

NuScale Power Modular and Scalable Reactor

Overview

Full Name	NuScale Power Modular and Scalable Reactor
Acronym	NuScale
Reactor type	Integral Pressurized Water Reactor
Coolant	Light Water
Moderator	Light Water
Neutron spectrum	Thermal neutrons
Thermal Capacity	1920 MW(th) (12 module plant)
Electrical Capacity	540 MW(e) (12 module plant)
Design Organization	NuScale Power
Last Update	July 2013

NuScale Power Modular and Scalable Reactor

1. Introduction

In 2003, Oregon State University, in collaboration with the Idaho National Engineering Laboratory, and Nexant-Bechtel, completed a project to develop a preliminary design for an innovative reactor called the “Multi-Application Small Light Water Reactor”, or “MASLWR.” The final results were published by the project sponsor, the U.S. Department of Energy and a description of the MASLWR design was included in IAEA-TECDOC-1536 [Ref. 1].

In 2007, NuScale Power Inc. was formed to commercialize the concept, and MASLWR was renamed to the NuScale Plant to reflect the significant improvements made to the original design. In early 2008, NuScale Power notified the U.S. Nuclear Regulatory Commission of its intent to begin Pre-Application discussions aimed at submitting an application for Design Certification of a twelve-module NuScale Power Plant. Fluor Corporation became the majority investor of NuScale Power in 2011 and will provide engineering, procurement and construction services for plant deployments.

A NuScale plant consists of 1 to 12 independent modules, each capable of producing a net electric power of 45 MWe. Each module includes an integral Pressurized Light Water Reactor operated under natural circulation primary flow conditions. Each reactor is housed within its own high pressure containment vessel which is submerged underwater in a stainless steel lined concrete pool. The following table summarizes the key features of the NuScale plant design.

Summarized Technical Data
NuScale Power Modular and Scalable Reactor

General plant data (Multi-Module Plant)		
Number of Modules	12	
Power plant output, net	540	MW(e)
General plant data (Single-Module)		
Reactor thermal output	160	MW(th)
Power plant output, net	45	MW(e)
Power plant efficiency, gross	>30.0	%
Mode of operation	Base Load	
Plant design life	60	Years
Plant availability target	>95	%
Primary Coolant material	Light water	
Power Circuit Coolant material	Light water	
Moderator material, if applicable	Light water	
Type of Cycle	Indirect	
Thermodynamic Cycle	Rankine	
Economic goals		
Mode of deployment	Distributed or Centralized	
Reactor Core		
Active core height	2.0	m
Fuel material	UO ₂ Ceramic Pellets	
Fuel element type	17 x 17	
Cladding material	Zircaloy-4 or Advanced Cladding	

Lattice geometry	Square Array	
Enrichment of reloaded fuel in equilibrium core	<4.95	Weight %
Fuel cycle length	24	Months
Average discharge burn-up of fuel	> 30	MWd/kg
Burnable absorber (mode of use/material)	Gadolinia	
Mode of reactivity control	Control Rods, Boric Acid	
Mode of reactor shut down	Control rods	
Primary Coolant System		
Reactor operating pressure	12.76	MPa
Power Conversion system		
Working medium	Steam	
Reactor Vessel		
Outer diameter of cylindrical shell	~2830	mm
Vessel Height	~20,000	mm
Steam generator or Heat Exchanger of the Power Circuit		
Type	Helical Coil	
Number	2	
Mode of operation	Secondary coolant inside tubes	
Primary Circulation System		
Circulation Type	Natural Circulation	
Number of Pumps	None	
Pressurizer, if applicable		
Type	Internal Electric Heaters	
Active devices used	Heaters and Sprays	
Primary containment		
Type	Deep Vacuum Containment	
Overall form (spherical/cylindrical)	Cylindrical	
Dimensions (diameter/height)	~4,600/~24,500	mm
Design pressure	>5.5	MPa
Residual heat removal systems		
Active/passive systems	Passive DHRS/ECCS	

Plant Configuration and Layout		
Plant configuration options	Land Based Multi-module Plant 1-12 Power Modules	
Surface area of the plant site	~160,000	m ²
Elevation or underground embedding of the nuclear island	Underground Containment, Control Room, Spent Fuel Pool	
Core catcher	Containment submerged underwater in SS lined concrete pool	
Protection against aircraft crash	Underground Containment, Control Room, Spent Fuel Pool; Seismic Category 1 Reactor Building	

2. Description of the Nuclear Systems

The basic configuration of a single NuScale reactor module is shown schematically in Figure 1.

