Simplified Method to Predict Time to Fire-Induced Electrical Failure of Cables in Two-layer Zone Model BRI2-CRIEPI

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Abstract: In implementing practical fire Probabilistic Risk Assessment (PRA) for nuclear power plants (NPPs), several fire scenarios need to analyze more realistic fire consequences near targets typically considered in fire PRA such as heat flux to targets from a flame, smoke gas layer or surrounding. In general, electrical cables are mainly addressed as the targets, and a fire simulation code is applied in the above analysis. The Nuclear Risk Research Center (NRRC) of the Central Research Institute of Electric Power Industry (CRIEPI) has continuously improved the two-layer zone model named BRI2-CRIEPI to allow the analysis of compartment fire behavior of NPPs. In recent developments, sub-models on radiative heat flux from fire consequences, and the time to failure on electrical cables have been incorporated in BRI2-CRIEPI.

This work presents the results of a case study for determining the zone of influence (ZOI) with the BRI2-CRIEPI. For predicting the time to fire-induced electrical cable failure, our modeling approach such as the heat soak model in NUREG-2178 volume 2 determines horizontal ZOI values by fire exposure conditions nearby targets such as heat flux and the value of integrated damage rate for electrical cables defined each by each fire exposure condition. Transient fire scenarios were assumed to be used to develop ZOI on the target failures.

The analytical results of the BRI2-CRIEPI were compared. Especially, the estimated total heat flux is very important to predict the time to fire-induced electrical failure of cables in fire PRA, the discussions about the applicability of this simplified method were summarized.

Keywords: Fire Modeling, Fire PRA, Zone of Influence, Fire-Induced Electrical Cable Failure

1. INTRODUCTION

An internal fire could significantly contribute to an NPP (nuclear power plant) since it may cause initiating events and loss of mitigation function. It could also affect human performance and plant safety. Hence, it is important for risk informed reinforcement of plant safety to identify and quantify internal fire scenarios and to identify the vulnerability of NPPs from the viewpoint of an internal fire.

Considering this background, the Nuclear Risk Research Center (NRRC) of the Central Research Institute of Electric Power Industry (CRIEPI) has conducted several research activities such as the development of an internal fire Probabilistic Risk Assessment (PRA) guide (herein after NRRC FPRAG) [1], the analysis of fire events [2] and the reinforcement of a fire model [3]. In implementing practical internal fire PRA for an NPP, fire scenarios must consider more realistic consequences of fire in nearby targets typically considered in fire PRA such as heat flux to targets from a flame, hot gas layer or the surrounding area. Such targets are generally electrical cables, and a fire simulation code is applied in the above analysis. To support Japanese NPP licensees, NRRC has been improving the two-layer zone model named BRI2-CRIEPI [3] to enable the analysis of compartment fire behavior of NPPs.

In a practical fire PRA manner, horizontal zone of influences (ZOIs) of targets from a flame are estimated under open atmospheric fire conditions for the screening process using a spreadsheet model such as the Fire Dynamics Tools (FDTs) [4]. These ZOIs are useful in first-step analysis but seem conservative approaches. For a more realistic approach, the ZOIs need to be evaluated under ventilated compartment fire conditions for detailed analysis using a two-layer zone model or a computational fluid dynamics (CFD) model. However, implementing such fire modeling is expensive, therefore proposals for efficient methods are required.

This work presents the results of a case study with a simplified model to predict the time to failure of electrical cables induced by fire consequences in BRI2-CRIEPI. To address the above issues, the ZOIs developed in this study were addressed to mechanically ventilated single compartment fire scenarios.

2. THEORETICAL BACKGROUND

2.1. Simplified thermal radiation model from a flame to a target in BRI2-CRIEPI

To estimate the radiative heat flux from a flame to a target $\dot{q}''_{sf}$ [kW/m2], BRI2-CRIEPI has incorporated two thermal radiation models as shown in Figure.1.

