ADVANCED PASSIVE SAFETY SYSTEMS FOR THE NUSCALE ENERGY FACILITY

Dr. Corey McDaniel

NuScale Power, LLC. 1100 NE Circle Blvd, Suite 350, Corvallis, OR 97330 USA

cmcdaniel@nuscalepower.com

Abstract

This paper presents an overview of the advanced passive safety systems implemented in the NuScale nuclear energy facility. During normal operation, each NuScale containment is fully immersed in a water-filled stainless steel lined concrete pool that resides underground. The pool, housed in a Seismic Category I building, is large enough to provide more than 30 days of core and containment cooling without adding water. After 30 days, the decay heat generation is sufficiently small that natural convection heat transfer to air on the outside surface of the containment coupled with thermal radiation heat transfer is completely adequate to remove core decay heat for an indefinite period of time. These passive safety systems can perform their function without requiring an external supply of water, power, or generators.

1. Description of a NuScale Energy Facility

NuScale Power LLC is commercializing a 540 MW(e) modular scalable nuclear power plant comprised of 12 factory fabricated, 45 MW(e) power modules that are delivered and installed as local power demand requires.[1] Each module consists of an integrated light water nuclear reactor vessel enclosed in a high strength containment vessel. The basic configuration of a single NuScale power module is illustrated in Figure 1. The entire module is completely immersed in a water-filled stainless steel lined concrete pool. The pool is deeply embedded and located inside of a seismic category 1 reactor building. Furthermore, each module is suspended by trunnions supported by seismic isolators. The hanging containment system and underwater placement make the system very resilient to seismic motion. The containment is roughly 19.8m (65 feet) long by 4.6m (15 feet) in diameter. The reactor pressure vessel, 13.7m (45 feet) long by 2.7m (9 feet) in diameter, contains the nuclear core, a set of helical coil steam generators, and a pressurizer. The nuclear core consists of an array of approximately half-height 17x17 PWR fuel assemblies with UO2 fuel enrichments below 5%. Core power is controlled using control rod clusters and core heat is removed entirely by natural circulation. Water is heated in the nuclear core to produce a low density fluid that travels upward through the hot leg riser. The helical coils wrapped around the outside of the riser provide a heat sink that cools the water, causing its density to increase. The density difference acting over an elevation difference results in a buoyancy force that drives the fluid flow around the loop. Natural circulation operation provides a significant advantage in that it eliminates pumps, external pipes, and valves and hence the maintenance and potential failures associated with those components. It also reduces in-house plant loads. This added simplicity enhances overall plant safety as well as improving economics.

