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NuScale Power: A modular, scalable approach to commercial nuclear power

By José N. Reyes Jr. and Paul Lorenzini

The multi-module NuScale reactor design has been optimized to meet the commercial power industry's requirements.

Support for the concept of small, modular, scalable light-water reactors is growing in the power industry. The new designs offer enhanced safety and provide new options for addressing plant financing and schedule, supply chain, and workforce issues. Initially conceived for specialized applications or for use as a small power source for remote locations, small modular reactors are now recognized as being able to reach a much broader commercial market and to play a major role in the worldwide nuclear renaissance.

Among the concepts being considered by commercial utilities in the United States is the design offered by NuScale Power. NuScale's integrated approach to deploying and operating modular scalable reactors is innovative, but the factory-fabricated power module and its standardized nuclear power plant design rely on well-known LWR technology, significantly reducing technological and regulatory risks. NuScale has optimized its multi-module plant design to meet the requirements of the commercial power industry.

Domestic utilities are taking a serious look at this technology because of the financial risks associated with large projects. Suppliers are also looking at the technology with an eye toward manufacturing NuScale modules and components in the United States.

Ten years in the making

Among the recipients of the first grants issued by the U.S. Department of Energy's Nuclear Energy Research Initiative program in 1999 was a collaborative research program proposed by Oregon State University (OSU), Idaho National Engineering and Environmental Laboratory (INEEL), and Nexant, a subsidiary of Bechtel at the time. Combining university creativity and testing capabilities, industry discipline and practicality, and the technical resources of a national laboratory provided a unique blend of perspectives and skills. The results of this three-year collaboration included a concept for a simpler type of LWR, an integral system test facility for design assessment and code validation, and a novel approach to the commercial deployment of nuclear power. A detailed report on the multi-application small light-water reactor (MASLWR) was issued by INEEL (now Idaho National Laboratory) in 2003.[1]

During the same period, the international nuclear power community actively investigated a wide range of reactor concepts to meet the growing needs of developing nations. Utility grids in developing nations simply cannot absorb large capacity additions. A general rule of thumb is that no single generating unit should provide more than 10 percent of the capacity of the interconnected system. The same percentage often holds true for developed nations as well.

The initial emphasis on small reactors for developing countries unfortunately had the effect of obscuring the advantages that modular plants can offer to conventional markets in developed countries. Small nuclear plants are uniquely suited not only for use in remote communities and for specific industrial applications, but also for situations where utility grids cannot absorb capacity additions in increments of 1000 MWe or more, especially when that capacity is all on one shaft that is driving the generator, and the failure of a single turbine results in the shutdown of the entire plant.

With small, modular plants, several units operate together to produce virtually any amount of capacity desired by the customer. These plants are scalable: Once the principal structures are in place, individual reactor module and turbine-generator units can be installed sequentially to match load growth. Since each unit would be prefabricated off site under controlled manufacturing conditions, the combined effect is a nuclear power alternative that has economic advantages similar to the addition of combustion turbines to a grid. This includes shorter lead times and less construction complexity. The result is the economic advantage of greater predictability and control of construction costs, which translates into lower financial risks.

It was with these advantages in mind that NuScale Power Inc. was formed in 2007 to commercialize the small nuclear power technology under development at OSU. The MASLWR was renamed NuScale to reflect the significant improvements that OSU made to the original design. In early 2008, NuScale Power started pre-application discussions with the U.S. Nuclear Regulatory Commission, with the intention of submitting an application for design certification for the modular, scalable reactor technology.

In April 2008, NuScale entered into a strategic partnership with Kiewit Construction. Kiewit, with its $8 billion in annual revenue, 125-year history, and 25 000 employees, is among the most capable and financially stable power constructors in the

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[1] Modro, S. M., et al., *Multi-Application Small Light-Water Reactor*—NERI Final Report, Idaho National Engineering and Environmental Laboratory, INEEL/EXT-04-01626, Dec. 2003.

United States. The NuScale plant design aligns with Kiewit's significant strengths in heavy concrete, civil, mechanical, and electrical engineering, and advanced construction techniques.

In 2009, Kiewit and NuScale engineers completed a detailed NuScale plant cost study, with the goal of creating a scalable-design power plant based on current industry standards that could be built cost-effectively and in a reasonable time frame. The study, which generated more than 500 drawings and required seven months and 16 000 labor-hours to complete, confirmed a competitive construction schedule from first concrete to fuel load. Also, a bottom-up estimate confirmed the engineering, procurement, and construction overnight capital costs in current dollars. The estimated cost to build and operate a nuclear power plant incorporating the NuScale technology and design was determined to be highly competitive with both nuclear and fossil alternatives.

With Kiewit in charge of overall construction management, NuScale looked for the best possible firm to manufacture the major modular component—the integrated containment and reactor module. NuScale identified General Dynamics Electric Boat as a potential module supplier to the NuScale team. Electric Boat brings significant experience to the design-build process, having delivered more than 100 nuclear submarines to the U.S. Navy. The company excels in completing multibillion-dollar, first-of-a-kind projects focused on safety, quality, schedule and cost reduction, and continuous improvement. Electric Boat would be able to apply lessons learned from the Navy nuclear program in module configuration and construction to the modular reactors developed by NuScale Power. This should allow the units to be built at lower cost and less risk to schedule. Electric Boat's manufacturing experience complements NuScale's "going-small" approach, which allows standard systems and components to be assembled in the factory, taking full advantage of automated forming, rolling, bending, and welding processes to produce precision products with high repeatability.

