Uncertainty Analysis For Input Parameters Of Electrical Cabinet Fire Simulation By Coupling Latin Hypercube Sampling And CFAST

Wanhong WANG[a], Dahuan ZHU[b], Hui BAO[c], Yun GUO[a], Changhong PENG[a]*
[a] School of Nuclear Science and Technology, University of Science and Technology of China, Hefei, Anhui, China
[b] Science and Technology on Reactor System Design Technology Laboratory, Nuclear Power Institute of China, Chengdu, Sichuan, China
[c] Institute of Plasma Physics, Chinese Academy of Sciences, Hefei, Auhui, China

Abstract: It has been proved that fire accident frequency in nuclear power plants is higher than we thought it was and fire accidents have a huge significant impact on the safety of nuclear power, so it is extremely necessary to analyze fire risks. Electrical cabinets are one of the most important fire ignition sources in nuclear power plants, since there are normally many combustible cable bundles inside them. When fire modeling has been performed in nuclear power plants, past studies have only considered a single fire scenario, which means that the uncertainties associated with fire combustion and propagation are ignored. The paper is based on electrical cabinet fire scenario simulations in nuclear power plants and analyze the uncertainty of input parameters related to fire combustion and fire detection by coupling Latin Hypercube Sampling and software-CFAST. Statistic results can be used for quantitative analysis in Fire Probabilistic Safety Assessment.

Keywords: CFAST, Latin Hypercube Sampling, Electrical Cabinet Fire, Uncertainty Analysis

1. INTRODUCTION

The Main Control Room (MCR) is a special fire compartment which is constantly occupied with operators to control and monitor the whole nuclear power plants. The controllers, indicators and alarm windows are all located inside this room. A large fire in the MCR can be harmful to safe shutdown capability, since cable bundles inside electrical cabinets and other important equipment can possibly be damaged and lead to uninhabitable conditions for operators there. If the MCR environment becomes uninhabitable, operators there must evacuate the MCR and go to the alternative shutdown panel to shut down nuclear power plants [1].

CFAST is a two-zone fire model that predicts the thermal environment caused by a fire within a compartmented structure. Each compartment is divided into an upper and lower gas layer. The fire drives combustion products from the lower to the upper layer via the plume. The temperature within each layer is uniform, and its evolution in time is described by a set of ordinary different equations derived from the fundamental laws of mass and energy conservation. The transport of smoke and heat from zone to zone is dictated by empirical correlations. Because the governing equations are relatively simple, CFAST simulations typically require a few tens of seconds of CPU time on personal computers [2].

CFAST consists of environment simulation conditions, thermal properties, compartments, wall vents, ceiling/floor vents, mechanical ventilation, fires, targets, detection/suppression, surface connections and output. By setting appropriate input parameters, it calculates time-evolving distribution of smoke and gaseous combustion production as well as the temperature throughout compartments during a user-prescribed fire scenarios.

Latin Hypercube sampling is a method of sampling that can be used produce input values for estimation of expectations of functions of output variables. By using this sampling approach, a near-random sample of parameter values from a multidimensional distribution can be generated. The sampling method is often used to construct computer experiments or for Monte-Carlo integration.

*Corresponding Author：Changhong PENG，E-mail：pengch@ustc.edu.cn

Latin Hypercube Sampling (LHS) operates by dividing the subspace of each vector component ν_i; i=1, 2,…, N into M=n disjoint subsets (strata) of equal probability $\boldsymbol{\Omega_{ik}}$; i=1, 2,…, N; k=1, 2,…, M. Samples of each vector component are drawn from the respective strata according to

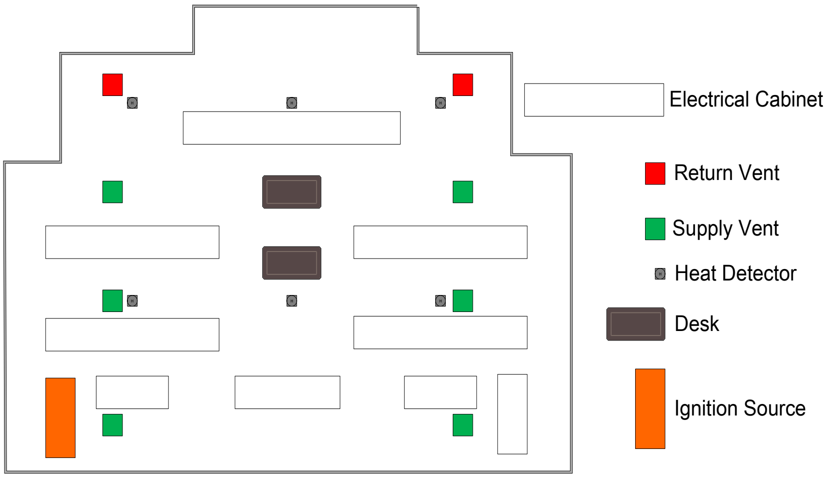
$$\chi_{ik} = D_{X_i}^{-1}(U_{ik}); \quad i = 1, 2, \dots, N; k = 1, 2, \dots, M \tag{1}$$

