
Collaboration on fire code benchmark activities around the international fire research program PRISME

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Abstract:

The French Institut de Radioprotection et de Sûreté Nucléaire (IRSN), performs fire experiments in confined and mechanically ventilated compartments. These fire scenarios are considered as typical ones in the nuclear industry and cover experiments at large scale, aiming to comply with fire modelling and fire hazard expertise needs. Among these programs, the OECD/NEA/CSNI PRISME fire research program conducted in an international frame deals with smoke and heat propagation mechanisms in multi-compartment fire scenarios, representative for nuclear plants. The PRISME Project includes several organizations from in total twelve OECD/NEA member countries.

At the same time, the partners evaluate the capabilities of fire codes to simulate fire scenarios based on the PRISME tests in the PRISME Benchmarking Group. Exercises are proposed and the analysis of the results allows exchanging the different points of view on the limitations of the fire codes, on the lack of knowledge, and on the validation process.

1 INTRODUCTION

The PRISME program (French acronym for “Fire Propagation in Elementary Multi-room Scenarios”) mainly aims on studying smoke and hot gases propagation in full scale, well-confined and mechanically ventilated fire compartments. In particular, the goals of the PRISME program are to understand and quantify, by means of an analytical approach, the propagation mechanisms of smoke and heat from a fire compartment towards one or several adjacent compartments in scenarios representative for nuclear plants. This also covers the feedback effects of vitiated air due to smoke and combustion products on fire source itself. This work is carried out in the framework of an international OECD (Organization for Economic Co-operation and Development) / NEA (Nuclear Energy Agency) / CSNI (Committee on the Safety of Nuclear Installations) project with partners from twelve member countries: Belgium (BEL V and SUEZ-TRACTEBEL), Canada (AECL), Finland (STUK and VTT), France (IRSN, EDF and DGA), Germany (GRS, iBMB, BfS), Japan (JNES), South Korea (a consortium represented by KINS), the Netherlands (VROM-KFD, NRG), Spain (CSN), Sweden (RINGHALS), UK (HSE) and USA (NRC).

Up to the time being, three separate effects test campaigns have been performed: PRISME SOURCE, PRISME DOOR and PRISME LEAK. The PRISME SOURCE series aim on characterizing the fire source in an open atmosphere as well as in confined and ventilated conditions. The objective of the two others series is to independently characterize the propagation modes involving several rooms and to quantify their respective weights, by mutual comparison, on the consequences of a fire for the neighbouring rooms. The

propagation mechanisms studied are: through an opening (door), through leakages and by a ventilation duct that crosses the room containing the fire and that ventilates an adjacent room. In 2010, global tests will be performed. Real fire sources such as cable trays or electrical cabinets will be used. The effects of sprinklers and fire dampers on fire extinguishing will be also studied.

These large scale fire experiments of the PRISME program have up to now generated a huge amount of data concerning many issues as, for instance, the fire source (heat release rate, mass loss rate and their dependencies with oxygen depletion), the smoke and heat gas flow (filling-box process, thermal stratification, gas concentrations, leakages, doorway flow), feedback on inlet and exhaust ventilation system (volume flow rates) and the heat transfers to targets (radiative and convective heat fluxes to the walls and to electrical cables located at two heights along the walls). All these valuable data are used for code development and validation on fire propagation phenomena.

At the same time, the partners of the OECD PRISME project evaluate the capabilities of fire codes to simulate fire scenarios based on the PRISME tests. The objective of this paper is to present the work performed by the PRISME Benchmarking Group composed of the partners involved in computer codes benchmarking.

2 PRISME BENCHMARKING GROUP

Fire codes are more and more used for safety analysis of nuclear power plants. For example, computer codes are used to simulate several fire scenarios in probabilistic risk analysis (fire PSA) or to evaluate the consequences of fires in nuclear plants in a deterministic approach, e.g. for fire hazard analysis (FHA). In several OECD member countries, the accuracy of the calculated predictions has to be demonstrated. To assess the applicability and predictability of fire simulations, codes are validated against different experiments.

