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Generic Small Modular Reactor Plant Design

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Generic Small Modular Reactor Plant Design

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Abstract

This report gives an overview of expected design characteristics, concepts, and procedures for small modular reactors. The purpose of this report is to provide those who are interested in reducing the cost and improving the safety of advanced nuclear power plants with a generic design that possesses enough detail in a non-sensitive manner to give merit to their conclusions. The report is focused on light water reactor technology, but does add details on what could be different in a more advanced design (see Appendix).

Numerous reactor and facility concepts were used for inspiration (documented in the bibliography). The final design described here is conceptual and does not reflect any proposed concept or sub-systems, thus any details given here are only relevant within this report. This report does not include any design or engineering calculations.

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ACRONYMS AND ABBREVIATIONS

AC	Alternating Current
AAC	Alternate AC Power Source
ARI	Alternate Rod Insertion
BCR	Backup Control Room
CAS	Central Alarm Station
CMT	Core Makeup Tank
CR	Control Room
CRB(1)	Control Room Building (1)
DC	Direct Current
DOE	Department of Energy
ECP	Entry Control Point
FSM	Fuel Storage and Maintenance
HECW	HVAC Emergency water system
HVAC	Heating, Ventilation, & Air Conditioning
I&C	Instrumentation and Control
iPWR	Integral Pressurized Water Reactor
LOCA	Loss-Of-Coolant Accident
LWR	Light Water Reactor
MW	Megawatt
NNR	Non-Nuclear Receiving
NR	Nuclear Receiving
OCP	Outside Containment Pool
PA	Protected Area
PCCS	Passive Core Cooling System
PCSAS	Primary Containment Service Air System
PIDAS	Perimeter Intrusion Detection and Assessment System
PPP	Preferred Primary Power
PRS	Pressure Relief System
PUHS	Primary Ultimate Heat Sink
RB1	Reactor Building 1
RPS	Reactor Protection System
SAS	Secondary Alarm Station
SCIS	Safety Control and Instrumentation System
SFR	Sodium Fast Reactor
SFP-CCS	Spent Fuel Pool Cooling and Cleanup System
SLCS	Standby Liquid Control System
SMR	Small Modular Reactor
SNL	Sandia National Laboratories
SUHS	Shared Ultimate Heat Sink
TB(1)	Turbine Building 1
UHS	Ultimate Heat Sink

1. OVERVIEW

The generic SMR design draws from several systems. These include the 1000 MW Gen 3+ reactor designs, advanced reactor designs, and proposed small modular light water reactor designs. The reactor technology is forced flow iPWR, capable of coasting into natural circulation at shutdown. Many of the engineered systems and operations are generalized from references and have not been evaluated for sizing, dimensions, etc. These systems and operations should, therefore, be viewed as ideas rather than realities. Safety systems can be generalized as PWR-based, with some exceptions being borrowed from BWR designs.

The general plant layout is shown in Figure 1. The Protected Area (PA) is surrounded by a Perimeter Intrusion Detection and Assessment System (PIDAS) and a vehicle barrier system. The PIDAS is approximately 14 acres (780 ft. by 780 ft.). The plant arrangement is composed of 17 main buildings in the PA. There are four Reactor Buildings (RB1-RB4), four Turbine Buildings (TB1-TB4), two Control Room Buildings (CRB1, CRB2), Non-Nuclear Receiving (NNR), Nuclear Receiving (NR), the Fuel Storage and Maintenance building (FSM), an office building, a security building, and a Central Alarm Station (CAS). Each of the RBs, the CRBs, the FSM building, and the basement of the office building (location of the Backup Control Room (BCR) and Secondary Alarm Station (SAS)) are all seismic category 1 buildings. Though there are four RBs, there are only two CRBs, each one controlling two reactors. In addition to earthquakes, these buildings are designed to withstand the effect of natural phenomena, including tornados, flooding, and tsunamis. Furthermore, these buildings are also designed to withstand events that originate from within, such as fires and pressurization.

Figure 1. Plant Layout.

The nuclear island is arranged to control and minimize access of personnel/equipment entering safety-related structures. Access to the nuclear island is restricted by security measures throughout the complex. Safety-related equipment and nuclear material is placed below grade. Movement of material and equipment between above-grade locations and below-grade locations is only possible through the use of dedicated cranes. Movement below grade is controlled through a number of access controls that compartmentalize both equipment and personnel. The physical separation of safety systems from the associated access controls is a fundamental characteristic of all SMR designs.

Outside the nuclear island, several other non-safety structures exist. These include the switch yard, dry cooling radiators/cooling towers, cask storage area, parking, and the visitor center. These buildings are all considered plant investment items and are protected as such.

1.1. Major Buildings and Structures

All buildings that house safety-related systems are designed to protect against natural phenomena and design basis threats. Generally, all safety-related systems are placed below grade and below a missile shield. Protection of structures, systems, and components from internally and externally produced missiles is accomplished by the following practices:

1. Location of the system or component in a missile proof structure.
2. Physical separation of redundant systems.
3. Fire walls.
4. Flood mitigation building designs.
5. Prevention of internal missile production, when possible.

Systems that are needed to shut down the reactor, maintain reactor shutdown, and ensure the containment of radioactive material require protection. These systems are:

1. Reactor Coolant Pressure Boundary (reactor pressure vessel, etc.),
2. Passive Decay Heat Removal System (UHS, CMT, OCP, etc.),
3. Decay Heat Removal System,
4. Automatic Depressurization System Relief Valves,
5. Control Rod Drive Scram System (hydraulic and electrical),
6. Fuel Pool Cooling and Cleanup System,
7. Control System (Remote Shutdown Panels, Control Room, Cables, etc.),
8. Reactor Protection System (depressurization system),
9. All Containment Isolation Valves,
10. Major Refueling Equipment (crane, etc.)
11. HVAC Emergency Chilled Water System,
12. HVAC Systems Required During Operation of Items (1) through (8), and
13. Electrical System for Operation of Items (1) through (12) (AC & DC).

