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OVERVIEW OF ADVANCED CONSTRUCTION TECHNIQUES FOR OPTIMIZING NEW NUCLEAR PROJECTS

May 2022

Introduction

The increasing interest in Advanced Reactors (ARs) is posing some questions on how to select and leverage the most appropriate construction techniques, as they play a key role in the efficient and cost-effective deployment of nuclear reactors. ARs are significantly different from large Light Water Reactors (LWRs) in terms of generation capacity, size, components, and safety features. These attributes set the stage for a reevaluation and optimization of the construction techniques that could be used in nuclear constructions. For example, the "modular" design of small modular reactors (SMRs) creates an opportunity for prefabrication, pre-assembly, and modularization (PPM) of the structures, systems, and components (SSCs), which can allow faster and more cost-effective fabrication in a factory environment rather than field construction.

Nuclear power is an essential part of the current and future energy generation portfolio because it delivers reliable and carbon-free energy. However, recent projects to build new nuclear power plants (NPPs) using traditional large LWR designs have often resulted in schedule delays and cost overruns. The nuclear industry is pursuing several AR approaches to reduce the cost of these plants, including use of designs that are significantly smaller than traditional plants, and designs that use alternative coolants to water. These new designs are intended to provide a lower risk and more cost-effective investment opportunity for power generation. Many of the AR designs are also well-suited for non-electricity generation applications such as hydrogen production.

In support of improving the economic feasibility of new construction nuclear projects, the nuclear industry is also currently developing advanced construction techniques with the objective of reducing construction time and cost. Many techniques used in the construction of traditional LWRs, as well as techniques used in other industries, can also be applied to AR construction. Usage of proven techniques has its own benefits for predictability of project schedule and risk. Accordingly, it will be important to judiciously implement advanced construction techniques to reach the goal of an optimized construction time and cost.

This paper reviews selected advanced construction techniques that could be utilized for advanced reactor designs. The objective of this paper is to provide background on these techniques and associated discussion points relevant to EPRI stakeholders in preparation for a workshop that will be held in May 2022. This workshop will address key challenges of nuclear reactor construction.

Background

Advanced Reactor Designs

SMRs are typically defined as nuclear reactors with electricity production of 300 MWe equivalent or less [1], which is considerably smaller than the typical large LWR with over 1,000 MWe of generation capacity. This difference in power output allows SMRs to have a much smaller footprint and a simpler design. For example, some SMR designs use a containment to house the reactor vessel, steam generators, and pressurizers all in a single package. This can eliminate the need for reactor coolant pumps, large bore piping, and other systems typically found in large conventional LWRs. Many of these designs are modules, small enough to be factory-built and easily transported to the plant site and installed without any field welding of the vessel itself. As shown in Figure 1, SMR designs are significantly smaller than conventional PWR or BWR designs [2].

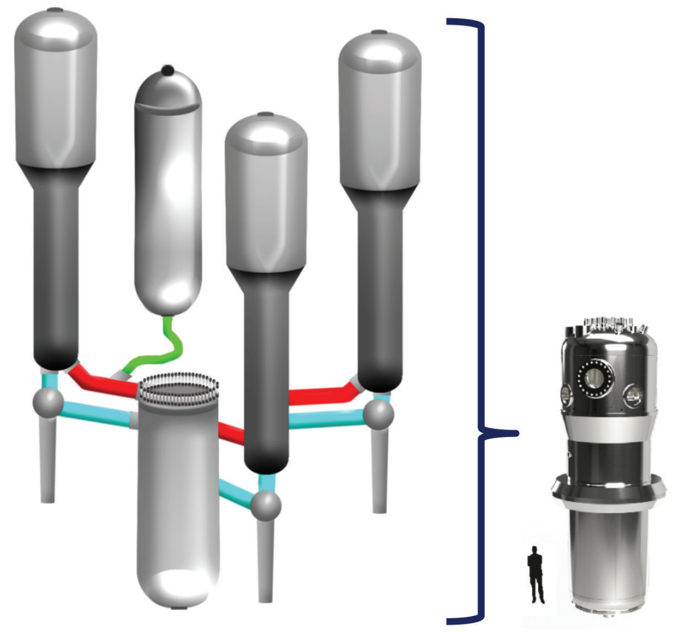

Figure 1. SMR versus PWR Size Comparison

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Non-light-water SMR reactor designs, such as high-temperature gas reactors, sodium-cooled reactors, and molten salt fast reactors, tend to differ from traditional nuclear reactors in heat sink options and involve a higher operating temperature. While the lower operating pressure means that there are fewer pressure-related safety concerns than in traditional reactors, the higher temperatures may raise new material integrity concerns and degradation mechanisms. These higher temperature designs are also typically much smaller than conventional LWRs.

