Transactions of the Korean Nuclear Society Spring Meeting
Jeju, Korea, May 7-8, 2026

Sensitivity Analysis of Fire Risk on Main Control Room Abandonment Scenarios Caused by Main Control Board Fires

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Keywords : Fire, Probabilistic Safety Assessment, Main Control Room Abandonment, Sensitivity Analysis

1. Introduction

Fires in the main control room (MCR) of nuclear power plants (NPPs) have been widely recognized as significant contributors to core damage frequency (CDF) in fire probabilistic safety assessments (PSAs). Because the main control board (MCB) contains control and instrumentation cables for major plant equipment, it is generally considered that operators may be forced to evacuate the MCR during a fire event. When a fire occurs in the MCR and operators are unable to remain due to loss of habitability (LOH), or when a loss of control (LOC) condition is encountered, operators are required to evacuate the MCR and transition to the remote shutdown panel (RSP) to maintain the plant in a safe shutdown condition [1,2]. LOH is typically associated with heat or smoke generated by the fire, whereas LOC may occur due to the failure of critical instrumentation or control equipment, even in cases where the MCR remains nominally habitable.

In the previous study [3], LOC was not explicitly considered in the MCR fire risk assessment, primarily because procedures addressing LOC conditions were not available for the domestic reference NPP at that time. However, more recent operator interviews related to MCR fire scenarios at the reference NPP suggest that LOC-inducing conditions can occur under certain circumstances [4]. In addition, the previous study quantified fire risk under the simplifying assumption that fire spread from the MCB occurs in only one direction. While this assumption was adopted for modeling convenience, NUREG-2178 [2] recommends that fire spread to both sides of the MCB be considered in MCB fire risk assessments. The earlier assumption of one-directional fire spread was based on the probabilities reported in NUREG-2178, where the probability of one-directional fire spread is 0.02 and that of bi-directional fire spread is 0.01 [2]. Given the expectation that the overall quantification results would not differ significantly, the simple one-directional fire spread assumption was employed in the previous study [3].

In the present study, LOC is explicitly incorporated into the previously developed fire PSA model [3], and a revised risk assessment model is constructed by additionally considering bi-directional fire spread from MCB fires. Sensitivity analyses are also conducted to evaluate the impact of alternative modeling assumptions, including cases in which fire spread is assumed to occur only in a single direction (right or left), LOC is excluded, and success sequences for transfer to the RSP are not credited. The sensitivity analysis related to successful transfer to the RSP is included because such scenarios have received limited attention in previous domestic fire PSA studies and may influence the overall quantification results.

2. Methods and Results

The MCB fire risk assessment methodology described in NUREG-2178 was applied to a sensitivity analysis study of MCR abandonment for the domestic reference NPP.

2.1 NUREG-2178

The MCB is generally composed of multiple panels, each of which contains switches, relays, and other equipment associated with plant operation and safe shutdown. When modeled as an ignition source in fire PSA, the MCB requires specialized treatment due to several distinguishing characteristics [2]:

- The MCB in the MCR is continuously occupied by personnel with a high degree of training and awareness.
- It is a relatively large set of cabinets with unique construction configurations and cable separation schemes relative to typical electrical cabinets located in other plant areas.
- It houses most of the plant control circuits within the scope of a fire PSA.
- Fires in the MCB may generate the need for alternative or remote shutdown strategies (that is, shutdown outside of the MCR).

MCB fires can affect multiple components or multiple systems considered in fire PSA. Due to these characteristics, explicitly modeling fire growth within the MCB is challenging. The methodology developed in NUREG-2178 [2] is therefore based on operating experience with MCB fires and event tree representations of plausible fire growth scenarios. Detailed modeling requires a comprehensive characterization of fire-induced event progression over time, which is represented by an event tree, as shown in Fig. 1. Descriptions of individual scenarios are provided in NUREG-2178. In Fig. 1, scenarios in which damage is limited to a single panel correspond to event sequences A, B, C, F, and I, whereas scenarios involving MCR evacuation correspond to sequences D, E, G, H, J, and K.

2.2 PSA Modeling of MCB Fire for the Reference NPP

For the reference NPP, fire risk was modeled by categorizing fire scenarios into two broad groups: general fires and MCR evacuation fires, as illustrated in Fig. 2. MCR evacuation fires include both evacuation scenarios associated with specific initiating events and scenarios in which operation from the RSP is assumed to be unavailable.

