Comparative Analysis of Operational Procedures in Conventional Nuclear Power Plants and Small Modular Reactors

Adam Haziq M.F, Jonghyun Kim*
Department of Nuclear and Quantum Engineering, Korea Advanced Institute of Science and Technology, 291, Gwahak-ro, Yuseong-gu, Daejeon, Republic of Korea
**Corresponding author: jonghyun.kim@kaist.ac.kr*

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1. Introduction

Human reliability analysis (HRA) is a technique for assessing human error and producing human error probabilities (HEPs) for use in probabilistic safety assessment (PSA). In the context of a PSA, the primary goal of HRA is to locate, evaluate, and measure every human failure event (HFE) that is shown in the logic structure of the PSA before, during, and following the accident, as these occurrences add to the plant risk as stated in the PSA. The standard HRA process includes (1) task analysis, (2) qualitative analysis, and (3) quantitative analysis [1]. However, this paper focuses solely on the task analysis section of HRA.

This study aims to provide insights from the comparison of analysis for control room operations within a small modular reactor (SMR) environment contrary to conventional nuclear power plant (NPP) to aid multimodule HRA. This study is structured to guide the reader through a comprehensive exploration of key topics. First, a detailed review of the characteristics of SMR operations is presented. Following this, the procedures currently in place for conventional NPPs are examined to identify best practices and areas for comparison. Finally, thoughtful recommendations are offered to enhance the operating procedures for SMRs, drawing on the insights gained from this analysis.

2. Characteristics of SMR Operations

As the nuclear industry continues to innovate, SMRs emerged as a promising technology that differs fundamentally from traditional nuclear power plants. The distinct design and operational strategies of SMRs are shaping a new approach to nuclear energy. In this section, this paper will examine the key characteristics of SMR operations as identified by Blackett et al. (2022). These characteristics, which include simplified plant designs, enhanced automation, and the extensive utilization of passive safety systems, are expected to significantly improve the safety and efficiency of SMRs while also redefining the operational roles of plant operators [2].

2.1 Simplified Designs

SMRs are built to be more compact and streamlined, with all primary systems housed within a single vessel. This makes the operations less complex and enhances safety by reducing the number of components that could potentially fail.

2.2 Reliance on Passive Safety Features

Unlike conventional plants that depend heavily on active safety systems, SMRs use passive safety mechanisms that work without the need for external power or immediate operator intervention. These features take advantage of natural processes like gravity and natural circulation to keep the reactor safe, meaning operators spend more time monitoring and less time actively controlling the system.

2.3 Higher Automation

SMRs are designed with advanced automation, meaning many operational tasks are handled by the system itself. This automation reduces the need for manual input from operators, allowing a smaller team to manage more reactors simultaneously.

2.4 Multi-Unit Operation

One of the standout features of SMRs is the ability to operate multiple reactor units from a single control room. This is a big shift from conventional plants, where each reactor typically requires its own dedicated team of operators. With SMRs, a few operators can manage several reactors, thanks to the simplified design and high level of automation.

2.5 Modular Growth

SMRs are designed to be scalable. This means that new reactor modules can be added as needed, allowing the plant to expand its power output over time. This flexibility also means that the operational needs might evolve, requiring operators to adapt as new modules come online.

2.6 Versatile Applications

In contrast to conventional NPP, which mainly focuses on electricity generation, SMRs can be used for a variety of purposes. They can provide heat for industrial processes, desalinate seawater, or even produce hydrogen. This versatility means that the operational procedures might vary significantly depending on what the SMR is being used for at any given time.

3. Review of Conventional Large-scale NPP Procedures

The operational procedures in conventional large-scale nuclear power plants are meticulously crafted to ensure the safety and reliability of the plant under both normal and emergency conditions. Key guidance on these procedures comes from regulatory documents such as NUREG-0899 and NUREG-4613, which outline essential principles for developing and implementing Emergency Operating Procedures (EOPs).

