FIRE MODELING OF SWITCHGEAR ROOM FOR MULTI-COMPARTMENT FIRE SCENARIO IN FIRE PSA

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The preliminary construction of the Hanul Unit 3 fire PSA model was performed with the fire modeling of only three fire areas. Quantification results of the Hanul Unit 3 fire PSA model showed that the multi-compartment fire scenario of the switchgear (SWGR) room was one of significant contributors to the core damage frequency (CDF). In this study, fire modeling of a multi-compartment scenario of SWGR room A was performed by Consolidated Fire Growth and Smoke Transport (CFAST) to identify the possibility of fire propagation from SWGR room A to B. Hanul Unit 3 has two SWGR rooms A and B for redundancy. The severe fire scenarios assumed were HEAF (high energy arching fault) induced cabinet fires: (1) the simultaneous fires of non-class 1E 4.16kV and class 1E 4.16kV cabinets, and (2) a 480V load center cabinet fire. Since the non-segregated phase bus (NSPB) is connected to the non-class 1E 4.16kV and class 1E 4.16kV cabinets, it was assumed that simultaneous fires might occur. The vertical cables are connected to 480V MCC and 480V AC load center cabinets. Thus, they can be ignited when any 480V cabinet fire occurs. The horizontal cables located near the vertical cables will be also ignited when the flame of the vertical cable fire reaches their heights. Fire simulation results showed that the peak hot gas layer (HGL) temperature of SWGR room A is 73.1 ℃ and 120 ℃, and that of SWGR room B is between 21.3 ℃ and 35 ℃. From the fire simulation results, we can determine that a fire of SWGR room A or B does not affect the integrities of the cables and components in adjacent fire areas. Thus, multi-compartment fire scenarios of SWGR rooms A and B were not considered for the Hanul Unit 3 fire PSA model.

I. INTRODUCTION

The Core Damage Frequency (CDF) of a level 1 fire probabilistic safety assessment (PSA) is expressed as a multiplication of fire frequency, severity factor (SF), non-suppression probability (NS) and conditional core damage probability (CCDP) (Ref. 1). The SF is the probability that a postulated fire will 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 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 calculated with consideration of fire induced effects on the equipment and human performance. NUREG/CR-6850 requires that the SF be estimated by fire modeling. If fire modeling is not performed, the SF should be conservatively estimated as 1. In addition, the possibility of damages of the components and cables located at adjacent compartments should be considered. Detailed fire modeling of multi-compartment fires refers to an evaluation of fire-generated conditions in one compartment that spread to adjacent compartments (Ref. 1). In general, the severity factor for a multi-compartment fire scenario is smaller than that of a single compartment scenario.

The preliminary construction of the Hanul Unit 3 fire PSA model was performed with the fire modeling of only three fire areas: the main control room, electrical equipment room, and cable spreading room. As shown in Fig.1, the preliminary quantification results of the Hanul Unit 3 fire PSA model showed that the multi-compartment fire scenarios of the switchgear (SWGR) room, fire propagation scenarios from SWGR room A(100-A01A) or B(100-A01B) to B or A, was one of significant contributors to the core damage frequency (CDF). In this study, fire modeling of a multi-compartment scenario of SWGR room A was performed by Consolidated Fire Growth and Smoke Transport (CFAST) 6.3 (Ref. 2) to identify the possibility of a fire propagation. First, we identified the ignition sources and design features of SWGR room A. Second, we performed the preliminary fire modeling for the selected ignition sources to identify the possibility of damage of the secondary combustibles. Third, we defined severe fire scenarios assumed to have the capability to affect the equipment and cables in SWGR room B. Fourth, we performed fire modeling for the defined fire scenarios using CFAST 6.3.

