Transactions of the Korean Nuclear Society Spring Meeting
Jeju, Korea, May 22-23, 2025

SMR BoP Piping Material Selection Methodology

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***Keywords** : Small Modular Reactor, Balance of Plant, Piping, Material Selection, Methodology

1. Introduction

Large Nuclear Power Plants (NPPs) efficiently supply electricity through economies of scale and are an environmentally friendly power generation method with zero carbon emissions. Their importance is increasing due to their role in addressing climate change and achieving carbon neutrality. However, large NPPs face various challenges, such as tightening safety regulations and power grid limitations. To address these issues, Small Modular Reactors (SMRs) have been proposed as an alternative. The innovative SMR (i-SMR) currently under development in South Korea adopts an integrated reactor structure, where major components of the Nuclear Steam Supply System (NSSS) are combined into a single vessel, as shown in Fig. 1 [1].

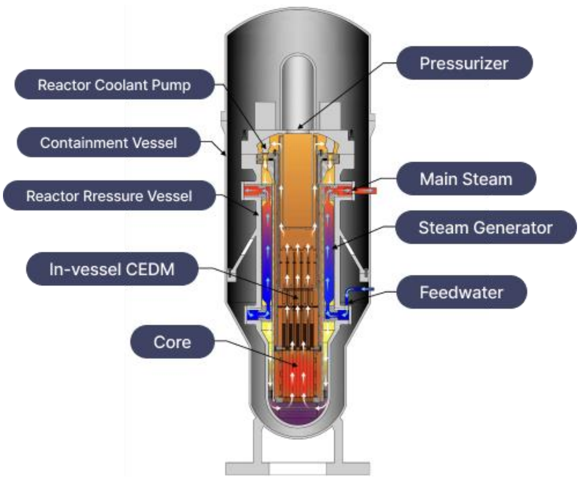

Fig. 1. i-SMR module configuration diagram

Since the coolant pipes are located inside the reactor vessel in this design, there is no possibility of radioactive leakage due to coolant pipe failure. Furthermore, SMRs offer advantages over large NPPs in terms of accident probability and self-cooling capability, which allows for a differentiated Emergency Planning Zone (EPZ). For instance, the EPZ radius of the NuScale SMR has been significantly reduced to a few hundred meters, compared to the several-kilometer EPZ required for large NPPs. If similar regulatory adjustments are implemented in South Korea, the constraints of the power grid could be overcome. However, as shown in Fig. 2, SMRs have a smaller power generation capacity than large NPPs, leading to higher unit power generation costs [2]. Therefore, for the successful commercialization of SMRs, cost-effective piping design and manufacturing are essential. To shorten construction periods and reduce operational costs, various manufacturing techniques have been developed. Among these, induction bent pipes, which eliminate welded joints, have gained attention as they help reduce material costs and minimize the extent of Non-Destructive Testing (NDT). However, research on SMR pipes specific regulatory requirements and materials, including those for bent pipes, remains insufficient.

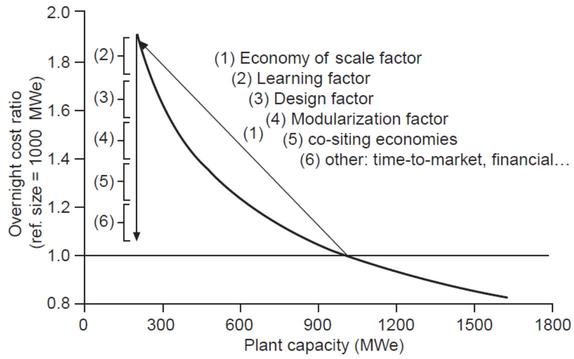

Fig. 2. Economies of Scale in Nuclear Power Plant Construction

From a safety perspective, SMR material selection should refer to materials already verified in long-term operating large NPPs. However, due to the integrated design of SMRs, the presence and arrangement of primary system piping significantly differ from those in large NPPs, making direct material reference challenging. Nevertheless, if SMR BoP systems resemble those in large NPPs, materials used in large plants can be considered for SMR piping material selection.

This study proposes a methodology for selecting SMR BoP piping materials by comparing system configurations between large NPPs and SMRs, evaluating the applicability of large NPP materials in SMR designs.

