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Experimental Assessment of Operator's Situational Awareness under Multi-Module Operation

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1. Introduction

Situational awareness is an essential metric for evaluating operator performance in comprehending the past, current, and future trend of the nuclear power plant (NPP) parameters [1]. As operators monitor, navigate, and respond to perceived information from their milieu, NUREG-0711 delineates the need for maintaining a sufficient level of situational awareness to minimize personnel errors [2]. Thus, control room designs and operator tasks should adhere to the human factors engineering guidelines supported by human performance studies.

To achieve economic viability and enhance safety functions, small modular reactors (SMRs) were introduced with advanced design features such as passive safety systems, high-level of automation, and modularization [3]. Corresponding to the systematic implementations, novel concept of operation was established to provide agenda for human actions especially targeting the multi-modality of the SMR – revised personnel roles and staffing, integrated main control room, and human-system interface for multiple modules [3, 4]. However, O'Hara et al and Boring et al raised concerns of potential human performance-issues driven by such changes [3, 4]. These include increased task complexity due to reduced staffing, collateral work demands for multi-module operation, and comprehensive interaction with diversified automatic systems that negatively affect the situational awareness of operators, resulting in human failure events [4].

Previous studies have toiled to collect and evaluate the situational awareness of operators in multi-module setting. Halden Research Project has performed 2019 Small Studies to examine operator actions in monitoring and prioritizing tasks under SMR conditions [5]. This study has demonstrated that unit confusion was not observed from operators under high task complexity and disturbances [5]. Furthermore, NuScale has conducted Revised Staffing Plan Validation to prove the adequacy of their concept of operation via performance-based testing [6]. Situational awareness questionnaire was developed specifically to assess the operator's ability in retaining awareness on plant activities and crew actions. The validation concluded with successful indication of high situational awareness throughout the testing for high workload scenarios. Despite such insights, both studies do not fully address operator's situational awareness under conditions such as various off-normal scenarios; extent of operator tasks; and number of modules requiring operator actions.

Consequently, the objective of this study is to experimentally assess the situational awareness of operators under multi-module operation. Simulator-based operational environment was formed to generate feasible combination of transient conditions across all modules. Then, human performance data were collected and statistically analyzed to derive relationship between operator's situational awareness and degree of multi-modality.

2. Experiment Design

2.1. Multi-Module Environment

Innovative SMR (iSMR design proposed by the Korean government was selected to establish multi-module environment. The main control room was composed of 4 modules maneuvered by three operators – 1 shift supervisor and 2 reactor operators. Each operator manipulated 2 modules whilst the shift supervisor observed both plant status and operator actions.

Compact Nuclear Simulator (CNS) – a Westinghouse three-loop PWR design developed by Korea Atomic Energy Research Institute (KAERI) – was utilized to emulate various operational modes [7]. It was selected due to its adequacy for conducting human performance experiments on both expert and non-expert participants [8]. Figure 1 denotes the control room layout and user interface for participants to control and access plant parameters.

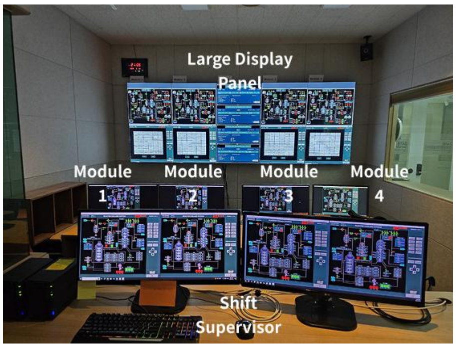

Fig 1. Multi-module environment and user interface

2.2. Experiment Scenarios

Experiment scenarios were feasible combination of off-normal conditions injected to differing number modules. Three transients – Loss of Coolant Accident (LOCA), Steam Generator Tube Rupture (SGTR), and Excess Steam Demand Event (ESDE) – were selected from researches evaluating human performance in CNS. In each scenario, participants have to recognize the tripped module and conduct necessary emergency operating procedures to achieve depressurization and cooling of the reactor. Table 1 delineates the transients and types of malfunctions applied to the simulator for each transient.

Table I. Types of Transients and Malfunction

Off-normal Conditions	Initial Conditions	Malfunctions
LOCA	Normal Operation (100%)	Leakage of Primary Coolant into Containment in Loop #2 Hot-leg
SGTR		Rupture of Steam Generator Tubes in Loop #2
ESDE		Main Steam Line Break in Loop #2 Inside Containment

To determine which accident is introduced for each module and the number of affected modules, accident module per operator (AMO) and accident homogeneity (AH) are further considered in the operational scenarios. Accident module per operator refers to the number of accident modules that each operator is required to manipulate. Accident homogeneity indicates whether each operator manages same or different types of off-normal conditions simultaneously. Table 2 delineates the levels of aforementioned factors additionally considered in this study.

Table II. Additional Factors for Experiment Scenarios

Accident Module per Operator	Accident Homogeneity
0.5	Same
1	
2	Different

Total 24 scenarios with 12 AMO = 2, 6 AMO = 1, and 6 AMO = 0.5 were experimented for this study. Each operating crew performed 2 AMO = 2, 1 AMO = 1, and 1 AMO = 0.5, resulting in total 4 scenarios per crew. Amongst the 12 AMO = 2 cases, half was AH = same whilst the other was AH = different.

