Transactions of the Korean Nuclear Society Spring Meeting
Jeju, Korea, May 9-10, 2024

Uncertainty analysis on the effect of combustion products in fire modeling analysis

Yongjae Kim*, Seokhyeon Han, Doohee Lee, Samwon Chung, Seungjun Oh
PNE Co., Ltd.
**Corresponding author: kyj@pnecorp.co.kr*

***Keywords:** Performance-based fire protection, Fire modeling, Uncertainty analysis, NFPA 805, effect of combustion products

1. Introduction

NFPA 805 provides standards for performance-based fire protection in US light water reactors, emphasizing the use of fire modeling to demonstrate safety and the analysis of associated uncertainties [1]. While Korea has adopted a deterministic fire protection standard so far, licensee may apply performance-based approaches under the permission of the regulatory body. Fire modeling is one of the key technologies of performance-based fire protection, understanding uncertainties in fire modeling is crucial for effective analysis. NFPA 805 identifies key input variables like heat release and fire growth rates, effects of ventilation, structural cooling effects, thresholds for thermal damage to equipment, effect of smoke on equipment, and compartment and fuel geometry which may influence the fire modeling outcomes [1].

In Korea, study on fire modeling uncertainty primarily focuses on well-known factors such as heat release rates and ventilation conditions [2,3,4]. However, comprehensive analysis addressing other critical variables is lacking. This paper aims to bridge this gap by examining the uncertainty surrounding the "effect of combustion product", a key input variable, as a part of a government (Korea Foundation of Nuclear Safety) task to develop technology for evaluating the appropriateness of fire modeling.

Smoke generated during combustion process contains various combustion products like carbon dioxide (CO_2), soot (C), and carbon monoxide (CO), which can impact equipment and personnel in affected compartments. While carbon dioxide and carbon monoxide typically have minimal effects in nuclear power plant fire scenarios, soot can significantly affect optical density and visibility of operators in Main Control Room (MCR) [5]. As optical density is a crucial element of deciding the loss of habitability of MCR[6], this study focuses on analyzing the impact of soot concentration on optical density and its implications for habitability in the MCR.

2. Uncertainty analysis method for fire modeling

Fire modeling uncertainty analysis aims to (1) identify key factors that cause uncertainty in predicting fire outcomes, (2) evaluate the potential impact of this uncertainty on prediction, and (3) evaluate the likelihood of these potential effects. This process involves two approaches to address uncertainties effectively.

Qualitative Approach: Analysts often incorporate conservatism into fire modeling analyses to qualitatively address uncertainties. This involves exercising judgment to introduce conservative assumptions regarding factors like fire size, fire growth rate, and damage criteria.

Quantitative Approach: Sensitivity analysis provides a quantitative method for assessing uncertainty. By evaluating how changes in input variables affect prediction outcomes, sensitivity analysis identifies the most influential factors and quantifies their impact on predictions. This involves varying input variables within specified ranges and observing resultant changes in prediction outcomes.

To evaluate the sensitivity of the combustion products on fire modeling analysis, quantitative approach was used in this study.

In fire scenarios handling critical spaces like the MCR in nuclear power plants, habitability assessment is required. Optical density, directly influenced by combustion products, particularly affects habitability of the MCR. Sensitivity of optical density to factors like soot concentration is critical in the fire modeling analysis.

For instance, the combustion of XPE/Neoprene($C_3H_{4.5}Cl_{0.5}$) cables, a common scenario in MCR fires, produces hydrogen chloride (HCl), water vapor (H_2O), carbon monoxide (CO), carbon dioxide (CO_2), soot (C), and nitrogen (N_2) as shown in the following equation (1) [7].