1.1.1. Reactor Building

The reactor building is a seismic category 1 reinforced concrete structure with an approximately 100-by-100-foot footprint. The building is designed to protect safety systems from all design basis threats, including aircraft impact. Furthermore, the building is designed to minimize radiation exposure to plant workers and the release of radioactive material to the environment. The building itself is composed of seven stories. Of these seven stories, five are below grade. At grade level, a reinforced concrete missile shield protects the safety related sub-floors from natural and hostile phenomena. The two floors above grade are constructed using nominal commercial construction practices, and do not house any safety-related systems. These floors house the non-safety grade, but preferred, power supply diesel generators, diesel tanks, HVAC equipment, an Ultimate Heat Sink (UHS) tank, and a crane for moving equipment to the lower floors. Movement of equipment to lower floors is accomplished by removing one of two missile shield hatches. The removal of these hatches triggers an alarm in the CR and CAS. Figure 2 shows a schematic of the two above-ground floors and roof.

Figure 2. Above Ground Reactor Building Floors.

Below grade, the building is divided into two sections by a two-foot-thick security-fire wall having minimal penetrations. This division was incorporated into the design to prevent/slow the propagation of antagonistic conditions to all redundant safety systems. Each floor contains a number of rooms/compartments; safety-related systems are generally housed in one of these locations. Due to the importance of such systems, access to each room is monitored. Additionally, these rooms are designed to protect against fires, flooding, and design basis threats. A second two-foot-thick concrete divider is installed between basement floor three and the ceiling of basement floor four. This second divider protects a third set of redundant systems located on the two bottom floors. These divisions are shown in Figures 3 and 4. Access from one division to another can only be accomplished through the first basement floor of the FSM building or through the above-grade floors in the reactor building. Equipment transfer between levels is accomplished through removable hatches, much like the one at ground level. All hatches

in the nuclear island are designed for fire and flood containment. Security engineered and administrative controls are in place for each hatch and associated cranes. Personnel movement is accomplished via two sets of stairs. Access from the stairwells to each floor is limited by access controls.

Figure 3. Reactor Building, Safety Divisions 1 & 2, Basement Floors 1-3.

Figure 4. Reactor Building, Safety Division 3, Basement Floors 4-5.

Each division has enough equipment to put the reactor into a safe shutdown. These systems include Instrumentation and Control (I&C), HVAC, electrical systems, switch gears, and DC battery banks. Other systems found in the reactor building include the high-pressure injection pumps, lab space, spare batteries and equipment, and the chemical volume control system (Cronje, 2012).

The reactor containment is housed in a concrete shielding structure centered in the reactor building. The containment is a freestanding steel structure that houses the reactor pressure vessel and associated systems. Access to the reactor during operation is not possible, and access during shutdowns is tightly controlled. Access to the reactor is accomplished through a shield plug on top of the shielding structure, personnel hatches, or the fuel/equipment canyon. The personnel hatches are located just below grade, while the shield plug is located at ground level. The canyon connects the RB and FSM building. Access is controlled by the reactor operator controls and the

health physics lockouts. In addition to the equipment associated with operations, several systems related to passive safety are housed inside the shielding/containment structure. These include, but are not limited to, makeup tanks, accumulators, residual heat removal heat exchangers.

The Outside Containment Pool (OCP) is housed external to the shielding structure. This body of water is used during normal shutdowns for decay heat removal, as well as for severe accident heat removal. A redundant heat exchanger system is used to transfer thermal energy from the reactor system to the OCP. Additional cooling is accomplished using the ultimate heat sink tanks that are located above grade.

The steam tunnel is located just below the missile shield, in between the two divisions of the reactor building. The tunnel sends steam from the steam generators to the turbine building, and transfers the corresponding condensed water back to the steam generators. Steam isolation valves are located in both the containment building and the turbine building.

1.1.2. Control Room Buildings

The two operating CRs are located below grade, beneath a missile shield, and between each pair of RBs. The operating CRs are only accessible via the below-grade level of the FSM. The main CRs are able to control the plant during normal and design basis accidents. The CRs can regulate both safety-related and non-safety-related systems. The CRB is composed of two below-grade floors and one above-grade floor. The below-grade floors house the CR, auxiliary meeting room, technical support center, alarm center, safety systems, emergency storage rations, a break room, and hygiene facilities. Auxiliary facilities equipment, such as HVAC systems, are located on the above-grade floor.

All controls are digital, with safety-related controls and instrumentation powered by a separate, secure power source. In the unlikely event of a station black-out, passive safety systems, such as compressed air and batteries, will allow for continued operation for no less than 72 hours; these systems are located in the CRB on the lower floor. If more than 72 hours is needed, the BCR could be used to increase this time to 1 week. **Outside of a system blackout, the operating CRs are serviced by redundant habitability systems.** There are three trains of control cables, which are physically separated for each reactor system except at the control building. Redundancy is ensured at this point by a BCR located away from the RBs.

The BCR has access to all of the safety control systems for each of the four reactors. Certain functions specifically related to plant startup cannot be accomplished from the BCR. The main objective of the BCR is to maintain safe shutdown in the event the nominal operation CRs are unavailable. Access to the BCR, and to the switch used to activate system control, is strictly controlled. The BCR is located next to the SAS, on the bottom floor of the office building. The same habitability and structure requirements are applicable to the BCR. The activation of the BCR automatically scrams all four reactors and locks out the other operating rooms. Alarms sound in the normal operating CR if access is granted to the BCR; additional alarms sound for each procedural step taken when transferring reactor controls to the BCR. The CRB is shown in Figure 5.

Figure 5. General Layout of a Control Room Building.

