NuSCALE PLANT SAFETY IN RESPONSE TO EXTREME EVENTS

THERMAL HYDRAULICS

KEYWORDS: *scalable modular reactors, passive safety systems, NuScale power plant*

JOSÉ N. REYES, Jr.

NuScale Power Inc., 1100 N.E. Circle Boulevard, Suite 350, Corvallis, Oregon 97330

Received May 4, 2011
Accepted for Publication October 13, 2011

The extreme events that led to the prolonged electrical power outage and finally to sever damage of four units of the Fukushima nuclear plant have highlighted the importance of ensuring a technical means for stable, long-term cooling of the nuclear fuel and the containment following a complete station blackout. This paper presents an overview of the advanced passive safety systems designed for the NuScale nuclear power plant and their role in addressing extreme events. The NuScale plant may include up to 12 power modules, and each module incorporates a reactor pressure vessel (core, steam generator, and pressurizer) and a containment vessel that surrounds the reactor vessel. During normal operation, each containment vessel 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 30 days of core and containment cooling without adding water. After 30 days, the core decay heat generation is so small that the natural convection heat transfer to air at the outside surface of the containment, coupled with thermal radiation heat transfer, are completely sufficient to remove the core decay heat for an unlimited period. These passive safety systems can perform their function without requiring an external supply of water or electric power. Computational and experimental assessments of the NuScale passive safety systems are being performed at several institutions, including the one-third scale NuScale integral system test facility at Oregon State University.

I. NuSCALE PLANT OVERVIEW

NuScale Power Incorporated is commercializing a scalable modular nuclear power plant comprised of factory-fabricated, 45 MW(electric) power modules that are delivered and installed as local power demand requires. Each module consists of an integrated light water nuclear reactor vessel enclosed in a high-strength containment vessel. The unique passive safety systems provide a remarkably robust response to extreme events leading to prolonged station blackout conditions. Of primary interest to this paper is the long-term cooling of the nuclear fuel, the containment, and the spent fuel pool.

Figure 1 shows a plan view of the reactor building with its adjacent turbine buildings for the 12-module, 540 MW(electric) reference plant. The drawing shows that the reactor pool is common to all the modules. Each power module is connected to its own set of dedicated equipment, including the steam turbine-generator. Because of its smaller size in comparison to traditional light water reactors (LWRs), the steam turbine-generator is easily transported, installed, and maintained. With dedicated equipment for each module, the single–turbine shaft risk of the NuScale plant is significantly reduced as compared to traditional LWRs. Specifically, shutdown of a module for refueling and maintenance, or the occurrence of a single initiating event within the plant, may affect 45 MW(electric) of output but would not halt electrical production for the remainder of the plant.

The 12-module NuScale plant uses an in-line refueling approach in which each module is refueled once every 2 years. Refueling is performed remotely using underwater flange stud tensioning/detensioning tools. That is, refueling operations would occur in a staggered manner at roughly 2-month intervals. During the evolution, a module is physically moved from its operating bay to the refueling bay. The refueling bay is shown in the longitudinal view of the reactor building shown in Fig. 2. Because it is isolated during the refueling

*E-mail: jnr@nuscalepower.com

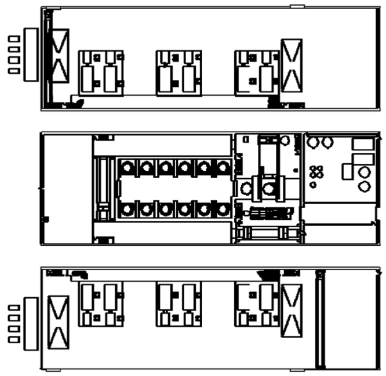

Fig. 1. Layout for the 12-module 540 MW(electric) NuScale power plant.

process, the module refueling can proceed while the plant as a whole continues to generate power. The in-line refueling approach eliminates the need for retaining, training, and establishing security for the large temporary contractor workforce typically used for refueling and maintenance of traditional LWRs. Instead, a small, well-trained team of permanent staff conducts refueling and maintenance tasks on an ongoing basis for the entire NuScale plant.

I.A. Description of a Single Module

Each NuScale power module is designed to produce 160 MW(thermal) of power. It consists of an integrated light water nuclear reactor vessel enclosed in a high-pressure containment vessel. The containment vessel is capable of withstanding internal pressure ≥4.1 MPa (600 psia) during accident scenarios. The configuration of a single module is illustrated in Fig. 3. The entire module is completely immersed in its operating bay and is suspended by trunnions located on the outside of the containment vessel. The trunnions are supported by seismic isolators located in the reactor building pool. The deeply embedded reactor building and the containment support system makes the containment very resilient to seismic motion.

The height and diameter of the containment vessel are roughly 19.8 m (65 ft) and 4.4 m (14.3 ft), respectively. The reactor pressure vessel is 13.7 m (45 ft) high and 2.7 m (9 ft) in diameter. It contains the nuclear core, the helical coil steam generators, and a pressurizer located in the upper region of the pressure vessel. The nominal operating pressure in the pressure vessel is 12.8 MPa (1850 psia). The nuclear core is situated in the lower region of the pressure vessel and consists of an array of approximately half-height 17 × 17 pressurized water reactor (PWR) fuel assemblies with UO_2 fuel with enrichment below 5%.

