Basic study on module technology for shortening i-SMR construction period: Effect of Modularization by Construction Package

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1. Introduction

The Republic of Korea possesses some of the most advanced Nuclear Power Plant (NPP) construction technologies in the world. In particular, the APR1400 has developed and integrated optimal construction management techniques through extensive experience, establishing a competitive position in the international market with a strategy focused on time and on budget.

However, research on the construction methodologies for integrated Small Modular Reactors (i-SMRs) is still limited, especially in the area of modularization techniques. This study offers a foundational analysis of modularization technology applicable to i-SMRs, leveraging the construction experience of the APR1400. Additionally, the study provides the advantages of modularization from both the Construction Package and Critical Path perspectives.

2. Background

2.1 Construction Package

The Construction Package (CP) system in the APR1400 is structured to systematically divide the various construction processes, ensuring an organized and efficient approach to the construction of NPPs. Additionally, it is utilized to calculate the progress rate in process management based on the construction ratio [1]. The construction framework of the APR1400 consists of 20 packages, labeled from CP-C1 to CP-E4. A detailed classification of these packages is provided in Table. 1.

- CP-C (Civil): Covers civil foundation work.
- CP-A (Architecture): Focuses on exterior and interior Finishing, including Painting.
- CP-M (Mechanical System): Encompasses the installation of mechanical systems such as the Nuclear Steam Supply System (NSSS), Turbine, and HVAC.
- CP-P (Piping and Insulation): Involves the fabrication and installation of primary and secondary Piping and Insulation.
- CP-E (Electrical and Instrumentation & Control System): Covers the installation of Cabling, Electrical and Instrumentation & Control (I&C) systems.

The implementation of the Construction Package system offers several advantages: Clearly defining the scope of work, optimizing resource allocation with proactive assignments and integrated risk mitigation, and delineating roles and responsibilities for each CP are essential for preventing task duplication and ensuring efficient project management.

Table. 1: Classification of CPs

PKG No.	Package	Components
CP-C1	Foundation Excavation	Site Development Work Main building foundation
CP-C2	Concrete Production Work	Concrete production and transportation Batch Plant, Crusher Plant
CP-C3	Outdoor Underground Installation	Outdoor Underground Piping (Sewage and Rainwater) Outdoor Underground Structure
CP-C4	Cooling Water System	Water InWater ntake structures and drainage channels
CP-Y1	Underwater Drainage Structure	Underwater Water Intake Structure
CP-A1	Construction of Main Building	Reactor Containment Building (RCB) Auxiliary Building (AB) Compound Building (CPB) Turbine Generator Building (TGB)
CP-A2	Architectural Finishing Work	Interior and Exterior Finishing Materials for Buildings, Door
CP-A3	Painting Work	Structural Finish Painting
CP-M1	General Equipment Installation	General Auxiliary Equipment (Pressure Vessels, Pumps, etc.) CLP(Concrete Liner Plate), SLP(Steel Liner Plate), Equipment Hatch
CP-M2	Condenser Installation Work	Condensers and Low-Pressure Water Heaters and Equipment
CP-M3	Turbine Generator Installation	Turbine Generator Peripheral Devices and Piping such as Moisture Separator Reheater
CP-M4	HVAC Installation	Duct Manufacturing and Installation HVAC equipment
CP-M5	Nuclear Steam Supply System(NSSS) Installation	Reactor Pressure System Lifting and Installation Nuclear Fuel Handling and Transport Facility NSSS Auxiliary System Equipment
CP-M6	On-Site Assembly Tank Installation	Tank Material Supply, Manufacturing, Assembly and Installation
CP-P1	Piping Installation	Embedded, Buried, Drainage Pipe Supply and Installation Supply and Installation of Pipes (Primary and Secondary System)
CP-P2	Insulation Work	Insulation Work for Pipes, Mechanical Equipment, Tanks, etc.
CP-E1	Electrical Equipment Installation	Power and Lighting for Construction Purposes Cable Tray Conduit
CP-E2	Cable Laying and Wiring Work	Cable Laying and Terminal Connection Work
CP-E3	Outdoor Switchyard Installation	Electrical Devices and Cable Laying related to Outdoor Switchyard
CP-E4	Instrumentation and Control (I&C) Installation	I&C Equipment

2.2 Critical Path of APR1400

Critical Path is a fundamental concept in project management that refers to the longest sequence of tasks in a project, which determines the shortest possible time required to complete the entire project. This sequence consists of tasks that must be completed on time for the project to meet its deadline. Any delay in these critical tasks will directly impact the overall project period.

The construction period for the Reactor Containment Building (RCB) spans 69 calendar months. This duration encompasses all activities from Power Block Excavation to the completion of mechanical installation, excluding the testing phases. Figure. 1 illustrates the main schedule for the RCB construction process by Work Type. Each type is composed of various activities. Table. 2 resents the Critical Path activities for each type of the RCB.