1.1.3. Fuel Storage and Maintenance Building

The Fuel Storage and Maintenance (FSM) building is a seismic category 1 building. Access to the RB and the operating CRBs is through the FSM below-grade floor. The FSM building's primary purpose is to store spent and new fuel (and related systems), and to provide for general equipment storage, movement, and repair. Like other buildings in the nuclear island, a concrete missile barrier is placed at grade. There are two main floors below grade. The first below-grade floor (subbasement) is a series of walkways and equipment storage areas. This floor provides the personnel access to the NR building basement, RBs, and operational CRBs. Access to each RB's subdivision is controlled and monitored by the CR and CAS. In case of major outages, temporary personnel areas can be created and controlled using removable gates. This floor also allows for a crane to move shielded fuel from the NR to the second subbasement floor.

On the second subbasement floor, a series of cranes and shielding systems allows for fuel movement from fuel storage areas to and from the RBs. The connection to the RB for fuel and equipment movement is secured during operation by interlocks and crane track disablement. This floor also contains the safety systems for the spent fuel pool. These systems are located in protected compartments having access controls. The only structures located below this floor are for the spent fuel pool, fuel/equipment canyons, and new fuel vault. Figure 6 shows the general layout of the FSM building.

There is an emergency exit (exit-only) in the FSM that personnel may use to exit from below grade into the office building in the event of an emergency. Security cages on the emergency exits prevent entry through them.

Figure 6. General Layout of the FSM Building.

1.1.4. Nuclear Receiving

Nuclear Receiving (NR) is the only entry and exit point for nuclear material. The building was built using traditional construction methods, because all nuclear material in the building will either be contained in a cask, or will not pose a risk. The building has two floors, one above grade and one below grade. The first floor allows for moving fresh fuel and casks to and from the basement, as well as for temporary storage. Movement of fuel and casks is accomplished via a system of hoists and cranes. Security-related engineered and administrative controls are in place for each hatch and the associated cranes. The basement does not cover the full footprint of the surface floor. The Entry Control Point (ECP) to below grade is located in the NR, and is the only way personnel can gain access to below grade (via the stairwell). NR allows for emergency exit of personnel from below grade in the event of an emergency; Security at the ECP will gather the personnel for accounting purposes. Each floor in NR has access to normal receiving and warehouse equipment, such as forklifts. There are no safety-related functions associated with this building. The layout of NR is shown in Figure 7.

Figure 7. General Layout of the Nuclear Receiving Building.

1.1.5. Non-Nuclear Receiving

NNR is the entry and exit point for all non-nuclear equipment and supplies. This is a one-story building. Equipment and supplies are unloaded and transferred to the above-grade floor of the FSM using either forklifts or cranes. The original shipping truck is not capable of driving into the FSM. After traversing the FSM, equipment can be moved into an RB through secured, hardened access panels on the RB's first floor. Compensatory security measures are put in place when these panels are opened, which is rarely. A parking and unloading area is located directly outside of the NNR building. A small barrier separates this area from the NR parking/unloading area. An area inside the NNR building is cordoned off to allow for temporary offices and break room facilities. This building has no safety-related function. NNR is shown in Figure 8.

Figure 8. General Layout of the Non-Nuclear Receiving Building.

1.1.6. Turbine Buildings and Transformers

The turbine building is a non-safety grade structure, although it is protected as plant capital. This building is based on traditional turbine building designs, but adds SMR characteristics, such as

modularity. The building has no personnel or equipment access points to the reactor building. The only connection is a steam tunnel that cannot be accessed without major effort.

There are three transformers located next to the turbine building. The largest transformer is the main step-up transformer. This transformer steps up the generated power, then sends that power to the switchyard and subsequently to the grid. The next two transformers are the unit auxiliary transformer and reserve auxiliary transformer (used as a backup to the unit auxiliary transformer). These transformers power non-safety related systems/equipment. The transformers step the AC power from the main generator down to the 6900V station bus voltage. The transformers/generator system has a failure rate of 1/40 per operation year. The transformers are surrounded by an 8-foot high chain-link fence. To prevent self-produced missiles affecting the neighboring transformer, a mild steel barrier separates the transformers. A general layout of the transformer building and associated transformers is shown in Figure 9.

Figure 9. General Layout of the Turbine Building.

1.1.6. Security Building

The security building provides entry control for personnel and vehicle access from the limited area to the protected area of the plant. All personnel and vehicles are inspected for unauthorized contraband, including explosives. Access controls are installed at the entry/exit portals and are manned 24/7 with a minimum crew of two guards. In the event of an attack, the Entry Control

Point (ECP) can be locked on a time delay. This time delay is set to the time that it takes for off-site law enforcement to arrive. The vehicle access entry point consists of hydraulic vehicle barriers and reinforced gates. The security building straddles the PIDAS; however, the roof of the building is alarmed to complement the detection coverage within the PIDAS.

The security building, as the name implies, houses the security force. The building is not a seismic category 1 building, but is reinforced to a level that will deter a direct adversary attack. Security personnel use the same personnel portals as the plant workers.

1.1.7 Central and Secondary Alarm Stations

The CAS and the SAS are located inside the protected area. The CAS is not a seismic category 1 building, but is reinforced to a level that will deter a direct attack. All alarms are annunciated, assessed, and communicated to the on-site and off-site response forces. All personnel access points into the CAS and SAS are positively controlled; these points are locked 24/7.

1.1.8. Radioactive Waste Building

The radioactive waste building houses waste from nominal plant operations. The building is not safety-related and does not house any material that requires a seismic category 1 structure. The building does pose a dirty bomb target, therefore it is located inside the protected area. The building generally stores solid waste, but can house liquid waste for short periods of time. The building has the capability to turn liquid waste into concrete for shipment. Entry into the building is managed through access controls.

1.2. Major Plant Components

1.2.1. Reactor System

The reactor is a forced-flow iPWR that is capable of using natural circulation at shutdown. It can produce 300 MWe or 1000 MWth, and operates with a two-year conventional fuel cycle.