Role of Advanced Construction Techniques in Nuclear Power Plant Construction

NPP construction occurred at a rapid pace in the 1970s and 1980s using conventional processes that were well-understood and effective, but time-consuming and potentially controlling the critical path. For example, the conventional cast-in-place process for building reinforced concrete structures is a serial process that includes erection of concrete forms, erection of rebar mats, placement of concrete, curing of concrete, and form removal. Plant systems and components were assembled piece-by-piece, in the field, often in sub-optimal conditions for access and exposed to the natural environment.

Some specific examples of challenges with conventional construction include the following:

- Out-of-tolerance conditions with concrete forms or reinforcement. These tolerances are typically very tight, and the field work associated with placement of concrete forms and reinforcement mats can be difficult (e.g., due to access limitations).
- Outdoor concrete placement is subject to delays from a number of factors, such as temperature variations and precipitation, which can require changing the concrete mix design or waiting until the weather improves.
- Rework for locations with inadequate consolidation. The typical use of dense rebar mats in NPP construction increases the chance of consolidation issues. Access limitations due to performing concrete placement at the construction site is a risk factor that increases the likelihood that rework is required.

Advanced construction techniques have been demonstrated in other industries to realize considerable cost and schedule savings, and offer similar potential for future NPP construction, including SMRs and ARs. EPRI's Advanced Nuclear Technology (ANT) program has been working with nuclear industry stakeholders to develop these advanced construction methods for years in preparation for the impending need to deploy a fleet of new SMRs and ARs to meet demand for clean and reliable energy. Selected areas of EPRI research include modularization [3], advanced welding [4], and advanced concrete mixtures [5].

Construction Techniques Overview

This section discusses selected advanced techniques that may be useful for both Nuclear Steam Supply System (NSSS) and Balance of Plant (BOP) construction and identify some of the challenges related to the techniques that might need further evaluation to ensure the benefits of using them.

Prefabrication, Pre-Assembly, and Modularization

Prefabrication, preassembly, and modularization (PPM) is a construction process that includes:

- Prefabrication - the manufacturing process that takes place at a specialized facility, forming a component or part to be ready for final installation.
- Preassembly - the process of joining prefabricated components and equipment together, typically making up portions of a system.
- Modularization - the consolidation of the prefabricated and preassembled pieces in a stand-alone unit (module)

The structural modules produced can be divided into three areas 1) precast concrete, 2) prefabricated steel-plates forms used for concrete placement at the site, such as Steelbricks™ 3) steel assemblies with pre-installed commodities [6].

The parallel production typical of a PPM approach significantly compresses construction time, consequently reducing overall construction costs. In fact, the use of PPM increases the number of locations where work can be performed and shifts fabrication/construction to a shop environment rather than a field environment, where quality control, especially for welding, and safety can be managed more effectively, reducing the manpower required at the construction site throughout the project.

However, PPM introduces risks not experienced in full-field construction. Adequate planning, design, and procurement should be completed up-front in the project to avoid changes in modules already produced and subsequent delays. Design changes can create

problems when the fabrication of components occurs in parallel and at separate facilities. These changes may cause issues with the module interfaces, requiring rework of already completed modules and delay of modules in progress.

Another risk of PPM is related to the maturity of the existing module fabrication infrastructure, especially regarding larger complex arrangements that include piping and electrical components. The fabrication infrastructure required to produce modules would ideally have experience in both modular and nuclear construction to reduce issues with quality, inspections, and documentation. If local suppliers are not available, significant quality assurance and transportation efforts would need to be implemented for obtaining modules from non-local suppliers. To address modular construction challenges, EPRI published a modular construction roadmap to identify gaps to improve modular construction in future nuclear constructions [3].