The core power is controlled using control rod clusters. Water is heated in the nuclear core to produce a low-density fluid that flows upward through the hot-leg riser. The helical coils of the steam generator 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 recirculation piping, and corresponding valves,

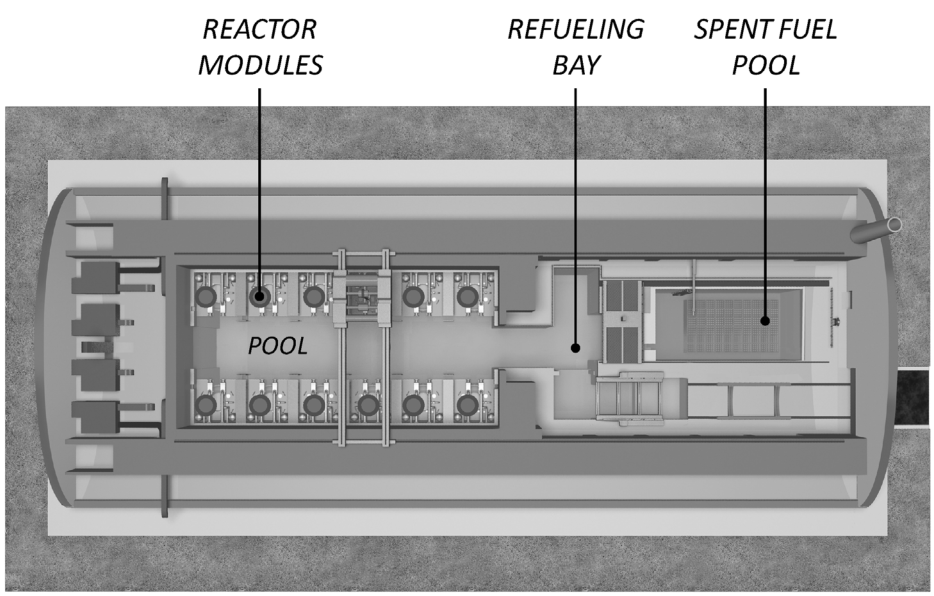

Fig. 2. Top view of reactor building layout for the 12-module 540 MW(electric) NuScale power plant.