1.2.2. Shielding Structure and Containment

The shielding structure is a large, circular, self-standing structure located in the center of the reactor building. The building is not built to withstand pressure transients, but rather to serve as a radiation shield and as physical protection to the reactor pressure boundary. The shielding structure's concrete base mat is an integral part of the reactor building's base mat. The foundation is 20 feet thick, while the walls are approximately 4 feet thick. This structure is designed to be a low-leak system. The shielding structure is approximately 15 meters in width and 30 meters high. The number of penetrations through the shield walls is minimized to decrease the amount of radiation exposure to plant workers. Access is possible through a single personnel interlock, through a large equipment hatch at the top of the structure, and through the nominal refueling canyon. This entire structure is located below grade. Major penetrations in this structure are for the steam tunnel, I&C cables, and passive heat-removal piping.

Inside the shielding structure sits the steel containment vessel. The steel containment vessel is built to withstand pressures up to 1.7MPa. The number of penetrations into the containment vessel is minimized; penetrations are generally only related to the secondary system (exceptions include the chemical volume control system and the high pressure injection systems). The limited penetrations into the primary system are automatically isolatable by the reactor containment isolation system. The containment vessel sits in a pool of water at the bottom of the concrete structure. This pool of water is an integral part of the passive safety feature, because it acts as heat sink and greatly increases the rate of heat transfer from the containment vessel during the most severe of accidents. There is no heat exchanger in this pool. The pool also helps with radiation shielding.

1.2.3. Fuel Storage

The new-fuel storage area is located in the FSM building in the new-fuel storage vault. The fuel storage vault is near the spent fuel pool and the cask preparation facility. The quantity of fuel stored at any one time is 40% of the fuel needed to run all reactors onsite, but is separated by reactor **destination**. The fuel is stored in high-density racks submerged in borated water (the borated water is not required for reactivity control). The new-fuel racks are designed to maintain sub-criticality ($k < .95$) under both normal and abnormal conditions. Each reactor new fuel section is designed to limit the amount of fuel removed at any one time by a time lock on the crane, so that only a single reactor's new fuel can be moved without encountering a time delay. The new fuel storage vault has a separate HVAC system that monitors for radioactivity. If radioactivity is detected, the vault and HVAC system are isolated to prevent a release.

Procedures for fuel handling dictate that no more than one assembly can be handled above the racks; this is accomplished using weight controls. The crane for fuel movement can be used for heavier loads, but, when doing so, is unable to cross the pool where the racks are located. Furthermore, the height and speed at which the fuel can be moved is also regulated. The crane is restricted through a series of electric interlocks so that fuel cannot be raised above the water, thereby bypassing the shielding requirements.

The spent fuel pool is located below grade in the fuel service building. The pool is approximately 40 feet deep and is sized to contain 15 full core loadings (in the case of a 4 module design). The spent fuel is stored in low-density racks that are submerged in a minimum of 20 feet of water. The racks are designed such that natural circulation occurs before the fuel reaches 100°F. The spent fuel pool is a seismic category 1 structure, constructed with walls 6 feet thick and having a one-half-inch thick steel liner. The spent fuel pool and associated canyons are designed such that water from the canyons drains and circulates into the pool. Low-density racks are also used for the spent fuel pool, in an arrangement to ensure that reactivity is less than .95; no credit is taken for burnup.

Pool gates, as well as fill and drain lines, are located at a height to ensure adequate water for shielding purposes. The circulation and filter lines for the spent fuel pool cooling and cleanup system (SFP-CCS) are designed to ensure that the pool cannot be drained through the use of vacuum breakers. Recirculation pumps remove decay heat from the spent fuel pool. The recirculation pump sends the pool water to a heat exchanger. A separate redundant heat exchanger can remove heat from the pool to one of the ultimate heat sinks. The pumps for the SFP-CCS are not safety-related.

1.2.4. Refueling Equipment

The refueling machine is a gantry crane used to transport fuel and reactor components to and from the pool storage area. This crane is separate from the spent fuel pool crane. Preprogrammed location limiters are used to prevent the crane from damaging equipment. A retractable vessel platform is available for vessel inspection. The platform must be moved from its resting area to an associated tract system by the containment crane. A large amount of tools and auxiliary equipment are available for the refueling process, including wrenches, slings, grapples, etc. All major machine movements (crane/platforms) are controlled by a local operator and monitored by the CR.

1.3. Miscellaneous Balance of Plant and Supporting Systems Design

1.3.1 Cask Storage Pad

The cask storage pad is located inside in the protected area. It is meant to store 20 years of spent fuel casks. If additional storage is needed, proposed ideas include an annex to the protected area, or off-site storage. The pad is a reinforced concrete structure, capable of meeting the load weights of casks with overpacks placed in a 4-by-4-meter pattern. There is no additional security or gating around this area, because the overpacks and casks provide adequate protection for design basis attacks.

1.3.2. Cooling Towers/Dry Cooling Radiators

Depending on the site location, either cooling towers or dry cooling radiators could be utilized. Cooling towers are typically constructed of reinforced concrete, while radiators are metal piping structures.

The inclusion of dry cooling radiators in the plant design is an advanced feature of SMRs. These radiators allow for heat rejection to the environment without the loss of water inventory or the need for large bodies of water. The radiators use high efficiency fans, powered from an offsite source to ensure that any surge from the fan motors and controls will not affect the power plant's safe shutdown. The radiators are designed such that they are only required to function at 80% efficiency to accomplish heat rejection during full-power conditions. The radiators are arranged to increase natural airflow, while berms are installed to prevent direct vehicle assault.

1.3.3. Switchyard

There are two switchyards. Each switchyard is subdivided into separate yards, each with access control. Each subdivision accounts for one reactor. The switchyard is located in the limited area, protected by a 10-foot high chain-link fence topped with razor wire.