3D Modeling

Three-dimensional (3D) modeling is the process of representing a surface of an object in three dimensions using specialized software. Large-scale 3D modeling is a prerequisite for the development of a digital twin, developing the model backbone of such a system. It can function as the single source of truth for design changes, streamlining the process for change tracking. Because the digital twin can be aligned with real-world behavior, it could serve an important role to optimize the constructability of modularized reactors. More specifically, these software can aid understanding of how modules interface with one another and ensure that interference or other fit-up issues are resolved before fabrication and on-site installation. This optimization can avoid delays, leading to a significant acceleration in the design and construction process. Additional information on digital twin and its application is provided in Reference 7.

On-Site Storage and Laydown Areas

Due to their typically smaller size, ARs present an accident source term considerably lower than that of the existing fleet of LWRs[1]. This significantly smaller footprint along with the capability to provide ancillary services, such as process heat, may result in siting ARs within existing industrial facilities or closer to population areas where available laydown areas for construction may be significantly limited. As a result, on-site storage may be limited and just-in-time delivery is expected to become an important supply chain strategy. Variability of the schedule that could be related to a PPM approach, could make just-in-time delivery a significant challenge on site.

Concrete Structures

Concrete structures have a large impact on the aging of nuclear power plants because, unlike mechanical and electrical components, they typically cannot be replaced during the life of the plant. The design parameters of concrete structures (e.g., minimum thickness), especially for those containing NSSS components, are often based on shielding requirements rather than structural requirements, which adds complexity in addition to high seismic loads and the many specification requirements and standards that should be met during construction. As new constructions, ARs provide an opportunity for using different technologies to build concrete structures efficiently. Selected technologies that could benefit AR construction are provided below.

Precast Concrete

Precast concrete is an alternative method to cast-in-place to build linear, shell, and three-dimensional elements. Precast is commonly used in transportation and mid-rise buildings but has not been often used in nuclear power plant construction, mainly due to the element size and the need for monolithic behavior. An SMR, that is more compact than large LWRs, could benefit from precast concrete to compress construction schedule and to help avoid bulk placement of cast-in-place concrete on the construction site [8].

One of the challenges of using precast concrete is related to the joining of modules. Recent techniques, such as the ones listed below might help overcome this issue:

- Closure placements made with cast in place concrete in a reinforcement lap splice region between two or more precast elements allows the structure to behave monolithically,
- Shear keys are a series of protruding and recessed features in neighboring segments that allow transferring force through bearing of the interlocked features,

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[1] Consequently, the reduction of the Emergency Planning Zone (EPZ) to approximately the size of the Exclusion Area Boundary (EAB), from 10-50 miles to 3000-4000 feet, is being realized in some cases and can be as small as the Protected Area (PA).

- Filigree precast construction uses a narrow plate of precast concrete connected at the site with cast-in-place concrete,
- Bolted connections eliminate the need for placement of concrete in the field.

Other challenges related to precast concrete include transportation, erection, and the final alignment of precast sections with exposed reinforcement. 3D modeling could prove to be a useful tool for precast concrete such as with PPM.

SC-Walls

Steel-plate concrete composite (SC) modules, like precast concrete, are a common technique used in modular construction. SC modules consist of large steel panels (faceplates) that can be positioned into parallel plane to build 2D or 3D forms connected by ties. Neighboring panels are then welded together on-site, and concrete is poured between the panels. The panels serve as the reinforcement, eliminating the need for most rebar. The rebar congestion issue, often encountered in nuclear construction, is reduced to only basemat and other special connections.

Experience with large modules indicates that the convenience of this method should be balanced with the need for internal stiffening and thicker faceplates to resist lifting and erection loads. Smaller SC modules have been more successful than large and high-complexity SC modules. The adoption of SC modules could benefit construction in several ways, such as reducing the time for placing thick concrete walls, avoiding the use of removable formwork, and simplifying commodities installation. Much lighter than precast concrete, SC modules are less limited by transportation challenges. Experienced erection personnel are important to the efficiency of SC module installation and to minimize module distortion, both during lifting and welding activities [9].

Self-Consolidating Concrete

Self-consolidating concrete (SCC) is a highly flowable, non-segregating concrete that does not require compaction using external mechanical force to consolidate. SCC placement is easier than conventional concrete, making it especially useful in complex forming systems and around congested forming without the aid of consolidation. The use of SCC allows for decreasing labor in precast concrete manufacturing facilities and increasing production rates. This technique is raising interest in the nuclear industry due to its advantages in terms of mechanical properties and higher impermeability [8, 10]. Additional information on SCC is provided in EPRI 3002005228 [11].