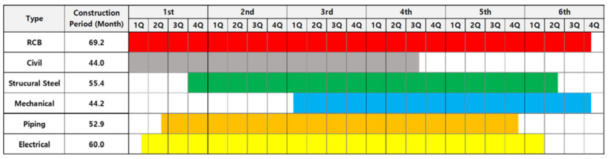

Fig. 1. Main schedule for the RCB by work type

Table. 2: Critical path activities for the RCB by work type

Type	Main Critical Path Activities
Civil	Power Block Excavation, Mudmat Concrete, Water Proofing/Protect Concrete, FR&P Basemat, FR&P Liner Cover Fill Slab, FR&P IRWST, FR&P Exterior Wall, FR&P. Shield Wall, FR&P Dome
Strucural Steel	Basemat Liner Plate, Wall Liner, Erect IRWST SSLP, Install Girders & Rails, Erect Dome Liner, Install & Tension Tendons, Install Pipe Whip Restraints
Mechanical	Install NSSS Equipment(RCV, RC, etc), Erect & Test Polar Crane
Piping	Install RCS L/B Pipe & Support before and after RV
Electrical	Cathodic Protection

3. Results

3.1 Critical Path by Construction Package

Table. 3 presents the Critical Paths corresponding to the CPs in APR1400. A total of five Construction Packages include activities on the Critical Path: C1, A1, M1, M3 and P1.

Table. 3: Activities and Critical Paths by CPs

PKG No.	Package	Activities	Critical Path
CP-C1	Foundation Excavation	Power Block Excavation, RCB Mudmat Concrete, FR&P Basemat	**O**
CP-C2 CP-C3	Concrete Production Work Outdoor Underground Installation	Plant Concrete Facilities & Production Yard Work (Yard Area Install Equip./Insulation/Misc.)	
CP-C4	Cooling Water System	Cooling Water Structure Work	
CP-Y1	Underwater Drainage Structure	Yard Work (Drainage, Wastewater Facilities)	
CP-A1	Construction of Main Building	FR&P Basemat, Wall, Dome, Strucural Steel	**O**
CP-A2	Architectural Finishing Work	Install Elevator & Equipment	
CP-A3	Painting Work	Painting & Coating	
CP-M1	General Equipment Installation	Install Mech. Equipment Wall Liner, Sump Liner, Dome Liner	 **O**
CP-M2	Condenser Installation Work	Re-Fabrication and Erect Condenser	
CP-M3	Turbine Generator Installation	Install Turbine Components	**O**
CP-M4	HVAC Installation	Install HVAC Duct & Support Install HVAC Equipment	
CP-M5	Nuclear Steam Supply System(NSSS) Installation	Install RC Pump Internals & Motor Set Reactor Vessel RPV Internals Installation	
CP-M6	On-Site Assembly Tank Installation	Yard Tanks Installation	
CP-P1	Piping Installation	Install Embedded Pipe Install L/B, S/B Pipe & Support	 **O**
CP-P2	Insulation Work	Pipe Insulation	
CP-E1 CP-E2	Electrical Equipment Installation Cable Laying and Wiring Work	Install Cable Tray & Support, Install Misc. Elect. Equipment, Conduit, Cabling & Termination	**(O)**
CP-E3	Outdoor Switchyard Installation		
CP-E4	Instrumentation and Control (I&C) Installation	Install I&C Equipment	

In contrast to Large Reactors, SMRs are integrated reactor vessels interconnected with various passive safety systems. Thus, the Piping and Electrical systems (including I&C) connected to the associated mechanical systems significantly influence the overall i-SMR construction period. Therefore, by focusing on these six CPs including E and implementing modularization techniques, it is possible to achieve maximum reduction in the overall construction period.

3.2 Modular items by Construction Package

In this study, modularization items are introduced for each CP. However, C1 and M5 Packages are excluded despite their significance in the Critical Path. This exclusion is due to C1 (Foundation Excavation) having low modularization applicability and M5 (NSSS Installation) already incorporating modularization techniques in i-SMR.

3.2.1 CP-A1: Steel Plate Concrete

The A1 Package includes the highest number of Critical Path activities in the APR1400 construction process. Among these, concrete work - comprising formwork, reinforcement, and pouring - constitutes the core construction activities for both the RCB and the Turbine Generator Building (TGB).

Steel-Plate Concrete (SC) replaced some structural elements due to its compatibility with modular construction [2]. For instance, AP1000 reactor was designed for modular construction, incorporating extensive prefabrication of components and structures in a factory setting [2]. Figure. 2 illustrates the potential application range of SC in i-SMR.

