Benchmark Simulations of Cable Tray Fires in PRISME CFS, CFP and BCM Tests

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1. Introduction

The PRISME (PRopagation d'un Incendie pour des Scénarios Multi-locaux Élémentaires) is an OECD/NEA joint international research project to experimentally and analytically investigate various real-scale fire spread and propagation phenomena in nuclear power plants (NPPs)[1]. Since its official launch in January 2006, the first phase (PRISME-1) was performed until June 2011 and the second phase of PRISME (PRISME-2) was performed until December 2016. The third phase of PRISME (PRISME-3) was started in January 2017 and will be concluded in December 2021 (Fig. 1). The PRISME was proposed by the Institut de Radioprotection et de Sûreté Nucléaire (IRSN) in France, and the various fire experimental tests of the PRISME are conducted using IRSN's two specially designed facilities in Cadarache: (1) SATURNE, a large enclosure equipped with a large-scale calorimeter in open atmosphere; and (2) DIVA, a large-scale multi-compartment facility including four (4) rooms and one (1) corridor connected with a mechanical ventilation system by means of inlet and outlet ducts and fans. In parallel to the experimental efforts within the Program Review Group (PRG), PRISME partners within the Analytical Working Group (AWG) are conducting various analytical activities using the PRISME experimental data to improve the predictive capabilities of various fire modelling codes.
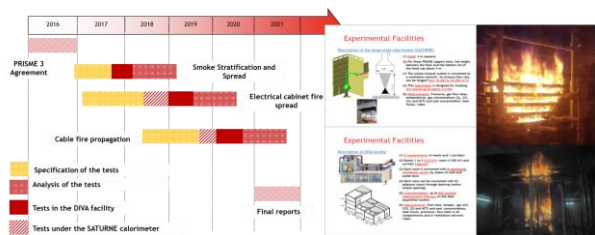

Fig. 1. Overview of the OECD/NEA PRISME-3 Project.

In the framework of the PRISME-3 AWG, it was proposed to perform benchmark simulations for complex and real cable tray fire scenarios in order to improve understanding and modeling accuracy of key phenomena such as fire spread and propagation on a vertical stack of multiple horizontal cable trays. This lead to the joint activity of two OECD/NEA projects, PRISME-3 and FIRE, called the PRISME/FIRE common benchmark exercise. In contrast to a well-controlled experiment, a real event does not occur in laboratory conditions, and thus, inputs and outputs are weakly under control. Assessing the quality of numerical results is therefore very challenging. Based on the fact that a code-to-code comparison is still possible, a three-step methodology [2] was proposed consisting of step #1 an open simulation of the PRISME-2 CFS test [2], step #2 a blind simulation of the PRISME-3 CFP test [3, 4], and step #3 a blind simulation of the real fire event from the FIRE project [5]. This three-step methodology is based on the expectation that step #2 and step #3 will show similar behaviors making it possible to extrapolate the error estimation. During the progress of the project, the step #2 has been subdivided into two steps: step #2.1 a blind simulation of the PRISME-3 CFP test [3]; and step #2.2 an open simulation of the PRISME-3 CFP-BCM tests [4] added to appropriately reflect conditions of the real fire event determined as a target of the step #3 simulation [5].

All benchmark exercise participants are required to perform simulations in their own way. The simulation models and results of all participants are reviewed and discussed during the PRISME meeting to reach a consensus for a better modeling approach. The step #1, #2.1, and #2.2 simulations have been completed in 2019, 2020, and the first half of 2021, respectively. The remaining step #3 simulation will be completed in the second half of 2021. Several promising approaches for modeling cable tray fires are being investigated. The primary focus of the simulations is to appropriately predict time evolutions of the Heat Release Rate (HRR) or Mass Loss Rate (MLR) from the cable tray fire, a key element to which is to appropriately model (1) horizontal outward fire spread along the length of each cable tray; (2) vertical upward fire propagation from each tray to the next tray above it; and (3) local pyrolysis & combustion phenomena.

