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Evaluation Logic of Main Control Board Fire Risk

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1. Introduction

The main control board (MCB) is defined as the collection of control panels inside the main control room (MCR) of a nuclear power plant (NPP). As the MCB has the control and instrumentation circuits of redundant trains for almost all plant systems, small fires within the control panels may be detrimental to the safe shutdown capability. A big fire affecting many panels in the MCB can cause a forced MCR abandonment of the operators as well as function failures or spurious operations of the control and instrumentation-related components. If the MCR cannot be habitable, a safe shutdown from outside the MCR can be achieved and maintained at an alternate shutdown panel electrically and physically independent from the MCR.

Because the MCB consist of many electrical panels, it may have internal barriers between them to prevent a fire from spreading from its origin to neighboring locations. However, most MCBs of domestic NPPs do not have internal barriers within them. When the fire modeling for an MCB was performed, past studies [1,2,3,4] have considered only a single fire scenario within an MCB, a non-propagating fire scenario, or a propagating fire scenario. Depending on the configuration of the MCB and its size, an MCB fire may or may not be propagated from the initial fire panel to the neighboring locations within the MCB. If the MCB cabinets are not separated by a double wall with an air gap, the fire propagation of an MCB panel fire cannot be ruled out [5]. Recently, Joglar et al. [6] proposed a new evaluation logic for the MCB panel fires and mentioned that an MCB fire can be divided into propagation and non-propagating fires for abandonment and non-abandonment fire scenarios. However, they [6] did not present the details on the fire modeling approaches and probability formulas for the fire scenarios. In this paper, a decision tree for evaluating the risk of an MCB fire is proposed to systematically determine the fire scenarios in terms of the fire modeling approaches.

2. Fire risk and abandonment criteria

2.1 Evaluation of the MCB fire risk

The CDF (core damage frequency) from a fire can be represented by Eq. (1) [5, 7].

$$CDF = \sum_{k=1}^{n} \lambda_k SF_k NS_k CCDP_k \quad (1)$$

λ_k= fire frequency of fire scenario *k*,
SF_k= severity factor of fire scenario *k*,
NS_k= non-suppression probability of fire scenario *k*,
$CCDP_k$ = CCDP (conditional core damage probability) of fire scenario *k*

The following definitions of “SF”, “NS”, and “CCDP” came from NUREG/CR-6850 [5]. The SF is the probability that a postulated fire will include certain specific conditions that influence the rate of growth, level of energy emanated, and duration (time to self-extinguishment) to levels at which the target damage is generated. The NS is an estimate of the overall likelihood that given a fire in the postulated fire ignition source, damage to the target set will occur before the fire is suppressed. The CCDP is conditional on a specific fire scenario in a fire compartment postulated as a fire-induced initiating event and includes the likelihoods of the combinations of the equipment failures (some may be directly induced by the fire itself) and operator failures that result in core damage.

The equation specified for the control room NS is given in Eq. (2) below [8].

$$NS(t) = e^{-\lambda t} \quad (2)$$

where λ is the suppression rate constant for the MCR fire, λ is 0.33/min, and t is the time to abandonment (min.). The minimum value of NS is 0.001 [8].

2.2 MCR abandonment criteria

The forced abandonment conditions for the MCR fire used in this study were adopted from NUREG/CR-6850 [5]. It is assumed that the MCR abandonment initiates if one of the following criteria is satisfied:

- The heat flux at 1.8m (6’) above the floor exceeds 1 kW/m^2 (relative short exposure). A smoke layer of around 95℃ (200℉) can generate such heat flux.
- The smoke layer descends below 1.8m (6’) from the floor, and the optical density of the smoke is less than 3 m^{-1}.
- A fire inside the MCB damaging internal targets 2.13m (7’) apart from each other.

Among the above three conditions, the conditions directly related to the fire modeling for all fire scenarios are the heat flux, temperature, and optical density. The third condition is related to the fire modeling for a propagating fire. The fire in the MCB having no internal barriers can be continuously propagated within the MCB panels. However, the third condition limits continuous fire propagation in the fire modeling for an estimation of the time to abandonment.

