WESTINGHOUSE SMALL MODULAR REACTOR. AN INNOVATIVE MATURE DESIGN CONCEPT

The Westinghouse Small Modular Reactor (Westinghouse SMR) represents the next step in the evolution of advanced light water reactor design simplicity and advanced passive safety systems in a compact design. This mature design concept is for a >225 MWe plant powered by an 800 MWt core. All safety-related systems required to bring the plant into safe shutdown are located below grade for protection against external threats. The Westinghouse SMR is sized to replace retiring fossil fuel plants and to accommodate a range of sites, including remote. The self-contained plant requires 160 times less land than an equivalent solar power plant and 4,000 times less than an equivalent wind power plant. Westinghouse is addressing economy of scale to contain plant construction costs by designing its SMR for 100 percent modular construction, limiting the size of components for ease in shipping and investing in advanced manufacturing technologies.

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REACTOR MODULAR DE WESTINGHOUSE UN INNOVADOR CONCEPTO DE DISEÑO AVANZADO

El Reactor Modular de Westinghouse (SMR) supone el siguiente paso en la evolución del diseño reactores avanzados de agua ligera asi como en los sistemas de seguridad en un diseño compacto. Este concepto de diseño avanzado es para una planta de> 225 MWe alimentada por un núcleo de 800 MWt. Todos los sistemas relacionados con la seguridad requeridos para poner la planta en parada segura están diseñados dentro de los niveles exigidos para protección contra amenazas externas. El reactor Westinghouse SMR está construido para reemplazar las plantas de combustibles fósiles que se están retirando y para acoplarse a diferentes lugares. Con este reactor, la planta autónoma requerirá 160 veces menos tierra que una planta solar equivalente y 4.000 veces menos que una de energía eólica. Westinghouse realizando una economía a escala para reducir los costes en la construcción de la planta diseñando su SMR para asumir el 100%, limitando el tamaño de componentes para la facilidad en el envío e invirtiendo en tecnologías de fabricación avanzadas.

The International Atomic Energy Agency describes the advantages of small modular reactor development as meeting the need for flexible power generation for a wider range of users and applications; replacing aging, carbon-generating fossil fuel power plants; enhancing safety performance through inherent and passive safety features; offering lower upfront capital costs; providing cogeneration and non-electric benefits; being a suitable option for remote regions with less developed infrastructure; and offering possibilities for hybrid energy systems that combine nuclear and alternate energy sources, including renewables.

The Westinghouse Small Modular Reactor (Westinghouse SMR) is a mature design concept that is sized to offer all of these benefits. The design is informed by more than 60 years of Westinghouse nuclear reactor development experience that began with designing and manufacturing the company's first specialized small reactor in the 1950s. This Westinghouse technology became the basis of approximately half of the reactors operating around the world today.

With commitment and technical diligence, Westinghouse continues to transform breakthrough ideas from concept to physical structures that benefit society and power generators worldwide. The company is now simultaneously building eight AP1000®nuclear power plants around the world based on its advanced pressurized water reactor standard design, which utilizes cutting-edge passive safety features. The new, smaller-footprint advanced light-water reactor design of the Westinghouse SMR represents the natural next step in the evolution of design simplicity and advanced passive safety.

The innovative, compact design incorporates the proven technology and passive safety features of the AP1000 nuclear power plant to provide safety and resiliency. The recent design, and global delivery and construction experience with the AP1000 plant, positively imparts certainty in licensing and construction.

WESTINGHOUSE SMR PLANT OVERVIEW

The Westinghouse SMR is a >225 MWe plant powered by an 800 MWt core capable of producing more power per volume of building materials than any other SMR design to date. It is right-sized to replace retiring fossil fuel plants, for which existing infrastructure such as transmission lines already exist, and is also suitable for a range of sites including those in remote areas. The entire power plant is created to be completely self-contained on a six-hectare site, requiring 160 times less land than an equivalent solar power plant and 4,000 times less land than a wind power plant. The Westinghouse SMR is also designed to be delivered as a stand-alone unit with no shared systems. This eliminates vulnerability to failures that can cascade from one unit to another in a multi-module station, an important consideration in a post-Fukushima environment (Figure 1).