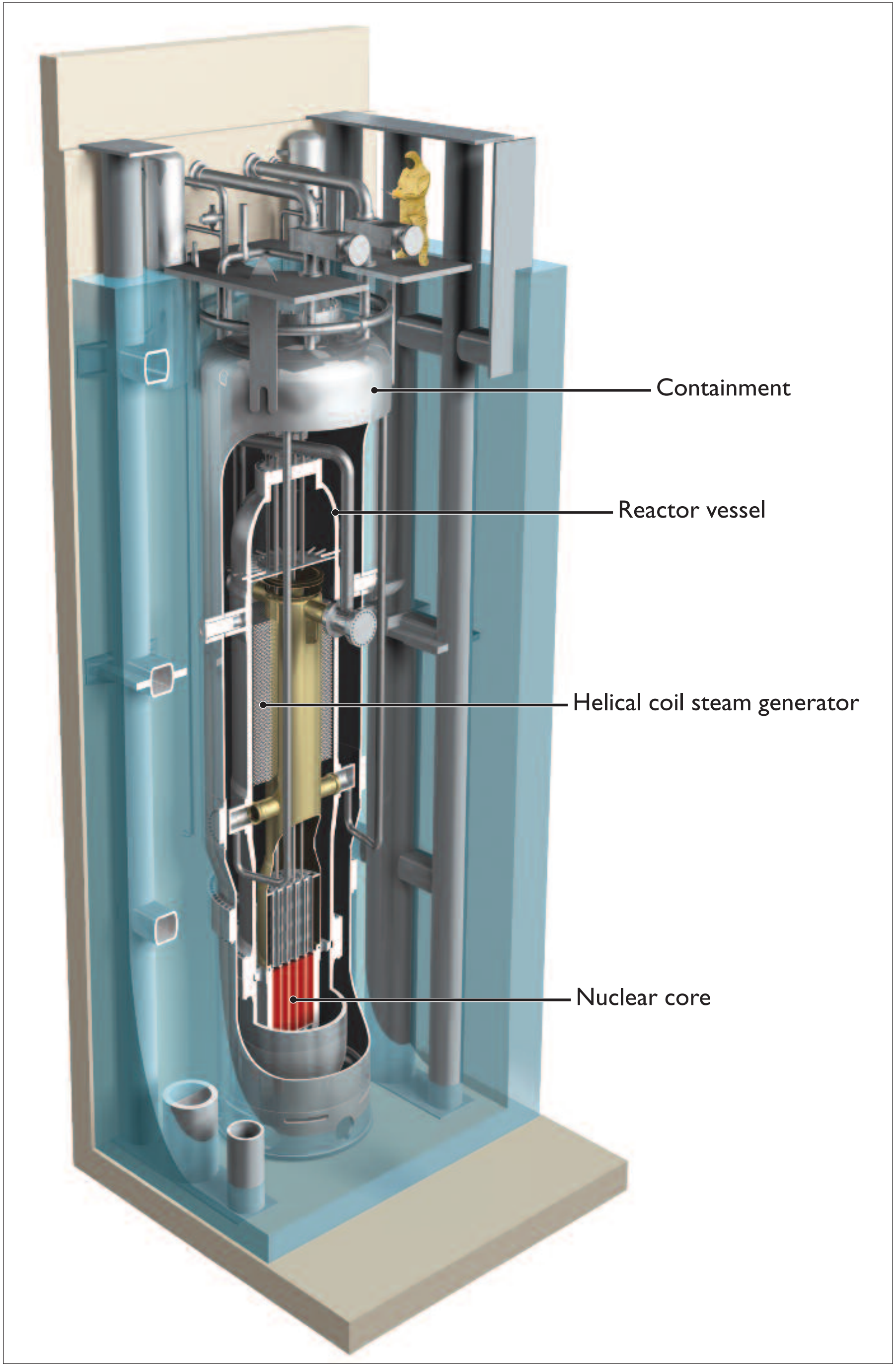

Fig. 1. Basic configuration of a single NuScale reactor module (nuclear steam supply system and containment), located in its bay

Simple, safe, economical, proven

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

The nuclear steam supply system (NSSS) is enclosed in a high-strength steel containment vessel that measures 60 feet long by 15 feet in diameter. The NuScale containment enhances safety while replacing the large, prestressed, post-tensioned concrete containment buildings required for other nuclear plants. The containment vessel includes the reactor pressure vessel, which measures 45 feet long by 9 feet in diameter and contains the nuclear core, a helical coil steam generator, and a pressurizer. The nuclear core consists of an array of half-height pressurized water reactor fuel assemblies at standard enrichments, and the control rod clusters. 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 and sprayers is located in the upper head of the vessel to provide pressure control.

The NuScale plant includes the following four essential features that in combination distinguish it from the many other small nuclear plants being developed today:

1. The plant is compact in size. The NSSS and containment can be prefabricated off site and shipped by rail, truck, or barge. Mid-size domestic suppliers can handle the fabrication, avoiding delays created by the international choke point for the forgings that are needed by conventional large plants.

