travel up and down the cased borehole, respectively. This pathway also contains electric cables as well as the pressurizer water, which makes a continuous path from the reactor to the surface. The remaining space in the casing above the reactor is filled with fresh water that provides a source for the Emergency Core Cooling System (ECCS). A diagram of the cross-section of the casing in a region above the steam generator but below the surface facilities is shown in Figure 4. The figure also shows the two narrow sampling tubes, also called pressurizer tubes. These tubes are used to obtain samples within the primary loop and use data to control boric acid and other chemicals, as well as filtering for the removal of particulates.

The steam pipe is covered with several centimeters of insulator. This can be rock wool, aerogel, vacuum, various other materials, or appropriate combinations of these insulators. Computations assuming rock wool show that approximately 2% of the energy in the steam will conduct and convect into the casing water as the steam rises to the surface. This heat will conduct and convect to surrounding rock and upward to the surface. Temperature rise of the surrounding rock is estimated to be no more than a few degrees Celsius.

By the time it reaches the surface, the steam is expected to have been dried by the long passage through the steam pipe. If necessary, the steam will pass through an additional drier to remove droplets. Next, it will flow into and turn a conventional steam turbine to provides power for an electric generator. At the output of the turbine, the low-pressure steam is condensed and waste heat may be used for commercial, residential, or industrial purposes, or released into the air externally by a cooling system. A forced air cooler the size and shape of a shipping container is being considered. The condensed water is then placed into the cold-water return pipe to descend to the steam generator.

The level of water in the vertical cold-water return pipe in the borehole is adjusted to maintain the desired pressure in the steam generator. For example, if an operator seeks to maintain a pressure of 65 atm at the bottom of the secondary loop to facilitate steam generation, then the liquid level of the cold-water pipe will be kept at 650 meters above the steam generator.

## 2.3 Principal Design Criteria

Principal Design Criteria (PDC) are still under development. Primary considerations of the design are increased safety and reduced complexity such as:

- All systems are resilient and will operate in a passive mode, allowing for reactor control, possibly without the need for constant human operation.

- Defense in depth: there are about 10 billion tons of rock in the 45-degree cone above the nuclear reactor. This natural containment environment provides a radiation barrier and an impediment for radioactive material to reach the public.
- Increased safety from natural disasters and human intrusion due to the remote location of the nuclear fuel and most of its waste deep underground.
- The ability to ship a prepackaged reactor to a site where boreholes can be drilled within days with emplacement and operation of the reactor within weeks of delivery.

## 2.4 Overall Characteristics

The DB-PWR is designed to operate up to full power conditions using natural circulation as the means of providing reactor coolant flow, eliminating the need for reactor coolant pumps.

The DB-PWR is surrounded by rock which provides a passive safety system. Each DB-PWR has a mile of water in the borehole and casing above the reactor, which provides water for the emergency core cooling system (ECCS). The water in the 1.6 kilometer- or 1 mile-long borehole and casing, and the rock along the length of the borehole, provides a sink for decay heat.

The DB-PWR is designed to perform all normal power operations. Electric power can be adjusted with turbine bypass to the condenser. In addition, core power maneuvering can be accomplished with control rods, soluble boron concentration changes, or a combination of control rods and soluble boron.

### 2.4.1 Nuclear Steam Supply System

The DB-PWR Steam Supply System consists of a reactor core, a steam generator that sits above the core, a tube that conveys the hot water from the core to the top of the steam generator, and a steam generator vessel that takes the hot water downward past a set of tubes that carries the low-pressure water of the secondary loop. The steam generator vessel contains hot water at the same pressure as the external water in the casing, so the stress on the casing is minimal. This casing can be manufactured as a single piece as part of the steam generator vessel. The conveyance within the primary loop is achieved by natural convective circulation. The flow of the secondary loop is achieved by pumps which set the level of the water in the delivery pipe at a level that provides the required pressure in the secondary loop to drive the circulation.

Using natural circulation, the primary reactor coolant flow path is upward through the central hot leg riser, and then downward around the outside of the steam generator tubes with return flow

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to the bottom of the core via a downcomer outside the core. As the reactor coolant flows across the steam generator tubes, heat is transferred to the secondary side fluid inside the steam generator tubes. Concurrently, in the secondary loop, as fluid progresses up through the inside of the steam generator tubes, it is heated and boiled to produce high pressure steam for the turbine generator unit.

### 2.4.2 Reactor Core

The reactor core contains 4 standard PWR fuel assemblies, each with a 17 x 17 rod configuration. Such fuel assemblies have 12-inch length diagonals and are 14-feet in height. A cross-section of the reactor core is shown in Figure 3. Each assembly has the standard 17 x 17 pin array with 264 fuel rods and 25 thimbles for control rods and instrumentation. Outside the fuel assemblies are four “lunes,” lunar-shaped regions for the downcoming, returning cool water from the heat exchanger to the bottom of the reactor. The four assemblies and the lunes are contained in the cylindrical reactor vessel. This vessel is, in turn, contained by the casing that lines the borehole. In between the reactor vessel and the casing is fresh water that is continuous to the surface. The reactor uses low enriched uranium (LEU) at less than 5% U-235 enrichment in uranium-oxide ceramic fuel, the same as used with traditional PWRs, with gadolinium added to help level the burn.

### 2.4.3 Pressurizer

The Pressurizer uses the hydrostatic pressure of a mile depth of water to provide and maintain the required pressure. Its primary component is the sampling loop tube that extends from the primary loop to a pressure adjust vessel near the surface. This tube can be seen near the top of Figure *2*, in the steam casing in Figure 4, and entering the Pressure Adjust and Volume Control tanks in Figure *5*.

These tubes serve multiple purposes, including a pathway for water from the initial expansion of the primary loop (when it is first heated) to enter the pressure tanks. The pressure of the air above the water in the left tank in Figure *5* can be maintained at about 1 atm, or slightly above or below. The pressure in the primary loop will then be the hydrostatic depth of the water, about 160 atm. If the water expands or contracts, the excess (or deficit) water will move up this tube, but the pressure will remain constant. A pump can move water from the left storage tank to the right one to reduce the pressure, or from right to left to increase it. This pump is automated to keep pressure constant, but it can be overridden by the reactor operator who has readings from the two pressure sensors. Because it depends primarily on hydrostatic pressure, the control of this system on the pressure in the primary loop is expected to require little or no adjustment by the operator. In this way, the reactor is taking advantage of the depth of the reactor.