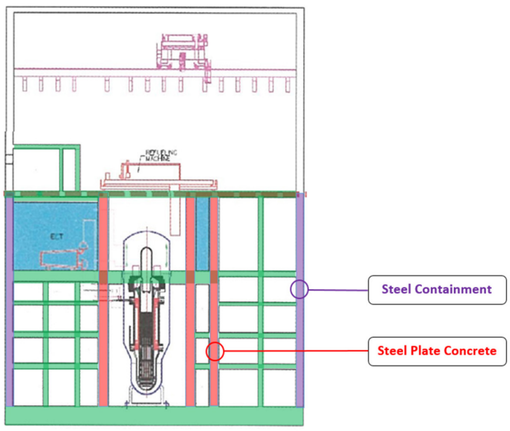

Fig. 2. Potential application range of SC in i-SMR

3.2.2 CP-A1, M1: Steel Modular

The A1 and M1 Packages encompass steel structures and Stainless Steel Liner Plate (SSLP) work along the

Critical Path. Steel modularization refers to the process of transforming conventional steel structures into modular components, which can be prefabricated off-site and subsequently assembled on-site.

In particular, Lloyd introduced the concept of Degree of Modularisation (DoM) and proposed a 100% external fabrication ratio for steel structures in plants with a power generation capacity of approximately 750 MW or less [3].

Figure. 3, Figure. 4 presents the construction sequence diagram for installing an apartment rooftop structure [4]. It is anticipated that the steel structure and SSLP in i-SMR can be installed using the same sequence of operations.

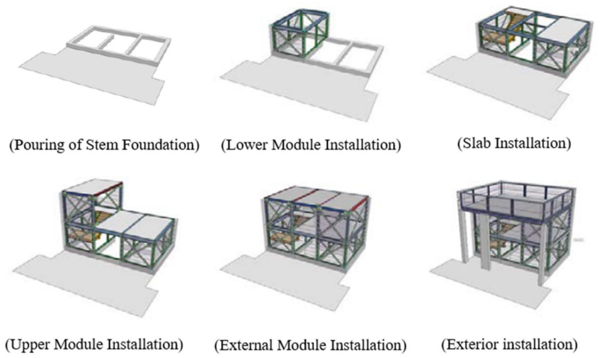

Fig. 3. Modular rooftop construction sequence [4]

Fig. 4. Modular rooftop construction sequence [5]

In the design-production-construction process of modular construction, BIM-based design and 3D scanning techniques play a crucial role in facilitating the integration of factory-fabricated modules with on-site constructed concrete structures [5].

3.2.3 CP-M1, P1, E: MEP Module

In traditional construction methods, pipe installation occurs after equipment is on-site, requiring additional time for cutting and connecting the elements. However, in the prefabricated method, pre-assembled components reduce on-site work, resulting in time savings compared to the original schedule [6].

Over the past decade, the modular prefabrication of mechanical, electrical, and plumbing (MEP) systems has become increasingly prevalent, driven by the growth of the prefabricated construction industry [7]. Figure. 5 presents the design of the MEP module for the firefighting system.

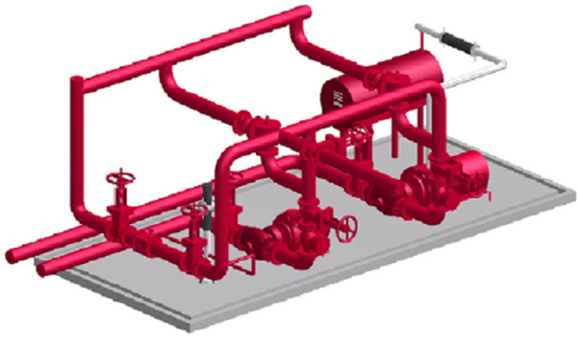

Fig. 5. MEP module for the firefighting system [7]

3. Conclusions

This study identifies the most effective work types and modularization strategies for shortening the construction period of i-SMR by correlating the CPs of the APR1400 with its Critical Path activities.

First, the period for concrete work can be reduced by applying SC in CP-A1. This approach is the most effective method to shorten the construction period, as CP-A1 includes the most critical path activities.

Second, Steel Modularization can be applied in the CP-A1, M1 to reduce the manufacturing and installation time for steel structures and SSLP. Particularly, the steel structure demonstrates the highest external manufacturing ratio by the DoM, making it the work type with the greatest applicability for modularization.

Third, the construction period can be further shortened by introducing the MEP module in the CP-M1, P1, E. Given the close relationship between the mechanical-piping-electrical connection process and the overall construction completion period in SMRs, the impact of modularizing this process is expected to be highly significant.

The adoption of this modularization strategy is anticipated to improve the competitiveness of i-SMRs by reducing construction costs.

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