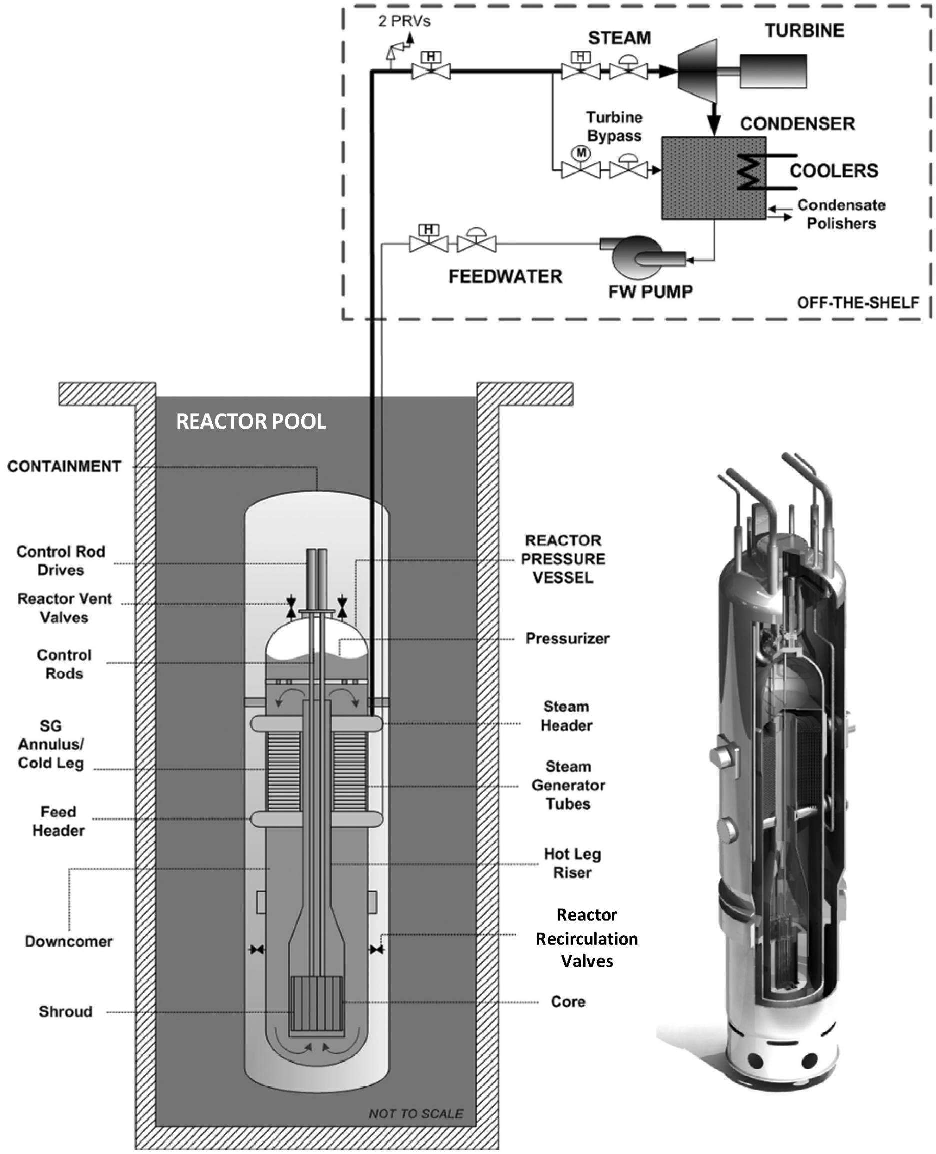

Fig. 3. Schematic view of a NuScale module installed underwater in its bay.

hence eliminating the maintenance and potential for upsets associated with those components. It also reduces the in-house plant electrical utilization that is a hallmark of traditional LWRs that must power large recirculation pumps. The simplicity afforded by the elimination of a recirculation system enhances overall plant safety as well as controlling manufacturing costs.

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. Heating elements and a spray system are located in the integrated pressurizer to provide pressure control.

II. DESIGN FEATURES THAT INHERENTLY ENHANCE SAFETY

The NuScale containment and reactor vessel include several design features that inherently enhance safety. These are shown in Fig. 4. During normal power operation, the containment atmosphere is evacuated to provide an insulating vacuum that significantly reduces the heat loss from the reactor vessel. As a result, the reactor vessel does not require surface insulation. This addresses the U.S. Nuclear Regulatory Commission (NRC) Generic Safety Issue-191 by eliminating the potential for sump screen blockage.[1] Furthermore, the deep vacuum in the containment vessel minimizes the amount of noncondensable gases, thus improving the steam condensation

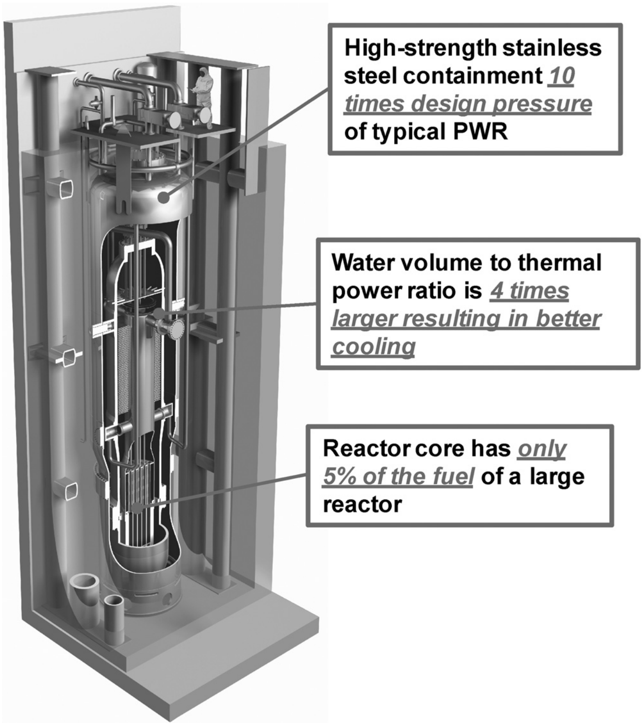

Fig. 4. The NuScale containment and reactor vessel include features that inherently enhance safety.

rates during any sequence where safety valves vent steam into this space.[2,3] Eliminating containment air prevents the creation of a flammable hydrogen-air mixture in the unlikely event of a severe accident (i.e., little or no oxygen) and eliminates the 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 that of a conventional PWR, resulting in better cooling characteristics and a much slower response to thermal transient upsets.

III. PASSIVE SAFETY FEATURES

Each NuScale module uses two independent and redundant 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 (Ref. 4).

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, shown in Fig. 5, 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). It is composed of the reactor vent valves (RVVs) located on the reactor vessel head and the reactor recirculation valves located on the sides of the reactor vessel, working in conjunction with the containment heat removal system (CHRS). These systems, shown schematically in Fig. 6, provide the means