NUREG-0899 provides a detailed framework for developing EOPs in nuclear power plants. It emphasizes creating function-oriented procedures that assist operators in maintaining critical safety functions, such as core cooling, containment integrity, and reactivity control, regardless of the specific incident. These guidelines advocate for the development of clear, consistent procedures through a plant-specific writer's guide, followed by rigorous verification and validation (V&V) through simulator exercises and control room walk-throughs. This validation ensures that the procedures are both technically accurate and practical for operators in real-world scenarios. Additionally, NUREG-0899 stresses the importance of continuous training for operators and regular updates to EOPs to keep them relevant as plant designs and operational practices evolve. [3].

Building on these principles, NUREG-4613 highlights the significance of integrating human factors engineering into the development of operating procedures. This document emphasizes designing procedures that reduce the cognitive load on operators, especially during high-pressure situations. Tools such as flowcharts and decision tables are recommended to enhance usability, minimize errors, and improve decision-making efficiency. NUREG-4613 also references NUREG-3968, which identified issues with the usability of existing procedures, particularly abnormal operating procedures, noting that poor organization can increase the risk of operator errors during critical situations. The document underscores the need for all procedures, not just emergency ones, to undergo thorough V&V to ensure they are well-structured and user-friendly [4].

4. Suggestion of Improvement for SMR Procedures

Applying the insights from NUREG-0899 and NUREG-4613 to SMRs involves tailoring these guidelines to the unique characteristics of SMR designs. Given the modular and integrated nature of SMRs, function-oriented procedures should be adapted to focus more on specific scenarios relevant to multi-module operations. For instance, EOPs should include steps for isolating a failed module while maintaining the operation of others, ensuring that critical safety functions are preserved across the plant. This might involve procedures for diverting cooling resources from unaffected modules to those experiencing issues, leveraging the modularity of SMRs.

4.1 Advanced Validation and Verification for Multi-Module Safety

Advanced V&V techniques, as emphasized in NUREG-0899, are particularly important for SMRs, which feature higher levels of automation and often involve managing multiple modules from a single control room. Validation exercises should simulate not only individual module failures but also the cascading effects that could occur in a multi-module setup. For example, a loss-of-coolant accident (LOCA) in one module should be tested to see how operators manage the event while ensuring that neighboring modules remain unaffected, ensuring overall plant safety.

4.2 Human Factors Integration and Cognitive Load Reduction

Incorporating human factors engineering, as detailed in NUREG-4613, is crucial for SMR operations, where the complexity of managing multiple reactors requires reducing operator cognitive load. This can be achieved through intelligent decision support systems that offer real-time assessments and suggest actions based on the current situation. For example, if a reactor coolant pump fails in one module, the system could guide the operator through the necessary steps to isolate the issue, assess the status of connected modules, and maintain plant stability. Additionally, the user interface should prioritize critical information to help operators manage multiple reactors effectively.

4.3 Scenario-Specific Procedures and Decision Support Systems

SMR procedures should also include scenario-specific flowcharts and decision aids, addressing specific incidents such as a Steam Generator Tube Rupture (SGTR) in one module while others continue operating. These procedures should outline steps for safely shutting down the affected module, rerouting power generation, and managing shared resources, ensuring overall plant stability.

4.4 Continuous Improvement and Adaptive Learning in SMR Operations

Finally, the importance of continuous improvement and adaptive learning, as highlighted in NUREG-0899, is particularly relevant for SMRs. As new modules are added or existing ones are upgraded, EOPs should be regularly revisited and refined. For instance, if certain automated responses are found to be too slow in preventing escalation during specific incidents, the procedures should be updated to include manual overrides or alternative actions. This iterative process ensures that SMR procedures remain effective as the technology and operational environment evolve.

5. Conclusion

This study compared the operating procedures of conventional NPPs with those of SMRs, highlighting how established NPP procedures can be adapted to the unique design and operational needs of SMRs. By leveraging insights from key NUREG documents, HRA analysts can develop more effective SMR procedures, reduce operator cognitive load, and improve safety through better qualitative analysis of Performance Shaping Factors (PSFs) and error modes. Ultimately, these adaptations can lead to more accurate estimations of human error probabilities (HEPs), enhancing the reliability and safety of SMR operations.

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