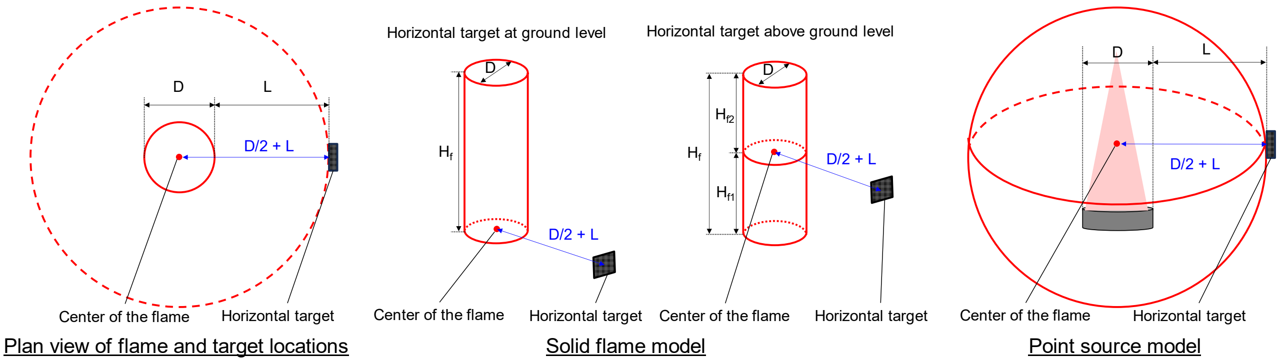

Figure.1 Illustration of two thermal radiation models from a flame [4][5]

(1) Solid flame model

This solid flame radiation model is like NUREG-2178 vol.2 [5]. In general, a fire is characterized by the diameter D [m], radiative fraction X_r [-], heat release rate (HRR) $\dot{Q}$ [kW], height of the mean flame region H_f [m], horizontal distance between flame and target L [m] and so on. According to several literatures [5][6], the flame shape is assumed to be a cylinder in which the height from the bottom of the flame to the mean flame region is estimated by Heskestad's correlation [3].

The radiant heat flux from the flame at the target by the solid flame model $\dot{q}''_{sf}$ is expressed by Eq. (1). $\dot{q}''_{sf}$ is calculated by the flame emissivity ε_f [-], the constant number of Stefan-Boltzmann σ (5.67×10-11)[kW/m^2/K^4], the flame temperature T_f [K] or the radiant energy flux at flame surface E_c [kW/m2] and the view factor between the assumed flame shape and target F_f [-].

$$\dot{q}''_{sf} = F_f \varepsilon_f \sigma T_f^4 = F_f E_c \qquad (1)$$

F_f is calculated by the following approximation formula [4]. Figure 1 also shows general definitions applicable to the cylindrical flame model under wind-free conditions. In BRI2-CRIEPI, horizontal targets are only considered at ground level or above ground level.

$$F_f = \frac{1}{\pi n}\tan^{-1}\left(\frac{m}{\sqrt{n^2-1}}\right) + \frac{m}{\pi}\left[\frac{(X-2n)}{n\sqrt{XY}}\tan^{-1}\left(\sqrt{\frac{X(n-1)}{Y(n+1)}}\right) - \frac{1}{n}\tan^{-1}\left(\sqrt{\frac{(n-1)}{n+1}}\right)\right] \qquad (2\text{-}1)$$

$$X = (1+n)^2 + m^2 \qquad (2\text{-}2)$$

$$Y = (1-n)^2 + m^2 \qquad (2\text{-}3)$$

$$m = H_f/(D/2) \qquad (2\text{-}4)$$

$$n = (D/2+L)/(D/2) \qquad (2\text{-}5)$$

E_c is calculated from the heat balance at the flame surface if the flame shape is assumed to be a cylinder as shown in Eq. (3). Here Ac [m^2] is the surface area of the cylindrical flame. The surface area of the top is disregarded for the conservative assumption in BRI2-CRIEPI.

$$E_c = \frac{X_r\dot{Q}}{Ac} = \frac{X_r\dot{Q}}{\pi D H_f} \qquad (3)$$

X_r is proposed by McGrattan [7] as Eq. (4). It is incorporated into BRI2-CRIEPI for estimating X_r of assumed fire sources. In addition, X_r can be set as a specific value in BRI2-CRIEPI.