Note that although the water in the primary loop is quite hot, the water in the sampling / pressure-control tube is cooled by the casing water, which is, in turn, cooled by the surrounding rock.

The Pressure Adjust and Volume Control tanks, in the conceptual design, are placed underground at 5 to 10 meters deep. They are accessible by a portal in the casing. They are isolated in this manner because the primary loop water, although expected to have extremely low radioactivity, could become radioactive if there is major damage in a fuel pellet and its cladding. At the end of the reactor lifetime, the water could be left there, if sufficiently low-level, or drained and moved to a permanent low-level waste facility.

Since the pressure of the water in the casing is also set by the depth of fresh water, the water within the reactor vessel will have the same pressure as the water outside. Since radiation shielding is not needed, and since the pressure difference is close to zero, the primary need for strength of this vessel is to maintain integrity during surface handing and emplacement.

### 2.4.4 Steam Generator

The steam generator is conventional in design, similar to that found in geothermal plants, although manufactured to nuclear standards. The tubes in the generator will likely be made of nuclear grade stainless steel. Figure 2 shows the hot primary water first flowing to the top and then heating the secondary loop as it descends, but the order could be reversed. Figure 2 shows straight tubes, but helical tubing is being considered.

### 2.4.5 Reactor Vessel

Unlike that of a surface PWR, the DB-PWR “Pressure Vessel” can be thin. The reactor vessel in a traditional surface PWR must safely hold 160 atmospheres of pressure difference, over 1 ton per square inch. The traditional pressure vessel has a thickness of 8 to 12 inches of steel, with great regard placed on the reactor vessel integrity over decades of life while it undergoes severe radiation exposure and frequent temperature and pressure cycling.

In contrast, the pressure differential across a DB-PWR wall is kept close to zero. The near-zero differential is possible because the ambient water pressure at 1 mile depth is 160 atmospheres, the same as the desired pressure inside the reactor. The pressure within the casing will also closely match the pressure of the water in the host formation rock. The host rock water may be 1 or 2 atmospheres greater since it consists of brine, which is heavier than fresh water. This natural 160 atm pressure is one of the most useful features obtained when a DB-PWR is placed at a mile depth.

For surface PWRs, the thick pressure vessel also serves the ancillary role of an additional barrier between the reactor core and the environment. For the DB-PWR, the role of the reactor vessel wall for nuclear material isolation is reduced, since if the reactor vessel is breeched, the path to the surface is a mile long. Possible accidents in which this wall is breached and radioactive material enters the casing water will be analyzed in detail to determine if there is a plausible mechanism to bring this water into contact with the public. The casing water is isolated from the surrounding rock, and the primary exit to the surface is restrained by gravity. Hot water from the primary loop would be cooled by the casing water, which serves as an emergency core cooling system. A blowout such as experienced in some oil and gas wells is not possible in the DB-PWR borehole because the heat produced in a nuclear reaction is limited by the fact that as soon as the water heats it expands and that expansion reduces the moderation of neutrons. The reactor turns off before steam can develop to an extent that might push the mile of water out of the casing. Fast heat generation is prevented by the role of delayed neutrons in the chain reaction. The DB-PWR probabilistic risk assessment will include these analyses.

For these reasons, in the DB-PWR, the reactor pressure vessel is termed simply the reactor vessel. Its walls need only be thick enough to provide strength to withstand use and surface handling impacts.

### 2.4.6 Containment

A traditional PWR has multiple levels of containment, including the fuel pellet, the cladding, the reactor vessel, and the containment building. The DB-PWR has containment from the pellets and cladding, has less protection from the reactor vessel, and benefits significantly from the natural containment provided by the mile of rock above it.

The technology of geologic containment has been studied in detail for its potential in the disposal of nuclear waste. Deep borehole disposal has been simulated using the TOUGH2 code which had previously been used to analyze the safety of the proposed Yucca Mountain Nuclear Waste Repository and others. Four studies were published in peer-reviewed journals. They include modelling of several different geologies, both sedimentary and metamorphic, from depths of 1 km to 1.6 km, or 1 mile. Each simulation had over 100 variants.

The basic conclusion of these papers is that deep borehole geology offers an exceptional isolation of radioactive isotopes from the human biosphere. The dominant pathways to the surface are diffusion through the rock, advection through the rock and rock fissures, advection up the cemented access borehole after the cement has crumbled, and advection up earthquake faults. The studies showed that advection through a mile of even porous rock took hundreds of thousands to millions of years. An exception might be a site that has a strong pre-existing vertical advective flow; however, any potential site can be studied using natural radioisotopes to determine if long term depth-to-surface flow exists and to measure its velocity and thence

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deduce safety. A result from these studies is proof of the long-term safety offered even in the presence of earthquake faults, old or new.

### 2.4.7 Safety Considerations

Safety is enhanced by the significant isolation provided by the mile of rock above the reactor, and by simple design and use of passive safety systems. The conceptual design has no moving parts at depth other than control rods and fluid flow. The safety compared to that of a conventional PWR is also improved by DB-PWR’s small fuel inventory. The integrated design of the DB-PWR eliminates external coolant loop piping, thereby removing many large-break Loss of Coolant Accident (LOCA) scenarios. Standard modes for loss of coolant accident do not occur because of the absence of air to replace coolant and the expectation that under most accident scenarios, high pressure is maintained.

The use of passive safety systems for decay heat removal, emergency core cooling, and deep geological isolation means external power is typically unnecessary during various accident conditions. Additionally, LOCAs are mitigated by the reactor's surrounding high-pressure water. If this high pressure is maintained during an accident, the high density of the gas at this pressure provides enough cooling capacity to prevent core meltdown.

Additional conceptual safety derives from the fact that if the core were to melt though some unexpected mechanism, it is already a mile underground.

With these passive safety systems, LOCAs are not expected to pose a safety threat to the plant. This results in a core damage frequency lower than that of the current light water reactor fleet.

