Analysis of Cue Availability for LOC Evaluation under MCB Fire Conditions

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Keywords : MCB fire, Cue availability, LOC analysis

1. Introduction

In fire probabilistic safety assessment (PSA) of nuclear power plants (NPPs), fires involving the main control board (MCB) in the main control room (MCR) are recognized as one of the dominant contributors to overall fire risk. The MCB contains circuits associated with most plant instrumentation and control functions during both normal operation and accident conditions, making it a highly risk-significant target in fire PSA.

MCB fires are particularly important because they can simultaneously affect multiple systems and impair the operators' ability to monitor and control plant conditions. In severe cases, fire-induced damage may lead to loss of habitability (LOH) or loss of control (LOC), requiring abandonment of the MCR and transition to the remote shutdown panel (RSP). NUREG/CR-6850[1] established the foundational methodology for MCB fire risk assessment. Appendix L discusses both LOH and LOC in the context of control room abandonment; however, the quantitative framework primarily focuses on LOH. The report provides explicit criteria for thermal conditions, smoke, and visibility to evaluate LOH, whereas LOC is treated conceptually without a corresponding quantitative evaluation procedure.

NUREG-2178[2] subsequently introduced an event tree (Figure 1) framework for MCB fire quantification that explicitly incorporates both LOH and LOC effects.

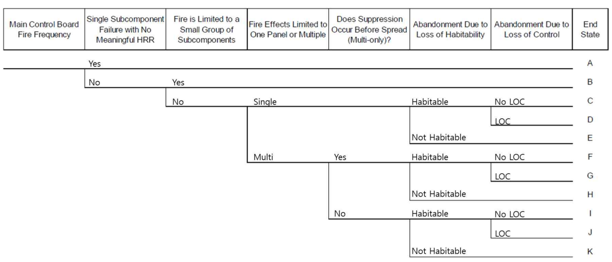

Fig. 1. MCB fire event tree (NUREG-2178)

Previous KAERI studies[3] implemented the NUREG-2178 event tree to evaluate MCB fire risk; however, LOC was assumed not to occur during the evaluation process. As a result, event tree branches corresponding to LOC end states were excluded from the quantification. To achieve a more realistic representation of MCB fire risk, a structured LOC evaluation procedure was previously proposed based on the NUREG-2178 framework.

During the development of this procedure, it was recognized that MCB fire damage may directly affect the panels hosting the instrumentation associated with the primary cues defined in fire human reliability analysis (HRA)[4-5]. Loss of the panel can therefore result in loss of the corresponding cue function. Conventional fire HRA defines primary cues for each human failure event (HFE) based on procedures and operator input, but typically does not consider the possibility that the cue itself becomes unavailable due to fire-induced panel damage. In an MCB fire scenario, however, panel damage introduces a realistic possibility that primary cues are lost, requiring evaluation of whether alternative secondary cues from unaffected panels can support operator diagnosis.

The objective of this study is to systematically identify secondary cues and their associated panels that can substitute for primary cues during MCB fire scenarios in a reference NPP. The scope of the analysis is limited to HFEs in the fire PSA model where primary cues are explicitly tied to plant instrumentation. For accident sequences requiring LOC evaluation, cases in which the panel hosting the primary cue instrumentation is assumed to be damaged by fire are examined, and candidate secondary cues from unaffected panels are identified. This approach provides a structured basis for refining LOC classification by explicitly considering cue availability under MCB fire conditions.

2. Methods and Results

The MCB of the reference plant consists of 11 panels, each responsible for specific plant systems and related monitoring and control functions. For confidentiality reasons, actual panel identifiers are replaced with generic labels (Panel A, Panel B, Panel C). This panel configuration is an important factor in evaluating cue availability under fire conditions, as fire damage may concentrate on certain panels and directly affect operator information sources. For example, Panel A mainly contains instrumentation associated with the reactor coolant system (RCS).

This panel configuration is important in MCB fire scenarios because fire damage may concentrate on certain systems and directly affect operator information sources.

Accident sequences requiring LOC evaluation were first identified from the MCB fire event tree in the fire PSA model of the reference plant. These correspond to end states C, F, and I in the NUREG-2178 event tree. For all HFEs included in these sequences, the relationship between fire-damaged panels (single-panel damage and adjacent panel propagation) and the panel locations of primary cue instrumentation was systematically evaluated.