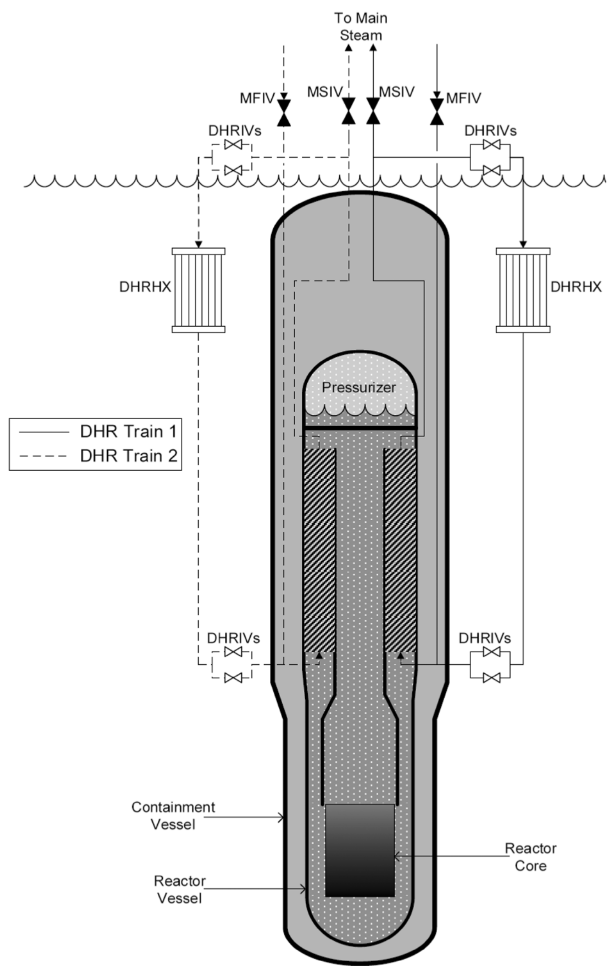

Fig. 5. The NuScale DHRS.

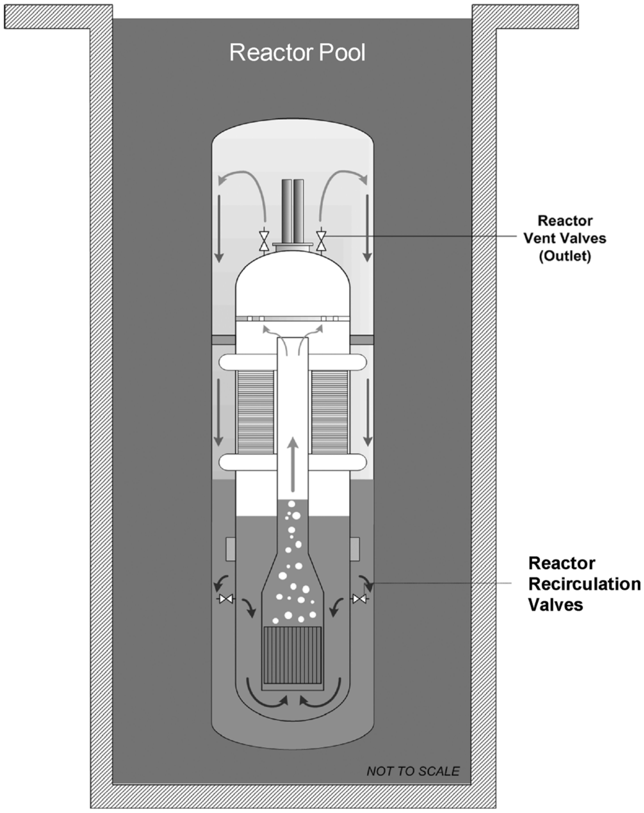

Fig. 6. Operation of the NuScale ECCS and CHRS.

of removing core decay heat when neither the normal feedwater system nor the DHRS is available. The ECCS 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's internal surface. The condensate collects in the lower region of the containment vessel. When the liquid level in the 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 the RVVs. The combination of high-pressure capability and immersion in water results in a NuScale containment cooling and decay heat removal approach that is remarkably simple, compact, and extremely effective.

IV. PROTECTION AGAINST EXTREME EVENTS

Nuclear power plants in the United States are required to have comprehensive procedures and systems to protect the plant against site-specific extreme events such as earthquakes, floods, tornados, and aircraft impact. Loss of all alternating current power may be the primary consequence of such an initiating event; therefore, redundant, independent, and diverse backup power supplies are part of the defense-in-depth approach for all U.S. commercial nuclear power plants, as described in 10 CFR