Since several years, the nuclear fire experts' community has periodically exchanged their point of view.. In 2000, the International Collaborative Fire Modelling Project (ICFMP) was initiated to share knowledge and resources of various expert institutions to evaluate and to improve the state-of-the-art on fire models for application to nuclear power plant fire safety assessment including fire hazard analysis and fire risk assessment. More than twenty institutions from six countries were represented in this collaborative project which ended in 2007 and provided valuable insights on fire model applicability and limitations (see [1]).

Several partners of the ICFMP participate now in the PRISME Benchmarking Group. This group meets twice a year. Twelve organizations perform simulations with eight different codes. Organizations performing benchmark exercises are BEL V, SUEZ-TRACTEBEL, VTT, IRSN, EDF, DGA with the help of the Université de Provence, GRS, iBMB, JNES, KINS, CSN, Vattenfall Ringhals with the help of Lund University, and NRG. The codes used are:

- CFD (computational fluid dynamics) codes: the open source codes FDS, developed by NIST (National Institute of Standards and Technology, USA) in cooperation with VTT, and ISIS, developed by IRSN, SAFIR developed by the Université de Provence;
- The lumped code COCOSYS, developed by GRS,
- Zone codes: CFAST, developed by NIST, MAGIC developed by EDF, OEIL developed by DGA and SYLVIA developed by IRSN.

Benchmark exercises are proposed and the results are discussed in this group, but the group also exchanges on fire models and on the validation process of fire codes.

3 DISCUSSIONS ON FIRE MODELS AND FIRE CODES VALIDATION

During the PRISME Benchmarking Group meetings, partners exchange on models used to simulate fires in ventilated and confined compartments and on the best way to compare simulation results to experimental data.

Discussions concerned e.g. the difficulties to predict the heat release rate in compartment fires. The PRISME SOURCE and PRISME DOOR tests (cf. [2], [3], [4], [5]) provide a large database from which the feedback of environmental parameters on the burning rate can be studied.

Indeed, the PRISME tests showed that compartment fires are often under-ventilated so that the oxygen concentration can decrease significantly and infer some effects on the mass loss rate (and until fire extinction in some cases). This point is of some importance because the mass loss rate (and consequently the burning rate) provides the heat release rate. A bibliographical review dealing with the effects of oxygen depletion on the fuel mass loss rate for pool fires in well-confined and mechanically ventilated compartments was presented and discussed during a meeting of the PRISME Benchmarking Group. Fire code developers exchanged on fire models reviewed and on improving methods to consider the effect of confinement on the mass loss rate. Some code developers, e.g. from GRS and IRSN, introduced in their codes a correlation proposed by Peatross and Beyer [6] and compared the improvements to the simulation results of the PRISME tests.

Another point being discussed was how to reduce experimental data for estimating the thermal interface and layers temperature. In fact, these values are calculated by zones codes and have to be compared against experimental results. Different methods are proposed in the literature but all the reduction methods assumed that the gas temperature of the upper layer is uniform. This assumption is not true in the PRISME tests, in which a thermal gradient is observed. A reduction method validated on real scale experiments [7] was therefore presented and discussed during a meeting. The aim of these discussions is to exchange the different experts' points of view of the best way to compare experimental measurements to simulation results in the validation process.

4 BENCHMARK EXERCISES

The PRISME Benchmarking Group is composed by developers and users of fire simulation codes. In order to exchange on the fire codes, benchmark exercises are proposed to the PRISME partners and organised by IRSN.

Since the beginning of the project, twelve partners performed two benchmark exercises. .

4.1 Benchmark Exercise No. 1

The major goal of the first exercise is to provide a more quantitative process to compare fire models with experimental data.

The use of metrics to assess the level of agreement between experimental data and fire code is not very widespread in the fire safety community. The analysts often have to evaluate some single-point comparisons (minimum/maximum of curves, values in stationary conditions) which are relatively easy to calculate and to analyze. In the case of time-dependent curves (unsteady conditions), the estimate of the agreement between two curves is more difficult to calculate (need to use the functional analysis with vector operations) and

sometimes more difficult to get a straightforward interpretation of the values obtained from this calculation. Usually, the metric operators are built on the relative difference (often normalized) between model predictions and experimental measurements, on which some mathematical norms (e.g. Euclidean and Hellinger norms, for example) from functional analysis are applied. These norms may allow getting a measure of average curve separation or a measure of curve shapes.