The reactor core has a smaller radioactive source term compared to a conventional 1,000 MWe nuclear reactor. Due to the smaller fuel inventory, the amount of radioactive material available for release during a hypothetical accident is reduced.

# 3.0 Engineered Safety Features and Emergency Systems

## 3.1 Geological Isolation

The primary “containment vessel” of the DB-PWR is the mile-thick geology of the Earth above the reactor. Moreover, isolation for any particular location can be measured prior to installation of the reactor using isotopic measurements to determine the past migration of natural radioisotopes at depth. This method is used by geologists to determine the age of deep water.

Such determination is done as follows: once the borehole or a narrow pilot borehole has been drilled, samples of rock and water taken at numerous varying depths are measured to determine the concentration of naturally-occurring radioisotopes. The method takes advantage of the vertical nonuniformity of mineral deposits. Uranium and thorium are inhomogeneous in the substrata, and spontaneous decay of these elements over the eons produced measurable quantities of these radioisotopes. radioactive iodine, chlorine, krypton, xenon, and others. If these volatile atoms drift from the original source, either by diffusion or by advection (water flow through the rock), then their distribution will not match that of their parent isotopes. In particular, distributions in the vertical dimension can be used to determine the vertical migration velocity.

If a site (location and depth) is drilled, and study of the isotopic geology indicates that the vertical migration velocity could lead to unsafe conditions for the public, then that site will not be used for a DB-PWR.

## 3.2 Seismic Analysis

A complete probabilistic risk assessment of the possible accidents occurring in the case of a large earthquake at or near the DB-PWR will be performed, but several initial observations can be made.

*Shaking*: Damage from earthquake shaking rarely exceeds 1-g of acceleration. This value is far too small to damage a DB-PWR. In earthquakes, the primary shaking damage usually comes from above-ground structures that were not designed to withstand horizontal acceleration. The small parts of the DB-PWR are easily held in place against 1-g or several-g accelerations.

*Faulting*: Existing or new earthquake faults do not create fast-paths for radioisotopes to the surface. This has been shown in several peer-reviewed publications, written in support of waste disposal programs but equally applicable here. Earthquake faults are not open spaces but are filled with crushed rock. Advection of water through long distances was shown in the peer-reviewed publications to provide poor pathways for motion of radioisotopes. The explanation provided in the publications is that as radioisotopes are carried upward, a fraction of them are absorbed into the surrounding rock every meter. This results in an exponential decline in the concentration of the radioisotope in the fault.

*Severing of the vertical borehole*. Some preliminary calculations suggest that the likelihood of this happening, even in earthquake-prone locations, is small. Preliminary analysis indicates that even if the borehole is severed, the risk presented to the public is low.

## 3.3 Loss of Coolant Consideration

The DB- PWR has a mile of water above it within the borehole casing, and this water plays a central role in the loss of coolant scenario. In a normal above-ground or near-surface PWR, loss of coolant refers to the replacement of water by air, and a subsequent overheating of the nuclear fuel even when the chain reaction has terminated. For air or other gas to replace water in the primary loop of a DB-PWR, there are two scenarios: high pressure and low pressure.

*High Pressure*. In the first scenario, the replacement of the coolant is local. For example, steam resulting from overheating could replace water in the fuel assembly. A full probabilistic risk assessment has not yet been done, but there is reason to think that this scenario will not lead to a failure of cladding or melting of fuel because of the high density of steam at this high pressure. The reason is that the chain reaction will halt due to the absence of sufficient moderation, and the steam has sufficient thermal conductivity to remove decay heat and convey it to the surrounding rock.

*Low Pressure.* In this scenario, the entire borehole is emptied of water by a transient at depth, and the borehole is filled with low pressure air. The energy required to do this is about 1 MWt. This scenario will be assessed in a probabilistic risk assessment, but it is expected that the removal of water will be self-limiting. A single transient can produce heat at the reactor that flashes water to steam, but as that steam lifts a mile of water upward, the steam cools due to the lifting work it is doing, and that loss of energy limits the possible extent of lift. For this reason, it appears that a full analysis is likely to show that a complete blowout of the water in the casing is not possible.

## 3.4 Fuel Handling Accident Analysis

In a scenario in which the fuel is disposed at depth in the same borehole that is being used for the reactor, then the only instance of high radioactivity at the surface would occur if it is deemed necessary to bring the reactor up to the surface after some initial energy production. Otherwise, there is never high radioactivity at or near the surface.

If a partially depleted reactor is brought to the surface for examination, then a temporary shield could be placed around the location where the reactor will surface. Alternatively, the subsurface room shown conceptually in Figure 5 (holding the Chemical, Volume, and Pressure Control System) could be used for the inspection. This room could provide a location for inspection, including X-ray and tomography.

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## 3.5 Other Features, Events, and Processes

There are many features, events, and processes that require careful probabilistic risk assessment before a DB-PWR can be deployed. The safety and security examples given in prior sections were chosen to illustrate how unique features of the borehole configuration affect some of the most well-known of these. Careful probabilistic risk assessments for a wide array of features, events, and processes will appear in the SDA Application.

## 3.6 Engineered Safety Feature Materials

The DB-PWR sits in a bath of fresh water, and this water can contain anti-corrosion chemicals if it is determined they are necessary. The DB-PWR will use similar metals and materials to those used in a standard gigawatt PWR.

Much of the reactor (core, neck, steam generator) will be constructed from austenitic stainless steel or Inconel, with little need for liners. Insulators currently under consideration include fiberglass, rock wool, aerogel, vacuum, and combinations of these. The casing of the borehole could be made from carbon steel, fiberglass, or other materials commonly used in large pipes. A more detailed study will be needed to determine final materials. It will be necessary to ensure that all materials will be compatible with the fluids they might be exposed to, not only during normal maintenance and testing conditions, but also during accidents.

## 3.7 Containment Systems

The primary containment for the DB-PWR comes from the mile depth, with only a 30-inch borehole connecting the reactor to the surface. Leakage through the rock has been determined through a series of peer-reviewed scientific papers to be negligible, and so the only issue is whether transport up the borehole is a possible pathway for radioactivity to reach the surface.