F-V	Acc.	BE#1	BE#2	BE#3	BE#4
0.117074	0.117074	%F-100-A01AH_100-A01B_SEA	N%100-A01AH_100-A01B_SEA	#GIE-TLOCCW-3	
0.100407	0.217481	%F-100-A01BH_100-A01A_SEA	N%100-A01BH_100-A01A_SEA	#GIE-TLOCCW-3	
0.089269	0.306750	%F-PM-MCB-PROP-NON	MCOPHPM-PROP-ABN-NON	S%MCB-PROP-NON	#GIE-F-PM-MCB-F
0.074082	0.380832	%F-100-A01A_100-A01B_SEA	N%100-A01A_100-A01B_SEA	#GIE-TLOCCW-3	
0.068514	0.449346	%F-100-A01B_100-A01A_SEA	N%100-A01B_100-A01A_SEA	#GIE-TLOCCW-3	
0.039010	0.488356	%F-PABA-125_144-PACR_SEA	N%PABA-125_144-PACR_SEA	#GIE-TLOCCW-3	
0.031389	0.519745	%F-100-A01AH_100-A01B_DOO	N%100-A01AH_100-A01B_DOO	#GIE-TLOCCW-3	
0.026921	0.546666	%F-100-A01BH_100-A01A_DOO	N%100-A01BH_100-A01A_DOO	#GIE-TLOCCW-3	
0.024586	0.571251	%F-077-A14A_PABA-077_SEA	N%077-A14A_PABA-077_SEA	#GIE-SLOCA-8	
0.021756	0.593007	%F-100-A11A_PABA-125_SEA	N%100-A11A_PABA-125_SEA	#GIE-LSSB-OUT-AB-FIRE-5	
0.019863	0.612870	%F-100-A01A_100-A01B_DOO	N%100-A01A_100-A01B_DOO	#GIE-TLOCCW-3	
0.018370	0.631240	%F-100-A01B_100-A01A_DOO	N%100-A01B_100-A01A_DOO	#GIE-TLOCCW-3	
0.017731	0.648970	%F-PABA-144_144-PACR_SEA	N%PABA-144_144-PACR_SEA	#GIE-TLOCCW-3	
0.017146	0.666117	%F-PM02-TRN-NON	MCOPHPM02-TRN	S%PM02-TRN-NON	#GIE-F-PM02-TRN
0.012862	0.678979	%F-PABB-077_PABA-077_SEA	N%PABB-077_PABA-077_SEA	VEOPHROOM-FIRE	#GIE-TLOCCW-3
0.012634	0.691613	%F-077-A14A_PABA-077_DOO	N%077-A14A_PABA-077_DOO	#GIE-SLOCA-8	
0.012042	0.703655	%F-PABA-165LAB	SDOPHEARLY	#GIE-LSSB-OUT-AB-FIRE-5	
0.011684	0.715338	%F-PABB-165LAB	SDOPHEARLY	#GIE-LSSB-OUT-AB-FIRE-5	
0.011610	0.726948	%F-PABA-077_PABB-077_SEA	N%PABA-077_PABB-077_SEA	VEOPHROOM-FIRE	#GIE-TLOCCW-3
0.010990	0.737938	%F-PM01-TRN-NON	MCOPHPM01-TRN	S%PM01-TRN-NON	#GIE-F-PM01-TRN

Fig. 1. High level cutsets for representing CDF for Hanul Unit 3 fire event before fire modeling of SWGR(100-A01A)

II. DESIGN FEATURES OF SWGR ROOM

Hanul Unit 3 has SWGR rooms A and B for redundancy. As shown in Fig. 2, SWGR room A has 13.6KV, 4.16KV, 480V load center (LC), and 480V motor control center (MCC) electrical cabinets to supply power to safety and non-safety related components. Additional fixed ignition sources are non-segregated phase buses (NSPBs), 480V LC electrical transformers, SWGR HVAC fans, junction boxes, and cable trays. The NSPBs are installed for supplying power from start-up transformers (SATs) and unit auxiliary transformers (UATs) to high voltage SWGRs (4.16KV and 13.8 KV). Non-class 1E 4.16KV SWGR power is supplied by class 1E 4.16KV SWGR through the NSPB. As all cables in SWGR room A are thermoset cables, there is no possibility of a self-ignited cable fire. In addition to a fixed ignition source fire, the HEAF (high energy arching fault) event can occur in the NSPBs, 480V LC, 4.16KV SWGR, and 13.6KV SWGR. If a Class 1E 4.16 kV cabinet is damaged due to a fire, loss of 4.16 kV AC event will occur. The main design features of SWGR room A are as follows:

- ■ Geometry
- \- Size of compartment: 26.6 m x 13.6 m x 7.5 m
- \- Material of floor, ceiling and wall: concrete
- \- Thickness of concrete: 0.6 m
- \- Material of cabinet and cable tray: steel
- ■ Cables: EPR insulated, CSM(CSP) jacketed cables
- ■ Mechanical ventilation: five supply and three return vents
- ■ Airflow rate: 0.2218 m^3/s (each supply vent) and 0.2596 m^3/s (each return vent)

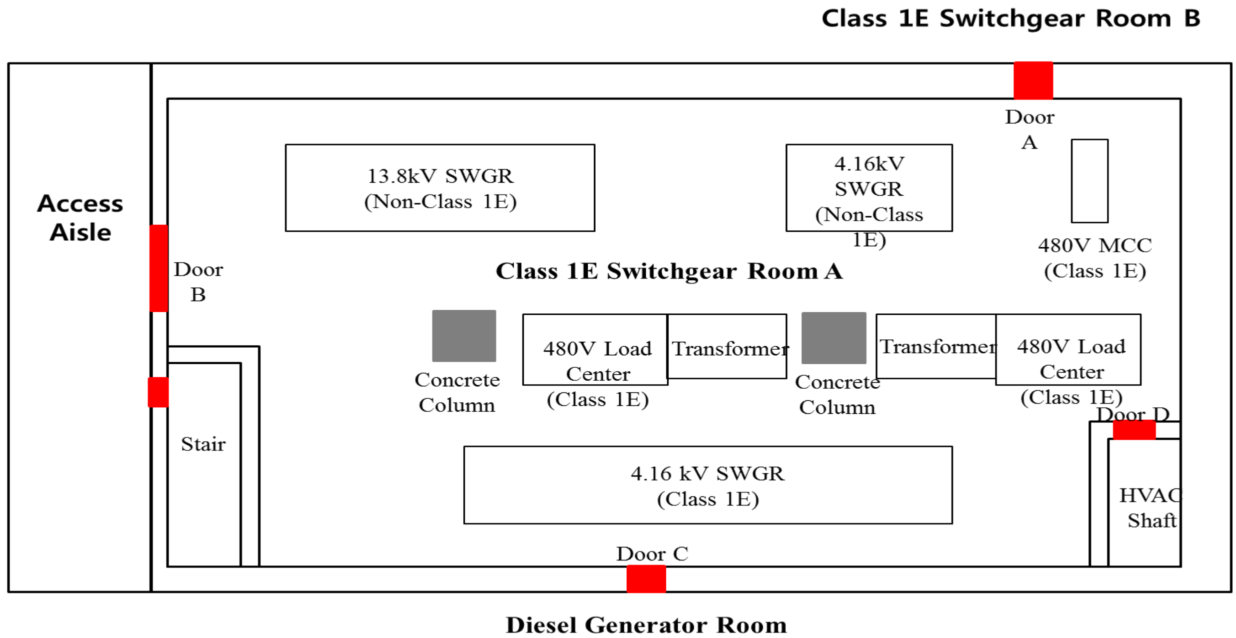


Fig. 2. Overview of SWGR room A

III. FIRE SIMULATIONS

III.A. Fire Scenarios and Assumptions

The expected fire scenarios of SWGR room A are the initial cabinet fires, and the secondary fires of other cabinets, and of cable trays above the cabinets. In the case of an HEAF event, the expected fire scenarios are cabinet fires due to an HEAF event, and the secondary fires of the other cabinets and cable trays above the cabinets. As a result of the preliminary fire modeling, it was identified that any cabinet fire including an HEAF event does not induce secondary fires of the other cabinets or horizontal cable trays above the cabinets. However, vertical cables connected to the cabinets were identified as the secondary combustibles for the cabinet fires. Based on the preliminary fire modeling and walk-down results of SWGR room A for Hanul Unit 3, we assumed that the severe fire scenarios were HEAF induced cabinet fires: (1) simultaneous fires of non-class 1E 4.16kV SWGR and class 1E 4.16kV cabinets, and (2) 480V LC cabinet fire.