The objective of this paper is to present simulation approaches and results of the PRISME-3 Korean participants, KAERI and KINS, conducted under the PRISME/FIRE common benchmark exercise.

2. Benchmark Simulation Approaches

The PRISME-3 Korean participants, KAERI and KINS are performing the multi-step benchmark simulations using Fire Dynamics Simulator (FDS) as a fire modeling tool, and two different approaches for modeling the HRR time evolution of the cable tray fire explained later in this paper. The FDS is a Computational Fluid Dynamics (CFD) model of fire-driven fluid flow developed by the National Institute of

Standards and Technology (NIST) of the United States, in cooperation with VTT Technical Research Centre of Finland. The FDS is the most common fire modeling tool chosen by many benchmark exercise participants.

2.1 Approach (1): FLASH-CAT FDS Model

The first approach for benchmark simulations is the FLASH-CAT (FLAme Spread over Horizontal CAble Trays) model [6, 7, 8]. This simple and widely used model for horizontal cable tray fires has been developed based on the basic approaches in Appendix R of NUREG/CR-6850 [6] and the small and intermediate-scale experimental data summarized in NUREG/CR-7010, Vol. 1 [7]. This model has been validated using the results of 26 multiple horizontal tray experiments [7] and 16 vertical tray and corridor experiments [8].

One of the most notable assumptions made for the FLASH-CAT model is that the cable trays are positioned in an open environment, which means they are not installed directly below a ceiling or in front of a wall; or confined within a relatively narrow corridor or shaft. Because the model may involve a considerable amount of uncertainty for cases beyond these assumptions, NUREG/CR-7010, Vol. 2 [8] suggests that the analyst should consider a range of parameters to appropriately determine the HRR profiles of such cable tray fires. Note that the cable fire tests conducted in PRISME-2 and 3 project involve an insulated side wall supporting a vertical stack of five horizontal cable trays, which is commonly found in all industrial plants including NPPs. The presence of a support wall has a strong effect on the cable fire spread and propagation characteristics. More specifically, the support wall facilitates the heat transfer from the hot gas plume to the unburnt cables.
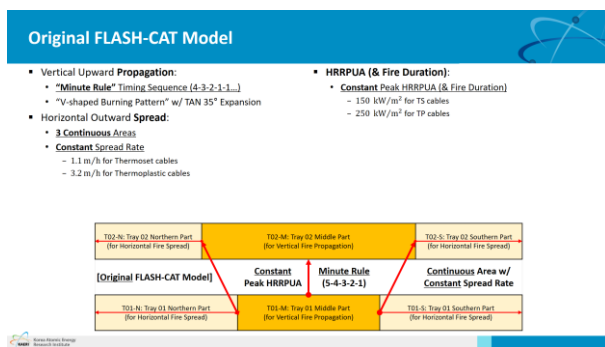

Fig. 2. Overview of the FLASH-CAT FDS Model.

P. Zavaleta et al. [9] modified the FLASH-CAT model for a better prediction of HRR time evolutions of the PRISME-2 CFSS-1, 2, 3 and CORE-1 tests. Their simulation results showed good agreement with the experimental data. However, it should be noted that their modifications are mainly based on video analysis results of the specific tests especially conducted in the

open atmospheric condition, and therefore, not directly applicable to other cable tray fires including the PRISME-2 CFS or PRISME-3 CFP tests especially conducted in the confined and mechanically ventilated condition.

The implementation of the FLASH-CAT model in the FDS does not require complex and difficult techniques. Each of outer parts of each cable tray used to simulate horizontal fire spread areas was set up as a single continuous area with constant spread rate and peak HRRPUA values recommended in the FLASH-CAT model depending on the cable materials.