For additional protection from external threats including natural phenomena, the nuclear island and the main control room are completely below grade. The nuclear island is divided into five distinct, physically separate sectors with no wireways, pipes or passageways traversing between them. Access to each is controlled; entry is made from above grade through an equipment hatch located at the top of the containment vessel. The nuclear island's sectors house a radiological control area, which includes the high-pressure containment vessel and spent fuel pool, as well as all safety-related and instrumentation and control systems. The containment vessel is completely submersed in water and is not accessible during power operation. Additionally, there are multiple security monitoring stations located in separate sectors. Westinghouse expects that these enhanced safety features will reduce the number of security personnel required.

Westinghouse is addressing economy of scale to contain plant construction costs by designing its SMR for 100 percent modular construction, limiting the size of components for ease in shipping and investing in advanced manufacturing technologies. These considerations permit a shorter construction or assembly schedule of 18 to 24 months, eliminate the need for new infrastructure for shipping by rail, truck or barge, and may offer further flexibility in design with reduced lead times and costs compared to traditional manufacturing methods.

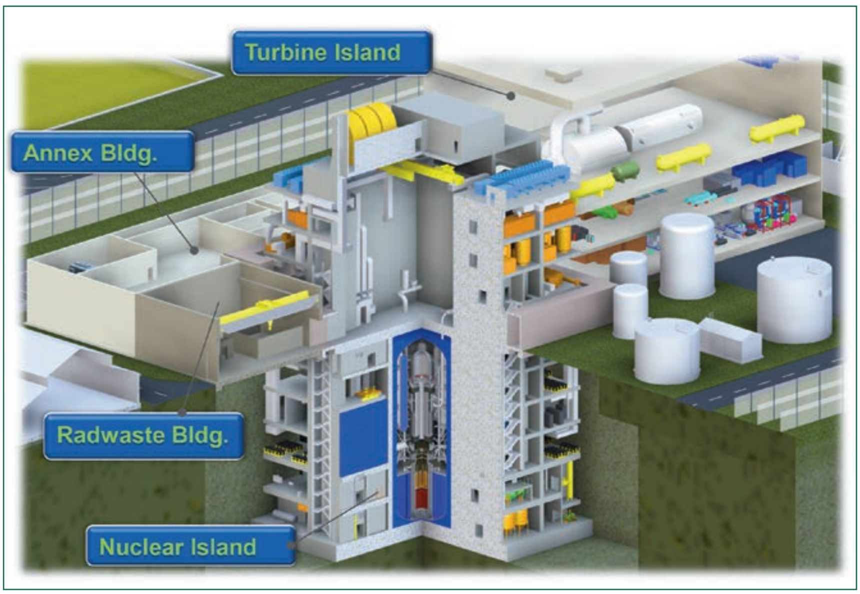

Figure 1. The Westinghouse SMR: All safety-related systems required to bring the plant into safe shutdown are located below grade for protection against external threats.

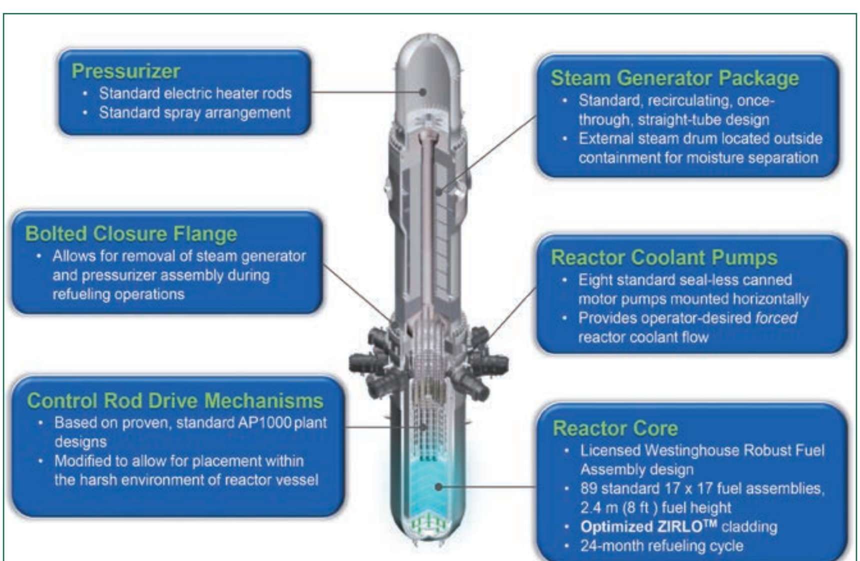

Figure 2. 225 MWe Integral Reactor Pressure Vessel: The compact integral reactor vessel packages proven components.

