Bel V R&D activities in the frame of improved understanding of fire behaviour in nuclear facilities

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Abstract:
The operating experience in the nuclear facilities shows that design assumptions may not be always realistic, particularly in the relation to fire initiation. Besides, the knowledge of accidental fire and especially fire modelling of fire scenarios has improved significantly over the last decades. This allows licensees and nuclear safety authorities to use fire modelling and risk information, along with prescriptive requirements to ensure that nuclear facilities will not challenge the workers, the population and the environment when an internal fire would occur. Bel V aims at acquiring proper knowledge and methodologies for initiating and reviewing risk informed fire analysis which will be conducted by the Belgian NPP licensees. In addition, activities to gain more experience and knowledge on specific fire behaviour and its consequences in nuclear (non-NPPs) facilities are launched to mark this evolution for all nuclear facilities. This contribution to the Eurosafe Forum briefly describe the scope of the current Bel V R&D activities on fire safety, conducted in order to familiarize with state-of-art techniques to perform suitable analysis, as well as regulatory and supervising activities. Furthermore, main outcomes of specific R&D projects on fire behaviour in nuclear facilities are cited. Perspective on future R&D on fire safety is given.

1 MOTIVATION OF CONDUCTING R&D ON FIRE SAFETY SCIENCE

The design of most nuclear power plants (NPPs) is based on the U.S. Nuclear Regulatory Commission Framework. This framework defines a set of deterministic rules which aim to incorporate a defence in depth as the method to sustain safety goals. Fire safety assessments and operational feedback gained from fire events have shown that fire contributes significantly to the overall fuel damage frequency of plant designs [1]. Indeed, a single fire may incapacitate multiple diverse and redundant engineered systems triggering a common cause failure that challenges nuclear safety. This is in particular the case at NPPs designed to earlier standards where the original fire protection concept was based on normal industrial practices with no or little attention to the specific requirements of nuclear safety. As a result, the basis for (fire) safety within nuclear facilities is continuously evolving, leading to the perception that older designs may constitute a larger threat to society when compared to newer designs. Nevertheless, the evolving nature of the conceptual design base is mainly overcome by the periodic safety reviews, which resulted in improved and back fitted fire safety for earlier designs. In contrast with NPPs, nuclear facilities are more diverse, so consequently nuclear facility design is rather based on profound engineering judgement.
In general, all nuclear facilities are designed in relation to accidental fire scenarios, under certain assumptions on their initiation and development mechanisms. However, conventional plant fire hazard analysis to life and property is based on the hypothesis of the presence of combustible materials in the buildings and limited number of simultaneous sources of fire. In addition, conventional fire safety assessment relies upon the presence of mitigation measures and fire related operational procedures. The operating experience in the nuclear facilities all over the world shows that these assumptions may not be always realistic in view of the development of safety strategies for a safe plant shutdown, particularly in relation to the fire initiation [2]. Indeed, the risk posed by fires can be comparable to or even exceed the

risk from internal events. As a result there is currently a movement towards more awareness of the risk of internal fires.
Progressively, an evolution towards enhanced robustness in nuclear fire safety design is started [3]. This evolution is made possible by the fact that the knowledge on accidental fire and especially on the modelling of fire scenarios has improved significantly over the last decade. This allows licensees to use fire modelling and fire risk information, along with previous and recent prescriptive requirements to ensure that nuclear power plants can be safely shut down in an event of fire or likewise that nuclear facilities will not challenge the workers, the population and the environment when an internal fire would occur. This evolution in state of art of fire knowledge was moreover not unnoticed by the nuclear safety authorities. For Belgium, the Reactor Harmonization Working Group of the Western European Nuclear regulators' Association [4] was the driving factor to encourage NPP licensees to prove amongst others the sustainability of their design towards internal fire. As a final result, the NPP licensees shall have (by law [5], at last in 2015) a Fire Hazard Analysis (FHA) to demonstrate that the fire safety objectives are met, that the fire design principles are satisfied, that the fire protection measures are appropriately designed and that any necessary administrative provisions are properly identified. This fire analysis shall also be complemented by Probabilistic Fire Safety Assessment (Fire PSA). The level 1 PSA shall contain assessment of fire in order to evaluate the fire protection arrangements and to identify risk risks caused by fire. Currently, considerations are made to implement and to enforce likewise assessments (e.g. FHA) for all nuclear facilities.
Finally, one can observe a worldwide movement to introduce performance-based analysis into fire protection engineering practice. In 2002, the National Fire Protection Association (NFPA) developed the NFPA 805, *"Performance-Based Standard for Fire Protection for Light-Water Reactor Electric Generating Plants"* [6] that since then has been two times revised. The tendency of applying performance based fire protection in modifications and for the Long Term Operation project is currently noticeable.
The above described evolution in the young fire engineering discipline with sometimes very complex fire modelling and associated uncertainties by many limitations creates the necessity for the licensees and even so for the authorities and TSOs to familiarize with techniques in order to perform suitable analysis and/or to perform regulatory and supervising activities. For the above reasons, the Belgian TSO Bel V aims at acquiring proper knowledge and methodologies for initiating and reviewing FHA and Fire PSA which will be conducted by the Belgian NPP licensees in order to fulfil legal requirements. In addition, activities to gain more experience and knowledge on specific fire behaviour and its consequences in nuclear facilities are launched to mark this evolution for all nuclear facilities.

2 SCOPE OF BEL V R&D ON FIRE SAFETY

2.1 Fundamental knowledge

As fire safety science is a relatively young discipline, major efforts are necessary to conduct fundamental research. However, Bel V, not being a research centre, does not conduct this kind of research. Nevertheless follow up of work conducted by researchers is done though the membership of the IAFSS [7], the SFPE [8], and Firepronet [9]. Occasionally, Bel V fire safety staff attends conferences and classes in order to be updated on new techniques and tendencies in the wide fire safety community. Additionally, in 2012, a first time financial support was granted to a post-doctoral researcher in combustion, fire & fire safety of Ghent University [10].

2.2 Update of knowledge and skills

As Bel V is only active in the relatively small nuclear world, experience feedback related to fire and fire safety is often limited. In addition, (industrial) fire safety is evolving tremendously in the last decades. For these reasons, there is a necessity to update knowledge on a continuous base throughout the wide fire safety community. Therefore, Bel V fire safety experts monitor a variety of organisation both nuclear and not nuclear related, which providing info related to fire safety, for example: IAEA, U.S. NRC, NBN-CEN Technical committees 72, 127, 191 and 305, ANPI Belgium, Fireforum Belgium, Institution of Fire Engineers (UK), CFPA Europe, NFPA, FM Global, etc. Contacts with several national and foreign fire specialists are initiated and maintained.

2.3 International collaboration

The increasing use of fire modelling in a number of fire safety assessment studies and to support regulatory decision making presents challenges such as the availability of verified and validated fire models that can reliably predict the consequences of fires in nuclear installation. Validation and verification study for fire model in nuclear installation has shown areas where the fire models can be improved, but it also highlights areas where engineers should have confidence or concerns when using the current generation of fire models. Several questions remain open to improve fire model prediction. One of the main technical issues in fire safety assessment is related to smoke and hot gases propagation in a nuclear plant through the possible ways taking into account the disturbance of the ventilation network and of the room depression levels due to the fire itself and to the behaviour of active fire barrier elements, such as fire dampers, fire break doors, etc. Bel V was involved in moving the boundaries of the state-of-the art of above desirable knowledge trough the participation in the OECD PRISME project [11].

2.4 Fire risk assessment review

At present, no clearly established methodology or knowledge base is available which covers the intended purpose of conducting a full independent Fire Risk Assessment (FRA) review as from a safety point of view. The verification of the proper use of fire models and review which also encompass fire modelling is however a necessity in the global safety assessment review conducted by the TSO. Therefore, within Bel V, the onset is given to set up a review methodology in order to support the review of FRA.

As part of the global process of safety assessments, the Belgian TSO has to verify if one makes use of deterministic fire models in a responsible manner, or make a direct review of assessments containing computer fire modelling. In order to perform this task, experience in fire modelling is necessary. In addition, maintaining skills in the determination of fire models limitations provide even more profound awareness.

2.5 Practical application of validated computer models for Fire Hazard Analysis in Nuclear Power Plants

Based on the established methodology to validate computer models and available test data, the characterization of the confidence in analysis made for nuclear power plants real fire scenarios have been investigated [12]. The validation of the computer models is on-going, among others in the framework of the OECD PRISME project dedicated to the study of fire propagation in nuclear installations. In this context blind and open calculations of the real fire tests performed in this project have been conducted in order to predict the propagation of the fire. As a next step, the computer models and the available data are continuously explored in their practical use for modelling real fire scenarios. Bel V has been investigating the transition, in theory and practice, of the available knowledge, validation of the models and the existing data, to the applied field. Real fire scenarios as encountered in NPPs have been and are currently being worked out. Computational Fluid Dynamics codes (CFD) as ISIS [13] and FDS [14] are being used. For this R&D effort, cooperation in the framework of IMFSE [15] via Ghent University was established and found to be very progressive.