The work in the PRISME Benchmarking Group is to investigate different metric operators to compare experimental data with numerical results and to discuss about them in order to evaluate the interest to use them in the validation process of fire codes.

In this exercise, the so-called 'open calculations' of the PRISME SOURCE test are performed by partners. For a fire computer code, 'open simulation' means that the heat release rate is not predicted using a specific model but imposed in the input data equal to the experimental measurement.

The configuration of the PRISME Source test chosen is a pool of liquid hydrogenated tetra propylene (TPH) burning in the centre of one room of the DIVA facility, mechanically ventilated. The surface area of the pool is 0.4 m^2 and the fuel depth is approximately 5 cm before ignition and decreases during combustion phase in proportion to the rate of pyrolysis. To ignite the fuel a propane gas burner is used.

The DIVA facility is equipped with a full ventilation system set at a renewal rate of 4.7 air changes per hour during experiment PRS-SI-D1, i.e. a nominal ventilation flow of $560 \text{ m}^3 \text{ h}^{-1}$. The inlet and outlet branches of the ventilation system are located at the upper part of the fire compartment (0.75 m below the ceiling, cf. Figure 1).

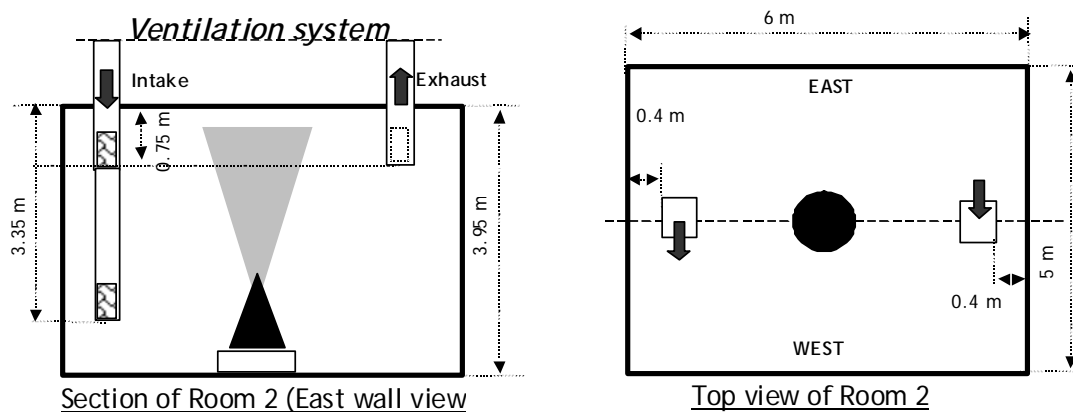


Figure 1: Configuration of the PRISME SOURCE test

For the benchmark exercise, the calculated values compared to experimental data are the mean gas temperature (cf. Figure 2), surface temperature in the middle of the wall, the total and radiative heat fluxes, the fire compartment pressure and the flow rate of the inlet branch of the ventilation network.

