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Benchmark Study of the Fire Modeling Analysis Guidelines

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1. Introduction

Detail analysis of fire area is a key element of performance-based fire protection program for operating nuclear power plants and is performed to find out the fire area vulnerability including target elements.

NFPA 805 requires fire modeling and uncertainty analysis to develop the fire scenario in nuclear power plants [1] and also states that fire models shall only be applied within the limitations of the given model and shall be verified and validated.

US NRC had published the fire modeling analysis guidelines as NUREG-1934 which describes the implications of the verification and validation (V&V) results for fire model users [2]. In this guideline, US NRC pointed out that one key element in risk informed performance based fire protection is the availability of verified and validated fire models that can reliably estimate the effects of fires.

Based on the guidelines, the benchmark analysis using FDS5 is performed to predict the potential damage to the cables within trays for the fire scenario in a multi-compartment corridor of nuclear power plant. This study is to review an applicability of the fire modeling analysis guidelines.

2. FDS5 simulation of multi-compartment corridor fire

FDS5 is the most widely used computer code to simulate a compartment fire. FDS5 simulates the computational regime with a numerical form of the Navier-Stokes equations, which are appropriate for the low speed and thermally-driven buoyant flow with an emphasis on smoke and heat transport from a fire [3]. LES turbulent model is used in combination with the Smagorinsky sub grid model.

The modeling area consists of interconnected compartments and corridors on the same level as shown in Fig. 1. Total volume of compartment is composed with 26.4x6.4x4.6 (m^3) and 6.4x40.6x4.6 (m^3). The geometry of compartment is nodalized with total cell number of 246,560 with each cubic cell size of 0.2 m^3. Fig. 2 shows the FDS5 modeling results of multi-compartment corridor in the auxiliary building of nuclear power plant.

Cable tray contained cross-linked polyethylene-insulated cables with a neoprene jacket is located near the ceiling as shown in Fig. 2.

There are 4 smoke detectors with a sensitivity of 4.9 %/m and no automatic fire suppressions in the corridor.

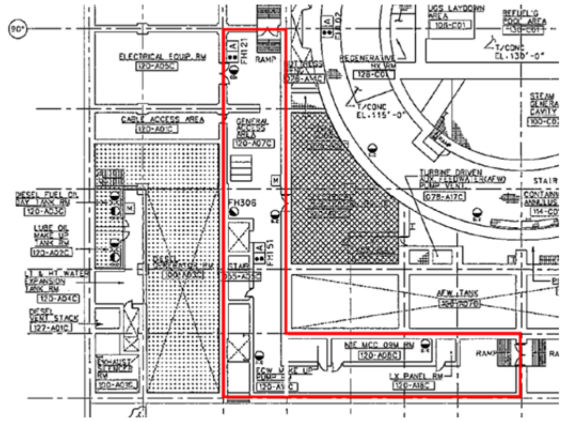

Fig. 1. Multi-compartment corridor in the auxiliary building of nuclear power plant

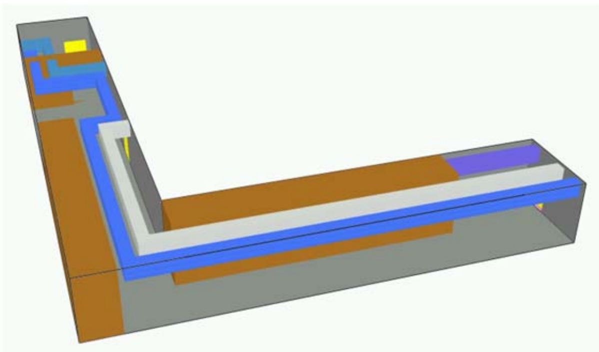

Fig. 2. FDS5 modeling of multi-compartment corridor

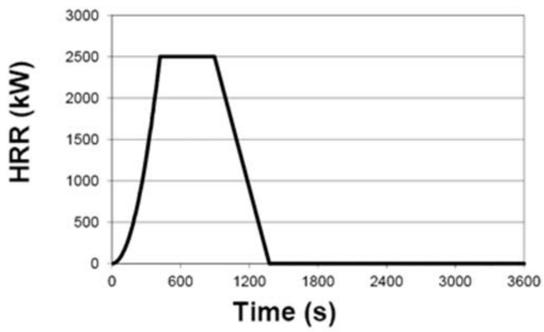

Fig. 3. HRR for the corridor fire scenario

2.1 Fire Scenario

A fire is assumed to start at wood pallets with trash bag located in the corner of right hand side entrance in the corridor. The heat release rate (HRR) of fire follows the 't-squared' curve to a maximum value of 2,500 kW in 7 min. and remains steady for 8 additional minutes. After that, HRR is assumed to reduce linearly to 0 in 12 min. The HRR curve is shown in Fig. 3.