where U_{ik} are iid uniformly distributed samples on $[\xi_k^l, \xi_k^u]$ with ξ_k^l=(k-1)/M and ξ_k^u=(k/M). The sample **x** are assembled by randomly grouping the terms of the generated vector components. That is, a term χ_{ik} is randomly selected from each vector component (without replacement) and these terms are grouped to produce a sample. This process is repeated M=n times [3].

2. FIRE MODELING

2.1. Design Feature in the MCR

Figure. 1. The Layout Of The MCR



The irregular geometry and layout of the referenced MCR are presented in Figure 1. The wall and ceiling are constructed out of concrete while the floors are constructed out of gypsum board. There are many electrical cabinets with lots of cable bundles in the MCR. During normal and emergency operations in the nuclear power plant, the volume flow rate of supply air to the MCR is 6 m^3/s, while the volume flow rate of exhaust air from the MCR is 2 m^3/s. The total number and the total area of these supply vents are 6 and 2.16 m^2, and those of the return vents are 2 and 0.72m^2. The door is assumed to be closed during the whole fire simulation. In this study, the location of operators in the MCR was assumed to be between two desks, and fire ignition was modeled 0.3 m below top surface of the ignited electrical cabinet.

Figure. 2. Fire Modeling For The MCR

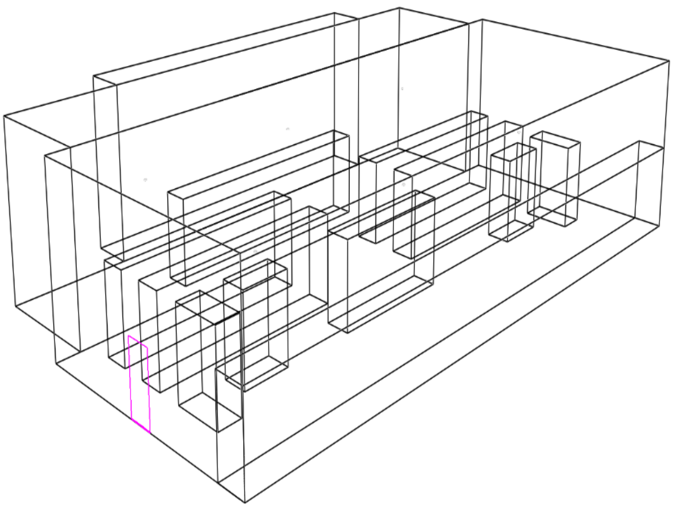


Figure 2 shows the fire model by using CFAST. According the characteristics of irregular geometry, the referenced MCR was subdivided into three fire compartments. By coupling Latin Hypercube sampling and the software-CFAST, output parameters, such as layer temperatures, layer heights and optical densities in different fire scenarios were collected. All these output parameters were used to determine the abandonment probability and abandonment time. Additionally, heat detectors' activation time were collected to determine how this output parameter is affected by response time index and activation temperature.

2.2. Input Parameters And Assumptions

Table 1 shows distribution characteristics of input parameters for CFAST. In this study, heat release rate, soot yield, activation temperature and response time index were selected as input parameters used for uncertainty analysis, since these input parameters associate directly with fire intensity, fire products and fire detection time and operators' habitability in the MCR, which are most important elements for fire simulations by using CFAST. Apart from that, other input parameters associated with fire combustion for CFAST fire simulations are presented in Table 2.