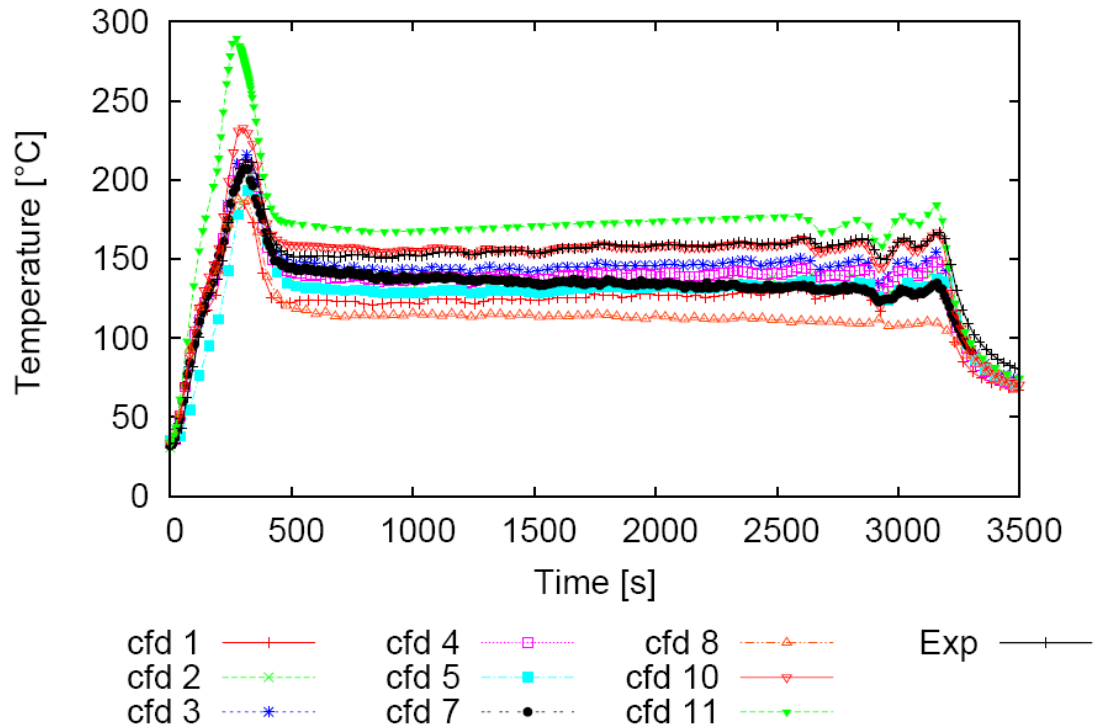


Figure 2: Example of benchmark results

For all these calculated values, several metrics are applied to quantify the difference between model predictions and experimental measurements. The relevant metrics are analyzed according to the peak values, to the stationary phase and to the shape of the curves (cf. Figure 3).

The conclusion of this first exercise is to propose three metrics which seem relevant to quantify the differences between experimental measurements and simulation results:

- The local maximum/minimum relative difference for peak values;
- The global relative difference to measure the difference in the overall magnitude of the curves;
- The inner product cosine to measure the difference in the shapes of the curves with a level of smoothing.

All the work performed by the group on this subject will be published.

