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Common Cable Fire Benchmark Activity of the OECD Nuclear Energy Agency PRISME 3 and FIRE Projects

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ABSTRACT

Based on a request from the OECD Nuclear Energy Agency (NEA) FIRE project in 2016, the recommendation was given by the PRISME 2 Program Review Group (PRG) that there should be a common benchmark exercise on a realistic cable fire scenario in an electrical system being as far as reasonably practicable representative of a real cable fire event recorded in the FIRE Database, using information on electrical cable fires from the OECD/NEA PRISME Projects.

The FIRE database has clearly demonstrated the significance of fire events involving cables and shows that a majority of these events were either safety related or had the potential to impair nuclear safety. Both PRISME and PRISME 2 cable fire experiments have significantly increased the knowledge on cable fire behavior and investigated various types of cables implemented in nuclear power plants (NPPs) in member states. The major goal of this benchmark exercise is to simulate a real cable fire scenario in order to assess and compare the capabilities of different types of fire simulation codes to model such a complex and realistic fire scenario.

The strong interest of experts from regulators, technical safety organizations (TSOs) and licensees in predicting cable fires shows that such a Benchmark Exercise is a unique opportunity for cross-cutting work between experts from the OECD FIRE and PRISME Projects. Due to the high expert interest, a decision was made to open the common OECD PRISME 3 and FIRE Benchmark Exercise to other CSNI member countries.

The real fire event selected for the Benchmark Exercise from the FIRE Database, covering more than 500 fire events, occurred in a heater bay of a NPP and involved two electrical cable trays loaded with PVC insulated cables. Since a numerical Benchmark on a real fire event is quite challenging, the following three-step methodology for conducting this Benchmark Exercise has been proposed: (1) a calibration phase, (2) a blind simulation of a PRISME cable fire experiment, and (3) the real fire event simulation. This methodology is based on the fact that a similar behavior is expected between the steps 2 and 3 making it possible to extrapolate the error estimation.

Keywords : Benchmark, Cable tray fire, FIRE Database, PRISME-3

1 INTRODUCTION

Based on a request from the OECD Nuclear Energy Agency (NEA) FIRE project in 2016, the 10th PRISME 2 Program Review Group (PRG) made recommendation that there should be a common benchmark exercise on a realistic cable fire scenario in an electrical system being as far as reasonably practicable representative for a real cable fire event included in the FIRE database, using information on electrical cable fires from the OECD/NEA PRISME Projects.

The FIRE database [1] has clearly demonstrated the significance of fire events involving cables and shows that a majority of these events were either safety related or had the potential to impair nuclear safety. On this topic, both PRISME and PRISME 2 [2] cable fire experiments have significantly increased the knowledge on cable fire behavior and investigated various types of cables implemented in nuclear power plants (*NPPs*) in member states.

Through this benchmark exercise (BE), the main goal is to simulate a real cable fire scenario in order to assess the behavior of fire models for such a complex and real fire scenario, from the knowledge available so far.

The strong interest of experts from regulators, technical safety organizations (TSOs) and licensees in predicting cable fires shows that such a BE is a unique opportunity for cross-cutting work between experts from the OECD FIRE and PRISME Projects. Due to the high interest, a decision was made to open the common OECD PRISME 3 and FIRE benchmark exercise to other CSNI member countries.

The real fire event selected for the BE from the FIRE database, covering more than 500 fire events, occurred in a heater bay of a NPP and involved two electrical cable trays loaded with PVC insulated cables. Since a numerical benchmark on a real fire event is quite challenging, the following three-step methodology for conducting this BE has been proposed: (1) a calibration phase, (2) a blind simulation of a PRISME cable fire experiment, and (3) the real fire event simulation. This methodology is based on the fact that a similar behavior is expected between the steps 2 and 3 making it possible to extrapolate the error estimation.

The FIRE Event Simulation Exercise (FREESE) dedicated website for this benchmark activity was created and is now available on the IRSN gforge website at the following address: <https://gforge.irsn.fr/gf/project/freese/>.

Benchmark participants come from Belgium, Canada, Finland, France, Germany, Japan, Korea, Spain, Sweden, the United Kingdom and the United States of America.