The casing is not considered as part of the containment except in the upper regions where it provides isolation from near-surface aquifers. A total breach of the casing does not significantly increase the geologic time period that it would take radioisotopes to reach the Earth’s surface through the geologic pathway.

The water in the casing above the reactor is a source of containment, playing a role similar to that of the water pool that surrounds some surface small and micro PWRs. The volume of the water is about 400 cubic meters; it would fit in a 7-meter cube. This water is capped at the surface by a concrete or metal shield (see Figure 5) that is opened only when the reactor is placed in the borehole or removed.

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For the radioisotopes to reach the casing water, they must breach the containment of the fuel pellets, the cladding, and the reactor vessel. Since the pressure inside the vessel is kept in equilibrium with the pressure outside, little flow out of the reactor vessel is expected. This and other scenarios will be investigated with simulations.

Most of the radioisotopes in the spent fuel are not soluble but still might be carried upward by convection. The primary concern would be gases and soluble isotopes such as iodine and chlorine. The casing water is expected to contain these isotopes in dissolved form even if they make it to the upper parts of the reactor borehole.

Simulations of this scenario are expected to show that the upward migration of these radioisotopes will slow and stop while still far from the surface, due to the mixing of the hot water with the cooler water above the steam generator. Heat generation will continue due to radioactive decay, but that will be dispersed by the mixing of the radioisotopes in the larger volume of the casing water and thence through the casing into the rock.

**Casing**

The thickness of the steel is expected to be between 0.5 cm and 3 cm, determined by the need to provide a minimal pressure containment (up to 3 atm) and to prevent loose rocks from falling into the reactor hole. The most likely material for construction is carbon steel, the material used for most oil and gas recovery. However, the casing could be made of other materials. .

If the reactor needs to be retrieved, then the casing above the reactor can be monitored for signs of corrosion by visual inspection using a remote camera mounted on a cable, and the condition of the entire casing can be monitored by sampling and testing the fresh water within the casing.

**Casing water**

The water in the casing serves multiple purposes: to provide pressure to equalize the pressure across the reactor vessel to allow thinner structures to contain the fuel assemblies and the steam generator; to provide insulation between the reactor vessel and the casing to keep the casing cool; to provide insulation between the steam pipe and the casing to keep the casing cool; to provide cooling for heat that leaks from the steam pipe insulation; and to provide coolant to keep the major length (above the steam generator) casing at an unchanging temperature as the reactor temperature changes. Changes in reactor casing temperature could result in longitudinal length changes that could stress the casing.

Sensors along the depth of the casing will monitor the temperature profile of the casing.

## 3.8 Emergency Core Cooling System

The mile of water in the casing above the reactor provides water for emergency core cooling. Simulations are expected to show that a conventional loss of coolant accident (LOCA) is not possible. In a LOCA the coolant is replaced by low pressure air, which does not conduct waste heat sufficiently to prevent cladding damage and meltdown. If coolant is lost, by (for example) boiling in the reactor replacing liquid with high-pressure steam, then the steam does not have sufficient density to serve as an effective moderator, so the chain reaction will stop but has sufficiently high density to carry away waste heat from radioactive decay of fission fragments and actinides.

## 3.9 Control Room Habitability

Control room habitability refers to providing adequate protection of control room operators against the effects of postulated external releases of radioactivity or toxic gases.

The Control Room Habitability program is expected to be simplified compared to current operating PWRs. It is anticipated that a probabilistic risk assessment will show that the likelihood of physically significant radioactivity from the borehole reactor to the surface will be extremely small, even if there is a total loss of power or other accident. If this proves to be the case, then the measures need be taken to assure safety can be proportionally smaller. The control room could be located in an existing building at the site (e.g. at a factory, campus, data facility), and need not be proximate to the wellhead.

## 3.10 Fission Product Removal and Control Systems

The Fission Product Removal and Control System in a nuclear reactor refers to a set of mechanisms and procedures designed to manage and mitigate the accumulation and release of fission products during reactor operation. This includes coolant purification, gas management, and (ultimately) spent fuel handling.

The DB-PWR is designed to minimize fission product release during a postulated design basis accident.

## 3.11 In-service Inspection

The in-service inspection program includes the pre-service examinations and the continuous testing capability provided by the sampling loop that brings a small fraction of the primary loop

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water to the surface. Inspection of the casing to a point several meters above the reactor can be achieved by in-place sensors, acoustic sensors, and in-reactor sensors.

## 3.12 Instrumentation, Controls, and Electrical Systems

Conventional core monitoring sensors are placed in the instrumentation thimbles in the manner identical to that currently used for traditional PWRs. Cables to the surface power the instruments and carry the signals to the control room. Anticipated signals include gamma and neutron flux sensors, thermometers, and pressure gauges. Nitrogen-16 gamma sensors will likely be placed near the top of the control rod region or above the steam generator. There will also be sensors to monitor the level of boron, pH, and mineralization in the primary loop water. Samples of that water taken from the sampling loop provide additional capability.

The DB-PWR is designed to allow sampling of the water in the primary loop and is done using the sampling tubes shown in Figures 2, 4, and 5.

The DB-PWR can also be lifted to the surface for visual or technical inspection such as X- or Gamma-ray tomography as needed. An overhead crane in combination with a small workover rig can be used. A small subsurface chamber at the borehole opening can hold the reactor for tomography so that the waste decay elements inside the reactor can be imaged to determine if there is any leakage out of the fuel rods.

The value of doing this procedure needs to be weighed against the possible accidents that could occur if the reactor with its waste is brought to the surface. Under some scenarios, with proper licensing, the spent fuel in the reactor is left underground for disposal in situ. In those scenarios there is never any spent fuel near or above the Earth’s surface, since the unburned fuel is contact safe (can be approached and handled without radiation danger) and if disposed at depth the nuclear waste is never closer than a mile from humanity.

Design of the instrumentation and control (I&C) system will include a separation between safety-related and non-safety related systems and simplified system functions.

During normal operations, the AC electrical power distribution system provides continuous power to equipment needed for the plant's startup, regular operation, and shutdown. The DB-PWR does not depend on onsite or offsite AC electrical power to handle design-basis events. The safety systems operate independently of AC or DC electrical power for activation.