MATURE CONCEPT DESIGN WITH PROVEN TECHNOLOGY MODELS AND INNOVATIVE FEATURES

The Westinghouse SMR employs the natural forces of evaporation, condensation and gravity to safely shut the plant down and remove decay heat from the core in the event of an accident. Incorporating and building on the safety features and principles of the AP1000 plant, the Westinghouse SMR is an advanced passive plant that does not rely on AC power or other support systems to perform safety functions. In the event of a design-basis accident, on-site water inventory provides the first seven days of passive heat removal without operator action; more water can be added for indefinite cooling without entering the plant. At currently operating reactors, a three-day minimum coping time is expected. The small size and low-power density of the reactor further limit the potential consequences of an accident as compared to a large plant (Figure 2).

There are additional design features incorporated in the Westinghouse SMR that minimize or eliminate the effects of other postulated accidents. The reactor core, steam generator, reactor coolant pumps and pressurizer are all housed in the same pressure vessel. The integral reactor design eliminates large-loop piping and potential large-break loss-of-coolant accidents, significantly reduces the flow area of postulated small-break loss-of-coolant accidents and eliminates a control rod ejection.

The Westinghouse SMR incorporates three passive and diverse decay heat removal methods: natural circulation cooling by gravity feed from the steam drum through the steam generator; cooling by passive decay heat removal heat exchangers; and passive cooling by continuous bleed and feed methods, including a two-stage automatic depressurization system, water injection and gravity-fed boric acid water replenishment. In effect, the Westinghouse SMR would be fully capable of withstanding extreme natural phenomena hazards and beyond-design-basis accident scenarios, including long-term station blackout.

Both the reactor vessel and the passive core cooling system are located within the high-pressure steel containment vessel. The containment vessel's

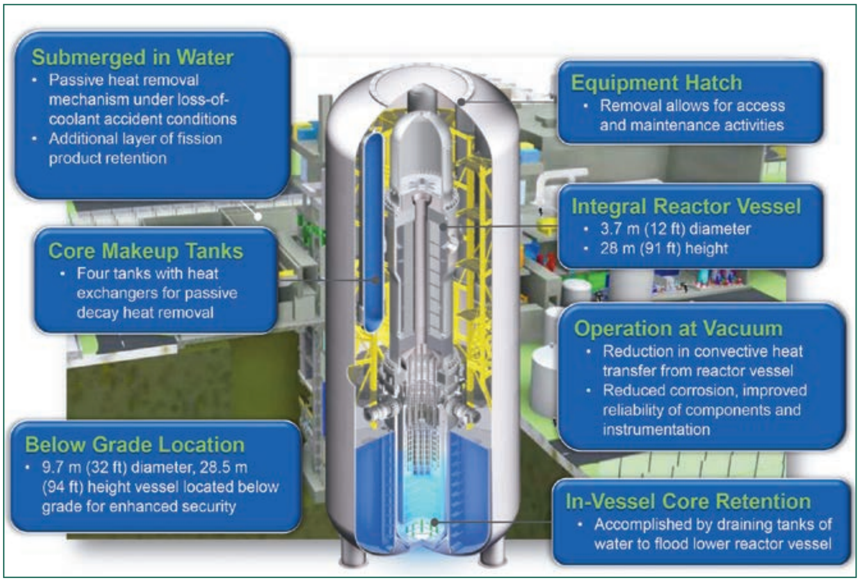

Figure 3. The Westinghouse SMR Containment Vessel is reduced in size for cost savings and below-grade construction.

compact design reduces cost considerably, facilitates modular construction and increases the allowable design pressure. Westinghouse designed the containment vessel to be fully submerged in water to facilitate heat removal during accident events while providing an additional radionuclide filter. The containment vessel is also designed to operate at vacuum to reduce corrosion and improve the reliability of components and instrumentation (Figure 3).

