Risk Assessment of Main Control Room Fire for Domestic Nuclear Power Plant

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1. Introduction

Previous fire probabilistic safety assessment (PSA) results of conventional analog type nuclear power plant (NPP) showed that the main control room (MCR) fire was recognized as one of the major contributors to fire risk for NPPs. Typical ignition sources of the MCR fire are the main control board (MCB), electrical cabinets, transient fires, and transient fire due to welding and cutting. Among the MCR ignition sources, the MCB fire has been identified as the greatest impact on MCR fire risk because the MCB contains the circuits of most of the equipment considered in the fire PSA. In this study, the risk of MCB fires in domestic reference NPP was quantified. Currently available risk assessment methods for the MCB fires of domestic NPPs are the EPRI method [1], the NUREG/CR-6850 method [2], and the NUREG-2178 method [3]. Three evaluation methods for the MCB fires were introduced and utilized for the quantification of CDFs of them.

2. Methods and Results

2.1 CDF equation

The total core damage frequency (CDF) of an NPP from a fire can be represented by Eq. (1).

$$CDF=\sum_{k=l}^{m} CDF_k \quad (1)$$

In Eq. (1), CDF_k represents the CDF of each zone or scenario. The CDF_k can be further represented as [2,4]

$$CDF_k=F_k \text{ x } S_k \text{ x } N_k \text{ x } CCDP_k \quad (2)$$

F_k= fire frequency of zone or scenario *k*
S_k= severity factor of zone or scenario *k*
N_k = non-suppression probability of zone or scenario *k*
$CCDP_k$ = conditional core damage probability (CCDP) of zone or scenario *k*

Since there are always operators in the MCR, in case of MCB fire, the MCR fire risk must be assessed taking into account operator evacuation in addition to the failure of MCB itself.

2.2 MCB of the reference NPP

As shown in Fig.1, the MCR has many kinds of cabinets. The horseshoe type cabinet in Fig. 1 is the MCB. The systems related to the MCB control panels are presented in Table I. Any fire of the PM01~PM11 control panels may lead to spurious operations or failures of the systems related to each MCB panel. For example, as presented in Table I, the PM02 fire may induce a loss of or total loss of the component cooling water system (LOCCWS or TLOCCWS). All cables installed in each MCB panel are thermoset cables. A smoke detector is installed on the inner part of the MCB and electrical cabinet and the upper part of MCR.

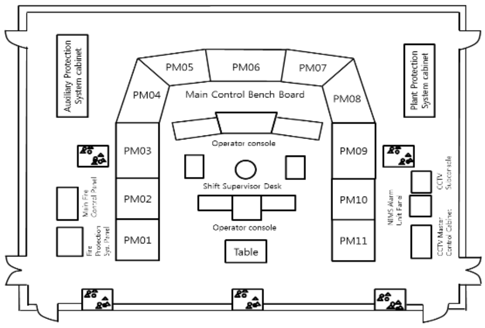

Fig.1. Overview of the MCB for the reference NPP

Table I: Systems of MCB panels

Name	Descriptions
PM01	MCB - HVAC system
PM02	MCB - CCWS, ESWS
PM03	MCB - Engineered Safety Feature
PM04	MCB – CVCS
PM05	MCB - Reactor coolant system
PM06	MCB – RPS
PM07	MCB - Main steam system
PM08	MCB – Feed water system
PM09	MCB - Turbine auxiliaries
PM10	MCB - 4.16KV Bus and EDG
PM11	MCB - UAT & SAT

2.3 EPRI method

Based on the EPRI method [1], fire scenarios for the PM0Z fire can be quantified as follows [5,6]:

$$CDF_{PM0Z} = CDF_{PM0Z-5} + CDF_{PM0Z-15} + CDF_{PM0Z-ABN} \quad (3)$$
$$CDF_{PM0Z-5} = F_{PM0Z} \text{x} CCDP_{PM0Z-5}$$
$$CDF_{PM0Z-15}=F_{PM0Z} \text{x} S_{MCR-CAB.} \text{x} N_{MCR-5} \text{x} CCDP_{PM0Z-15}$$
$$CDF_{PM0Z-ABN}= F_{PM0Z} \text{ x } S_{MCR-CAB} \text{ x } N_{MCR-15} \text{x} CCDP_{PM0Z-ABN}$$

