

Exploratory Analysis of Shift Supervisor Effects on Unsafe Acts in Multi-Module Operations

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***Keywords :** multi-module operation, shift supervisor, unsafe act, recovery initiator, human reliability analysis

1. Introduction

Integrated control rooms for small modular reactors (SMRs) may allow a single operating crew to monitor and control multiple reactor modules. In this paper, staffing efficiency denotes the ratio of control-room operating personnel to reactor modules: because one crew covers several modules, this ratio is lower than in the conventional arrangement of one dedicated crew per unit. Although this arrangement can improve staffing efficiency, it may introduce new human-performance challenges associated with concurrent module monitoring, attention switching, task prioritization, and team communication [1-4]. When accident mitigation is required simultaneously in several modules, reactor operators (ROs) must process more information and execute multiple procedures in parallel, increasing the importance of cross-checking and coordination within the crew.

The shift supervisor (SS) can provide shared oversight of the overall plant condition rather than focusing exclusively on the procedural execution of a single module. In this role, the SS can cross-check operator judgments and actions, coordinate activities across modules, and support recovery from inappropriate actions. Accordingly, SS participation can be considered a crew-level operational factor that may influence human performance in multi-module environments, particularly when several accident modules must be monitored and mitigated concurrently.

In the present experiment, the crew consisted of two ROs who shared responsibility for four reactor modules, with RO1 assigned to modules M1 and M2 and RO2 assigned to M3 and M4; the SS participated in some scenarios and was absent in others. The SS was selected as the crew-level factor examined here for two reasons. First, within this crew structure the SS is the only position whose activity addresses the crew as a whole rather than a single module, so varying SS participation changes the amount of cross-module oversight available without changing the number of operators who execute procedures. Second, SS participation was the staffing condition explicitly varied in the experimental design, so that both conditions were run with the same emergency operating procedures and the same accident scenario types.

A shift technical advisor (STA) position was not included in the simulator configuration, so the present

dataset contains no observation of STA activity. This is a relevant limitation, because exemption of the STA position is among the staffing arrangements under consideration for multi-module SMRs [2]. The STA function, which is independent technical assessment of safety-function status rather than direction of procedural execution, differs from the cross-checking and coordination functions examined here, and evaluating it would require a crew configuration and a scenario set designed for that purpose. The influence of STA presence or exemption on multi-module performance is therefore identified as a subject for future experiments rather than addressed by the present data.

Empirical evidence on the relationship between SS participation, unsafe acts (UAs), and recovery characteristics in multi-module operations remains limited. This study analyzes simulator data structured using the HuREX (Human Reliability data Extraction) framework to (1) compare the UA rate per accident module-run between SS-present and SS-absent conditions, (2) examine how the observed difference varies with the multi-module operation (M/O) level, and (3) compare the proportion and initiators of formally recorded recoveries after UAs. The analysis is exploratory and descriptive; its purpose is to characterize observed relationships rather than to estimate a causal effect of SS participation.

2. Data and Analysis Methods

2.1 Analysis data and unit of analysis

The analysis included 126 multi-module simulator scenarios. One accident module-run was defined as one reactor module for which accident mitigation actions were required within a scenario. This definition yielded 378 accident module-runs in total. The SS-present condition comprised 81 scenarios and 261 module-runs, whereas the SS-absent condition comprised 45 scenarios and 117 module-runs. The M/O level represented the extent of concurrent multi-module accident-mitigation demand, expressed as the number of accident modules per RO: because every scenario was operated by two ROs, M/O=0.5, 1.0, and 2.0 corresponded to one, two, and four accident module-runs per scenario, respectively.