The benchmark methodology, as well as the tools used to quantify the differences between simulation results and experimental data, are presented in section 2. Section 3 briefly describes the real fire event selected from the OECD FIRE database and whose simulation will be addressed during the third step of the benchmark. Results for predictive simulations of the first step are presented in section 4. The overall conclusions on the work done so far and future plans are presented in section 5.

2 PRESENTATION OF THE BENCHMARK

2.1 Benchmark Methodology

Contrary 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 simulating such an event is therefore very challenging. Based on the fact that a code-to-code comparison is still possible, a three-step methodology is proposed.

The first step (#1) consists of a calibration phase, i.e. in simulating a well-controlled fire scenario (a cable fire test from the PRISME 2 project) for which all the experimental data and uncertainties are available and provided to the participants. The second step (#2) will consist of a blind simulation of a cable fire experiment from the PRISME 3 project. Only the

input data will be accessible to the participants, the output data will not be provided to them. Finally, the last step (#3) will consist in performing a real fire event simulation on the basis of the available information, recorded in the FIRE database. This methodology is based on the fact that a similar behavior is expected between step #2 and step #3 making it possible to extrapolate the error estimation.

The three phases are described below:

- Step 1: Calibration phase on a cable fire experiment.
 - The goal is to calibrate the fire models of each participant using a cable fire experiment from the OECD PRISME 2 project (CFS campaign [3-4]). The choice of the fire experiment is based on the cable type and ventilation renewal rate that should be as close as possible to the real fire event characteristics,
 - Features: open calculation, experimental data available, assessment of numerical versus experimental results (error estimation), assessment of the relative behavior of numerical results (behavior estimation).
- Step 2: Blind simulation phase of a cable fire experiment.
 - The goal is to simulate a cable fire scenario from PRISME 3 in blind condition (CFP campaign). The fire test selection also depends on the cable type and ventilation renewal rate that should be as close as possible to the real fire event characteristics.
 - Features: blind calculation, experimental data available after completion of the test, assessment of numerical versus experimental results (error estimation), assessment of the relative behavior of numerical results (behavior estimation).
- Step 3: Blind simulation phase of the real fire event.
 - The goal is to simulate a real cable tray fire event coming from the OECD FIRE database.
 - Features: blind calculation, few output data available, few assessment of numerical versus event results, assessment of the relative behavior of numerical results (behavior estimation).

2.2 Error estimation

The error estimation is aimed at quantitatively comparing the difference between a simulation result (the output) and an experimental result and between several simulation results.

The output quantities selected for comparison are chosen from the usual fire quantities: the fire heat release rate, the fuel mass loss rate, gas temperatures, oxygen and carbon dioxide concentrations, relative pressure, mass flowrates at the inlet and outlet branches of the ventilation network, and wall temperature.

An orientation chosen at the beginning of the exercise was that the quantities must be calculated by every code. Computational fluid dynamics and zone models can be distinguished on some quantities but common values, usually the average in space, should make the link.

A previous work on quantifying the differences between simulation results and experimental results was made in the framework of the PRISME-Source program [5]. It dealt with a pool fire scenario in a confined and mechanically ventilated compartment. Authors of this document detailed many ways for quantifying differences between numerical and experimental results. Quantifying the capabilities of fire models can be made by using metric operators as suggested by the ASTM guide [6], which may depend on the characteristics of the data (single point comparison, steady-state regime or time-dependent values).

The mathematical methods first depend on the characteristics of the studied data and a distinction is made between a single point comparison, steady-state comparison, and time-dependent values.

For a single point comparison, the data do not depend on time and space. It is typically a peak value, either a minimum or a maximum value, e.g. a temperature peak, a critical oxygen concentration, or a pressure peak etc. In this case, the quantitative comparison can be made using an absolute or relative difference. Based on the work of [5], the normalized relative difference seems to be well appropriate for this study. It enables to take into account the initial state of the calculation as a reference state and to avoid any unit troubles. It is called the local error and expressed as follows:

$$\epsilon_{local} = \frac{(y - y_0) - (x - x_0)}{x - x_0}$$

where “x” is the experimental value and “y” is the numerical one, and “x₀” and “y₀” are the initial values.

For a steady-state regime, in the case of stationary systems or low-fluctuation quantities, it is recommended to compare the average difference.