2. The nuclear core is cooled entirely by natural circulation, both during normal operation and when the reactor is shut down. 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 pro-

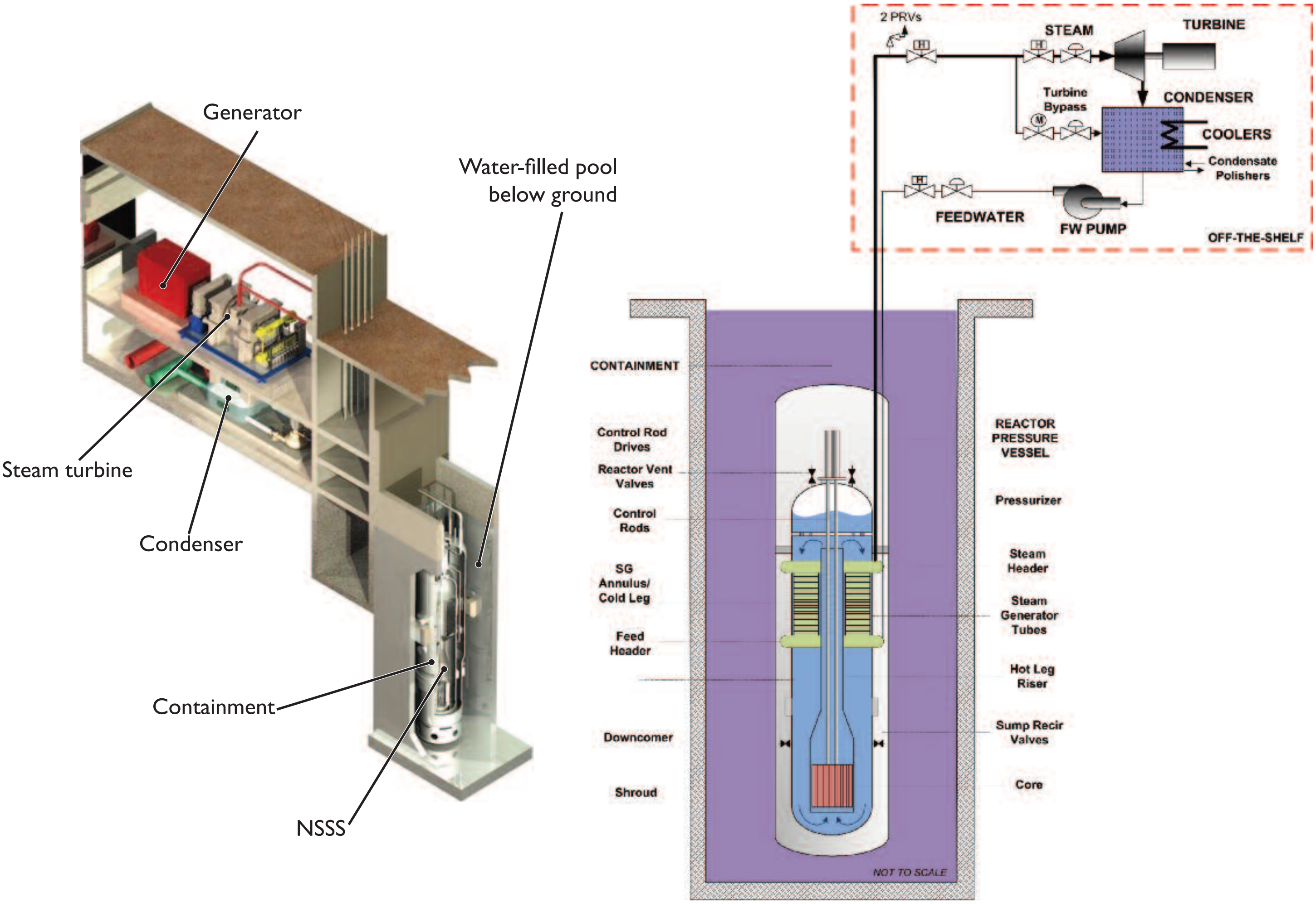

Fig. 2. A single NuScale Power unit. At left, a cutaway computer rendering, and at right, a diagram of the turbine-generator and containment arrangement.

vide 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 provides a significant advantage in that it eliminates pumps, pipes, and valves, and, therefore, the maintenance and potential failures associated with those components. It also reduces in-house plant loads. This added simplicity enhances overall plant safety and improves economics as well.

3. The design relies on well-established LWR technology. The NRC has said that the NuScale reactor can be licensed within the existing framework for commercial reactors and is already proceeding with pre-application meetings and Licensing Topical Report reviews. The NuScale design draws on a vast body of established research and development, proven codes and methods, and existing regulatory standards.

4. The design is supported by a one-third–scale, electrically heated integral test facility that operates near prototypic fluid conditions. An integral test facility of this kind is mandatory with any new design for which regulatory approval is sought from governing bodies such as the NRC. Customers also will want assurance from integral facility tests that the design will perform as predicted. The NuScale prototype test facility at OSU will provide the benchmark data for the safety analysis codes that will be used for NRC licensing.

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

As indicated in Fig. 2, the NuScale module is located below grade in a pool of water. The water provides passive containment cooling and decay heat removal for approximately three days without the need for pool cooling. The pool also provides a means of dampening seismic events, a buoyancy force that simplifies module transport during refueling, an additional fission product barrier, radiation shielding outside containment, and physical security, since the pool is below grade.