Since the NSPB, which can generate an HEAF event, is connected to the non-class 1E 4.16kV SWGR and class 1E 4.16kV cabinets, it was assumed that the simultaneous fires of these cabinets might occur. 480V MCC and 480V AC LC cabinets have vertical cables above them. These vertical cables might be ignited when any 480V cabinet fire occurs. Because the vertical cables are connected to the horizontal cables, the horizontal cables will also be ignited when the flame reaches the height of the cables. In the case of an HEAF event, the vertical and horizontal distances for its ZOI (zone of influence) are 1.5m and 0.9m(Ref.1), respectively. Thus, a HEAF event in any section of cabinets may lead to simultaneous fires of their three sections. A 480V LC cabinet fire due to a HEAF event was selected as a postulated fire scenario. The fire simulations for each fire scenario were performed using CFAST. TABLE I shows the input data for fire simulations. The assumptions used for fire simulations are as follows.

■ Cabinet fire
- Heat release rate (HRR) grows following a “t-squared” in 12 min. and remains steady for 8 additional min. After 20 min., it decays linearly to zero in 19 min. (Ref. 1,6).
- Peak HRR of SWGR and LC is 170 kW (Ref. 3).
- Cabinets of Fig.1 consist of several sections.
- Any section fire of a cabinet is propagated to both side sections at 15 min. after the fire ignition (Ref. 1).
- An HEAF event in any section of cabinet results in the simultaneous fire of its three sections.

■ Cable fire
- Fire ignition time of vertical cables is the same as that of a cabinet.
- Horizontal cables start burning when the flame reaches the cable height.
- There are no data for EPR/CSM (CSP) cables for fire modeling. Therefore, XLPE/neoprene cable data are used for it.

- HRR of cable is calculated using FLASH-CAT (Flame Spread over Horizontal Cable Trays) Model (Ref. 5,7).

■ Door connected to SWGR room B is opened.
■ Assumed target is any cables in SWGR room B.
■ The damage criteria of thermoset cable are 11 kW/m^2 for heat flux and 330 °C for temperature (Ref. 1).

TABLE I. Input Data for Fire Simulations

Parameter	Value	Source
Maximum Heat Release Rate of Cabinets	SWGR & LC: 170 KW	NUREG-2178Table 4-1(Ref. 3)
Effective Fuel Formula	$C_3H_{4.5}Cl_{0.5}$ [1)]	SFPE Handbook 4th ed. Table 3-4.16 (Ref. 4)
Heat of Combustion	17,400 kJ/kg	SFPE Handbook 4th ed. Table 3-4.16 (Ref. 4)
CO2 yield	0.99 kg/kg	SFPE Handbook 4th ed. Table 3-4.16 (Ref. 4)
Soot yield	0.082 kg/kg	SFPE Handbook 4th ed. Table 3-4.16(Ref. 4)
CO yield	0.09 kg/kg	SFPE Handbook 4th ed. Table 3-4.16 (Ref. 4)
Radiative Fraction	0.62	SFPE Handbook 4th ed. Table 3-4.16 (Ref. 4)
Mass fraction of combustible	0.77 [2)]	NUREG/CR-7010 Vol.1 Table 3-2 (Ref. 5)
Residue yield	0.25	NUREG/CR-7010 Vol.1 (Ref. 5)
Total mass per unit length	Horizontal: 0.594 kg/m Vertical: 0.694 kg/m	Hanul 3 SWGR room A Tray Information (SWGR room A 480V MCC)
Tray width	0.6 m	Hanul 3 Tray Information

[1)] Since the composition of EPR/CSM cable for Hanul Unit 3 is not known, the chemical formula of XLPE/Neoprene cable were used for that of EPR/CSM cable.
[2)] To be conservative, the lowest value was selected for the copper mass fraction of EPR/CSM cable.