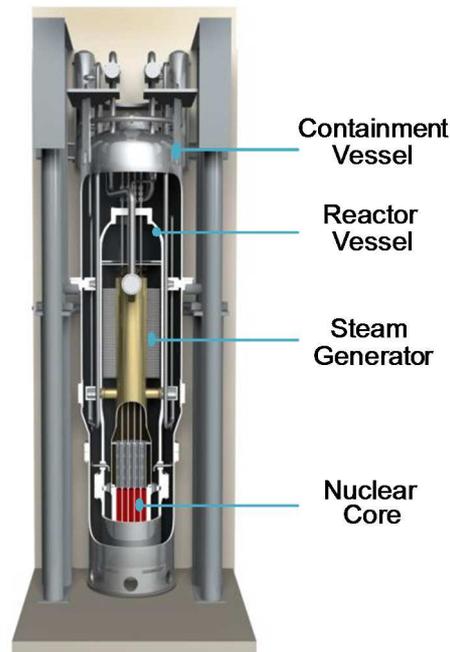


Figure 1. Description of a NuScale Module (NSSS inside Containment) shown submerged in water in a steel lined concrete pool

The integrated nuclear reactor pressure vessel contains the nuclear core, a helical coil steam generator, and a pressurizer. It is approximately 20.0 m (65 ft) long by 2.8 m (9.3 ft) in diameter. The nuclear core consists of an array of reduced height LWR fuel assemblies and control rod clusters at standard enrichments. 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. A set of pressurizer heaters is located in the upper head of the vessel to provide pressure control. The entire Nuclear Steam Supply System (NSSS) is enclosed in a steel containment that is 24.6 m (80 ft) long by 4.6 m (15 ft) in diameter.

There are five essential features of the NuScale plant, which in combination, distinguish it from the many other small nuclear plants being developed today. The first is its compact size. The NSSS can be entirely prefabricated off site and shipped by rail, truck or barge. At this size, it can be fabricated by mid-size domestic suppliers, avoiding the international choke point for forgings for conventional large plants.

Second, the nuclear core is cooled 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, 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.

Third, the design relies on well-established light water reactor technology. The NuScale plant can be licensed within the existing LWR regulatory framework, drawing on a vast body of established R&D, proven codes and methods, and existing regulatory standards.

Fourth, the NuScale design is supported by a one-third scale, electrically heated integral test facility which operates at full pressure and temperature. Operation of an integral test facility for such a non-conventional design is highly useful in seeking regulatory approval from governing bodies such as the U.S. Nuclear Regulatory Commission (NRC). Customers will also want assurance from integral facility tests that the plant will perform as predicted. This prototype test facility will provide the necessary supporting data required for licensing.

Finally, the NuScale design is the only SMR that utilizes a compact movable modular containment, in contrast to a traditional cast in-place concrete design. Similar to the reactor vessel, the use of a compact containment that is prefabricated off site and shipped by rail, truck or barge, enhances the economics and deployment flexibility.

This unique set of features, specifically the synergy created by plant simplicity, reliance on existing light water technology, and the availability of an integral test facility, all combine to position the NuScale plant for early deployment.

Modular configuration

As can be seen in Figure 2, the NuScale module is located below grade in a pool of water. The water serves multiple purposes. First, it provides passive containment cooling and decay heat removal. That is, the pool provides a heat sink with a capacity to absorb all the decay heat produced by a fully mature core for greater than 30 days. Second, it provides a means of dampening seismic events. Third, it provides an additional fission product barrier. Fourth, it provides radiation shielding outside containment. Last, the below grade pool provides physical security. Each power unit has its own dedicated turbine-generator set.