Because the RSP is designed to contain only the safety-related equipment required for safe shutdown, certain systems—such as the safety depressurization system (SDS), high-pressure safety injection system (HPSIS), and alternate AC power (AAC)—are not available for operation from the RSP. Consequently, for specific initiating events, operator actions at the RSP were judged to be not feasible. For these cases, the operator error probability was set to 1, as shown in Fig. 3. The initiating events treated in this manner include:

- Small Loss of Coolant Accident (SLOCA)
- Station Black-Out(SBO)
- Large secondary Side Break A, B(LSSB-AB-Fire)
- Interfacing System LOCA(ISLOCA)

All other initiating events were modeled using event trees, as shown in Fig. 4. These event trees account for potential failures of the transfer switch to the RSP, associated operator actions, and additional operator actions required following successful transfer. The first event sequence in Fig. 4 is linked to the corresponding initiating event fault tree, as shown in Fig. 5. The initiating events modeled in this manner include the following:

- General Transient (GT)
- Loss of Condenser vacuum (LOCV)
- Loss of Component Cooling Water System (LOCCW)
- Total Loss of Component Cooling Water System (TLOCCW)
- Loss of 125V DC A (LODCA)
- Loss of 125V DC B (LODCB)
- Loss of 4.16KVA (LOKVA)
- Loss of Off-site Power (LOOP)
- Large secondary Side Break (LSSB)
- Large secondary Side Break B (LSSB-B-Fire)

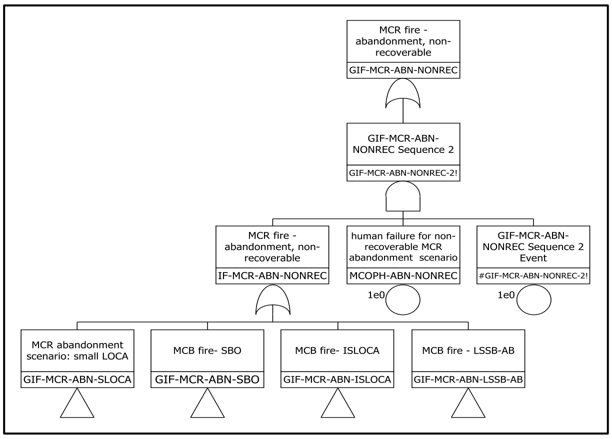


Fig.3. Fault Tree of MCR Abandonment Failure Scenarios

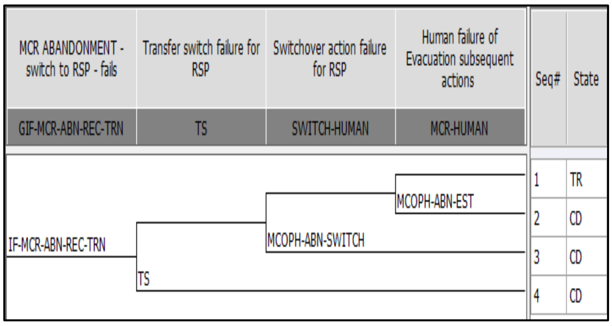


Fig.4. General Transient Event Tree for MCR abandonment caused by MCR Fires

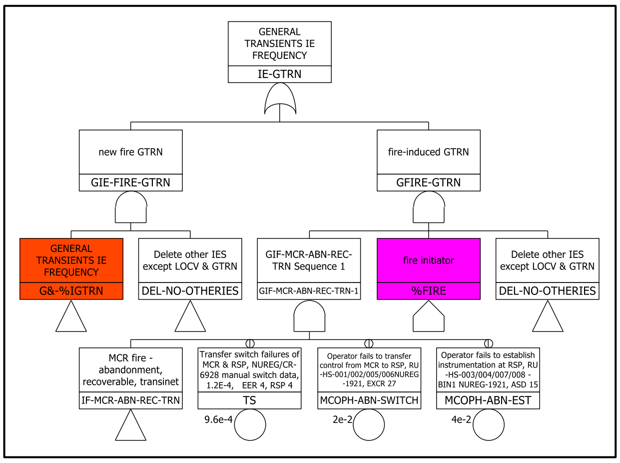


Fig. 5. Fault Tree Modeling of the Successful Transfer Sequence for General Transient Event Tree