Welding Techniques

Advanced welding techniques can improve construction through higher welded connection strength, increased speed of fabrication, and lower flaw rates, without increases in necessary craft skill. An overview of some of the advanced welding techniques that could be used for steel-plate joining between modules and large bore pipe installation in an AR is provided below.

Improvements in Tungsten Inert Gas Welding

Hot-wire gas tungsten arc welding (GTAW) is an improvement to the traditional GTAW process. It allows for much higher deposition rates than GTAW. Another improvement is GTAW with reciprocating wire feed, which through the use of vibratory effects of a hot wire, agitates the molten weld pool and disrupts the surface tension, in addition to a hot wire current, which deposits higher weld energy in the welding region, saving up to 20% in cost and smoothing welds. The operation of both is very similar to GTAW welding but the consumable wires are fed through a wire feed system rather than manual feed. The wire feed system is a semi-automatic process that increases the rate of deposition, without increasing the necessary craft skill or flaw rate. The size of the torch can limit its use in narrow and deep weld locations. In addition to the space limitation, copper contamination of the weld can occur in case a short circuit occurs and if not cleaned properly [12]. Code approval is not a concern due to the similarity to GTAW which is approved by AWS D1 standards and ASME B&PV Code Section IX.

Friction Stir Welding

Friction stir welding is a solid-state process where a rotating tool joins materials through plastic deformation and frictional heat. The weld is usually susceptible to fewer defects compared to conventional welding because friction stir welding remains below the material's fusion temperature. The process permits the joining of dissimilar and exotic materials where dissolution and element precipitation are of concern [13]. The rotating tool cost and life limit the process use case. Friction stir welding is currently approved through ASME B&PV Code Section IX.

The highest opportunity for application in ARs lies in thin, solid sections, such as plates and bars. Currently, friction stir welding has been mainly used with aluminum. Experience with steels, which are stronger, harder, and have higher melting temperatures, is limited. Additional building experience and use cases with steel will provide more information on how this technology could be used in the nuclear industry.

Laser Beam Welding

Laser Beam Welding (LBW) is a fusion joining process that uses a laser (e.g., CO_2, Diode) as the welding heat source; the material increases in temperature due to the absorption of the laser light. LBW is usually autogenous, underlying the importance of fit-up, joints, and cleaning procedure before performing the weld. The use of a filler wire has been found to widen the fit-up tolerance and can help control the formation of inclusions during the process. LBW is approved through ASME B&PV Code Section IX [13].

LBW enables high precision and high-speed weldments that are not possible by conventional arc-based methods. The narrow beamwidth results in high energy density, and a low and localized heat input. Consequently, the heat affected zone (HAZ) and fusion zone are narrow, and the distortion is low. While providing many benefits, this technology has still a high capital cost compared to other welding techniques, due to laser costs and the required skilled operator.

Electron Beam Welding

Electron beam welding (EBW) is a fusion joining process that uses a beam of high-energy electrons. As the beam impacts the metal, the kinetic energy of the electrons is transformed into heat, which melts the two metals together. High vacuum is used to perform the welding to prevent dissipation of the electron beam and avoid oxidation of the metal. Due to the high energy density of the beam, this method is capable of forming deep and narrow welds. EBW is a well-established process used in other industries, and it is approved through ASME B&PV Code Section IX.

EBW requires vacuum chambers that encompass the components to be welded. There are a select number of vacuum chambers in the world that can handle large components such as small modular reactor (SMR) pressure vessels. For this reason, EPRI and other collaborators are proposing Modular In-Chamber (MIC) electron beam welding as an alternative approach. MIC-EBW consists of individual modular ring sections that can be stacked on one another and reconfigured to different heights to address each pressure vessel girth weld [14]. This concept has been previously used in the shipbuilding and pipeline industry and could be readily implemented by the nuclear industry at a considerably lower cost than building large vacuum chambers.

Automatic Welding Techniques

The automation of the welding process allows for welding in narrow spaces (e.g., welds between the reactor vessel head and the nozzle) or in areas with restricted access, improving deposition rates and reducing the defects rate compared to manual methods. Welding can be automated with traditional processes (such as SMAW) and advanced processes (laser and electron beam). The automation also requires fewer operator skills, reduces fatigue due to the constant precision required by the welder, and can help decrease the welding time and cost. Skilled programming is necessary to design, implement, and validate the welding route. Automatic welding could be combined with image processing technologies and machine learning to improve welding consistency by identifying possible flaws formation and correcting them online [15].