(1) $A(C_3H_{4.5}Cl_{0.5}) + B(0.21O_2 + 0.79N_2) \rightarrow C(HCl)$
$+D(H_2O) + E(CO) + F(CO_2) + G(C) + H(N_2)$[7]

The soot concentration of the smoke is altered by the amount of soot produced by the combustion process which is determined by the coefficient of soot of the equation (1). Therefore, to analyze the impact of uncertainty of soot production on optical density, a total of 11 sensitivity analysis scenarios were developed by modifying the soot coefficient (G) of the equation (1). The average soot coefficient value (0.8495), presented in the SFPE Handbook 5th ed. Table A.39[8], was altered from -50% to +50% in increments of 10% by adjusting the complete and incomplete combustion reaction yield of the XPE/Neoprene cable. When the soot coefficient varies, the coefficient of the products and reactants should be adjusted to balance equation (1). The adjusted stoichiometry of 11 scenarios are shown in Table I and the data for MCR fire based on XPE/Neoprene cable are listed in Table II.

Table I: The stoichiometry of the combustion type

No.	Change in soot coefficient (%)	A	B	C	D	E	F	G	H
1	-50	1.0	16.4321	0.5	2.0	0.2491	2.3262	0.4247	12.9814
2	-40	1.0	16.0469	0.5	2.0	0.2409	2.2494	0.5097	12.6771
3	-30	1.0	15.6619	0.5	2.0	0.2326	2.1727	0.5947	12.3729
4	-20	1.0	15.2771	0.5	2.0	0.2244	2.0960	0.6796	12.0689
5	-10	1.0	14.8919	0.5	2.0	0.2162	2.0192	0.7646	11.7646
6	0	1.0	14.5071	0.5	2.0	0.2080	1.9425	0.8495	11.4606
7	10	1.0	14.1224	0.5	2.0	0.1998	1.8658	0.9344	11.1567
8	20	1.0	13.7371	0.5	2.0	0.1916	1.7890	1.0194	10.8523
9	30	1.0	13.3521	0.5	2.0	0.1833	1.7123	1.1044	10.5482
10	40	1.0	12.9674	0.5	2.0	0.1751	1.6356	1.1893	10.2442
11	50	1.0	12.5821	0.5	2.0	0.1669	1.5588	1.2743	9.9399

Table II: Data for MCR fire based on XPE/Neoprene electrical cable

Comp. Info.	Size of Comp. [m]			Operator Location [m]			Ventilation Condition	
	Length	Width	Height	X	Y	Z	Forced Ventilation	Natural Ventilation
	20	22	6	7.5	10.5	1.8	OFF	Closed Door

Ignition Source Info.	Ignition Source Type	Fire Area [m^2]	Radiative Fraction	HRR(98^{th}) [kW]	HRR Profile [min]			Ambient Temp. [°C]
					Growth	Peak	Decay	
	Main Control Board (MCB)	0.26	0.53	700	12	8	19	22

3. Results of fire modeling uncertainty analysis

The virtual MCR was developed to assess the impact of varying soot concentrations on habitability assessment in the MCR. Utilizing the Fire Dynamics Simulator (FDS), uncertainty analysis was conducted for 11 scenarios, simulating different levels of soot concentration based on adjustments to the soot coefficient. Results indicated that under the most conservative assumption of no fire detection and suppression activities, loss of habitability occurred in the MCR across all scenarios. However, the timing of habitability loss displayed sensitivity to changes in the soot coefficient. The soot coefficient and habitability loss time for each scenario were compared to those of the base scenario (scenario 6) to calculate the percentage change in both the soot coefficient and the habitability loss time. Fig. 1 illustrates the percentage change in habitability loss time relative to the percentage change in soot coefficient.

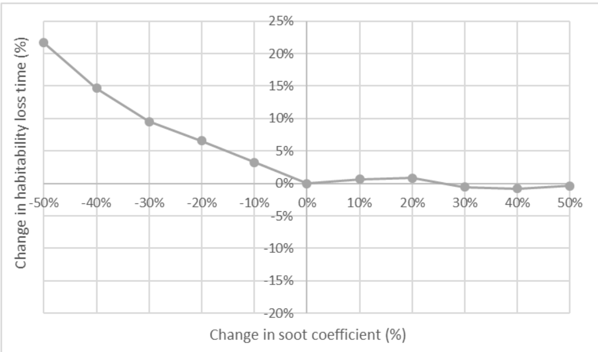

Fig. 1. The change in habitability loss time

As smoke concentration decreased (reflected by a lower soot coefficient), habitability loss time increased. This effect stemmed from reduced soot volume in the smoke layer, leading to slower acquisition of optical density damage criteria. This underscores the critical influence of uncertainty in soot concentration on habitability assessment.

