

Modeling of Heat Release Rate of Horizontal Cable Tray Fire in PRISME CFS-2

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1. Introduction

The PRISME (PRopagation d'un Incendie pour des Scénarios Multi-locaux Elémentaires) is an OECD/NEA joint international research project to investigate heat and smoke propagation mechanisms in multi-compartment fire scenarios[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 with IRSN's specially designed facilities in Cadarache, called DIVA and SATURNE. The DIVA is 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. The SATURNE is a large enclosure equipped with a large-scale calorimeter in open atmosphere. 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.

In parallel to the experimental efforts within the Program Review Group (PRG), PRISME partners within the Analytical Working Group (AWG) have evaluated and improved the predictive capabilities of various fire modelling codes to simulate fire scenarios based on the PRISME experimental data. A number of benchmark exercises are one of these activities.

In the framework of the PRISME-3 AWG, it was proposed to perform a benchmark simulation for a real cable fire scenario in order to improve understanding and modeling methodology of key phenomena in complex and real fire scenarios in NPPs. This led to the joint activity of two OECD/NEA projects, PRISME-3 and FIRE, called the PRISME-3 and FIRE common benchmark exercise. In contrast to a well-controlled experiment, a real fire 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 (1) an open simulation of the PRISME-2 CFS-2 test, (2) a blind simulation of the PRISME-3 CFP test, and (3) a blind simulation of the real fire event from the FIRE project. 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.

The goal of the step #1 of the PRISME-3 and FIRE common benchmark exercise is to calibrate the fire modeling of participants with the CFS-2 test, for which the experimental data are available. It was proposed for all benchmark exercise participants to perform the first simulation of the step #1 using the prescribed HRR time evolution data as a reference simulation, and the second simulation using the HRR time evolution data determined in their own way. The HRR models suggested and simulation results based on them will be reviewed and discussed during the next PRISME meeting to reach a consensus for a common HRR modeling. This paper is aimed at presenting the strategy of the PRISME-3 Korean participants, KAERI and KINS, for step #1 simulation, especially focusing on the modeling of Heat Release Rate (HRR) or Mass Loss Rate (MLR).

Fire Dynamics Simulator (FDS) was used as a fire modelling code for the step #1 simulation. 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.

2. PRISME Cable Fire Tests

As part of the PRISME-2 project, a set of cable fire experimental tests were conducted to investigate fire spread phenomena over cable-related complex fire sources such as horizontal cable trays or electrical cabinets especially in a confined and ventilated multi-room configuration [1].

Seven (7) cable fire tests, called Cable Fire Spread (CFS), were conducted in confined and mechanically ventilated rooms of the DIVA facility. Among them, the CFS-1 to CFS-4 tests involved a fire source composed of a vertical stack of five (5) horizontal cable trays. Meanwhile, the CFS-5 to CFS-7 tests involved a fire source that consists of an open-door electrical cabinet and three (3) overhead cable trays. Four (4) cable fire tests, called Cable Fire Spread Support (CFSS), were conducted under a large-scale calorimeter of the SATURNE facility to characterize the fire source of five (5) horizontal cable trays in open atmosphere.

Eight (8) fire tests, called Complementary and REpeatability tests (CORE), were conducted for completing and repeating some of the fire tests carried

out during the PRISME-2 project. Among them, CORE-1, 2, 3, 4, and 7 tests were conducted for a vertical stack of five (5) horizontal cable trays with “different type of TP cables” (CORE-1), “protective” trays (CORE-2), “slanted” trays (CORE-3), and trays with “fire barriers” (CORE-4), and “lower renewal rate and fire door as a target” (CORE-7). Except for these highlighted conditions, all other experimental conditions were exactly the same as those of CFSS-1, 4 (CORE-1), CFSS-2 (CORE-2, 3, 4) and CFS-2 (CORE-7) tests, respectively. Whereas, CORE-6 test was conducted for an open-door electrical cabinet and three (3) overhead cable trays with “two (2) adjacent cabinets and a false floor as multiple targets”. Except for these highlighted conditions, all other experimental conditions were exactly the same as those of CFS-6 test. Lastly, CORE-5 and 8 tests were conducted for lubricant oil pool fires, and therefore, have no direct relevance to cable fires.