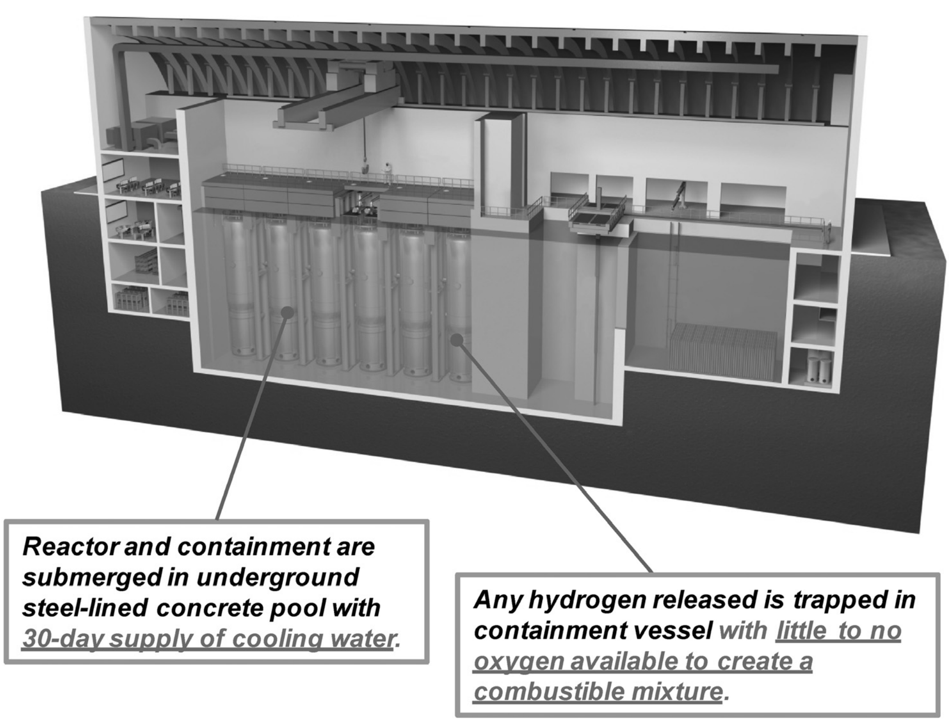

Fig. 7. NuScale reactor building.

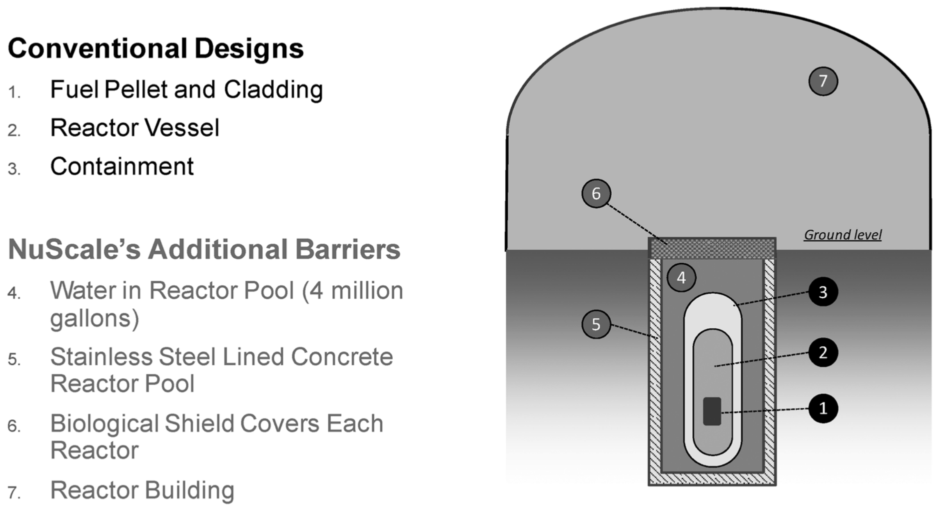

Fig. 8. Additional barriers to fission product release.

50.63 (Ref. 5). This section briefly outlines the NuScale plant's protection against extreme events.

IV.A. Reactor Building with Deeply Embedded Reinforced Pools

Figure 7 shows a cross section of the 12-module NuScale reactor building. The key feature of the design is that the containment vessels are submerged in deeply embedded stainless steel–lined concrete pools containing a 30-day supply of cooling water. As a result, all of the water needed for cooling of the reactors 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. In general, underground structures exhibit superior

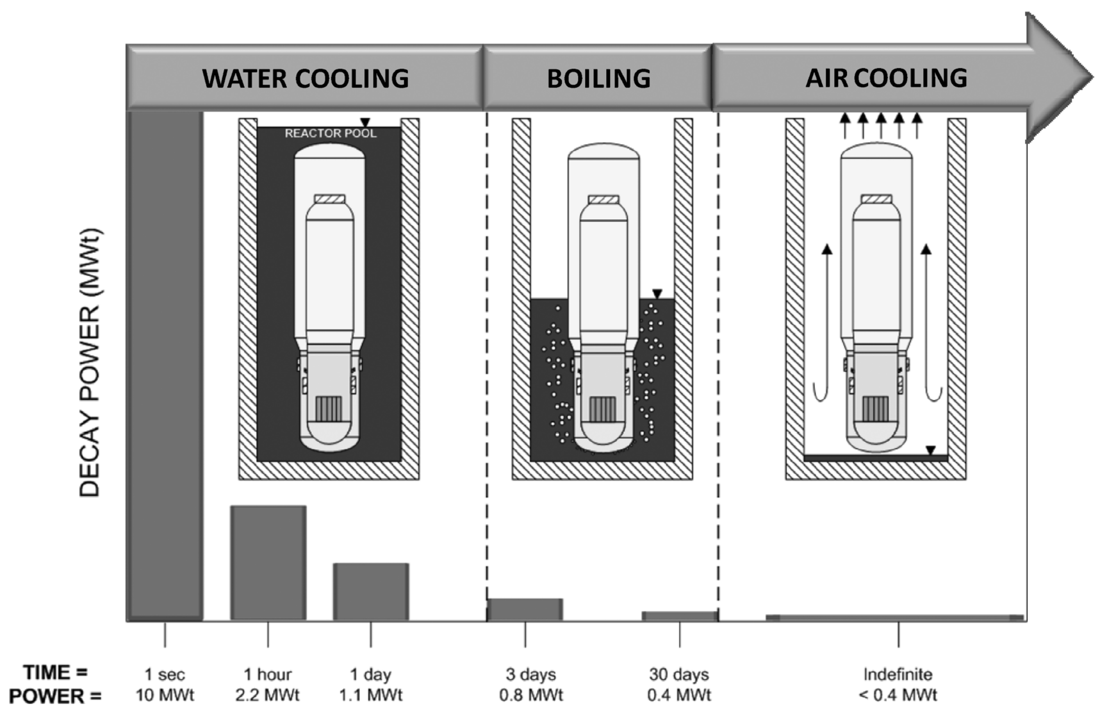

Fig. 9. Passive LTC provides decay heat removal for an unlimited period.

earthquake performance because they are constrained and supported by the surrounding medium (soil or rock). Their motion is limited to that of the medium, and the structure is less likely to experience vibration amplification (see Ref. 6).

