Developing a Simulator-based Experiment Framework to Assess the Performance Shaping Factors in Multi-Module Operation of SMR

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1. Introduction

With its promising outlook as future energy source, small modular reactor (SMR) introduced new systemic safety features and concept of operation distinct from the conventional nuclear power plant (NPP) [1]. However, O'Hara et al has delineated the potential human factors issues induced by such novelties – new plant mission, levels of automation, staffing levels, passive safety system, and multi-module operations and teamwork – that degrade or negatively impact human performances [1]. To assure competent level of performance, human reliability analysis (HRA) is implemented to identify feasible error-inducing scenarios and estimate the likelihood of potential human failure events (HFE) in a risk-informed manner [2]. Qualitative and quantitative assessment of HRA incorporates the use of performance shaping factors (PSFs), which instigate unsafe actions. Whilst there were attempts to identify HFEs, no HRA methods dedicated to SMR multi-module operation exists and there is a lack of defining performance shaping factors to provide analytical basis of human performance in such operating conditions [1]. NuScale has proposed to translate insights obtained from single module PRA to multi-module risk evaluation for 12 module configurations [3]. The multi-module PSF multiplier derived from this report suggested 10 as adequate [3]. Nonetheless, taxonomy of PSFs considered in this report was not specified nor provided with sufficient technical evidence for validation.

Consequently, this research aims to develop an experimental framework to assess PSFs pertaining to SMR operational environment. First, feasible taxonomy of multi-module PSFs are opted to provide new set of PSFs for consideration. Then, detailed experiment design is constructed to propose a human performance data collection scheme in a simulator-based multi-module setting.

2. Performance Shaping Factors for Multi-Module Operation

2.1. Revisiting PSFs in Conventional HRA Methods

Various HRA methods were developed with unique set of PSFs to estimate the error probabilities of human performance in conventional NPP. To investigate multi-module performance shaping factors, this study has revised the PSFs of existing HRAs still relevant in SMR operation. Table I lists the taxonomy of representative PSFs organized by Kim et al. reviewed from available HRAs such as THERP, HEART, ATHEANA, CREAM, and etc. [4]. Based on PSF classification in Kim et al., generic PSFs are redefined as follows.

Table I: A taxonomy of Representative PSFs from conventional HRAs and Revised PSFs

Representative PSFs [4]	Generic PSFs (Revised)
- Training/Experience - Procedures - MMI/Information - Time - Stress - Workload - Motivation - Task complexity - Simultaneous goals/tasks - Working environment - Supervision - Team factors - Communication - Adequacy of resources - Decision making Criteria - Response dynamics and system coupling - Availability and operability of equipment - Trend and value of critical parameters - Time of day - Organization factors - Task Organization - Safety culture	- Workload due to simultaneous goals/tasks - Staffing - Cues and time availability - Team characteristics - Task complexity - Task type/attribute - Ergonomics/HMI quality - Procedures/administrative control - Working environment - Need for special tools, parts, and outfits - Special fitness needs - Accessibility and operability of equipment - Plant policy and safety culture

2.2. Defining PSFs for Multi-Module SMR Operation

Along with the generic PSFs, newly identified human factors evoked from SMR plant design were extracted to suggest significant multi-module PSFs considered in this research. Human failure events defined in previous studies accentuate on how operator's workload and situation awareness will be affected by the new concept of operation [1]. Among the predefined generic PSFs, Table II provides the ones that are still relevant in multi-module operation while considering new PSF, which is passive and automation system failure indication.

Table II: PSFs redefined for Multi-Module Operation

Generic PSFs	Redefined PSFs	Details
Workload due to simultaneous goals/tasks	Module/Operator Ratio	Number of modules controlled by operator
	Mental Model	Whether operator has to manage simultaneous of different scenarios
Staffing	Surveillance	Existence of shift supervisor in the operation crew to monitor and review reactor operator actions
Team Characteristics		
Passive Safety System/Automation System	Passive Safety System Failure Indication	Availability of information that operator can recognize failure of the passive systems
	Automation System Failure Indication	Availability of information that the operator can recognize failure of the automation systems

3. Experiment Design

3.1. Data Collection

Strategies to collect human performance data are (1) reviewing operational experience, (2) studies via partial or full-scope simulators, and (3) other sources such as event reports or logs. However, such techniques are non-viable as there are no currently operating multi-module SMRs and limited scope of dedicated simulators to garner relevant data [5]. Therefore, this study suggests the use of existing simulator – Compact Nuclear Simulator (CNS) – to construct a multi-module environment for assessing the feasibility of the suggested performance shaping factors

CNS is a three-loop Westinghouse type simulator referenced from KORI unit 3 and 4. Developed by Korea Atomic Energy Research Institute (KAERI), it serves as a training device to generate various fundamental operational conditions analogous to real NPP.

3.2. Scenarios

Operable scenario of concern in multi-module SMR includes the management of off-normal and emergency conditions [3]. There are four typical off-normal scenarios simulated in the CNS: Loss of Coolant Accident (LOCA), Main Steam Line Break (MSLB) or Excess Steam Demand Event (ESDE), Anticipated Transient Without Scram (ATWS), and Steam Generator Tube Rupture (SGTR). This research will focus on assessing human performance under three emergency conditions – LOCA, ESDE (MSLB), and SGTR – to explore the relative significance of each performance shaping factor.

3..3 Experiment Setting

To test the viability of the suggested PSF list, this study has constructed multi-module main control room environment based on the Korean innovative SMR's concept of operation. 4 modules and 3 staffs – 2 reactor operator and 1 shift supervisor – are to be utilized for this experiment as displayed in Figure 1.

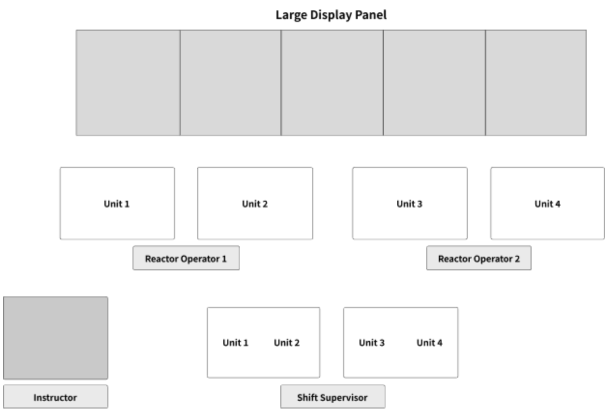

Fig. 1.

4. Conclusion

In order to address the human reliability issues of interest in SMR, this study has proposed the experimental framework of the suggested the feasible performance shaping factors essential in multi-module operation. First, performance shaping factors were redefined to extract candidates specific to SMR – module/operator ratio, mental model, surveillance, passive safety system failure indication, and automation system failure indication. Then, to investigate the relative importance and relationship between the aforementioned factors, simulator-based experiment design was established with 4 modules and 3 staffing members that consist of 2 reactors and 1 shift supervisor. Future works are expected to elicit a novel approach in assessing human performance in multi-module environment via performing the above experimental agenda with the suggested multi-module PSFs.

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