2.3 Quantification Results of MCB Evacuation Fire PSA for the Reference NPP

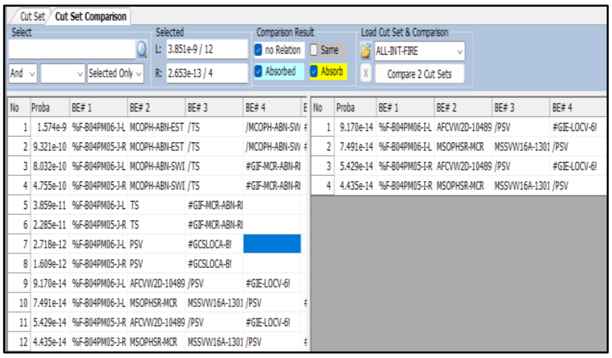
For the domestic reference NPP, MCR evacuation scenarios were identified as scenarios E, I, J, and K in Fig. 1. Among these, only scenario J is associated with LOC, whereas the remaining scenarios are associated with LOH. The frequencies of MCB fire spread scenarios considered in this study are summarized in Table I. In Table I, %F-B04 denotes the MCB fire initiating event, PMXX denotes the specific MCB panel, I, J, and K correspond to the fire event sequences shown in Fig. 1, and L and R indicate fire spread to the left and right, respectively. For example, %F-B04PM05-J-R represents a scenario in which fire propagates to the right due to an LOC condition originating from an MCB panel PM05 fire.

Table II summarizes the percentage increase or decrease in CDF relative to the base case for both total plant fire risk and MCB fire risk. The base case includes both LOC occurrence during MCB fires and bi-directional fire spread. Fig. 6 compares the minimal cut sets for the base case and for a case in which LOC is not considered, illustrating differences in the dominant contributors to CDF.

The sensitivity analysis results indicate that, relative to the base case, the MCB CDF increases by approximately 6.62% when fire spread is assumed to occur only in the right direction. Conversely, when fire spread is assumed to occur only in the left direction, the resulting CDF is lower than that of the base case. These results appear to be influenced by the specific design features and equipment layout of the domestic reference NPP. In particular, the set of components susceptible to fire damage varies by MCB panel, and the assumption of single-direction fire spread results in a fire spread probability that is effectively doubled relative to the bi-directional assumption. From a conservative modeling perspective, these observations suggest that both single-direction and bi-directional fire spread scenarios should be considered in MCB fire risk assessments. Excluding LOC from the analysis does not result in a substantial change in the quantification results for the reference NPP, which is likely attributable to the relatively low frequency of LOC-inducing conditions at this plant. However, for plants with a larger number of LOC-inducing scenarios, the impact of excluding LOC may be more pronounced. When successful transfer to the RSP is not credited, the total CDF is reduced by approximately 3.63% relative to the base case. When the analysis is limited to MCB fire scenarios, the reduction in CDF increases to approximately 22.88%. These results indicate that successful transfer to the RSP plays a non-negligible role and important factor in CDF quantification.

Table II: Sensitivity Analysis Results of Total and MCB CDFs

Cases	Right	Left	NO RSP	NO LOC
Total CDF	1.05%	-1.05%	-3.63%	0.0%
MCB CDF	6.62%	-6.62%	-22.88%	-0.24%