As part of the PRISME-3 project, additional cable fire tests, called Cable Fire Propagation (CFP), will be conducted. The primary object of these tests is to investigate the effects of under-ventilated fire conditions or a corridor configuration on cable fires.

3. CFS-2 Test

As explained above, the CFS-2 test is one of thirteen (13) cable tray stack fire tests conducted under the PRISME-2 project, and also the target of the step #1 of the PRISME-3 and FIRE common benchmark exercise.

3.1 Fire Source

The fire source of the CFS-2 test was a vertical stack of five (5) horizontal cable trays that are filled with forty four (44) Halogenated Flame Retardant (HFR) type control cables made of Poly Vinyl Chloride (PVC) material, and thus, classified as a ThermoPlastic (TP) cable rather than a ThermoSet (TS) cable. This type of cable was also used in the CFSS-4 and CORE-7 tests. An important thing to note for the cable tray stack is that it is set up against an insulated side wall.

A square propane sand burner was installed below the first horizontal cable tray and at its center, and used to ignite the cable tray stack during the tests. The starting time of the burner operation corresponds to the onset of the test.

3.2 Ventilation and Compartment

The CFS-2 test was conducted in confined and mechanically ventilated two rooms of the DIVA facility with Ventilation Renewal Rate (VRR) of 15 h^{-1} , and therefore, classified as a well-ventilated fire condition rather than an under-ventilated fire condition. Such a high VRR of 15 h^{-1} was also used in the CFS-4 test.

Only room R1 and room R2 of the DIVA facility were used for the CFS-2 test. The fire source, i.e., the cable tray stack was located in R1 (the fire room)

against the west wall of the room. The room R2 (the adjacent room) was connected to the east side of the R1, and communicated with the R1 through an open doorway on the common concrete wall located between them.

Two (2) rooms were also connected with the ventilation network of the DIVA facility equipped with supply and exhaust fans through the inlet duct located in the fire room and the outlet duct is located in the adjacent room. Because two (2) rooms have a total volume of about 240 m^3 , the volumetric flowrate that corresponds to the VRR of 15 h^{-1} is expected to be initially about $3600 \text{ m}^3/\text{h}$.

3.3 Experimental Data

The CFS-2 test implemented about 250 sensors to measure heat flux, gas temperature, pressure, gas and soot concentrations mainly in the fire room and the adjacent room, as well as gas velocity through the doorway between these two (2) rooms. The main experimental data selected for comparison with simulation results and the associated measurement points were provided to all benchmark exercise participants by IRSN [2].

The MLR was measured during the experiment using the weighting system located beneath the cable tray stack. The HRR was determined by both thermal and chemical methods. Gas temperatures of the fire room were measured using three thermocouple (TC) trees located at the NW, NE, and SE corner of the fire room. Concentrations of oxygen and combustion products such as carbon dioxide and monoxide were also measured at three different elevations in the SE corner of the fire room.

4. Modeling of Heat Release Rate

4.1 Experimental Data

As explained above, the MLR was measured during the experiment and the HRR were determined based on that. The first simulation was performed using this prescribed HRR time evolution data as a reference simulation. The results of this reference simulation were compared with those of the second simulation as well as the experimental data.

S. Bascou et al. [3] performed cable fire simulations for the CFSS-2 test conducted in open atmosphere and the CFS-3 & 4 tests conducted in the confined and mechanically ventilated condition using the CFD-based CALIF3S/ISIS. In their CFS-3 & 4 simulations, they calculated an equivalent fuel MLR based on the experimental HRR as a function of time and the average EHC evaluated in the experiment, and applied this equivalent MLR uniformly onto the top faces of all five (5) horizontal cable trays as a fire boundary condition for the entire duration of the simulation.

