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Analysis of Performance Shaping Factors in Multi-Module Operating Environments

Dohun Kwon, Gyunyoung Heo*
Department of Nuclear Engineering. Kyung Hee University, Yongin-si, Gyunggi- do
**Corresponding author: gheo@khu.ac.kr*

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1. Introduction

According to the IAEA, as of 2024, more than 60 SMRs are under development worldwide, and it is common practice to design SMRs as multi-module plants to enhance economic feasibility and operational efficiency[1,2]. For example, the innovative Small Modular Reactor(i-SMR) currently being developed in Korea is designed with four modules, while NuScale in the United States aims to configure a plant with 6 to 12 modules. Consequently, operator performance in a multi-module operating environment is inevitably different from that in conventional large-scale nuclear power plants where multiple operators manage a single unit. Since two or more modules may simultaneously be in different operating states—such as normal power, shutdown/low power, or emergency—the workload of operators is expected to increase significantly when only a limited number of staff are available[3].

Such human factors must be considered in probabilistic safety assessment (PSA), where safety-critical tasks are identified and their associated human error probabilities (HEPs) incorporated into the plant safety evaluation. In calculating HEPs, performance shaping factors (PSFs)—such as available time, stress, and operator experience—are reflected. However, beyond these conventional PSFs, it is also necessary to account for PSFs specific to multi-module operation. Currently, no simulator environment representing multi-module iSMR operation exists in Korea. To address this, task completion time measurement experiments were conducted using the NuScale simulator (E2 Center) installed at Seoul National University, which reflects SMR characteristics. By measuring the execution time of specified tasks and comparing them with task times obtained in single-module settings, it becomes possible to analyze PSF multipliers through ratio factors.

2. Methodology for Analyzing Performance Shaping Factors

2.1 Quantification Method for Human Error Probability

Most HRA methods calculate human error probability (HEP) by applying multipliers to major performance shaping factors (PSFs). As a representative example, Table 1 presents the stress-level multipliers considered in the SPAR-H (Standardized Plant Analysis Risk–Human Reliability Analysis) method.

Table I. PSF Multipliers for Stress Levels Provided in SPAR-H

PSFs	PSF Level	Multiplier
Stress/ Stressors	Extreme	5
	High	2
	Nominal	1
	Insufficient Information	1

Through such multiple PSF analyses, the quantitative effect of PSFs can be expressed by the following equation.

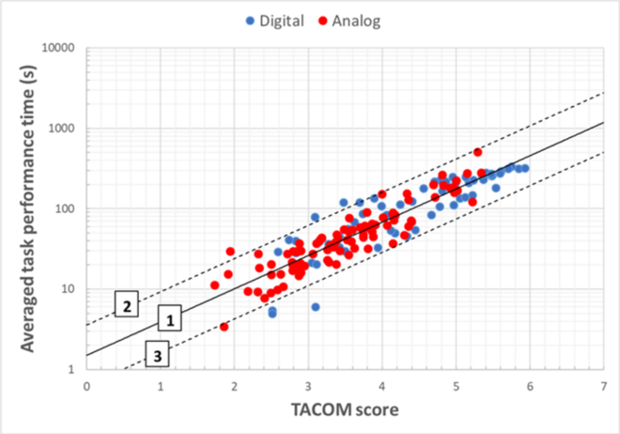
$$HEP = Nominal\ HEP \times \prod_{i=1}^{n} PSF_i$$

2.2 Incorporating Characteristics of Multi-Module Operating Environments

Fig. 1. Example of Control Room Layout
(Right: Conventional NPPs, Left: Multi-Module SMR)

As shown in Figure 1, there are significant differences between the main control rooms of conventional nuclear power plants and multi-module SMRs, primarily in the number of reactors managed and the number of operators. Therefore, directly applying PSFs evaluated in single-unit nuclear power plants to multi-module control room environments may lead to unrealistic results. To address this, operator performance in large conventional nuclear plants and in SMRs is compared based on procedural task complexity. Experiments were conducted to derive ratio factors that enable comparison of operator performance in these two different environments, using the TACOM (TAsk COMplexity) scale, which is widely applied to assess task complexity in large nuclear plants.