Where,
F_{PM0Z}: Ignition frequency of panel PM0Z
$S_{MCR-CAB}$: MCR cabinet severity. 0.25[1]
$N_{MCR-5 \text{ or } 15}$: Non-suppression probability within 5 or 15min.. 0.12 or 0.008 [1]
$CCDP_{PM0Z-5 \text{ or } 15 \text{ or } ABN}$: CCDP of PM0Z fire within 5

or15 min. or at abandonment
$CDF_{PM0Z\text{-}5\ or\ 15\ or\ ABN}$: CDF of PM0Z fire within 5 or15 min. or at abandonment

Data for the quantifications of PM0Z fire are presented in Table II. CCDPs of Table II are assumed data based on the real internal PSA results of the reference NPP. For the comparison, data of Table II were also used for the quantification of the MCB fire with other methods. CDF for PM0Z fire can be quantified as follows:

$$CDF_{PM0Z} = 1.86E\text{-}4/yr \times 1.0E\text{-}5 + 1.86E\text{-}4/yr \times 0.25 \times 0.12 \times 3.0E\text{-}3 + 1.86E\text{-}4/yr \times 0.25 \times 0.008 \times 0.1 = 1.86E\text{-}9/yr + 1.67E\text{-}8/yr + 3.72E\text{-}8/yr = 5.58E\text{-}8/yr$$

Limitations of the EPRI method [1, 5] are as follows:1) evacuation time is determined based on the assumption, 2) loss of control scenario is not considered, and 3) fire spreading to the adjacent panel is not considered.

2.4 NUREG/CR-6850 method

Based on NUREG/CR-6850[2], fire scenarios for the PM0Z fire can be quantified as follows:

$$CDF_{PM0Z} = CDF_{PM0Z\text{-}target} + CDF_{PM0Z\text{-}ABN} \quad (4)$$

Fire scenario for the failure of the target sets in panel PM0Z can be quantified by using the following Eq.[5]:

$$CDF_{PM0Z\text{-}target} = F_{MCB} \times [S \cdot N](d) \times CCDP_{PM0Z\text{-}target} = F_{MCB} \times 0.0058e^{-1.34d} \times CCDP_{PM0Z\text{-}target} \quad (5)$$

Where,
F_{MCB}: fire ignition frequency of the MCB
d: distance between the targets
$CCDP_{PM0Z\text{-}target}$: CCDP for the failure of the target set

Fire scenario for the abandonment due to PM0Z fire can be quantified by using the following Eq.:

$$CDF_{PM0Z\text{-}ABN} = F_{PM0Z} \times S_{PM0Z} \times N_{PM0Z} \times CCDP_{PM0Z\text{-}ABN}$$

Where,
$CCDP_{PM0Z\text{-}ABN}$: CCDP for the abandonment due to PM0Z fire

Severity (S_{PM0Z}) and non-suppression probability (N_{PM0Z}) are estimated based on the calculated evacuation time. The evacuation time can be obtained through the fire modeling results for the habitability conditions of the MCR operator. If the target distance is 7 cm and the multiplication of severity and non-suppression probability is 2.0E-4, fire scenarios for the PM0Z fire can be quantified as follows:

$$CDF_{PM0Z} = 2.05E\text{-}3/yr \times 0.0058\exp^{(-1.34*7/100)} \times 3.0E\text{-}3 + 1.86E\text{-}4/yr \times 2.0E\text{-}4 \times 0.1 = 3.25E\text{-}8/yr + 3.72E\text{-}9/yr = 3.62E\text{-}8/yr$$

Limitations of the NUREG/CR-6850 approach are as follows:1) unrealistic representation of Eq.(5) for the real MCB fire event 2) no guidance for modeling fire spreading to the adjacent panel.