All nuclear power plants offer significant barriers to fission product release in the event of a severe accident. This includes the fuel cladding, the steel reactor vessel, and the steel-lined, prestressed, posttensioned concrete containment. The schematic in Fig. 8 shows that the NuScale design includes these three barriers and adds four additional fission product barriers. Because the NuScale containment resides underwater, the water can scrub fission products in the event that they are released from the containment. Similarly, the stainless steel–lined underground concrete pool structure prevents fission products from reaching the soil. Each module is covered by a large concrete biological shield that can capture fission gases. Lastly, the reactor building has independent and redundant air handling and filtering systems that can also be used to capture fission products.

IV.B. Long-Term Cooling Without Power or External Water Supply

Federal regulations [10 CFR 50.46(b)(5)] require 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."[7]

As shown in Fig. 9, the NuScale design could provide long-term cooling (LTC) for the case of a complete station blackout without additional cooling or water addition to the reactor pool. Figure 9 illustrates three distinct phases of LTC defined in terms of the heat transfer mechanisms on the outside surface of the containment vessel and also shows the amount of decay heat required to be removed during each phase. It is important to note that because of the relatively low initial power in each module, at the end of the first second after reactor shutdown, the core decay heat is only 10 MW(thermal) per module; i.e., it is less than the operating power of some university research reactors (see Ref. 8). During the first phase of LTC, water cooling, the containment is completely immersed in water, and at least one train of the passive ECCS/CHRS would be in operation. The liquid levels and pressures inside the containment and reactor vessels would have equalized with core decay heat being deposited into the reactor building pool via natural convection heat transfer from the containment outside surface. 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. It is conservatively estimated that the liquid level in the pool would be at the top of the containment in about 3 days. By the end of phase 1, $<$1 MW(thermal) of core heat needs to be rejected per module.

The second phase of LTC is defined as the period during which the liquid level in the pool is below the top of containment and above the bottom of containment. The second phase is conservatively estimated to extend from ~3 to 30 days. During this period, 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 ~30 days. This calculation very conservatively neglects the convective heat transfer from the uncovered portion of the containment surface, convective and thermal radiation heat transfer to the reactor pool

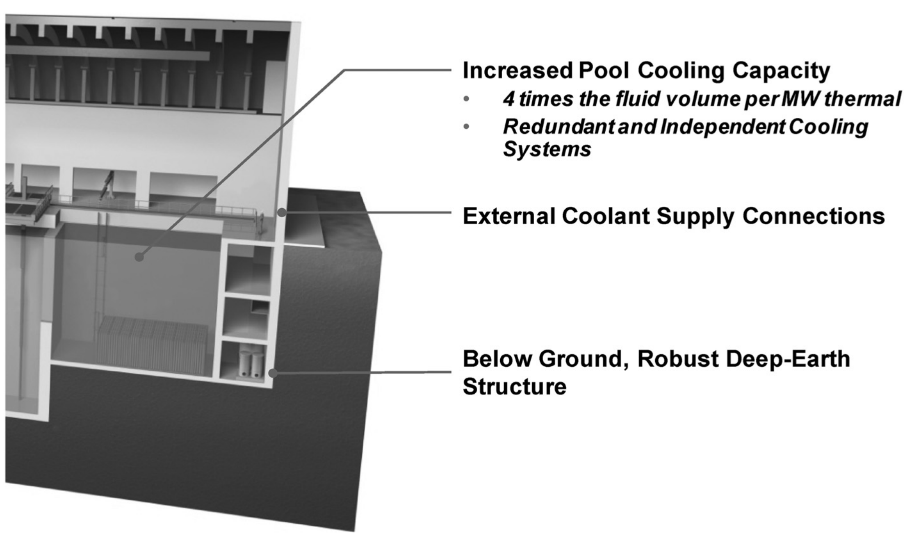

Fig. 10. SFP safety features.

TABLE I

NuScale Design Features Relevant to the Fukushima Cooling Issues

	Fukushima	NuScale Plant
Reactor and containment	Emergency diesel generators required	Emergency diesel generators not required
	External supply of water required	Containment immersed in 30-day supply of water
	Coolant supply pumps required	Coolant supply pumps not required
	Forced flow of water required for LTC	LTC (beyond 30 days) by natural convection to air
Spent fuel pool	Water cooling of spent fuel	Extended cooling capability: four times the water of conventional spent fuel pools per MW power
	Elevated SFP	Deeply embedded SFP
	Limited access to backup supply of water	Accessible backup supplies of water

liner, and conduction heat transfer to earth. At the end of the second phase of LTC, the core power is estimated to be 0.4 MW(thermal) per module.