III.B. Simulation Results

Figs. 2 and 3 illustrate the scenarios as modeled by CFAST. The red cone means the flame and the small grey circle in the other room is the target. Because the door that connects SWGR rooms A and B is located downward from the room, it can underestimate the hot gas layer (HGL) temperature of SWGR room B. For this reason, a sensitivity analysis that changes the door position to upward of the room was conducted. A summary of the simulation results is shown in Table II.

- #1 : simultaneous cabinets fire due to HEAF event of NSPB (base case)
- #2 : simultaneous cabinets fire due to HEAF (door position changed)
- #3 : 480V LC cabinet fire due to a HEAF event (base case)
- #4 : 480V LC cabinet fire due to a HEAF event (door position changed)

TABLE II. Fire Simulation Results

Fire scenario #	# 1	# 2	# 3	# 4
SWGR room A peak HGL temperature [℃]	77	73.1	120	114
SWGR room B peak HGL temperature [℃]	21.3	28.3	22.1	35.4

The peak HGL temperature of SWGR room A is between 73.1 ℃ and 120 ℃ and that of SWGR room B is between 21℃ and 35.4 ℃. In the case of changing the position of the door, the HGL temperatures of SWGR room B is predicted to be higher than those for the base case. With these simulation results, we can determine that any fire in SWGR room A does not affect the integrity of the components and cables in SWGR room B.

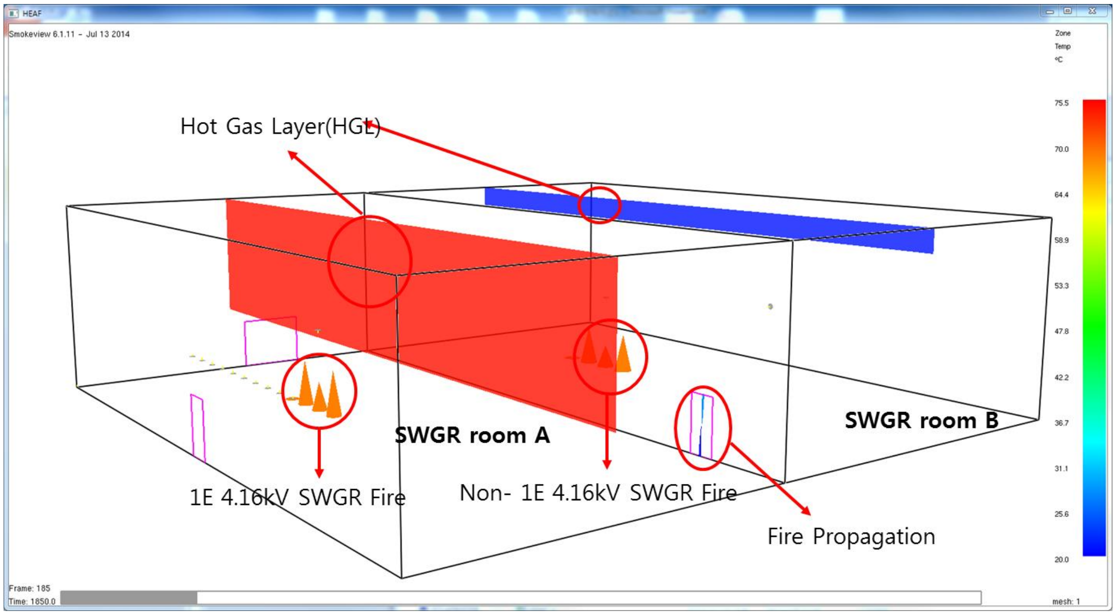
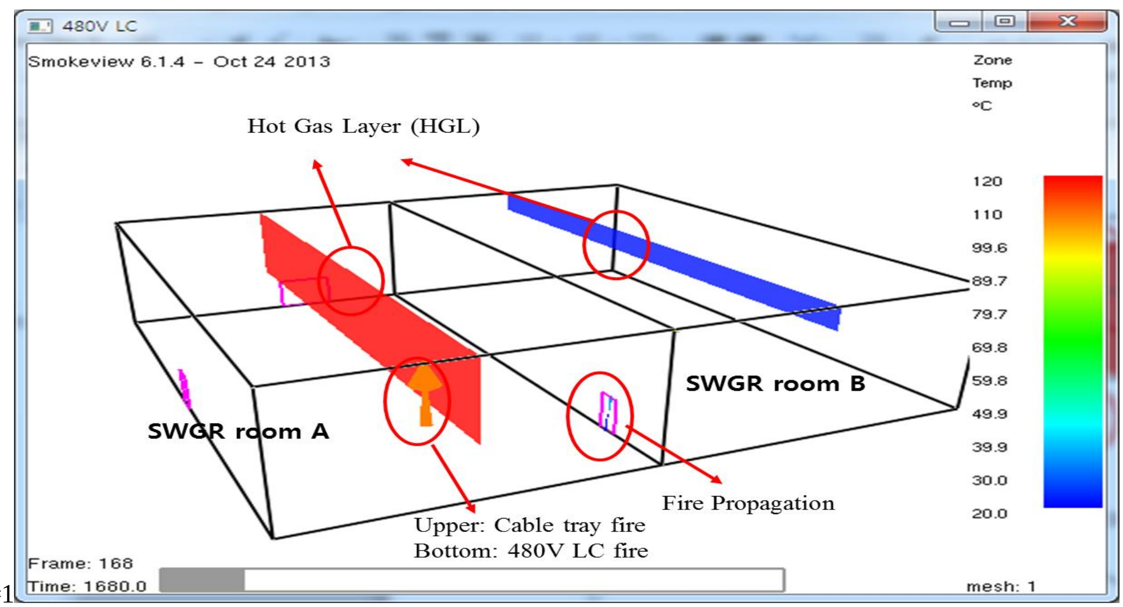