Table I: Dataset composition by M/O and shift-supervisor condition

M/O	SS	Scenarios	Module-runs
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0.5	Present	9	9
0.5	Absent	9	9
1.0	Present	18	36
1.0	Absent	18	36
2.0	Present	54	216
2.0	Absent	18	72
Total	-	126	378

2.2 Classification of unsafe acts and recovery measures

HuREX is a framework for systematically extracting and organizing operator-performance information needed for human reliability analysis (HRA) from nuclear power plant simulator records [5]. The Information Gathering Template (IGT) is the structured recording format used within HuREX. This study used two complementary records: the Response IGT, which documents operator responses and performance outcomes by procedural step in chronological order, and the UA IGT, which organizes information on each identified unsafe act and its subsequent recovery. A UA was defined, in accordance with the HuREX classification framework, as an inappropriate operator action with the potential to adversely affect plant safety [5]. A formally recorded recovery was defined as a case in which, after a UA occurred, the crew recognized the problem and took subsequent action that returned the procedure or equipment state toward the intended operating path. The recovery initiator was defined as the person who first triggered the recovery process and was classified as self, SS, or another RO. Because the numbers of scenarios and accident modules differed across conditions, UA counts were normalized by the number of accident module-runs.

$$\text{UA rate} = N(\text{UA}) / N(\text{accident module-run}) \quad (1)$$

$$\text{Recovery ratio} = N(\text{formally recorded recovery}) / N(\text{UA}) \quad (2)$$

The analysis first compared the SS-present and SS-absent conditions across the full dataset and then stratified the UA rate by M/O=0.5, 1.0, and 2.0. For recovery, the recovery ratio and the distribution of recovery initiators were compared between SS conditions. Because the number of observations was limited and factors other than SS participation—including participant differences, accident type, experiment order, and scenario characteristics—could affect performance, the study focused on descriptive trends rather than statistical inference or causal estimation.

3. Results

3.1 UA rate by SS condition

In the SS-present condition, 86 UAs occurred across 261 accident module-runs, corresponding to a UA rate of 0.330 per module-run. In the SS-absent condition, 57 UAs occurred across 117 module-runs, corresponding to a UA rate of 0.487. Thus, the observed UA rate per accident module-run was 32.4% lower in the SS-present condition. The number of UAs per scenario was 1.06

with an SS and 1.27 without an SS. However, because the scenario counts and the distribution of M/O levels were not balanced between the two SS conditions, the overall difference should not be interpreted as a direct causal effect of SS participation.

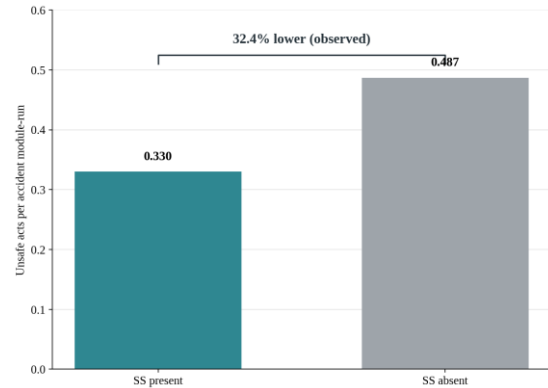


Fig. 1. Unsafe-act rate by shift-supervisor condition.

3.2 UA rate by M/O level and SS condition

When the data were stratified by M/O level, both SS conditions had four UAs at M/O=0.5, yielding the same rate of 0.444 UA/module-run. At M/O=1.0, the rates were 14/36=0.389 with an SS and 15/36=0.417 without an SS, indicating only a small difference. At M/O=2.0, however, the SS-present condition had 68 UAs in 216 module-runs (0.315), whereas the SS-absent condition had 38 UAs in 72 module-runs (0.528). The observed UA rate at M/O=2.0 was therefore 40.4% lower in the SS-present condition. The largest difference between SS conditions was observed under M/O=2.0, where four accident modules required concurrent monitoring and mitigation.

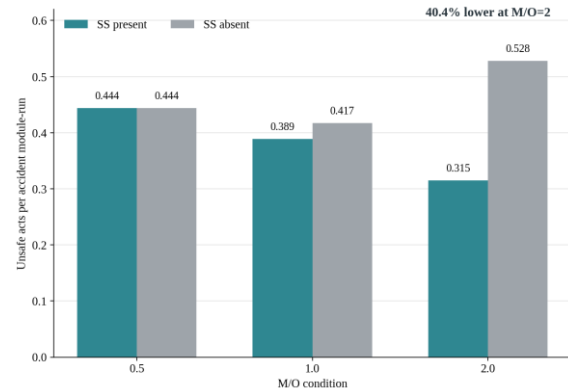


Fig. 2. Unsafe-act rate by M/O and shift-supervisor condition.