2.5 NUREG-2178 method

Based on the MCB fire experiences and characterization of fire growth in the MCB, the new MCB fire risk method, NUREG-2178 method [3], is being developed by USNRC. It consists of screening and detailed analyses. The detailed analysis is performed by using the event tree presented in Fig.2. As shown in Fig.2, NUREG-2178 method systematically considers all fire scenarios including MCR abandonment due to loss of habitability (LOH) or loss of control (LOC). Quantification results for PM0Z fire are presented in Table III. Input data sources of quantification are presented in Table IV.

3. Conclusions

This study introduced three evaluation methods for the MCB fires scenarios and performed risk quantification of the domestic reference NPP using them. The results of this study show that the NUREG-2178 method is the most realistic approach for the quantification of the MCB fire. The applications of the NUREG-2178 method to domestic NPPs are expected to significantly reduce the MCB fire risk. Note that the MCB fire risk results vary by detailed models and assumptions. Therefore, the risk results presented in this study can be changed a little depending on them.

Acknowledgments

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Table II: Data for CDF Quantification of MCB fire

MCB frequency (F_{MCB})	Panel PM0Z frequency(F_{PM0Z}, λ_g)	$CCDP_{PMOZ-ABN}$	$CCDP_{PM0Z-5}$ $CCDP_{single-train}$	$CCDP_{PM0Z-15}$ $CCDP_{PM0Z-target}$ $CCDP_{panel}$	$CCDP_{single-highest}$
2.05E-3/yr	1.86E-4/yr	0.1	1.00E-05	3.00E-03	3.00E-07
NUREG-2178 Vol.2	2.05E-3(MCB frequency)/11(panel number)	assumed value based on the internal PSA results of the reference NPP			

