MODULAR CONSTRUCTION FOR EVENTUAL DECONSTRUCTION AND DECOMMISSIONING - 10300 [1]

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ABSTRACT

Modular construction techniques will be a key element of the new plants that are being built and those that are planned as a result of the worldwide renaissance in nuclear power. Modular construction has the advantages of greatly simplifying the complex construction of a nuclear power plant and significantly reducing the construction schedules. This in turn translates into major capital cost savings for the project.

Even though the upfront costs are the main driver of modular construction, the dividends from modular construction will continue long after the completion of construction of the nuclear power plant. The eventual decommissioning phase will also benefit significantly from the modular construction and the application of advanced construction technologies.

It is now recognized in the industry that the decommissioning considerations should be a part of the reactor development process right from the design phase of the project. It is also important that eventual decommissioning of the new reactors will need to take into account the construction techniques used during the building and the wrecker ball approach of the past may not be the best approach from many perspectives. A systematic isolation of systems, decontamination, and modular deconstruction will provide the best alternative for decommissioning and dismantling of these plants when they enter the decommissioning phase in their lifecycle.

INTRODUCTION

The nuclear power generation is in the midst of a renaissance as the energy demands across the world increase and future projections show nuclear power gaining a greater share of the energy mix. The net electricity generation worldwide, as a part of the energy mix, is projected to total 33.3 trillion kilowatt-hours in 2030, nearly double the 2005 total [1]. Even though natural gas and coal are projected to remain the main fuel sources for electricity with projections at 25% and 46%, respectively, the electricity generation from nuclear reactors is projected to account for approximately 11% of the total. Significant expansion of nuclear power on the world horizon is substantiated by the planned addition of anywhere from 60 to 130 new reactors worldwide over the next twenty years.

[1] The views expressed in this paper are those of the author and do not necessarily reflect the views of his employer or the clients.

Several new reactor designs, so called Gen III +, are being built around the world and several more designs are in the certification stages. Advances in materials technology, manufacturing, heavy equipment handling, transportation, and 3D computer simulation have provided the best chance yet that nuclear power plants can be built and operated in a cost-competitive manner as compared to other electricity production sources.

Modular construction techniques will play a key role in the building of the new nuclear power plants. Modular construction has the advantages of greatly simplifying the complex construction of a nuclear power plant and significantly reducing the construction schedules and the capital costs for the project. Interest in modular construction is not surprising as the companies and utilities have seen the projected construction costs soar from the industry and government estimates of only a few years ago. Thus, the main driver for modular construction and application of advanced construction technologies remains the upfront capital costs. However, the dividends from modular construction continue through the operating period where repair\and replacement of systems and components is facilitated by the modular designs of the systems. After the long operating period, that for the newer plants may extend to sixty plus years, the eventual decommissioning phase will also benefit significantly from the modular construction.

This paper reviews the modular construction of the new reactor designs with a view towards eventual decommissioning at the end of their operating period. It captures the significant benefits of modularization and application of other advanced construction techniques. It also describes the issues related to their implementation and their impact on the eventual decommissioning phase of the new reactors.

MODULARIZATION IN CURRENT PROJECTS AND NEW REACTOR DESIGNS

The past practices in building power reactors involved building the project entirely at the site and the current fleet of US commercial reactors was built in that manner in the past decades. Since then, the construction technologies and infrastructure have evolved dramatically and construction of future nuclear plants is now expected to be increasingly modularized. In fact, modularization is being successfully implemented in Japan and elsewhere in the new reactors that are currently under construction. In some cases modularization has been adopted on a whole-scale basis for the entire project. In other cases, it has found a limited use in parts of the project activities. Toshiba has modularized the ABWR construction in Japan. Hitachi and GE have also modularized ESBWR to a large degree. AREVA's EPR units under construction in Europe have adopted a modular approach for the balance of plant components while the main nuclear island remains as a site-built activity. AECL's ACR design uses extensive modularization with parallel construction strategies to reduce the construction time. Almost all future designs use some degree of modularization.