Figure 3 shows a plan view of the layout of a 12-module array with a total capacity of 540 MWe. In the layout, a reactor building houses the modules. Within the reactor building, there is a separate below-ground refueling area, which also houses the spent fuel storage pool. Two turbine generator buildings sit to either side of the reactor building. Each holds the six turbine-generator sets for the six adjacent reactor modules. Each module resides in a bay that is open to a common stainless steel–lined concrete pool. Although each reactor module and turbine generator set produces 45 MWe, higher capacity levels can be reached by simultaneously operating as many as 12 units in one facility.

In-line refueling

The configuration shown in Fig. 3 offers significant economic advantages in that it eliminates single-shaft risk—that is, the temporary shutdown of a single unit does not require the shutdown of the entire plant—and the layout permits refueling to be completed on a single module while the other modules continue to generate power. Each module can operate for two years between refuelings.

The refueling process begins once the reactor is brought to cold shutdown conditions, after which the feedwater lines and the steam lines are disconnected from the module. The module is then connected to an overhead crane and moved from its bay into the central pool area of the reactor building. From the central pool the module

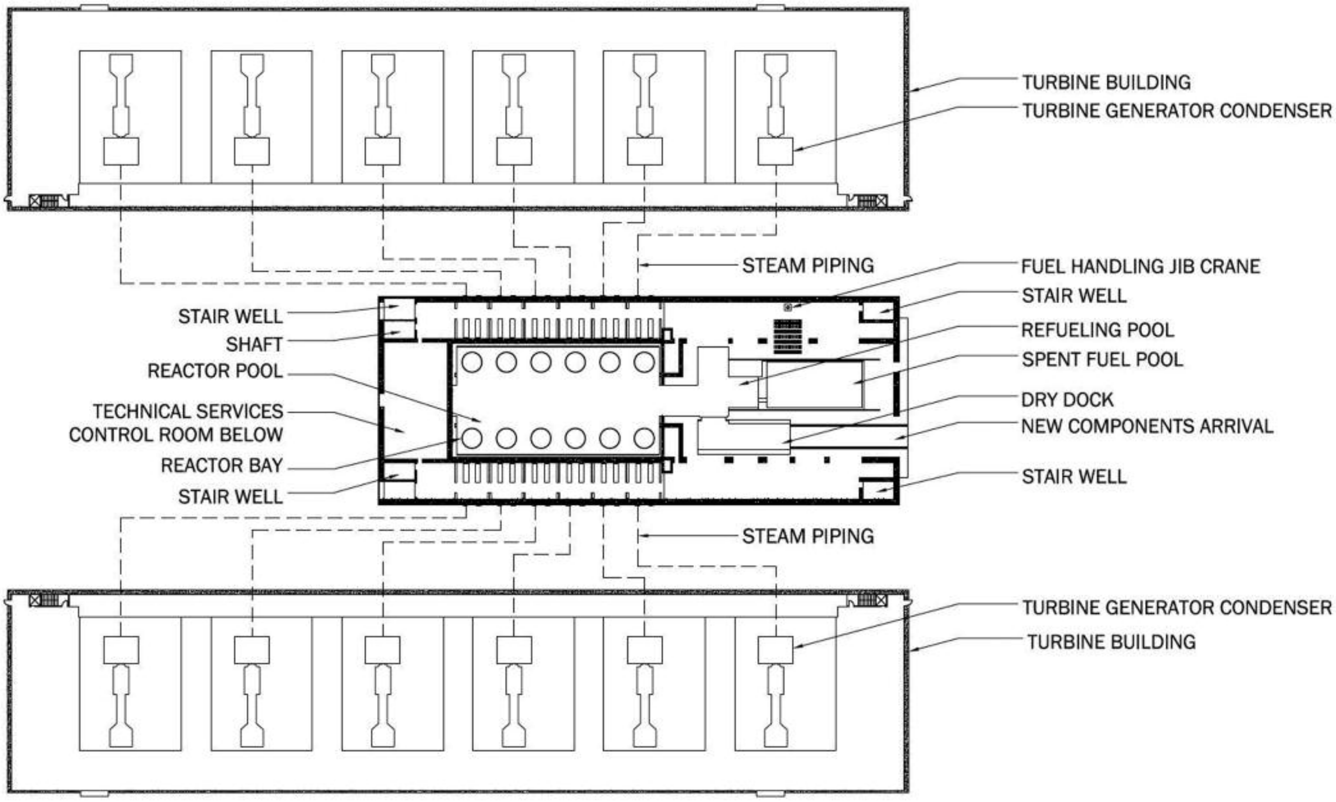

Fig. 3. Plan view of the layout of a 12-module NuScale reactor and turbine buildings

is transported through a set of gates into the refueling area, where it is remotely disassembled and refueled. The module is then reassembled and transported back through the gates to its designated bay, where the feedwater and steam lines are reconnected and the startup process is initiated. Economics may support the idea of having a spare module ready in advance.

This staggered refueling of individual modules—that is, in-line refueling—can be done by a small, well-trained, permanent team rather than by a large, temporary workforce that would have to be brought in. In a 12-module plant, one individual module would be taken out of service approximately every two months for refueling and for NRC-required inspections and tests. During the refueling of one module, the other 11 modules would remain on line producing power. 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 downtimes.

Figure 4 shows the site layout for a 12-module NuScale plant. The layout is extremely compact and low profile.