Excavation Methods

Excavation work is notoriously expensive and time-consuming, but is necessary to construct the foundations of the power block, BOP, and ancillary service structures. Furthermore, less excavation also reduces the amount of engineered backfill required once the structure is completed. Excavation is particularly relevant for advanced reactors because many of these designs rely on below-ground installation to achieve specifications for security and passive safety. Alternatives to traditional drilling and mechanical excavation methods include precision blasting, chemical/foam expansion, and shaft sinking. Additional information on these methods is provided below.

Shaft Sinking

Shaft sinking, or vertical shaft construction, excavates an area vertically from the top using a lowering unit and a shaft or a bore with initially no access to the bottom of the shaft. The shafts are lined with concrete as the excavation process takes place. This process typically takes place continuously until the maximum depth is reached, a best practice from tunnel boring. The more advanced shaft machines are equipped with a telescopic roadheader, which can swivel up and down and rotate [17]. The shaft machines include drainage systems for excavated material from the shaft bottom, which could

be pumps with channel rotors or jet water pumps [18]. This method is typically used in soft and stable soil and it is capable of excavating up to approximately 12 meters in diameter and 1,000 meters deep [19]. Shaft sinking is expected to be applicable to AR designs that are below grade, and could reduce construction schedule by minimizing the excavation size and need for engineered backfill. Shaft diameter size, equipment availability, and experienced craft may pose challenges with this excavation method. The potential forhigh costs are expected to be easily offset by the faster excavation rate and overall reduced excavation required [20].

Precision Blasting

Precision blasting uses explosives for excavation of rock instead of a mechanical excavation and can remove or loosen a large portion of rock in a short amount of time while requiring much less personnel and equipment than other excavation methods. This technology is widely used outside of NPP construction. Although precision blasting is a faster method compared to other traditional techniques, it does require extensive training and knowledge for the operators, as improperly controlled blasting has the potential to damage the local geology, and the surrounding personnel and environment. For this reason, blasting has been highly regulated and could be a site-specific challenge [15].

Chemical/Foam Expansion

Chemical or foam expansion is based on a non-detonating chemical compound that produces gas that expands very quickly when ignited, entering the microfractures of the rocks causing shearing or splitting. This allows removing rocks or other hard components without the dangers of high-energy explosives. This process can allow for very precise excavations without the disturbance of blasting, which is ideal for excavating in the vicinity of active nuclear reactors or other sensitive industrial facilities, such as chemical facilities [8].

Conclusion and Next Steps

These advanced construction techniques could improve AR deployment if they can reduce the construction schedule without undue risk or complexity. Advanced construction techniques are one of the topics that will be discussed during a workshop that will be hosted by EPRI in May. The workshop will provide an opportunity for EPRI stakeholders (e.g., Future AR owners, Original Equipment Manufacturers (OEMs), architectural designers, and construction contractors) to reflect on and discuss the role of advanced construction techniques and what the next steps are to set the stage for a successful deployment of ARs.

Questions that could prompt discussion during the workshop are provided below:

- The smaller scale of SMR designs lend themselves more to PPM compared to traditional large NPPs. How can the right level of modularization be determined for a particular design that optimizes advantages and reduces risks?
- How can advanced design, fabrication, and construction tools be used to improve communication between stakeholders in an environment where many suppliers are unfamiliar with working in the nuclear industry culture?
- How can the nuclear industry prepare an adequate supply chain that can meet nuclear standards and the demand that will come with AR construction?
- Where do advanced concrete form/placement techniques improve the construction schedule over cast-in-place techniques? How can this trade-off be determined in the design phase?
- How can advanced welding techniques facilitate design and fabrication methods that are not conventionally available? How can advanced welding processes preclude troublesome degradation mechanisms or reduce monitoring and inspection demands during AR operation?
- In what circumstances would conventional fabrication, welding, and/or construction methods still be the optimal approach?
- What industry standards, guidelines, and regulations need to be created or revised to capture the opportunity presented by advanced construction techniques?

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Advanced Nuclear Technology

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