## 3.13 Power Conversion System

The power conversion systems of the DB-PWR includes a main steam system, a conventional steam turbine generator set, a conventional condenser and cooling tower setup, and a condensate and feedwater system.

## 3.14 Fuel Handling and Storage Systems

The conceptual design assumes that although the reactor and its steam generator will be handled on site, that separate fuel handling will not. Fuel rods and control rods will be placed in the reactor off-site and shipped to the installation site, where they will be filled with fresh water, connected to the primary loop sampling and pressure control tubes, connected to support cables, placed above the borehole and lowered to the operating depth using the support cables.

## 3.15 Plant Cooling Water Systems

The primary purposes of the plant cooling water system are to:

- Remove the heat produced by nuclear fission in the reactor core;
- Transfer the thermal energy to steam generators and then to turbines for electricity generation;
- Condense the steam back into water for reuse in the power generation cycle; and
- Release waste heat to the environment in a controlled and environmentally responsible manner.

In the conceptual design, the Deep Fission Plant Cooling Water System consists of the Reactor Coolant System, Steam Condensation System, Circulating Water System, Cooling Tower System, Auxiliary Heat Removal System, and Emergency Core Cooling System.

## 3.16 Radioactive Waste Management System

The radioactive waste management system is responsible for water removed from the primary loop through the sampling tubes that reach the near surface chemical, volume, and pressure control system (CVPCS), shown in Figure 5. The amount of material collected over the lifetime of the reactor is expected to be several cubic meters and can be placed in underground holding tanks. The radioactivity of this water depends on leakage from the fuel pellets that penetrate damaged zircaloy cladding and will be examined in greater detail in the future.

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# 4.0 General Arrangement of Major Structures and Equipment

The principal above ground or near-surface structures are the:

- CVPCS structure located at the wellhead and illustrated in Figure 5;
- Piping from the borehole to the steam drier, which may not be necessary since the mile long steam pipe may accomplish this task;
- Steam drier, which removes droplets that might damage the turbine;
- Steam Turbine;
- Condenser, which converts steam out from the turbine water and provides low pressure for the outlet of the turbine;
- Steam Distribution System, which can distribute low temperature steam for local use, such as combined heat and power;
- Cooling Tower—possibly a shipping container-sized forced air cooler that disposes of excess heat; and
- Control Room, potentially remote.

## 4.1 Reactor Building

The DB-PWR does not include a traditional reactor building since the key components are a mile underground and contained in a borehole. The near-surface chemical, volume, and pressure control system, in the conceptual design (Figure 5), sits in a small chamber just below the surface, covered by a concrete or steel shield, and accessible through a port.

Because of the simplicity of the system, the control room is anticipated to be small. If the site contains other nearby buildings (e.g., as it would at a factory, campus, or military base) then the building can share facilities. It could also be located in a small, prefabricated structure.

## 4.2 Fuel Handling and Reactor Maintenance Areas

Traditional fuel handling is not anticipated. When the reactor fuel is spent, the reactor can be lifted out and taken to a remote storage or disposal area. The site will require the capability of handling the reactor but not fuel assembly replacement. The reactor can be brought to the surface using the permanently attached cables. At or below the surface, it is placed in shields, and then lifted above the surface for horizontal orientation and transportation away from the site.

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The reactor removal area needs to be large enough to accommodate the shield brought in to contain the reactor when it is brought above ground and shipped. There needs to be room to bring in a crane to lift the reactor, and space to hold the steam pipe and other tubes that will be removed when the reactor is retrieved.

Once the reactor has been removed, a new reactor can be lowered into the same borehole. After inspection, it could be deemed safe to reuse some or all of the piping used for the first reactor. The Pressure Adjust and Volume Control tanks (Figure 5) can be emptied, and the water can be disposed locally, if not radioactive, or shipped to a low-level disposal area.

A second alternative would be to store the reactor with its spent fuel at depth. In this alternative, the borehole serves that role that a dry cask serves for a surface or near-surface reactor.

A third alternative is to leave the reactor in-place, but to sever the secondary loop pipes (but not the cables) just above the steam generator. The primary loop sampling tube would be closed and then cut above the closed section. It might be instead desirable to leave that loop in place to allow sampling of the water in the spent fuel assembly. A new reactor can then be lowered and operated above the previous one. In this alternative, the lower reactor can be considered to be in storage or in the first stage of disposal.

A fourth alternative is similar to the third. In this alternative, the reactor is severed from the secondary loop pipes and then lowered into a storage/disposal region below its original depth (Figure 2). The cables would remain in place, fitting in the space between the reactor vessel and the casing, and facilitate the eventual removal of the reactor (if necessary).

## 4.3 Refueling Operations

When the fuel has been depleted to the level that a sustained nuclear chain reaction is no longer possible, the fuel is defined as spent nuclear fuel. There are currently several options for the next phase for the spent fuel in the DB-PWR, none of which involve refueling but include replacement of the reactor and steam generator. In these scenarios, the reactor vessel serves as the role that a fuel canister plays in large reactor storage or disposal.

## 4.4 Control Room

The Control Room location will depend on the deployment scenario, whether the reactor a single borehole or a set of many or if it is in an industrial campus, factory, or community. The control room can be designed to accommodate for any of these applications. It will contain monitors for pressure, temperature, and radioactivity and controls for boron and lithium injection, fresh water dilution control, and movement of control rods. It would also include monitors and controls for the steam turbine, the cooling tower, and the pump in the wellhead chambers.

As with other traditional PWRs, the DB-PWR has a strong negative temperature coefficient that helps stabilize the reactor during normal operation, and which provides a moderate load-following capability. A fast negative coefficient comes from the thermal Doppler broadening in the fuel pellets. A slower but very powerful negative coefficient comes from the thermal expansion of the water, which, at 300°C, is 3 times larger than at room temperature. Lesser contributions to the negative temperature coefficient come from the increasing transparency of the reactor vessel, casing, and fuel pellets as the temperature rises.