Safety, security, asset protection

The NuScale plant is designed to provide an unparalleled level of safety, security, and asset protection. Its unique engineered safety features provide stable, long-term nuclear core cooling and plant recovery under all design basis accident conditions, as well as severe accident mitigation for low-probability, beyond–design basis accidents.

The engineered safety features include a high-pressure containment vessel, a passive decay heat removal system, a containment heat removal system, and in-vessel retention for severe accident mitigation.

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, eliminating 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. Also, the elimination of containment air—and, therefore, oxygen—prevents the creation of a combustible hydrogen mixture in the unlikely event of a severe accident and eliminates corrosion and humidity problems inside containment.

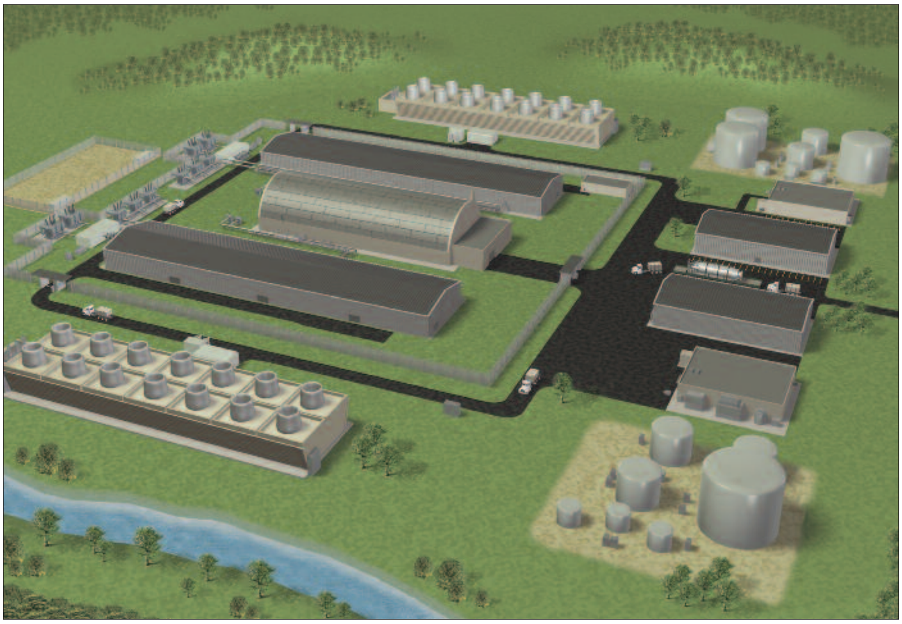

Fig. 4. Site layout for NuScale power plant

Finally, because of the vessel's relatively small diameter, it has been designed to a maximum pressure of 3.8 MPa (550 psia). As a result, in the event that the entire contents of the pressure vessel are vented into the containment, the equilibrium pressure between the reactor and the containment will always be below the containment design pressure.

Each NuScale module includes two redundant passive safety systems to provide pathways for decay heat to reach the containment pool.

Passive safety systems

With all nuclear plants, a primary safety issue is the need to ensure that decay heat can be removed following a reactor shutdown. For traditional LWRs, the limiting safety condition has been the need to provide cooling for accidents in which supplies of cooling water are lost through some form of breach, usually a break in the largest cooling pipe. Emergency core cooling systems ensure the availability of cooling water for such accidents.

In the first generation of nuclear plants, emergency core cooling was accomplished with "active" systems that required emergency pumps to operate and thus imposed requirements for adequate supplies of emergency electricity generation. Safety at plants that are being built today is enhanced by the use of "passive" emergency cooling systems to supply backup sources of cooling water delivered by way of natural circulation systems that do not require pumps to operate.

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 containment heat removal system (CHRS). These systems do not require external power for actuation.

The DHRS, shown in Fig. 5, uses either of the two independent helical coil steam generator tube bundles to transfer heat generated within the core to the containment pool. Feedwater accumulators provide initial feed flow while the DHRS transitions to natural circulation flow. After the discharge of the feedwater accumulators, water is drawn into the steam generator tubes from the containment cooling pool through a sump screen. Water boils inside the steam generator tubes to remove core decay heat, and the steam is then vented through spargers and condensed in the pool.

The CHRS, shown in Fig. 6, provides a means of removing core decay heat in the event that the steam generator tube bundles are not available. It operates by opening the vent valves located on the reactor head and venting primary system steam 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 valves are opened to provide a natural circulation path from the sump through the core and out of the reactor vent valves.

The combined effect of these features is to eliminate the traditional design basis loss-of-coolant accident (LOCA). First, there is no design basis scenario in which a failure causes coolant to be lost from the module. Second, even for small-break assumptions, there is no design basis scenario in which the core becomes exposed or uncovered; it will always be underwater, so