For time-dependent values, the numerical result is compared with the experimental values all over the fire scenario duration. These time-dependant quantities can be either averaged in space (important for comparison with zone code results) or measured at a specific point (comparison with CFD codes). This approach introduces the concept of vector norms. In that case, the difference is called the global error and is defined as the normalized Euclidean distance between two vectors and expressed as follows:

$$\epsilon_{global} = \frac{\|\vec{y} - \vec{x}\|}{\|\vec{x}\|} = \sqrt{\frac{\sum_{i=1}^n (y_i - x_i)^2}{\sum_{i=1}^n (x_i)^2}}$$

To perform such a calculation, it is required to interpolate the numerical and experimental data to a common time discretization with a constant time-step [5].

Obviously, metrics can be used to conduct both code-to-experiment and code-to-code comparisons.

Simulation results will be compared to the experimental results and also to the mean simulation results, obtained by calculating the average value from all the simulations. The difference between the mean simulation and the experimental results will also be assessed

making the link between the simulation trends and the experiment in the manner of an expert panel review. This last point is particularly important for the last step of the benchmark on the simulation of the real fire event whose output results for comparison are limited. Consequently, the mean-simulation should be foreseen to act as a reference base for extrapolating the error estimations.

3 FIRE EVENT FROM THE OECD FIRE DATABASE

3.1 Event selection criteria

In May 2017, the latest version of the OECD FIRE database, called 2016:01, was released gathering nearly 500 fire events.

The criteria for the cable tray fire event selection, prescribed by the PRISME 2 PRG members, are the following:

- a cable fire scenario with flames and smoke;
- a quite recent event (from the last 10 years);
- a sufficiently well-documented event;
- the significance of being able to receive additional information;
- the closeness to PRISME cable fire experimental scenarios;
- preferably only one compartment involved by the fire;
- a fire duration between 15 min and 60 min.

A shortlist of four potential candidates was presented at the third PRISME 3 meeting in April 2018 giving a quite detailed description of the ignition phase and sequence of the events from the available information so far. Further investigations were carried out to gather as many data as possible. To do so, licensees concerned by these events were contacted by the National Coordinators of the corresponding countries. Based on these investigations, the ability of gathering enough data on the event from licensees supporting the activity was the decisive criterion for the final event selection.

An agreement on the selection of the event presented in chapter 3 was reached during the first benchmark meeting held in Aix-en-Provence, France, in November 2018.

3.2 The selected event

Authors emphasize that specific details on the fire event, in particular the power plant name, remain undisclosed due to confidentiality matters.

The fire event occurred in 2014 in the heater bay of the turbine building of a nuclear power plant. The fire involved two 90-cm-wide horizontal cable trays loaded with PVC insulated cables and was caused by a non-conforming cable routing. The fire started by the self-ignition of power cables due to an arc fault. It was initiated when the high humidity and condensate from a steam leak provided the environment necessary for the existing flaw in an electrical cable to fault to ground. The source of the cable flaw was identified as routing inconsistent with the current standard for minimum static bend radius for this type and size of cable, i.e. resting across rungs on a horizontal cable tray and exiting at a sharp angle downward into a 12-m vertical run, as illustrated in Fig. 1.

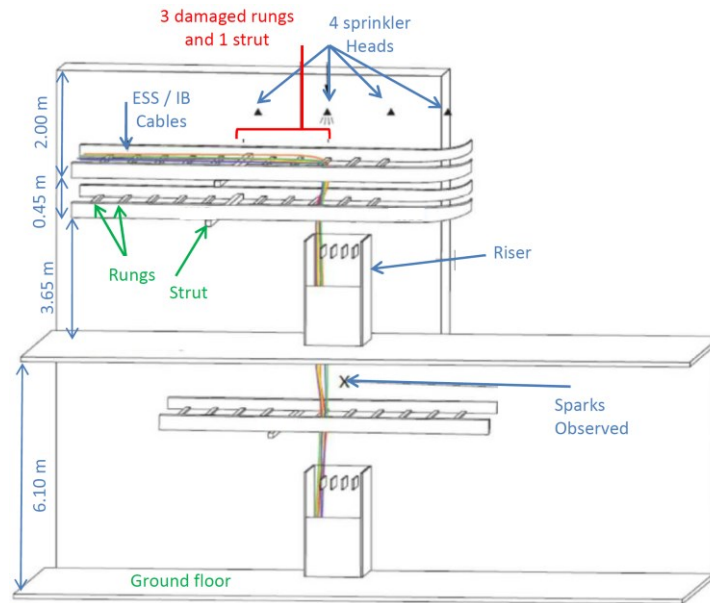


Fig. 1. Front view scheme of the heater bay and IB-ESS cable routing.