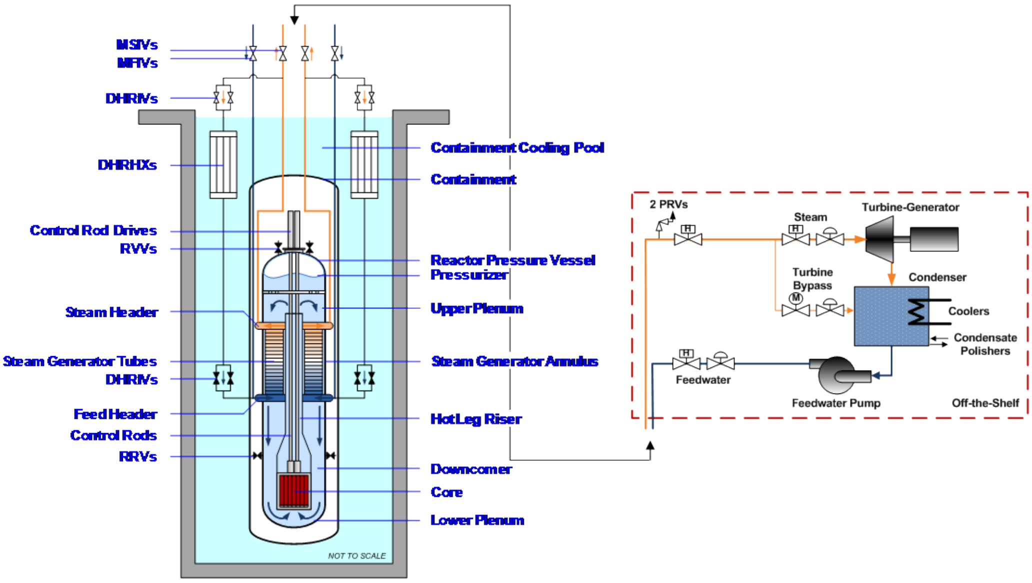


Figure 1. NuScale Module installed underwater in its underground stainless steel lined concrete bay

The helical coil steam generator consists of two independent sets of tube bundles with separate feedwater inlet and steam outlet lines. Feedwater is pumped into the tubes where it boils to generate superheated steam. Because of their relatively small size, the steam generators are replaceable. A set of pressurizer heaters and sprays is located in the upper head of the reactor vessel to provide pressure control.

1.1 Inherent Safety Features

The NuScale containment and reactor vessel include several design features that inherently enhance safety. These are identified in Figure 2. During normal power operation, the containment atmosphere is evacuated to provide an insulating vacuum that significantly reduces heat loss from the reactor vessel. As a result, the reactor vessel does not require surface insulation. This eliminates the potential for sump screen blockage. Furthermore, the deep vacuum improves steam condensation rates during any sequence where safety valves vent steam into this space. Eliminating containment air prevents the creation of a combustible hydrogen mixture in the unlikely event of a severe accident (i.e., little or no oxygen), and eliminates corrosion and humidity problems inside containment. Finally, because of its relatively small diameter, the high strength containment vessel has a design pressure in excess of 4.1 MPa (600 psia) which is ten times that of a conventional containment structure. The equilibrium pressure between the reactor and the containment in the event of a reactor vessel steam release will always be below the containment design pressure.

The reactor vessel has both a smaller nuclear core, with only 5% of the fuel of a typical large reactor, and a much larger fluid inventory. The reactor vessel water volume to thermal power ratio is four times larger than a conventional PWR; resulting in better cooling characteristics and a much slower response to thermal transient upsets.

