ICCEPM 2020
The 8th International Conference on Construction Engineering and Project Management
Dec. 7-8, 2020, Hong Kong SAR

Issues of New Technological Trends in Nuclear Power Plant (NPPs) for Standardized Breakdown Structure

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Abstract: Recent efforts to develop a common standard for nuclear power plants (NPPs) with the aim of creating (1) a digital environment for a better understanding of NPPs life-cycle management aspect and (2) engineering data interoperability by using existing standards among different unspecified project participants (e.g., owners/operators, engineers, contractors, equipment suppliers) during plants' life cycle process (EPC, O&M, and decommissioning). In order to meet this goal, there is a need for formulating a standardized high-level physical breakdown structure (PBS) for NPPs project management office (PMO). However, high-level PBS must be comprehensive enough and able to represent the different types of plants and the new trends of technologies in the industry. This has triggered the need for addressing the issues of the recent operational NPPs and future technologies' ramification for evaluating the changes in the NPPs physical components in terms of structure, system, and component (SSC) configuration. In this context, this ongoing study examines the recent conventional NPPs and technological trends in the development of future NPPs facilities. New reactor models regarding the overlap of variant issues of nuclear technology were explored. Finally, issues on PBS for project management are explored by the examination of the configuration of NPPs primary system. The primary systems' configuration of different reactor models is assessed in order to clarify the need for analyzing the new trends in nuclear technology and to formulate a common high-level PBS. Findings and implications are discussed for further studies.

Key words: nuclear power plants (NPPs), project management organization (PMO), physical breakdown structure (PBS), reactor model (RM), reactor coolant system (RCS)

1. INTRODUCTION

While the world's nuclear power generation is expected to increase in the coming decades, the nuclear power plant construction market is also growing, and there is a need for creating an international standard for nuclear digital environment. In order to develop a common set of rules or standards for the digital ecosystem of NPPs with the intention of addressing (i) NPPs life-cycle management aspects amongst different project participants (e.g., owners/operators, engineers contractors, equipment vendors), plant life cycle process (EPC, O&M, and Decommissioning), and multiple value chain, (ii) issues to digitally exchange NPPs information handover from EPC to O&M and then to decommissioning, (iii) life cycle engineering data interoperability by using existing international standards (e.g., ISO 15926, 10303, CFIHOS). For this purpose, it is crucial to understand the recent conventional NPPs and global trends in the radical transformation of future reactors to compare the changes in the plant's physical asset in terms of structure, system, and components (SSC), as well as plant configuration.

The physical component of a plant facility with respect to the project management organization (PMO) of owners/operators and contractors has intrinsic values and is used as a project scoping mechanism for different project management practices, including but not limited to project performance management and life-cycle information management [1]. Project managers use different practical methodologies for defining an organized set of physical components of a plant facility, and physical breakdown structure (PBS) is one of the techniques. Although the term PBS has been defined in a number of ways, PBS is a hierarchically organized set of project physical components with combined entities of project administration activity, incorporating different aspects of project deliverables, in the context of this study. As in other projects, PBS in the NPPs project consists of different leveled asset entities or SSC together with NPP managerial aspects in a top-down course of action.

In order to formulate a common standardized high-level candidate entity for a common PBS, representing recent plants and advanced reactors of the future, it is vital to analyze different trends in nuclear technology in the nuclear plant facility. This ongoing research examines the different types of nuclear plants, interrelated technological trends in reactor advancement, and the gradual changes in the power plant's reactor system. The recent reactor model types with the perspective of new trends are explored. Finally, the need for exploring nuclear power technology to formulate a standardized PBS by examining the configuration of the primary system, which contains the reactor system of different reactors as an example, is discussed.

This study is organized in a four-step research framework as shown in Figure 1. The four steps include: (1) an extended classification of NPPs identified based on the previous research of the authors [2], (2) new trends of technological changes in the developed reactor analyzed through literature review, (3) different reactor models regarding interrelated new trends, (4) assessing the primary systems configuration of different reactor models in order to clarify the need for analyzing the new trends in nuclear technology and to formulate a common PBS.

