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Proposed Framework for Fire Risk Assessment of Main Control Boards Considering Loss of Control (LOC)

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1. Introduction

In fire probabilistic safety assessment (PSA) of nuclear power plants (NPPs), fires in the main control board (MCB) within the main control room (MCR) have been identified as a major contributor to overall fire risk. The MCB includes circuits for most instruments and components during normal and emergency conditions, making it a critical element in fire PSA.

MCB fires are particularly significant because they can affect multiple systems simultaneously and, due to loss of habitability (LOH) or loss of control (LOC), may force operators to abandon the MCR and transfer to the remote shutdown panel (RSP). NUREG/CR-6850 introduced an initial methodology for MCB fire risk assessment, and NUREG-2178[1] later enhanced it by adopting an event-tree-based approach (Figure 1). This approach defines seven damage states associated with MCB fire propagation and systematically derives eleven fire scenarios (A–K).

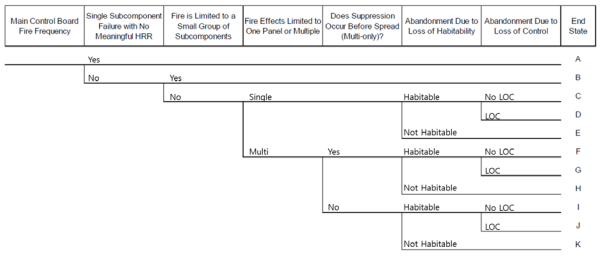

Fig. 1. MCB fire event tree (NUREG-2178)

The event tree of NUREG-2178 defines the propagation of MCB fires and the corresponding abandonment conditions. If a fire is limited to a localized group of subcomponents and suppression is successful before spread, the fire is contained (branches A or B). If suppression is not successful, the progression depends on whether the fire affects a single panel or multiple panels and whether the MCR remains habitable. When the MCR is habitable, operator control may be either maintained (no LOC, branches C, F, I) or lost (LOC, branches D, G, J). When the MCR becomes uninhabitable due to smoke, heat, or other conditions, abandonment occurs due to LOH (branches E, H, K).

Based on NUREG-2178, a preliminary risk assessment of domestic NPPs was conducted in KAERI[2]. The study considered LOH but excluded LOC, assuming that LOC events would not occur. That is, only branches C, F, and I, where LOC does not occur in Figure 1, were considered. Consequently, scenarios leading to branches D, G, and J of the event tree were omitted.

The objective of this study is to address a limitation of previous preliminary assessments that excluded LOC from the analysis of MCB fire risk. While LOH has been systematically evaluated due to the availability of clear criteria, LOC has not been analyzed because of the absence of well-defined guidance. This omission represents a limitation, as LOC may influence operator actions, MCR abandonment (MCRA), and plant safety.

Therefore, this study aims to establish a practical definition of LOC, propose a process for its evaluation, and apply the process to analyze the likelihood of LOC scenarios in MCB fire events. By incorporating LOC into the event-tree framework of NUREG-2178, the study seeks to provide a more comprehensive and realistic assessment of MCB fire risk in nuclear power plants.

2. Methods and Results

2.1 Definition of LOC

NUREG-1921[3], NUREG/CR-6850[4], and NUREG-2178 all consistently define LOC, although their wording differs slightly. In general, LOC refers to situations where the MCR remains physically habitable, but fire-induced failures render plant control functions inoperable, thereby forcing MCRA. A comparison of the definitions is summarized in Table 1.

Based on these definitions, we defined abandonment due to LOC in the event tree of NUREG-2178 as the state in which the MCR must be abandoned during an MCB fire–induced plant trip because instrumentation or control operations cannot be performed from the MCR. Thus, in this study, if an MCB fire accident sequence reflected in the fire PSA model included a human failure event (HFE) and the associated operator action could not be performed from the MCR due to the fire, the situation was defined as an LOC condition. Furthermore, if the same action could be performed from the RSP, it was defined as abandonment due to LOC.

Table 1. Comparison of LOC Definitions

Document	Summary of LOC Definition	Key Point
NUREG-1921	LOC occurs when plant control cannot be maintained from the MCR due to fire damage, even though the room is still habitable	Focuses on loss of functional control rather than habitability
NUREG/CR-6850	Abandonment may result from LOH or LOC; LOC is the inability to perform required control functions in the MCR due to fire-damaged instrumentation or controls	Highlights the inoperability of instruments/controls
NUREG-2178	If the MCR remains habitable, operators may still need to abandon it and rely on shutdown procedures outside the MCR when fire affects control capability	Emphasizes reliance on procedures outside the MCR when controls are impaired

2.2 Evaluation of LOC

In this study, the following procedure was defined and applied to evaluate whether LOC occurs in MCB fire scenarios:

1. Identification of relevant scenarios: From the MCB fire cases considered in the PSA model, accident sequences corresponding to branches C, F, and I in Figure 1 were identified:

   - C: Fire limited to a localized group of subcomponents
   - F: Fire contained within a single MCB panel due to successful suppression
   - I: Fire involving two adjacent MCB panels with suppression achieved

2. Extraction and analysis of scenarios involving HFEs: Accident sequences including HFEs were extracted, and the feasibility of performing the associated operator actions was analyzed (excluding actions carried out outside the MCR).