2.6 Interaction between fire and ventilation system – focus on Fire Hazard Analysis and dynamic confinement in nuclear facilities

In parallel to the investigation on modelling real fire scenarios for NPPs, the specific field of modelling the interaction between ventilation systems (including behaviour of pressure cascades and leakages) and fire is considered. These configurations are of particular importance for nuclear facilities.
A first work [16] conducted aimed to investigate the confidence of zone and field modelling, starting with a single-room configuration. Different modes of smoke and heat propagation from a room where the fire occurs toward an adjacent room have been treated. These propagation modes concerned: propagation of smoke through circular holes located in the upper and lower part of the wall separating the fire compartment and the adjacent room, the propagation of smoke through a vertical slot opening, the propagation of smoke through a real fire door or the propagation of smoke through a real fire door as well as the propagation of heat through a ventilation duct exposed to the fire and blowing air in the adjacent room. Pressure variations within these compartments have been investigated and the significance of impact of these variations on several fire modelling parameters were regarded. A major part of the input for code validation was obtained from the OECD PRISME project. For this R&D effort, again, cooperation in the framework of IMFSE via Ghent University was established and found to be very progressive.
A second work [17] focused on the INTEGRAL test series from the OECD PRISME project. Four rooms are involved in these tests, including one corridor. These four rooms are connected by doors. Mechanical ventilation is used to ventilate these rooms. Two INTEGRAL tests were being simulated. For the first test, a pool fire served as fire source in the middle of the fire room. For the second case, the fuel source is an electrical cabinet. In addition, fire dampers on inlet and exhaust branches are used in the latter case. In total 12 basic cases are run for these two fire scenarios with the two-zone model Sylvia [18] developed by IRSN. Open simulation and blind simulation are run. For both test cases, conclusions are drawn for predicting heat release rate, ventilation flow rate and flow rate trough doors. Additional results with the field code ISIS are currently being obtained.
As a next step, the effects of fire within a hot cell and different (potential) fire protection strategies used for hot cells have been studied [19]. Considering the high cost of hot cell, the difficulty to test cells with permanent high level of contamination and, the damage a real fire would have on a hot cell, it is not practical to conduct many fire tests on hot cell. An alternative to fire testing is using fire simulation tools. The two-zone model Sylvia is used for this purpose. This model is able to model the complexity of a real ventilation system. Two different configurations have already been considered. The first case is a single hot cell configuration based on a cutting cell located in Belgoprocess[1]. The second case is based on a multi-cell scenario as encountered in the SCK-CEN[2].

3 MAIN OUTCOMES OF R&D ON FIRE BEHAVIOUR

3.1 Cooperation in OECD/NEA PRISME project

The design of nuclear plants and facilities makes the study of fire development and propagation complex since there is a strong interaction between fire and ventilation conditions. The objectives of the OECD PRISME project were to investigate different modes and mechanisms involved in the spread of hot gases and smoke from the fire compartment towards adjacent rooms (from 1 to 3 rooms as shown in Figure 1) via the following elements:

[1] Belgoprocess, a private company founded in 1984 in the Belgian nuclear area of Mol-Dessel, offers integrated nuclear waste management and decommissioning services, driven by safety and backed by hands-on industrial experience (http://www.belgoprocess.be).
[2] SCK•CEN is one of the largest research centres in Belgium with laboratories in Mol and registered office in Brussels. Today, about 700 employees advance the peaceful industrial and medical applications of ionising radiation and contribute to SCK•CEN's overall purpose: maintain a centre of excellence for research and peaceful applications of nuclear science (http://www.sckcen.be/).

- Open door(s);
- Leakages (through openings, narrow slot and a certified firebreak door;
- Ventilation network (for example, reverse flow due to the effects of pressure, effect of forced vs. natural flow rate in the doorways);
- Ventilation duct(s) crossing the fire compartment and blowing out an adjacent room.

The fire sources are liquid pool fire and typical real fire sources such as PVC cables and electrical cabinets. At the same time as the experimental tests, the partners of the OECD PRISME project evaluated the capabilities of various fire codes to simulate fire scenario based on the PRISME tests.

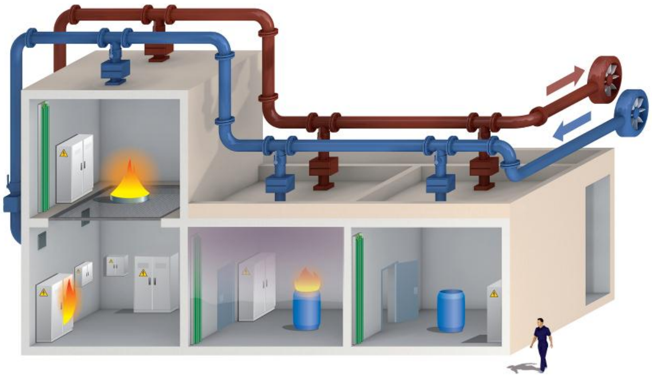


Figure 1: Scheme of the DIVA facility and its ventilation network

The main outcomes of the OECD PRISME Program concern smoke movement from the fire compartment to adjacent rooms, the effects of under-ventilated conditions on the fire source, the electrical cable behaviour submitted to high thermal stress, the building up of a large experimental database and the establishment of an efficient international network on this topic. It is not the intention of the authors to enlarge on the project in too much detail, so reference is made to the OECD/NEA PRISME Project Application Report which includes the current list of publications [11]. Additional publications to the wide fire safety engineering community will be made in the near future.

3.2 Deterministic fire risk assessment review approach

In the proposed review approach for fire risk assessment (FRA) [20], the review process is subdivided into three basic tasks: (1) regulatory review, (2) control of quality, and (3) evaluation of (minimal) technical requirements. The choice of partitioning this process is arbitrary and can subsequently be discussed. However, the choice is defended since the tasks are judged independent and complete for the intended purpose. The review methodology must be seen as complementary to the global TSO review work and therefore no specific site considerations have been described as this does not fit into a general methodology. These considerations are important to consider in a review. Nonetheless, the understanding of these site specific items is believed to be sufficiently established in the years of experience of the Belgian TSO.
A structured database with information needed to adequately perform an independent review is set up. A Knowledge Base, supplemented by a so called ‘Technical Application Base’, provides a comparative framework for the reviewer of proposed methodologies, developments, and computations made by the licensee in the framework of deterministic FRA analyses. The lists with explanations are intended to identify possible defects or lacks of treatment when being confronted with reviewing FRA methodologies, studies and (sub)analyses. It is the task of the reviewer whether or not to launch appropriate actions in the larger framework of the TSO review work when deficiencies are encountered, taking into account the general and more detailed aspects of the analysis.

In order to fulfil the objective of maintaining skills in fire modelling and be aware of the limitations, an internal assessment methodology for fire models has been proposed. Since it is desirable to reflect on both the ability of the numerical fire models to adequately simulate the different fire scenarios, and how the numerical results should be interpreted, the complementary use of two documents is proposed: ASTM E1355 “Evaluating the Predictive Capability of Deterministic fire Models” [21] and ISO 16730 “FSE – Assessment, verification and validation of calculation methods” [22]. Because both documents assess the same aspects, such an approach is feasible. Moreover, it is also convenient to have a methodology that meets the requirements of two commonly used standards. The methodology for the assessment of fire models proposed is shown in Figure 2.