Advanced technologies are now playing a greater role in the construction of the new power plants. These include not only the advanced construction technologies but also the computer technologies such as 3D modeling that allows design activities to be specific, precise and cost-effective. Prior to even initiating any fabrication, construction, and installation activities for structure, and components (SSCs), the whole system can be designed in segments and fitting of the segments can be examined. Other areas of advanced technologies of relevance include the advanced concrete aggregates, very heavy lift (VHL) cranes and equipment, and the transportation equipment. In addition, the regulatory changes have also positively contributed to the new build activity for nuclear reactors.

Key Construction Technologies

Three construction technologies are of specific interest.

Modularization: Modular construction allows parallel construction activities to proceed with significant reductions in construction schedule. Modular construction can include the system modules that are fabricated off site under controlled environment in a fabrication facility as well as the structural modules that are pre-fabricated and transported to the site for installation. In practice a module can consist of an assembly of multiple components such as structural elements, piping and valves, cable trays and conduits, instrument racks and electrical panels, access platforms and ladders or stairs, and other items.

Slip Forming: Slip forming allows continuous construction of a structure. The concrete is poured continuously between two climbing wall faces and multiple platform levels allow for work to continue. By using this technique, construction time of a concrete reactor building is cut down significantly.

Open Top Construction: Open top construction facilitates installation of large components and large modules. In concert with the modular construction, it leads to significant reduction in the project schedule. In open top construction, the reactor building is partially completed and left open at the top and large components can be lowered into place from above with heavy lift cranes and then installed. Open top construction permits more activities to be progressed in parallel because the placement and installation of modules can occur through the open top of the structure with the use of heavy lift cranes.

Advantages of Application of Advanced Construction Techniques

The modular construction in concert with the other advanced construction techniques has the most potential to help realize the nuclear renaissance, especially in the United States. The future of new build depends on two primary factors: licensing regulatory reform and the capital costs for building the new power reactors. Through the new combined construction/operating licensing application (COLA) process, The US Nuclear Regulatory Commission (NRC) has put in place a more streamlined and simplified licensing proves for the new reactor projects. However, the capital costs for the new build, in terms of "overnight costs" remain a major concern. These cost estimates have increased sharply in the past several years as shown by the data summarized from industry sources [2, 3] in Table 1.

Table 1: Capital Cost Estimates

Estimate Year	Capital Cost per kWe installed	Reference Plant Cost 1100 MWe
2000-2002	$1,200 to $1,500	$2 billion to $4 billion
2006-2007	$3,600 to $4,000	$4 billion to $4.5 billion
2008	$5,500 to $8,100	$6 billion to $9 billion

Realistically, the capital costs are likely to be in the range of $2,000 to $4,000 per kWe installed depending on the reactor design, location and other site-specific factors.

Modular construction can significantly reduce the costs of the reactor building as well as the construction of other major buildings at the site and thus help contain the capital costs for the project.

Construction schedules can also be shortened by a combination of the technologies, such as slip forming with modular design technology. Through continuous pouring of concrete at a controlled rate, slip forming allows vertical walls to be constructed at a rate of approximately two meters per day compared to a typical value of about one meters per day for standard construction. Similarly, slip forming with modular floor design technologies uses short sections of steel formwork, that are lowered into place, welded on to the supports embedded in the concrete walls, and filled with concrete.

While the modular construction techniques are new to the nuclear power industry, they have been employed for decades in other industries, such as chemical industry, petroleum industry, and shipbuilding. Albeit, given the nature of the nuclear industry, application of the modular construction requires many other pieces of the puzzle to fit together, for example, the use of open top construction, use of VHL cranes, and regulatory development and acceptance of the new techniques. Prefabrication of large modules in off-site shops saves time and allows for construction under controlled conditions with less chances of rework and the modules can be transported to the site by truck, rail or barge, and then assembled on-site with the use of heavy lift cranes. It is in this area that the modular construction can have the biggest impact.

In past construction practices, the fabrication of the mechanical and electrical systems and components was done on-site and typically awaited until the civil work on the reactor building was complete. Modularization allows maximum utilization of parallel construction activities in civil, mechanical and electrical areas to proceed. Many of the mechanical/and electrical modules for equipment, piping, I&C, and electrical systems can be built off-site. The interfacing systems are typically included in the modules and can facilitate installation.

