Human Performance Data Acquisition and Analysis for Multi-Module SMR HRA

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1. Introduction

Recently, interest in Small Modular Reactors (SMRs) has been rising as a solution to meet the increasing power demands of artificial intelligence data centers and to achieve global decarbonization targets [1]. SMRs are defined as nuclear reactors with an electrical output of 300 MWe or less [2]. They are distinguished from conventional large-scale Nuclear Power Plants (NPPs) by several key features: enhanced reliability through passive safety systems, flexible operations by high-levels of automation, and improved operational and economic efficiency via multi-module operations.

However, distinct designs and operational environments of SMRs pose significant challenges for the direct application of existing Probabilistic Safety Assessment (PSA) methodologies and reliability data. As SMRs currently face a cold start problem due to the lack of empirical data, ensuring the high fidelity of reliability data is important for verifying safety during the design and licensing phases.

Among the various reliability data, human reliability data is one of the substantial uncertainty sources due to the inherent variability of human factors [3]. In multi-module SMRs, different Main Control Room (MCR) staffing configurations impose a fundamental shift in operator roles which may induce undefined cognitive workloads and may affect Situation Awareness (SA) in the ways not observed in the existing environments [4]. Consequently, establishing a HRA database for multi-module SMRs is essential but the empirical data collection remains extremely limited [5].

This study aims to identify key Performance Shaping factors (PSFs) influencing human performance in multi-module environment and to analyze their impacts. Human performance data for Human Reliability Analysis (HRA) for multi-module SMRs was acquired via simulator experiments, which were conducted with nine professional subjects, each possessing a minimum of eight years of large commercial reactor operation experience.

This paper validates whether the defined key PSFs yield statistically significant differences in Human Error Probabilities (HEPs) and other performance measures to provide a technical basis for constructing HRA databases and to enhance the overall reliability of PSA for multi-module SMRs.

2. Methodology

2.1. Testbed Implementation

This study utilized four units of the Compact Nuclear Simulator (CNS) [6] to construct an integrated MCR environment for multi-module SMRs. The staffing consisted of two Reactor Operators (ROs) and one Shift Supervisor (SS), where each RO assigned control authority over two distinct SMR modules. The configuration and overview of testbed are illustrated in Fig 1, Fig 2.

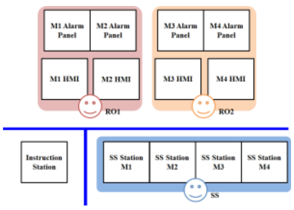

Fig 1. Configuration of Testbed

Fig 2. Overview of Testbed

In the event of an abnormal or emergency condition, operators enter the procedures to perform mitigation tasks. The SS monitors the overall status of all modules and provides support for recovery actions. To reflect the design characteristics of SMRs, the Safety Injection (SI) system and the Auxiliary FeedWater (AFW) system of the CNS were mapped to represent the automatic and passive safety systems of SMR, respectively. Also, supportive Human-System Interface (HSI) was developed to provide supplementary status monitoring for these safety systems.

2.2. PSFs and Accident Scenarios

The PSFs in this study were categorized into scenario-level (4 types) and module-level (1 type).

2.2.1. Scenario-Level PSFs

Accident Modules per Operator (AMO): Real-numbered value which defines the ratio of modules in an off-normal state to the total number of ROs in the MCR.

$$(1)\quad \mathrm{AMO} = \frac{(\text{Number of Off}-\text{Normal Module})}{(\text{Number of ROs})}$$

Accident Homogeneity (AH): Binary-type value which indicates whether the mental model for a individual RO remains consistent across their assigned modules.

$$(2)\quad AH = \begin{cases} \text{Same} & \text{if Identical Accident Type} \\ \text{Different} & \text{if Distinct Accident Types} \end{cases}$$

Surveillance Existence (SS): Binary-type value which indicates whether the SS exists in the staffing configuration.

Supportive HSI (HSI): Three-staged categorical value which indicates the level of the supportive HSI for safety systems. Categorized into: No supports, Partial support (single system) and Full supports (both systems)

2.2.2. Module-Level PSFs

Malfunction of Safety Systems (M): Categorical value which indicates the failure status of safety systems. Categorized into: No failure, SI failure, AFW failure

2.2.3. Accident Scenarios

The simulated accident scenarios included Loss of Coolant Accident (LOCA), Steam Generator Tube Rupture (SGTR), and Excess Steam Demand Event (ESDE). The experiments were terminated when all off-normal modules successfully entered the "SI reduction" or "SI termination" steps of procedure, indicating a stable plant state.