Table 1. Material Properties of a Corridor

Material	Thermal Conductivity, (W/m/K)	Density, (kg/m^3)	Specific Heat, (kJ/kg/K)	Reference
Concrete	1.6	2400	0.75	NUREG-1805
Steel	54	7850	0.465	NUREG-1805
Cables	0.235	0.235	1.39	NUREG/CR-6850

Table 2. Normalized Parameter Calculation Results

Quantity	Normalized Parameter	Validation Range	Benchmark results	In Range ?
Fire Froude Number	$Q_d^* = \frac{\dot{Q}}{\rho_\infty c_p T_\infty D^2 \sqrt{gD}}$	0.4~2.4	0.76	Yes
Flame Length, L_f, relative to Ceiling Height H_c	$\frac{H_f + L_f}{H_c}$, $\frac{L_f}{D} = 3.7\dot{Q}^{*\frac{2}{5}} - 1.02$	0.2~1.0	0.69	Yes
Ceiling Jet Horizontal Radial Distance, r_{cj}, relative to H_c	$\frac{r_{cj}}{H_c - H_f}$	1.2~1.7	0.89	No
Equivalence Ratio, φ, as an indicator of Ventilation Rate	$\varphi = \frac{\dot{Q}}{\Delta H_{O_2} \dot{m}_{O_2}}$, $\dot{m}_{O_2} = \begin{cases} 0.23 \times \frac{1}{2} A_o \sqrt{H_o} & (Natural) \\ 0.23 \rho_\infty \dot{V} & (Forced) \end{cases}$	0.04~0.6	0.15 (Forced)	Yes
Compartment Aspect Ratio	$\frac{W}{H_c}$ or $\frac{L}{H_c}$	0.6~5.7	W/H:1.39 L/H:1.57	Yes
Radial Distance Ratio	$\frac{r}{D}$, $D = \sqrt{\frac{4A}{\pi}}$	2.2~5.7	N/A	N/A

The ventilation system supplies the air to the corridor at the rate of 1.67 m^3/s. There are 3 doors leading into the corridor, all of which are closed during normal operation but each has a 2 cm gap between the floor and its base

The cables within each cable tray are modeled as 1.5 cm cylinders with uniform thermal properties given in Table 1.

2.2 Target Damage Criteria

This study is focused on a target consisting of cables in tray and considers damage of target due to thermal impact only. The cables are assumed to be damaged when the cable temperature reaches 320℃ or the exposure heat flux reaches 11 kW/m^2 [4].

FDS V&V effort concluded that FDS can reliably predict heat flux and surface temperature within about 25% [5]. Thus, the lower bound failure criteria used in this study are 240℃ and 8.25 kW/m^2.

2.3 Validation

Table 2 lists the model parameters for validation and the applicable range of the NRC/EPRI validation study in NUREG-1824. The parameter related to ceiling jet radial distance is not within the range of validation.

The ceiling jet distance ratio is a measure of the ceiling jet position at which data is sought relative to the compartment height. A low ceiling jet distance ratio indicated that the position is within the impingement zone and that the conditions would be dominated by the thermal plume. A high ceiling jet distance ratio suggests that the position is approaching the edge of the ceiling jet. The ceiling jet ratio is applicable primarily when sprinkler or heat detector actuation is calculated [2]. An additional detector would be added at a distance that would fall within the validation range (4.8~6.8m).

2.4 Benchmark Analysis Results

The main purpose of this benchmark analysis is to determine whether cables in corridor will fail or not and to check the operability of smoke detectors activation.

Fig. 4 shows the physical locations of fire source, targets and smoke detectors in the analysis regime.

Fig. 5 shows the cable temperatures in each tray. Cable 2, located just above the fire location, had experienced the most severe conditions. As shown in Fig. 5, the function of Cable 2 could fail due to the cable temperature exceeded the damage criteria (330℃). The temperature of Cable 1 and 3, located away from the fire location, are below the damage criteria. It means Cable 2 and 3 are like to be not damaged. The peak temperatures of each cable are shown in Table 3.