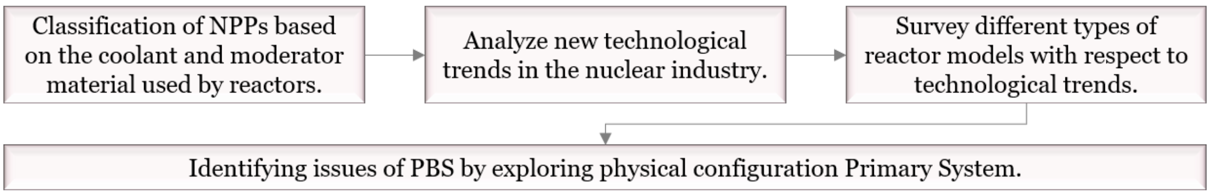

Figure 1. Research Design

2. CLASSIFICATION AND STATUS OF NUCLEAR POWER PLANT (NPPs)

The primary system of any NPPs, containing the reactor coolant system (RCS) and reactor system (RS), is the critical system that determines the plant efficiency and overall plant configuration, as well as commissioning process. There are over 86 reactor models in the world, which are classified from a previous research by the authors, under eight power plants based on the type of coolant and moderator materials the RCS uses [2], as shown in Figure 2. Hence, the coolant and moderator materials determine a specific power reactor type.

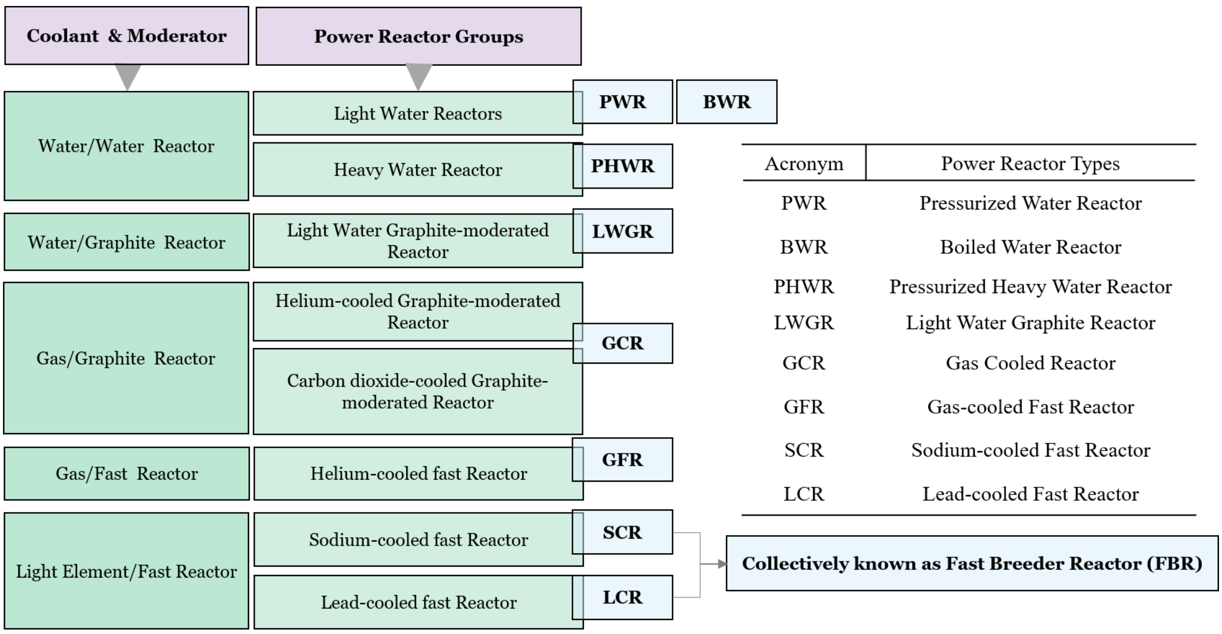

Figure 2. Classification of power plants based on coolant and moderator materials

According to the International Atomic Energy Association (IAEA) nuclear power reactor information system [3], as of August 2020, the record shows that 439 NPPs are currently operational, and 52 plants are under construction all around the globe. Pressurized Water Reactor (PWR) is one of the most used power plant types followed by boiling water reactor (BWR), pressurized heavy water reactors (PHWR), and light water gas cooled reactors (LWGR), respectively. With over 65% all operational plants and 85% of plants under construction PWR recently integrates more advanced features.