$$X_r = 0.35exp(-0.05D) \qquad (4)$$

ε_f can be calculated from the energy conservation at the flame surface as shown in Eq. (5) [3]. To calculate ε_f with a part of the output from the heat feedback model in BRI2-CRIEPI, the cylindrical flame shape is divided into the continuous flame region (surface area A_{cc} [m^2], radiant energy flux at the surface E_{cc}: 81 kW/m^2) and the mean flame region (surface area A_{ci} [m^2], radiant energy flux at the surface E_{ci}: 52 kW/m^2). More detailed information refers to the previous work [3]. Hence T_f can also be calculated from Eq. (6).

$$\varepsilon_f = \frac{X_r \dot{Q}}{(A_{cc}E_{cc} + A_{ci}E_{ci})} \tag{5}$$

$$T_f = \sqrt[4]{\frac{E_c}{\varepsilon_f \sigma}} \tag{6}$$

(2) Point source model

This is a point source radiation model like NUREG-1805 [4]. The model is shown as Eq. (7). The radiative heat flux at targets with the point source model $\dot{q}''_{ps}$ is computed by the radius of the sphere as the total distance from the center of the fire source to targets.

$$\dot{q}''_{ps} = \frac{X_r \dot{Q}}{4\pi (D/2 + L)^2} \tag{7}$$

2.2. Simplified thermal radiation model from a smoke to a target in BRI2-CRIEPI

The radiative heat flux from a smoke to a target $\dot{q}''_{smoke}$ [kW/m^2] is expressed by Eq. (8). $\dot{q}''_{smoke}$ is calculated by the hot gas layer emissivity ε_{HGL} [-], the constant number of Stefan-Boltzmann σ (5.67×10-11)[kW/m^2/K^4], hot gas layer temperature T_{HGL} [K], initial ambient temperature T_0 [K] and the view factor between the hot gas layer interface and target F_{HGL} [-] in BRI2-CRIEPI. The values of ε_{HGL} and T_{HGL} are estimated by the sub-models of BRI2-CRIEPI.

$$\dot{q}''_{smoke} = F_{HGL}\varepsilon_{HGL}\sigma(T_{HGL}^4 - T_0^4) \tag{8}$$

For a simplified approach in BRI2-CRIEPI, F_{HGL} is calculated by an approximate formula whereby the target location is conservatively assumed to be the center part of the fire compartment (see Fig.2). Hence F_{HGL} is expressed by Eq. (9).

$$F_{HGL} = 4\left[\frac{1}{2\pi}\left(\frac{A}{\sqrt{1+A^2}}\tan^{-1}\frac{B}{\sqrt{1+A^2}} + \frac{B}{\sqrt{1+B^2}}\tan^{-1}\frac{A}{\sqrt{1+B^2}}\right)\right] \tag{9-1}$$

$$A = (W_r/2)/(H_{HGL} - H_t) \tag{9-2}$$

$$B = (L_r/2)/(H_{HGL} - H_t) \tag{9-3}$$

Here H_r, W_r and L_r are the ceiling height of the fire room, the width of the fire room and the length of the fire room, respectively. H_{HGL} is the height of the hot gas layer interface from the floor level. H_t is the height of the target location from the floor level to the top of the target.

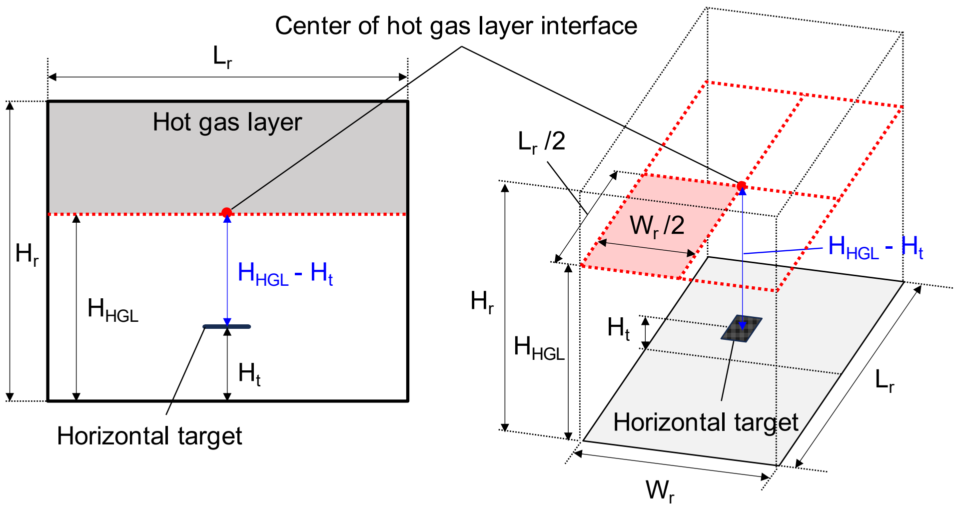

Figure.2 Illustration of a thermal radiation model from a smoke layer (left: Side view, right: Bird's eye view)