The fire duration between ignition and extinguishment by wet pipe sprinkler was estimated to be about 20 min (± 2 min). Investigations lead by the licensee provided a detailed description of the fire behavior and sequence of the event detailed hereafter.

The non-conforming cable routing concerned three Instrument Bus (IB) and three Essential Service (ESS) cables. The arc fault from one of the six cables to the rung at the exit point damaged the insulation of nearby cables and heated the rung, leading to the severing of five (2 IB and 3 ESS) of the six cables. This conclusion is based on in-situ examination noting the remaining riser portion of each of the five cables, of equal length, with severed ends at the rung, and the remaining horizontal portions of two of the ESS bus cables also aligned with the rung. When they were severed, the two line cables for the IB feed arc faulted together. These cables continued to arc fault until approximately 61 cm of copper had been consumed from each of the IB line cables.

The arc fault between the IB line cables ended at a strut support, as evidenced by the ends of the IB cables being found aligning with and in the melted portion of the strut. It is likely that the breaker for the IB feed tripped at this time, as evidenced by the remaining intact copper. The total time from the initial arc fault to the IB feed breaker trip is estimated to be about one minute and corresponds to the time when sparks were observed outside the heater bay (see Fig. 1), and the time of the swap of the IB from its main feed to a backup feed.

The fire in the bottom tray was started by debris falling from the fire in the top tray. This is evidenced by the concentration of the damaged cable in the upper levels of the bottom tray, with the lower levels undamaged or much less damaged. Additionally, there is no example of melted copper conductor in the bottom tray. The fire in the bottom tray appears to have continued to burn until extinguished by the suppression system.

There were four sprinkler heads located in the vicinity of the fire, at about 1.20-1.50 above the top tray. The sprinkler heads initiate by thermal links set to break at 100°C. The heat generated by the fire caused flow from only one of the four sprinkler heads in the area. Laboratory testing determined that the three un-initiated sprinkler heads had no existing

flaws and were physically capable of responding if required to initiate. The sprinkler head that did initiate suppressed the cable tray fire.

3.3 Available results from the fire event

This paragraph presents additional results of post-event examination. At the exit point from the top tray (see rung location on Fig. 2), cables were severed and the applicable jacket/insulation had been removed due to excessive heat. Initial inspection showed localized fire damage in the shape of a semicircle 76 cm long and 51 cm wide (Fig. 2). Charring was present throughout the entire depth of cables in that section (approximately 15 cm deep). The extent of cable damage in this region included cables severed, cable jacket/insulation damage, cable jacket/insulation completely removed and sections of cable missing. The most extensive charring and damage was noted on the cables located on the bottom of the top tray with signs of an arc flash. Initial inspection of the bottom tray showed localized fire damage in the shape of a semicircle approximately 102 cm long and 66 cm wide (Fig. 2). Charring was present throughout the top 10 cm of cables in that section. Molten drip could be seen on top of numerous cables in the bottom tray (tests subsequently verified that cuprous oxide was present in large quantities on the cables of the bottom tray).

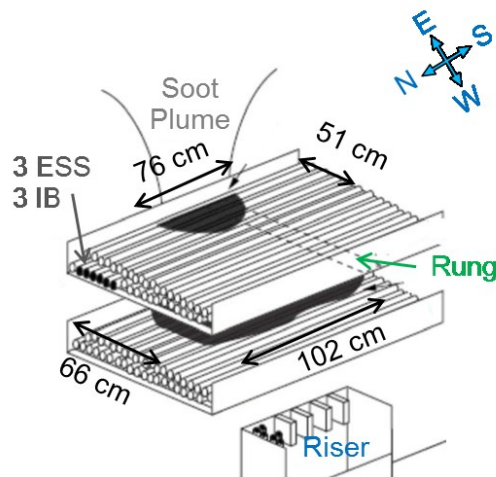


Fig. 2. Damage pattern of the trays.

