NUSCALE POWER SMALL MODULAR REACTOR

The NuScale Power small modular reactor (SMR) is an innovative design that builds on 60 years of world-wide experience with the commercial application of pressurized, light-water-cooled reactor (LWR) technology. The design incorporates several features that reduce complexity, improve safety, enhance operability, and reduce costs. From the outset, the top level design goals for the NuScale plant have been to achieve a high level of safety and asset protection while providing an affordable approach to nuclear power that gives the plant owner the maximum flexibility in construction, operation and application.

BACKGROUND

The NuScale SMR design concept was first conceived as part of a research grant awarded in 2000 by the US Department of Energy to a consortium of Idaho National Engineering and Environmental Laboratory, Oregon State University, and NEXANT, Inc. The original concept focused on achieving high levels of safety and simplicity while also providing a flexible solution for a diverse range of energy applications, [1]. The resulting Multi-Application Small Light-Water Reactor (MASLWR) design combined a very robust, low-power module with a highly flexible multi-module plant layout.

After the conclusion of the research project in 2003, Oregon State University continued to mature the design and eventually commercialized it in 2007 with the formation of NuScale Power, Inc. In 2011, Fluor Corporation, a major global engineering, procurement and construction company, became the dominant investor and strategic partner. Additional strategic partners joined the design development effort and in 2014, the US Department of Energy selected NuScale Power to receive a $217M cost-shared grant to help accelerate development and licensing of the design. Currently there are approximately 600 full-time-equivalent staff members dedicated to completing the NuScale SMR design. An application was completed in 2016 and has been submitted to the US Nuclear Regulatory Commission to certify the design as suitable for subsequent construction in the United States. The certification process will take approximately 40 months to complete.

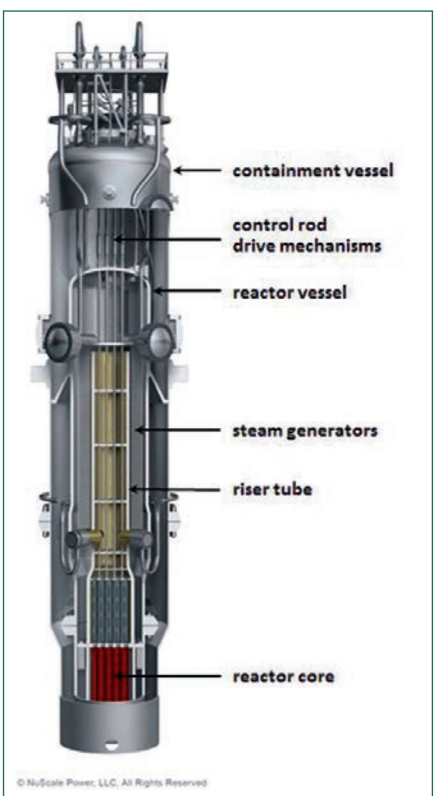

Figure 1. Cutaway model of NuScale power module.

DESIGN DESCRIPTION

The fundamental building block of the NuScale plant is the NuScale power module. The power module consists of a small 160 MWt reactor core housed with other primary system components in an integral reactor pressure vessel surrounded by a steel containment vessel and immersed in a large pool of water. Several power modules –as many as 12– are co-located in the same pool. A cutaway model of a single power module is shown in Figure 1 and a cutaway view of the reactor building is shown in Figure 2.

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NUSCALE REACTOR MODULAR PEQUEÑO

El pequeño Reactor Modular NuScale (SMR, por sus siglas en inglés) es un innovador diseño que se basa en 60 años de experiencia mundial en la aplicación de la tecnología de reactores a presión, de refrigeración por agua ligera (LWR). El diseño incorpora varias características que reducen la complejidad, mejoran la seguridad y la operatividad y reducen los costes. Desde el principio, los objetivos de diseño de NuScale han sido lograr un alto nivel de seguridad y protección, mientras que proporciona un enfoque asequible a la energía nuclear que da al propietario de la planta la máxima flexibilidad en la construcción, operación y aplicación.