2.3. Fire damage integrated model using the exposure of heat flux in BRI2-CRIEPI

The fire damage integrated model, like the heat soak model in NUREG-2178 vol.2 [5], is incorporated into BRI2-CRIEPI to estimate thermal induced electrical cable failures. The damage integral value ω [-] caused by the fire consequence is expressed by Eq. (10). $R(t)$ is the damage rate [min^{-1}] at time t as a function of the heat flux range that is defined as being inverse of the fire damage time t_{damage} [min] listed in the tables of Appendix H of NUREG/CR-6850 [8]. BRI2-CRIEPI applies the damage rate $R(t)$ by linear interpolation with each heat flux shown in Figure 3. The range of heat flux less than 6 kW/m^2 for thermoplastic cable (TP cable) and 11 kW/m^2 for thermoset cable (TS cable) is assumed $R(t)$ of 0 min^{-1}. In addition, the range of heat flux greater than 16 kW/m^2 for TP cable and 20 kW/m^2 for TS cable is assumed to be a maximum $R(t)$ of 1 min^{-1}. The time to electrical cable failure would then determine with a ω of 1 or greater than 1.

$$\omega = \int_0^{t_{damage}} R(t)dt \quad (10)$$

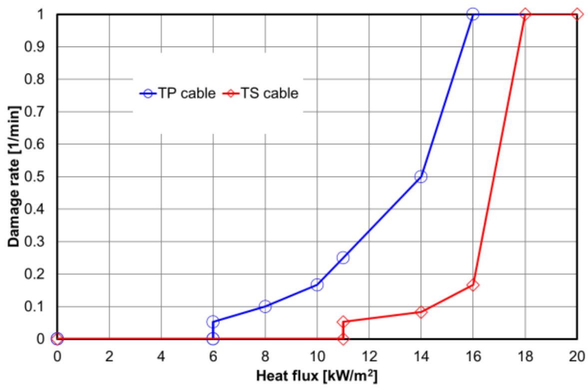

Figure.3 Damage rate $R(t)$ as a function of heat flux to a target

In BRI2-CRIEPI, the fire exposure conditions are considered as the exposure heat flux $\dot{q}''_{exposure}$ near the targets. $\dot{q}''_{exposure}$ is defined by Eq. (11). Usually, $\dot{q}''_{flame}$ applies the larger of the two models in BRI2-CRIEPI as shown by Eq. (12). However, $\dot{q}''_{sf}$ only applies the solid flame model in this study.

$$\dot{q}''_{exposure} = \dot{q}''_{flame} + \dot{q}''_{smoke} \quad (11)$$
$$\dot{q}''_{flame} = Max(\dot{q}''_{sf}, \dot{q}''_{ps}) \quad (12)$$

3. NUMERICAL CASE STUDY AND DISCUSSION

3.1. Overview of Case Study

To predict the time to fire-induced electrical cable failure, our modeling approach, like the heat soak model in NUREG-2178 volume 2 [4], determines the time to failure by fire exposure conditions in nearby targets such as heat flux and the value of the integrated damage rate for electrical cables defined by each fire exposure condition. This study also referred to the new guidance for transient fire modeling in NUREG-2233[9].

In this case study, only a transient fire scenario was considered. The time dependent curve of the generic transient fire scenarios which peak HRR 278 kW at 98th percentile in NUREG-2233[9], was applied to determine horizontal ZOIs with BRI2-CRIEPI (see Figure.3). The location of a fire source was in the middle of single room. The burning area of a fire source and X_r were set as 0.42 m^2 and 0.4, respectively. The top of a fire source was set at 0.15 m from the floor level. The dimensions H_r, W_r and L_r of single room, the volume V_r, the ventilation volume rate Q_r and the renewal rate $N_r$were listed in Table 1. The area of openings for mechanical ventilation was set at 0.3 m height by 0.8 width. The top of the openings was located at 2.4 m from the floor level. The illustration of the fire scenario is shown in Figure 3.