The advantages of the advanced construction techniques can be summarized as follows:

- Reduction in project schedule by allowing parallel construction activities on system and structural modules
- Reduction in manpower needs at the project site
- Uniformity in systems and structural modules for multiple units at the same site and/or of the same design at different sites.
- Better quality control through initial testing of the components at the fabrication facility.
- Reduction in facility footprint
- Reduction in system components
- Reduction of work congestion at the construction site
- Mass production capability providing economies of scale
- Significant cost savings.

In addition to the technologies discussed above, the following are also worth noting.

Recent advances in the composition of concrete aggregates have allowed improved strength, corrosion resistance, curing at low temperatures, and better workability. They have also facilitated the application of slip forming and modular construction of structural elements. The low-heat concretes also makes the large volume pours practical and pours up to several meters deep can be utilized for construction sections such as the base slab. Construction of areas as the base slab, containment walls and internal structural walls also benefit from prefabrication of the rebar assemblies. This eliminates the time consuming construction practice of placement of individual bars at the site.

Use of automatic welding that reduces the time required for welding and improves the weld quality. Its application especially in the areas of steel containment liner and the piping systems reduces the schedule significantly for such construction activities. Another area of interest is prefabrication of concrete reactor vessels. Installation of the reactor vessels is the biggest milestone in the construction schedule of a power plant. The reinforced concrete containment vessel is a unique feature of the ABWR projects. The VHL cranes of today facilitate all this because they can lift modules weighing approaching 1000 tonnes.

Current Experience in Modular Construction

Modular construction has been successfully implemented in Japan by Toshiba, Hitachi, and Mitsubishi in designs and/or at project sites. The new build projects have shown shortened construction schedules and major cost benefits, primarily through simultaneous manufacture of critical path components at off-site locations. Open top construction and VHL canes have allowed the placement and installation of very large scale modules into the reactor building.

Recent examples of modular construction include Shimane 3, a 1373 MWe ABWR, where Hitachi is employing modular construction techniques. The construction started in December 2005 and is three quarters complete with the unit scheduled for going on-line in December 2011. Shimane 3 is using a total of some 190 modules and many being produced in an off-site dedicated factory. Large capacity cranes have been built and are being employed at the site. The vessel was installed in July 2009 by one of the world's largest crawler cranes with a maximum rated load capacity of 930 tonnes.

At Kashiwazaki Kariwa-7 in Japan, the seven floors of the reactor building were divided into three modules and fabricated in a pre-assembly yard before the pieces were successively lifted into place by a VHL crane. The heaviest and most complicated module was the ‘upper drywell super large scale module’ which consisted of a gamma shield wall, pipes, valves, cable-trays, air-ducts and their support structures. This module weighed 650 tonnes.

Another example is the Westinghouse AP1000, a 2-loop PWR, where the modular approach to design defines modules within each major structure: containment, auxiliary building, turbine building, annex building. The modular design consists of a total of approximately 350 structural and mechanical modules. The construction time for the plant is anticipated to be 48 months and the design approach reduces the number of components by approximately fifty percent from a standard 1000 MWe PWR.

At the world's first AP1000 in China, Sanmen Unit 1 which is projected to go on-line in August 2013, first of the nuclear island modules, has been successfully hoisted into place, using a high capacity crawler crane. This module is the largest component to be used in AP1000 construction.

It measures 20 m long, 14 m wide and 20 m high. For the AP1000 design at Sanmen, more than 18 modules weigh more than 500 tonnes, while another 50 weigh in excess of 100 tonnes.

At another project in China, at Lingao (Ling Ao in Chinese literature), modularization has been used for various components. At Lingao-4 (also listed as Ling Ao Phase II Unit 2; a Chinese PWR, CPR-1000, derived from AREVA design), the containment dome was assembled as a single module weighing 143 tonnes, with a diameter of 37 meters and a height of 11 meters. This substantially reduced the time it normally takes to assemble the dome by moving various segments into place.