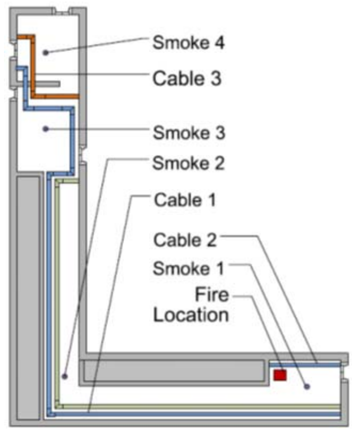

Fig. 4. Location of Fire Source, Targets and Smoke Detectors

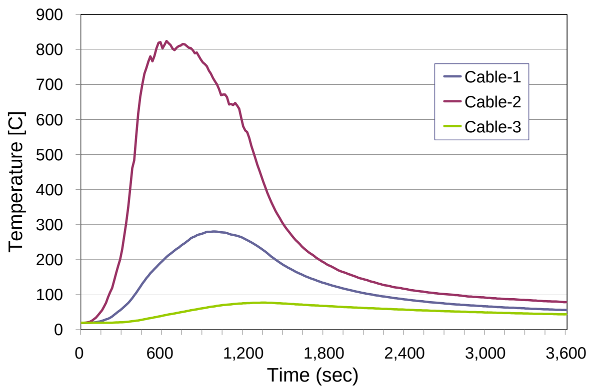

Fig. 5. Cable Temperature in the Tray

Table 3. Fire Analysis Results of the Corridor

Target	Max. Temp.	Damage Criteria	Damage Probability
Cable 1	280 ℃	330 ℃	4.6%
Cable 2	824 ℃	330 ℃	100%
Cable 3	77 ℃	330 ℃	0%

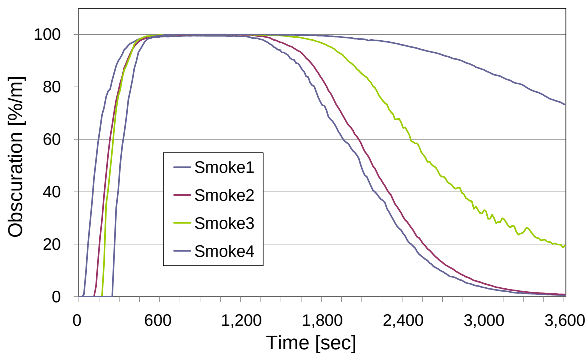

Fig. 6. Obscuration of Smoke Detectors

Chap. 4 of NUREG-1934 provides guidance on how to express the uncertainty of fire model predictions.

The uncertainty of fire model could be estimated using bias factor (δ), the relative standard deviation of fire model (σ_M) and the experiments (σ_E). Bias factor indicated the extent to which the model, on average, under- or over-predicts the measurements of a given quantity. σ_M and σ_E indicate the uncertainty or degree of "scatter" of the fire model and the experiments, respectively.

In this analysis, FDS5 predictes a peak temperature of Cable 1 as a 280 ℃. It means a temperature rise of Cable 1 due to a transient fire, M = 280 – 20 = 260 ℃.

As shown in Table 4-1 of NUREG-1934, the δ of FDS predictions for target temperature rise is 1.02 with a σ_M of 13%. The adjusted average temperature $\mu = M/\delta = 260/1.02 = 254.9$ and the standard deviation $\sigma = \mu^* \sigma_M = 254.9*0.13 = 33.1$.

The probability of exceeding damage criteria is expressed as:

$$P(T > T_c) = \frac{1}{2} erfc\left(\frac{T_c - \mu}{\sigma\sqrt{2}}\right)$$

The probability of exceeding damage criteria for Cable 1 is:

$$P(T > 330) = \frac{1}{2} erfc\left(\frac{330 - 20 - 254.9}{33.1\sqrt{2}}\right) \cong 4.6\%$$

With a same procedure, the probability of exceeding criteria for Cable 2, $P(T > 330)$, is almost of 1.0 and for Cable 3, $P(T > 330)$, is almost of 0.0.

Fig. 6 shows the obscuration of smoke detectors. In this analysis, the activation of smoke detector sets as 4.9 %/m of obscuration. All of smoke detectors activate at initial phase of fire.

3. Conclusions

The benchmark study to demonstrate the applicability of the fire modeling analysis guidelines described in NUREG-1934 is performed for a transient fire in the corridor of standard nuclear power plant using FDS5.

The purpose of this study is to predict the potential that a transient fire in a corridor will damage overhead cables and adjacent cables.

For the validation of model parameters, the ceiling jet radial distance is not within the range of validation. An additional detector would be added at a distance that would fall within the validation range (4.8~6.8m).

The detail analysis with FDS5 demonstrates that a transient fire is likely to fail the cables in the cable tray directly above the fire location but it is unlikely that the fire would damage the adjacent cables.

With this benchmark study, it is concluded that the fire modeling analysis guidelines as described in NUREG-1934 is useful to determine the potential of target damage in a given fire scenario.

This benchmark study demonstrates the applicability of the fire modeling analysis guidelines as described in NUREG-1934. The insight of possibility to determine the potential of target damage in a given fire scenario is acquired.

Acknowledgement

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