Transactions of the Korean Nuclear Society Spring Meeting
Jeju, Korea, May 17-18, 2018

Sensitivity Study on Fire Modeling for HVAC Equipment Room

Yong Hun Jung [a*], Dae Il Kang [a], and Kiyoon Han [b]
[a]*KAERI, 111 Daedeok-daero 989beon-gil, Yuseong-gu, Daejeon, 34057, Republic of Korea*
[b]*KINS, 62 Gwahak-ro5, Yuseong-gu, Daejon, 34142, Republic of Korea*
[*]*Corresponding author: juingyh@kaeri.re.kr*

1. Introduction

The purpose of an internal fire event probabilistic safety assessment (PSA) is to identify vulnerabilities and suggest potential improvements in design and operation of a nuclear power plant (NPP) to fire-induced accident scenarios through the quantification of fire-induced risk, primarily represented as core damage frequency (CDF) for the level-1 PSA and large early release frequency (LERF) for the level-2 PSA. The CDF is generally expressed as the sum of the products of fire ignition frequency (IF), severity factor (SF), non-suppression probability (NS), and conditional core damage probability (CCDP) of each fire scenario.

Among them, the SF is the probability that the postulated fire would include certain specific conditions that influence its rate of growth, level of energy emanated, and duration (time to self-extinguishment) to levels at which the target damage is generated. The SF is estimated by fire growth and propagation analysis, i.e., fire modeling analysis in a broader perspective [1]. In a fire PSA, a fire scenario is generally modeled as a progression of damage states of targeting equipments and cables over time that is initiated by a postulated fire involving an ignition source. Fire modeling analysis in a fire PSA is a tool used to determine the damage states of targets and the associated time.

The objective of this paper is to analyze how the different values for important input parameters affect results of fire modeling. Input parameters of interest in this study are those used to generate a heat release rate (HRR) profile. The HRR profile, which describes fire intensity as a function of time, is one of the most important elements characterizing the fire scenario itself and significantly affecting the results of fire modeling [2] such as properties of fire plume, ceiling jet and hot gas layer (HGL), and target response to incident heat flux.

2. Methods and Results

2.1 Design features of HVAC Equipment Room

Hanul Unit 3 has two HVAC equipment rooms, A and B, for redundancy. Between two, room B was selected as a target for this study, and its floor plan is shown in Fig. 1. Main design features of HVAC equipment room B are as follows:

- ■ Size of compartment:
  A = 400 m² (except AHU area), H = 7.2 m
- ■ Floor, ceiling and walls: 0.6 m thick concrete
- ■ Mechanical Ventilation:
  two for injection with a total of 0.599 m³/s,
  two for extraction with a total of 0.599 m³/s
- ■ Fixed ignition sources:
  - ● 480V MCC Cabinet Set #1 (four cabinets)
  - ● 480V MCC Cabinet Set #2 (six cabinets)
  - ● 480V MCC Cabinet Set #3 (five cabinets)
  - ● Spare Battery (one)
  - ● HVAC Control Panel (one)
  - ● Vertical & horizontal cable trays
    (EPR insulated, CSM(CSP) jacketed cables)