The TACOM scale is a theoretical framework for quantitatively evaluating task complexity, with particular emphasis on proceduralized tasks[4]. It consists of five sub-criteria. Previous studies have demonstrated that task complexity has a statistically significant influence on operator performance in complex systems such as the nuclear industry. Figure 2 compares task completion times with TACOM values for analog and digital main control rooms[5]. Despite substantial differences between analog and digital environments, a consistent correlation is observed between TACOM scores and task times. Since SMRs also employ proceduralized task environments, it is assumed that ratio factors for PSF multipliers can be determined through task time comparisons. Based on this assumption, experiments measuring task performance times were carried out using an SMR simulator to build a database for ratio factor analysis.



1: Regression line $\quad$ Time = $1.499\cdot e^{(0.953\cdot \mathrm{TACOM})}$
2: Upper 95% prediction limit $\quad$ Time = $3.572\cdot e^{(0.952\cdot \mathrm{TACOM})}$
3: Lower 95% prediction limit $\quad$ Time = $0.629\cdot e^{(0.955\cdot \mathrm{TACOM})}$

Fig. 2. Comparison of Task Performance Time and TACOM Values

3. Experimental Results and Analysis of Task Performance Time

3.1 Experimental Environment

In Korea, the only experimental environment capable of simulating multi-module SMR operation is the E2 Center installed at Seoul National University, which models 12 NuScale Power reactor modules. The E2 Center is a digital twin simulator that integrates 38 subsystem models (e.g., Studsvik S3R 3D core, RELAP5-HD thermal hydraulics, SimExec® electrical systems, etc.) for 12 NuScale modules. Based on a man–machine interface, the simulator can reproduce in real time the simultaneous operation of 12 modules, automation, emergency procedures, alarms, and safety function status. Hierarchical alarms are recorded as Plant Notifications, while equipment operations and operator actions are automatically stored in the Plant Event Log.

The major functions of the E2 Center are as follows:

- Electronic Procedure and Automation System (Process Library):

- Provides electronic procedures for normal, abnormal, and emergency scenarios.

- Includes a place-keeping function that displays step-by-step progress, allowing operators to easily identify their current procedural position. Each checkpoint transition is automatically logged.

- Includes a peer-check function for cross-verification among operators, preventing misoperations or deviations during procedure execution.

- Hierarchical Alarm System:

- As shown in Figure 3, alarms are categorized into three levels: red (Alarm), yellow (Caution), and blue (Notice), guiding operators according to urgency.

- Red alarms require immediate action and are accompanied by continuous audible alarms.

- Yellow alarms indicate conditions that require monitoring but not immediate action; these are announced with a single audible signal.

- Blue alarms provide information only with a visual alert, without any audible signal.

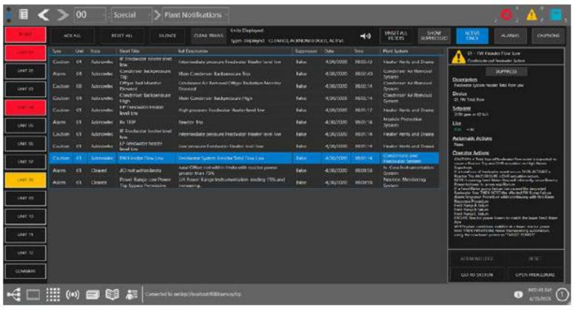


Fig. 3. Example of Plant Status Notification Window

- Automation and Power Control Functions:

- By entering the target power and generation output, the turbine speed and valve positions are automatically adjusted within the range of 50%–300% of rated capacity.

- A bypass function that fully opens the turbine bypass valve (100%) enables stable operation under load variations and allows rapid load adjustment independent of the grid.

- Control authority for RO1, RO2, and RO3 is visualized with graphic tokens, preventing role confusion during multi-module control.

- Safety Function Status Display:

- The status of the three major safety functions—containment isolation, reactivity control, and core heat removal—is displayed in a color-coded panel (green, yellow, red).

- The status of the four levels of defense-in-depth is also presented, and clicking a color indicator provides direct access to the relevant procedure, enabling timely operator response.