The plants that are under construction use variants of advanced reactors, with an increase in the number of new technologies being seen. The new reactor models are designed for self-reliance and use less complicated design features. Since the late 2000s, the reactor models that are being commissioned for NPPs mostly fall under the new variants, generation III, III+, IV, and small modular reactors (SMRs) of interrelated technologies; for example, System-integrated Modular Advanced Reactor Technology (SMART) is a small-sized, modularized, fast, and integrated pressurized water reactor.

The global growth of nuclear power energy slowed during the 2008 global economic recession. After the Fukushima-Daiichi nuclear accident, a radical change in the design innovation of NPP's structure, system, component (SSC) triggered countries to improve their long-existing conventional plants to a safer, optimized, and economical version [4,5]. Due to facing greater project complexity and demands for higher safety requirements, the NPPs industry continually seeks ways to improve plant performance through alternative advanced nuclear energy systems. By adopting advanced design features based on the self-reliant technologies, the early 2010s has been the period of developing an advanced nuclear reactor and has projected a minimum of 40% increase in nuclear power production by 2035 [4]. Among the promising directions for NPP technological development is the introduction of less complex smaller units that are more affordable, using fast reactors with enhanced safety systems, as well as plants that can operate up to 60 years as discussed in Section 3.

3. TECHNOLOGICAL CHANGE IN NUCLEAR POWER PLANTS (NPPs)

Based on the objective above, reactor design changes greatly affect the physical configuration especially the reactor system and additional facilities depending on the operational purposes of the plant. Major configuration changes are occurring in the plant's structure, reactor system, power production systems, and auxiliary systems. However, there is a slight lower-level difference between the balance of plant systems (electrical system, HVAC system, instrumentation, and control system). The key concerns for alternative nuclear technologies are, but not limited to, the need for: standardized design and reduction in capital and life cycle cost, optimized construction duration, easy operability and less vulnerability to accidents, minimum nuclear waste, and advanced passive safety system [6,7]. NPPs technological ramification can be manifested by four interrelated technological trends as illustrated in Figure 3.

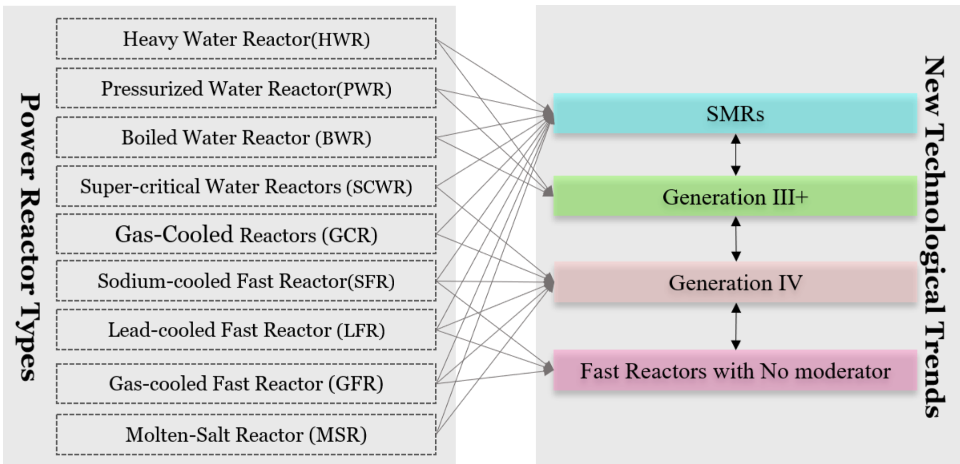

Figure 3. Classification of power plants based on coolant and moderator materials

Generation III+ reactor models, currently under deployment by different countries with a growing number of plants under construction, is the future of NPPs [4,8]. Generation III+ reactors are evolutionary extension from Generations II and III of pressurized water reactors (PWR), boiled water reactors (BWR), and PHWR designs with some radical changes, including advanced safety features without any control equipment.