Westinghouse will power its SMR with a reduced-height version of the licensed, high-performing Westinghouse 17 x 17 Robust Fuel Assembly. This successful fuel product has proven itself in 60 plants worldwide to date, with 23,600 fuel assemblies with six million fuel rods. For the more compact Westinghouse SMR, the fuel height is shortened to 2.4 meters (8 feet). The fuel will be clad with Westinghouse's Optimized ZIRLO™ fuel cladding, which is an advanced high-burnup material that is resistant to corrosion. Better neutron economy and reduced enrichment requirements to less than the existing statutory limit will be achieved with a metallic radial reflector. Additionally, the core is designed for efficiency and economy with an operating cycle of 700 effective full-power days. This coincides with existing regulatory surveillance intervals and equates to replacing approximately 40 percent of the fuel every two years.

Westinghouse has prepared for Westinghouse SMR fuel fabrication, well beyond the conceptual design phase. The company built two full-scale prototype fuel assemblies for the Westinghouse SMR design, conducted full-scale hydraulic grid-to-rod fretting wear tests under simulated Westinghouse SMR operating conditions and completed a readiness assessment for manufacturing. Hydraulic grid-to-rod fretting is the most prevalent failure mechanism for pressurized water reactor fuel. The hydraulic testing and readiness assessment showed very positive results indicating readiness to move forward with the SMR fuel design. Westinghouse plans to manufacture its SMR fuel at its Springfields Fuel Facility in the U.K.

For reactivity control during load-follow and similar operations, the integral pressure vessel's upper internals support 37 high-temperature-resistant internal control rod drive mechanisms. They are part of the wireless instrumentation, which consists of hardened electronics and is based on proven AP1000 designs. Westinghouse modified the instrumentation to withstand operation within the harsh environment of the reactor pressure vessel. This design virtually eliminates the possibility of control rod drive mechanism penetrations through the pressure vessel head, thereby removing concern for postulated rod ejection accidents and potential nozzle cracking.

Digital Instrumentation and Control System

The Westinghouse SMR control and protection systems are founded on the same Ovation™-based digital instrumentation and control system developed for the AP1000 plant. This Ovation-based system has been licensed for use in AP1000 plants in the U.S. and China, and is expected to be completed through the Generic Design Assessment process in the U.K. in the near future. The digital instrumentation and control system includes the protection and safety monitoring system and the plant control system. The protection and safety monitoring system detects off-normal conditions and actuates appropriate safety-related functions that shut down the plant. The plant control system controls nonsafety-related components that are operated from the main control room or from a remote shutdown workstation.

On-site Power

The Westinghouse SMR on-site power system is designed for uninterruptible power operations with right-sized, diverse and redundant power sources with a main AC power system and a DC power system. The main AC power system does not perform any safety-related functions. The plant DC power system powers safety and non-safety-related systems. Safety-related DC power supports reactor trip and engineered safeguards actuation. The batteries are sized to provide DC power and to support uninterruptible AC power for purposes such as protection and safety monitoring system actuation, control room functions including habitability, DC-powered valves in the passive safety-related systems, and containment isolation. There are also two diverse, nonsafety AC power backup systems: one powered by diesel-driven generators for defense-in-depth electrical loads, and one powered by decay heat for powering the plant following a reactor trip.

DELIVERY CERTAINTY

Westinghouse is the first reactor vendor in the United States to license and apply modular manufacturing processes to a nuclear power plant design, pioneering modular construction with the AP1000 plant. Lessons learned in constructing AP1000 plants in China have already benefited subsequent units both in China and in the United States. Westinghouse will apply the improvements made to modular construction techniques through its lessons learned implementation process to benefit the company's SMR modular construction. Since the entire Westinghouse SMR, including the nuclear island and the balance-of-plant systems, structures and components, is 100 percent modular, the benefits of this experience will be significant.

The concept of 100 percent modularity enables the economic viability of a small reactor by:

- reducing the construction or assembly schedule and plant construction costs;
- improving site construction safety;
- permitting extensive supermodule outfitting and pre-assembly/construction testing;
- providing significantly higher levels of quality control;
- allowing for all elements of the plant to be shipped without requiring any transportation infrastructure modifications;
- and removing the historic long-lead procurement items such as the reactor vessel from the critical path construction schedule.

Westinghouse designed its SMR's nuclear island, for example, to be comprised of a set of as many as 15 large supermodules which are each made up of smaller submodules. The submodules are completely outfitted with systems and components. They will be fabricated, tested and inspected at off-site facilities, shipped to the plant site and assembled into the supermodules in the site's designated assembly area, where inspections and integrated testing will also be conducted. The supermodules will then be lifted and placed by crane before being connected for final inspection and testing.