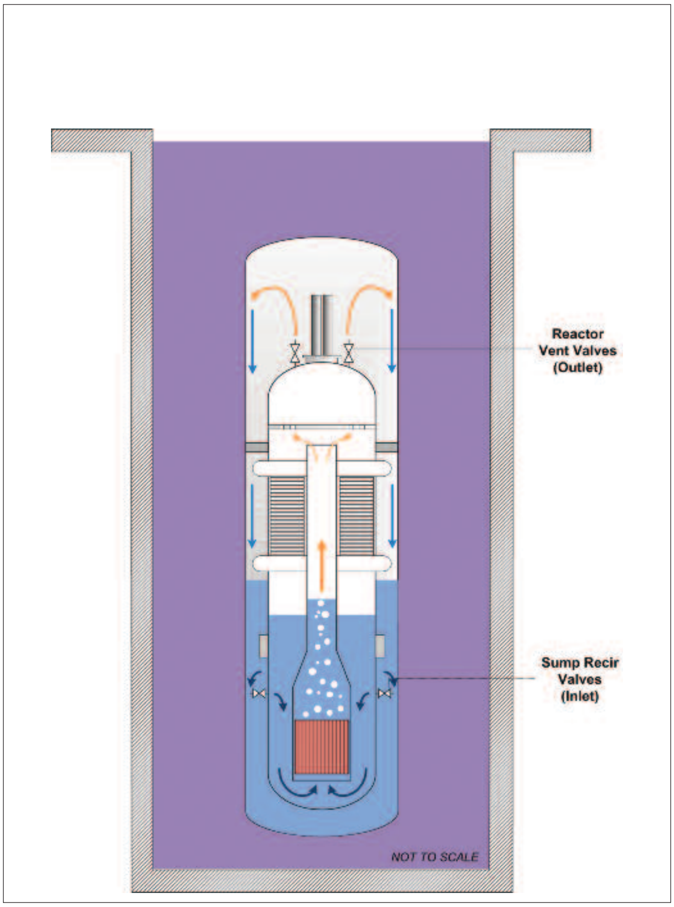

Fig. 5. The decay heat removal system (DHRS)

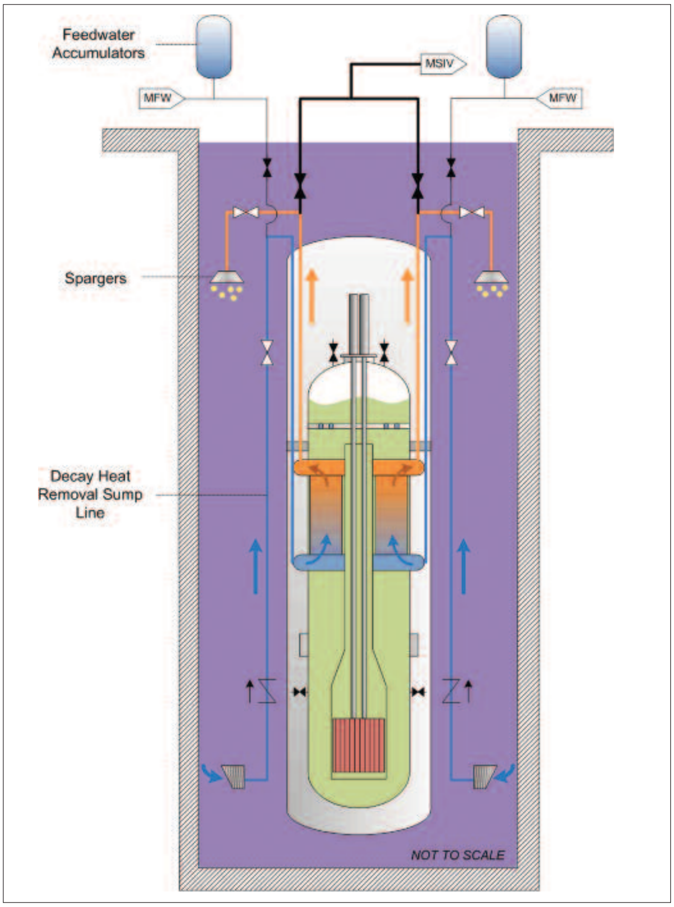

Fig. 6. The containment heat removal system (CHRS)

Fig. 7. José Reyes, lead designer of the NuScale reactor, stands on the platform of the Integral System Test Facility at Oregon State University. (Photo: Bruce Ely/*The Oregonian*)

cooling pathways are always available to remove decay heat. As described below, the safety system design approach has been confirmed in integral system tests conducted at OSU.

It is important to note that the actuation of the NuScale engineered safety features ensures that the fuel does not experience a temperature excursion and that all system pressures and temperatures remain within design limits. Recovery from a design basis LOCA would be similar to a typical refueling outage, representing a new level of asset protection.

Severe accident mitigation

The NuScale plant design offers significant severe accident mitigation features: 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 (limited 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; and defense-in-depth is provided by the inclusion of additional fission product barriers. As with conventional large LWR designs, the fuel pellet, cladding, reactor vessel, and containment prevent the transport of fission products to the outside atmosphere. The NuScale design provides additional barriers that further reduce the potential for severe accident releases, including the containment cooling pool, the stainless steel–lined containment pool structure, a biological shield, and, finally, the reactor building.

Initial probabilistic risk assessment studies show a significantly reduced core damage frequency (CDF) on the order of 10^{-8} per reactor per year. This CDF, coupled with a reduced source term and additional fission product barriers, indicates a reduced overall risk to the public and offers significant advantages for emergency planning and response.

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 presents structures with a low profile and facilitates design features that provide resistance to aircraft or other potential security threats.

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 one-third–scale, full-pressure, and full-temperature integral system test facility for the original MASLWR design as shown in Fig. 7. NuScale, through its technology transfer agreement with OSU, has active use of the test facility. NuScale has contracted with OSU to modify the facility to incorporate and evaluate design improvements and to conduct integral system tests required for NRC certification. OSU has significant testing capability, having performed the DOE and NRC certification tests for the Westinghouse AP600 and AP1000 reactor designs under 10 CFR Part 50 Appendix B, NQA-1, and 10 CFR Part 21.