2. KEY COMPONENTS OF THE PASSIVE CORE COOLING SYSTEM

The reactor was designed to have a low power density, which allows for the core to be cooled through natural circulation during shutdown and design basis accidents. The Passive Core Cooling System (PCCS) is composed of several components, including core makeup tanks, outside containment pool, and the UHS tanks. The reactor system uses redundant Core Makeup Tanks (CMTs) that are located inside of containment. These tanks are able to immediately inject water at high pressure into the pressure vessel. The injection of high-pressure water is done only when AC power is available. If AC power is not being provided, the system can passively inject low-pressure water into the system. For this to occur, the reactor system must be depressurized. The CMTs are connected to the Outside Containment Pool (OCP), and heat is transferred from containment to this pool through a series of redundant heat exchangers. The OCP is allowed to boil off, and is constantly being refilled by the ultimate heat sink tanks located outside the reactor building. An overview of this process is shown in Figure 10.

Figure 10. Passive Safety Design.

2.1 Core Makeup Tanks

The bottoms of these tanks are connected to the reactor vessel through a direct vessel injection system. A heat exchanger inside each of these tanks is connected to the outside containment pool. The water in these tanks is significantly cooler than the primary core water, so that when the injection lines open, the heavy colder water that enters near the top of the pressure vessel begins a natural circulation loop in the primary pressure vessel.

2.2. Outside Containment Pool

The Outside Containment Pool (OCP), not to be confused with the pool located at the bottom of the shielding structure, is connected to the CMTs through redundant heat exchangers. These heat exchangers are always in operation, and can only be closed in the case of a line breach. A line breach is not expected to occur inside containment, but rather outside containment; a double breach is outside of the design basis. There is a set of three heat exchanger lines, only two of which are needed for full decay heat removal. Steam from the OCP is sent through a HEPA filter to the atmosphere, and is monitored from the Control Room for radionuclides.

The OCP holds approximately 28000 cubic feet of ordinary water. The tank's base is ~400 square feet and rises ~70 feet. This is enough water to cool the reactor system after operating for two years at a power level of 1200 MWth (with a safety margin).

2.3. Ultimate Heat Sink

The OCP is connected to two ultimate heat sinks (UHSs). The UHSs are tanks of water that are used to refill the OCP. As stated above, one ultimate heat sink is shared (SUHS), while another is the primary UHS (PUHS) for each reactor unit. Both UHSs are connected to the OCP in a redundant fashion. The connection is designed such that these OCP-UHS lines are always open, constantly ensuring that the OCP is filled. The manual closing of these lines sounds an alarm in the CR.

The ultimate heat sinks are steel tanks located above the missile shield in the reactor building or the fuel handling building. The tank located in the reactor building is ~20 feet in diameter and 60 feet tall. This tank holds ~2000 cubic feet of water, enough water to cool a reactor system for an additional four days. The shared tanks are located in the FSM building above the ground and the missile shield. These tanks offer redundancy for UHS tanks located in the reactor building. Each tank can provide four days of cooling, with the shared tank capable of providing eight days. The tanks are used to fill the OCP. Furthermore, the tanks can be filled by an external water source. The pumps for filling the tanks are operated outside the PIDAS. The shared tanks can also be used to send makeup water to the spent fuel storage pool.

2.4. Pressure Relief System

The Pressure Relief System (PRS) automatically depressurizes the reactor system in the event of a loss-of-coolant accident (LOCA), in which the CMT systems fail to maintain the reactor vessel water level. The depressurization of the nuclear system allows the low-pressure flooders systems to supply enough cooling water to adequately cool the fuel. This system is not part of the nominal passive safety procedures.

3. OTHER SAFETY SYSTEMS

3.1 Decay Heat Removal System

Decay heat removal during normal operation is accomplished via the passive system, which is used unless there is a loss of offsite power. The system is essentially the same as the passive decay system, but uses a pump to enhance the the passive system's effectiveness. These pumps are located on a line parallel to the lines that connect the CMTs and OCP. Additionally, two heat exchangers are installed in the OCP that is connected to a radiator on top of the reactor building. This system is also powered by an electrical pump. The operation of this system decreases the OCP temperature, preventing significant loss of water inventory due to evaporation.

3.2 Instrument & Controls (I&C) and Safety Control & Instrumentation System (SCIS)

The safe operation of the plant requires a system to ensure that vital functions occur. Non-safety-related controls and associated instrumentation are controlled by the I&C system. While the I&C is important, not all I&C is directly related to safety, and must be built accordingly. The Safety Control and Instrumentation System (SCIS) is a subcategory of the I&C system. This system is charged with ensuring the control of reactivity, removal of heat from the core, and containment of radioactive material. This plant design uses a fully digital control/instrumentation system. The SCIS is housed in the RB, the CRB, and, to a limited extent, in the BCR (located in the basement of the office building).

These systems control reactivity within operational limits, prevent transients, shut down the reactor system, and maintain system shutdown within the design basis threat conditions. The systems also control all of the valves and pumps related to both the passive safety systems and the decay heat removal systems for both the reactor and the spent fuel pool. Finally, the system is charged with isolating the reactor pressure vessel, the containment, and the reactor/FSM buildings. Building closure is initiated by HVAC controls.

3.3. AC Power

An AC electrical power distribution system provides reliable power to the plant for all nominal operations, including startup, operation, shutdown, and outage operations. The plant does not require offsite AC electrical power to cope with design basis accidents. In the case of a loss of offsite power, a safety set of diesel generators will start automatically. These diesel generators can power all safety systems indifferently (with refueling). A second set of generators can also provide power. These generators are not safety-related and are generally stored off site. When installed, these systems are referred to as Preferred Primary Power (PPP), and the safety diesel generators become a redundant safety system. The safety diesel generators are located on top of the control building at a height that protects them from flooding. Due to the smaller and less demand load of SMR designs, the diesel generators can use air-cooling. Air-cooling reduces complexity, as well as cost, while increasing the reliability of the system.