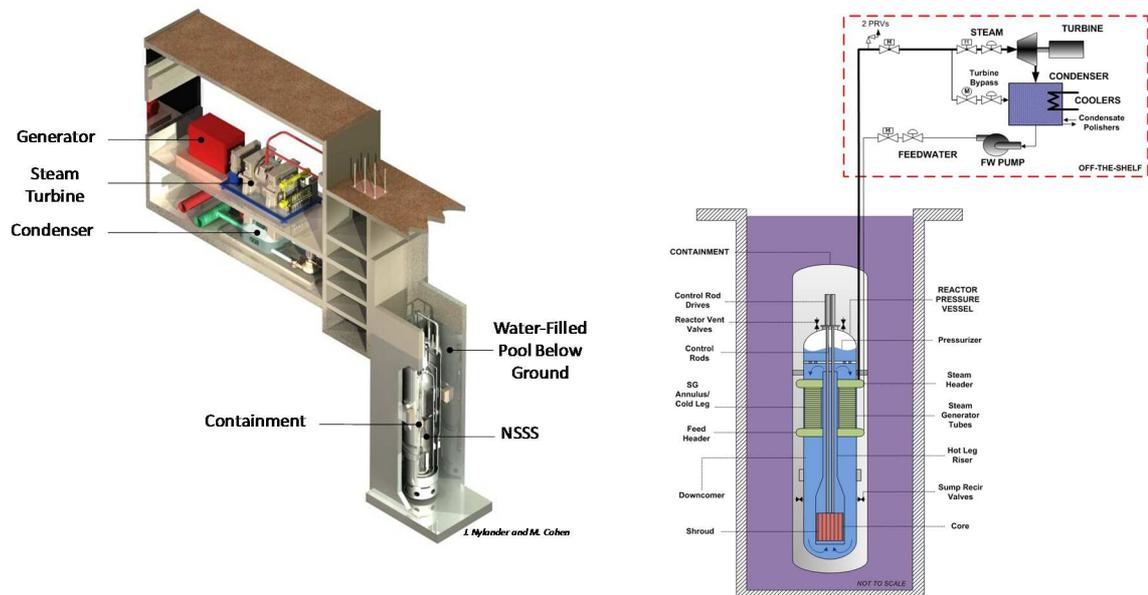


Figure 2. Description of a Single NuScale Power Unit.

3. Description of Safety Concept

The NuScale plant includes a comprehensive set of engineered safety features designed to provide stable long term nuclear core cooling under all conditions, as well as severe accident mitigation. They include a high pressure containment vessel, two passive decay heat removal and containment heat removal systems, and severe accident mitigation. These safety systems are briefly described in the sections that follow.

High Pressure Containment

The containment vessel has several features that distinguish it from existing containment designs. 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. Further, by eliminating containment air, it prevents the creation of a combustible hydrogen mixture in the unlikely event of a severe accident (i.e., little to no oxygen), and eliminates corrosion and humidity problems inside containment, and eliminates the need for hydrogen recombiners. Finally, because of its relatively small diameter, it has been designed for a maximum pressure of approximately 5.5 MPa (800 psia). As a result, the equilibrium pressure between the reactor and the containment vessels in the event of a small break LOCA is achieved within a few minutes and will always be below the containment design pressure.

Passive Safety Systems

Each NuScale module has its own set of independent passive safety systems.[2] As shown in Figure 1, the entire NSSS including its containment, is immersed in a pool of water capable of absorbing all decay heat generated following a reactor shutdown for greater than 30 days followed by air cooling for an unlimited length of time. The water is contained in a stainless steel lined concrete structure that is entirely below grade.

Each NuScale module includes two redundant passive safety systems to provide pathways for decay heat to reach the containment pool: the Decay Heat Removal System (DHRS) and the Emergency Core Cooling System (ECCS). These systems do not require external power for actuation. The DHRS uses either of the two independent helical coil steam generator tube bundles to transfer heat generated within the core to the containment pool.

The ECCS, shown in Figure 3, provides a means of removing core decay heat in the event the steam generator tube bundles are not 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 (sump). When the liquid level in the containment sump rises above the top of the recirculation valves, the recirculation valves are opened to provide a natural circulation path from the sump through the core and out of the reactor vent valves.