Figures 8 and 9 present the data for a small-break stuck-open reactor vent valve test conducted in the MASLWR test facility. As can be seen from the measured data, the accident was completely mitigated for these conditions without the need for external power or operator actions. Figure 8 shows pressurizer pressure and containment pressure reaching equilibrium. The remainder of the test demonstrated long-term cooling and continued containment and core cooling. Complete cooling was achieved using the CHRS alone; 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 Fig. 9, which shows that the collapsed liquid level remained well above the top of the core throughout the entire transient. The core was never close to becom-

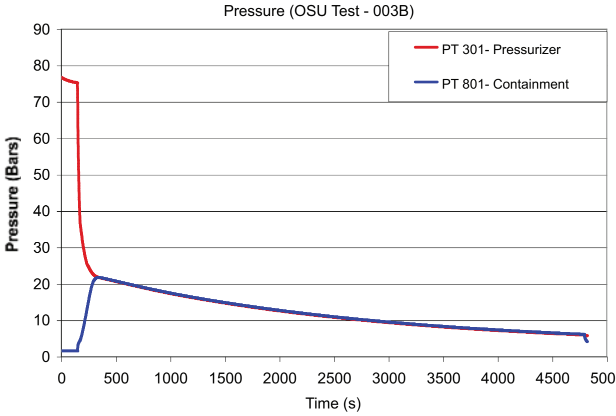

Fig. 8 Pressurizer and containment pressure measured for Test OSU-003B

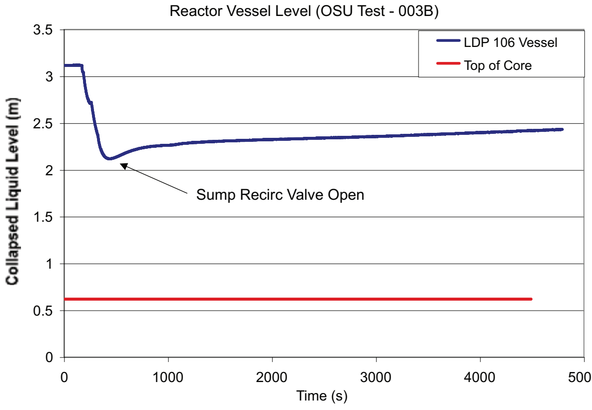

Fig. 9. Collapsed liquid level measured in the reactor vessel for Test OSU-003B

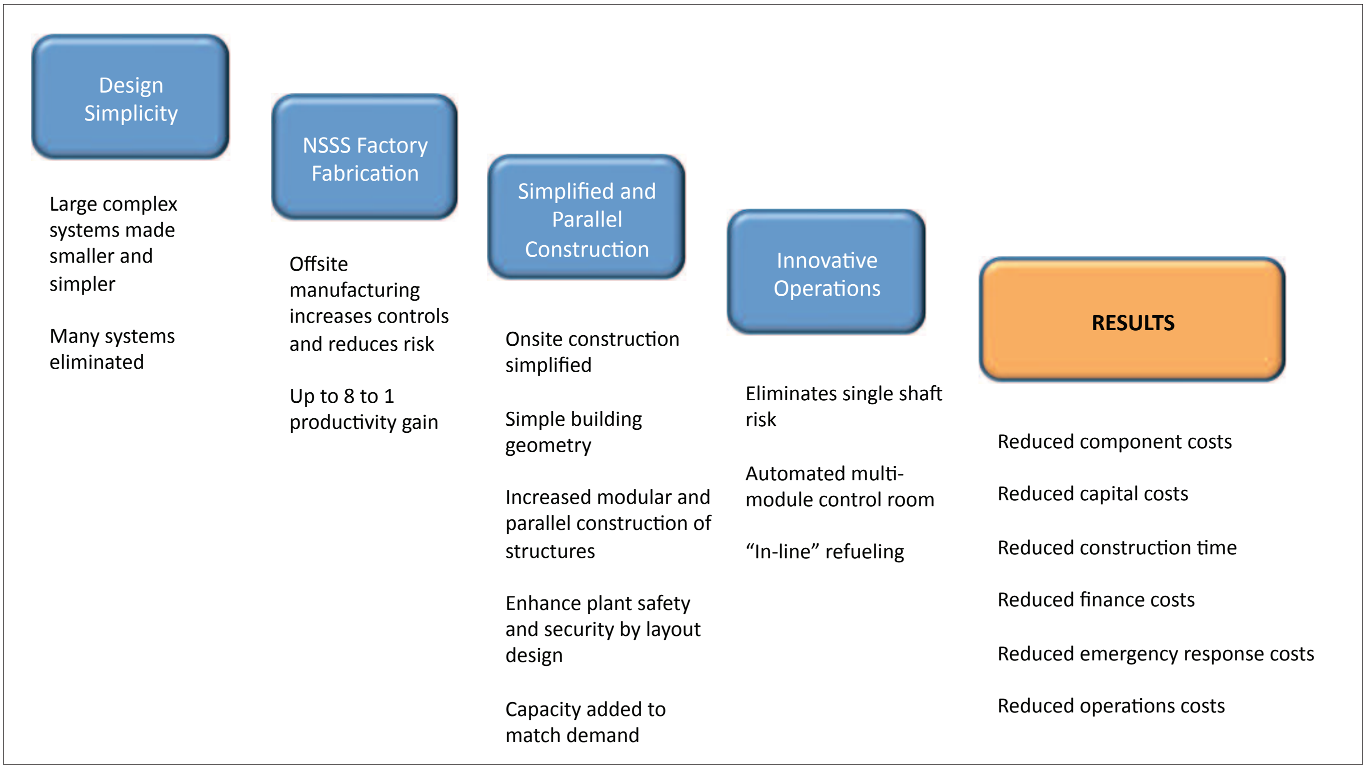

Fig. 10. The “economies of small” for the NuScale plant

ing uncovered in this scenario. A complete set of tests is planned for the NuScale design.