The AC power system is designed redundantly, as are all safety components. The system is a class 1E power system with three divisions, with any two divisions being adequate to place the unit in a hot shutdown condition. A system of protective relays allows for the isolation of malfunctioning equipment. Voltage relays are used on safety-rated systems for the disconnection of AC power and the connection of emergency battery power. All safety-related breakers, generators, transformers, and circuits can be monitored and/or controlled via the CR. The class 1E power load is divided into three divisions, with each division joined to an independent class 1E bus. These divisions have access to one onsite power source, two offsite power sources, and the alternate PPP source. The safety systems that are connected to this power system are:

1. Safety System Logic and Control Power Supplies, including the Reactor Protection System,
2. Core and Containment Cooling Systems,
3. Safe Shutdown Systems, and
4. Class 1E Monitoring Systems.

3.4. Reactivity Control System

Reactivity is normally accomplished through electrically driven control rods (i.e, the Reactor Protection System (RPS)). The reactor protection system uses the fine movement control rod drives to insert control rods into and remove control rods from the reactor. In the case of an operator-signaled or an RPS automatic scram, these motors quickly drive the control rods into the core, thus shutting the reactor down. If control cannot be regained gained by the RPS, the Alternate Rod Insertion (ARI) function can be used. Through a series of automatic signals related to the failure of the RPS and/or operator command, the ARI causes a hydraulic scram. Both of these systems can respond to transients. A third system, the standby liquid control system (SLCS), can be used for non-transient control.

3.5. Standby Liquid Control System

If the operator cannot shut down or ensure the continued shutdown of the reactor system, the SLCS can be used to bring the reactor to shutdown by the addition of borated water. This system is a safety-related system. The system is not capable of SCRAM or any other fast reactivity transients. The system is tested periodically using non-borated water. The system is exercised through automatic reactor alarms or by operator actions. The system is operable any time the reactor can reach criticality. Procedural system locks are used to ensure the unintentional operation of the system by operators. The borated water is injected through a high-pressure line. The pressure is sufficiently high to overcome any postulated reactor environmental conditions. The system is located in the reactor building in safety division three.

3.6. Core Thermal-Hydraulic Internals

As an integrated PWR design, there are no pumps located inside the pressure vessel. Major components include the down comer, steam generator, core support structure, pumps, pressure valves, water makeup lines, instrumentation components, and chemical control lines. All these systems are safety-related and failure of any one of these systems results in a scram. The reactor

system is brought to operating pressure and temperature through a series of fine control rod movements. The reactor system cannot be brought to significant power production at non-operating temperatures/pressures and without the secondary system in operation.

3.7. Safety Related HVAC

The HVAC Emergency Cooling Water system (HECW) provides chilled water to the safety-related equipment in the reactor building, fuel service building, control building, and the control building habitability area. The system is designed to work under both normal and abnormal reactor conditions. The system is powered from Class 1E buses. In the event of abnormal conditions, the system can be powered from the Alternate AC power source (AAC). The system is housed in a category 1 seismic building, protected from missiles. The system is both robust in design, as well as protected from non-nominal power supply conditions (surges) and short transient operations. Fill tanks and associated equipment are designed to prevent drainage through operation.

The system is subdivided into three redundant subsystems; any two can provide enough cooling to the control building and to all redundant safety-related systems. A single subsystem can cool one train of redundant safety systems and maintain the habitability of the Control Room and the associated operating envelope. The associated envelope is large enough to allow personnel to move in and out of the control building, but the habitability of non-critical floors/facilities will not be ensured. Each subsystem is physically separated, with one system located in each of these buildings: control building, reactor building, and fuel facility. Each piece of equipment needing to be served by this HVAC system is served by no fewer than three fan coil units (one related to each of the three HVAC subsystems previously mentioned). The system is initiated after ensuring that the secondary containment isolation signal has been received. An example of the subsystem division is shown below.

1. Safety-Related Subsystem Division A

- (1) Safety-related battery Division I.
- (2) HECW chiller Division A.
- (3) Decay Heat Removal water pump and heat exchanger Division A.
- (4) HVAC equipment Division A.
- (5) Safety-related electrical equipment Division I.
- (6) Non-safety-related power supplies.
- (7) Non-safety-related electrical equipment.

3.8. Primary Containment Service Air System

The Primary Containment Service Air System (PCSAS) is a safety-related system, and therefore a category 1 seismic system. The system is redundantly designed to ensure primary containment air quality for normal operation. The PCSAS is used to keep the containment and the shielding structure at a negative atmospheric pressure during outages. When the plant is operating, this

system is used only for the shielding structure's maintenance of negative pressure. Air quality inside this structure is not maintained due to the high radiation field preventing occupation.

3.9. Fire Containment/Control System

Reactor safe shut-down equipment is divided into redundant systems, each capable, by itself, to shut down the reactor safely. This is accomplished through plant arrangement, redundant safety system separation, fire containment/suppression, personnel access, alarm, and HVAC controls. In terms of fire control, each system is separated by firewalls to prevent any single fire from removing the redundancy. All doors, walls, floors, and ceilings are rated for a three-hour fire. Overpressure protection is accomplished by blowout panels. Blowout panels, HVAC, and cable routing for safety-related equipment are separated into their given fire control division. These divisions are directly related to the redundant safety subsystems. The only place where these subsystems meet is at the CR; redundancy at this location is ensured by the BCR. Furthermore, the effect of spurious responses resulting from the effects of a fire is prevented by using a dual channel digital system, where two identical signals are required at the de-multiplexer for the control signal to be recognized. Fire suppression is provided by sprinklers, an AFFF sprinkler system, alarms, detectors, portable firefighting equipment, and other generally expected systems. Fire in containment is not possible during operation, due the inert nature of containment. Special procedures and precautions are taken when containment is not inert.