After 30 days, in phase 3 of LTC, 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., $<$400 kW(thermal) per module].

IV.C. Spent Fuel Pool Design

NuScale implements a spent fuel pool (SFP) design that incorporates numerous safety features, as shown in Fig. 10. First, the SFP is a deep-earth structure that is housed in a seismically robust reactor building. The SFP walls are located underground; hence, they are shielded from tsunami wave impact and damage from moving debris. The stainless steel pool liners are independent of the concrete walls. This provides a space for leak detection and retains pool integrity during events that could produce cracks in the concrete walls. The construction of the SFP below ground in an engineered medium limits the potential for fluid leakage.

Second, the SFP has increased cooling capacity because it has four times greater water volume per MW(thermal) of decay heat than a conventional LWR. The pool can accommodate high-density fuel racks that meet NRC and Electric Power Research Institute requirements or low-density racks that meet NRC requirements and also offer the potential for long-term air cooling. It uses redundant, cross-connected reactor and refueling pool heat exchangers to provide full backup cooling to the SFP. Finally, the SFP has auxiliary external water supply connections that are easily accessible to plant personnel and away from potential high-radiation zones.

IV.D. Comparison of NuScale Design Features to Fukushima Cooling Issues

Table I compares briefly the NuScale design features related to the cooling issues faced at the Fukushima plants. As shown in Table I, the fact that no external power or water supply is required to cool the nuclear fuel or containment greatly simplifies a NuScale plant's response to extreme events leading to station blackout conditions. Similarly, the spent fuel pool design provides extended cooling and the opportunity to easily add water from other plant sources if it is needed.

V. STATE-OF-THE-ART ANALYSES AND TEST PROGRAMS

NuScale and its contractor, GSE, have developed a state-of-the-art simulator for a single NuScale power module. This effort currently includes detailed thermal-hydraulic and neutronic modeling to predict the real-time behavior of a single module with all of the safety systems and balance of plant for power production. Figure 11 shows the configuration being used for simulator-assisted engineering of the plant features. The construction of a full-scope main control room simulator (with 12 modules) in support of the NuScale human factors engineering study is under way.

NuScale has also established a comprehensive test program to benchmark its computer codes, to ensure the adequacy of the passive safety systems, and to reduce commercial risk for any first-of-a-kind components. One of these programs is the NuScale integral system test program at the Oregon State University (OSU). The test facility, shown in Fig. 12, models the integrated reactor vessel, the containment vessel, the reactor building pool, the ECCS,

Fig. 11. NuScale/GSE simulator for a single power module.

Fig. 12. NuScale integral system test facility at OSU.

and the safety system actuation logic. The reactor vessel includes the internal helical coil steam generator, an electrically heated fuel bundle simulator, internals, and a pressurizer. The test facility is being used to obtain test data to benchmark the NuScale safety analysis computer codes in support of the design certification effort.

Tests conducted in 2003 demonstrated the functionality of the ECCS and CHRS operation.[9] Figure 13 shows pressure histories measured in the reactor vessel and containment for a test scenario initiated by the inadvertent opening of an RVV. As can be seen, the fluid pressure in the reactor decreased rapidly and the containment pressure increased until equilibrium was reached. The heat transfer to the pool continued to remove heat generated in the reactor vessel, causing the system temperatures and pressures to decrease over time. As shown in Fig. 14, the collapsed liquid level in the reactor vessel remained well above the top of the core throughout the entire transient. A large variety of tests are being conducted at OSU to assess the LTC capability of the ECCS/CHRS.

VI. CONCLUSIONS

It is recognized that the extreme events leading to the long-term loss of electrical power at four units (out of six) of the Fukushima plant were beyond the design basis for the plant. The remarkable efforts of the plant operators and emergency responders to provide temporary power, identify and redirect water supplies, and augment fission product barriers mitigated the consequences of this severe accident. Their actions reflect their high-level training and dedication.