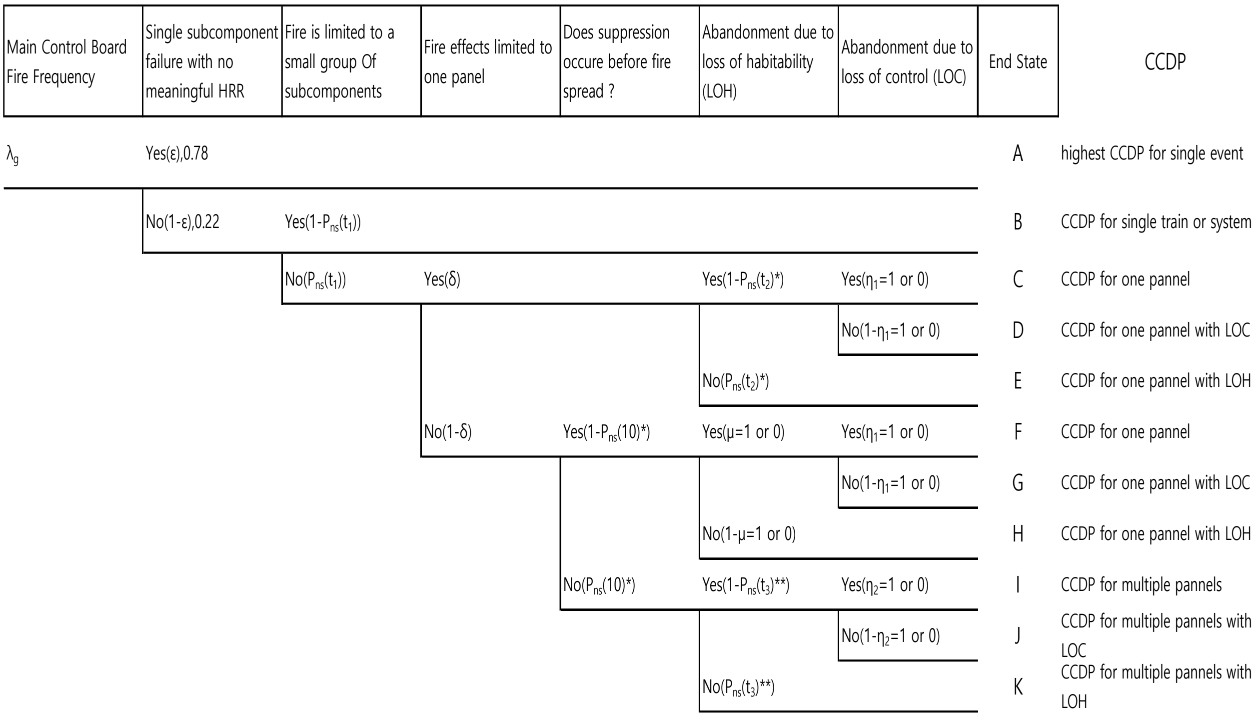

Fig. 2 Event Tree for MCB fire quantification

Table III: Results of event tree evaluation for MCB fire

Sequence	Branch Parameters	Branch Frequency	CCDP	CDF
A	$\lambda_g\varepsilon$	1.45E-04	3.00E-07	4.35E-11
B	$\lambda_g(1-\varepsilon)(1-P_{ns}(t_1))$	4.04E-05	1.00E-05	4.04E-10
C	$\lambda_g(1-\varepsilon)P_{ns}(t_1)\delta(1-P_{ns}(t_2)^*)\eta_1$	4.52E-07	3.00E-03	1.35E-09
D	$\lambda_g(1-\varepsilon)P_{ns}(t_1)\delta(1-P_{ns}(t_2)^*(1-\eta_1)$	0.00E+00	n/a	n/a
E	$\lambda_g(1-\varepsilon)P_{ns}(t_1)\delta P_{ns}(t_2)^*$	1.05E-07	1.00E-01	1.05E-08
F	$\lambda_g(1-\varepsilon)P_{ns}(t_1)(1-\delta)(1-P_{ns}(10)^*)\mu\eta_1$	0.00E+00	n/a	n/a
G	$\lambda_g(1-\varepsilon)P_{ns}(t_1)(1-\delta)(1-P_{ns}(10)^{**})\mu(1-\eta_1)$	0.00E+00	n/a	n/a
H	$\lambda_g(1-\varepsilon)P_{ns}(t_1)(1-\delta)(1-P_{ns}(10)^*)(1-\mu)$	0.00E+00	n/a	n/a
I	$\lambda_g(1-\varepsilon)P_{ns}(t_1)(1-\delta)P_{ns}(10)^*(1-P_{ns}(t_3)^{**})\eta_2$	0.00E+00	n/a	n/a
J	$\lambda_g(1-\varepsilon)P_{ns}(t_1)(1-\delta)P_{ns}(10)^*(1-P_{ns}(t_3)^{**})(1-\eta_2)$	5.42E-08	1.00E-01	5.42E-09
K	$\lambda_g(1-\varepsilon)P_{ns}(t_1)(1-\delta)P_{ns}(10)^*P_{ns}(t_3)^{**}$	8.61E-09	1.00E-01	8.61E-10
			Sum	1.84E-08

Table IV: Input Data for the quantification of MCB fire event tree

Input Parameter	Input Value	Input Value Source
λ	3.85E-01	Suppression rate, experience data, NUREG-2178 Vol.2
λ_g	1.86E-04	2.05E-3(MCB frequency)/11(panel number)
ε	7.80E-01	Failure of single subcomponent, experience data, NUREG-2178 Vol.2
δ	8.82E-01	Failure of single panel, Table 8-15 of NUREG-2178 Vol.2
$P_{ns}(t_1)$	1.30E-02	Failure of small group of components, Table 8-13 of NUREG-2178 Vol.2
t_2	15.16	assumed based on fire modeling result for single panel
t_3	15.16	assumed based on fire modeling result for two panels
$P_{ns}(10)$*	1.00E+00	$P_{ns}(10)$* =MIN($P_{ns}(10)/P_{ns}(t_1)$,1), $P_{ns}(10)$=2.13E-2
$P_{ns}(t_2)$*	2.25E-01	$P_{ns}(t_2)$* =MIN($P_{ns}(t_2)/P_{ns}(t_1)$,1), $P_{ns}(t_2)$=2.92E-4
$P_{ns}(t_3)$**	1.37E-01	$P_{ns}(t_3)$** =MIN($P_{ns}(t_3)/P_{ns}(10)$,1), $P_{ns}(t_3)$=2.92E-4
μ	1.00E+00	1- habitable condition
η_1	1.00E+00	1- control maintained
η_2	0.00E+00	0- control lost