   - For cases where fire damage is limited to the MCB or spreads to two adjacent panels, it was assessed whether the operator actions (operation or control) required in the accident sequence could be performed from the MCR.
   - From a conservative standpoint, if component operation is possible but control cannot be maintained, the action was judged as not feasible.

3. Evaluation of LOC conditions: If the required operator actions could not be performed from the MCR, the situation was evaluated as LOC

4. Modification of event tree branches: if the switches required for the corresponding operator actions exist in the RSP, the corresponding event tree branch was modified to consider MCRA due to LOC:

   - D: Fire in a single MCB panel resulting in abandonment due to loss of control
   - G: Fire in a single MCB panel with abandonment on loss of control.
   - J: Fire in two adjacent MCB panels, resulting in abandonment due to loss of control

5. Modification of HEPs: event tree branches: From the list of scenarios evaluated as LOC, if the switches required for the corresponding operator actions do not exist in the RSP, the original C, F, and I branches were applied; however, the corresponding HEP was revised to 1.0 (i.e., failure probability of execution was set to 1.0).

For example, if an HFE corresponds to the failure to open atmosphere dump valves (ADVs) from the MCR, and a fire occurs in PM07 (where the ADV switch is located) or extends from PM06/PM08 to PM07, resulting in damage, then the required operator action could no longer be performed in the MCR.

2.3 Results

From the fire PSA model of the reference plant we developed, accident sequences associated with fires in the eleven MCB panels (PM01–PM11) located in the MCR were examined. Among these, the accident sequences corresponding to branches C, F, and I in Figure 1 that included HFEs were identified.

For the extracted accident sequences, operator actions performed outside the MCR were excluded, and the feasibility of the operator actions was evaluated. Specifically, for each accident sequence, it was assessed whether the required operator actions could still be performed from the MCR in cases where the relevant MCB was directly damaged by fire or where damage occurred due to fire propagation to adjacent panels.

Based on this evaluation, the results were derived, and Table 2 summarizes the cases that were judged to involve LOC.

3. Conclusions

In this study, the applicability of LOC, which had not been considered in the existing event-tree-based MCB fire risk assessment based on NUREG-2178, was examined. Among the MCB fire accident sequences, four cases (including three operator actions) were identified as LOC situations. Depending on the availability of related control switches in the RSP, either modifications of fire scenarios (i.e., adjustments to event tree branches) or revisions of failure probabilities in the MCR were proposed.

These results are expected to improve the accuracy of MCB fire risk assessments beyond the current approach.

Acknowledgment

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Table 2. Operator Actions in MCB Fire Scenarios Classified as LOC

MCB	MCB fire branch	HFE	Operator action	Feasibility (MCR)	Feasibility (RSP)	Remarks
PM05	I	MSOPHSR	Operator fails to remove steam (ADV/TBV)	Control is not possible because the RCS average temperature must be maintained below 297 ℃ using the related valves (ADV or TBV), but the RCS average temperature instruments are located in PM05 and PM06, which are damaged	Operation and control are possible since the related instruments and switches exist in the RSP	The branch of the event tree should be revised to J, and the failure probability of transfer to the RSP and execution failure at the RSP are additionally considered.
PM06	I	SDOPHEARLY	Operator fails to perform F&B operation early	Operation is not possible because switches for SDS isolation and control valves are located in the adjacent panel PM05, which is damaged	No switches for related devices exist in the RSP (HPSI PP, SDS isolation valve, and control valves)	Since the action cannot be performed in the MCR, the original HEP value is revised to 1.0.
PM08	I	MSOPHSR	Operator fails to remove steam (ADV/TBV)	Operation is not possible because all switches for the devices are located in PM07, and a fire in PM08 spreading to PM07 causes damage	Operation and control are possible since the switches and instruments are available in the RSP.	The branch of the event tree should be revised to J, and the failure probability of transfer to the RSP and execution failure at the RSP are additionally considered.
PM09	I	MFOPHSUFWP	Operator fails to line up MF S/U pump	Operation is not possible because the switch for the device is located in PM08, which would be damaged if the fire spreads from PM09 to PM08	No related switches exist in the RSP.	Since the action cannot be performed in the MCR, the original HEP value is revised to 1.0.

TBV: Turbine bypass valve
F&B: Feed and bleed
MF S/U: Main feedwater startup
HPSI PP: High-pressure safety injection pump
SDS: Safety Depressurization System