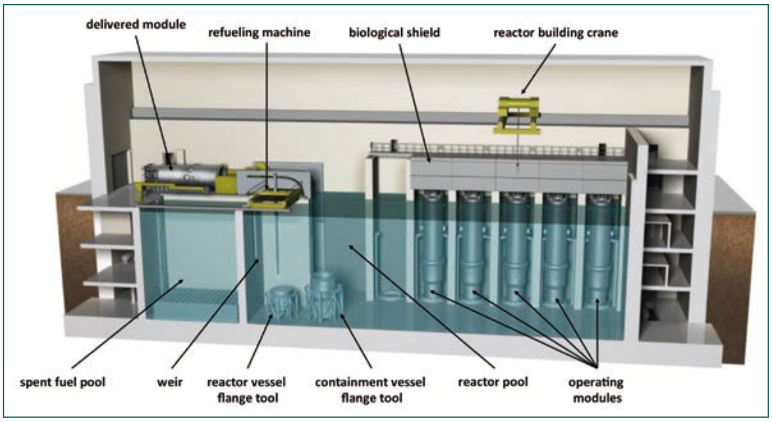

Figure 2. Cutaway model of reactor building for a 12-module NuScale plant showing five modules located in their operating bays and one module being delivered for assembly and installation.

Figure 4. Section of full-scale steam generator assembly being prepared for testing in Italy.

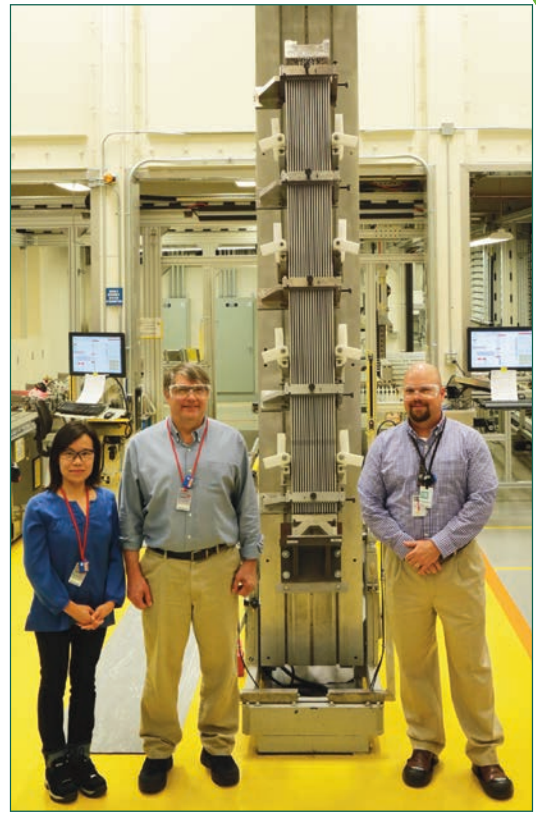

Figure 3. Prototypic mockup of NuScale fuel assembly. Shown in the photo are (left to right): Maggie Wang, Larry Linik, and Jeff Reed.

The reactor vessel is approximately 20.0 m tall and 2.7 m in diameter. The integral vessel contains the nuclear core consisting of 37 fuel assemblies and 16 control rod clusters. The fuel assemblies are shorter than assemblies in traditional pressurized water reactors but use the same 17 by 17 pin array geometry, same structural and clad materials, and same fuel type. Figure 3 shows a prototypic NuScale fuel assembly. Above the core there is a central hot riser tube, a helical coil steam generator surrounding the hot riser tube, and a pressurizer. The helical coil steam generator consists of two independent sets of tube bundles with separate feedwater inlet and steam outlet lines. A full-scale mockup of a portion of the steam generators is shown in Figure 4. A set of pressurizer heaters and sprays is located in the upper head of the vessel to provide pressure control.

Figure 5 shows a diagram of the primary reactor coolant path, which is circulated upward through the reactor core. The heated water is transported upward through the hot riser tube and is turned downward at the pressurizer plate. It then flows over the shell side of the steam generator, where it is cooled by conduction of heat to the secondary coolant and continues to flow downward until its direction is again reversed at the lower reactor vessel head and turned upward back into the core. The coolant circulation is maintained entirely by natural buoyancy forces of the lower density heated water exiting the reactor core and the higher density cooled water exiting the steam generator. On the secondary side, feedwater is pumped into the tubes where it boils to generate superheated steam, which is circulated to a dedicated turbine-generator system. Low pressure steam exiting the turbine is condensed and recirculated to the feedwater system.