For determining horizontal ZOIs, BRI2-CRIEPI assumed many virtual targets at a horizontal distance divided into 0.05 m intervals from 0.05 m to 1.25 m from the flame edge. The target location for the fire damage integrated model was assumed to be at the same horizontal distance, and at 0.74 m vertical distance from the top of the fire source. Types of cable TP cable and TS cable were addressed as targets.

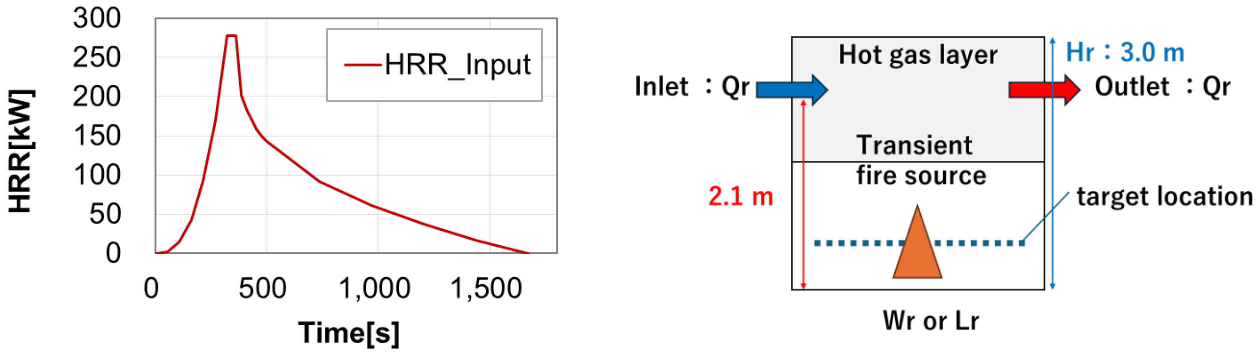

Figure. 3 HRR time dependent curve and scenario of the generic transient fire in single compartment [9]

Table. 1 Dimensions and ventilation rates of compartment in case study

Case	H_r [m]	W_r [m]	L_r [m]	V_r [m^3]	Q_r [m^3/h] (N_r [h^{-1}])
N-1	3	4	4	48	240 (5)
N-2	3	6	6	108	540 (5)
N-3	3	8	8	192	960 (5)
N-4	3	9	9	243	1215 (5)
N-5	3	10	10	300	1500 (5)

3.2. Results and Discussion

Figure 4 showed the time history of fire consequences such as fire HRR, temperature of hot gas layer and interface height of hot gas layer in this case study. Table 2 summarized the maximum or minimum values. The single compartment fire scenario results showed peak HRR, the temperature of the hot gas layer and the height of the hot gas layer interface varied depending on the floor area. According to the peak HRR, the fire consequences of N-1 and N-2 seemed to be based on the ventilation-controlled fire conditions. Meanwhile, the fire consequences of N-3 to N-5 seemed to be based on the fuel-controlled fire conditions. The temperatures and the interface heights of hot gas layer were more severe values with the smaller floor area.

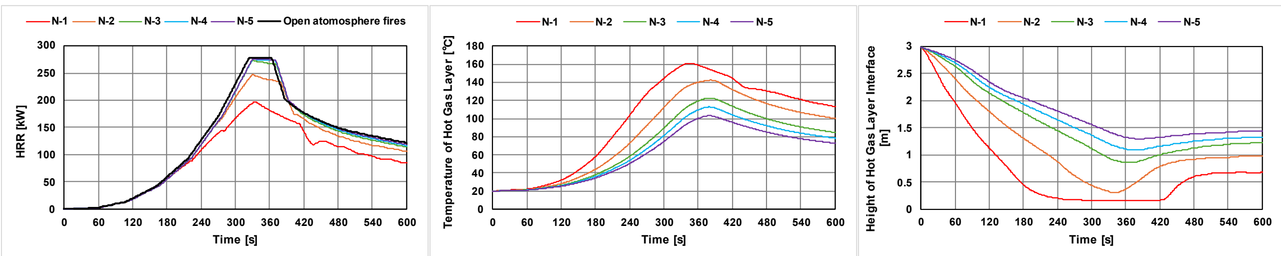

Figure. 4 Time history of fire consequences in this case study

Table. 2 Calculation results of fire consequences

Floor Area[m^2]	N_r : 5 h^{-1}		
	Maximum		Minimum
	HRR[kW]	T_{HGL}[°C]	H_{HGL}[m]
16	197	161	0.16
36	247	142	0.30
64	273	123	0.86
81	275	113	1.09
100	275	103	1.29
Open atmosphere fires	278	NA	NA