Fig. 3. CFAST/Smokeview rendering of fire scenario #1



#1

Fig.4. CFAST/Smokeview rendering of fire scenario #3

In addition to a sensitivity analysis on the position of the door, we performed additional sensitivity analyses on the fire propagation time and HRR. In this study, we used 15 minutes as fire propagation time between cabinet sections. In the sensitivity study, 10 minutes is assumed to be propagation time. As mentioned in NUREG-1934 (Ref. 6), the HRR is the most important input parameter affecting the predictions of the hot gas layer and target temperatures. The HRRs of the cabinets used in this study are much smaller than those presented in NUREG/CR-6850(Ref. 1). With the HRR data of NUREG/CR-6850, we assumed that the cabinets of SWGR room A for Hanlul unit 3 were vertical cabinets with more than one qualified cable bundle and the 98 percentile of the HRR was 702kW. Fire simulations were performed for the scenario # 1 case, simultaneous cabinet fires due to a HEAF event of NSPB. Fig. 5 shows the hot gas layer (left) and target (right) temperatures of SWGR room A. The target was assumed to be a horizontal cable at 5 m above each 4.16KV cabinet. As presented in Fig. 5, there are little differences in the predicted temperatures between the base case and 10 minute propagation time. However, for the hot gas layer and target temperatures, the change in HRR brought about big differences between the base case and the sensitive analysis case. Since the target temperature is predicted to be above the thermoset damage criterion, the fire simulation is to be conducted again with the HRR coming from the horizontal cable tray fires. In this study, no more fire simulations were performed.