2.3. Participants

Total 18 students enrolled in the Nuclear and Quantum Engineering degree: those with Master's degree were delegated as shift supervisor, with assumption that the level of knowledge regarding the NPP safety systems and accident propagation are higher than those with or currently enrolled in undergraduate program.

2.4. Procedures

Experiment sessions were divided into training and main to saturate the simulator familiarity and operator's performance on base scenarios to minimize learning effects. Recruited members were trained via 2 ~ 3 reference cases, composed of transient occurring at one module in. Then, main cases as described in section 2.2 were performed in random order.

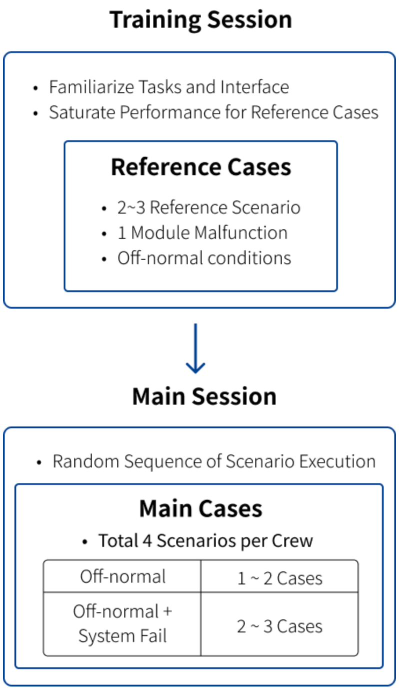

Fig 2. Experiment procedure from training to main sessions

2.5. Data Collection

Two survey-based questionnaires were developed to collect comprehensive data on the situational awareness of operators – Situation Awareness Rating Technique (SART) and Situation Awareness Control Room Inventory (SACRI) [1, 9].

SART is a subjective situation awareness assessment tool devised by Taylor [9]. The questionnaire consists of 10 questions developed from three categories – demand, supply, and understanding of the attentional resources and situation [9]. Each question is scaled from 1 to 7 in the incremental order to evaluate the situation awareness experienced by the personnel. Participants were given the survey after the termination of each scenario.

Since SART provides generic perspective on operator's situation awareness for assigned events, SACRI was incorporated as supplementary measure. Questions in SACRI ask about the trend of significant parameters varying from past, present, and to future monitored in the control room [1]. Total 9 variables were opted to represent the plant state – safety injection flow, containment pressure, steam generator water level, steam generator pressure, average operating temperature, pressurizer pressure, pressurizer water level, containment radiation level, and secondary radiation level. Answers were scored based on the actual values at the moment when the questionnaire was taken after operator's diagnosis of the accident. Participants were assigned to answer the survey for each accident module. According to NUREG/IA-0137, SACRI results are evaluated as A' and R:S ratio [1]. A' refers to operator's ability to identify fluctuations; R:S ratio measures the response bias in overestimation or under-estimation of the parametric changes [1].

3. Results

Statistical methods such as analysis of variance (ANOVA) were implemented to provide a comprehensive analysis of the acquired data. Results obtained were assessed based on one of the factors used to formulate the scenarios – accident homogeneity – for extensive evaluation of situation awareness using both SACRI and SART scores.

Table 3 lists the summary of survey questionnaires collected with respect to accident homogeneity. As there are SACRI scores for each module in AMO = 2, both A' and R:S ratio of modules in the identical scenario were averaged for comparison with those of other AMO levels. From the ANOVA results, A', R:S ratio, and SART scores for AH = same had higher situational awareness than those of AH = different. However, the results were not statistically significant, meaning that the differences were minute.

Table 3. Summary of SART and SACRI for Accident Homogeneity

Levels	A'(average)		R:S(average)		SART	
	Mean	p-value.	Mean	p-value.	Mean	p-value
Same	0.773	0.1	0.414	0.853	20.58	0.327
Different	0.616		0.403		17.67	

To verify the above result using averaged values is acceptable, differences in the SACRI scores between modules in the analogous scenarios from AH = different were compared. Table 4 shows that the A' and R:S ratio of modules was statistically significant in the difference between the modules. This indicates that the operators were able to only focus on one module in the scenario with different accident per module as the situational awareness of the other module is significantly lower.

Table 4. Differences in the SACRI Scores Between Modules with Different Accident Homogeneity

Levels	A'		R:S	
	Mean	p-value	Mean	p-value
High	0.802	0.023	0.482	0.021
Low	0.478		0.324	

4. Conclusion

In conclusion, this research experimentally assessed the operator's situational awareness in multi-module operation though survey-based questionnaires: SART and SACRI. From iSMR design, 4 CNS modules with 3 operators as an operating crew were established as multi-module environment. Scenarios consisted of three off-normal conditions – LOCA, SGTR, and ESDE – each injected in the modules according to the AMO and AH designated for each scenario. Participants majoring in Nuclear and Quantum Engineering were recruited; operator roles were assigned based on the academic degrees.

Statistical analysis of the results discloses that the situation awareness of operators facing different accidents simultaneously tend to have high A' and R:S scores on only one of the modules whilst the focus reduces significantly on the other module. These insights were not observed in the averaged values of the SACRI and SART measures. Thus, the comprehensive evaluation of utilizing both metrics indicate that operators need supportive tools or systems to enhance the situational awareness across all modules under operation.

Future works will expand on the number of participants to derive generic tendencies of the situational awareness in multi-module setting. Also, further measures for human performance will be utilized to provide extensive insights on the operator actions.

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