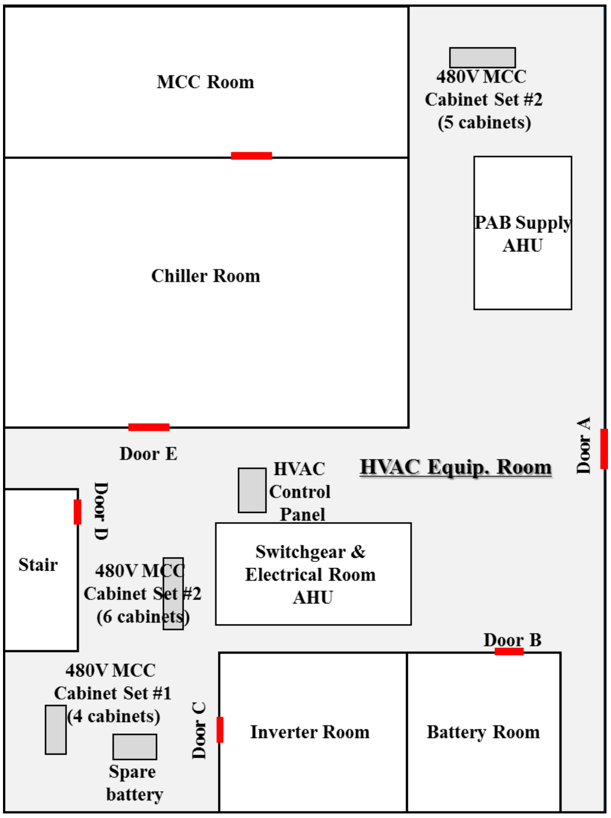

Fig. 1. Floor Plan of HVAC Equipment Room B.

2.2 Fire scenario and assumptions

In this study, CFAST (Consolidated model of Fire And Smoke Transport) [3] was used as a tool for the fire modeling analysis. The CFAST is a representative “multi-room two-zone fire model” that is capable of predicting the fire environment in a multi-compartment structure and subdivides a compartment into two control volumes: a relatively cold lower layer and a relatively hot upper layer. There exist no spatial variations within a single control volume, which means that conditions within each control volume are considered as uniform at any given time.

Fire scenarios of HVAC equipment room B are expected to follow the steps shown below:

(1) an initial fire in one of five types of electrical enclosures, i.e., 480V MCC cabinet set #1, 2, 3, spare battery and HVAC control panel;
(2) fire propagation to adjacent cabinets;
(3) secondary fires in other cabinets and/or vertical & horizontal cable trays above the cabinets.

Fire scenario initiated by fire in 480V MCC cabinet set #1 was selected as the severest fire scenario to be analyzed although it consists of only four cabinets. The following are bases for this selection.

(1) First, heat released from cable fire is generally greater than that from cabinet fire.
(2) Second, 480V MCC cabinets, unlike spare battery and HVAC control panel, are connected to vertical cable trays, and among three, the 480V MCC cabinet set #1 has the largest number of vertical & horizontal cables above it.

We conservatively assumed that vertical cable trays ignite at the same time as the 480V MCC cabinet set #1 ignites [2]. We also combined all fires in four cabinets of the 480V MCC cabinet set #1 and two vertical cable trays into a single initial fire that has a single data set for the HRR profile. Result of preliminary analysis show that flame of the initial fire (from cabinets and vertical cable) reaches to the lowest horizontal cable tray in 240 sec (based on the peak HRR value of 702 kW) or 280 sec (based on the peak HRR value of 130 kW) after the initial fire occurs. Therefore, we made the horizontal cable trays ignite in 240 sec or 280 sec after the initial fire occurs.

Major conditions and assumptions used in this study are as follows:

- HRR profile of 480V MCC cabinet fire follows the model shown below [1]:
  (1) t-squared growth from zero to peak for 12 min.
  (2) steady burning at peak for 8 min.
  (3) linear decay from peak to zero for 19 min.
- Peak HRR value of a single 480V MCC cabinet was set to 130 kW [4] – 702 kW [1].
- Time to fire propagation to adjacent cabinet was set to 10 min. – 15 min [1].
- Peak HRR value and HRR profile of horizontal & vertical cable fires were calculated using FLASH-CAT (Flame Spread over Horizontal Cable Trays) model [5, 6].
- Any cables in the HVAC equipment room B were set to targets and their electrical failure criteria were set to 11 kW/m² for heat flux and 330 °C for temperature [1] assuming that they are all thermoset cables.

Other input parameters including thermal and fire properties of concrete and EPR/CSM cable were specified in accordance with the references such as SFPE Handbook 4th ed. [7], NUREG-1805 [8], NUREG/CR-7010 Vol.1 [5], and Hanul Unit 3 NPP Tray Information. The chemical formula of XLPE/Neoprene cable, i.e., $C_3H_{4.5}Cl_{0.5}$, was used for that of EPR/CSM cable because the composition of EPR/CSM cable for Hanul Unit 3 is unknown. For calculating mass fraction of combustible of EPR/CSM cable, we conservatively used data of CHRISTIFIRE cable 212 that has the minimum mass fraction of copper among all the EPR/CSPE type CHRISTIFIRE cables [5].