The planned control rod adjustment system minimizes moving parts by using linear stepping motors. Induction motors are also under consideration. Strong high-temperature permanent magnets such as Alnico, which operate up to 525°C, or a special version of samarium-cobalt magnets which remain magnetized at 400°C are attached to the control rods. The linear stepping motors move each rod independent of the others. The coils don't move but their magnetic fields are controlled by electric cables that connect with the control room at the surface. The only moving parts are the control rods themselves. Deep Fission plans to use the traditional gray, relatively weak neutron absorption, rods for control, and the black, relatively high neutron absorption, rods for emergency shutdown. Loss of power results in the lowering of the control rods into the reactor automatically by gravity. Load following is accomplished in the same manner used for traditional reactors, by injection and removal of control rods and boric acid.

Boric acid concentration typically starts at 1,600 parts per million (ppm), and is diluted by 1.6 ppm per day, that is, by 0.1%. Since the volume of the primary loop is about 4,800 liters, such dilution initially takes replacement of 4.8 liters of water per day. This can be done with a small-diameter tube that deposits the removed water in the Pressure Adjust and Volume Control tanks shown in Figure 5.

## 4.6 Radioactive Waste Storage

As discussed previously, radioactive waste storage can be achieved by bringing the reactor to the surface and placing it in dry cask, or by leaving it in the borehole until ready for disposal.

# 5.0 Major Systems

## 5.1 Decay Heat Removal System

Decay heat removal during normal operation, when the reactor is shut down or normal secondary loop water is not available, is not a separate system but is inherent in the design of the reactor. At full pressure, the decay heat will be conducted and convected from the core to the walls of the reactor, through those walls, and to the water that sits between the reactor vessel and the casing (about 1000 cubic meters of fresh water). This water will convect upward, carrying away the heat, depositing most of it in the rock along the way, and being quickly replaced by cool water flowing downward.

## 5.2 Ultimate Heat Sink

In a design basis accident, decay heat is removed from the reactor through passive heat transfer described in Section 5.1. Because of the high pressure at depth, the water in the casing will never boil, but will instead transfer the heat to surrounding casing and rock, or up to cooler regions. The amount of water in the casing (about 1000 cubic meters) is expected to be adequate to remove the waste heat indefinitely. The capability of the geologic formation for this purpose has been simulated and published in a series of peer-reviewed publications.

The water in the casing provides an additional means of fission product retention beyond that of the fuel, fuel cladding, and the containment for certain events.

## 5.3 Chemical and Volume Control System

In the DB-PWR, the Chemical and Volume Control System is combined with the Pressure Control System and contained in a subterranean chamber located at the wellhead, as shown in Figure 5.

Under steady state operation of the reactor, if a surface valve is opened, water flows up one of the sample pipes and down the other. Boric acid can be added to this flow. A typical 3% boration requires 30 liters of boric acid (injected into the boron injection system shown in Figure 5) and removal of 30 liters of primary coolant that is stored in the Pressure Adjust and Volume Control tanks (also in Figure 5). To reduce the boron to 1.5%, the amount of non-borated water added would be about a thousand liters (1 cubic meter), and a similar amount of water would be removed from the loop. This process would have to be repeated for every halving of the boron

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content. This water requires storage, and for the DB-PWR, that storage can be done in underground tanks adjacent to the borehole (Figure 5). This borated water may be low in radioactivity if there is no leakage from fuel rods.

Particulates, removed by the filtration system shown in Figure 5, potentially lead to radioactive filters which need to be stored and ultimately disposed of. The volume of these will be small compared to that of the borated water. They can be removed through the access port.

As in a traditional PWR, a small amount of alkaline (such as lithium hydroxide) is added to the water to neutralize the acidity of the boric acid. This addition can be done externally at the surface using the boron injection system of Figure 5, or a similar system.

## 5.4 Other Site Structures

### 5.4.1 Turbine Generator Shed

The Turbine Generator Shed is a small shelter holding the turbine and the condenser. It can be located close to the reactor wellhead, or it could be distant if that is more convenient at the reactor site. The condenser and cooling water system are also located inside the Turbine Generator Shed.

### 5.4.2 Auxiliary Services

All auxiliary services will be provided within the building that contains the control room or in a nearby building.

### 5.4.3 Security Services

All security services will be provided in an appropriate location. The physical security plan will be developed using appropriate physical security requirements commensurate with the potential consequences to public health and safety and the common defense and security.

### 5.4.4 Centralized Utilities

Utilities such as chemical treatment equipment, and maintenance equipment, will be housed in the building that contains the control room, or in a structure close to the wellhead.

## 5.4.5 Backup Diesel Generator Buildings

A single backup diesel generator will be considered if required. However, no functions of the reactor require electricity to safely shutdown the reactor.

## 5.4.6 Human Factors

Based on modern human performance best practices, the DB-PWR can be fully controlled with minimal staffing and with the possibility of utilizing remote operation in a centralized control room. All reactor controls are passively safe allowing for reactor shutdown regardless of human intervention. Digital systems in the control room will relay all required information to trained operators.

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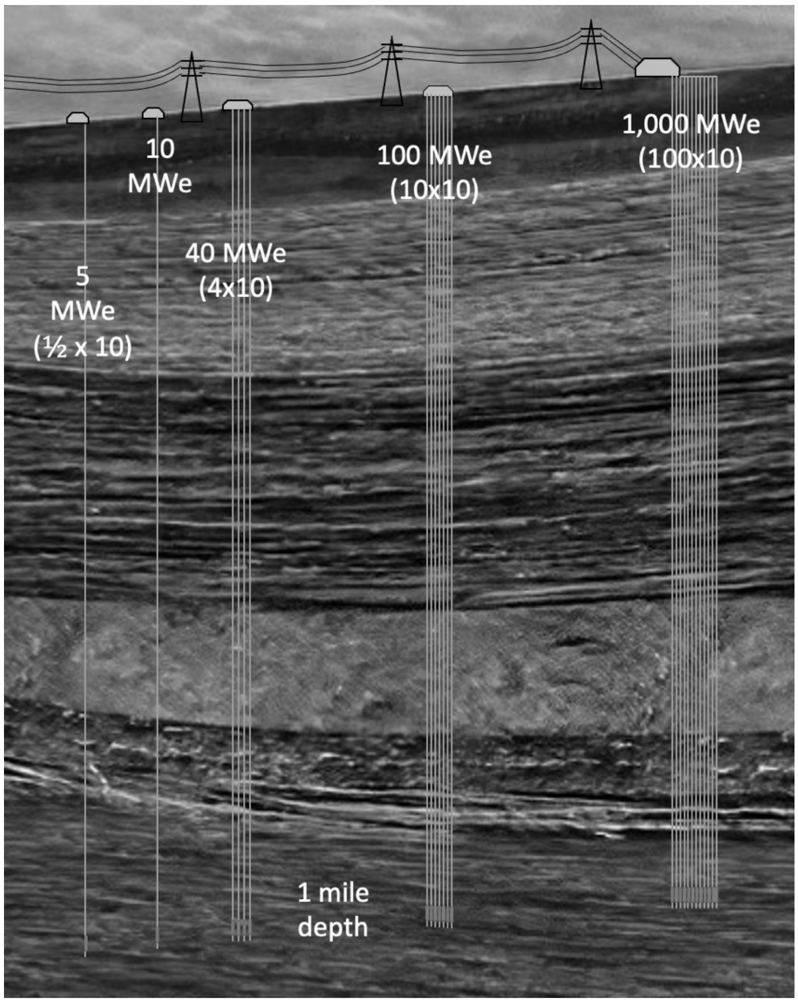