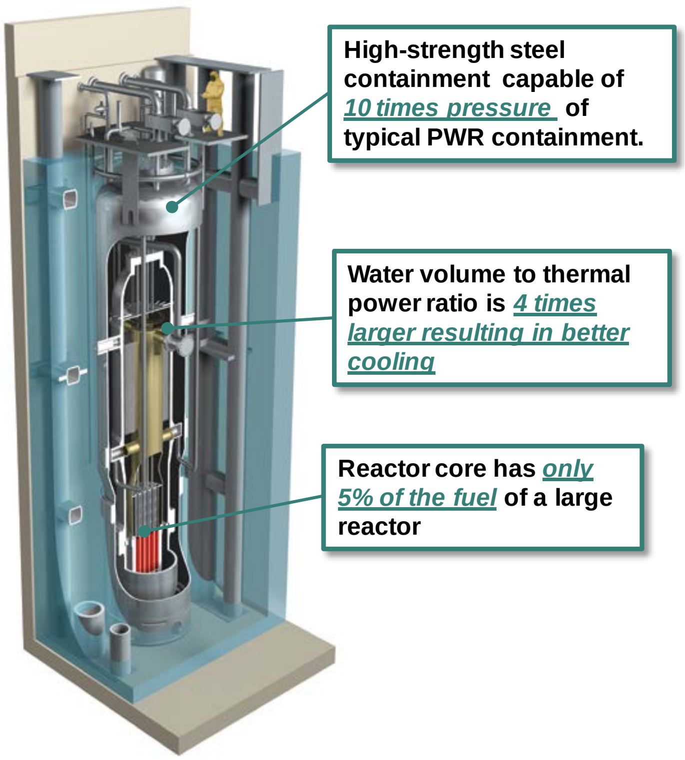


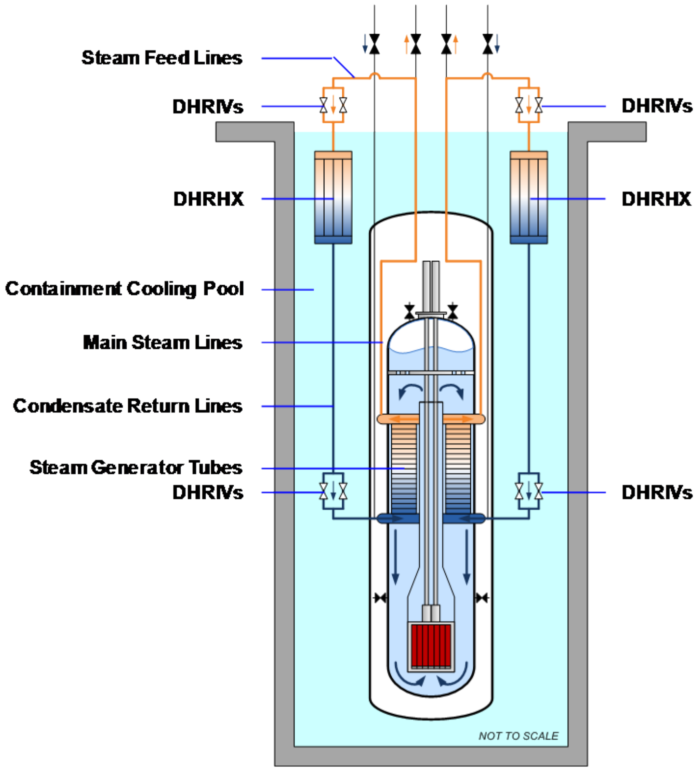
Figure 2. The NuScale Containment and Reactor Vessel include enhanced safety features.

1.2 Passive Safety Features

Each NuScale module employs two independent passive safety systems. In general, a passive safety system provides cooling to the nuclear core and containment using processes such as, natural convection heat transfer, vapor condensation, liquid evaporation, pressure driven coolant injection, or gravity driven coolant injection. It does not rely on external mechanical and/or electrical power, signals or forces such as electric pumps. A useful list of terminology related to passive safety is found in IAEA-TECDOC-626. [2]

The NuScale passive decay heat removal system (DHRS) is capable of transferring core decay heat from either of the two steam generators to isolation condensers immersed in the reactor pool. Feedwater accumulators and long term boiling/condensing heat transfer provide the driving head for DHRS flow. The DHRS is capable of decay heat removal for a minimum of 3 days without pumps or power.

The second passive safety system is the Emergency Core Cooling System (ECCS). The Reactor Vent Valves (RVV) located on the reactor vessel head and the Reactor Recirculation Valves (RRV) located on the sides of the reactor vessel working in conjunction with the Containment Heat Removal System (CHRS) comprise the ECCS. These systems are shown schematically in Figure 4 and provide the means of removing core decay heat in the event that neither the normal feedwater system nor the DHRS is available. It operates by opening the vent valves located on the reactor head. Primary system steam is vented from the reactor vessel into the containment where it condenses on the containment surfaces. The condensate collects in the lower containment region. When the liquid level in the lower containment rises above the top of the recirculation valves, the recirculation valves are opened to provide a natural circulation path from the lower containment through the core and out of the reactor vent valves. The combination of high pressure capability and immersion in water results in a NuScale containment cooling approach that is remarkably simple, compact, and extremely effective.



Fugure 3.The NuScale Decay Heat Removal System (DHRS).