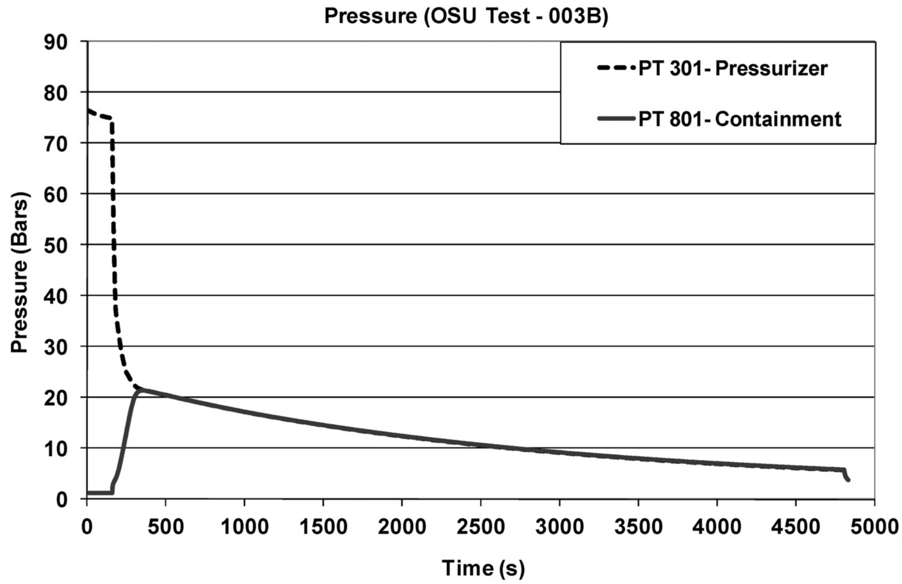

Fig. 13. Pressure history measured for the reactor vessel and containment following the inadvertent opening of an RVV.

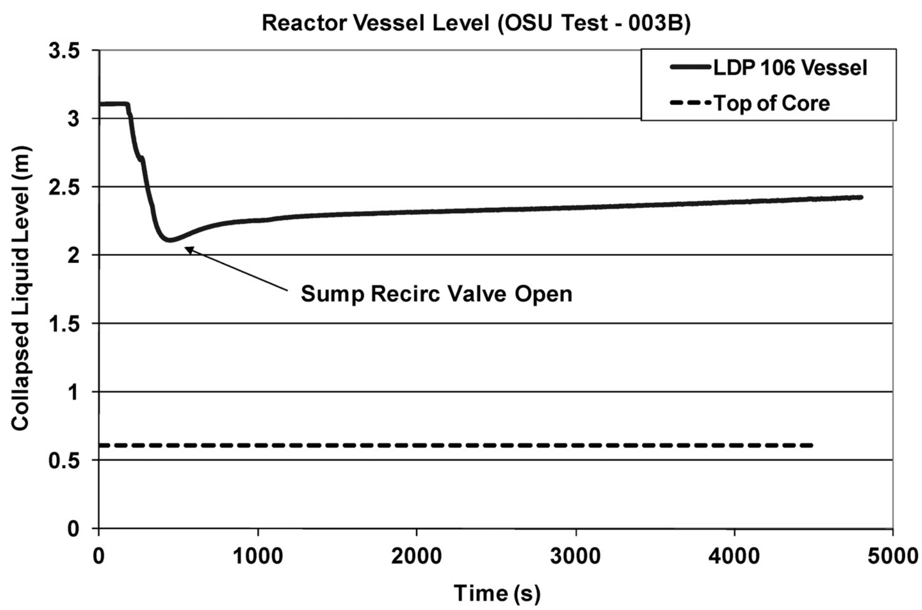

Fig. 14. Collapsed liquid level history measured for the reactor vessel following the inadvertent opening of an RVV.

The NuScale design uses an advanced approach to provide LTC, namely, passive safety systems and placement of the entire containment in an underground pool of water. The aim was to ensure a very high level of safety and security. The passive safety systems do not rely on on-site or off-site electrical power, or 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.

REFERENCES

1. "Potential Impact of Debris Blockage on Emergency Recirculation During Design Basis Accidents at Pressurized-Water Reactors," GL 2004-02, U.S. Nuclear Regulatory Commission (Sep. 13, 2004).

2. L. E. HERRANZ, M. H. ANDERSON, and M. L. CORRADINI, "A Diffusion Layer Model for Steam Condensation Within the AP600 Containment," *Nucl. Eng. Des.*, **183**, 133 (1998).

3. M. H. ANDERSON, L. E. HERRANZ, and M. L. CORRADINI, "Experimental Analysis of Heat Transfer Within the AP600 Containment Under Postulated Accident Conditions," *Nucl. Eng. Des.*, **185**, 153 (1998).

4. "Safety Related Terms for Advanced Nuclear Plants," IAEA-TECDOC-626, International Atomic Energy Agency (Sep. 1991).

5. *Code of Federal Regulations*, Title 10, "Energy," Part 50, "Domestic Licensing of Production and Utilization Facilities," Sec. 50.63, "Loss of All Alternating Current Power," U.S. Nuclear Regulatory Commission (Aug. 28, 2007).

6. J.-N. WANG, "Seismic Design of Tunnels: A Simple State-of-the-Art Design Approach," Parsons Brinckerhoff Inc. New York (1993).

7. *Code of Federal Regulations*, Title 10, "Energy, Part 50, "Domestic Licensing of Production and Utilization Facilities," Sec. 50.46(b)(5), "Acceptance Criteria for Emergency Core Cooling Systems for Light-Water Nuclear Power Reactors," U.S. Nuclear Regulatory Commission (Aug. 28, 2007).

8. ANSI/ANS-5.1-1994, "Decay Heat in Light Water Reactors," American National Standard, American Nuclear Society, LaGrange Park, Illinois.

9. S. M. MODRO et al., "Multi-Application Small Light Water Reactor Final Report," INEEL/EXT-04-01626, Idaho National Engineering and Environmental Laboratory Bechtel BWXT Idaho (Dec. 2003).