Figure 1: Geologic Layout Showing Examples of Deployment

Figure 1 shows examples of deployment. The base design reactor is 10 MWe, but it can be operated at half power (5MWe). It is fully modular, and boreholes can be spaced close to each other: 10 to provide 100 MWe, or 100 to yield 1 GWe. The figure does not show all the boreholes; for example, the 1,000 MWe reactor would have 100 in a 2D rectangular or triangular grid. Close-spaced reactors can share a steam generator and condenser. The modular nature allows the reactors to be spread across a military base or a large city.

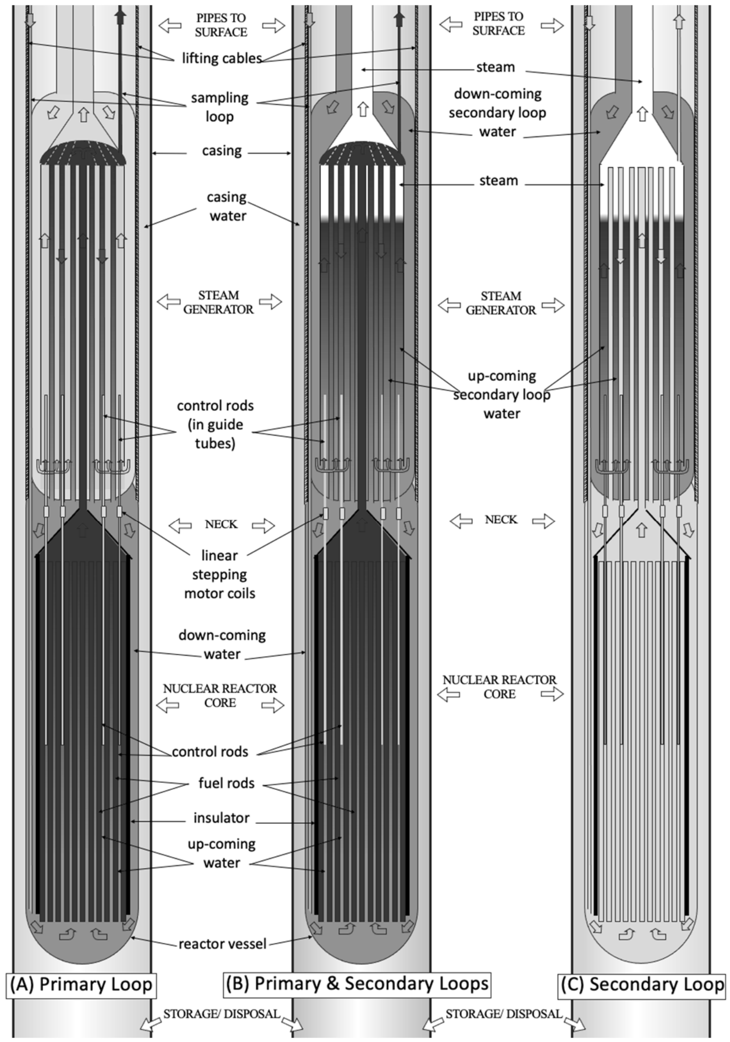


Figure 2: Reactor Components

Figure 2 shows major reactor components. On the left, (A) shows the components of the primary loop in darker grey. Included is a proposed linear steam generator, although a coiled steam generator is also under consideration. In the center, (B) shows all components of the reactor in strong contrast. On the right, (C) emphasizes the secondary loop with the other components in lighter grey. Below the reactor vessel is a region for reactor storage and/or disposal.

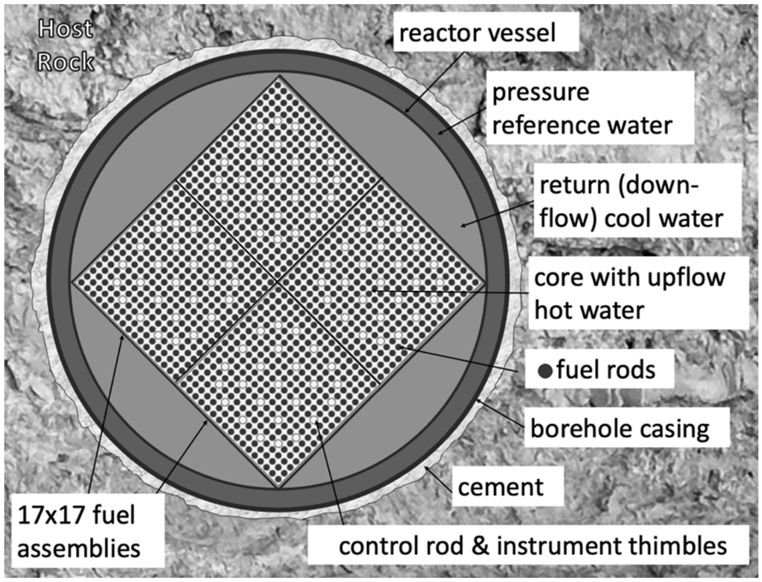


Figure 3: Plan View of Core

Figure 3 shows the core of the reactor in plan view. The core consists of 4 conventional 17x17 fuel assemblies, surrounded by a round reactor vessel. The space between the fuel assemblies and the vessel serves as the downcomer for return water from the steam generator to reach the bottom of the core. The space between the reactor vessel and the casing is filled with fresh water.