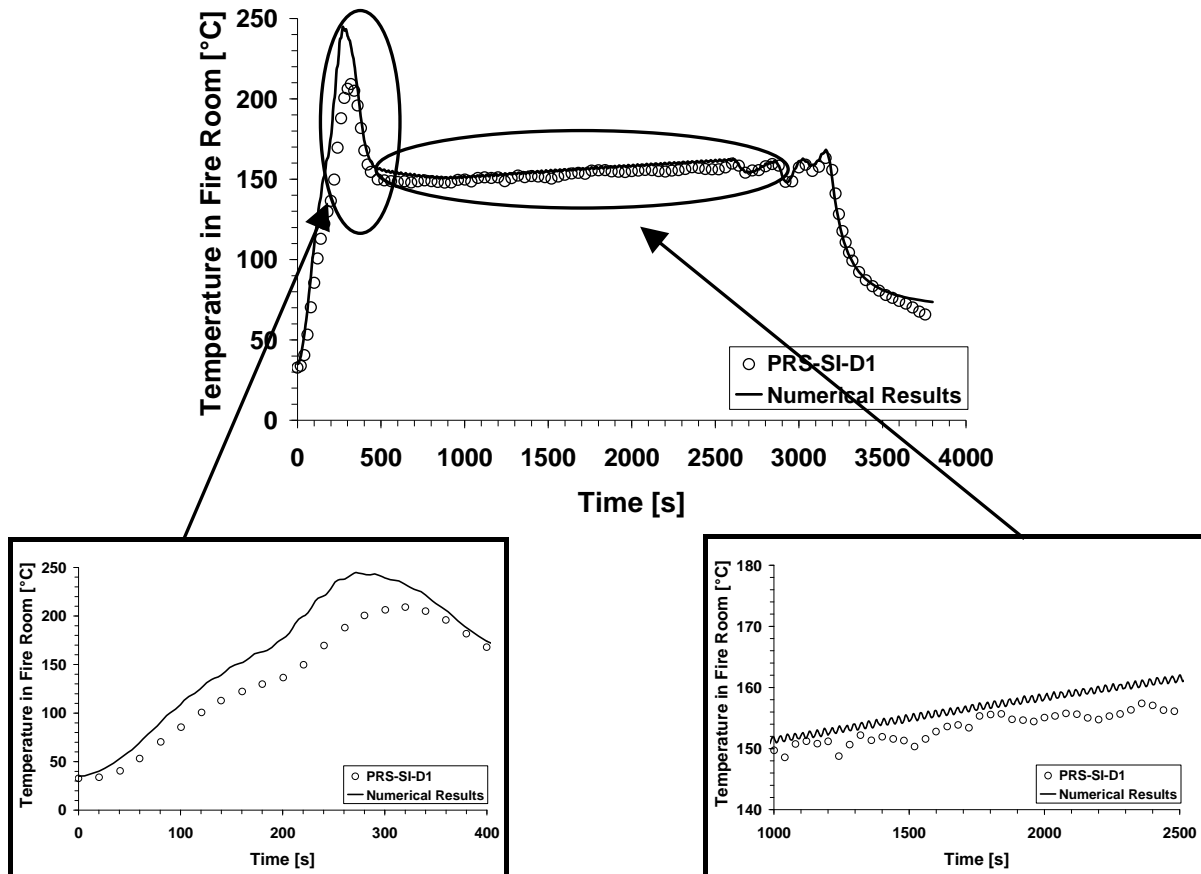


Figure 3: Example of experimental data compared with numerical results

4.2 Benchmark Exercise No. 2

The second exercise, still in progress, aims to study the main sensitive parameters of the fire simulation codes and to compare different sampling generation methods (Fractional Factorial Design (FFD) and Monte Carlo approach).

To assess the accuracy and predictability of fire simulations, codes are validated against various experiments, however additional knowledge about uncertainty bands for different results is needed. In a fire scenario, uncertainties of the simulations result from:

- The fire source: codes are not able to predict the fire growth and the heat released by a fire in confined conditions; it is interesting to evaluate the effect of this modelling weakness on the fire codes responses;
- Thermal properties of the wall: approximately 60 %, even more, of the energy released by a fire is dissipated by the walls; these thermal properties are not always known, in particular the emissivity;
- The ventilation network: the ventilation network of a facility needs to be well characterized to perform simulations of a fire in a mechanically ventilated room; but these data are difficult to obtain for real plants.

Therefore, it was decided during a meeting of the benchmarking group to perform a sensitive analysis on the following input parameters of fire codes: the fire source (the mass loss rate and the radiative fraction), the thermal properties of the walls and the ventilation flow rates.

The objective is to evaluate the effect of the lack of knowledge of these input parameters on the following code output parameters: the mean gas temperature, the minimum oxygen concentration at the maximum value and during the steady phase, the maximum wall temperature, the heat fluxes, and the pressure, in particular the overpressure in the ignition phase and the under-pressure in the fire extinguishing phase. The reference case is the PRISME SOURCE test studied during the first exercise. The first results on this exercise have been presented and discussed this year during the Benchmarking Group meetings in April and October.

A second objective of this exercise is to compare different sampling generation methods. A common method for sensitive analysis is to use a Monte Carlo approach. But such method requires a large number of simulations, several hundreds runs, which it is partly difficult with CFD codes. The PRISME Benchmarking Group proposed to compare a Monte Carlo method with a Fractional Factorial Design (FFD) approach which requires a smaller number of simulations, only eight runs for this exercise.