The heat release rate (HRR), measured in kW or BTU/s, is the rate at which the combustion reaction produces heat and is the critical input parameter affecting the fire simulation results [5]. The discretized probability distributions of the HRR for the different ignition sources are presented in Appendix E of NUREG/CR-6850. The discretized distributions of the HRR consist of fifteen Bins, and the severity factor is assigned to each HRR Bin. Table 1 shows one example of the discretized distributions and severity factors of HRRs for vertical cabinets with a qualified cable, with a fire in more than one cable bundle. Fire simulations using the HRR point values from Bin 15 to Bin 1 in Table 1 are carried out to estimate the time to the MCR abandonment conditions. If the HRR of a specific Bin does not induce abandonment conditions, the fire simulations are stopped. Abandonment probability, P_{AB}, is calculated by summing up all multiplying pairs of the severity factors and non-suppression probabilities for each HRR Bin causing an MCR evacuation.

Table 1. Example of the discretized distributions and severity factors of HRR [5]

Bin	Heat Release Rate - kW (Btu/s)			Severity Factor
	Lower	Upper	Point Value	(SFi)
1	0 (0)	90 (85)	34 (32.7)	0.506
2	90 (85)	179 (170)	130 (123)	0.202
3	179 (170)	269 (255)	221 (209)	0.113
4	269 (255)	359 (340)	310 (294)	0.067
5	359 (340)	448 (425)	400 (397)	0.041
6	448 (425)	538 (510)	490 (464)	0.026
7	538 (510)	628 (595)	579 (549)	0.016
8	628 (595)	717 (680)	669 (634)	0.01
9	717 (680)	807 (765)	759 (719)	0.006
10	807 (765)	897 (850)	848 (804)	0.004
11	897 (850)	986 (935)	938 (889)	0.003
12	986 (935)	1076 (1020)	1028 (974)	0.002
13	1076 (1020)	1166 (1105)	1118 (1060)	0.001
14	1166 (1105)	1255 (1190)	1208 (1145)	0.001
15	1255 (1190)	Infinity	1462 (1386)	0.001

3. Evaluation logic of MCB fire risk

3.1 Decision tree for evaluating MCB fire risk

In this study, the MCB fire risk assessment logic is proposed, as shown in Fig.1, to determine the MCB fire scenarios. In Fig.1, it is assumed that prompt suppressions addressed in the previous study [6] are unavailable, any fire in the MCB causes a plant trip, and the ignition frequency is one. The headings in Figure 1 are described as follows:

- IG (Ignition): Any fire in the MCB panel.
- PAN (Panel failure): This heading represents the damage of the panel including the target sets.
- PR (Propagation): This heading represents scenarios involving fire propagation from one panel to one or more adjacent panels. In the case of large panels, this heading represents the fire propagation within the panel of the MCB. The MCB panel fire is not suppressed by the fire propagation initiation time.
- AB (Abandonment): This heading describes the forced abandonment of the operators owing to the inhabitability conditions of the MCR. For the case in which a propagating fire within the MCB is addressed, this heading may also include a fire inside the MCB damaging internal targets 2.13m (7') apart from each other.

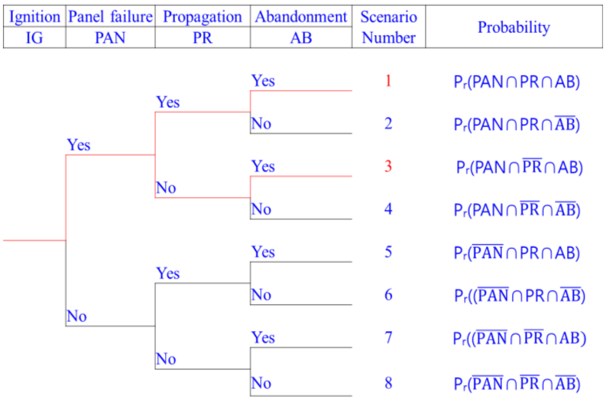

Fig. 1. Decision tree for evaluating the risk of the MCB fire.