The same HRR modeling approach was employed in our first, i.e., reference simulation for the CFS-2 test. Time evolution of MLR measured or HRR determined from the CFS-2 test was uniformly applied onto the top faces of all five (5) horizontal cable trays as a fire boundary condition for the entire duration of the simulation.

It is obvious that this approach is only applicable to simulations for the experiment under control, but not to complex and real fire events due to the lack of available data. In addition to that, as emphasized by S. Bascou et al., this approach cannot separately take into account the effects of some local pyrolysis and combustion phenomena as well as horizontal outward spread and vertical upward propagation of cable fire along the length of a tray and to the next tray above. These are the reasons why we need to develop a methodology for cable fire modeling.

4.2 FLASH-CAT Model

As explained above, all benchmark exercise participants are required to perform the second simulation using the HRR time evolution data determined in their own way. The second simulation was performed based on the FLASH-CAT (FLAME Spread over Horizontal Cable Trays) model [4, 5, 6]. The results of this FLASH-CAT simulation were compared with those of the first, i.e., reference simulation as well as the experimental data. The FLASH-CAT is a simple flame spread model for horizontal tray configurations that uses semi-empirical estimates of lateral and vertical flame spread and measured values of combustion-related data of cables. Fig. 1 shows time evolution of HRR of the CFS-2 test assessed using the FLASH-CAT model and that determined from the experiment. As shown in Fig. 1, the HRR time evolution assessed using the FLASH-CAT model clearly differs from the experimental data in that the former has slower growth rate, higher peak, and shorter fire duration in comparison to the latter.

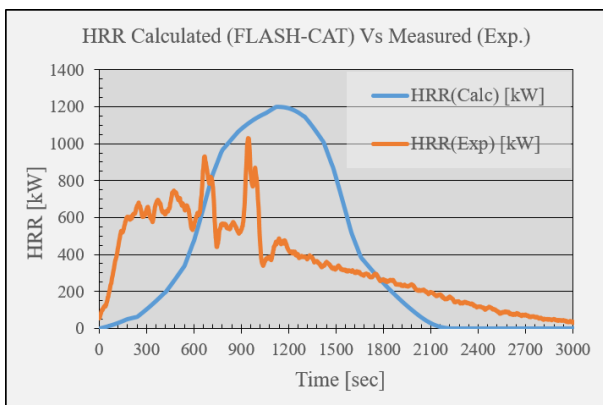


Fig. 1. Time Evolution Curves of HRR of Horizontal Cable Tray Fire of CFS-2 Test Determined from the Experiment and Assessed Using FLASH-CAT Model.

One of important assumptions of the FLASH-CAT model is that the cables burn in the open environment, in other words, they are away from walls and well below the ceiling. However, the cable fire tests conducted in PRISME-2 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 characteristics. More specifically, the support wall facilitates the heat transfer from the hot gas plume to the unburnt cables.

P. Zavaleta et al. [7] modified the FLASH-CAT model mainly based on their video analysis results for better prediction of HRR time evolutions of the CFSS-1, 2, 3 and CORE-1 tests.

One of their FLASH-CAT modifications is related to the spread parameters such as the horizontal spread rate V_H and the ignition time of each cable tray (for vertical propagation) t_{ig} . They proposed to set the horizontal spread rate V_H for the 1st, 2nd, 3rd, 4th, 5th trays to 3, 3, 6, 6, 6 mm/s, respectively, for the TP cables, and to 1, 1, 2, 2, 2 mm/s for the TS cables, instead of using the FLASH-CAT recommended values 0.9 mm/s for the TP cables and 0.3 mm/s for the TS cables without distinction of tray. They also proposed to set the ignition time of cable tray t_{ig} to 1, 2, 3, 4, 5 min for the 1st, 2nd, 3rd, 4th, 5th trays, respectively, at an interval of one minute for the TP cables. For the TS cables, they proposed to set the ignition time of cable tray t_{ig} to 5, 9, 12, 14, 15 min at 5-4-3-2-1 minute intervals, the same as the FLASH-CAT recommended values, because video analysis results indicated that they are similar to the recommended values. It is believed that the enhanced heat transfer from the hot gas plume to the unburnt cables by the support wall strongly affected the video analysis results, and consequently, the modification of spread parameters.