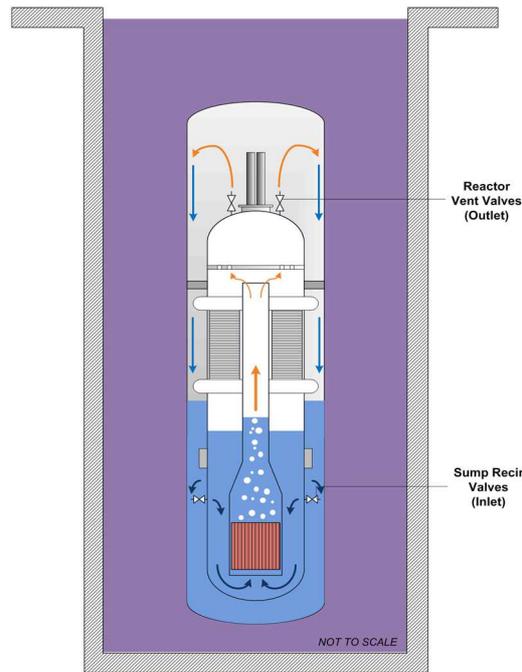


Figure 3. Description of the Containment Heat Removal System (CHRS)

The integral configuration eliminates the traditional Large Break Loss of Cooling Accident (LOCA) by design. For design basis small break assumptions, there is no scenario in which the core becomes exposed or uncovered – it will always be under water. Thus cooling pathways are always available to remove decay heat. Because of the assured heat removal path and the fail-safe nature of the ECCS valves, which passively open upon loss of power, the reactor can be safely cooled for an unlimited time with no AC or DC power, no operator action, and no additional water.

Severe Accident Mitigation Design Features

The NuScale plant design offers significant severe accident mitigation features. First, each module has a smaller fuel inventory and therefore a reduced source term. The containment vacuum eliminates the need for combustible gas control inside containment (little or no oxygen). The steel containment immersed in a stainless steel lined pool eliminates the potential for molten concrete coolant interactions. The ability to reliably equilibrate containment and reactor pressure prevents the possibility of a high-pressure “corium” melt ejection. Lastly, the NuScale plant builds on defense-in-depth by including additional fission product barriers. As with conventional large light water designs, the fuel pellet, cladding, reactor vessel, and containment prevent transport of fission products to the outside atmosphere. The NuScale design provides additional barriers which further reduce the potential for severe accident releases, including: the containment cooling pool, the stainless steel lined containment pool structure, biological shield, and finally the reactor building.

The results of the preliminary Probabilistic Risk Assessment studies performed by NuScale are included in Figure 4. It shows an internal events core damage frequency (CDF) of less than 10^{-8} per reactor per year. The independence of each module, the simplicity of the design, its passive safety features, small source term, and additional fission product barriers suggest that the NuScale plant will have a Large Release Fraction (LRF) well below that of existing large nuclear plants. This combination of attributes offers significant advantages for emergency planning and response.

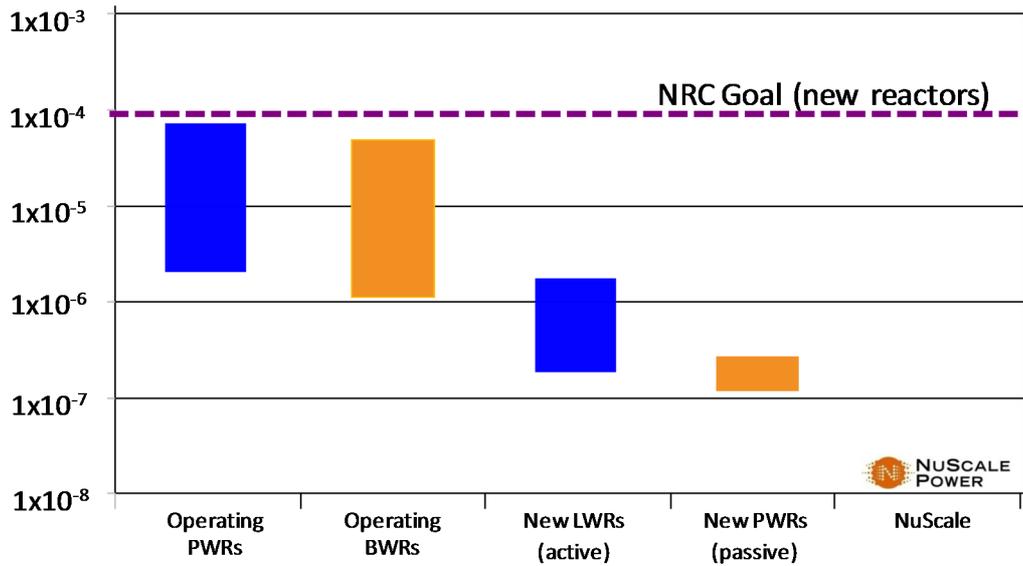


Figure 4. NuScale CDF for internal events compared to NRC Goal described in NRC White Paper, Implementation of Risk Metrics for New Reactors, D. Dube 2/12/09