1.3 Stages of Long Term Coolng

The Code of Federal Regulations, specifically 10 CFR 50.46(b)(5) [3] requires that after any calculated successful initial operation of the ECCS, the calculated core temperature shall be maintained at an acceptably low value and decay heat shall be removed for the extended period of time required by the long-lived radioactivity remaining in the core. Simple bounding calculations indicate that the NuScale ECCS can provide long term decay heat removal without the pool cooling system or requiring water addition to the reactor building pool. That is, long term cooling can be achieved without operator actions or external power.

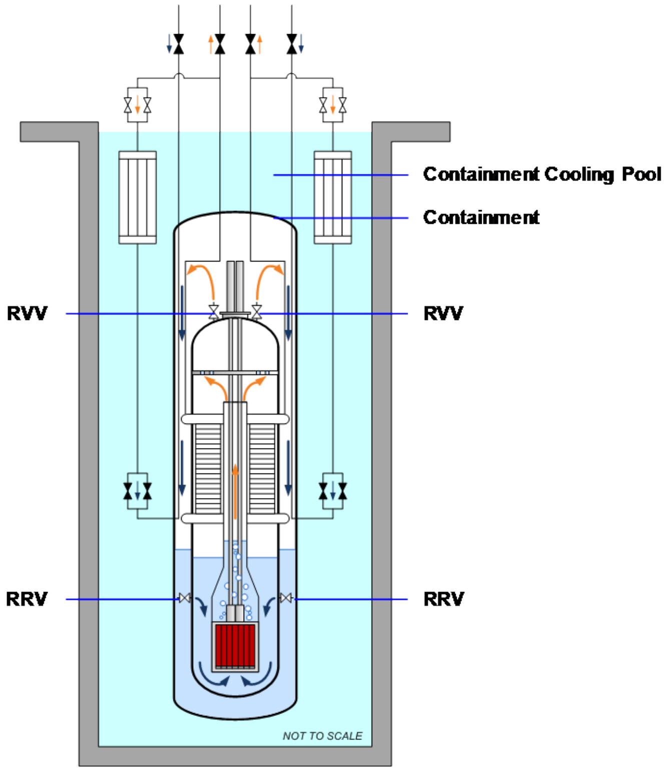


Figure 4.Operation of the NuScale Emergency Core Cooling System and Containment Heat Removal System.

Subsequent to the actuation of the ECCS/CHRS, core decay heat is deposited into the reactor building pool via heat transfer through the containment wall. If the pool cooling system is not available and no water is added to the pool, the liquid level in the pool will drop over time as a result of evaporation, and later, saturated liquid boiling. As a result, the heat transfer mechanisms on the outside surface of the containment will change as the pool liquid level decreases. The internal heat transfer mechanisms would remain the same once the reactor vessel and containment vessel pressures and liquid levels equalize. Figure 5 shows the Long Term Cooling (LTC) phases for the case of no pool cooling or water addition.

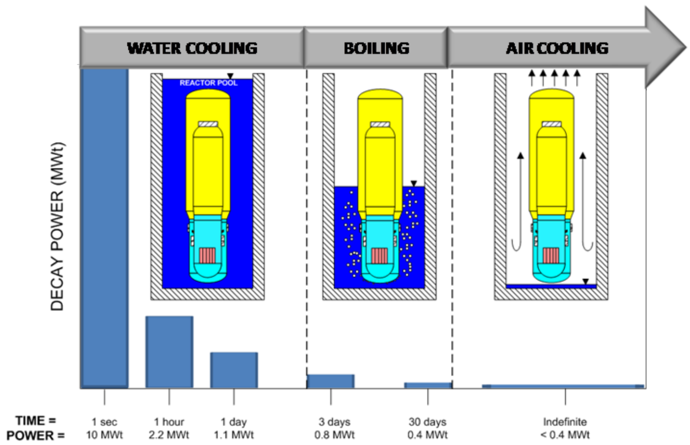


Figure 5. Passive long term cooling provides decay heat removal for an unlimited period.