The entire nuclear steam supply system is enclosed in a steel containment that is 24.6 m tall and 4.6 m in

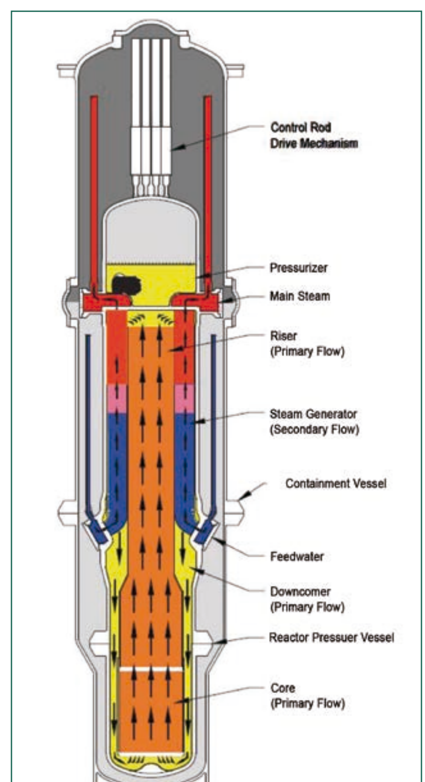

Figure 5. Diagram of NuScale power module showing primary coolant flow path.

diameter. The small volume, high design pressure containment vessel is a unique feature of the NuScale design and contributes significantly to the large safety margins and overall resilience of the plant design.

The NuScale module is located below grade in a pool of water that is contained in the seismic category I reactor building. The reactor pool provides passive containment cooling and decay heat removal. Specifically, the pool provides an assured heat sink with a capacity to absorb all the decay heat produced by up to 12 fully mature cores for more than 30 days, after which air cooling of the vessel is sufficient to avoid fuel damage. The pool also provides an additional fission product barrier in the unlikely event of fuel failure and provides radiation shielding outside containment to reduce operational exposure. Finally, the below grade pool provides enhanced physical security by adding an additional barrier to fuel access.

The simplicity and robustness of the module design allows for an increased level of automation in the control and operation of the modules. This enables the entire NuScale plant to be operated from a single control room. A multi-module control room simulator was constructed to confirm the feasibility and safety of controlling up to 12 reactors from the same location, including operator tasking analyses and human-system interface development. Figure 6 is a photograph of the world's first 12-reactor control room simulator.

Figure 6. Photograph of NuScale multi-module control room simulator.

RESILIENCE AGAINST FUKUSHIMA-TYPE EVENTS

An important characteristic of the NuScale design that enhances its attractiveness for many applications is its high level of plant resilience afforded by the small unit size. A new benchmark for nuclear plant resilience was set by the 2011 tragedy in Japan. The horrific earthquake-induced tsunami that struck Japan in March 2011 destroyed four out of the six nuclear reactors that comprised the Fukushima Daiichi nuclear power station on Japan's eastern coast. As a result of this accident, a higher level of scrutiny on new nuclear plants has evolved along with a higher standard for plant resilience to unanticipated extreme events.

The NuScale design offers an unparalleled level of plant resilience to the type of event that happened in Japan, [2]. A key feature in achieving this level of resilience is the containment vessel, which has several features that distinguish it from existing containment designs. The containment has been designed to a rated pressure of 6.9 MPa (1000 psia), which is approximately 15 times higher than traditional containments. As a result, it can withstand all loss-of-coolant accidents (LOCA) that can occur inside containment. During normal power operation, the containment atmosphere is evacuated to provide an insulating vacuum that significantly reduces parasitic heat loss from the reactor vessel. As a result, the reactor vessel does not require fibrous surface insulation, which minimizes the potential for sump screen blockage within containment—an issue that has plagued many large LWRs.

A closely coupled innovation is the immersion of the containment vessel in a large reactor pool. The pool provides the heat capacity needed to absorb and remove decay heat from each of the reactor cores during off-normal events. Conventional designs provide this "ultimate heat sink" in large external tanks that must be accessed when needed through a network of pipes, valves and heat exchangers. The NuScale design simplifies heat transfer to the ultimate heat sink by immersing the containment in it, thereby assuring its availability and eliminating the cost and maintenance issues associated with those additional coolant transfer systems.