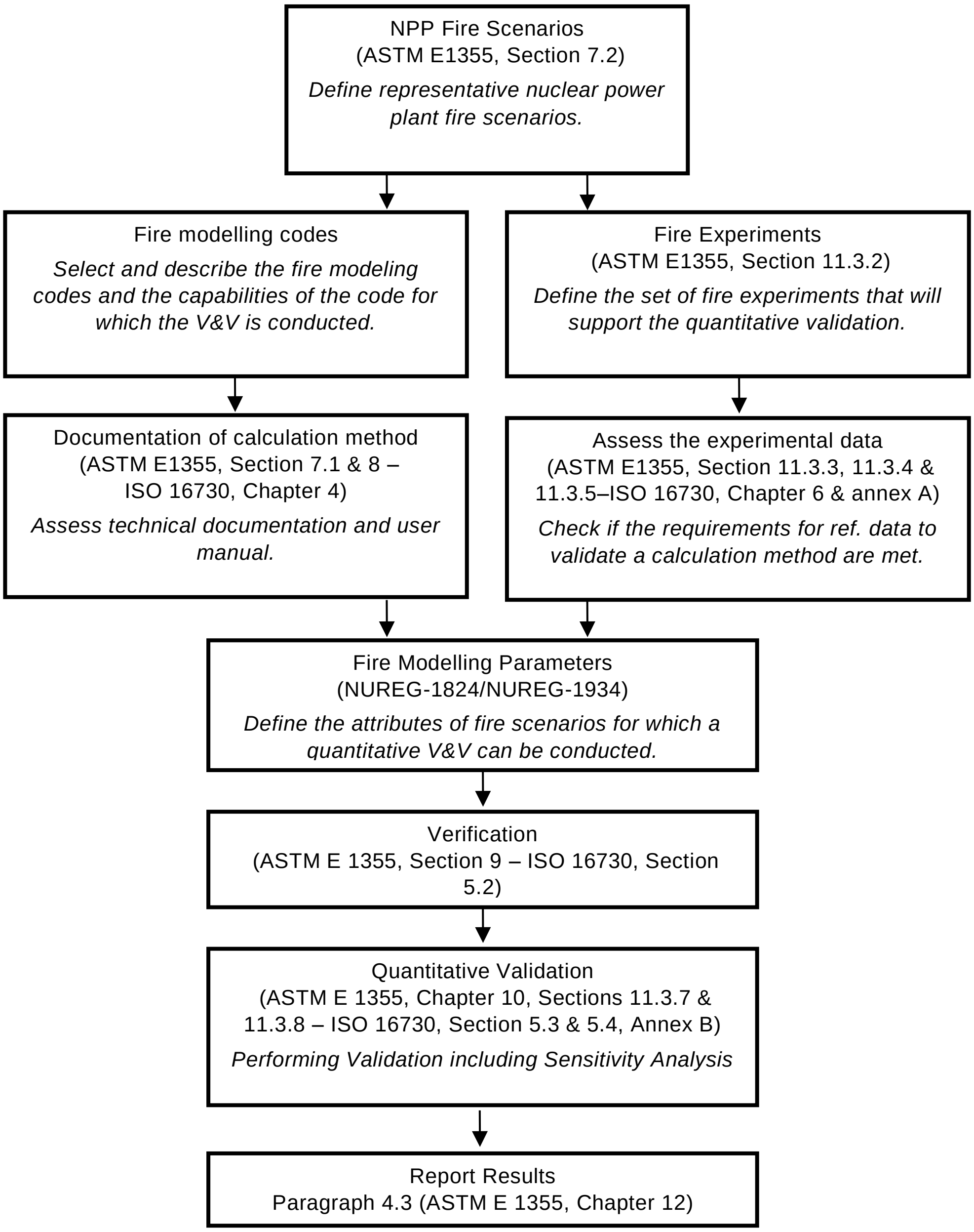


Figure 2: Overview of the approach for Verification and Validation (V&V) study of selected fire models for nuclear power plant applications (Based on [23])

3.3 Practical application of validated computer models for FHA in NPPs

As stated above, the main objective of this on-going work is to assess the fire safety in real scenarios of NPPs by means of validated fire simulation programs. The simulations of these scenarios have to be conducted in such a way that the results are trustable for taking action in order to improve fire safety. In order to achieve this objective, a first work divided in three parts has already been completed [12]:

- Validation of the software and the user by mean of a comparison between simulations and fire test;

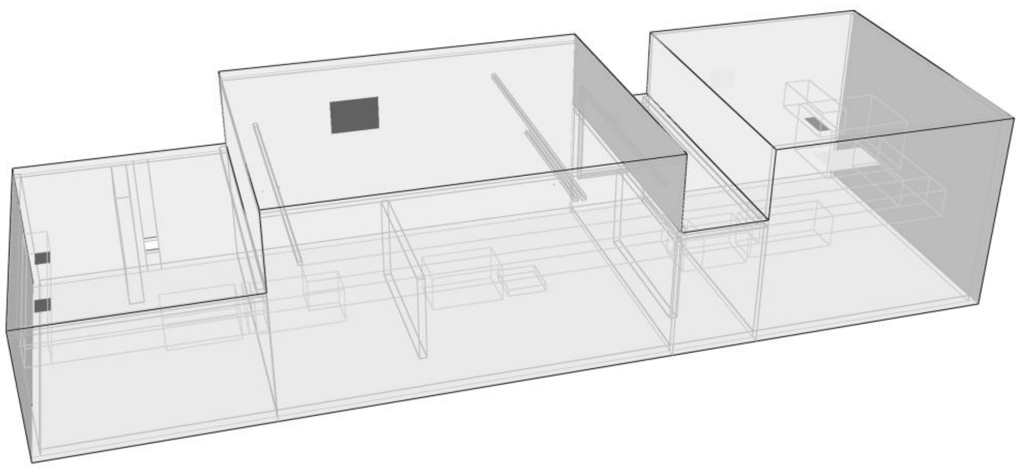
- Validation of the user through a blind simulation;
- Assessment of real fire scenario.

Each stage has a different degree in complexity and a particular way of approaching the results. In all the stages the program selected for the simulations is ISIS. ISIS is a Reynolds-Averaged Navier-Stokes (RANS) CFD code, developed by IRSN, that uses different physical models for solving the flow turbulence, combustion, soot production and heat transfers in order to calculate the development of a fire. One of the important features of this code is its capability of computing fire scenarios in closed rooms with mechanical ventilation, like the ones that can be found commonly in NPPs.

The comparison of the simulation in ISIS and the experiments has shown a good agreement between the temperatures measures in the gases. This is confirmed for some exercises of validation in the frame of the OECD PRISME Project and previous works [24]. This makes this simulation reliable for this specific variable. There were some problems in the representation of this variable near the floor, where the values were over predicted. The representation of the oxygen concentration is also good for the higher part of the compartment but the error is bigger for the points near the floor. The radiation has a similar behaviour than the previous variables. On the other hand, it was not possible to achieved trustable results for the total heat flux because the error were bigger than 30% for almost all the calculated points. The major error for this variable is related with the convective heat flux that is underestimated by the ISIS code. This can be related to the size of the cells near the wall and the representation of this zone by the wall functions. The validation scenarios with refinement of the mesh near the wall will be run in order to achieve more knowledge for this situation.

Most of the analysed variables have shown curves with a similar shape to the experimental ones. Therefore, the representations of the physical phenomena are correct for a qualitative point of view. The development of a data base with comparison of experiment and ISIS simulation to quantify the uncertainty would be desirable for a simpler application of the approach proposed in chapter 4 of NUREG-1934 [25]. More development will be done in order to attain such data base.

Two generic cases were studied using the same method described in the NUREG-1934 [25]. Furthermore a sizeable sensitivity study was performed. The fire safety goal set for these cases was the continuity of operation. The objectives to be met were translated in the demand that at least one of the safety related equipment (pumps) in the room should survive a fire. The failing criteria set foreword were linked with the temperature in the gases near the cables used for power the pumps and the radiation heat flux on these cables. For the case I (Figure 3), the outcomes were negative (the critical temperature was higher than the temperature of the criteria) for all the cases without activation of an automatic deluge system, hence two different approaches for improving the fire safety were analysed. Covering the cables with intumescent paint or with a material of low thermal conductivity, in order to improve the fire resistance, was the first approach. The second approach takes into account water curtains separating the different pumps to avoid smoke and heat propagation. Another conclusion was that more research is needed in order to have better understanding of how to model the proposed solutions.



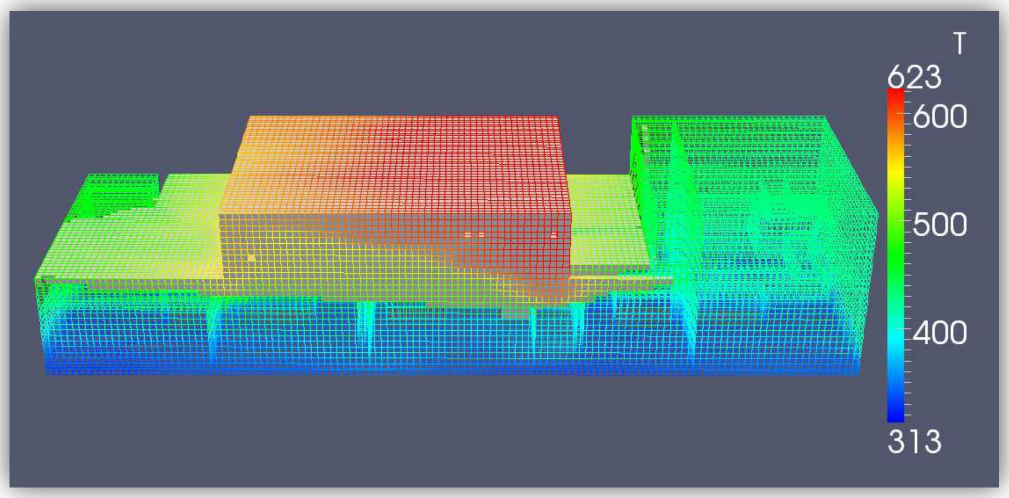


Figure 3: Analysis impression of the generic configuration of case I

For the second generic case, the outcomes for this case were considered positive, meaning that the temperatures and radiant heat fluxes were under the failure criteria for all the analysed scenarios.