Table. 1. Distribution Characteristics Of Input Parameters For CFAST

Parameter	Distribution	Parameter1	Parameter2
Heat Release Rate [4]	Gamma	α=0.7	β=216
Soot Yield [5]	Gamma	α=2.375	β=0.047
Activation Temperature	Normal	μ=80	σ=10
Response Time Index [6]	Normal	μ=0.25	σ=0.03

Table. 2. Input Parameters Associated With Fire Simulation

Parameter	Value
Effective fuel formula	$C_2H_{4.5}Cl_{0.5}$
Heat of combustion	28300kJ/kg
CO yield	0.0340kg/kg
Radiative fraction	0.35

2.3. Abandonment Criteria

As mentioned above, abandonment probability and time should be considered when it comes to fire scenarios in the MCR, and it is critical to determine abandonment criteria when analyzing abandonment time. Generally speaking, the criteria are determined by layer temperature, visibility, or toxic gas concentration in the MCR. In this study, they were determined by the guidelines presented in NUREG-6850 and NUREG-0700.

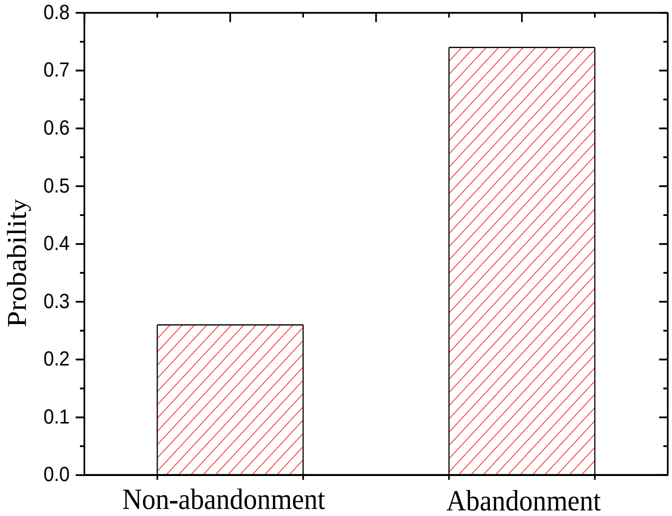
According to NUREG/CR-6850, the temperature criterion for abandonment is 95 degree centigrade, which leads to radiant flux exceeding 1 kW/m^2, the minimum heat flux for pain to skins. However, if the smoke layer were to immerse an operator, the exposure temperature thresholds are between 50 degree centigrade and 80 degree centigrade according to NUREG-0700. Conservatively, 50 degree centigrade would be appropriate temperature criterion when the smoke layer in the MCR immerses an operator (average height of operators in the MCR is assumed to be 6').

According to NUREG/CR-6850, the visibility abandonment criterion for the MCRs is based on the optical density, and operators are forced to have to abandon the MCR for the sake of their safety when the optical density in the MCR is equal to or greater than 0.3 m^{-1}. In this study, the layer temperature, layer height and optical density in the MCR were collected and analyzed to determine whether operators should abandon the MCR and when operators are forced to abandon the MCR for the sake of their safety and health.

3. RESULTS

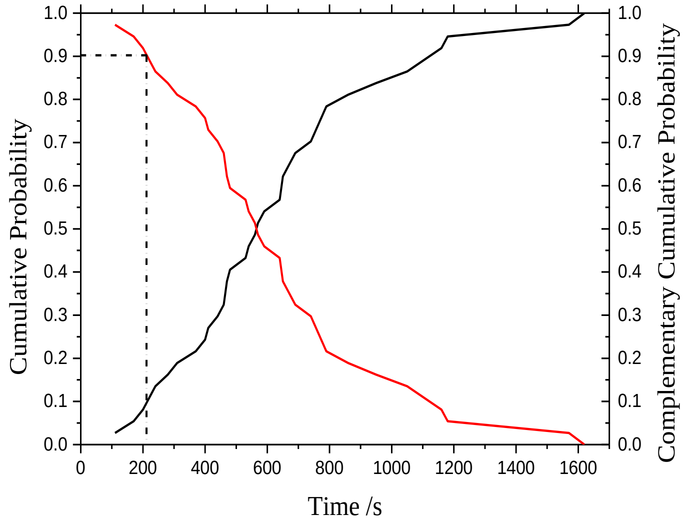
3.1 Abandonment Time

Figure. 3. Abandonment Probability Based On Abandonment Criteria



The abandonment probability based on abandonment criteria is presented in Figure 3. The proportion of fire simulation cases where operators are forced to abandon the MCR for the sake of their safety and health is 74 %, while in only 26% of fire simulation cases it is not expected to do harm to operators' safety and health according to the abandonment criteria, thereby operators unnecessarily abandoning the MCR.