Interestingly, when the soot coefficient increased by 50% above average, resulting in a significant increase in soot concentration, the difference in habitability loss time was less pronounced. This observation highlights that habitability loss in the MCR primarily hinges on optical density exceeding thresholds as the smoke layer descends. Thus, even with high soot coefficient, habitability loss may not occur until the smoke layer reaches the critical height (1.8 m in this study).

4. Conclusion

In the pursuit of enhancing performance-based fire protection approaches, this study conducted a comprehensive analysis of uncertainty surrounding fire modeling, focusing on the effect of combustion products. The examination of uncertainty of soot concentrations and their impact on habitability assessment in the MCR revealed critical insights for safety evaluations in nuclear power plants. Results demonstrated that while loss of habitability in the MCR occurred across all scenarios with conservative assumptions, the timing of habitability loss was sensitive to changes in soot concentration. Specifically, decreased soot concentrations led to prolonged habitability, highlighting the significance of soot concentration uncertainties in fire modeling analysis. These findings emphasize the importance of considering soot concentration uncertainties in fire modeling analysis, particularly in critical areas like the MCR. While lower soot concentrations may prolong habitability, conservative assumptions should be applied unless supported by substantial evidence due to the safety-critical nature of these assessments.

Moving forward, future research should continue to refine and validate fire modeling techniques, ensuring their efficiency in safeguarding nuclear power plant operations. Additionally, efforts should be directed towards expanding the scope of uncertainty analysis to other critical input variables, further enhancing the robustness of performance-based fire protection approaches. Ultimately, this study will contribute to the ongoing evolution of fire safety practices in nuclear power plants, fostering a proactive approach towards mitigating potential risks and ensuring the continuous protection of nuclear power plants.

Acknowledgment

This work was supported by the Nuclear Safety Research Program through the Korea Foundation Of Nuclear Safety (KoFONS) using the financial resource granted by the Nuclear Safety and Security Commission (NSSC) of Republic of Korea (No.2105031)

REFERENCES

[1] W. D. Holmes, et al., NFPA 805, Performance-Based Standard for fire Protection for Light Water Reactor Electric Generating Plants 2001 Edition, National Fire Protection Association, Massachusetts, 2001.
[2] J.H. Cho, C.H. Hwang, J.S. Kim, and S.K. Lee, Sensitivity Analysis of FDS Results for the Input Uncertainty of Fire Heat Release Rate, Journal of the Korean Society of Safety, Vol.31, p.25-32, 2016.
[3] S.W. Chung, S.H. Han, Y.J. Kim, and S.J. Oh, Study on flame extinction conditions of fire modeling using FDS, Proceedings of the Korea Institute of Fire Science and Engineering Conference, p.80, 2023.
[4] D.I. Kang, K.Y. Kim, S.C. Jang, and S.Y. Yoo, Risk assessment of main control board fire using fire dynamics simulator, Nuclear Engineering and Design, Vol. 289, p.195-207, 2015.
[5] R.P. Kassawara, and J. S. Hyslop, NUREG/CR-6850 Vol.2, EPRI 1011989: EPRI/NRC-RES Fire PRA Methodology for Nuclear Power Facilities, Final Report, US Nuclear Regulatory Commission, Washington D.C., 2005.
[6] B.J. Kim, J.H. Lee, S.Y. Kim, and W.G. Shin, Habitability evaluation considering various input parameters for main control benchboard fire in the main control room, Nuclear Engineering and Technology, Vol.54 Issue 11, p.4195-4208, 2022.
[7] M.H. Salley, NUREG-1934, Nuclear Power Plant Fire Modeling Analysis Guidelines (NPP FIRE MAG), Final Report, US Nuclear Regulatory Commission, Washington D.C., 2012.
[8] J.H. Morgan, SFPE Handbook of Fire Protection Engineering 5th Edition, Springer, New York, 2016.