The peak HRR value is an important variable as much as, or even more important variable than duration time of each stage (growth, steady burning, decay) for generating the HRR profile considering the fact that, if the enough information on the time is unavailable, a constant HRR profile at the peak value should be used [1]. Recommended HRR values for electrical fires vary widely by the reference. NUREG-2178 [4] Table 4-1 recommends 130 kW as the 98th percentile HRR value of classification group II “MCCs and Battery Chargers” with Fuel Type “TP” to which the single 480V MCC cabinet corresponds. According to NUREG/CR-6850 [1] Table G-1, the single 480V MCC cabinet corresponds to the ignition source category II, “Vertical cabinets with qualified cable, fire in more than one cable bundle”. The 98th percentile HRR value of category II recommend by this table is 702 kW. In this study, we analyzed sensitivity of the peak HRR value of the single 480V MCC cabinet by varying it between 130 kW to 702 kW. As described, change in the peak HRR value from 130 kW to 702 kW causes change in the time in which the flame of the initial fire reaches to the lowest horizontal cable tray, and thus, the horizontal cable trays ignite from 280 sec to 240 sec.

Sometime after ignition of a single cabinet, fire may propagate to adjacent cabinets. NUREG/CR-6850 [1] provides recommendations for fire propagation to adjacent cabinets as follows:

- if fire propagation cannot be ruled out, or cabinets are separated by a single metal wall, assume that no significant heat release occurs from the adjacent cabinet for –
  (1) 10 min. if cables in the adjacent cabinet are in direct contact with the wall, and
  (2) 15 min. if cables in the adjacent cabinet are not in direct contact with the wall.

It is obvious that these recommendations are not applicable to all types of cabinet fire, and in reality, there may exist other factors and conditions to consider. Therefore, engineering judgements based on visual examinations are essential for determining “time to fire propagation to adjacent cabinets”. Considering the difficulties and uncertainties during the process, it is safe to set the propagation time to 10 min. (note that the minimum propagation time was observed as 11 min in the cabinet fire experiments conducted at VTT.) In this study, we analyzed sensitivity of this “time to fire propagation to adjacent cabinets” by varying it between 10 min to 15 min. This parameter is used to generate the HRR profile, which is, as already mentioned, one of the most important elements in fire modeling. Unlike the peak HRR value, change in the propagation time from 15 min. to 10 min. does not affect the time in which the flame of the initial fire reaches to the lowest horizontal cable tray, i.e., the horizontal cable trays ignite.

HVAC equipment room is not a rectangular room. It is rather a corridor which connects other smaller rooms such as inverter room, battery room, MCC room, and chiller room, and forms a huge rectangular space together with the others. Therefore, the HVAC equipment room B was virtually divided into three rectangular compartments for fire modeling analysis. The 480V MCC cabinet set #1 is located in compartment #1. Therefore, fire occurs in compartment #1 and propagates through compartment #2 to compartment #3. The area occupied by two AHUs was eliminated when modeling the compartments. Fig. 2 shows CFAST/Smokeview rendering for the severest fire scenario of HVAC equipment room B.

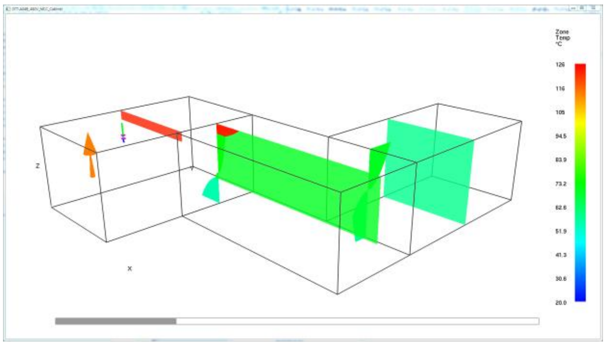

Fig. 2. CFAST/Smokeview Rendering for Fire Scenario of HVAC Equipment Room B.

2.3 Results of fire modeling

Fig. 3 and 4 show the HRR profiles of the initial fire in 480V MCC cabinet set #1 and vertical cable trays when the fire propagates to adjacent cabinets every 15 min or 10 min, based on the peak HRR value of 130 kW (Fig. 3) and 702 kW (Fig. 4). As shown in the both Fig 3 and 4, with the fixed peak HRR value, the area under the curve, i.e., total amount of heat remains unchanged regardless of the propagation time but the shape of curve becomes steeper as the propagation time decreases. On the other hand, as expected, changes in the peak HRR value from 130 kW to 702 kW lead to the dramatic expansion of the area under the curve as well as the height of the curve.

