Timeline-based Task Analysis for Multi-module SMRs

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1. Introduction

Small Modular Reactors (SMRs) are designed to be operated by a small crew in a single Integrated Control Room (ICR) while supervising multiple reactor modules. This operational concept differs fundamentally from conventional large nuclear power plants, which are typically designed around single-unit operation. As a result, the roles, responsibilities, workload, and coordination of control room operators are expected to change significantly in SMR environments. Determining and justifying appropriate staffing levels during the design phase is therefore a critical component of initial staffing verification for new reactor concepts.

Regulatory guidance such as NUREG-1791 recommends performing systematic task and staffing analyses to justify minimum staffing levels for advanced reactors [1]. Traditional task analysis approaches in nuclear power plants have primarily focused on procedure-based analyses for single-unit operations [2]. While such approaches are effective for conventional plants, they may not adequately capture the unique operational characteristics of SMRs, particularly the need for operators to monitor and control multiple modules simultaneously from an integrated control room.

In SMR environments, a single operator may be responsible for supervising more than one module which increases the likelihood that operators will be required to perform concurrent tasks across multiple modules. However, conventional procedure-based task analyses typically do not explicitly consider the temporal overlap of operator tasks, making it difficult to evaluate potential task interference, role coordination, and staffing adequacy in multi-module event scenarios.

To address this gap, this study applies a timeline-based task analysis to a common system failure scenario affecting multiple modules using results from an i-SMR simulator experiment with licensed operators. By identifying concurrent operator tasks and potential role interference, this work aims to highlight the importance of time-dependent task analysis for initial staffing verification in multi-module SMRs.

2. Methods

This study applied a scenario-based simulator experiment combined with a timeline-based task analysis to support initial staffing verification for SMRs. The analysis was conducted through an i-SMR ICR simulator experiment involving licensed operators.

2.1 Participants and Experimental Environment

The study utilized results from an initial staffing verification experiment conducted in November 2025. The Experiment involved licensed operators holding either a Reactor Operator (RO) license or Senior Reactor Operator (SRO) license.

The experiment was performed using a full-scope integrated control room simulator developed based on the i-SMR design. Various staffing configurations(3+1 crew and 6-person crew) were evaluated during the experiment. This study focuses on the application of the timeline-based task analysis to the 3+1 staffing configuration as a representative example.

2.2 Initial Staffing Configuration

The analyzed staffing configuration consists of four positions: Shift Supervisor (SS), Reactor Operator 1 (RO1), Reactor Operator 2 (RO2), and Assistant Reactor Operator (ARO). The SS, RO1, and RO2 are stationed in the integrated control room, while the ARO is normally stationed in the field operator room and moves to the control room upon request.

The SS is responsible for overall monitoring and supervision of the integrated control room. During multi-module events, the SS prioritizes plant responses, assigns operators to affected modules, and determines whether to call the ARO for support.

ROs (RO1 and RO2) monitor and control assigned modules by executing operating procedures and reporting key actions to the SS. The ARO moves to the ICR upon request and supports the SS by monitoring unaffected modules and assisting with control room activities. The roles, licenses, and locations of the initial staffing configuration are summarized in Table I.

Table I: Initial Staffing Configuration for the i-SMR ICR

Position	License	Location	Primary Responsibilities
SS	SRO	ICR	Supervision & Prioritization
RO1	SRO	ICR	Assigned Module 1&2 control
RO2	SRO	ICR	Assigned Module 3&4 control
ARO	RO	Field Office → ICR	Support & Module monitoring

2.3 Scenario Selection

Since it is impractical to analyze all possible operating scenarios, a common system failure scenario was selected to represent the multi-module characteristics of SMRs. A failure of common systems can simultaneously affect multiple modules and requires coordinated responses from multiple operators, making it a representative multi-module event for staffing evaluation.

2.4 Timeline-Based Task analysis Framework

To address the limitations of conventional procedure-based task analysis, this study applied a time-based task analysis framework to evaluate operator task demands during multi-module events.

The framework consists of three key elements:

- Time-axis integration: Operator actions, module status changes, and scenario progression are aligned on a shared timeline.
- Multi-layer representation: Operators, module, and task execution intervals are visualized in an integrated timeline.
- Concurrency evaluation: Potential task overlap and crew coordination demands in a multi-module environment are assessed.

[Analysis Method]

1. Identification of operator tasks using simulator recordings and operational logs
2. Construction of an integrated timeline including operators, modules, and time
3. Definition of task execution intervals for each operator
4. Identification of periods of potential concurrent task execution
5. Qualitative assessment of task interference and coordination demands

This study focuses on identifying time-dependent task characteristics in the SMR staffing configuration; quantitative workload assessment was not performed.

3. Results

Figure 1 presents the timeline developed for the common system failure scenario affecting four modules.

All modules were simultaneously affected; however, different operational states were observed. Modules 1 and 3 transitioned to Emergency conditions (Station Black Out, SBO), while Modules 2 and 4 remained in abnormal operating states.

Around 10 minutes after the event, RO1 and RO2 simultaneously performed situation assessment and procedure initiation for the affected modules. During the same period, the SS conducted decision-making and assigned module responsibilities based on information provided by the RO1&2. This indicates concurrent information gathering and supervisory decision-making during the early event phase.

After the SS initiated the call for the ARO, the ARO moved to the ICR and assumed monitoring task. After the ARO joined the control room crew, monitoring responsibilities were partially redistributed.

Overall, Figure 1 shows that concurrent operator task occurred during the early event phase and that the pattern of task overlap evolved over time as additional crew support was introduced.

4. Discussion

The Timeline analysis of the common system failure scenario indicates that operator task overlap is most pronounced during the early phase of the event in a multi-module environment. Immediately after the event, RO1 and RO2 were required to detect abnormal conditions and collect information from their assigned modules, and this information was used by the SS to determine the priority module for response. This phase required concurrent information gathering and reporting across multiple modules.

The SS then evaluated module severity and determined the priority response module while simultaneously monitoring lower-priority modules and deciding whether to call the ARO. This demonstrates that supervisory decision-making and monitoring tasks occur concurrently during the early event phase. After the ARO joined the control room crew, monitoring responsibilities were redistributed, and the pattern of task overlap changed over time.

These findings suggest that task overlap in multi-module SMR environment is dynamic and evolves across event phases.

5. Conclusions

This study applied a time-based task analysis to a common system failure scenario to examine operator task overlap in a multi-module environment. Concurrent information gathering, decision-making, and monitoring were observed during the early event phase, followed by redistribution of tasks after ARO arrival. These findings highlight the importance of time-based task analysis for initial staffing verification in the i-SMR ICR.

REFERENCES

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Fig. 1. Sample Result of Common System Failure Scenario

Time(min.)			10	12	14	16	18	20	22	24	26	28	…	70
Module Situation		M1	Emergency (Station Black Out)											
		M2	Abnormal (Station load operation)											
		M3	Emergency (Station Black Out)											
		M4	Abnormal (Station load operation)											
Operator Task	SS	M1	Decision	Call ARO							Backup Monitoring			
		M2		Monitoring										
		M3									Backup Monitoring			
		M4		Monitoring										
	RO1	M1	Detection	Procedure										
		M2	Detection											
	RO2	M3	Detection	Procedure										
		M4	Detection											
	ARO	M2			Moving to ICR						Monitoring			
		M4									Monitoring			
Task Overlap			**SS, RO1&2**	**SS**							**ARO/SS**			