NuScale Integral System Test Facility

As part of the original research effort, a scaling analysis was used to guide the design, construction and operation of a 1/3-scale, full-pressure and full-temperature integral system test facility shown in Figure 6. NuScale, through its technology transfer agreement with Oregon State University (OSU), has exclusive use of the test facility. The NuScale Integral System test facility is being used to evaluate design improvements, and to conduct integral system tests for NRC certification. OSU has significant testing capability, having performed certification tests for the U.S. Department of Energy (DOE) and for the U.S. NRC for the AP600 and AP1000 designs under 10 CFR 50 Appendix B, NQA-1, and 10 CFR 21.



Figure 5. NuScale Integral System Test Facility at OSU.

Figures 6 and 7 present data for a “Small Break” stuck-open reactor vent valve test conducted in the test facility. The initiating event for this test was essentially identical to that for the accident at Three Mile Island. However, as can be seen from the measured data, the results

were significantly different and the accident was completely mitigated without requiring external power or operator actions. Figure 6 shows reactor pressure and containment pressure reaching equilibrium followed by long term cooling and continued containment and core cooling. Complete cooling was achieved using only the ECCS. The DHRS was not implemented in this test. As expected, water accumulated in the space between the pressure vessel and the containment and was not lost to the system. This is verified in Figure 7 which shows that the collapsed liquid level remained well above the top of the core throughout the entire transient.

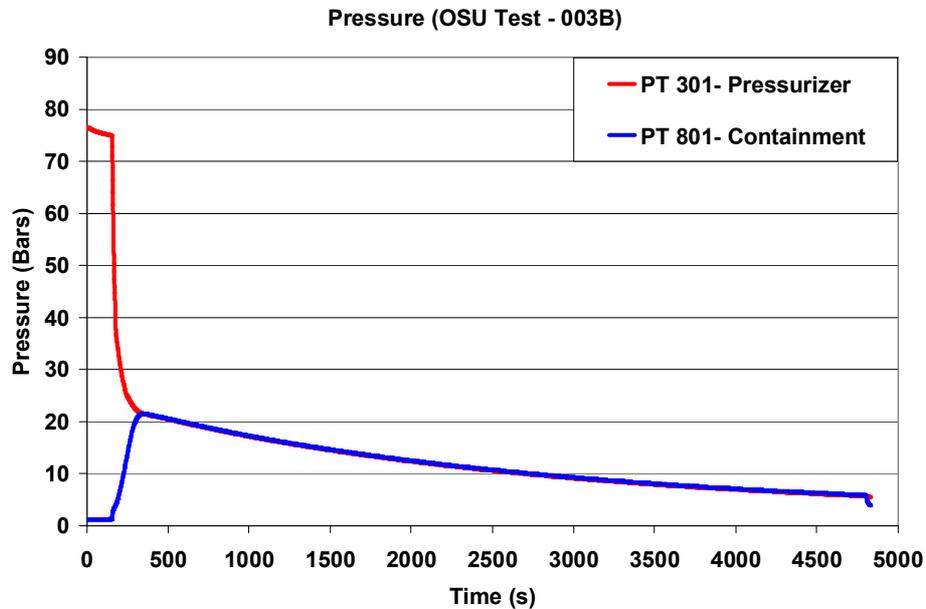


Figure 6. Pressurizer and containment pressure measured for Test OSU-003B.