Table 3 and Table 4 summarized the calculation results of horizontal ZOI and damage time for the TP and TS cable. For discussion, the ZOIs in open atmosphere fire conditions were estimated at 0.45 m for TP cable and at 0.3 m for TS cable by the fire damage integrated model of BRI2-CRIEPI. This was smaller than the ZOIs estimated as 1.49 m (solid radiation model) and 0.85 m (point source model) for TP cable and 0.97 m (solid radiation model) and 0.54 m (point source model) for TS cable by FDTs[4] using the damage threshold values[8] of 11 kW/m^2 and 6 kW/m^2 (hereinafter damage threshold model). Therefore, the fire damage integrated model may be effective in eliminating conservatism on ZOIs in a fire PRA. NUREG-2233[9] reported the horizontal ZOIs at 0.36 m for TP cable and at 0.11 m for TS cable using similar calculation conditions. The difference of ZOIs seemed to be mainly affected from the higher value 0.4 of X_r than the value 0.3 of NUREG-2233[9].

Table. 3 Calculation results of horizontal ZOI for TP cable

Damage threshold model by FDTs[4]		Floor Area[m^2]	Case Study by BRI2-CRIEPI	
Horizontal ZOI[m]			Horizontal ZOI[m]	Damage Time[s]
Point source model	Solid flame model		Solid flame model	
-	-	16	0.35	401
		36	0.45	457
		64	0.45	429
		81	0.45	430
		100	0.45	432
0.85 m	1.49 m	Open Atmosphere	0.45	434

Table. 4 Calculation results of horizontal ZOI for TS cable

Damage threshold model by FDTs[4]		Floor Area[m^2]	Case Study by BRI2-CRIEPI	
Horizontal ZOI[m]			Horizontal ZOI[m]	Damage Time[s]
Point source model	Solid flame model		Solid flame model	
-	-	16	0.2	349
		36	0.3	451
		64	0.3	371
		81	0.3	371
		100	0.3	372
0.54 m	0.97 m	Open Atmosphere	0.3	369

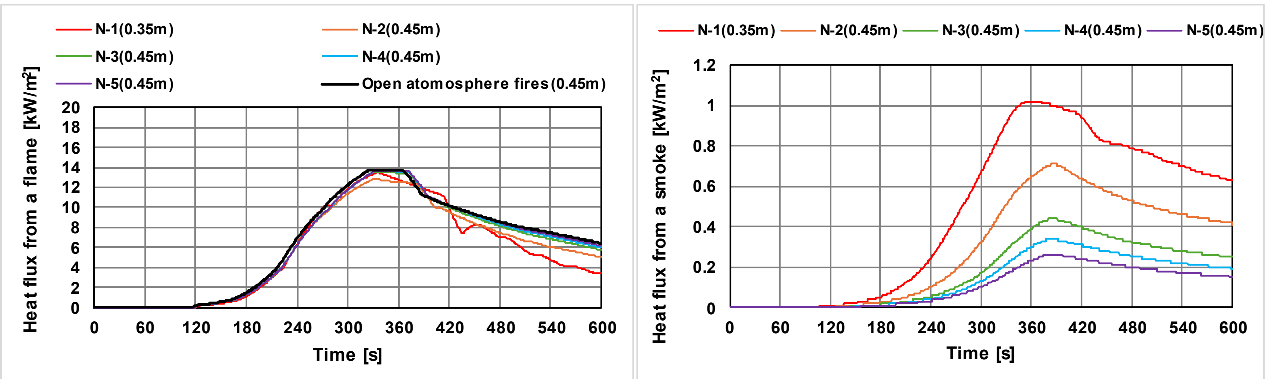

Figure. 5 Results of heat flux from a flame and a smoke at the ZOIs for TP cable based on Table 3