2.2 Approach (2): Semi-Empirical FDS Model

W. Plumecocq et al. [10] proposed a semi-empirical model for horizontal cable tray fires, implemented the model in the two-zone based fire modeling tool SYLVIA, and performed simulations for the PRISME-2 CFS-1 to 4 tests conducted in confined and mechanically ventilated condition. The semi-empirical model basically utilizes experimental data and empirical approaches used in the FLASH-CAT model. On the other hand, the model also makes full use of analytical approaches and additional experimental observations, especially in evaluating time evolutions of the fire spread and propagation and the Heat Release Rate Per Unit Area (HRRPUA) as well. This enables the model to appropriately reflect the effects of the heat transfer deterioration due to the local oxygen depletion and the heat transfer enhancement due to the presence of structures (walls and/or ceilings), which is a distinct advantage over the FLASH-CAT model.
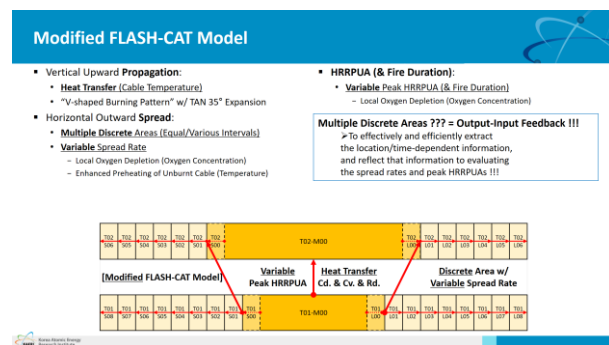

Fig. 3. Overview of the Semi-Empirical FDS Model.

This semi-empirical model was used as the second approach for benchmark simulations with some modifications. KAERI developed implementation strategies of the semi-empirical model in the CFD-based fire modeling tool FDS [11]. The implementation of this semi-empirical model in the FDS requires more complex and difficult techniques than that of the FLASH-CAT model within FDS does. The key implementation strategy is to divide each of outer parts of each cable tray used to simulate horizontal fire spread areas into multiple discrete areas with variable spread

rate and peak HRRPUA values evaluated within the model. This is to effectively and efficiently extract the location and time dependent information, i.e., the local oxygen concentrations and temperatures at each time step, and reflect that information to evaluating the spreading rates and peak HRRPUAs.

3. Results of Benchmark Simulations

3.1 Step #1 Benchmark Simulation for PRISME-2 CFS-2 Test

Step #1 benchmark simulation is conducted for the PRISME-2 CFS-2 test, a fire test for five horizontal cable trays(open ladder type, 2.4 m long, 0.45 m wide and vertical spacing of 0.3 m) filled with PVC (TP) cables under the confined and ventilated condition in the DIVA facility. This paper omits the details of this test.

Fig. 4 shows PyroSim 3-D layouts of step #1 benchmark simulation FDS Model for the PRISME-2 CFS-2 test. Fig. 5 shows the main result of step #1 benchmark simulation, i.e., HRR time evolution curves of the PRISME-2 CFS-2 test predicted using the FLASH-CAT FDS model (ORG) and the semi-empirical FDS model (MOD). Table I presents HRR global/local errors of the predicted curves compared to the experimental curve, which is not depicted in Fig. 5).

As shown in Fig. 5, the two HRR curves look a little differ from each other. The HRR curve predicted using the semi-empirical FDS model has a faster growth rate, a similar peak, and a shorter fire duration in comparison to that predicted using the FLASH-CAT FDS model. The both predicted curves are somewhat different from the experimental HRR curve (not shown in Fig. 5), mainly due to their higher peaks than that of the experimental HRR curve. However, it has been observed that the HRR curve predicted using the semi-empirical FDS model is at least on the conservative side in terms of a growth rate, contrary to that predicted using the FLASH-CAT FDS model. The results imply that the use of the semi-empirical FDS model provides more conservative prediction in cases of this kind.
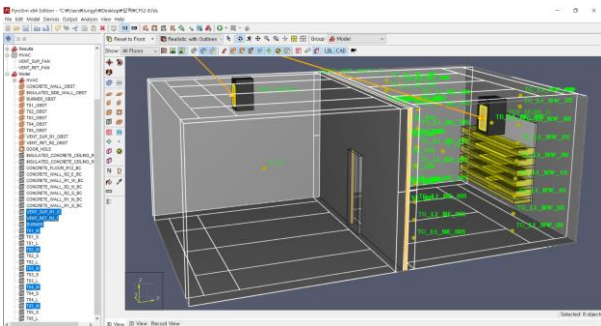