AREVA's EPR designs under construction in Europe (such as Okiluoto 3 in Finland) have adopted a stick build approach but use a modular approach for the balance of plant components.

Above discussion is based on the information from the vendors [4, 5, 6], recent progress reported in the industry [7] and a technical documents and publications from the IAEA [8, 11]. [Also, note that ESBWR is another advanced BWR, and US EPR is a version of AREVA's EPR for the US market]. A few examples of advanced technologies in construction are illustrated in Figures 1-4.

AECL has used the modular construction in the CANDU 6 Qinshan project in China. AECL is also adopting the same strategy including advanced construction technologies for its ACR-700 and ACR-1000 reactor designs. The AECL claims that the designs using the latest construction methods can achieve a 36 month construction period for a replicated unit [9].

Issues and Challenges

Key issues for application of advanced construction techniques can be summarized as follows.

- Advanced Construction Techniques discussed above (modularization, slip forming and open top construction) require considerable advance planning and detailed engineering to support the fabrication and assembly of large modules for the structures and systems.
- Modular construction involves bigger logistical challenges. This involves construction or fabrication at off-site facilities and transportation over long distances. Transportation by barge is the preferred route for large modules. The land route transportation restrictions may limit the design and the size of the construction modules.
- Some activities may involve first-of a- kind engineering activity.
- Modularization at nuclear power plant construction involves the use of heavy lift cranes. The VHL cranes are a costly equipment to erect and operate at the site.
- Modularization and off-site fabrication may require setting up or expanding existing factories or manufacturing facilities to accommodate the module size and scope. This may involve additional expenses.
- Larger modules may need to be designed and fabricated as multiple sub-modules, which can then be assembled at the site.
- Open top construction methods will require the use of a temporary weather cover.
- A review of the regulatory codes and standards has not identified any issues at the current project sites. However, future deployment of these technologies in the US and other countries may require assessment of compliance with national codes and standards and/or revisions to such codes and standards.
- Module connections to the structure must be precisely designed and the installation sequence determined in advance. Reliability of these joints and connections may require additional analytical methodologies and their validation.

Figure 1: Shimane-3 Construction (Image courtesy: Hitachi)

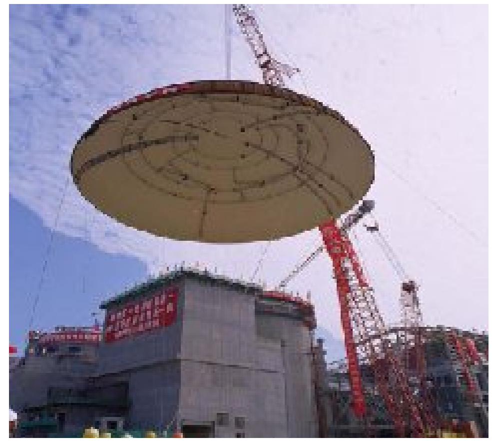

Figure 2: Lifting the dome module into place at Lingao-4 (from Reference [11])

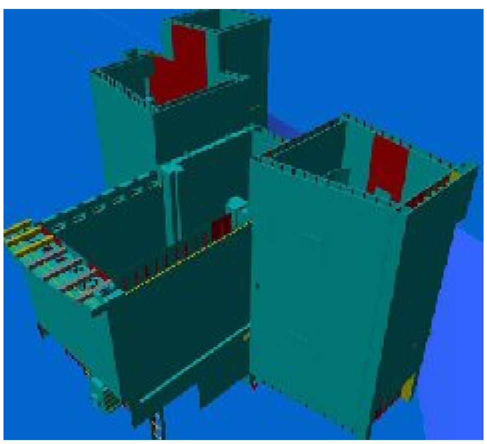

Figure 3: A structural module for AP1000 (Image courtesy: Westinghouse)

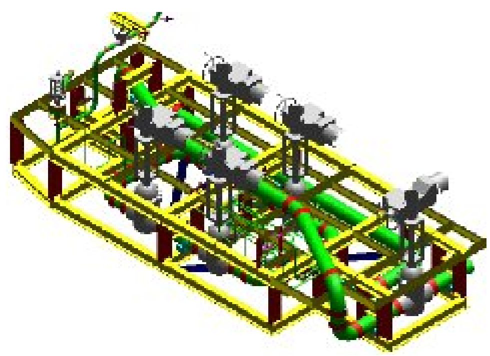

Figure 4: A piping module for AP1000 (Image courtesy: Westinghouse)