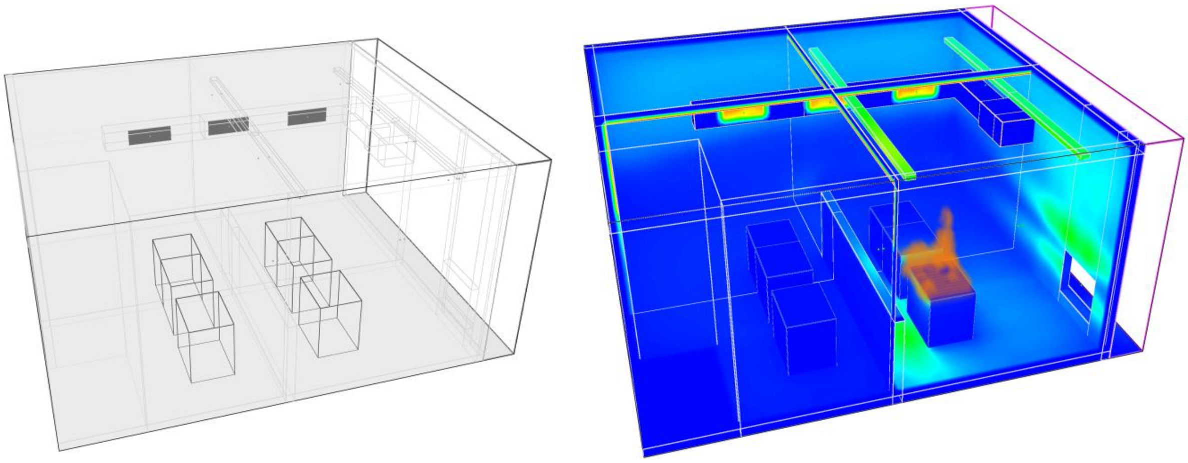


Figure 4: Analysis impression of the generic configuration of case II

The above configurations are now being investigated using the CFD code FDS instead of ISIS. A publication is foreseen in the near future to describe more on the results and to compare and explain analysis results made with both codes.

3.4 Interaction between fire and ventilation systems

The specific field of modelling the interaction between ventilation systems (including behaviour of pressure cascades and leakages) and fire is considered. These configurations are of particular importance for FHA and even more for assessing static and dynamic confinement in nuclear facilities. As the current literature has little to offer on the subject, Bel V puts a lot of effort in acquiring sound knowledge on the subject. Three projects have already been completed.

3.4.1 Application of Zone- and Field codes to model heat and smoke propagation in support of Fire Hazard Analyses of Nuclear Power Plants

In this work [16], four tests from the OECD PRISME Project that were dedicated to leakage have been studied. The PRISME Leak fire experiments were carried out in the DIVA facility. DIVA (the name DIVA is a French acronym for "experimental facility for the study of fires,

ventilation and airborne contamination") was built by IRSN in order to study fires in several rooms configuration (Figure 1). Two rooms are involved (see Figure 5): Room 2 (also called fire room) which holds the pool fire located in its centre and Room 3 (also called target room), the adjacent room, in which the impact of smoke and hot gases propagation were analysed. These two rooms have identical sizes (length*width*height=6*5*4m). They are connected to the ventilation network to manage accurately the renewal rates of air in fire and adjacent rooms.
The four side walls and the ceiling of the fire room are insulated with Rock-wool panels fixed on metallic frames screwed on the concrete. The ceiling of the target room is also insulated with Rockwool.

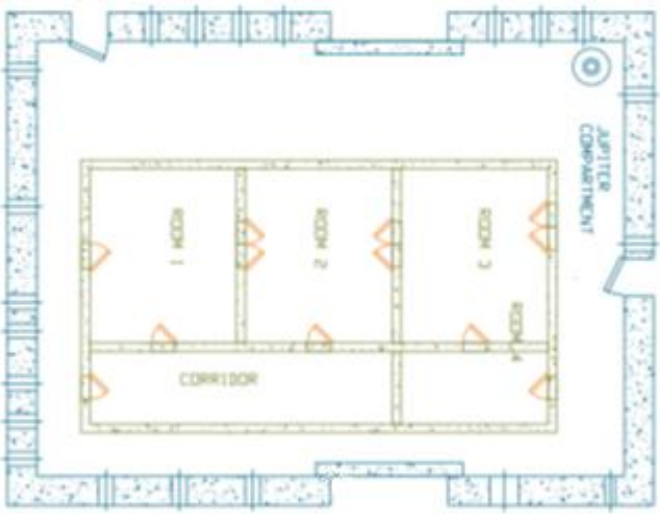


Figure 5: plan view of DIVA facility

Leak1 case: The aim is to simulate the leakage between two rooms. The connection between these two rooms consists of two circular pipes located in the upper part and lower part on the wall between rooms 2 and 3. The pipe is welded on the rectangular steel plate used as crossing plate between the 2 rooms. This scenario is depicted in Figure 6.

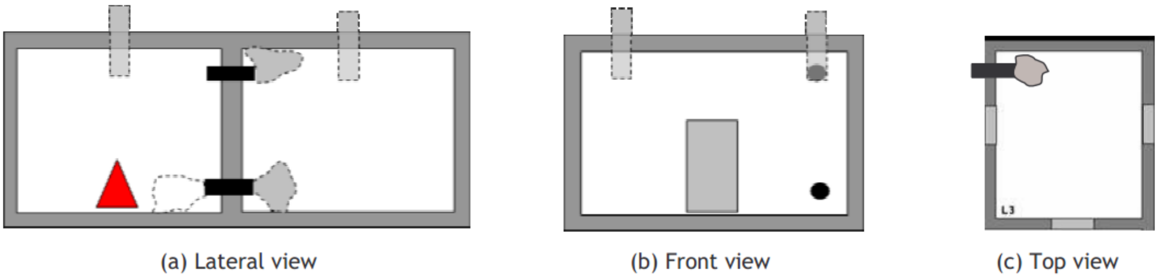


Figure 6: Description of Leak 1 scenario

The first circular duct is located in the upper part of the fire room. The second one is located in the lower part of it near the floor.

Leak2 case: One vertical slot is set between the two rooms. It consists in a vertical slot located at the centre of the wall separating the 2 rooms.

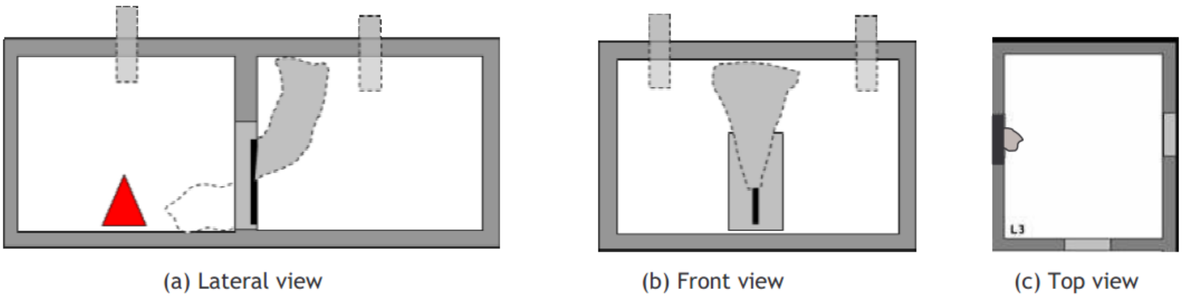


Figure 7: Description of Leak 2 scenario

Leak3 case: Fire room and target room are connected by a fire door. The fire door was closed during the test. However the fire door itself is leaky.

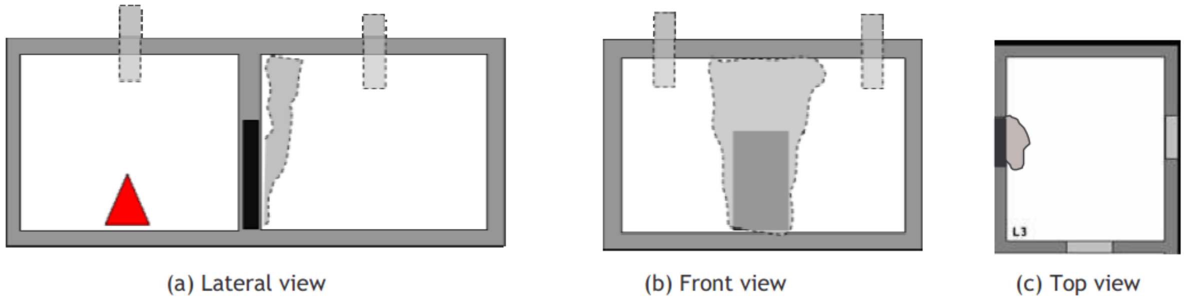


Figure 8: Description of Leak 3 scenario

Leak4 case: The connection between the fire room and the target room of Leak4 is the same as Leak3. However, in Leak4 there is one additional internal steel duct going through the fire room which ventilates the target room.