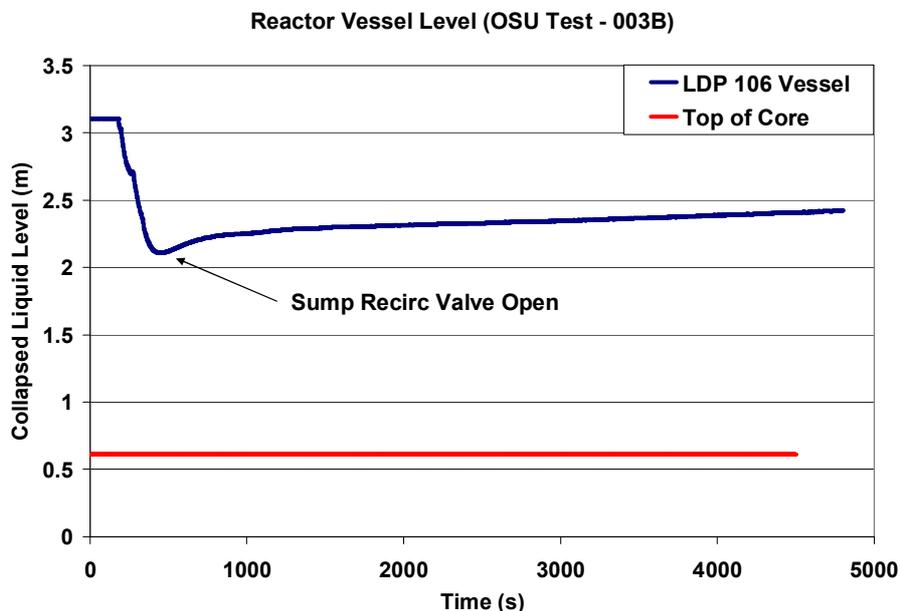


Figure 7. Collapsed liquid level measured in the reactor vessel for Test OSU-003B.

4. Security

From a plant security perspective, a configuration in which the entire NSSS, the containment, the control room and the spent fuel pool are all located below grade offers a low profile and

facilitates design features which provide resistance to airplane or other potential security threats. Sealed underwater containments provide additional barriers during operation.

5. Description of turbine-generator systems

Each NuScale reactor would implement a small 45MW(e) conventional steam turbine generator set optimized to NuScale steam generator outlet conditions. These are readily available and widely used in the fossil fuel power generation industry and can be dedicated for service in nuclear plants. The small size allows for air cooling of the generator, thus avoiding maintenance and safety issues associated with hydrogen cooling of the generator.

6. Electrical and I&C systems

A unique feature of a NuScale multi-module plant is the control room strategy. Because of the reduced operating requirements afforded by the simplicity of the design and the advancement in digital controls, it is proposed that one operator would control multiple reactors. Comprehensive human factors engineering and human/system interface studies are underway to determine the optimum number of reactors that can be effectively and safely controlled by a single operator and a control room simulator has been constructed to provide a technical basis for the selected strategy (shown in Figure 8).

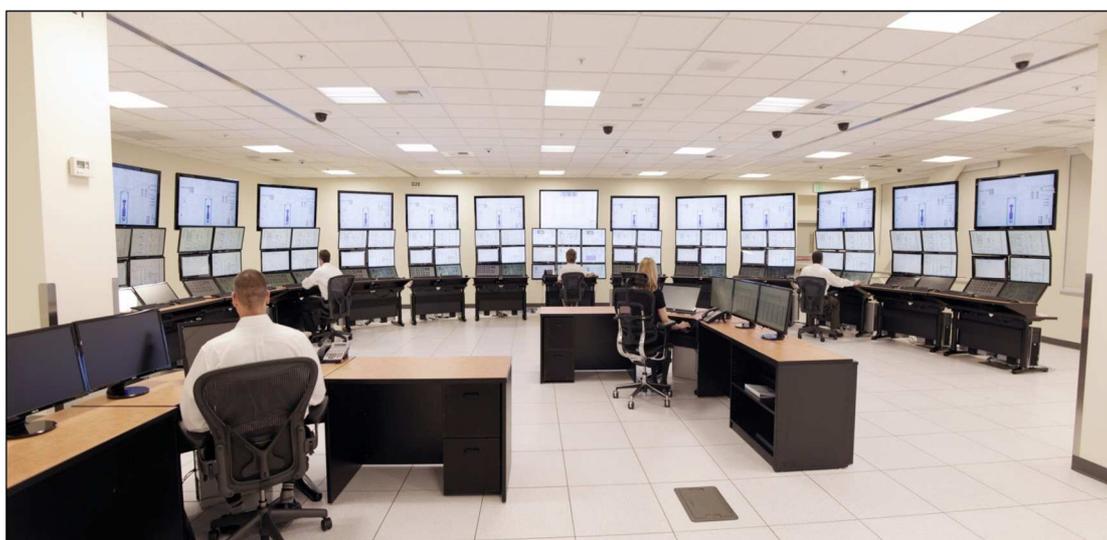


Figure 8 Control Room Simulator Facility for developing operator staffing strategy.