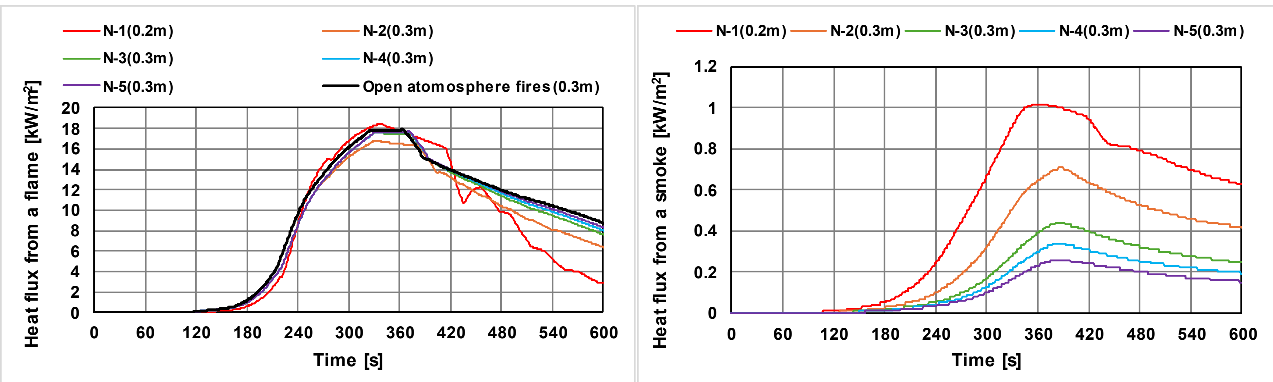

Figure. 6 Results of heat flux from a flame and a smoke at the ZOIs for TS cable based on Table. 4

Figure 5 and Figure 6 show the heat flux from a flame and a hot gas layer in the case of N-1 to N-5 and the open atmosphere fire scenario. The heat flux from a flame decreases in value as the heat release rate decreases. Meanwhile, the heat flux from a hot gas layer increases as the temperature of hot gas layer increases. The maximum heat flux from the flame to targets were around 13 to 14 kW/m^2 at ZOI 0.45 m for TP cables and around 17 to 18 kW/m^2 at ZOI 0.3 m for TS cables in the compartment fire scenarios. The maximum heat flux from the hot gas layer to targets ranged from around 0.25 to 1.0 kW/m^2.

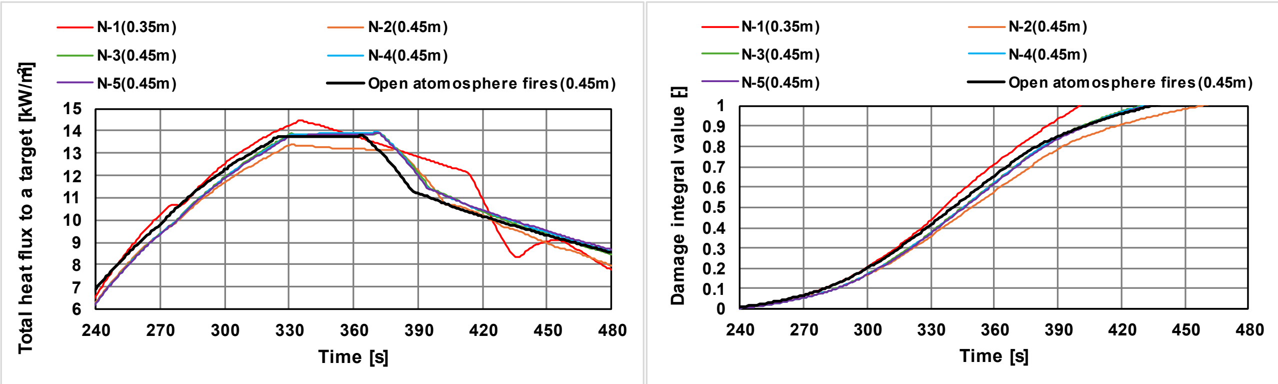

Figure. 7 Results of total heat flux and damage integral value at the ZOIs for TP cable based on Table.3