L: 3.851e-9 / 12

R: 2.653e-13 / 4

ALL-INT-FIRE

No	Proba	BE# 1	BE# 2	BE# 3	BE# 4
1	1.574e-9	%F-B04PM06-I-L	MCOPH-ABN-EST	/TS	/MCOPH-ABN-SW
2	9.321e-10	%F-B04PM05-I-R	MCOPH-ABN-EST	/TS	/MCOPH-ABN-SW
3	8.032e-10	%F-B04PM06-I-L	MCOPH-ABN-SWI	/TS	#GIF-MCR-ABN-RI
4	4.755e-10	%F-B04PM05-I-R	MCOPH-ABN-SWI	/TS	#GIF-MCR-ABN-RI
5	3.859e-11	%F-B04PM06-I-L	TS	#GIF-MCR-ABN-RI	
6	2.285e-11	%F-B04PM05-I-R	TS	#GIF-MCR-ABN-RI	
7	2.718e-12	%F-B04PM06-I-L	PSV	#GCSLOCA-8!	
8	1.609e-12	%F-B04PM05-I-R	PSV	#GCSLOCA-8!	
9	9.170e-14	%F-B04PM06-I-L	AFCVW2D-10489	/PSV	#GIE-LOCV-6!
10	7.491e-14	%F-B04PM06-I-L	MSOPHSR-MCR	MSSVW16A-1301	/PSV
11	5.429e-14	%F-B04PM05-I-R	AFCVW2D-10489	/PSV	#GIE-LOCV-6!
12	4.435e-14	%F-B04PM05-I-R	MSOPHSR-MCR	MSSVW16A-1301	/PSV

No	Proba	BE# 1	BE# 2	BE# 3	BE# 4
1	9.170e-14	%F-B04PM06-I-L	AFCVW2D-10489	/PSV	#GIE-LOCV-6!
2	7.491e-14	%F-B04PM06-I-L	MSOPHSR-MCR	MSSVW16A-1301	/PSV
3	5.429e-14	%F-B04PM05-I-R	AFCVW2D-10489	/PSV	#GIE-LOCV-6!
4	4.435e-14	%F-B04PM05-I-R	MSOPHSR-MCR	MSSVW16A-1301	/PSV

Fig. 6. Differences in Minimal Cutsets with (Left) and Without (Right) LOC

3. Concluding Remarks

In this study, LOC conditions were explicitly incorporated into the fire PSA for MCB fires in the MCR, and fire risk was quantified by additionally considering bi-directional fire spread from MCB panels. Sensitivity analyses were also performed to examine the effects of alternative assumptions, including single-direction fire spread, exclusion of LOC, and exclusion of successful safe shutdown following transfer to the RSP.

The results indicate that, for the domestic reference NPP, assuming fire spread only in the right direction leads to a modest increase in total CDF (approximately 1.05%) relative to the base case. This increase appears to be driven by plant-specific design and layout characteristics. Excluding LOC does not significantly affect the quantification results for the reference NPP, reflecting the relatively low frequency of LOC-inducing conditions at this plant. In contrast, excluding successful transfer to the RSP results in a substantial reduction in MCB fire CDF (approximately 22.88%), highlighting the importance of appropriately modeling RSP transfer success in fire PSA. The findings of this study are expected to support future NUREG/CR-6850–based fire PSA applications by domestic industry and regulatory organizations.

Acknowledgments

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

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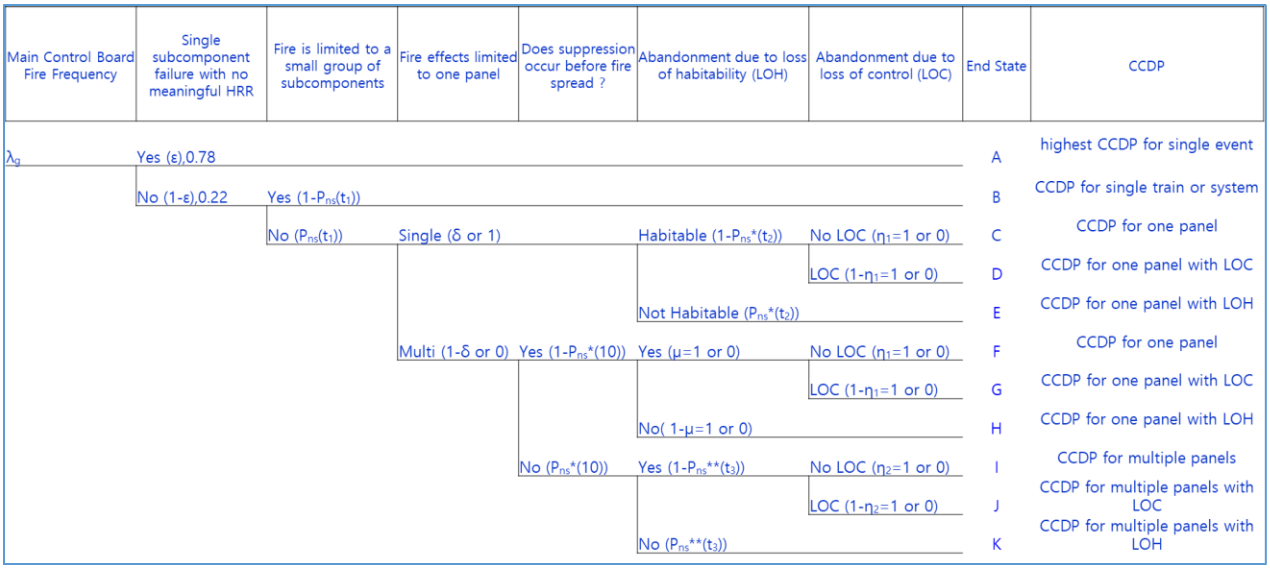