8. Spent Fuel and Waste Management

The multi-module NuScale plant spent fuel pool consists of a steel lined concrete pool located underground. It is designed with the capability of storing and cooling all of the fuel offloaded from 12 modules, as well as an additional 10 years of used nuclear fuel. After 10 years of storage in the spent fuel pool, air-cooled interim storage is possible as with conventional nuclear plants. By staying with well-known fuel technology, new challenges are not introduced to the nuclear fuel cycle.

9. Plant layout

A plan view of a layout showing a 12 module array with a total capacity of 540 MW(e) is shown in Figure 9. The layout shows a reactor building which houses the modules, a turbine building, and a separate refueling building. The refueling building also houses the spent fuel

storage pool. Each module resides under a biological shield in a three-sided bay that is open to a common, stainless-steel lined, pool.

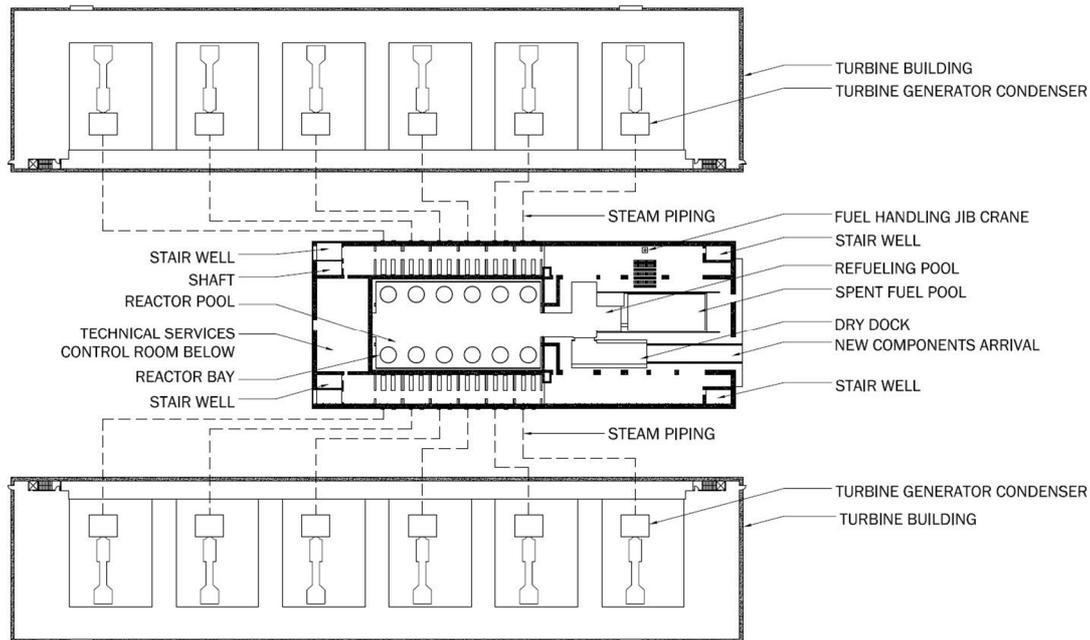


Figure 9. Example of a 12-Unit (540 MWe) NuScale Power Plant.

Refueling a Multi-Module Plant

The configuration shown in Figure 10 offers significant economic advantages. First, it eliminates single shaft risk. That is, the temporary shutdown of a single unit does not require shutdown of the entire plant. Second, the layout permits refueling to be completed in a single module while the other modules continue to generate power. This staggered refueling of individual modules can be done by a small, well-trained, permanent team rather than employing a large temporary workforce. Refueling operations could be conducted throughout the year while keeping the remaining modules online. In addition, skid mounted turbine-generator sets and ample lay down areas in the turbine building permit ease of maintenance and turbine replacement to reduce single unit down-times. Figure 11 shows an example building layout for a 12 module plant. It includes two independent turbine buildings each housing 6 steam turbine generator sets, a central reactor building which houses all of the modules, 2 sets of forced air evaporative coolers, and supporting electrical and mechanical equipment.