3.10. Communication Equipment

The reactor facility has several communication systems throughout. Due to the robustness of the site structure and safety concerns, wireless communication is prevented. Two hard-wired systems are typically available, depending on the local function. The first system is a site-wide powered communication line. The second is a sound-powered telephone system that is used in areas of the facility that are safety related. Furthermore, the site contains a third paging system that resides on its own dedicated transmission network, which allows for communication during normal operations. The only safety-related system is the sound-powered telephone system.

4. OPERATION PROCEDURES

4.1. Refueling

Refueling begins with the shutdown of the reactor. Immediately after shutdown, the pressure vessel is depressurized and the decay heat removal system is initialized. The secondary coolant system is isolated through a series of valves. These valves are used to prevent contamination of the secondary side. During this process, the gates separating the FSM and the RB are removed. After their removal, the crane is moved into the shielding structure. The containment vessel head is removed, and the containment and containment well are flooded. Next, the pressure vessel head is removed, followed by the associated reactor internals. The crane is then used to remove the fuel from the core. The fuel is then moved, under 20 feet of water, to the spent fuel pool through the fuel/equipment canyon. Concurrently, fresh fuel is removed from the new fuel vault and placed inside the spent fuel pool, in preparation for installation into the core. The process of preparing for refueling is executed in reverse prior to nominal inspections. Figure 11 shows the process in more detail.

Figure 11. Generic Refueling Operation.

4.2. Fuel Shipments

Fuel is delivered, by truck or rail, in a fresh fuel cask. After inspection, the fuel cask is brought to nuclear receiving. At NR, the fuel, in its cask, is unloaded and transferred by crane to the NR basement. In the basement, the fuel is transferred, using the FSM crane, to the new fuel vault. The new fuel vault lid is removed and the fuel is unloaded. The fuel is then placed into the vault. This process is detailed in Figure 12.

Spent fuel, after cooling in the spent fuel pool for a minimum of five years, can be removed from the spent fuel pool and placed into a cask for external storage. This process begins by using the FSM crane to lower a specially-designed canister system into the cask loading machine. The canister machine is flooded and spent fuel is loaded into the canister. The canister lid is positioned and secured. Water is removed from the canister and is inerted. The canister is then loaded into the cask, which is positioned next to the canister. The cask system is checked and then moved out of the FSM via the same crane system that brings in fresh fuel. A more detailed description of this operation is shown in Figure 12.

Figure 12. Generic Refueling Operation.

4.3. Personnel Entry and Exit

Access control begins at the site perimeter fence. The only access point from offsite to the plant site limited area is through the gate near the visitor center. The only access from the limited area to the protected area is through the ECP in the security building. All personnel, including security personnel, access the protected area through this protected area ECP. A thorough inspection of personnel and vehicles for unauthorized contraband, including explosives, is carried out before entry is authorized. Subsequent entry into any of the buildings is tightly controlled, with all safety-related structures further controlled.

Within the protected area, there is restricted access through the rear of the office building to the above-grade floor of the following: the FSM, the two main CRs, NR, and NNR (a single-story building). Only dedicated internal vehicles (i.e., forklifts) can move between NNR and the above-grade floor of the FSM.

There is only one ECP to below grade located at the NR building. It allows personnel restricted access to below grade via the stairwell. Although the RBs do have stairwells that go all the way up to the above-grade floor, there are secure, hardened access panels between the above-grade floor of the FSM and the above-grade floor of the RBs. This prevents access from the above-grade floor of the FSM to the stairwells that go all the way down to the reactors. Compensatory security measures are put in place whenever the access panels are opened (rarely) to allow items, such as replacement parts, to be moved from NNR via the above-grade floor of the FSM to one of the RBs.

Within each RB, access to inside the reactor can be gained through crane hatches for items, or by staircases for personnel. The staircases are monitored by the CAS. Opening the crane hatches will trigger a scram if the plant is operating, with immediate initiation of the alarms in the CRs and CAS.

There are two “exit-only” emergency exits that personnel may use to exit from below grade in the event of an emergency. Each of the emergency exits is equipped with a security cage to prevent entry through them. The west side emergency exit is through NR; the east side emergency exit is from the FSM through to the office building. After exiting, personnel will be gathered by security for accounting purposes.

4.4. Security Systems

The site perimeter is bounded by an 8-ft chain linked fence with razor wire on top. The site perimeter is not alarmed, but the area is randomly patrolled inside the perimeter by the guard force. The protected area is surrounded by a PIDAS. The PIDAS includes the appropriate technology to detect and assess unauthorized access. All alarm devices and transmission lines are tamper-indicating and self-checking to provide an automatic indication when an alarm system (or alarm system component) fails, or when the system is operating on back-up power. The intrusion detection system is used to initiate a timely response against an adversary threat. Passive and active vehicle barrier systems are located inside the inner fence of the PIDAS to prevent

unauthorized entry of various sizes of vehicle into the PA. The PIDAS and PA are illuminated at all hours by a series of lights located inside the PIDAS. Each light is capable of operating in a diminished capacity by using solar powered batteries as backup power in the case of a station blackout.

The nuclear island and all safety-related equipment are located below grade, inside the PA. The below-grade siting is a key feature that provides enhanced security and safety to SMR designs.

There is only one ECP to below grade located at the NR Building. Both the ECP leading below grade and the ECP at the security building into the PA are manned 24/7 with a minimum crew of two. In the event of an attack, the entry point can be locked on a time delay. This time delay is set to the time that it takes for off-site response to arrive. All access control is monitored for personnel entering and exiting the buildings in the PA for emergency preparedness and security. All ECPs and sensitive areas are monitored by closed-circuit television (CCTV) cameras. Table 1 provides an overview of Physical Barriers and Access Controls.