2.3. Metrics

Various human performance metrics were derived in this study: HEPs, Mean task completion Time per instruction (MT), SA and workload. Both HEP and MT were derived through operator observation data via HuREX framework [7]. SA was evaluated using the SART [8] and SACRI [9] questionnaires, while workload was measured via the Modified Cooper-Harper (MCH) [10] scale.

3. Experiment

Simulator experiments were performed with a total of nine subjects. Each subject holds either a Reactor Operator (RO) or a Senior Reactor Operator (SRO) license, with a minimum of 8 years and average of 18 years of reactor operation experience. The experimental session for each shift were conducted over a two-day period, which the assigned roles (RO or SS) remained fixed to ensure consistency in performance. A total of 32 experiments were successfully executed. The overview of simulation experiments are illustrated in Fig 3 and Fig 4. The overview of acquired data is summarized in Table 1.

Fig 3. Overview of Experiment

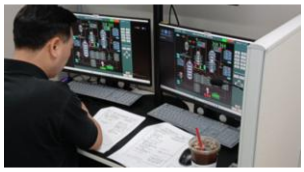

Fig 4. Overview of Experiment (RO)

Table 1. Overview of Acquired Data

Acquisition Target	Number of Acquisitions
Experiments	32
Accident Modules	102
MCH	82
SART	107
SACRI	82

4. Results and Discussion

4.1. Quantitative Results

The estimated HEPs and MT derived from experiments are summarized in Table 2, while the 'Conventional NPPs' column exhibits the HuREX HEP estimates from conventional large-scale NPP simulators [7]. The estimated frequency of Error of Omission (EOO) is nearly identical, whereas Error of Commission (EOC) is lower than the commercial one.

Table 2. Estimated HEPs and MT

Metrics	Multi-Module SMRs	Conventional NPPs [7]
HEP(EOO)	7.53E-03	7.71E-03
HEP(EOC)	2.87E-03	5.39E-03
MT	30.06s	-

The SA and workload evaluated via questionnaires are summarized in Table 3 while the values falling outside $(Q1 - 1.5 \times IQR, Q3 + 1.5 \times IQR)$ was excluded as outliers. The 'Single-Module' column exhibits the results from the study which was evaluated from a single-module CNS experiments with experienced operators.

Table 3. Evaluated Mean SA and Workload

Metrics	Multi-Module SMRs	Single-Module [11]
MCH	4.70	3.13
SART	22.56	25.86
SACRI A'	0.86	-
SACRI R:S	0.60	-

It shows that the multi-module environment increases operator's workload (MCH) as well as decrease SA (SART). The evaluated mean workload is 4.70, which corresponds 'Moderately high operator mental effort is required to attain adequate system performance',

Table 4. Hypothesis Test p-values

Metrics	AMO	AH	SS	HSI	M	Acc	P
HEP(EOO)	0.036*	0.323	0.016*	0.978	0.004**	<0.001***	0.207
HEP(EOC)	0.060(a)	0.060(a)	0.258	0.003**	0.029*	0.763	0.039*
MCH	<0.001***	0.265	0.682	0.338	0.228	0.972	0.059(a)
SART	0.018*	0.485	0.452	0.264	0.819	0.24	0.674
SACRI A’	0.966	0.628	0.317	0.782	0.01*	0.65	0.79
SACRI R:S	0.274	0.985	0.786	0.333	0.106	<0.001***	0.114
MT	<0.001***	0.370	0.189	0.739	0.948	0.531	<0.001***

indicates ‘Mental workload is high and should be reduced’ [10]. It implies that the parallel monitoring and control of multi-modules impose substantial cognitive demands on operators.

The SACRI A’, which regards objective SA, is remained high as 0.86. The SACRI R:S ratio, which represents the proportion of perceived versus actual number of changed variables is 0.60, indicating that operators tended to perceive fewer variable fluctuations than actual in the multi-module environment.