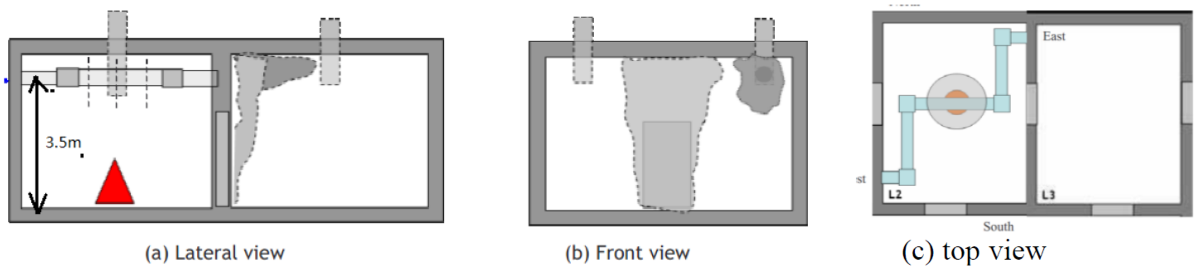


Figure 9: Description of Leak 4 scenario

The Table 1 below shows the cases that are run by ISIS and Sylvia. Thorough work out was only done the Leak1 scenario and focus was only drawn to the difference with Leak 1 for the other Leak scenarios..

Table 1: Overview of simulations

	ISIS	Sylvia
Leak1	ISIS can model leak1. Several simulations are run for this case including sensitivity analysis	Sylvia can model leak1 scenario. Several simulations are run for this case including sensitivity analysis
Leak2	ISIS can model leak2. No sensitivity is made for leak2	Sylvia can model leak2. No sensitivity is made for leak2
Leak3	ISIS is not able to simulate leak3 for the reason that it is unable to model the real firebreak door	Sylvia can model leak3. No sensitivity is made for leak3
Leak4	ISIS is not able to simulate leak4 for the reason that it cannot model the heat transfer to the internal duct	Sylvia can model leak4. No sensitivity is made for leak4

The applicability of the validation results can be determined using normalized parameters traditionally used in fire modelling applications [25]. Normalized parameters allow users to compare results from scenarios of different scales by normalizing physical characteristics of the scenario. The range of normalized parameters that were considered, based on NUREG-1934, are given in Table 2. One parameter specific for fire scenarios involving leakage is proposed in this work. This parameter is called leakage ratio. It is the ratio between the hourly leakage and the volume of the target room. Higher leakage ratio value means that there is lots of gas leakage compared to the volume of the room. Two zone model Sylvia and CFD model ISIS have been studied.

Table 2: Range of normalized parameters use for validation purposes

Quanlity	Normalized Parameter	Range for ISIS (Leak1~Leak2)	Range for Sylvia (Leak1~Leak4)
Fire Froude Number	$Q^* = \frac{\dot{Q}}{\rho_\infty c_p T_\infty D^2 \sqrt{gD}}$	1.17~1.23	1.17~2.78
Flame Length Ratio	$\frac{H_f + L_f}{H_c}$	0.74~0.75	0.74~1
Equivalence Ratio	$\varphi = \frac{\dot{Q}}{\Delta H_{O_2} \dot{m}_{O_2}}$ $\dot{m}_{O_2} = 0.23 \rho_\infty \dot{V}$	0.56~0.6	0.56~1.33
Compartment Aspect Ratio	L/H or W/H	1.25~1.5	1.25~1.5
Radial Distance Ratio	$\frac{r}{D}$	3.4~4	3.4~4
Leakage Ratio	$\frac{3600 * \dot{V}}{V}$	5~6.25	5~6.25

The authors will not elaborate more on this subject for now as, in the near future, publication will be foreseen within the fire safety community which would describes the study in more detail. Finally, Table 3 gives an overview of the capabilities of fire models in predicting fire modelling attributes. The conclusions are made based on the results which are analysed in chapter 4 of [16]. Readers should be aware to not adopt the conclusions prior to consulting and accepting [16].

Table 3: Overview of models' capability based on the results obtained in [16]

	ISIS	Sylvia
Radiative heat flux	Good prediction[6].	Over-prediction. Possible problem existing with the radiation calculation of Sylvia.
Wall temperature	General good prediction for single layer wall. Unable to predict temperature for multilayer wall.	Unbiased however largely dispersed prediction.
Soot concentration	Good prediction in the fire room. Large relative difference in the target room.	Overprediction in both rooms.
Oxygen concentration	Good prediction.	Good prediction.
Carbon dioxide	Good prediction.	Good prediction.
Pressure	Bad prediction. Possible error with the output of pressure.	Good prediction.
Ventilation flow rate	Good prediction.	Good prediction.
Leakage flow rate	Good prediction.	Good prediction.
Gas temperature	Good prediction of hot gas layer temperature.Overprediction of lower layer temperature. More sensible temperature than experimental data for fire plume.	As two zone temperature.
Interface height	N/A	None of the interface height is predicted correctly.
Two zone temperature	N/A	The hot gas layer temperature is overpredicted because of wrong prediction of interface height.

3.4.2 Simulations of PRISME Integral 4 and Integral 6 Fire Tests with Sylvia

This R&D project is on the validation of fire codes on the basis of two OECD PRISME Integral tests:

- PRS-INT-4: a pool fire in a 4-rooms configuration;
- PRS-INT-6: an electrical cabinet fire in a 4-rooms configuration with dampers activation.

The aim of these open calculations is to compare assumptions and models used to simulate pool fire in a multi-rooms configuration, electrical cabinet fire and fire dampers closure.
Two zone model Sylvia (whole ventilation system modelled) [17] and CFD model ISIS have been studied by Bel V. Basic configuration of the fire scenario and representation in Sylvia is shown below.