The different mean gas temperature variations obtained applying a Monte-Carlo approach with SYLVIA and COCOSYS codes are shown in Figure 4. The deviation for this response, e.g. in the order of 25 % for SYLVIA, confirm the need to perform a sensitivity analysis for the complex scenario of a fire in ventilated compartments.

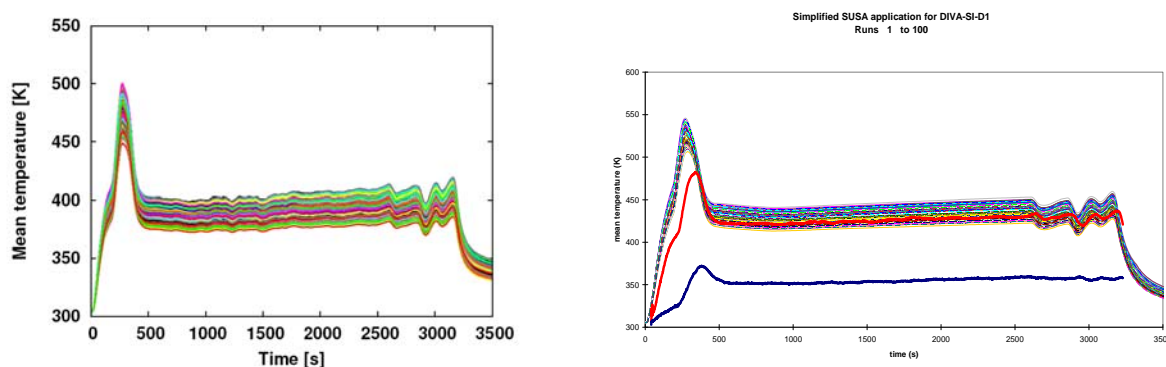


Figure 4: Mean gas temperature variation versus time calculated by the SYLVIA code (left) and by COCOSYS code [8] (right), obtained with a Monte-Carlo approach

GRS and IRSN performed the comparison of the different sampling generation methods. GRS used their tools, the lumped parameter code COCOSYS and SUSA (Software System for *Uncertainty and Sensitivity Analyses*), and IRSN used the fire zone codes SYLVIA and SUNSET (*Statistical Uncertainty and Sensitivity Tools*). The first conclusions of the two organizations are similar: both methods, Monte Carlo as well as Fractional Factorial Design, show quite comparable results. Figure 3 illustrates this trend for all the different input factors for the SYLVIA code using three sampling generation methods: Monte Carlo, Full Factorial Design and Fractional Factorial Design.

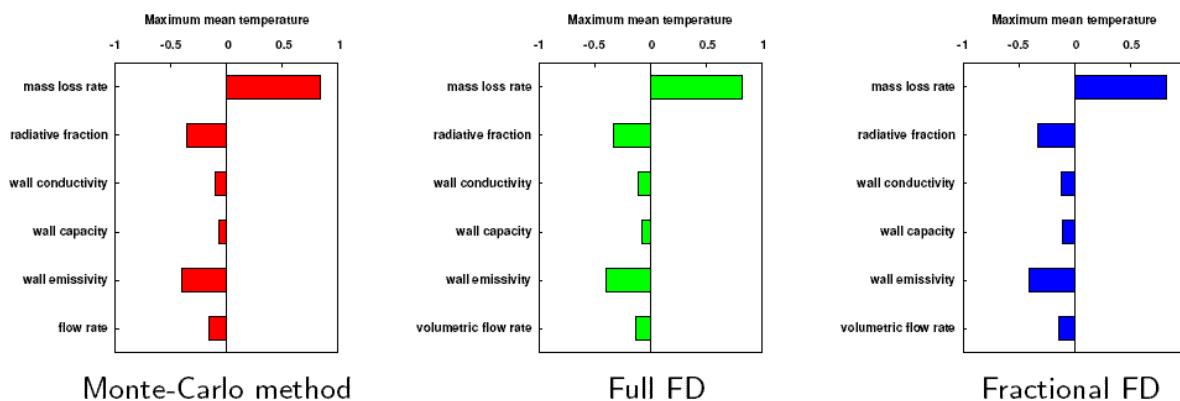


Figure 5: Sensitivity analysis of the SYLVIA code for the mean gas temperature response, performed with the Monte Carlo (200 runs), Full Factorial Design (64 runs) and Fractional Factorial Design (8 runs) methods

Analyses of all partners' results on this benchmark exercise will allow to highlight the most sensitive models in fire codes used to simulate fires in confined and ventilated conditions. On the basis of these results for all fire codes, partners will discuss the possible reasons of such sensitivity and will analyse the lack of knowledge.