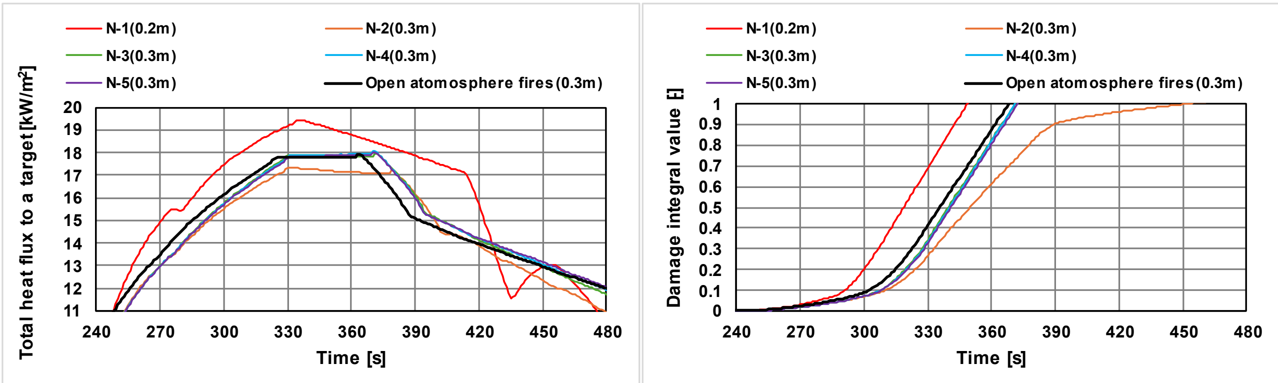

Figure. 8 Results of total heat flux and damage integral value at the ZOIs for TS cable based on Table.4

Figure. 7 and Figure. 8 show the results of the total heat flux to a target defined in Eq. (11), and damage integral value in the case of N-1 to N-5 and the open atmosphere fire scenario. The maximum total heat flux to the targets estimated over 14 kW/m^2 at ZOI 0.35 m for TP cables and over 19 kW/m^2 at ZOI 0.2 m for TS cables. According to the results of N-1, we found the decrease of ZOI distance induced by the decrease of HRR in the ventilation-controlled fire conditions may increase the heat flux to the target at the ZOIs because approaching the flame. Meanwhile, the results of N-2 indicated that the time to damage could be longer even if the ZOI distance for TP or TS cable was same. From Figure 7, it can be confirmed that the damage integral value of N-3 to N-5 is larger than that under the open atmosphere fire scenario at around 400 s in case of TP cables. We found that such a decrease in HRR and increase in heat flux from smoke in response to mechanically ventilated conditions are characteristics of compartment fires and may result in shorter damage times than in open atmosphere fire scenario. In case of TS cable, the influence of radiative heat flux from the flame seems to be significant compared to the heat flux from the hot gas layer (see Figure 6). Thus, the damage integral value at the ZOI 0.3 m reaches the value of 1 earlier under the open atmosphere fire condition than under compartment fire conditions of N-2 to N-5 (see Figure 8).

Compared to the open atmosphere fire scenario and the ventilated compartment fire scenarios, the difference of horizontal ZOI ranged from 0 m to 0.1 m because of the influence of the heat flux from a flame or a hot gas layer in ventilation-controlled fire conditions. The results of ZOI determination in this case study suggest the significance for implementing a detailed fire modeling because the ZOI distance may be same or shorter but the time to damage for targets tends to be longer or shorter than under open atmospheric fire scenarios. In addition, if we develop a library of ZOIs information using fire modeling tools in response to various compartment fire scenarios, it may be applicable to estimate a simplified ZOI in first step analysis for a fire PRA. These findings indicate that a case study using a fire modelling tool may be useful to develop an efficient method for a more realistic ZOI evaluation. However, since this study is a case study of a single compartment with a ceiling height of 3 m, it is essential to expand the knowledge by considering the actual operating conditions of NPPs for developing a simplified ZOIs applicable to the ventilated compartment fire scenarios.

4. CONCLUSION

We have presented a case study using a simplified fire modeling approach to determine the horizontal ZOI and time to failure of electrical cables subjected to fire consequences. The fire damage integrated model concept, like that of NUREG-2178 vol.2, is used in BRI2-CRIEPI. The proposed method has the potential to define a simplified ZOI and time to fire-induced electrical failure in real fire scenarios in nuclear power plants.

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