Fig.1. MCB fire event tree

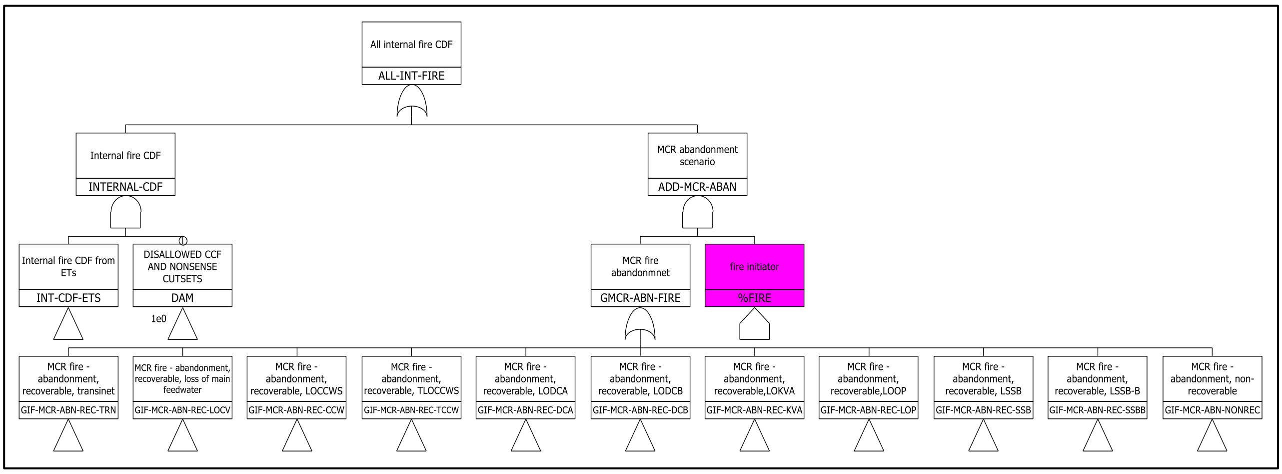

Fig. 2. Top-level Fault Tree Logic of the Domestic Reference NPP Incorporating MCR Evacuation Scenarios

Table I: Fire Scenario Frequencies for the Sensitivity Analysis

Fire Initiating Events	Descriptions	Base	Right	Left	NO LOC
%F-B04PM05-I-L	fire IE of B04PM05-I-L	2.38E-08	0	4.76E-08	2.38E-08
%F-B04PM05-I-R	fire IE of B04PM05-I-R	0	0	0	2.38E-08
%F-B04PM05-J-R	fire IE of B04PM05-J-R	2.38E-08	4.76E-08	0	0
%F-B04PM05-K-L	fire IE of B04PM05-K-L	3.78E-09	0	7.56E-09	3.78E-09
%F-B04PM05-K-R	fire IE of B04PM05-K-R	3.78E-09	7.56E-09	0	3.78E-09
%F-B04PM06-I-L	fire IE of B04PM06-I-L	0	0	0	4.02E-08
%F-B04PM06-I-R	fire IE of B04PM06-I-R	4.02E-08	8.04E-08	0	4.02E-08
%F-B04PM06-J-L	fire IE of B04PM06-J-L	4.02E-08	0	8.04E-08	0
%F-B04PM06-K-L	fire IE of B04PM06-K-L	6.40E-09	0	1.28E-08	6.40E-09
%F-B04PM06-K-R	fire IE of B04PM06-K-R	6.40E-09	1.28E-08	0	6.40E-09