Signs of minor concrete spalling were observed on the diagonal concrete overhang located above the affected cable trays. The smoke damage to the wall formed a v-pattern that had a wide shape that extended to the ceiling, indicating a slow burning fire.

Severe degradation was noted on a 9-cm thick strut located just north of the semicircle fire damaged area (Fig. 1). More damage was present on the south side of the strut than on the north side and the top of the strut was completely melted between the north and south sides. Three rungs located south of the affected strut and north of the riser had sections completely melted through.

Additional degradation was noted on the east side of the top tray, which consisted of the east cable tray side wall bowing away from the fire. This bowing was locally centered in the semicircle fire damage previously noted.

4 CURRENT STATUS AND PROGRESS

Investigations made by the National Coordinator with the licensee indicated that several cable types were involved in the fire, all of them contained chlorine. During the fire, there was no forced ventilation in the fire room which is about 30 m x 5 m x 6 m. Considering the large dimensions of the fire room and the restricted propagation and location of the fire (see paragraph 3), the oxygen limitation on the fire is supposed to be small. This information leads to the selection of the PRISME-2 CFS-2 experiment [4] characterized by the highest ventilation renewal rate ($15h^{-1}$) and a stack of five cable trays loaded with PVC cables for the open simulation in step#1.

The first simulation results for step#1, not shown in this work, were presented during the second benchmark meeting held in May 2019. These results consisted in the prescribed simulation of CFS-2, i.e. using the experimental heat release rate measured during the experiment as an input data. Nine simulations with five different fire models were performed.

A second set of simulation results concerned predictive simulations of the CFS-2 experiment. Seven predictive simulations were performed, as indicated in Table 1.

These simulation results for the heat release rate (HRR) and mass loss rate (MLR) are presented in Fig. 3 and Fig. 5. **Erreur ! Source du renvoi introuvable.** The mean-simulation values, as well as the minimum and maximum values, are given in Fig. 4 and Fig. 6.

Error values from the comparison with the experiment are indicated in Fig. 7 and Fig. 8 for the simulation results, as well as for the mean-simulation:

- the relative difference compared during the first 500 s « ϵ_{local_1} vs EXP»,
- the relative difference compared during the first 2000 s « ϵ_{local_2} vs EXP»¹,
- the normalized Euclidean distance during the first 500 s « ϵ_{global_1} vs EXP»,
- the normalized Euclidean distance during the first 2000 s « ϵ_{global_2} vs EXP».

Table 1. Participants in the predictive phase of step#1.

Simulation	Software	Organization
CFD 2	ISIS	IRSN
CFD 4	COCOSYS ²	GRS
CFD 5	FDS	NRC
CFD 6	FDS	IBMB
CFD 7	FDS	VTT
ZC 1	SYLVIA	IRSN
ZC 2	BRI2002	CRIEPI

¹ Available for the MLR only in order to avoid considering peaks due to the fast combustions under the ceiling (550s-1200s) which are unpredictable (or at least not in the scope of the benchmark).

² COCOSYS is a lumped parameter software but it is considered as a CFD model in the post processing of the results since all the “CFD-required” quantities were provided (e.g. temperatures at several elevations).

As illustrated in Fig. 3, participants performing predictive simulations of the CFS-2 experiment obtained results in good accordance with the experiment, with some under or overestimations or time shift.

The HRR peaks during the first 500 s of the transient are predicted within the range of -15% up to +17% (see ϵ_{local_1} in Fig. 7). The mean simulation underestimates the HRR peak by about 6% and it can be seen on Fig. 4 that the predicted evolution is smoother than the experimental one characterized by some oscillations where the experimental peak value is reached. Concerning how close curves are, it can be seen that the mean simulation has a global error of about 8% over the first 500 s and 25% all over the first 2000 s of the transient.

Global values calculated over the period when fast combustions occur under the ceiling get large due to sharp unpredictable evolutions leading to large distances between the curves.