In the event of a complete station blackout, as experienced at the Fukushima Daiichi plant, heat is removed from the reactor modules by fail-safe actuation of the emergency core cooling system and allowing the reactor building pool to heat up and boil. Water inventory in the reactor pool is sufficient to cool all of the reactors and prevent fuel damage for at least 30 days without any source of power, operator action, or makeup water—an achievement that is referred to as the "triple crown of nuclear safety." After 30 days, water boil-off and passive air cooling of the containment vessel provide adequate cooling for an unlimited period of time.

This extremely robust feature is a direct consequence of the unique design of the compact containment vessel, the assured supply of long-term cooling afforded by the reactor pool, and the relatively low power output of each module. As a result, the plant poses a very low risk to radiological releases making it suitable for locating the plant closer to population centers. More importantly, it enables more efficient coupling of the plant to process heat users since this requires the transport of steam or similar heat transport medium between the nuclear plant and the industrial plant.

MEETING DIVERSE ENERGY REQUIREMENTS

There are several key features of the NuScale plant that collectively distinguish it from the many other SMRs being developed today and make it especially well-suited for a broad spectrum of energy applications. Some key features include:

- *Compact size.* The nuclear steam supply system, including containment vessel, can be entirely prefabricated off site and shipped by rail, truck or barge for installation at the plant site. This reduces construction time due to parallel fabrication and construction processes and reduces overall schedule uncertainty due to the reduced amount of on-site construction activities.

- *Natural circulation cooling*. Natural circulation operation provides a significant advantage since it eliminates many pumps, pipes, and valves and hence the maintenance and potential failures associated with those components. This added simplicity enhances overall plant safety as well as improved economics.
- *Light water reactor technology*. The NuScale plant can be licensed within the existing LWR regulatory framework, thus drawing on a vast body of operational data, proven codes and methods, and existing regulatory standards. This will facilitate expeditious licensing of the plant and reduce uncertainties in the plant's performance.
- *Nuclear modularity*. The NuScale design extends modular construction strategies to the nuclear steam supply system. Each power module is contained within a compact, factory-manufactured containment vessel and provides output steam to a dedicated and independent power conversion system. Also, the scalability of the plant from 1 to 12 modules further enhances plant economics and deployment flexibility.
- *Dedicated power trains*. Because each power module, including the power conversion system, is independent of other modules, it is possible to operate the plant in such a manner that some modules produce only electricity while other modules produce only steam for thermal heat applications. This allows the plant to co-generate at the plant level to support multiple applications without the additional complexities of steam extraction from one or more turbine stages. The independent power trains also allow the plant to provide power at very high levels of assurance.

The synergy created by these unique features, especially plant simplicity, reliance on existing light water technology, and the plant-level flexibilities afforded by the multi-module configuration, all combine to position the NuScale plant for early and successful application to new energy markets. A series of studies have been conducted to assess the practicality of using a NuScale plant to provide electricity and heat to a variety of non-traditional applications, including secure electricity generation for critical facilities, integration of electricity supply with intermittent sources such as wind turbines, and co-generation of electricity and heat for industrial complexes.

The first study determined that the NuScale multi-module configuration uniquely allows it to provide power to a dedicated "micro-grid" user at a very high level of reliability.[3] A detailed probabilistic analysis of the operation of a 12-module NuScale plant over the entire 60-year lifetime of the plant concluded that the plant could provide at least 100 MWe of power to a private micro-grid at a 99.99% assurance level with the remaining power being provided to the commercial grid. Specific features of the plant that contribute to this unprecendented reliability include: multiple independent modules and power trains, staggered refueling of individual modules, and the capability to operate the plant in "island mode" whereby the plant is able to continue operation during a total loss of off-site power.

The integration of a NuScale plant with vaiable output from a small wind farm was also investigated.[4] Specifically, the balancing of the the output from the Horse Butte Wind Farm near Idaho Falls, Idaho was evaluated using actual wind farm output data. The study demonstrated that it was technically feasible to offset the wind farm variability in order to match a typical power demand profile due to three primary power management features of the NuScale plant: (1) shutdown and restart of individual modules for longer duration changes in power needs, (2) power manuevering of one or more modules using control rods for mid-term power adjustments, and (3) up to 100% turbine bypass for rapid power adjustments. Figure 7 shows two options for offsetting the variable output of the wind farm in order to meet the local power demand.