Fig. 4. PyroSim 3-D Layouts of Step #1 Benchmark Simulation (PRISME-2 CFS-2 Test) FDS Model.
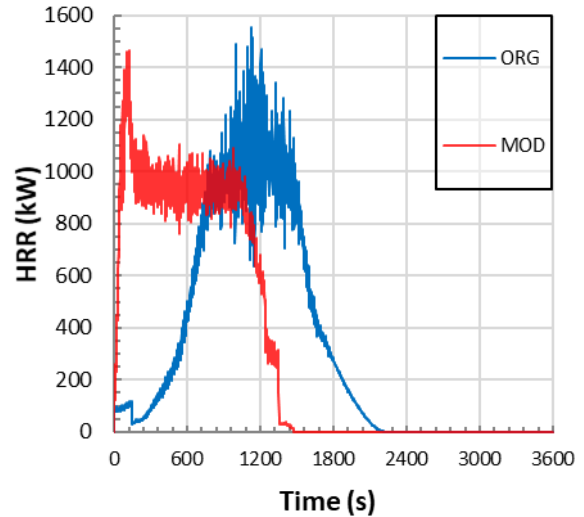

Fig. 5. HRR Time Evolution Curves of Cable Tray Fire of Step #1 Benchmark Simulation (PRISME-2 CFS-2 Test) Predicted Using FLASH-CAT FDS Model (ORG) and Semi-Empirical FDS Model (MOD).

Table I. HRR Global/Local Errors of Cable Tray Fire of Step #1 Benchmark Simulation (PRISME-2 CFS-2 Test) Predicted Using FLASH-CAT FDS Model (ORG) and Semi-Empirical FDS Model (MOD).

HRR Errors	**ORG** vs EXP	**MOD** vs EXP
Global	+8.77E-01	+7.14E-01
Local (Peak)	+5.05E-01	+4.22E-01

3.2 Step #2.1 Benchmark Simulation for PRISME-3 CFP-D1 Test

Step #2.1 benchmark simulation is conducted for the PRISME-3 CFP-D1 test, a fire test for five horizontal cable trays(open ladder type, 2.4 m long, 0.45 m wide and vertical spacing of 0.3 m) filled with EVA/PE-ATH (TS) cables under the confined and ventilated condition in the DIVA facility. This paper omits the details of this test.

Fig. 6 shows PyroSim 3-D layouts of step #2.1 benchmark simulation FDS Model for the PRISME-3 CFP-D1 test. Fig. 7 shows the main result of step #2.1 benchmark simulation, i.e., HRR time evolution curves of the PRISME-3 CFP-D1 test predicted using the FLASH-CAT FDS model (ORG) and the semi-empirical FDS model (MOD). Table II presents HRR global/local errors of the predicted curves compared to the experimental curve, which is not depicted in Fig. 7).

As shown in Fig. 7, the two HRR curves clearly differ from each other. The HRR curve predicted using the semi-empirical FDS model has a faster growth rate, a higher peak, and a shorter fire duration in comparison to that predicted using the FLASH-CAT FDS model. Between two HRR curves, the HRR curve predicted using the semi-empirical FDS model is more similar to

the experimental HRR curve. The results indicate that, in cases of this kind, the use of the semi-empirical FDS model provides much more conservative and better prediction, as well. The results also indicate that there exist strong effects of the heat transfer deterioration due to the local oxygen depletion and the heat transfer enhancement due to the presence of structures such as a wall and/or ceiling.
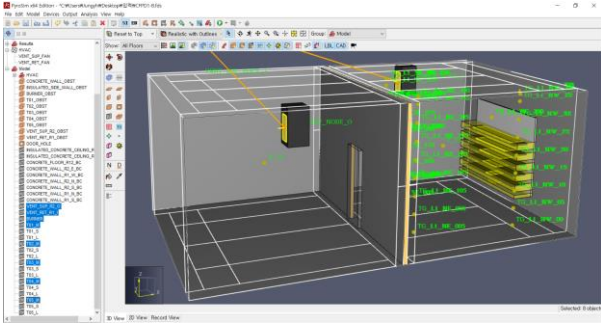