5 CONCLUSIONS

The PRISME Benchmarking Group is composed by developers as well as users of fire simulation codes. During the different meetings, the active members discussed on fire models and on the validation process for fire codes based on the full scale experiments performed in the OECD PRISME Project.

Metrics were tested in the frame of the first exercise to quantify the differences between experimental measurements and simulation results. The analysis has shown the interest to combine several metrics in the validation process in order to have a good representation of the fire code capabilities to simulate unstationary phenomena of a fire under confined and ventilated conditions.

The comparison of different sampling generation methods (Fractional Factorial Design and Monte Carlo approach) performed during the second exercise has demonstrated quite comparable results with both methods.

Up to the time being, the exercises have shown a relatively good agreement between experimental measurements and simulation results. However, the simulations for the two exercises are realized in so-called 'open calculations', e.g. the experimental heat release rate and, for some codes, ventilation conditions are fixed as boundary conditions.

Discussions of the experts group on the capabilities of codes to predict consequences of a fire in under-ventilated conditions will continue. In fact, open calculations were not the subject of the benchmark exercises but pre-calculations of the PRISME tests have shown the fire codes limitations to predict the heat release behaviour of a pool fire under confined and mechanically ventilated conditions. PRISME INTEGRAL tests, involving real fires, will also probably raise a lot of questions on fire models.

6 REFERENCES

- [1] Röwekamp, M., Dreisbach, j., Miles, S., et al., International Collaborative Fire Modeling Project (ICFMP) - Summary of Benchmark Exercises 1 to 5; GRS-227, Gesellschaft für Anlagen- und Reaktorsicherheit (GRS) mbH, ISBN-Nr.: 978-3-939355-01-4, Köln, September 2008
- [2] Prétrel, H., Querre, P., Forestier, M., Experimental study of burning rate behaviour in confined and ventilated fire compartments, Fire Safety Science proceedings of the Eighth International Symposium, 2005
- [3] Le Saux, W., Prétrel, H., Lucchesi, C. and Guillou, P., Experimental study of the fire mass loss rate in confined and mechanically ventilated multi-room scenarios, 9th Symposium of IAFSS, 2008
- [4] Melis, S., Audouin, L., Effects of Vitiation on the Heat Release Rate in Mechanically-Ventilated Compartment Fires, 9th Symposium of IAFSS, 2008
- [5] Le Saux W., Prétrel, H., Moreau S., Audouin L., The PRISME OECD Fire Research Project: Experimental Results About Mass Loss Rate and Soot Concentration in Confined and Mechanically Ventilated Compartment, 11th International SMiRT Post-conference Seminar on "FIRE SAFETY IN NUCLEAR POWER PLANTS AND INSTALLATIONS", 2009
- [6] Peatross, M. J., Beyler, C. L., Ventilation Effects on Compartment Fire Characterization, Fire Safety Science - Proceedings of the Fifth International Symposium, International Association for Fire Safety Science, 1997, pp. 403-414
- [7] Audouin L., Tourniaire, B., New Estimation of the Thermal Interface Height from Measured Parameter Profile in Enclosure Fire Experiment, 6th International Symposium on Fire Safety Science, 1999
- [8] Klein-Heßling, W., Höhne, M., Uncertainty And Sensitivity Study On PPRISME Pool Fire Experiment PRS-SI-D1 Inside The DIVA Facility, 11th International SMiRT Post-conference Seminar on "FIRE SAFETY IN NUCLEAR POWER PLANTS AND INSTALLATIONS", 2009