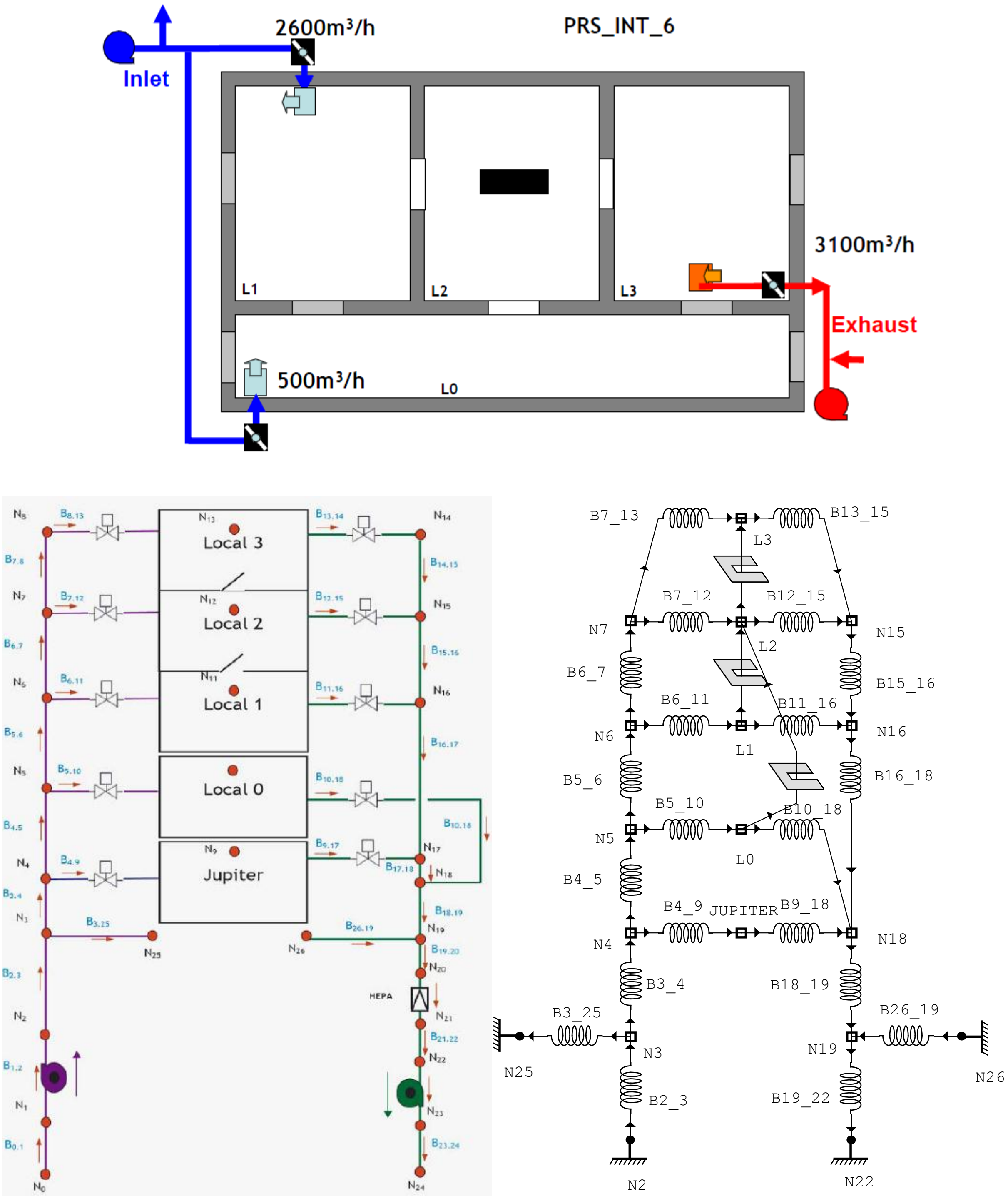


Figure 10: Configuration of the fire scenario

The above described configurations became part of the first exercise of the Analytical Working Group of the PRISME 2 OECD Project [26]. In order to honour the commitments elaborated in the OECD PRISME 2 project, no further details will be provided here.

At the end of the PRISME2 Analytical Working Group's exercise, guidelines for simulations of such fire scenario should be proposed. The lack of model capability should also be highlighted.

The preliminary Bel V study showed that, with proper Sylvia input parameters, even blind simulation can give a very good prediction of the mass loss rate (MLR) of the fire, which would determine the most significant parameter HRR (heat release rate). In addition, Sylvia generally predicts the ventilation flow rate quite well and with appropriate value of the door discharge coefficient, it is possible to get a reliable prediction of flow rate trough door. Specific for test INT-6, NUREG/CR-6850 electric cabinet heat release data [27], in combination with the Lower Oxygen Limit model build in Sylvia, gives quite accurate prediction for HRR in blind simulations. It has also been shown that discrepancies between test and simulation can also be attributed to experimental data which is not accurate enough, which was apparently the case for INT-6.

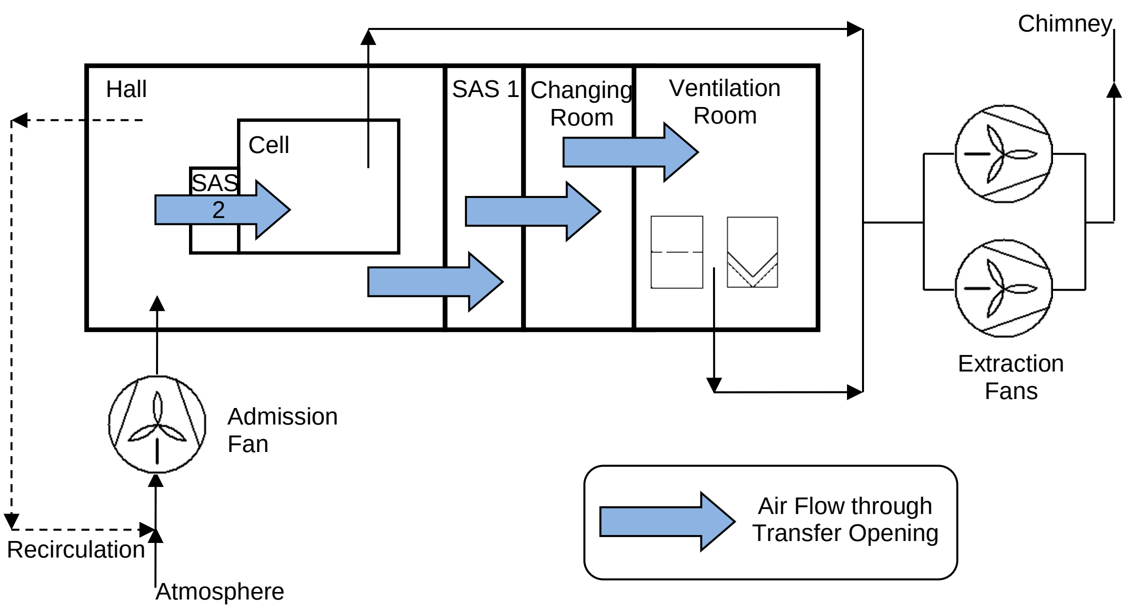
Final report by IRSN would be expected in June 2013. Possible publication to the wide fire safety community would be in a later stage.

3.4.3 Strategy of fire protection in hot cells

A pressure rise is expected during the breakout of a fire in a room. The pressure rise may reverse the pressure cascade obtained by the ventilation system designed for the hot cell. This may result in the flow of air from the contaminated area to uncontaminated area, which is unacceptable in view of safety. Therefore, it is of great importance to study the effect of a fire on the pressure distribution of those facilities and the effect of different fire control strategies.

Sylvia, a two-zone model is used for this purpose. This model is able to model the complexity of a real ventilation system. Validation studies on Sylvia show that Sylvia can predict the pressure behaviour of a compartment quite well in face of fire (PRISME). Thus, it is reliable to use Sylvia in this study for the hot cell. Two different hot cell scenarios are studied and modelled [19].

The first scenario consists of one large hot cell inside an industrial building as shown in Figure 11. The volume of the hot cell is 125 m^3.



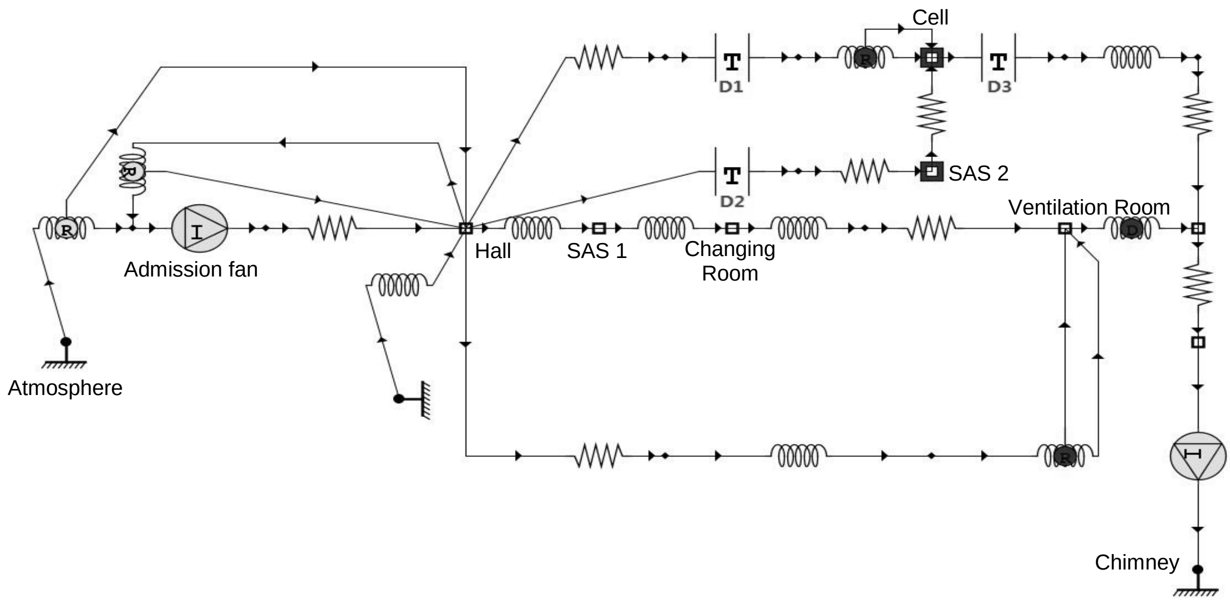
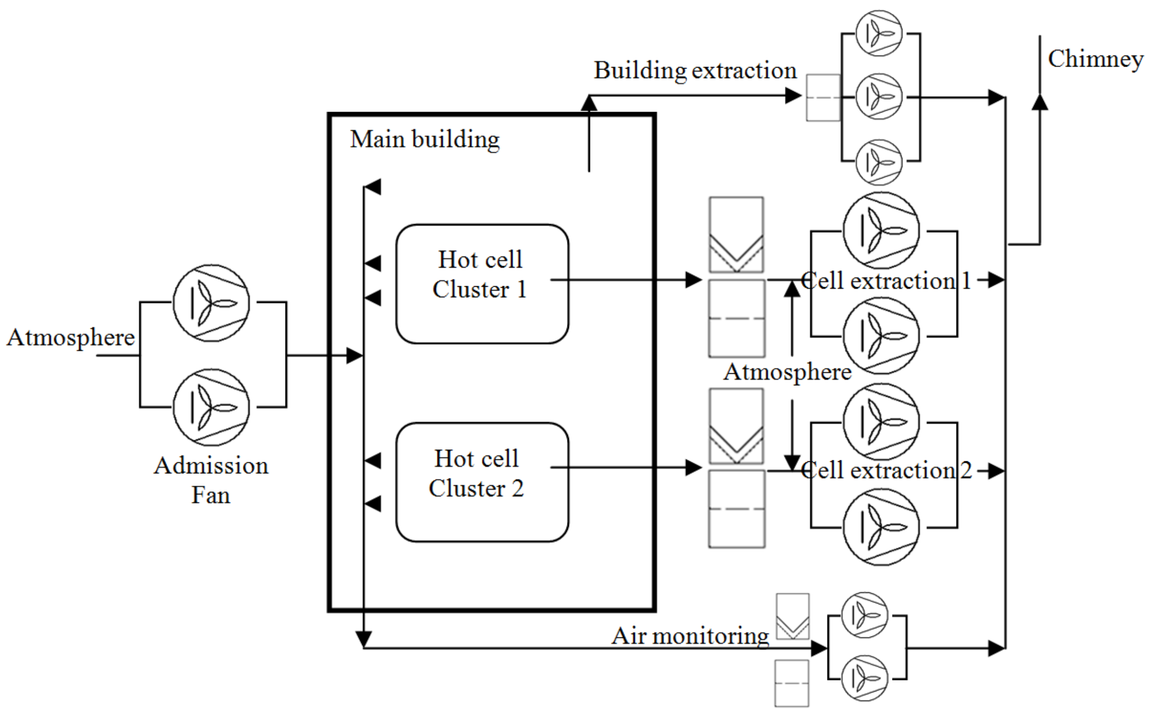