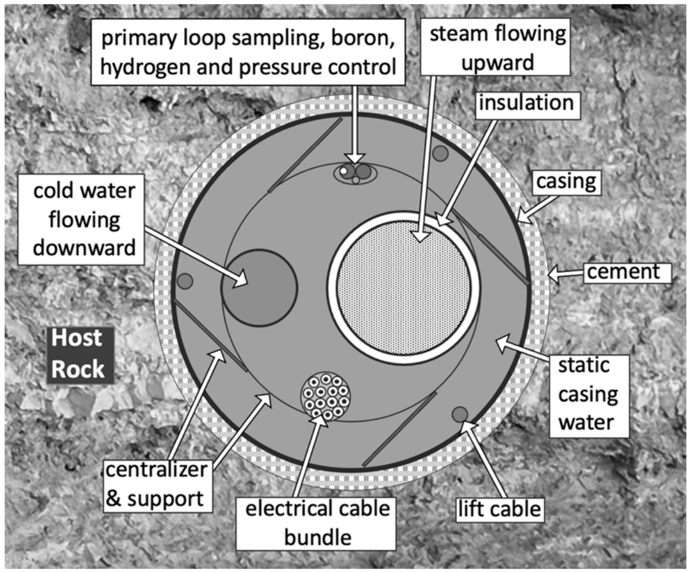


Figure 4: Cross Section of Casing above Steam Generator

Figure 4 shows a plan view section of the casing above the steam generator, from the steam generator to the surface room. The secondary loop consists of the cold water flowing downward and the steam flowing upward. The sampling tubes extend down to the primary loop. These tubes allow samples of the primary water, and serve as a means for boron adjustment, filtering, volume, and pressure control for the primary loop.

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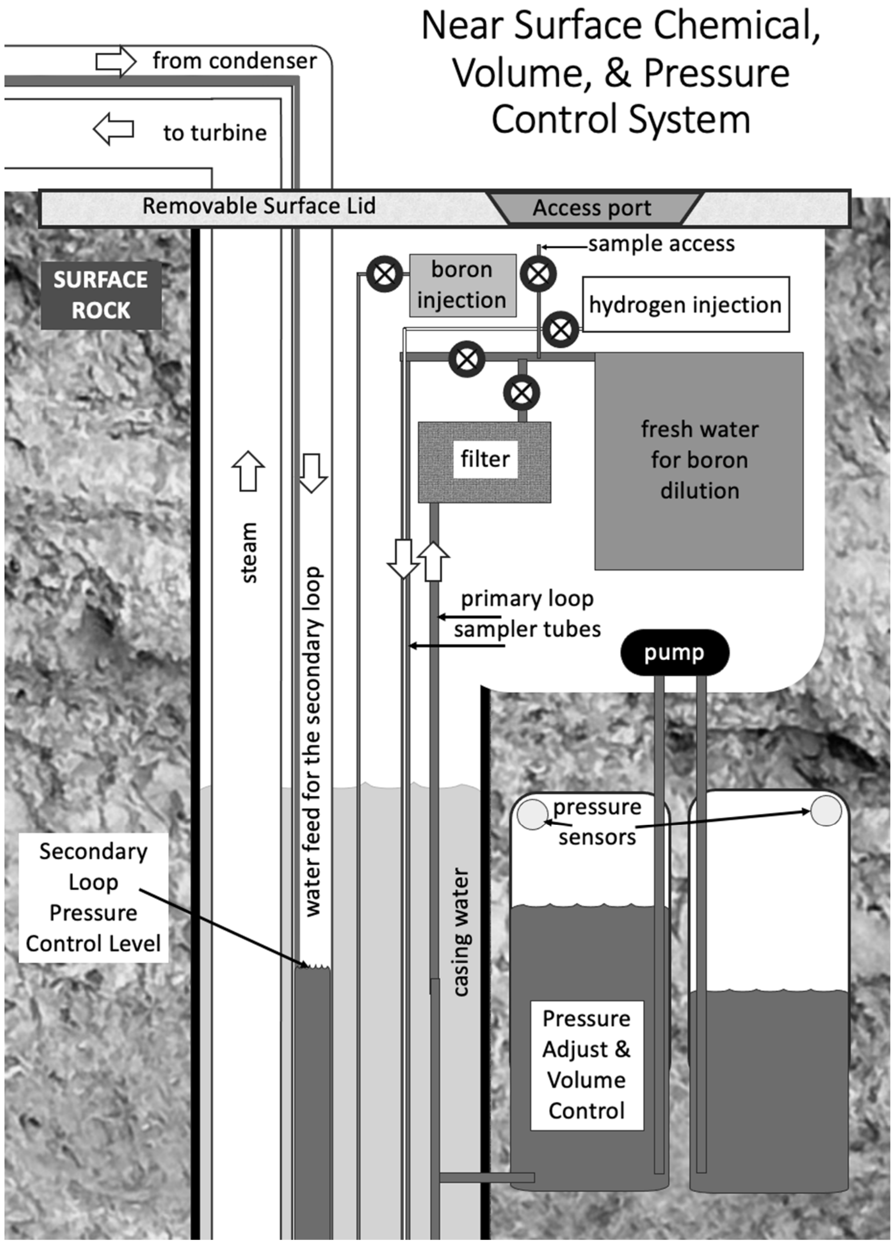


Figure 5: Conceptual Chemical, Volume, and Pressure Control Structure

Figure 5 shows the conceptual layout of the Chemical, Volume, and Pressure Control structure. The vault can be located below the surface (as shown) or above the surface. Radioactivity in the room is minimal, possibly zero (above ambient), and occurs only if there is leakage through damaged cladding. The access port allows for opening of the upper section to take samples of the primary loop coolant. The lid would normally be lifted only during initial placement of the reactor; the cables that support the reactor are not shown. Most of the water in the Pressure Adjust and Volume Control tanks comes from the initial expansion of the water in the reactor when the reactor is initially brought to criticality and the water within it expands by 40%.

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