2. Methods and Results

In this section, the system configurations of NuScale SMR and APR1400 are compared based on their respective Design Certification Application (DCA) and Final Safety Analysis Report (FSAR) [3,4]. The results confirm that it is appropriate to select SMR BoP piping materials based on materials used in large NPPs.

Additionally, to reduce manufacturing costs, this study proposes a methodology to simplify the variety of materials used in SMR piping.

2.1 Comparison of SMR and Large Nuclear Power Plant

Before selecting SMR materials, the required procedure is illustrated as a flowchart in Fig. 3. First, the major systems of commercial large NPPs and SMRs are analyzed. Next, their operational environments are reviewed to classify common systems, identifying target systems for further evaluation. Prior to material simplification, considerations such as historical material modifications, design improvements, and aging degradation cases in large NPPs must be incorporated. The detailed procedure for this step is covered in Section 2.2. Finally, the feasibility of material substitution is evaluated to determine the most representative materials.

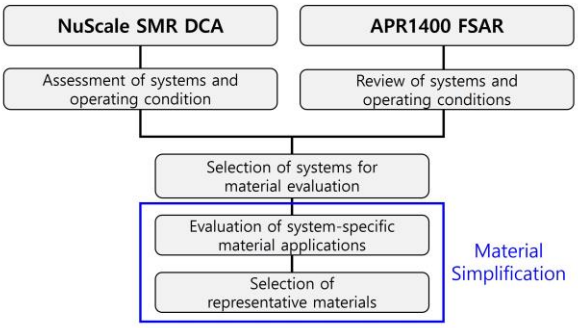

Fig. 3. SMR Piping Material Selection Flowchart

As the first step in this flowchart, the DCA of NuScale SMRs and FSAR of APR1400 were reviewed to analyze system differences [3,4]. The systems were classified according to Category 1 and Category 2 as defined in the FSAR, as shown in Table I. Under Category 1, both SMRs and large nuclear power plants exhibit similar system configurations. Under Category 2, differences are observed in the Engineered Safety Features System of the primary system. For example, the Emergency Core Cooling System (ECCS) in NuScale SMRs encompasses the function of the Safety Injection System in APR1400, performing a similar role but with differences in cooling mechanisms. Furthermore, Safety Depressurization and Vent System (SDVS) and In-containment Water Storage System (IWSS), which exist in large nuclear power plants, are absent in NuScale SMRs. Consequently, applying large nuclear power plant materials to primary system piping in SMRs is challenging. However, Auxiliary Systems and Steam and Power Conversion Systems within BoP system identical compositions between large nuclear power plants and NuScale SMRs, suggesting that materials used in large nuclear power plants can serve as references for SMR BoP piping design. For systems outside Category 2, system names and functions may vary, and if SMRs are located in urban areas, non-standard pipe configurations may be adopted to improve placement flexibility. Therefore, when selecting BoP systems for material review, these factors should be comprehensively considered.

Table I: Comparison of Systems in NuScale SMRs and APR1400

System Category 1	System Category 2	NuScale SMR	APR1400
Engineered Safety Features	Containment Systems	Y	Y
	Emergency Core Cooling System	Y	Y
	Safety Injection System	N	Y
	Control Room Habitability	Y	Y
	Fission Product Removal and Control Systems	Y	Y
	Safety Depressurization and vent system(SDVS)	N	Y
	In-Containment Water Storage System(IWSS)	N	Y
Auxiliary Systems	Fuel Storage and Handling	Y	Y
	Water Systems	Y	Y
	Process Auxiliaries	Y	Y
	Air Conditioning, Heating, Cooling, and Ventilation Systems	Y	Y
	Other Auxiliary Systems	Y	Y
Steam and Power Conversion System	Turbine Generator	Y	Y
	Main Steam System	Y	Y
	Other Features of Steam and Power Conversion System	Y	Y

2.2 Simplification of Large Nuclear Power Plant Materials

The BoP systems in large NPPs consist of multiple subsystems and a wide variety of materials. Due to economies of scale, large NPPs achieve cost-effectiveness by mass-producing diverse materials. However, directly applying these materials to SMRs without review could result in higher costs due to small-scale production constraints. To enhance economic efficiency, material specifications must be simplified. The material simplification process is illustrated in Fig. 4.