4.2. Hypothesis Test and Discussion

Hypothesis test was conducted to evaluate the effects of the five PSFs and two experimental factors—accident scenarios (Acc) and number of participations (P). Barnard's Exact Test was applied to analyze HEP, while the Kruskal-Wallis Test was employed for other metrics. Table 4 summarizes the p-value of each test, where superscript * means p-value < 0.05, ** means p-value < 0.01, *** means p-value < 0.001, and (a) means 0.05 ≤ p-value < 0.1.

AMO: The results indicate that multi-module operation increases EOO, MCH and decreases SART, as multi-module operation requires more information processing from operators. Conversely, MT and EOC exhibited a declining trend. It is primarily attributed to the learning effect resulting from the sequential order of the experimental sessions, which appears as an experimental factor P.

AH: When operators should perform distinct mitigation process for each module simultaneously, EOC exhibits an increasing trend due to the cognitive demand of maintaining different mental models.

SS: The present of SS led to a reduction in EOO, which shows the effectiveness of redundant monitoring and recovery support by the supervisor.

HSI: Refer to Table 5 for estimated values. It shows that the application of a status monitoring interface for single safety system reduces EOC. However, expanding this support to both of systems resulted in an increase in EOC, suggesting a potential information overload effect.

Table 5. Estimated Metrics about HSI

Metrics	No Supports	Partial Support	Full Supports
HEP(EOC)	5.12E-03**	1.74E-03**/*	3.56E-03*

M: Failure of safety system increases both EOO and EOC while simultaneously degrading SA (SACRI A'). This trend is attributed to the operator’s failure to detect system unavailability when automatic or passive system fails.

Acc: Significant variations in EOO and SACRI R:S were observed depending on the specific type of accident scenarios. Especially, ESDE shows the most negative results for EOO. Furthermore, the SACRI R:S ratio for ESDE was recorded at 0.327, the lowest value among all analyzed experimental factors. This performance gap is attributed to the diagnostic difficulty of ESDE (modeled as in-containment MSLB in this study) and the accident familiarity compared to the other scenarios like LOCA and SGTR.

P: Denotes the cumulative number of experimental sessions completed by each operator, include preliminary trial. P is categorized into 3 distinct phases: Phase 1 (1st to 3rd sessions), Phase 2 (4th to 6th sessions) and Phase 3 (7th to 9th sessions). Table 6 summarizes estimated metrics with respect to P.

Table 6. Estimated Metrics about P

Metrics	Phase 1	Phase 2	Phase 3
HEP(EOC)	3.95E-03	3.27E-03*	1.36E-03*
MCH	4.600(a)	5.067(a)/*	4.450*
MT	47.010**	29.880**/***	20.741***

From Phase 1 to Phase 2, EOC decreased slightly, but the change lacked statistical significance. Conversely, MCH exhibited an increasing trend, while MT decreased substantially. These observations suggest that operators, upon recognizing the inherent complexity of multi-module operations during the initial phase, allocated additional cognitive resources to maintain their adequate performance

From Phase 2 to Phase 3, EOC and MT continued to improve, and MCH recovered. EOC was reduced by more than half compared to Phase 2 and was lower than that observed in Phase 1. It indicates that operators successfully adapted to the multi-module environment, enabling them to execute tasks with greater precision and speed while utilizing fewer cognitive resources.

5. Conclusions

In this study, we empirically acquired and analyzed the impact of five PSFs and two experimental factors on human performance during multi-module operation experiments with professional operators.

The results indicate that while HEPs in a multi-module SMRs remain comparable to those in commercial NPP data, operators experience significantly higher workloads and lower SA than in single-module operations. These findings confirm that multi-module operations impose more cognitive burden on operators.

Regarding specific PSFs and experimental factors, the presence of SS was found to effectively decrease EOO, whereas failure of safety system led to an overall increase in HEPs. Furthermore, while providing appropriate status information for safety systems is beneficial for performance, excessive information may be detrimental due to information overload. The study also validates that human performance is positively correlated with the operators' familiarity with the multi-module environment and specific accident scenarios, highlighting the critical need for Multi-Module SMR-specific training programs.

The findings of this paper serve as a technical basis for developing SMR-specific HRA methodologies and improving the estimation of HEPs for SMR PSAs. Future research aims to provide more solid technical foundations by conducting an integrated analysis of the SMR-specific unsafe acts identified during the experiments.

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