In addition to the modification of spread parameters, they also proposed to double the width of the cable tray used for calculating the burning area $A(t)$ and local fire duration Δt_f in the FLASH-CAT model. This was derived from the idea that both the top and bottom areas of cable trays are involved with the fire and heat release in ladder-type open cable trays. Lastly, they also proposed to set the char (residue) yield ν to 0.25 for TP cable, instead of using the FLASH-CAT recommended value 0 based on the experimental data.

P. Zavaleta et al. finally compared HRR time evolution assessed using modified FLASH-CAT model with the experimental HRR time evolution. As indicated in their paper, the results showed good agreement with the experimental data. However, it should be noted that part of this study is based on video analysis results of the CFSS-1, 2, 3 and CORE-1 tests conducted in the open atmospheric condition, and therefore, not directly applicable to other cable fires including the CFS tests conducted in the confined and mechanically ventilated condition.

4.3 Semi Empirical Model

W. Plumecocq et al. [8] developed a semi-empirical model of horizontal cable tray fire in confined and mechanically ventilated condition that is partly based on the approach used in the FLASH-CAT model and on experimental findings from the PRISME-2 cables fire tests. They implemented this semi-empirical model in the two-zone based SYLVIA and performed simulations for the CFS-1 to 4 tests conducted in confined and mechanically ventilated condition.

In this study, the HRR was modeled by basically using the empirical correlation for the peak HRR of the cable fire developed by Lee [9] and by additionally applying the correction factor to take into account the effect of the oxygen depletion in the confined and mechanically ventilated enclosure on the MLR or HRR. The correction factor is represented as a linear function of the dimensionless fuel MLR ranging from 0 to 1 according to the oxygen volume fraction available for combustion near the flame base, i.e., the fuel surface ranging from 11% to 21% based on the oxygen-limiting law proposed by Peatross and Beyler [10].

The fire extinction time was estimated by calculating the mass loss per unit length considering the correction factor, and comparing it to the mass of the fuel per unit length. The horizontal outward fire spread rate along the cable length was modeled based on the spread law proposed by J. Quintiere [11]. The ignition time of each cable tray (for vertical upward fire propagation) was estimated by calculating the temperature at the internal sheath surface of each cable tray, and comparing it to the ignition temperature of the cable.

The implementation of this semi-empirical model into the FDS is more complex and difficult process than that of the FLASH-CAT model. This semi-empirical model will be used for the second simulation as an alternative to using the FLASH-CAT model.

5. Concluding Remarks

The PRISME project has built up a significant experimental database and established an efficient international research network on the fire safety. The latest benchmark exercise of the PRISME project highlighted that the fire simulation codes are not yet mature enough to accurately predict the behavior of complex cable fire scenarios. Several promising approaches are being investigated in the PRISME-3 and FIRE common benchmark exercise.

As a HRR modeling strategy of cable fires, the PRISME-3 Korean participants, KAERI and KINS, adopted the FLASH-CAT based semi-empirical model developed and implemented into the two-zone based SYLVIA by W. Plumecocq et al. [8]. This model will be implemented into the CFD-based FDS which can provide more accurate prediction of fire environments within more complex configurations. This effort is

expected to improve understanding and modeling accuracy of key phenomena found in complex and real cable fire scenarios caused by environmental factors such as the presence of a support wall and local oxygen depletion.

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