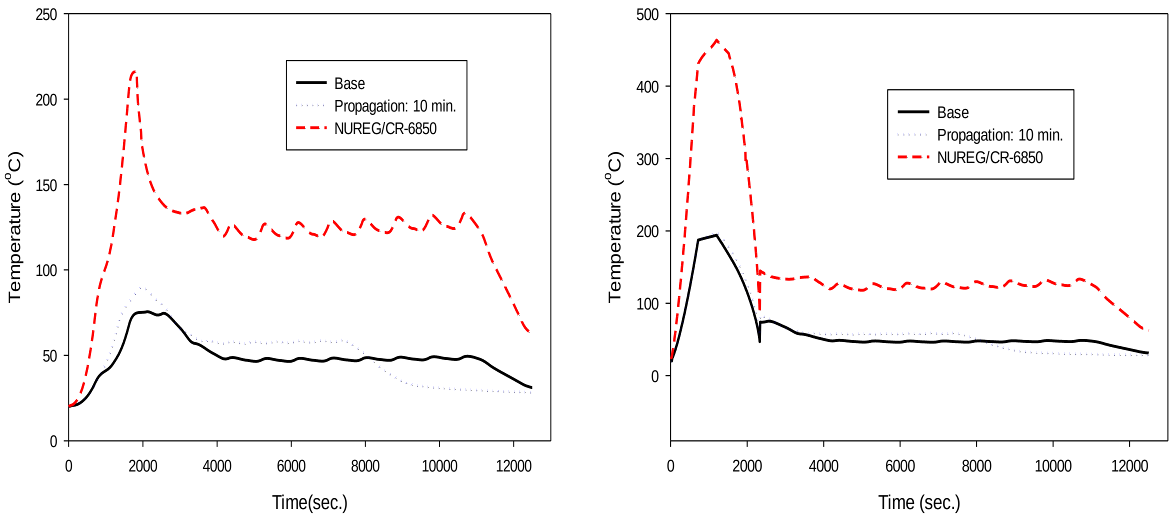


Fig. 5 Sensitivity analysis results of hot gas layer (left) and horozontal tray (right) temperatures

IV. CONCLUDING REMARKS

In this study, multi-compartment fire modeling for a fire propagation scenario from SWGR room A to SWGR room B was performed using CFAST. From the fire simulation results, it was identified that a fire of SWGR room A did not affect the integrities of the cables and equipment in the adjacent fire areas. This means that multi-compartment fire scenarios related to SWGR rooms can be neglected. Fig. 6 shows high level cutsets for representing CDF for a Hanul Unit 3 fire event after fire modeling of SWGR room A. There are no cutsets for representing multi-compartment fire scenarios for SWGR rooms. A similar approach for fire modeling of SWGR room A was applied to other significant multi-compartment fire scenarios for Hanul Unit 3.