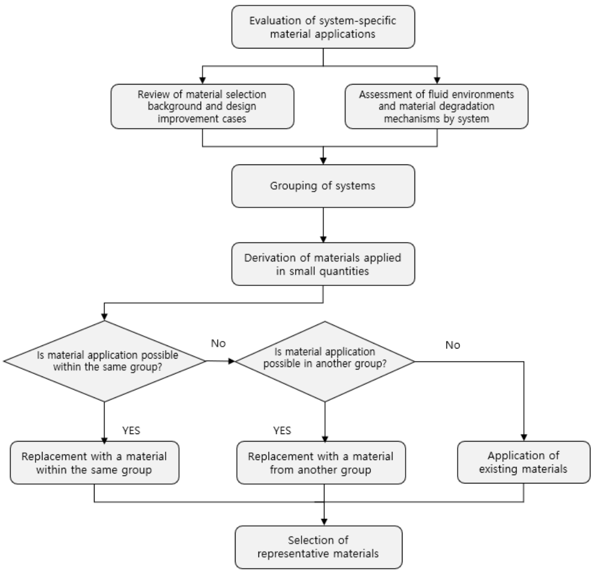

Fig. 4. Material simplification process diagram

To simplify materials, the entire material inventory must be analyzed to identify and reduce the materials used in small quantities. To determine which materials should be consolidated, the background for selecting existing materials must be analyzed. Additionally, since actual degradation mechanisms in operational environments may differ from those predicted through experiments and simulations, references to design improvement cases resulting from material degradation during operation are necessary. Furthermore, considering the long-term operational environment, material selection must account for aging degradation effects. To replace materials used in small quantities, it is advantageous from a degradation management perspective to prioritize materials already widely used in similar environments. Thus, the fluid environment and potential degradation mechanisms for each system should be analyzed, allowing the grouping of systems with similar environmental and degradation characteristics. An example of the grouped system-material status is shown in Fig. 5.

Material Spec.	Quantity	Review Required	Group A	Group B	Group C	Group D	· ·	Group Z
Spec. 1	724	-	200	-	-	300	· ·	120
Spec. 2	390	-	-	121	150	119	· ·	-
Spec. 3	14	O	-	4	-	10	· ·	-
Spec. 4	523	-	-	-	200	150	· ·	135
Spec. 5	8	O	-	-	3	5	· ·	-
Spec. 6	689	-	-	200	110	-	· ·	-
:	:	:	-	:	:	-	· ·	
Spec. N	715	-	-	-	-	320	· ·	150

Fig. 5. Example of grouped system-material status

For instance, if Material Spec. 3, which is used in Group B, cannot be replaced with another material within the same group (Spec. 2 or Spec. 6), its replacement feasibility with materials from other groups (Spec. 1 or Spec. 4) should be evaluated. If a replacement from another group is also infeasible, the original material must be used from a safety perspective. Through this approach, the optimal selection of SMR BoP piping materials can be achieved. Additionally, the quantitative evaluation of piping fabrication costs in future studies will allow further validation of economic improvements resulting from material simplification.

3. Conclusions

In this study, a methodology for selecting materials for SMR BoP piping was proposed to enhance economic feasibility by referring to materials used in large NPPs and simplifying material types. Following the SMR piping material selection flowchart, the first step involved analyzing the DCA of NuScale SMR and FSAR of APR1400. This analysis confirmed that, on a broad scale, the BoP systems of SMRs and large NPPs composition similarities. Therefore, it was determined that materials used in large NPPs can serve as a reference for the design of SMR BoP piping. Additionally, a process for simplifying the type of materials used in large NPPs was devised. This process involves reviewing the background of material selection in large NPPs, examining cases of design improvements due to material degradation and identifying materials that can be consolidated into fewer types. Subsequently, a step-by-step approach was developed to determine whether materials used in small quantities can be replaced by widely used materials within the same system group. If no substitute exists within the same group, materials from other groups are assessed for compatibility and interchangeability. However, since SMRs are expected to operate for an extended service life, they may experience different degradation mechanisms compared to existing large NPPs. Furthermore, design and operational environment differences between SMRs and large NPPs must be carefully considered. Therefore, when selecting materials for SMR BoP piping, these factors must be fully taken into account.

ACKNOWLEDGEMENTS

This work was supported by the Korea Institute of Energy Technology Evaluation and Planning (KETEP) and the Ministry of Trade, Industry & Energy (MOTIE) of the Republic of Korea (No. RS-2024-00509038).

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