Figure 11: Ventilation schema and Sylvia impression of first scenario

For the second scenario, the whole ventilation system (Figure 12) can be divided into three parts based on their functionality: ventilation of main building, ventilation of the cells and ventilation for monitoring. The scenario incorporates 35 hot cells. The volume of most of the hot cells is quite small, ranging within 0.5m^3 to 5m^3. Nevertheless, there exist some larger hot cells in the second scenario.



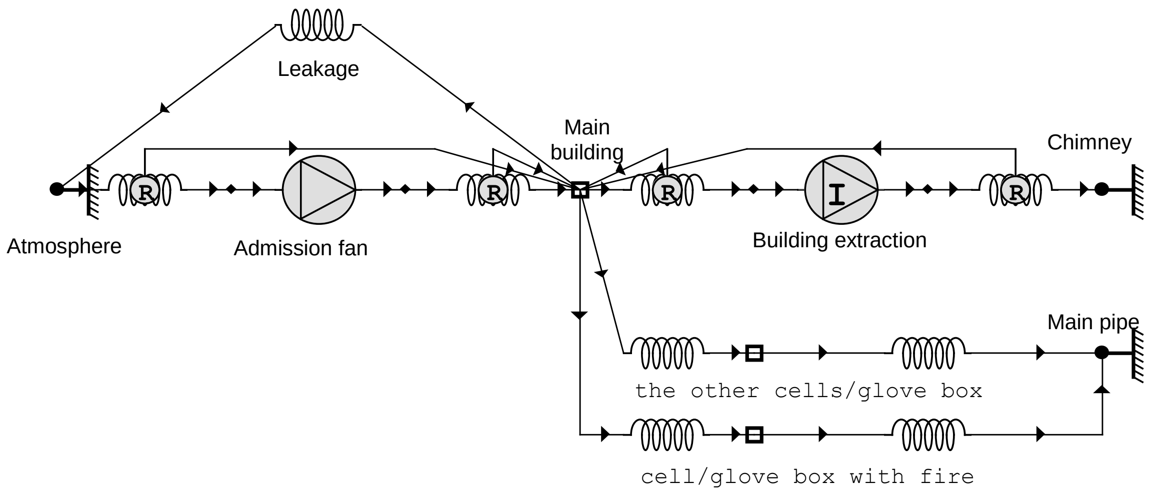


Figure 12: Ventilation schema and Sylvia impression of second scenario

The reasons for choosing these two cases are multiple. It is interesting to study both configurations. In the first scenario, the volume of the hot cell is large compared to the whole system volume. This indicates that a fire in this kind of hot cell would possibly influence the whole ventilation system. However, in the second scenario, most of the hot cells are quite small. Any change in each single one of the hot cells would not affect the whole ventilation system to great extent. It is possible that different strategies might be necessary in face of fire in two different scenarios. A serial of different cases are run based on these two scenarios. Although there is no test data from the scenarios used in this study, Sylvia does provide a good representative of the ventilation system of a hot cell in reality.

3.4.3.1 More on the 1st scenario: large single hot cell

From a first analysis, we could draw the conclusion that the peak heat release rate determines the pressure value inside the rooms. It is indeed quite intuitive that the fire growth rate and peak heat release rate would affect the pressure behaviour. Thus, several extra cases with different MLR input have been run. In addition, two criteria were used to evaluate the pressure cascade of the facility. The first one is that the hall loses its underpressure during the fire. The second one is that the pressure in the hot cell becomes higher than that in the hall. The severity of the fire in the hot cell depends on both fire growth rate and peak heat release rate. The larger the fire, the more severe the fire is by both criteria. However, for fire growth rate the conclusion is not that straightforward.
Different fire control strategies are used and simulated in Sylvia and results are presented.

Fire Dampers

The fire dampers would activate as soon as the fire is detected in the hot cell. There are two admission branches into the hot cell, thus there are two fire dampers. Readers are referred to Figure 11 for the position of each fire damper (D1, D2, and D3). Three different scenarios have been studied:

Table 4: Overview of damper scenarios

Scenario	*Fire damper condition*
A	Fire damper in the admission branch (D1)
B	Both fire damper in the admission branch (D1, D2)
C	All fire dampers (D1, D2, D3)

For each fire damper scenario, 6 sub scenarios are run with different HRR input. In total 18 cases are run for this case.
It is possible to put fire dampers in the admission branch of the hot cell. We can either close the admission totally or partly. If the admission is closed totally, higher underpressure value

can be obtained. However, higher extraction temperature would also be a result. Thus, the degree of the closure of the admission branch needs to be determined by the pressure as well as the extraction temperature. In case of extraction filter with low temperature resistance, we need more air admission to cool down the extraction temperature. In case of extraction filters with high temperature resistance, it is reasonable to cut off the admission totally. In either case, the extraction branch must remain unchanged; otherwise there would be huge pressure build-up in the hot cell, which would incur the propagation of contamination.

Gaseous fire suppression

Effect of gas injection is also being investigated. The application of the injection starts when the fire is detected in the hot cell. The admission branches of the hot cell should be cut off at the same time. In all cases, Sylvia predicted fire extinguishment. The larger the (for this case, nitrogen) injection mass flow rate, the quicker it is to extinguish the fire. Additionally, the injection helps to extinguish the fire as well as cool down the extraction gas temperature. The underpressure in the hot cell is still maintained by cutting of the admission branches. However, after the fire is extinguished, the hot cell gradually loses its underpressure and would even obtain large overpressures. Cutting of the extraction branch when injection is stopped could overcome this undesirable effect.

Combination of different strategies

Combination of above considerations brought up a potential comprehensive strategy for this specific facility under study.