During the water cooling phase, natural convection heat transfer from the containment external surface to the water causes the pool to reach saturation temperature at atmospheric pressure in about 3 days. From approximately 3 days to 30 days, saturated boiling dominates the heat rejection from the containment to the pool. If no water is added to the pool, it is conservatively estimated that the pool level would reach the bottom of the containment in about 30 days. This calculation conservatively neglects heat transfer to the reactor pool liner and conduction heat transfer to earth. Subsequent to 30 days, natural convection to air and thermal radiation heat transfer from the external surface of the containment are adequate for removing the very low levels of decay heat that would be generated, (i.e., < 400kW). [4]

2. Protection Against Extreme Events

Figure 6 shows a cross-section of the NuScale reactor building which would house up to 12 modules. It reveals a key feature of the design, the containment vessels are submerged in an underground steel-lined concrete pool containing a 30-day supply of cooling water. All of the water needed for safety cooling of the fuel is already in place prior to any event. The underground placement provides significant protection against extreme events, such as earthquakes, floods, tornados and aircraft impact. Table 1 summarizes the protective features.

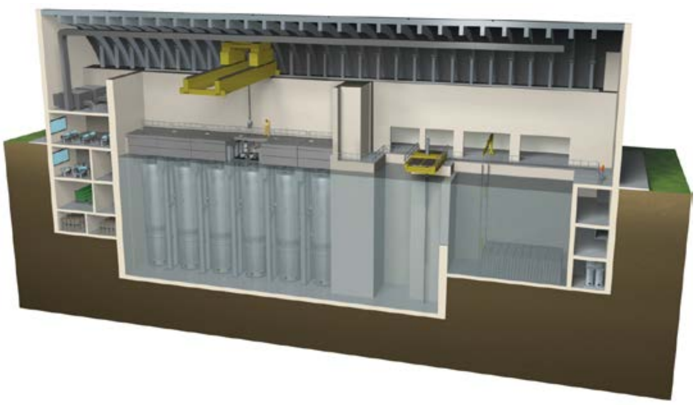


Figure 6. Reactor and containment are submerged in underground steel-lined concrete pool with 30-day supply of cooling water. chapter.

Table 1 Protection against Extreme Events

Events and Threats	NuScale Plant Design Features
Earthquakes, Floods, Tornados, Aircraft Impact	• Deeply embedded reactor building provides robust seismic and external hazards protection.
Complete Station Blackout/ Loss of Offsite Power	• Passively Safe Nuclear Fuel and Containment Cooling Systems do not require onsite power, offsite power or diesel generators for safety.
Emergency Core Cooling	• No external water required for safety. • Containments submerged in underground stainless steel-lined concrete pool filled with 30 day supply of cooling water. • Air cooling adequate for unlimited period of decay heat removal beyond 30 days.
Containment Integrityand Ultimate Heat Sink	• No combustible mixture of hydrogen and oxygen inside containment. • Unlimited performance window: No need for external intervention.
Spent Fuel Pool Integrity and Cooling	• Housed in underground protected structure. • Has approximately 4 times the water volume of conventional spent fuel pools per MW of thermal power. • Accessible supplies of backup water

3. Conclusions

The NuScale design incorporates passive safety systems and a deeply embedded reactor building aimed at providing a very high level of safety and security. The passive safety systems do not rely on onsite or offsite AC power, pumps, or emergency diesel generators to perform their safety function. The NuScale ECCS and CHRS can provide core decay heat removal for an unlimited period without the addition of water or activation of forced cooling systems. It is expected that passive safety systems will play an important role in the evolution of the next generation of nuclear power plants.

Nomenclature

CHRS	Containment Heat Removal System
DHRS	Decay Heat Removal System
ECCS	Emergency Core Cooling System
PWR	Pressurizer Water Reactor
RVV	Reactor Vent Valve
RRV	Reactor Recirculation Valve
UO_2	Uranium Dioxide

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