- Multi-Module Integrated Monitoring and Control:

- As shown in Figure 4, a Multi-Module Overview consolidates and displays on a single screen the key parameters of all 12 modules, including power, core/turbine ΔP and ΔT, alarms, and safety function status.

	Thermal Power	T-Average	PZR Pressure	PZR Level	RCS Flow	CNT Pressure	CE Rad Mon	CAR Off gas
01	99.8 %	543.3 °F	1849 psia	58.5 %	9424 gpm	0.21 psia	10 cps	30 cpm
02	99.8 %	543.3 °F	1849 psia	58.5 %	9425 gpm	0.21 psia	10 cps	30 cpm
03	99.8 %	543.3 °F	1849 psia	58.5 %	9425 gpm	0.21 psia	10 cps	30 cpm
04	99.8 %	543.3 °F	1849 psia	58.5 %	9425 gpm	0.21 psia	10 cps	30 cpm
05	99.8 %	543.3 °F	1849 psia	58.5 %	9426 gpm	0.21 psia	10 cps	30 cpm
06	99.8 %	543.3 °F	1849 psia	58.5 %	9426 gpm	0.21 psia	10 cps	30 cpm
07	99.8 %	543.3 °F	1849 psia	58.5 %	9426 gpm	0.21 psia	10 cps	30 cpm
08	99.8 %	543.3 °F	1849 psia	58.5 %	9426 gpm	0.21 psia	10 cps	30 cpm
09	99.8 %	543.3 °F	1849 psia	58.5 %	9424 gpm	0.21 psia	10 cps	30 cpm
10	99.8 %	543.3 °F	1849 psia	58.5 %	9424 gpm	0.21 psia	10 cps	30 cpm
11	99.8 %	543.3 °F	1849 psia	58.5 %	9424 gpm	0.21 psia	10 cps	30 cpm
12	99.8 %	543.3 °F	1849 psia	58.5 %	9424 gpm	0.21 psia	10 cps	30 cpm

Fig. 4. Multi-Module Integrated Monitoring and Control

- Scenario Simulation Support Tools:

- A Malfunction Library enables the immediate injection of fault scenarios, allowing the reproduction of single-module accidents, multi-module accidents, and sequential accident scenarios.

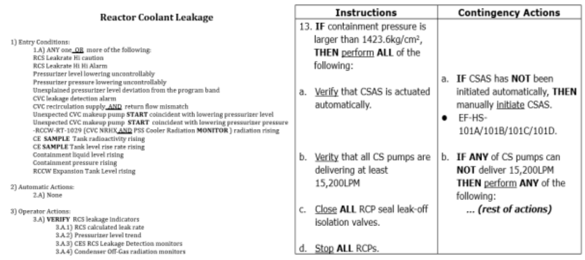
3.2 Experimental Procedures

In the case of NuScale, when a reactor is tripped, automation is designed to minimize operator actions. Therefore, for the experiment, abnormal scenarios listed in Table 2 were considered.

Table II. Types of Procedures and Their Purposes

Procedure Type	Purpose
Reactor Coolant Leakage	Early detection of coolant leakage → Ensure core integrity by reducing power safely and proceeding to shutdown.
RA-4RTS Actuation (RED)	Following the generation of a Reactor Trip Signal (RTS), promptly verify control rod insertion and the status of heat removal systems to transition to a safe mode and ensure core integrity.

The procedures used in the E2 Center are organized in a format different from the emergency operating procedures applied in domestic nuclear power plants, as illustrated in Figure 5.



Reactor Coolant Leakage

1) Entry Conditions:
    1.A) ANY one OR more of the following:
    RCS Leakrate Hi caution
    RCS Leakrate Hi Hi Alarm
    Pressurizer level lowering uncontrollably
    Pressurizer pressure lowering uncontrollably
    Unexplained pressurizer level deviation from the program band
    CVC leakage detection alarm
    CVC recirculation supply AND return flow mismatch
    Unexpected CVC makeup pump **START** coincident with lowering pressurizer level
    Unexpected CVC makeup pump **START** coincident with lowering pressurizer pressure
    -RCCW-RT-1029 (CVC NRHX AND PSS Cooler Radiation **MONITOR**) radiation rising
    CE **SAMPLE** Tank radioactivity rising
    CE **SAMPLE** Tank level rise rate rising
    Containment liquid level rising
    Containment pressure rising
    RCCW Expansion Tank Level rising