Capturing economies of small

The nuclear industry was built on the belief—backed by experience—that larger plants are necessary to capture the economies of nuclear power. Although economies of scale have been achieved, this approach has posed difficulties in maximizing the ability of nuclear power to achieve its full potential.

First, many markets do not need large plants. This is true not just in developing countries, where grid size, system capacity, and financial reserves are less able to support large plants, but also in domestic markets. Second, as plant size grows to the point of stretching global manufacturing capabilities, designs begin to encounter some “diseconomies of scale,” as described by Li.[2] The most obvious diseconomies are the significant financial commitment and associated financial risk that come with multibillion-dollar investments. Other potential factors include limited component availability, increased plant complexity leading to increased maintenance requirements, and greater construction risks. NuScale presents a different deployment model based on capturing the “economies of small.”

NuScale’s economies of small are built on four principles as summarized in Fig. 10: design simplicity, NSSS factory fabrication, simplified and parallel construction, and innovative operations. The application of all four principles has resulted in a NuScale plant design that has lower capital investment, shorter construction times, and competitive pricing on a cost-per-MWe basis.

Design simplicity

Rather than attempting to scale down a large nuclear plant with all of its inherent complexity, we believe that the key is to design the plant from the bottom up in a manner that exploits every economic, safety, and security advantage afforded by going small. This requires invoking extreme simplicity in a manner that promotes a robust domestic supply chain, employs standardized components with ensured manufacturability, and guarantees ease of transport. This was the approach taken by NuScale.

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The passive, natural circulation–based NuScale systems eliminate nearly all of the expensive and redundant NSSS active systems commonly found in large plants while offering an enhanced level of safety and security. The smaller-diameter vessels provide high internal pressure capabilities using reduced vessel wall thickness and also offer a much greater ratio of surface area to internal volume. In the case of passive containment cooling, this translates into a significant enhancement in decay heat removal per metric ton of vessel metal mass, and reduced metal mass directly corresponds to reduced plant component costs.

NSSS factory fabrication

Going small and simple enables the NuScale NSSS and containment to be fabricated entirely in a factory. A factory assembly line using smaller, less-expensive standardized systems and components is expected to yield lower-cost, high-quality power modules. Experience has shown as much as an 8-to-1 productivity advantage in assembly-line manufacturing over on-site fabrication. Furthermore, assembly-line production with a reasonable throughput offers a short learning curve with the potential for significant manufacturing optimization.

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[2] Li, Ning, “A Paradigm Shift Needed for Nuclear Reactors: From Economies of Unit Scale to Economies of Production Scale,” *Proceedings of the 2009 International Congress on Advances in Nuclear Power Plants (ICAPP ’09), Tokyo, Japan, May 2009.*

Simplified parallel construction

Factory fabrication of the NuScale NSSS and containment greatly simplifies on-site construction. A three-year construction time for the 12-module plant is readily achievable using modern construction methods combined with parallel off-site fabrication of the NuScale modules. The on-site construction is greatly simplified because the nuclear components are not installed until after the on-site civil construction is essentially completed. The estimate is that this approach would reduce by as much as one-third the on-site workforce requirements for the construction of a conventional nuclear plant of comparable power. This combination of reduced workforce requirements, a simpler build, and a shorter construction schedule results in lower capital costs, with a commensurate reduction in financial risk.

Innovative operations

Designing from the bottom up offers an opportunity to introduce some innovation into operations that are unique to a NuScale plant. First, the in-line refueling approach eliminates the need for a large contractor workforce to perform refueling and maintenance during outages. This in turn eliminates costly contractor training and security screening, as well as the labor associated with the setup and takedown of refueling and monitoring equipment.

Second, the NuScale power modules offer simpler, more automated operations, with reduced financial consequences in the event of a reactor trip. Only 45 MWe would be lost to the grid with a single reactor trip, while the remainder of the plant would continue to produce power. Similarly, the passive nature of the safety systems and the placement of the modules, the control room, and the spent fuel pool underground result in numerous enhancements to plant security.

Ready for market

NuScale is actively working with top U.S. manufacturers to create a supply chain that is robust, competitive, and aligned for mass production. Because NuScale power modules and skid-mounted systems are relatively small, new opportunities are being created for high-quality, mid-size manufacturers of forgings, flanges, pressure vessels, and small steam turbine-generator sets. The supply chain will include suppliers of valves, controls, instrumentation, and piping, and regular services for heavy-load rigging and transport.

NuScale has completed four pre-application meetings with the NRC to discuss the unique features of a multi-module plant. The goal is to submit a completed design certification application in early 2012, and the first nuclear power plant using NuScale's modular, scalable reactor technology could begin commercial operation as early as 2018. NN