The MLR peaks during the first 500 s of the transient are predicted within the range of 5% up to +18% and between -9% to 20% during the first 2000 s (see ϵ_{local_1} and ϵ_{local_2} respectively in Fig. 8). The mean simulation overestimates the MLR peak by about 5% over the first 500 s and it underestimates the global peak by about 4%. It can be seen on Fig. 6 that the mean simulation is very close to the experimental one and that the latter is encompassed in the minimum and maximum values of the predictions. The mean simulation has a global error of about 12% over the first 500 s and over the first 2000 s of the transient.

The simulation results are very satisfying in particular when keeping in mind that simulating predictive cable tray fires in confined conditions is a difficult task. Resorting to a mean simulation also seems to be relevant to be considered as an expert opinion as raised in paragraph 2.2.

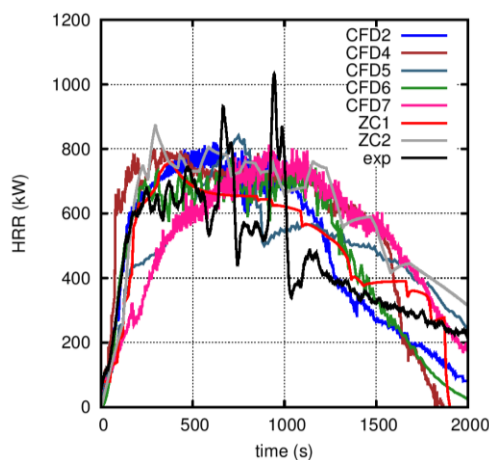


Fig. 3. Predictive simulation results of the HRR for step#1, comparison with the experiment.

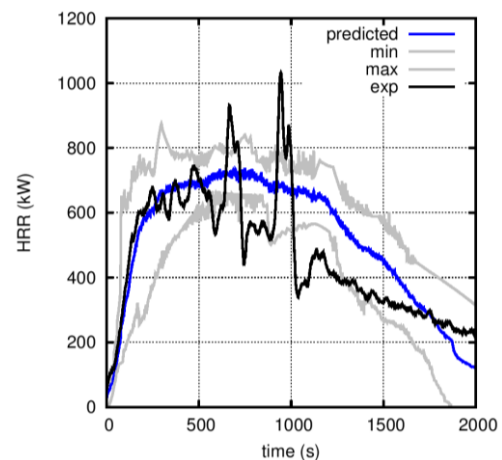


Fig. 4. Minimum, maximum and average simulation values of the HRR of step#1.

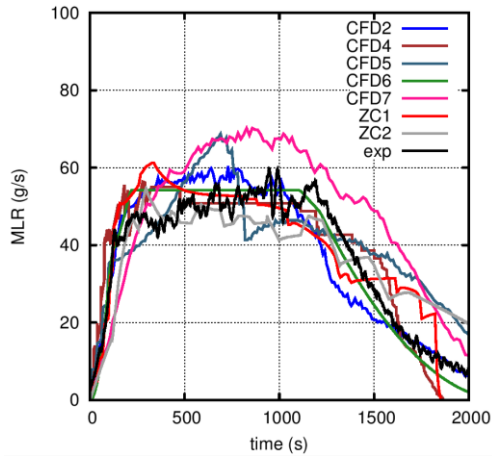


Fig. 5. Predictive simulation results of the MLR for step#1, comparison with the experiment.

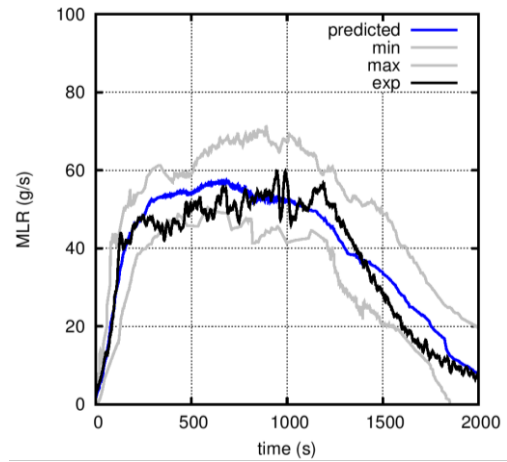


Fig. 6. Minimum, maximum and average simulation values of the MLR of step#1.