F-V	Acc.	BE#1	BE#2	BE#3	BE#4	BE#5	BE#6	BE#7	BE#8
0.067658	0.067658	%F-TBB073-T07	EGDGK3T-1A1B1E	NR-AC15HR	/PSV	/RCPSEAL_2S	#GIE-SBOR-07		
0.032249	0.099907	%F-SA125-P034	EGDGR01A	EGDGR01B	NR-AC15HR	/PSV	/RCPSEAL_2S	#GIE-SBOR-07	
0.022127	0.122034	%F-PA-165LAB	SDOPHEARLY	#GIE-LSSB-AB-FII					
0.021794	0.143828	%F-TBB073-T07	EGDGW3T-1A1B1	NR-AC7HR	/PSV	/RCPSEAL_2S	#GIE-SBOS-07		
0.021468	0.165296	%F-PB-165LAB	SDOPHEARLY	#GIE-LSSB-AB-FII					
0.020458	0.185754	%F-TBB135-T01	EGDGK3T-1A1B1E	NR-AC15HR	/PSV	/RCPSEAL_2S	#GIE-SBOR-07		
0.015425	0.201179	%F-SA125-P034	EGDGR01A	EGDGS01B	NR-AC15HR	/PSV	/RCPSEAL_2S	#GIE-SBOR-07	
0.015425	0.216605	%F-SA125-P034	EGDGR01B	EGDGS01A	NR-AC15HR	/PSV	/RCPSEAL_2S	#GIE-SBOR-07	
0.015418	0.232023	%F-100-P01	HCCQMCCPA	VEOPHRMCLNG-F:	#GIE-GTRN-6				
0.012119	0.244142	%F-PM07-NON	S%PM07-NON	SDOPHEARLY-MCI	#GIE-LSSB-AB-FII				
0.010176	0.254318	%F-100-P01H	EGDGR01A	EGOPHDG01E	NR-AC15HR	/PSV	/RCPSEAL_2S	#GIE-SBOR-07	
0.009435	0.263753	%F-PM10-NON	NR-AC7HR	/PSV	/RCPSEAL_2S	S%PM10-NON	#GIE-SBOS-07		
0.008588	0.272341	%F-SA125-P034	EGDGK3T-1A1B1E	NR-AC15HR	/PSV	/RCPSEAL_2S	#GIE-SBOR-07		
0.008477	0.280818	%F-SA125-P034	EGDGK3D-1A1B	NR-AC15HR	/PSV	/RCPSEAL_2S	#GIE-SBOR-07		
0.007901	0.288720	%F-TBB073-T07	EGDGR01A	EGDGR01B	EGOPHDG01E	NR-AC15HR	/PSV	/RCPSEAL_2S	#GIE-SBOR-07
0.007548	0.296268	%F-SA125-P034	CWCUW4Q-1A2A:	NR-AC15HR	/PSV	/RCPSEAL_2S	#GIE-SBOR-07		
0.007378	0.303646	%F-SA125-P034	EGDGS01A	EGDGS01B	NR-AC7HR	/PSV	/RCPSEAL_2S	#GIE-SBOS-07	
0.007166	0.310812	%F-100-P01H	EGDGM01E	EGDGR01A	NR-AC15HR	/PSV	/RCPSEAL_2S	#GIE-SBOR-07	
0.007052	0.317864	%F-TBB100-T06H	EGDGK3T-1A1B1E	NR-AC15HR	/PSV	/RCPSEAL_2S	#GIE-SBOR-07		
0.006659	0.324523	%F-100-P01H	EGDGR01A	EGDGR01E	NR-AC15HR	/PSV	/RCPSEAL_2S	#GIE-SBOR-07	

Fig. 6 High level cutsets for representing CDF for Hanul Unit 3 fire event after fire modeling of SWGR(100-A01A)

ACKNOWLEDGMENTS

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REFERENCES

1. NAJAFI, B., ET AL., "Fire PRA methodology for nuclear power facilities", NUREG/CR-6850, USNRC (2005).
2. JONES, W., R. PEACOCK, G. FORNEY, AND P. RENEKE, "CFAST – Consolidated Model of Fire Growth and Smoke Transport (Version 6) User's Guide", NIST Special Publication 1041r1, National Institute of Standards and Technology (2012).
3. N.MELLY, ET AL., "Refining And Characterizing Heat Release Rates From Electrical Enclosures During Fire (RACHELLE-FIRE)" Volume 1: Peak Heat Release Rates and Effect of Obstructed Plume, NUREG-2178, USNRC (2015).
4. SFPE, "SFPE Handbook of Fire Protection Engineering", 4th Edition (P. J. DiNenno, Editor-in-Chief), National Fire Protection Association and The Society of Fire Protection Engineers (2008).
5. KEVIN MCGRATTAN., ET AL., "Cable Heat Release, Ignition, and Spread in Tray Installations During Fire (CHRISTIFIRE) Phase 1: Horizontal Trays", NUREG-7010, USNRC (2012).
6. D.STROUP., ET AL., "NUCLEAR POWER PLANT FIRE MODELING ANALYSIS GUIDELINES (NPP FIRE MAG)", NUREG-1934 USNRC (2012).
7. KEVIN MCGRATTAN., ET AL., "Cable Heat Release Ignition, and Spread in Tray Installations During Fire (CHRISTIFIRE) Phase 2: Vertical Shafts and Corridors", NUREG-7010, USNRC (2013).