Additional studies have been conducted to evaluate the coupling a NuScale plant to industrial facilities that use large amounts of process heat such as oil refineries and desalination plants. In one study, a NuScale plant was coupled to a 250,000 barrels/day oil refinery using detailed process-level heat balances,[6]. It was concluded that a 10-module plant was sufficient to provide all of the electricity needed by the refinery and a portion of the process heat for which an extenal supply of steam from the NuScale plant could reasonably match the process heat requirements. No credit was taken for the heat needed to produce hydrogen within the refinery, which is normally done using a methane reforming process. The result was the avoidance of 190 metric tons per hour emission of carbon dioxide. In a subsequent study, the output steam from a NuScale plant proved to be suitable for producing hydrogen using high-temperature steam electrolysis. If applied

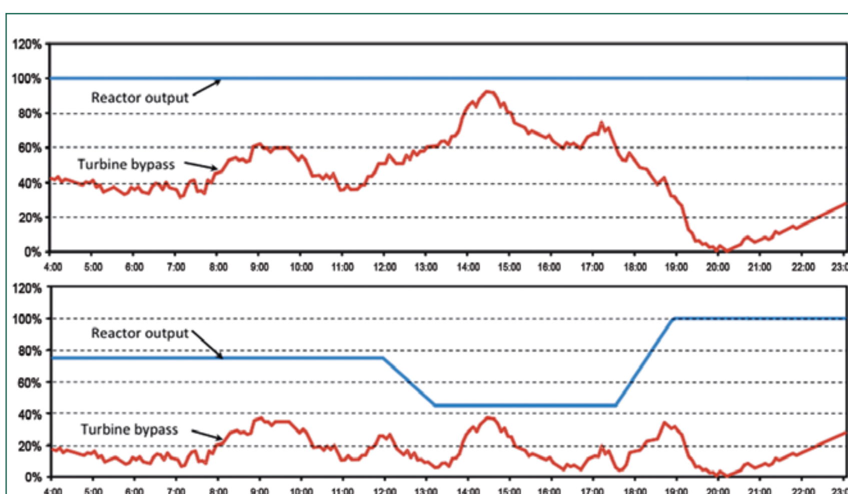

Figure 7. Two load-following options to compensate for variable wind output: use only turbine bypass while running the module at 100% power (upper graph), or use combination of reactor power maneuvering and turbine bypass (lower graph).

to the earlier refinery results, using nuclear-supplied steam to produce hydrogen would more than double the carbon dioxide avoidance rate from the refinery.

The final study evaluated both the technical and economic viability of coupling a NuScale plant to a desalination plant, including membrane and distillation processes,[5]. The key NuScale feature that provides a high level of flexibility in the coupling options is utilizing multiple, independent power trains. This feature allows for consideration of low-pressure coupling from the turbine exhaust, mid-pressure coupling with steam extracted from a turbine stage, or high-pressure coupling with the steam output from a module's steam generator. The study included a case study that demonstrated that an 8-module NuScale plant could be coupled to a modern commercial-scale reverse osmosis plant to provide sufficient clean water and clean power for a city of 300,000 people.

DEPLOYMENT STATUS

The NuScale design is progressing rapidly toward commercial deployment with approximately $500 million invested to date. An application for design certification was completed at the end of 2016 and has been submitted to the US Nuclear Regulatory Commission. Design approval could be received as early as 2020. Several domestic utilities are actively pursuing the potential construction of NuScale plants and one utility consortium, the Utah Associated Municipal Power Systems (UAMPS), has begun preparing an application for construction and operation of a NuScale plant as a cornerstone of the their Carbon Free Power Project. The preferred site for the UAMPS plant has been recently selected and is located on the federal reservation at Idaho National Laboratory. Commercial operation of this lead plant is expected to begin in 2026. In addition to utility interests in the United States, other countries have also expressed interest in pursuing SMR deployment. The UK, for example, is conducting a competition to select the best value SMR for the UK, and NuScale has been deemed eligible to participate in the first phase of this competition. The combined benefits of increased affordability, enhanced plant resilience and flexibility of use for a broad range of energy applications will make the NuScale design an attractive option in the future global clean energy mix.■

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