International collaboration is organized to develop future advanced nuclear reactor energy systems and form the Generation IV International Forum (GIF). GIF's effort contributes to the advancement of multi-purpose reactors (hydrogen production, water desalination, and other commercial operations) [4]. GIF is based on six reactors (GFR, LFR, SFR, molten salt reactors [MSR], supercritical water-cooled reactors [SCWR], and very high-temperature reactor [VHTR]). However, the actual deployment of GIF reactors is expected to happen in the coming decades.

An important manifestation of new development activities in the area of nuclear plant design is the widespread interest in small plants incorporating passive, rather than active, safety features and simplified systems design. The small plant may be the best choice for applications on a relatively small grid or when load growth rate is expected to be low on a large grid. The concept of Small Modular Reactors (SMR) can be manifested either by small, medium-sized, or modular reactors with a power outage of 300MWe per module. SMRs are based on a small-scale version of existing-generation II & III reactor designs, to entirely new advanced generation III+/IV by means of modular-based reactor designs [5,6]. The majority of SMRs are from conventional light water reactors. However, there has been a growing number of generation IV small scaled test reactor recently as shown in Table 1. When conventional reactor models are compared, SMRs can offer a significant benefit because of the size, modularity, and simplicity of the design, as well as its advantages of scalability, flexibility, deployment ability, optimized economics, and passive safety approaches. The small-scaled plants have a less complicated structure and system configurations in which sub-systems are confined into a single system, unlike previous conventional reactor designs.

Fast-Reactors, offering optimized usage of nuclear fuel, fast reactors have no moderator materials [9]. Due to its operational characteristics, fast reactors are cooled by liquid metals, usually sodium and lead metal. Different technological programs have been improving sodium-cooled Fast Reactor (SFR) and Lead-cooled Fast Reactor (LFR), collectively known as fast breeder reactors (FBR) [8]. In some countries, fast-reactor development activities are performed within the framework of the GIF.

It is becoming increasingly clear that safety and economics are the driving issues for reactor advancement and a reactor which is built and operated to high safety standards tends to be a reliable reactor which is economically viable. An overlap of the above-mentioned new reactor trends is shown in Figure 4.

			Generation IV Reactors						
Generation III+ Reactors							Fast Reactors		
PWR	BWR	HWR	GCR	iPWR	SCWR	MSR	GFR	LFR	SFR
AP 1000	ABWR	ACR-1000	GTHTR300C	IMR	CSR1000	IMSR-400	ALLEGRO	ALFRED	4S
AP-600	ABWR-II	AHWR	HTR-PM	NuScale	HP-LWR	LFTR	EM2	BREST-OD-300	ASTRID
APR+	BWRX-300	EC6	PBMR	SMART	JSCWR	Mk1 PB-FHR	KAMADO FBR	CLEAR-I	BN-1200
APR1000	ESBWR	IPHWR-220	Prismatic HTR			MSFR		ELECTRA	CFR-600
APR1400	KERENA	IPHWR-700	SC-HTGR			MSR-FUJI		ELFR	FBR-1 & 2
APWR	RMWR					MSTW		G4M	JSFR
ATMEA1						SmAHTR		LFR-AS-200	MBIR
EPR						ThorCon		MYRRHA	PGSFR
FBNR								PEACER	PRISM
HAPPY200								SEALER	TWR-P
KLT-40S								SVBR-100	
NUWARD								W-LFR	

❖ iPWR & SCWR are advanced pressurized water reactors (PWR), ● SMRs

Figure 4. Trends and Interrelations of future reactor models (Reorganized by using data from [3])

4. PBS FORMULATING ISSUES FOR PROJECT MANAGEMENT

In the context of NPPs, PBS is a structured representation in a top-down manner of a nuclear plant facility's physical and managerial scopes. The first level of a PBS in a nuclear facility indicates the managerial aspect, which relates to the tasks or work category. In addition, the first level includes plants' structural and architectural systems (nuclear reactor system, turbine-generator, axillary), as well as balance of plant system (electrical system, HVAC systems, instrumentation, and control) entities.