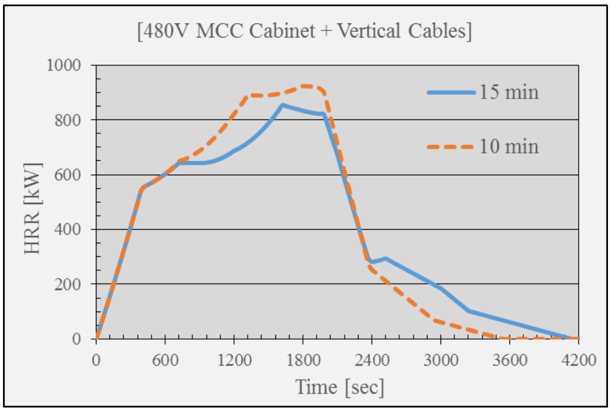

Fig. 3. HRR Profile of Initial Fire in 480V MCC Cabinet Set #1 and Vertical Cable Trays Depending on Time to Fire Propagation to Adjacent Cabinets (Peak HRR = 130 kW)

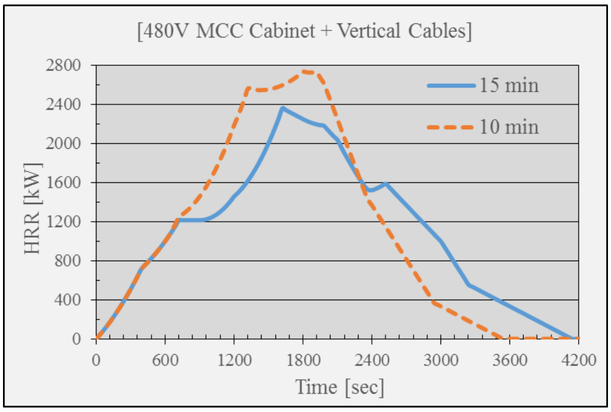

Fig. 4. HRR Profile of Initial Fire in 480V MCC Cabinet Set #1 and Vertical Cable Trays Depending on Time to Fire Propagation to Adjacent Cabinets (Peak HRR = 702 kW)

Fig. 5 and 6 show the HGL temperature profiles in modeling compartment #1 of HVAC equipment room B over time when the fire propagates to adjacent cabinets every 15 min or 10 min, based on the peak HRR value of 130 kW (Fig. 5) and 702 kW (Fig. 6). Table I summarized changes in the peak HGL temperatures of each modeling compartment. Fig. 5, 6 and Table I show that the peak HGL temperature maintains well below the failure temperature criteria of thermoset cable, 330 °C [1], irrespective of changes in the propagation time and the peak HRR value.

The results indicate that, as the propagation time changes from 15 min. to 10 min., the peak HGL temperature in modeling compartment #1 increases from 126.5 °C to 133.4 °C by 5% (based on the peak HRR value of 130 kW) and from 172.9 °C to 193.6 °C by 12% (702 kW). The also indicate that, as the peak HRR value changes from 130 kW to 702 kW, the peak HGL temperature in modeling compartment #1 increases as much as 37% (based on the propagation time of 15 min.) or 45% (10 min.).

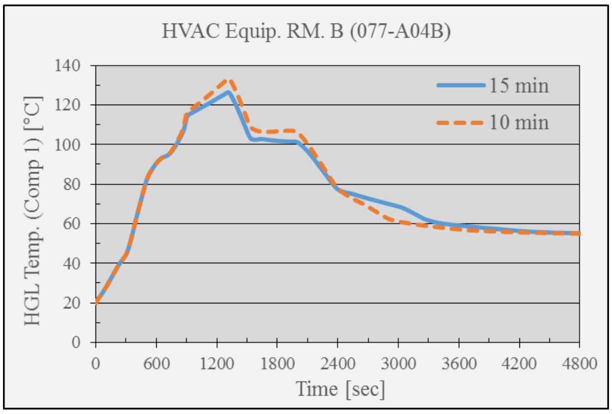

Fig. 5. HGL Temperature Profile in modeling compartment #1 of HVAC Equipment Room B Depending on Time to Fire Propagation to Adjacent Cabinets (Peak HRR = 130 kW)