3.3 Formally recorded recovery and recovery initiators

A total of 25 formally recorded recoveries were identified among the 143 UAs. In the SS-present condition, 15 of 86 UAs were recovered, corresponding to a recovery ratio of 17.4%. In the SS-absent condition, 10 of 57 UAs were recovered, corresponding to 17.5%. The overall recovery ratio was therefore nearly identical between the two conditions. The composition of recovery initiators, however, differed. Of the 15 recoveries in the SS-present condition, eight were self-recoveries, six were initiated by the SS, and one was

initiated by another RO. All 10 recoveries in the SS-absent condition were self-recoveries.

Table II: Formally recorded recoveries and recovery initiators

Condition	UA	Recovery	Recovery initiator
SS present	86	15 (17.4%)	Self 8; SS 6; RO 1
SS absent	57	10 (17.5%)	Self 10
Total	143	25 (17.5%)	Self 18; SS 6; RO 1

3.4 Representative cases of SS involvement

Scenario 21801U involved verification of auxiliary feedwater supply and steam-generator (SG) isolation status. The SS identified that an auxiliary feedwater control valve remained closed and prompted the RO to correct the condition within 23 s. The SS subsequently identified an additional problem with SG isolation status, which was corrected within 22 s. This case illustrates how independent supervisory cross-checking can detect an already developed performance deviation and directly initiate recovery.

Scenario 06801U illustrates a potential adverse effect of supervisory intervention during a Response Not Obtained (RNO) branch decision in an emergency procedure. The RO initially made an appropriate branch judgment, but the SS interpreted the procedural condition differently and directed the crew to perform the RNO, leading to entry into an incorrect procedural path. The crew subsequently recognized the error and recovered. This case shows that the SS can provide an additional monitoring and recovery resource, but inaccurate supervisory situation assessment or procedural interpretation can also create a new error pathway.

Scenario 22601U occurred during mitigation of an excessive steam demand event (ESDE). Two ROs working on different modules made the same incorrect judgment regarding a reactor coolant system (RCS) pressure criterion and stopped the reactor coolant pumps (RCPs). The SS detected the interpretation error and prompted corrective action, but the subsequent attempt to restart the RCPs failed, and full system recovery was not achieved. This case demonstrates that error detection and the initiation of corrective action do not necessarily lead to successful system recovery; these stages should be distinguished when evaluating supervisory intervention.

3.5 Integrated interpretation of UA occurrence and recovery initiation

Taken together, the results indicate two distinct aspects of SS involvement. First, SS presence was associated with a lower observed UA rate, with the largest difference at M/O=2.0. Second, once a UA occurred, the overall proportion of formally recorded recoveries was almost unchanged by SS condition, but the recovery pathway differed. In the SS-present condition, six of the 15 recoveries (40.0%) were initiated by the SS and one additional recovery was initiated by another RO. Thus, SS participation did not correspond to a higher aggregate recovery ratio, but it

introduced an additional source of recovery initiation beyond operator self-recovery.

These findings suggest that UA occurrence and recovery initiation capture different aspects of crew performance. Under high multi-module demand, the SS may contribute additional monitoring and coordination capacity before or during operator performance, while also providing an independent route for initiating recovery after a UA has occurred. Accordingly, aggregate recovery frequency alone may not fully characterize the supervisory contribution to crew performance.

Recovery initiation should also be distinguished from successful restoration of the plant state. A recovery initiator identifies who first triggered the corrective process, not whether the subsequent corrective action was technically adequate or whether the system was ultimately restored. Therefore, interpretation of SS performance in HRA should separate at least the occurrence of a UA, detection of the deviation, initiation of corrective action, and the final system outcome.

4. Discussion

Across the full dataset, 143 UAs and 25 formally recorded recoveries were identified. The overall UA rate was 0.330 in the SS-present condition and 0.487 in the SS-absent condition. The difference depended strongly on the M/O level: no difference was observed at M/O=0.5, only a small difference was observed at M/O=1.0, and the largest difference occurred at M/O=2.0 (0.315 versus 0.528). This pattern suggests that SS participation may become more consequential as the operating context requires simultaneous monitoring and mitigation of several accident modules, where additional cognitive oversight and coordination resources are more likely to be useful.