Early Decision and Application

Decisions to apply modularization, open top construction and other advanced technologies must be made early in the project, ideally at the conceptual design stage. The equipment modules should be designed to fit into their spaces in the appropriate structures or structural modules. The structural modules must be designed taking into account the lift capacity of the cranes to be used at the site and other logistics such as transportation to the site. From transportation perspective, barges can transport much larger and heavier modules than the truck transport. Larger modules can also be planned as multiple sub-modules that can then be shipped to the site and then assembled into the larger modules prior to installation.

The application of modularization requires planning of the system as a whole. This allows equipment to be designed to fit into a structural module, sub-modules to be designed to fit and form a large module, modules sizes and weights to be within the capacity of the transportation mechanism, the modules to be within the capacity of the heavy lift crane for installation.

MODULAR DECONSTRUCTION AND DECOMMISSIONING

Decommissioning is a unique part of the lifecycle of a nuclear power plant and it requires a different set of activities to be planned and implemented. From the past lessons learned from decommissioning of existing reactors, recognition of the above was not always a fact. Also, from the past lessons, decommissioning was not given much consideration during the design phase of these reactors.

By and large, the reactor designs are optimized for cost economics and defense-in-depth issues. Because of the long operating period, and possible license extensions, the decommissioning phase is so far into the future, that it dose not always get the appropriate degree of emphasis during the design stage. This early input into the design process is very important to the ultimate decommissioning of the reactors. A more complete discussion of the decommissioning factors during the design stages is available in Reference [10].

Just as the decommissioning considerations should be a part of the design process from the very beginning, decommissioning phase of the new e\reactors will have to adapt to the new design approaches. Eventual decommissioning of these reactors will have to take into account the construction techniques used during their building and the wrecker ball approach of the past may not be the best approach from many perspectives. A systematic isolation of systems, decontamination, and modular deconstruction will provide the best alternative for decommissioning and dismantling of these plants. In that regard the availability of the large capacity cranes and handling equipment will be important. This has been a significant issue at many of the current decommissioning sites.

Modularization and advanced techniques applied during construction will facilitate intact removal of large components during the decommissioning phase. One piece removal of reactor vessel has many advantages. Precluding the necessity of segmentation of the pressure vessel and other large components has benefits in terms of reduction in worker radiation exposure, reduction in hazards for potential dispersion of contaminants, reduction in total waste produced, and more cost effective waste disposal. In a future society, where recycling of the material is not only environmentally sound but also an economic reality, modular construction and deconstruction will facilitate dismantling of the systems with a goal towards recycling of the materials.

Another area of interest to the decommissioning phase is the disposal of low level radioactive waste, which is a significant part of the decommissioning project cost. [Note that disposition of the spent nuclear fuel is also a significant national issue in most countries; however, this is outside the scope of this paper]. The low level radioactive waste disposal and major component disposal can account for 30 to 60% of the total project costs based on the industry experience in the United States. The newer designs result in significant reductions in the decommissioning waste produced and hence provide an overall reduction in the decommissioning cost. This is achieved by a reduction in the footprint of the structures, a significant reduction in structural materials, as well as a significant reduction in the plant systems and components. This is discussed in more detail below.

Impact of New Designs on Decommissioning

One of biggest impacts of the new reactor designs on the decommissioning phase is the overall reduction in total amount of construction materials used. As shown by the data in Table 2, the new reactor designs use significantly less rebar and concrete than the past designs of the reactors that are currently operating. For example, on the per MWe capacity installed, the current designs use less than half the concrete. For comparison, the AP 1000 design uses about one third the amount of concrete than a typical PWR in operation today in the US and about one fifth of Sizewell B in UK. Similar material reductions are in the rebar steel.