The analysis showed that, for several HFEs, panel damage did not result in simultaneous loss of all primary cue instrumentation. For example, in the case of SDOPHEARLY (Operator fails to perform feed & bleed operation – early), although certain panels could be damaged depending on the fire origin and propagation direction, the panels hosting the primary cues were not simultaneously lost. Therefore, operator diagnosis was not structurally prevented in these scenarios.

However, for some HFEs, fire-damaged panels overlapped with the panels hosting primary cue instrumentation. In such cases, primary cues may become unavailable under specific fire conditions. These HFEs are summarized in Table 1.

Table 1. HFEs with Potential Primary Cue Loss Due to Fire Damage

HFE	Description	Primary Cue (panel)	Fire Origin Panel	Damaged Panel
MSOP HSR	Operator fails to remove steam ADV/TBV	RCS average temperature (Panel A, Panel B)	Panel A	Panel A → Panel B
			Panel B	Panel B → Panel A
FSOPV SIAS	Operator fails to manually generate SIAS	PZR pressure (Panel A, Panel B), Containment pressure (Panel B)	Panel A	Panel A → Panel B
			Panel B	Panel B → Panel A
FSOPV CSAS	Operator fails to manually generate CSAS	Containment pressure (Panel B)	Panel A	Panel A → Panel B
			Panel B	Panel B
			Panel B	Panel B → Panel C
			Panel B	Panel B → Panel A
FSOPV AFAS	Operator fails to manually generate AFAS	SG 1/2 WR level (Panel B)	Panel A	Panel A → Panel B
			Panel B	Panel B
			Panel B	Panel B → Panel A

ADV: Atmospheric Dump Valve
TBV: Turbine Bypass Valve
SIAS: Safety Injection Actuation Signal
CSAS: Containment Spray Actuation Signal
AFAS: Auxiliary Feedwater Actuation Signal
PZR: Pressurizer

In these cases, the loss of primary cue availability introduces a limitation not explicitly considered in conventional fire HRA, where cue availability is generally assumed once defined. To address this limitation, plant procedures were reviewed and operator interviews were conducted to identify secondary cues that remain available from unaffected panels. The identified secondary cues and their associated panels are summarized in Table 2.

Table 2. Identified Secondary Cues and Associated Panels

HFE	Primary Cue	Secondary Cue	Panel ID	Base	Remarks
MSOP HSR	RCS average temperature (Panel A, Panel B)	SG pressure	Panel B, Panel C	ERP-01 Operator interview	SG pressure may respond slowly
FSOPV SIAS	PZR pressure (Panel A, Panel B) Containment pressure (Panel B)	SIAS actuated alarm	Panel C	Operator interview	
FSOPV CSAS	Containment pressure (Panel B)	CSAS actuated alarm			
FSOPV AFAS	SG 1/2 WR level (Panel B)	AFAS actuated alarm			

PZR: Pressurizer
ERP: Emergency Response Procedure
ARP: Abnormal Response Procedure

Secondary cues were selected based on procedures, alarm indications, system behavior, and operator input. In some cases, secondary cues may respond more slowly or provide indirect information compared to primary cues. Nevertheless, they provide sufficient information for operator diagnosis and help maintain control capability under MCB fire conditions.

These results indicate that assuming automatic LOC whenever a primary cue panel is damaged may be overly conservative. By considering panel damage patterns and cue redundancy together, LOC classification can be refined to better represent actual operator capability under MCB fire conditions.

3. Conclusions

This study systematically evaluated primary cue loss and identified secondary cues in order to refine the LOC evaluation procedure for MCB fire scenarios in a reference plant based on the NUREG-2178 event tree framework. For HFEs included in accident sequences requiring LOC analysis, the relationship between fire-damaged panels and the panel locations of primary cue instrumentation was evaluated. The results show that, for some HFEs, fire damage may overlap with the panels hosting primary cues. In such cases, the cue availability assumed in conventional fire HRA may not be maintained, which can limit the operator's ability to perform diagnosis. To address this limitation, plant procedures were reviewed and operator interviews were conducted to identify secondary cues available from unaffected panels. The analysis confirms that, under certain fire conditions, operator diagnosis can still be supported by secondary cues. This suggests that assuming automatic LOC whenever a primary cue is lost may not always represent actual operator capability.

The study demonstrates that considering both panel damage patterns and cue redundancy provides a more reasonable basis for LOC classification under MCB fire conditions. Future work is needed to quantitatively evaluate the reliability and response characteristics of secondary cues.

Acknowledgment

This work was supported by the National Research Foundation of Korea (NRF) grant funded by the Korean government, Ministry of Science and ICT. (Grant Code: RS-2022-00144204)

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