Westinghouse limited the size of larger components to allow for unrestricted shipment – reducing the need for costly infrastructure and increasing the number of possible sites. Each of the modules and submodules will be manufactured to remain within the boundaries of the maximum size constraints of rail, road and barge transporters. Westinghouse can adjust module shipment size configurations to the preferred form of transportation for a particular site. Supermodule weights will be restricted based on the crane lifting limits demonstrated with the successful lifts and placements of AP1000 plant modules.

Economic Benefits

Westinghouse incorporates its full understanding of nuclear power plant economics into its SMR design, manufacturing and construction plans, leveraging its historical and current knowledge of operating plants and new AP1000 plants being constructed. Capital investment, construction duration, production costs and resource considerations have helped shape the Westinghouse SMR to maximize power output while maintaining total costs to be within the financial reach of most utilities globally.

For example, the Westinghouse SMR's compact, high-pressure steel containment vessel reduces the size of this higher-cost structure to approximately one-twenty-fifth that of a large pressurized water reactor containment while maintaining one-fifth of the larger plant's power output. By planning the containment location underground, Westinghouse eliminates the need for a Shield Building and reduces security costs. Westinghouse also simplified the passive safety systems by combining the functions of passive residual heat removal, diverse shutdown and high-head injection into a single set of components.

To reduce both cost and schedule duration for component manufacturing and for module fabrication and assembly, Westinghouse is currently working with government, university and industry collaborators to develop and implement advanced manufacturing technologies. The Westinghouse advanced manufacturing program is funding development of multiple technologies including: metals additive manufacturing, powdered metal – hot isostatic pressing, advanced welding and cladding, machining, factory automation, three-dimensional scanning and digital manufacturing. These could offer further flexibility in design with reduced lead times and costs compared to traditional forging, among other benefits such as reducing material, machining and welding activities, and, in some cases, completely eliminating welds and associated inspections.

Recently, the U.K.'s Nuclear Advanced Manufacturing Research Centre (NAMRC) conducted a design for manufacturability review and an advanced manufacturing technology benefits analysis for the Westinghouse SMR reactor pressure vessel with positive results. Westinghouse is also working with the NAMRC and Cammell Laird to benchmark non-nuclear industry best practices and to investigate additional advanced manufacturing and fabrication technologies that could further reduce the fabrication costs and schedule duration for the Westinghouse SMR structural modules.

Advancing manufacturing technology development and design for manufacturability efforts for the Westinghouse SMR will not only result in reduced manufacturing costs and module fabrication, assembly and construction schedule durations, but will also improve component quality.

Regional Benefits

The advanced modularity and construction of the Westinghouse SMR will help the company meet its goal to assemble rather than construct the Westinghouse SMRs on-site by pushing fabrication back up the supply chain into factories. With the construction of the AP1000 plants, Westinghouse successfully worked to expand the international supplier base capable of meeting the stringent quality requirements of the commercial nuclear power industry. Westinghouse will draw on this supplier base and also apply the company's sourcing model to further expand it, which will benefit new suppliers that are attained through customer-specific localization requirements. This model includes vetting bidders, visiting suppliers and developing strategic relationships where suppliers share lessons learned across the supply base to continually drive fabrication improvements.

REGULATORY CERTAINTY

The success Westinghouse has had with the first Generation III+ nuclear power plant to be licensed by the U.S. Nuclear Regulatory Commission reflects both the company's long-standing experience and commitment to bringing viable new nuclear power plant designs to market. The AP1000 plant also has been licensed in China, has interim approvals in the U.K., and is considered to be the most scrutinized nuclear power plant design licensed to date.

These recent AP1000 plant licensing experiences will further inform pursuit of the Westinghouse SMR design license.

FUTURE PLANS

Westinghouse is currently considering a number of business models for successfully deploying the Westinghouse SMR globally. Most of these models assume varying levels of sharing first-of-a-kind development and licensing costs with an industry consortium and/or government partners to advance the Westinghouse SMR toward early site permits and design certification. Companies around the globe, from a variety of different nuclear power and non-nuclear power markets, are considering the Westinghouse SMR to meet their generation needs. ■