Fig. 6. PyroSim 3-D Layouts of Step #2.1 Benchmark Simulation (PRISME-3 CFP-D1 Test) FDS Model.
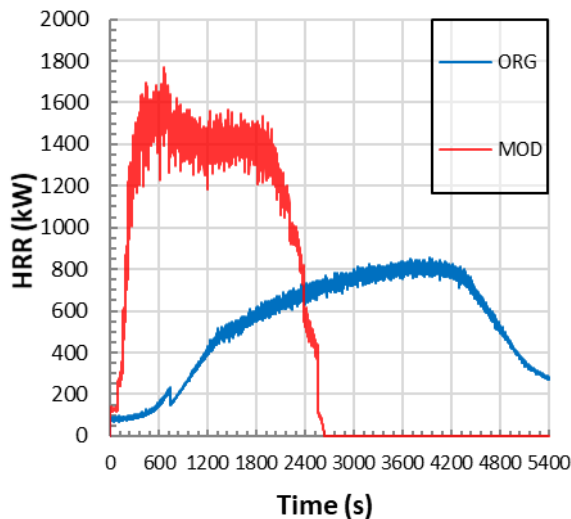

Fig. 7. HRR Time Evolution Curves of Cable Tray Fire of Step #2.1 Benchmark Simulation (PRISME-3 CFP-D1 Test) Predicted Using FLASH-CAT FDS Model (ORG) and Semi-Empirical FDS Model (MOD).

Table II. HRR Global/Local Errors of Cable Tray Fire of Step #2.1 Benchmark Simulation (PRISME-3 CFP-D1 Test) Predicted Using FLASH-CAT FDS Model (ORG) and Semi-Empirical FDS Model (MOD).

HRR Errors	**ORG** vs EXP	**MOD** vs EXP
Global	+6.97E-01	+6.92E-01
Local (Peak)	-5.35E-01	-3.78E-02

3.3 Step #2.2 Benchmark Simulation for PRISME-3 BCM-S1 & S2 Tests

Step #2.2 benchmark simulation is conducted for the PRISME-3 BCM-S1 & S2 tests, two fire tests for two horizontal cable trays(open ladder type, 2.4 m long, 0.9 m wide and vertical spacing of 0.45 m) filled with PE/PVC (TP) cables under the open atmosphere condition in the SATURNE facility. The only difference between two tests is an initial ignition method. This paper omits the details of these tests.

Fig. 8 shows PyroSim 3-D layouts of step #2.1 benchmark simulation FDS Model for the PRISME-3 CFP-D1 test. Fig. 6 and 7 show the main results of step #2.2 benchmark simulation, i.e., HRR time evolution curves of the PRISME-3 BCM-S1 & S2 tests predicted using the FLASH-CAT FDS model (ORG) and the semi-empirical FDS model (MOD). Table III presents HRR global/local errors of the predicted curves compared to the experimental curves, which are not depicted in Fig. 9.