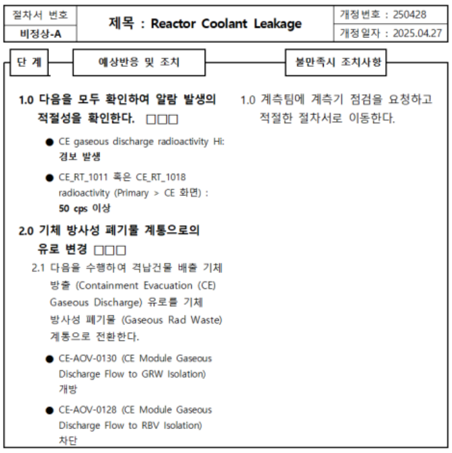
2) Automatic Actions:
    2.A) None

3) Operator Actions:
    3.A) **VERIFY** RCS leakage indicators
        3.A.1) RCS calculated leak rate
        3.A.2) Pressurizer level trend
        3.A.3) CES RCS Leakage Detection monitors
        3.A.4) Condenser Off-Gas radiation monitors

Instructions	Contingency Actions
13. **IF** containment pressure is larger than 1423.6kg/cm², **THEN** perform **ALL** of the following:	
a. Verify that CSAS is actuated automatically.	a. **IF** CSAS has **NOT** been initiated automatically, **THEN** manually initiate CSAS. ● EF-HS-101A/101B/101C/101D.
b. Verity that all CS pumps are delivering at least 15,200LPM	b. **IF ANY** of CS pumps can **NOT** deliver 15,200LPM **THEN** perform **ANY** of the following: ***... (rest of actions)***
c. Close **ALL** RCP seal leak-off isolation valves.	
d. Stop **ALL** RCPs.	

Fig. 5. Comparison of Procedure Formats
(Left: E2 Center procedure, Right: Conventional large NPP procedure)

Since the purpose of this experiment was to examine differences in human performance under multi-module operating environments through a comparison of task completion times, the procedures were standardized into a unified format as shown in Fig. 6. For the experimental environment, the procedures were also translated into Korean.



절차서 번호	제목 : Reactor Coolant Leakage	개정번호 : 250428
비정상-A		개정일자 : 2025.04.27

단 계	예상반응 및 조치	불만족시 조치사항
	1.0 다음을 모두 확인하여 알람 발생의 적절성을 확인한다. □□□ ● CE gaseous discharge radioactivity Hi: **경보 발생** ● CE_RT_1011 혹은 CE_RT_1018 radioactivity (Primary > CE 화면) : **50 cps 이상**	1.0 계측팀에 계측기 점검을 요청하고 적절한 절차서로 이동한다.
	2.0 기체 방사성 폐기물 계통으로의 유로 변경 □□□ 2.1 다음을 수행하여 격납건물 배출 기체 방출 (Containment Evacuation (CE) Gaseous Discharge) 유로를 기체 방사성 폐기물 (Gaseous Rad Waste) 계통으로 전환한다. ● CE-AOV-0130 (CE Module Gaseous Discharge Flow to GRW Isolation) 개방 ● CE-AOV-0128 (CE Module Gaseous Discharge Flow to RBV Isolation) 차단	

Fig. 6. Example of Modified Operator Procedure

3.3 Experimental Procedure

A total of 12 graduate and undergraduate students participated in the experiment, with an average age of 27.6 years. Of the participants, 11 were male and 1 was female, and all were majoring in nuclear engineering (see Fig. 7).

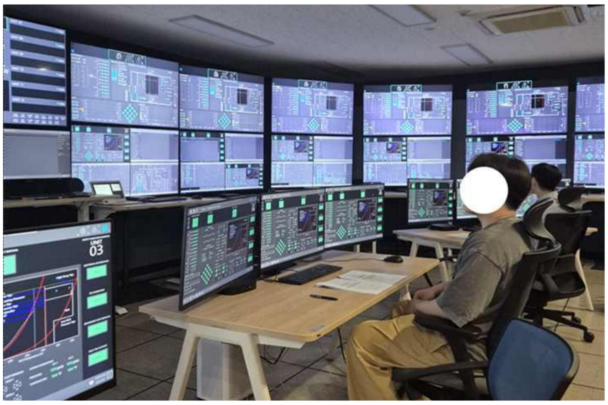


Fig. 7. Experiment Participation at the E2 Center Simulator

Each subject was assigned to control and manage three modules, after which either one or two abnormal scenarios were introduced. When two abnormal scenarios occurred, the procedures were performed alternately as prescribed.