If the MCB fire is suppressed before the occurrence of the event for each heading, the event for each heading does not occur. Therefore, in Fig. 1, the probabilities of all headings except IG can be represented using Eq. (2). Further, the probabilities of "PAN", "PR", and "AB" in Fig. 1 can be defined as the functions of time t. It is assumed that each event of "PAN", "PR", or "AB" occurs at time t1, t2, and t3. In addition, the relations between times are assumed to be t1 $\leq$ t2 $\leq$ t3. If the event for "PR" or "AB" has occurred, the event for "PAN" is assumed to have occurred. For the case in which the event for "PR" has not occurred, the relations between the times are assumed to be t1$\leq$t3. Based on the assumptions mentioned above, each scenario of Fig. 1 can be represented as follows:

- Scenario 1: $P_r(PAN \cap PR \cap AB) = P_r(PR \cap AB) P_r\{PAN|(PR \cap AB)\} = P_r(PR \cap AB) = P_r(AB)\ P_r(PR|AB) = P_r(AB) = P_{AB\text{-}prop}$
- Scenario 2: $P_r(PAN \cap PR \cap \overline{AB}) = P_r(PR \cap \overline{AB}) = P_r(PR) P_r(\overline{AB}\ |PR) = P_r(PR)\{1-P_r(AB|PR)\} = P_r(PR)\{1-P_r(AB)/P_r(PR)\} = P_r(PR)-P_r(AB) = P_{PR} - P_{AB\text{-}prop}$
- Scenario 3: $P_r(PAN \cap \overline{PR} \cap AB) = P_r(\overline{PR} \cap AB\} = P_r(\overline{PR}\ ) P_r(AB) = Pr(AB) - Pr(PR)Pr(AB) = P_{AB\text{-}non} - P_{PR}P_{AB\text{-}non}$
- Scenario 4: $P_r(PAN \cap \overline{PR} \cap \overline{AB}) = P_r(PAN \cap \overline{AB}) P_r(\overline{PR}) = P_r(PAN) P_r(\overline{AB}\ |PAN)\ \{1-P_r(PR)\} = P_r(PAN)\{1-P_r(AB|PAN)\}\ \{1-P_r(PR)\} = \{P_r(PAN)-P_r(AB)\}\{1-P_r(PR)\} =$

$P_{PAN\text{-}non} - P_{AB\text{-}non} - P_{PR}P_{PAN\text{-}non} + P_{PR}P_{AB\text{-}non}$

- Scenario 5: $P_r(\overline{PAN} \cap PR \cap AB) = P_r(\overline{PAN})P_r\{(PR \cap AB) | \overline{PAN}\} = 0$
- Scenario 6: $P_r(\overline{PAN} \cap PR \cap \overline{AB}) = P_r(\overline{PAN})P_r\{(PR \cap \overline{AB}) | \overline{PAN}\} = 0$
- Scenario 7: $P_r(\overline{PAN} \cap \overline{PR} \cap AB) = P_r(\overline{PAN} \cap AB)P_r(\overline{PR}) = P_r(\overline{PAN})P_r(AB | \overline{PAN})P_r(\overline{PR}) = 0$
- Scenario 8: $P_r(\overline{PAN} \cap \overline{PR} \cap \overline{AB}) = P_r(\overline{PAN} \cap \overline{AB})P_r(\overline{PR}) = P_r(\overline{X})P_r(\overline{PR}) = \{1-P_r(PAN \cup AB)\}P_r(\overline{PR}) = \{1-P_r(PAN)\}\{1-P_r(PR)\} = 1- P_{PAN\text{-}non} - P_{PR} + P_{PR}P_{PAN\text{-}non}$

  $X = PAN \cup AB$

The definitions of probabilities mentioned above are as follows:

P_{AB} : abandonment probability
$P_{AB\text{-}non}$:abandonment probability owing to non-propagating fire
$P_{AB\text{-}prop}$:abandonment probability owing to propagating fire
$P_{PAN\text{-}non}$:panel failure probability owing to non-propagating fire
P_{PR} : fire propagation probability
$P_r(X)$: probability of an event X
$P_r(\overline{X})$: probability of an event X's complement
$P_r(X \cup Y)$: probability of the union of two events X and Y

$$P_r(X \cup Y) = P_r(X) + P_r(Y) - P_r(X \cap Y) \quad (3)$$

$P_r(X \cap Y)$: joint probability of two events X and Y

$$P_r(X \cap Y) = P_r(X)\, P_r(Y|X) = P_r(Y)\, P_r(X|Y) \quad (4)$$

$P_r(X|Y)$: conditional probability. probability of X, given Y

3.2 Modified decision tree for evaluating MCB fire risk

Using the probability formulas mentioned above, the decision tree in Fig. 1 can be simply represented as Fig. 2. In Fig. 2, the probability of “PAN” can be estimated using Figure L-1 of NUREG/CR-6850. The probability of “PR” is estimated using Eq.(2). The probability of “AB” can be defined as the product of the severity factor (SF) and the non-suppression probability (NS). The SFs are given in accordance with the Bin of the HRR presented in Appendix E of NUREG/CR-6850, and the NSs are estimated using the fire simulation results and Eq. (2). In Fig. 2, the multiplication terms are excluded because the fire propagation probability, P_{PR}, is much less than 0.1. The abandonment scenarios in Fig. 2 are scenarios 1 and 3. Non-abandonment scenarios are scenarios 2 and 4. Scenario 5 results in neither MCR abandonment nor damage to the MCB panel.

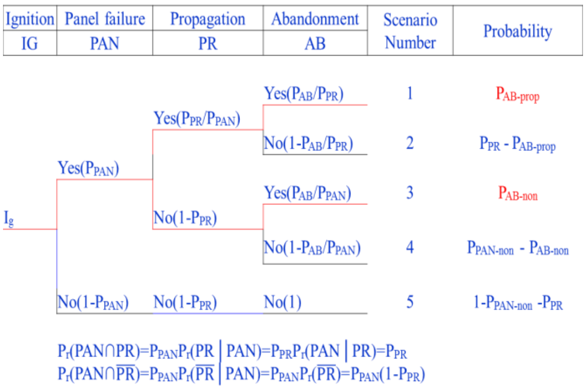

Fig. 2. Modified decision tree for evaluating the risk of the MCB fire

The approach for estimating the probability of each scenario in Fig. 2 is as follows:

- Scenario 1: Propagation and abandonment fire scenario. $P_{AB\text{-}prop}$ is estimated based on the fire simulation results and Figure L-1 of NUREG/CR-6850. It is assumed that the MCB control panel fire is not suppressed within the fire propagation initiation time. Thus, the fire simulation results for scenario 1 are taken into account only when the time to abandonment is greater than the fire propagation initiation time. Otherwise, they are not taken into account. The HRR for the fire modeling should address the propagating fire. Figure L-1 of NUREG/CR-6850 can also be used for the estimation of the abandonment probability due to the damage of MCB internal target sets 2.13m apart from each other. If the widths of electrical panels within the MCB having internal barriers are too small, this scenario may not be considered.
- Scenario 2: Propagation and non-abandonment fire scenario. P_{PR} is estimated using Eq. (2) when the time is the fire propagation initiation time.
- Scenario 3: Non-propagation and abandonment fire scenario. $P_{AB\text{-}non}$ is estimated based on the fire simulation results. It is assumed that the MCB control panel fire is suppressed within the fire propagation initiation time. Thus, the fire simulation results for scenario 3 are taken into account only when the time to abandonment is less than the fire propagation initiation time. Otherwise, they are not taken into account. The HRR for fire modeling should address only the non- propagating fire.
- Scenario 4: Non-propagation and non-abandonment fire scenario. $P_{PAN\text{-}non}$ can be estimated using Figure L-1 of NUREG/CR-6850[5].
- Scenario 5: Negligible risk. The risk for scenario 5 is negligible compared to that for scenarios 1, 2, 3, or 4. Thus, scenario 5 may not be considered for the estimation of risk for an MCB fire.

4. Concluding remarks

This paper proposed a decision tree for evaluating the risk of an MCB fire to systematically determine the fire scenarios in terms of fire modeling approaches. In the proposed decision tree, five scenarios were considered for an estimation of the MCB fire risk. In addition, the fire modeling approaches for the abandonment scenarios were presented and discussed.

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