As shown in Fig. 9, the two HRR curves clearly differ from each other. The HRR curve predicted using the semi-empirical FDS model has a faster growth rate, a higher peak, and a shorter fire duration in comparison to that predicted using the FLASH-CAT FDS model. Between two HRR curves, the HRR curve predicted using the semi-empirical FDS model is more similar to the experimental HRR curve. The results indicate that, in cases of this kind, the use of the semi-empirical FDS model provides much more conservative and better prediction, as well. The results also indicate that there exist strong effects of the heat transfer deterioration due to the local oxygen depletion and the heat transfer enhancement due to the presence of structures such as a wall and/or ceiling.
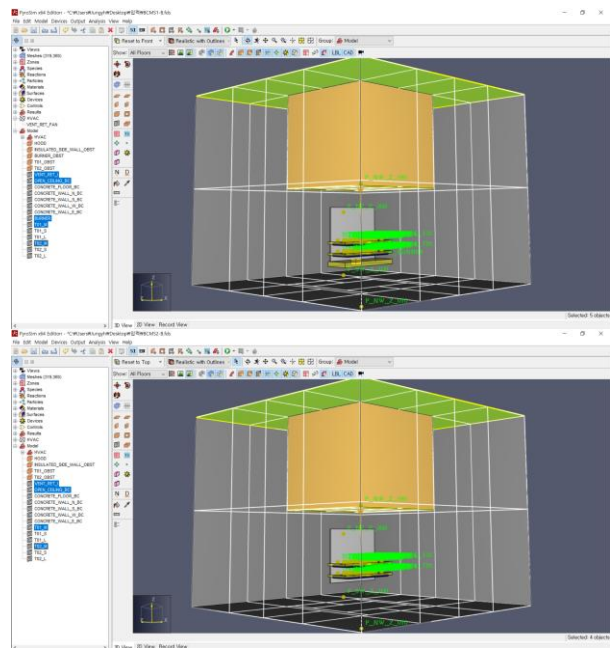

Fig. 8. PyroSim 3-D Layouts of Step #2.2 Benchmark Simulation (PRISME-3 BCM-S1/2 Test) FDS Model.
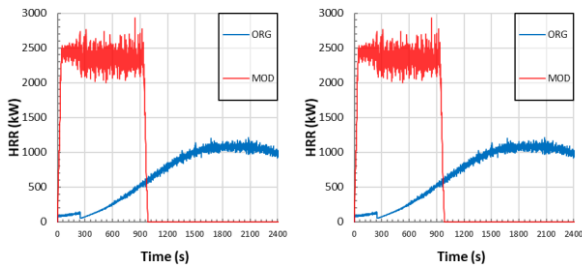
Fig. 9. HRR Time Evolution Curves of Cable Tray Fire of Step #2.2 Benchmark Simulation (PRISME-3 BCM-S1/2 Test) Predicted Using FLASH-CAT FDS Model (ORG) and Semi-Empirical FDS Model (MOD).

Table III. HRR Global/Local Errors of Cable Tray Fire of Step #2.2 Benchmark Simulation (PRISME-3 BCM-S1/2 Test) Predicted Using FLASH-CAT FDS Model (ORG) and Semi-Empirical FDS Model (MOD).

HRR Errors	**ORG** vs EXP	**MOD** vs EXP
Global	+9.81E-01 (S1) +1.07E+00 (S2)	+9.32E-01 (S1) +6.77E-01 (S2)
Local (Peak)	-4.52E-01 (S1) -4.59E-01 (S2)	+3.32E-01 (S1) +2.31E-01 (S2)

4. Concluding Remarks

The PRISME project has built up a significant experimental database and established an efficient international research network on the fire safety. The last PRISME project highlighted that the fire modeling codes are not yet mature enough to accurately predict the behavior of complex and real cable tray fire scenarios. Several promising approaches for modeling cable tray fires are being investigated under the PRISME/FIRE common benchmark exercise.

As PRISME-3 Korean participants, KAERI and KINS are performing the multi-step benchmark simulations. KAERI developed implementation strategies of the semi-empirical model in the CFD-based fire modeling tool FDS that can maximize the advantages of the semi-empirical model. The resulting semi-empirical FDS model is being used as a main modeling approach of KAERI and KINS.

The results of this study verified that use of the semi-empirical FDS model can enhance modeling accuracy of key phenomena found in complex and real cable tray fire scenarios, i.e., fire spread and propagation on a vertical stack of multiple horizontal cable trays, especially affected by environmental factors such as the local oxygen depletion and/or the presence of structures. The results and insights obtained through this study are expected to eventually contribute to evaluating fire-induced risk of NPPs in a more realistic and effective way.

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