The recovery results provide a complementary interpretation. Recovery ratios were nearly identical with and without an SS (17.4% and 17.5%, respectively), yet six of the 15 recoveries in the SS-present condition were initiated by the SS and one by another RO, whereas every recovery in the SS-absent condition was self-initiated. Thus, evaluating supervisory influence only through the recovery ratio would obscure an important change in crew recovery structure. The SS may not simply increase the probability that a recovery is recorded; instead, the SS can serve as an independent recovery initiator when an operator does not recognize or correct the problem autonomously.

The representative cases also show that SS influence is not uniformly beneficial. In 21801U, independent supervisory checking directly supported rapid correction. In 06801U, inaccurate supervisory guidance created an incorrect procedural path. In 22601U, the SS successfully detected and challenged an incorrect judgment, but the subsequent equipment recovery failed. These observations support treating the SS not as a uniformly positive performance-shaping factor, but as a

context-dependent crew-level factor whose influence depends on operating complexity, the accuracy of supervisory judgment, communication with operators, and the technical outcome of the subsequent response.

This study is limited by its descriptive and exploratory design. The numbers of SS-present and SS-absent scenarios were unbalanced, and potential confounding factors such as participant differences, experiment order, accident type, and scenario-specific difficulty were not controlled. Future work should therefore test the interaction between M/O level and SS participation using hierarchical or event-level regression models that account for participant and scenario effects. A more detailed event-based analysis should also decompose supervisory intervention into shared monitoring and problem detection, the timing and content of the intervention, the operator response to supervisory input, the corrective action taken, and the final system outcome. Such a framework would capture supervisory influences that are not represented by aggregate UA and recovery ratios alone, including interventions made before a deviation is formally classified as a UA, inaccurate supervisory guidance, and cases in which an error is detected but successful system recovery is not achieved. Comparison with crew configurations that include or omit an STA position would further inform staffing decisions for multi-module SMRs.

5. Conclusion

This study examined UA occurrence and recovery characteristics associated with SS participation using HuREX-based performance data from 126 multi-module simulator scenarios and 378 accident module-runs. A total of 143 UAs were identified: 86 UAs in 261 module-runs with an SS (0.330 UA/module-run) and 57 UAs in 117 module-runs without an SS (0.487 UA/module-run). The observed UA rate per accident module-run was therefore 32.4% lower in the SS-present condition.

The difference varied with M/O level. The UA rate was identical at M/O=0.5 (0.444 in both conditions), differed only slightly at M/O=1.0 (0.389 with an SS versus 0.417 without an SS), and showed the largest separation at M/O=2.0 (0.315 versus 0.528), where the observed rate was 40.4% lower in the SS-present condition. The association between SS participation and UA occurrence was therefore most pronounced under the highest concurrent multi-module accident-mitigation demand examined in this study.

Twenty-five formally recorded recoveries were identified, and the recovery ratios were similar in the SS-present and SS-absent conditions (17.4% and 17.5%). However, six of the 15 recoveries in the SS-present condition were initiated by the SS and one by another RO, whereas all recoveries without an SS were self-initiated. The results suggest that SS participation may affect not only the occurrence of UAs under high multi-module demand but also the structure of crew recovery by providing an additional recovery pathway.

The representative cases further indicate that supervisory intervention can support recovery, create a new error pathway when guidance is inaccurate, or detect an error without guaranteeing final system restoration. Future HRA treatment of the SS should therefore consider both the context of intervention and the sequence from detection to corrective action and system outcome.

ACKNOWLEDGEMENTS

This work was supported by the Innovative Small Modular Reactor Development Agency grant funded by the Korea Government (No. RS-2023-00258118).

This work was supported by Korea Institute of Energy Technology Evaluation and Planning(KETEP) grant funded by the Korea government(MOTIE)(RS-2024-00403194, Next-Generation Nuclear Technology Creation IP-R&D Talent (Human Resources) Development Project).

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