Table 3 illustrates for three new reactor types how the designs provide very significant reductions in various components. Note that the reactor design life and fuel cycle for these three designs are similar. These data are compiled from the information available from the vendors [5, 6, 7] and other industry information.

For eventual decommissioning this translates into significant reductions in schedule, material handling, waste disposal, and total costs.

Table 2: Concrete and Rebar Comparison

Era	Concrete	Rebar
1970s	m^3/MWe installed 190+	t (metric)/MWe installed 40+
Current Designs	90	40
Comparisons Sizewell B (UK) US typical ABWR AP1000	Total Concrete m^3 520,000 300,000 351,000 <100,000	Total Steel t (metric) 65,000 46,000 <12,000 Approx.10,000

Table 3: Reduction in Components for New Reactor Designs

AP1000	ESBWR	US EPR
Design life - 60 years	Design life - 60 years	Design life - 60 years
18 month refuel cycle	24 month refuel cycle	12 to 24 month refuel cycle
Reduction in components • 87% less control cable • 80% less piping • 50% fewer valves • 35% fewer pumps	Reduction in components • 11 systems eliminated • 25% of pumps, valves and motors eliminated	Reduction in components • 44% fewer heat exchangers • 50% fewer tanks • 47%fewer valves • 16% fewer pumps

The experience with decommissioning projects so far shows that removal activities for systems and structures (including decontamination, demolition, and removal) and their disposal can account for approximately 60 percent of the decommissioning costs. The opportunity to optimize the reactor with respect to eventual decommissioning during the design stage can not be overstated. Once the reactor has started operation and the core gets irradiated and the primary system components become radioactive, decommissioning costs of the reactor are already a permanent reality. Thus, reduction in system components and structural materials has greatest advantage in reducing the amount and type of radioactive materials that must be dealt with during the decommissioning phase. System and structural design optimization with respect to decommissioning considerations reduces the eventual decommissioning cost of both the removal activities and the disposal costs for the waste. This is illustrated in Table 4, where low level radioactive waste volume from AP1000 design is compared with a current 1000MWe PWR. The decommissioning waste in this category for AP1000 is nearly half that of the standard PWR.

Table 4: Waste Volume Comparison

Waste Volume	Current PWR 1000 MWe	AP1000
Operational (Dry and Wet Wastes)	270 m^3/y (9540 ft^3/y)	163 m^3/y (5760 ft^3/y)
Decommissioning waste (low level)	18,340 m^3 (647,500 ft^3)	Approx. 10,000 m^3 (353,000 ft^3)
Comparison from an actual decommissioning of a full size reactor: Decommissioning waste (low level) from Main Yankee : 19,800 m^3 (700,000 ft^3)		

A reduction in the system components and a modular design will facilitate dismantlement activities leading to cost reduction. An additional benefit of an optimized design will be the reduction in the overall radiation exposure to the decommissioning workers.

From the discussion above it can be surmised that decommissioning costs for systems and structures for the new designs will be significantly lower. This is especially relevant to the reactor designs where the secondary systems are not expected to become contaminated (for example the AP1000, ACR-700 and ACR-1000), even though this is dependent on the reliability of the steam generators and the ability to contain the radioactive material within the primary system boundary throughout the plant life. For the BWR designs (ABWR and ESBWR), the decommissioning costs for systems and structures are generally higher due to the contaminated secondary system components. Nevertheless these costs are also expected to be much smaller than the costs of the reactors being decommissioned today.

CONCLUSIONS

Significant savings in schedule and capital costs can be realized in new nuclear power projects through the application of modular construction, open top installation and other advanced construction technologies. The modular designs allow a smaller foot print for the structures with significant reduction in structural materials such as concrete and rebar. The new designs also provide a significant reduction in the systems and components. These, in turn facilitate dismantlement activities during the decommissioning phase and will reduce the overall costs of decommissioning. An additional benefit will be the reduction in the radiation exposure to the decommissioning workers. Thus, optimization of the new reactors designs for decommissioning is necessary along with the other main technical and economic factors. Modular construction of new reactors will allow modular deconstruction during the decommissioning phase. This will ensure that their decommissioning is cost-effective, safe, and timely when they are eventually retired.

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