Table 1. Area-Specific Access Controls and Physical Barriers.			
Plant Area	Building	Equipment of Interest	Access Controls and Physical Barriers
Reactor Safety System Rooms	Reactor Building	Batteries, I&C, switchgear, etc.	Key card access control Earthquake-resistant barriers
Chemical Control Room	Reactor Building	Piping to the RPV	Key card access control Earthquake-resistant barriers
Shielding Structure	Reactor Building	Containment and safety related equipment	Key card access control with radiation interlock. Earthquake-resistant, bullet-resistant barriers and doors.
Reactor Building Safety Division	Reactor Building	Safety Related Equipment/Reactor	Dual card, key card access control with guard present if equipment hatches are open.
CRB	CRB	Controls for plant and passive safety systems	Dual card, key card access control with guard present if equipment hatches are open.

Table 1. Area-Specific Access Controls and Physical Barriers.			
Plant Area	Building	Equipment of Interest	Access Controls and Physical Barriers
Cable Spreading Room	Control Building	Cables for control of plant operating systems and engineered safety features.	Key card access control Earthquake-resistant barriers.
Control Room	CRB Second basement	Controls for plant and passive safety systems	Key card access control. Bullet-resistant walls, doors, ceiling, floor, and windows.
Scram Relay Room	Control Building First Basement Floor	Relays and logic cabinets for Reactor Protection System (SCRAM) system.	Key card access control.
Ultimate Heat Sink	Roof of Reactor Building	Water required for passive safety after 72 hours.	Double-wall tank, 24-inch concrete wall, earthquake-resistant barrier. Lock-and-key access control to valves, and other insider sabotage targets.
Fuel Storage and Maintenance Building	Fuel Storage and Maintenance Building	Spent Fuel Pool/Fresh Fuel Vault	Dual card, key card access control with guard present. Earthquake-resistant barriers.
Turbine Building	Turbine Building	Plant Capital Protection Equipment	Key card access control. Earthquake-resistant barriers.

The guard force protection strategy comprises three types of security personnel: a dedicated, armed, on-site response force located below grade of the nuclear island to implement a below-grade denial strategy during an adversary attack; an armed guard force to support CAS/SAS functions, patrol the PA, and establish a containment strategy during an adversary attack; and local law enforcement for tertiary response during an adversary attack.

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6. APPENDIX

Many of the design elements for this generic design will change depending on the reactor technology used. Such technologies could be gas cooled, molten salt, natural circulation LWR, and sodium. To demonstrate the possible changes the following table lists some of these attributes for a modular sodium fast reactor.

Component	Difference
Reactor Building	The reactor building will be similar to that of an LWR-SMR. The building will house a large vault of sodium for the reactor and have no water present in the building. Furthermore, due to likelihood of HEU fuel, the building will be secured as such.
Fuel Storage and Maintenance Building	This building will be capable of handling metal fuel that is both stored and contains sodium. There will be numerous remote control machines. This will be required due to the reaction of sodium with the atmosphere and water. Depending on the driver of the system design, this building could be very large and house reprocessing capabilities.
Nuclear Receiving	Will be similar to that of LWR-SMR designs, but again will have increased security due to the fuel safeguards.
Radioactive Waste Building	Could become a structural part of the reactor building or the FSM building.
Reactor System	Non-pressurized, sodium cooled fast system. Primary pumps, intermediate heat exchangers and direct reactor auxiliary cooling system (DRACS) all housed in the reactor vessel. Argon is pumped in-between the bulk sodium and reactor vessel cover
Reactor Vessel	Depending on power output, expected to be around 5-10 meters and 15-30 meters in height. Penetrations are only through the top vessel cover/shield. Common designs of the shield plug that rests on top of the vessel is a two plug designs. Each vessel cover has a access port that can be aligned to allow access to the vessel by rotating the plugs. A steel guard vessel surrounds the reactor vessel and is meant to contain any unexpected leaks.
Guard Vessel	Guard vessel surrounds the reactor vessel. The gap between the two is large enough to allow for vessel inspection.
Shielding Structure	Is the concrete containment.
Containment	Concrete structure that is steel lined and inerted.
Reactor Fuel	Likely a metal fuel, much shorter than a LWR assembly. Can be HEU or a combination of uranium and transuranics such as plutonium.
Fuel Storage	Fresh fuel will be hotter if it contains transuranics, thus it could require a more robust active cooling. Spent fuel can be stored in either liquid lead or sodium.

Refueling Equipment	Unique equipment will be required. Furthermore all systems would be accomplished out of sight of operators.
Refueling Strategy	Depending on fuel, the fuel can have an expected life of up to 10 years (some designs could be in excess of 30). Fuel shuffling is expected more often than a refueling. Refueling will be infrequent but more complicated/longer.
Core Makeup Tanks	These will not exist in a pool type system. Pool will simply raise and fall with density changes.
Outside Containment Pool	Depending on the design a large volume of sodium is used to slow the thermal response of the system.
Pressure Relief System	Much less important for a non-pressurized system
Ultimate Heat Sink	Atmosphere, no water tanks on primary loop.
Decay Heat Removal System	DRACS system.
Fire Containment	Due to the hazards of sodium, a suppression system will likely be used
Security System	Depending on the fuel enrichment, the security system could be similar or more robust.
Reactor Control	Dependent on design, but use of control rods, voided regions (GEMS), and B4C balls should be expected.
Reactor Coolant Cleanup System	Depending on fuel design, possibility of fission gas release into the system instead of a plenum is possible. This design would require a robust system to clean out the coolant.
Reactor Coolant Heating System	To prevent freezing of Na during shutdown, a heating system is provided that can compensate for the continues loss of thermal energy by the DRACS. This system is safety related and will be protected as such.
Energy Conversion System	Could be a Na-Na-Rankine or Na-Na-Supercritical CO2 Brayton cycle. If the later, the footprint will be significantly smaller than the traditional Rankine Cycle.
Emergency Backup System	A more robust battery system is needed to ensure a cost down of the pumps for the first 30 mins-hours of the pumps, time required is design dependent, but is needed until natural circulation starts.