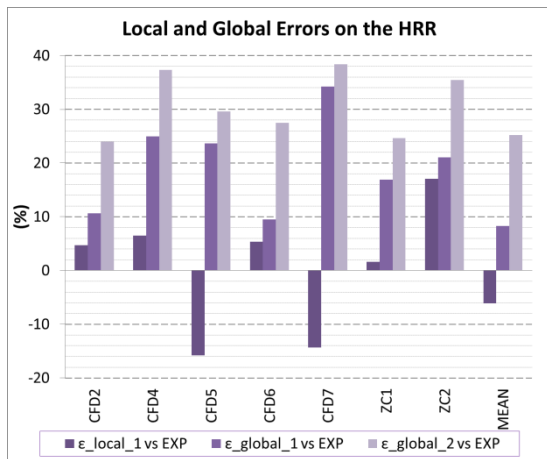


Fig. 7. Local and global errors on the HRR for the predictive phase of step#1.

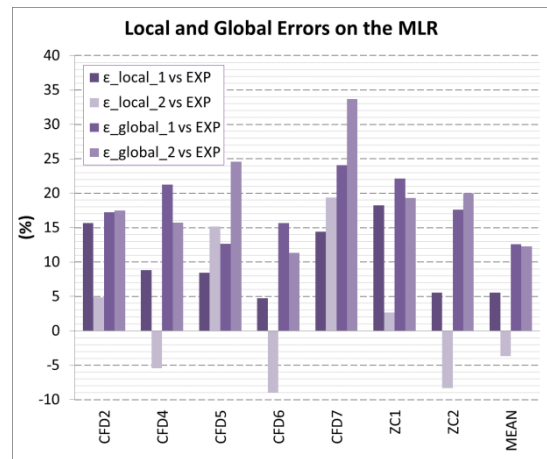


Fig. 8. Local and global errors on the MLR for the predictive phase of step#1.

5 CONCLUSION AND DISCUSSION

This document presents the methodology that is proposed to assess the capability of simulation softwares to model a real fire scenario like an event recorded in the database of the OECD FIRE project with the knowledge brought by the OECD PRISME experimental projects.

The proposed methodology features three steps. It consists of a calibration phase on the CFS-2 experiment from the PRISME 2 project, a blind simulation of an experiment to be performed during the PRISME 3 project, and the real fire event simulation. Metrics operators namely the local error on peak values and the global error defined as the normalized Euclidean distance between two vectors are used to quantify the differences between the simulation results and experimental ones. The 3-step methodology is based on the fact that

a similar behavior is expected between step#2 and step#3 making it possible to extrapolate the error estimation of step#3 for which comparison points are few.

The real fire scenario is an event that took place in the heater bay of a nuclear power plant in 2014. The fire involved two electrical cable trays loaded with PVC insulated cables. The fire was initiated by an arc flash on cables whose routing was non conforming thus creating an existing flaw. The fire propagated from the upper tray down to the lower tray by falling debris and continued to burn for about 20 min before being extinguished by a sprinkler. Damages to the electrical equipment included cable severed, cable jacket and insulation damaged or completely removed, extensive charring and sections of cable missing with melting of the copper conductor. The extent of the damages is quite limited with a length of cable tray burnt about 1 m.

First simulation results are presented for the first step of the benchmark with predictive simulations of the CFS-2 experiment. Local errors on peak values for the heat release rate and mass loss rate are calculated, as well as the global errors on different portions of the fire scenario. These error values illustrate that the simulation results are satisfying, in particular for predictive simulations of cable tray fires. The mean simulation is calculated as a post-processing of the simulation results in order to be used as a reference in the manner of an expert panel opinion. For example, the local and global errors on the mass loss rate for the mean simulation are about 5% and 12% respectively.

The next step in the benchmark activity is the blind simulation of an experiment to be performed during PRISME 3 with the same type of fire source as in the CFS-2 experiment and in a corridor configuration. The error values between the blind simulations and the experimental results will be performed once the experimental results are available. Local and global error between the simulation results and the mean-simulation values can be calculated whenever needed throughout the benchmark.

A continuous task of the benchmark is also to improve the understanding of the real fire event, its ignition mechanisms and the circumstances that lead to the post-event observations as a preparation work for step#3.

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