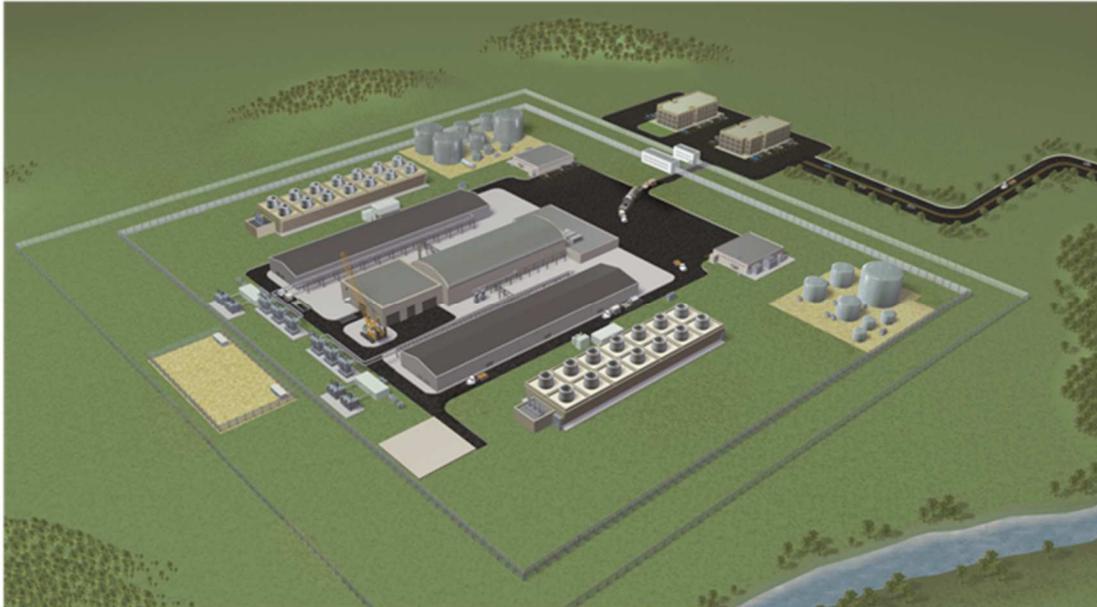


Figure 10. Example Layout of a 12-Unit (540 MWe) NuScale Power Plant.

10. Plant Performance

The NuScale design has been informed by the use of Probabilistic Risk Assessment studies, four expert panel reviews for Phenomena Identification Ranking Table (PIRT) development, and external contractors. Because of the reduced number of plant components, simplicity of operation and high reliability systems, a NuScale plant is predicted to have >95% capacity factor. The potential of having a “spare” module offers additional refuelling flexibility and an opportunity to increase the capacity factor further.

Detailed cost estimates and construction schedules have been developed by NuScale. The use of well-known, readily available nuclear fuel results in fuel cost predictions by NuScale comparable to that of existing PWRs. NuScale predicts that the compact plant design, layout, and modular construction will make the cost/kW of a NuScale plant equal to or better than large nuclear scale nuclear plants. In addition, initial capital costs are significantly lower for a smaller project, and the predicted short construction period (36 months) reduces the cost of interest charges and financial risk.

11. Deployment status and planned schedule

NuScale is seeking design certification through the United States Nuclear Regulatory Commission (NRC). This effort is aimed at deploying NuScale plants to address the immediate needs of the US utility market. Multiple pre-application meetings have been held with the NRC to discuss the plant design, plant operations and staffing, the safety analysis codes, preliminary safety analysis results, expert panel reviews, the PRA results, severe accident analyses, and emergency planning studies. Development of the Design Certification Application is underway for submittal in 2015 .

12. References

- [1] INTERNATIONAL ATOMIC ENERGY AGENCY, “Status of Small Reactor Designs without Onsite Refuelling,” IAEA TECDOC-1536, IAEA, Vienna (2007).
- [2] J.N. Reyes, Jr. “NuScale Plant Safety in Response to Extreme Events,” Nucl Tech, 128, 153-163 (May 2012).