Execution of Step 1 in the Reactor Coolant Leakage procedure → Execution of Step 1 in the RA-4 RTS Actuation (RED) procedure → Execution of Step 2 in the Reactor Coolant Leakage procedure → Execution of Step 2 in the RA-4 RTS Actuation (RED) procedure → [...]

The task completion time for each step described in the procedures was measured as the difference between the step's end time and start time. If errors were observed during time measurement but did not affect the overall procedure execution, no intervention was made by the observers. However, if the errors impacted procedure execution, an independent observer paused the experiment and intervened to guide the subject in the correct direction.

3.4 Analysis of Experimental Results

The 95% prediction limit in Fig. 2 represents the estimated result with a maximum 95% confidence level for a given TACOM value. Because similar results were obtained across different environments, such as analog and digital control rooms, this value can be assumed as the maximum allowable time for performing procedural tasks without additional workload. In other words, since operators in conventional large nuclear plant control rooms generally completed the assigned tasks within the 95% prediction limit, task completion times exceeding this threshold can be attributed to the influence of the multi-module operating environment.

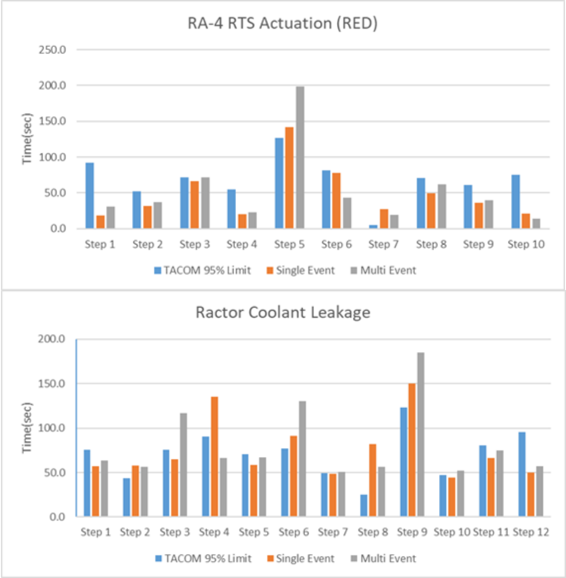


Fig. 7. Results of NuScale Simulator Experiments

Based on this assumption, task completion times obtained from the NuScale simulator were analyzed as shown in Fig. 7. The results revealed that certain operator procedures exceeded the 95% prediction limit of the TACOM value. In this experiment, 32% of the steps in single-event scenarios exceeded the 95% prediction limit, whereas in multi-event scenarios, the proportion increased to 45.5%. These findings indicate that responding to multiple simultaneous events is more challenging than responding to a single event.

4. Conclusion

It is necessary to establish an experimental database of procedural task times that allows direct comparison between HRA results derived from single-reactor operations and those from multi-module SMRs. Observing human performance using a simulator that reflects the characteristics of SMRs is particularly effective. For this reason, a ratio factor–based methodology for task time measurement experiments was developed, and a database of task times was constructed using the E2 Center NuScale simulator installed at Seoul National University. This simulator was chosen because it is currently the only available multi-module SMR simulator in Korea. However, as it is designed primarily for educational purposes, certain functions—such as event progression and fault injection—are limited.

Through the analysis of TACOM values for the tasks used in the experiment and the average task times observed for each task, a preliminary analysis of ratio factors was completed. Therefore, in future domestic iSMR licensing processes, it will be necessary to validate the applicability of the experimental database presented in this study, taking into account design and operational characteristics. In this study, preliminary analysis of ratio factors was performed using TACOM to demonstrate the validity of the task completion time data. In subsequent stages, particularly during the review of PSA results, further analyses tailored to specific objectives will be required to derive precise values.

Acknowledgement

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