Nuclear power plant structural facilities are mainly composed of nuclear island (RCB), auxiliary building (AUX), turbine island (TUB), radwaste building (RWB), control building (COB), yard structure (YARD), hydrogen production facility, and site improvements (SITE). In the case of new reactors, some of the structures are combined in a single structure. In the case of molten salt reactor, RCB and TUB are confined in a single structure, while SFRs AUX, TUB, and RCB are combined in a single facility [2].

However, among the first-level entities, the primary system which contains the reactor coolant system (RCS), manifest a variant of plant configuration with respect to the reactor model type and inclusive of new trends of technology. RCS provides reactor cooling by transferring the heat from the core to the secondary system to produce steam for the turbine. The major components of the RCS consist of a reactor vessel (RV), steam generators (SGs), reactor coolant pumps (RCPs), pressurizer, pressurizer relief tank (PRT), reactor coolant pipes, and valves. Primary system configuration is different based on the power reactor types and related technological trends as shown in Table 1.

Similarly, the RCS systems and structures of a power plant have different types of configuration according to the type of reactor model. In order to formulate a comprehensive PBS, it is vital to assess the new trends of technologies in the industry.

There is a high possibility of formulating a high-level entity for a common standardized PBS with a high comparative capability of different types of NPPs.

Table 1. An example of primary system configuration

Power reactor type	Reactor model name	New trends	Primary system configuration
PWR	SMART	Generation IV SMR	All major primary components, such as core, steam generators, pressurizer, control element drive mechanisms, and main coolant pumps, are installed in a single reactor pressure vessel [8].
	CAREM	Generation III+ SMR	The entire high energy primary system-core, steam generators, primary coolant, and steam dome is contained inside a single reactor pressure vessel [8].
BWR	ESBWR	Generation III+	The technology uses natural circulation for coolant recirculation within a reactor pressure vessel; therefore, there are no recirculation pumps and none of the associated piping, power supplies, heat exchangers, and instrumentation and controls [10].
GCR	HTGR	Generation IV SMR	Instead of RCS, there is an intermediate heat exchanger (IHX) that transfers the heat from the reactor vessel to the turbines [11].
SFR	PRISM	Generation IV SMR Fast-Reactor	Unlike PWRs, the RCS is kept within the reactor vessel which also encompasses IHX [12].

5. CONCLUSION

This study was intended to provide a comprehensive summary on the changing of NPPs' reactor technologies and new trends of reactors in order to formulate a standardized high-level PBS for owners/operators of PMO. Therefore, this paper presented a short overview of trends in the development of new NPPs, which primarily depended on the reactor model technologies. Relative to the current conventional NPPs technologies, the claimed benefits of the new trends included improved safety systems, longer plant life, easy deployment, and optimized plant performance. To this day, these diverse new issues have been manifested by four variants of new global trends of nuclear technology: generation III+, generation IV, SMRs, and fast reactors, as discussed in Section 3. In addition, the new reactor models were explored regarding the new technologies. Finally, an overview of NPPs' primary system configuration in different reactor models were discussed in order to show how it is necessary to analyze conventional reactors and future technological trends in order to formulate a standardized high-level physical breakdown structure. Future works will explore the SSC configuration of selected reactor models from every reactor type in order to come up with a common entity for a high-level PBS for owners/operators of PMO.

ACKNOWLEGEMENTS

This study was supported by the Korea Evaluation Institute of Industrial Technology (KEIT) under Grant No. 200117820.

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