Figure. 4. Cumulative Probability And Complementary Cumulative Probability For Abandonment Time

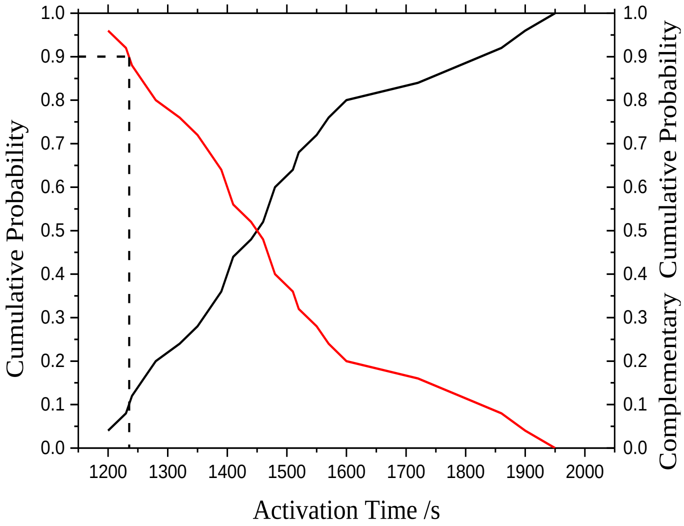


Cumulative probability and complementary cumulative probability for abandonment time are presented in Figure 4. The 0.9-quantile for complementary cumulative probability curve is around 220 s, which can be seen as the abandonment time and conservatively used for Fire Probabilistic Safety Assessment in nuclear power plants.

3.2. Activation Time

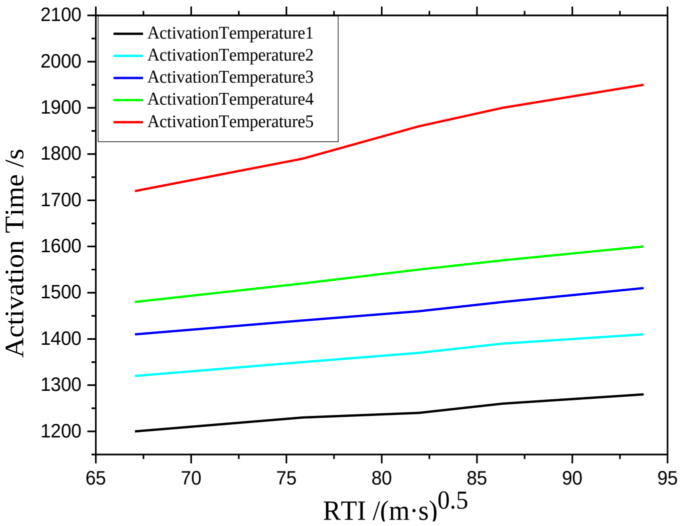
Cumulative probability and complementary cumulative probability for heat detectors' activation time for fire simulations are presented in Figure 5, and the 0.9-quantile for complementary cumulative probability curve in this figure is around 1240 s, which is way longer than the abandonment time from fire simulation results.

Figure. 5. Cumulative Probability And Complementary Cumulative Probability For Heat Detector's Activation Time



The relation among RTI, activation temperature and activation time is presented in Figure 6. The activation time increases with RTI and activation temperature increasing. In order to get accurate activation time from fire simulation, determining accurate RTI and activation temperature for fire simulation is necessary and important.

Figure. 6. Relation Among Response Time Index, Activation Temperature And Activation Time



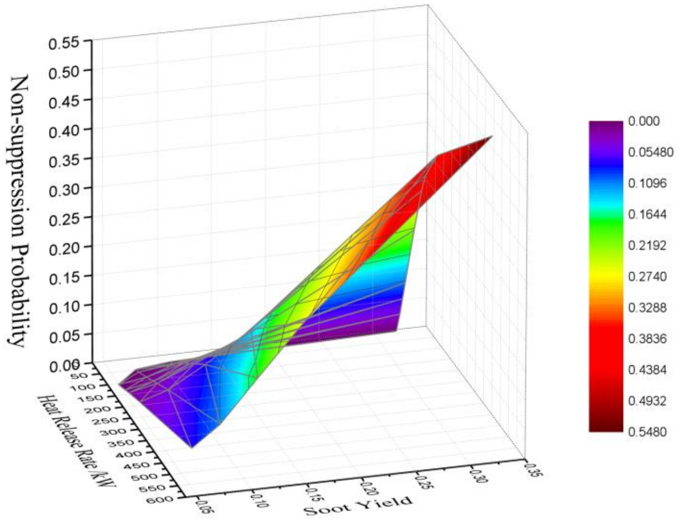
3.3. Non-suppression Probability

In real fire scenarios, automatic suppression systems are possibly used to suppress fire and operators can also take some actions to prevent fire propagation, which means that there is the possibility that the fire is suppressed before targets are damaged. In Fire Probabilistic Safety Assessment, the probability of non-suppression is an estimate of the overall likelihood that given a fire scenario in the postulated fire ignition source, the damage to the target set will occur before the fire is finally suppressed. According to NUREG/CR-6850, the non-suppression probability can be calculated by the following equation:

$$NS(t) = e^{-\lambda t} \quad (2)$$

where λ is the suppression rate constant and 0.33/min was used for the MCR fire in this study. *t* is the time from fire ignition to operators abandoning the MCR for the sake of their safety. In this study, *t* was assumed to be the abandonment time from fire simulation results and time used for fire detection in early phase was not considered in this paper.

Figure. 7. Relation Among Heat Release Rate, Soot Yield And Non-suppression Probability



The relation among heat release rate, soot yield and non-suppression probability is presented in Figure 7. The relation is the reflection of how heat release rate and soot yield affect values of non-suppression probability. Non-suppression probability gradually increases with heat release rate and soot yield increasing, which means that the bigger values of heat release rate and soot yield are, the more difficult suppressing fire is.

4. CONCLUSION

By coupling Latin Hypercube Sampling and CFAST, this paper did uncertainty analysis for input parameters of electrical cabinet fire simulations. The sampling data not only quantitatively reflect how these input parameters affect output results, reminding analysts of the importance of parameters associated with fire combustion during fire simulations, but also help determine the abandonment time and abandonment probability for Fire Probabilistic Safety Assessment.

Heat release rate and soot yield are the most important factors associated with fire combustion for fire simulations, and can lead to the MCR's inhabitability. Abandonment probability is 74 %, which means that in most cases layer temperature and optical density will threaten operators' habitability in the MCR and operators are forced to abandon the MCR for the sake of safety. The 0.9-quantile for complementary cumulative probability curve is around 220 s, which can be conservatively used for abandonment time in Fire Probabilistic Safety Assessment. Besides, heat detectors' activation time is heavily affected by activation temperature and response time index, and constantly increases with both activation temperature and response time index rising. The non-suppression probability increases with heat release rate and soot yield increasing in the MCR fire scenarios, which means that analysts are expected to be careful when selecting appropriate input parameters, especially those associated with fire combustion, for fire simulation by using CFAST.

The reasonability of the fire simulation model and how the size of sampling affects statistic results are supposed to be considered further. Dividing the MCR into many compartments instead of taking the MCR as the whole compartment for fire scenario simulations might be more accurate and appropriate in terms of output results. Additionally, the effect of toxic gases on operators' habitability in the MCR was not analyzed in this paper. It is reasonable and sensible to consider toxic gases in fire simulations in the future.

Acknowledgements

The author would like to thank the Science and Technology on Reactor System Design Technology Laboratory of Nuclear Power Institute of China for financial support of this work.

References

[1] Zhong Shan. Abandonment Times Evaluation of Main Control Room at Baya Bay Nuclear Plant [C]. 11th International Probabilistic Safety Assessment and Management Conference & the Annual European Safety and Reliability Conference. Finland: 2012.
[2] CFAST-Consolidated Fire and Smoke Transport (Version 7) volume 1: Technical Reference Guide [M]. Gaithersburg: National Institute of Standards and Technology, 2015.
[3] Michael D. Shields, Jiaxin Zhang. The generalization of Latin hypercube sampling [J]. Reliability Engineering and System Safety, 2016, 148: 96-108.
[4] EPRI, NRC-RES. NUREG/CR-6850 EPRI/NRC-RES Fire PRA Methodology for Nuclear Power Facilities Volume 2: Detailed Methodology [R]. U.S. Nuclear Regulatory Commission and Electric Power Research Institute, 2005.
[5] Tom Elicson, Jim Bouchard, Heather Lucek, Bentley Harwood. Calculation of Fire Severity Factors and Fire Non-Suppression Probabilities for a DOE Facility Fire PRA [C]. ANS PSA 2011 International Topical Meeting on Probabilistic Safety Assessment and Analysis. Wilmington: ANS, 2011.
[6] Jia Jia. Study on Assessment Methodology of Ship Fire survivability [D]. Hefei: University of Science and Technology of China, 2014.