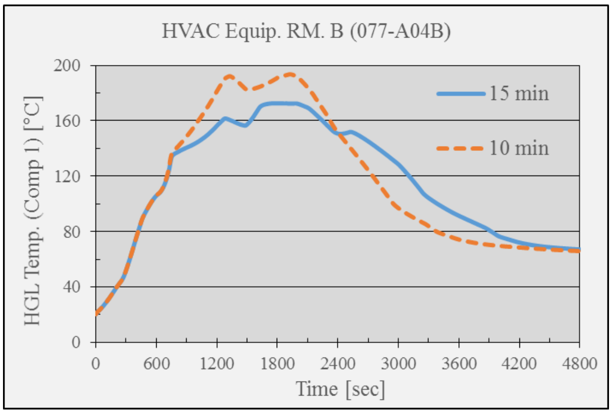

Fig. 6. HGL Temperature Profile in modeling compartment #1 of HVAC Equipment Room B Depending on Time to Fire Propagation to Adjacent Cabinets (Peak HRR = 702 kW)

Table I: Peak HGL Temperature of HVAC Equipment Room B Depending on Time to Fire Propagation to Adjacent Cabinets

Time to Fire Propagation to Adjacent Cabinets [min.] / Peak HRR [kW]	Peak HGL Temp. [°C] of Comp. 1 / 2 / 3
15 / 130	126.5 / 73.4 / 62.0
10 / 130	133.4 / 77.6 / 65.4
15 / 702	172.9 / 115.1 / 95.7
10 / 702	193.6 / 130.9 / 108.1

3. Concluding Remarks

In this study, we selected and conducted fire modeling for the severest fire scenario of HVAC equipment room B in which a fire occurs in 480V MCC cabinet #1.1 and propagates to adjacent 480V MCC cabinets (#1.2, 1.3, 1.4), to vertical cable trays, and finally to horizontal cable trays. Sensitivity analysis was conducted by changing the peak HRR value of a single 480V MCC cabinet between 130 kW to 702 kW and "time to fire propagation to adjacent cabinets" between 10 min to 15 min.

Through the sensitivity analysis, we found that the severest fire in HVAC equipment room B does not damage any other equipments and cables in it except those burnt as ignition sources, regardless of changes in the propagation time and the peak HRR value. Note that a significant amount of experimental data for cable failure temperature have been accumulated through the experimental programs conducted for U.S.NRC by Sadia National Laboratories to confirm the cable failure temperature criteria provided by NUREG/CR-6850. These experimental data show that, among a total of 28 thermoset cables, nothing failed before reaching at least 369.6 °C [9], which is much larger than the peak HGL temperature results of this study ranging from 126.5 °C to 193.6 °C. Therefore, we deemed that the fire modeling of this study does not require the uncertainty analysis related to the peak HGL temperature considering the huge gap between the experimental data and the results of this study in spite of many conservative conditions and conditions during the fire modeling.

We confirmed that the wide variation of the peak HRR value depending on the reference substantially affects the HGL temperature of HVAC Equipment Room B for this fire scenario. We also confirmed that effect of the propagation time is relatively smaller than that of the peak HRR value but it becomes stronger as the peak HRR value increases. Note that, in this specific fire scenario, the 480V MCC cabinet set #1 has a large number of vertical & horizontal cables above it, and heat released from the fire in 480V MCC cabinet set #1 is far smaller than that from vertical & horizontal cables. It is expected that the propagation time would more significantly affect the results in the fire scenarios that involve fires in cabinet sets composed of many cabinets containing a lot of cables within them, but do not involve fires in vertical & horizontal cable trays outside the cabinet. Further sensitivity studies are required to examine the effect of modeling compartment for HVAC equipment room.

Acknowledgements

This work was supported by Nuclear Research & Development Program of the National Research Foundation of Korea grant, funded by the Korean government, Ministry of Science and ICT (Grant number 2017M2A8A4016659).

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