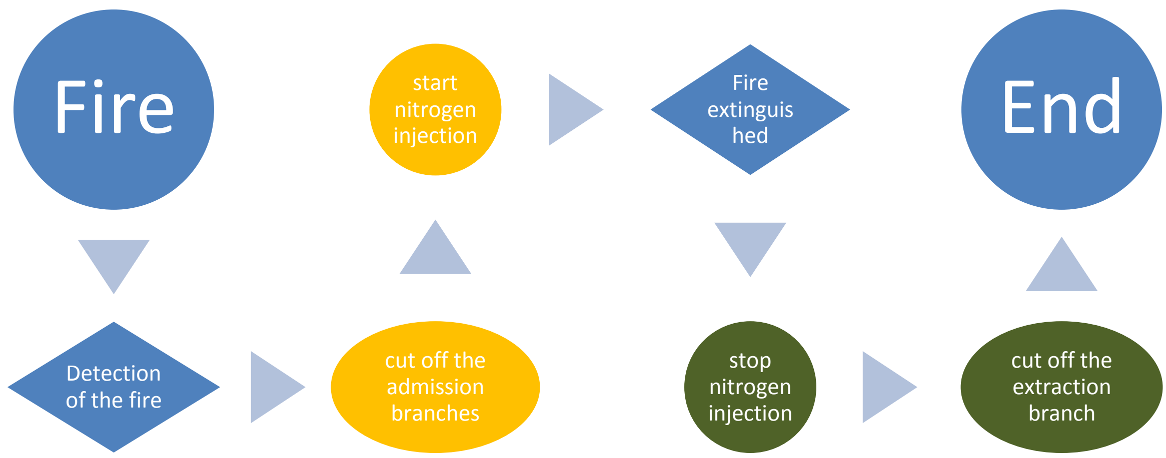


Figure 13: Sequence of control strategy for large single hot cell within the specific facility

<u>3.4.3.2 More on the 2nd scenario: multi-cell scenario</u>

Due to different dimensions of the hot cells, glove boxes and fume hoods, a simplified approach was applied for the multi-cell scenario. As it was not the intention of re-designing the whole ventilation system, two families of hot cells and one kind of glove box have been defined, respecting the height of the cells when the system was simplified as an electrical analogy (Figure 12). The cell families are chosen in the way that they can more or less represent the real case. The total number of hot cells and glove boxes remained unchanged for the simulation. The total volume of those cells was also unchanged. Some conclusions could be made:

- The maximum HRR largely depends on the volume of the hot cell, which determines the amount of oxygen available for the combustion.

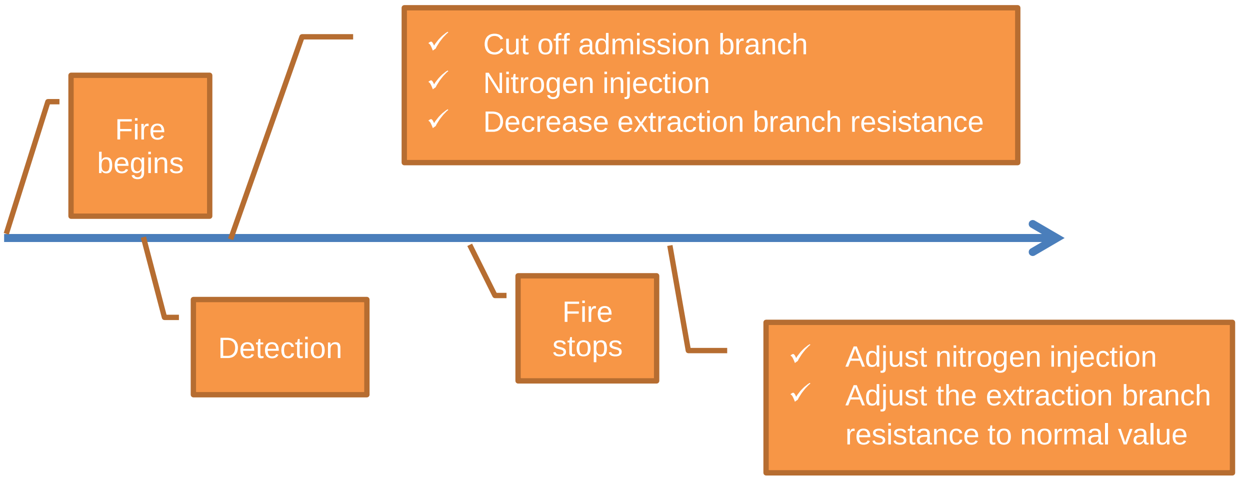
- The fire would have larger effect on the pressure of the hot cell if the volume of the cell is small.
- The temperature in the small hot cell is higher.
- High HRR in big hot cell can result in high gas temperature.

Again, two potential fire control strategies have been studied. The first one is cut off the admission branch by fire damper. The second one is gaseous injection and cutting of the admission branch.

Fire Dampers
The pressure in hot cell and glove boxes drops immediately after activation of the fire damper in the admission branch. The fire damper helps to maintain the underpressure in hot cell. Also, the closure of fire damper reduces the air supply to hot cell and thus also reduces the peak HRR. Subsequently, lower maximum temperatures are obtained due to lower HRR. In glove boxes, the pressure potentially increases (even above initial pressure) after damper closure. This can be explained; as soon as the fire damper is activated, the gases from the glove box cannot exit through the admission branch and therefore, pressure builds up more quickly. Fire is generally quicker extinguished by damper activation.

Gaseous fire suppression and lowering of extraction resistance
For this scenario, the injection of a gaseous suppression agent would increase the pressure in the hot cells to a great extent. This is due to the fact that for this specific case, the resistance of the ventilation branches is much higher than was for the first scenario of one single hot cell. However, Sylvia predicted that fire becomes extinguished. After injection of suppressant, the high pressure rise in the hot cell induces a problem to deal with. A potential solution to this difficulty is the lowering of the extraction resistance when extinction occurs, thus additional simulations were run.
It could be observed that lowering the resistance of the extraction branch regulator can reduce the pressure in the hot cell effectively. However, this would also lead to larger flow rate through the hot cells, which also means more oxygen available for the combustion. As a result, in all sub scenarios studied, the HRR is higher. The gas temperature is inevitable also higher. Nevertheless, this is an effective way to lower down the pressure in the fire cell. How the lowering of the resistance extraction branch can be achieved in a practical way for existing systems was not studied.

Combination of different strategies
Based on the effect of each strategy, a method that is a combination of strategies is a potential comprehensive strategy for this specific facility under study.



With this combined strategy, it could be observed that the hot cell never loses its underpressure. The gases temperature is never too high, which mean the filters are safe for temperature exposure (no analysis was made for water vapour in the smoke filters, which is one of the main reasons active carbon traps degrade). Also, the fire in the hot cell is extinguished successfully. A drawback could be an even too high underpressure obtained. Anyhow, all of this results show that the strategy proposed in this study was valid for the multi-cell scenario under study.

4 PERSPECTIVE ON FIRE SAFETY R&D

4.1 Continuing international collaboration - OECD/NEA PRISME 2 project

The main outcomes of the OECD PRISME Program concern smoke movement from the fire compartment to adjacent rooms, the effects of under-ventilated conditions on the fire source, the electrical cable behaviour submitted to high thermal stress, the building up of a large experimental database and the establishment of an efficient international network on this topic [11].
Based on the discussion with PRISME partners, three main topics need further work:

- Smoke and hot gases propagation through horizontal openings;
- Fire spreading on real fire source such as cable trays and electrical cabinet and fire propagation from one fire source to another;
- Fire extinguishing.

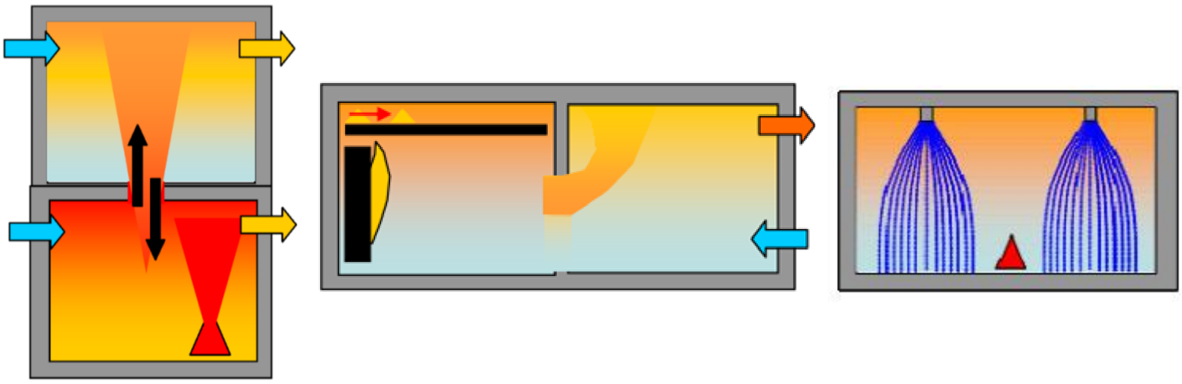


Figure 14: Scenario impression of the PRISME 2 Project

Based on these topics, the OECD PRISME 2 project has been defined [26]. This new project will answer some of issues but others will remain open. During the OECD PRISME 2 project, the improvement of the heat release rate prediction is still particularly important. Based on experimental results, code guidelines to simulate complex fires, such as cable trays or electrical cabinets, will be another important objective as there is a lack of knowledge on these types of fire sources and, following the assumptions of simulation, the discrepancy of the results is important.

4.2 Practical application and further validating computer models in the frame of Fire Hazard Analysis in Nuclear Power Plants

Not only validation of the available simulation codes, but likewise the relation with the assessment of real scenarios needs continuous attention. Therefore, more generic cases as example was given in paragraph 3.3 will be investigated. The latter exercises are particular useful in the assessment of FHA performed by the Licensee.

4.2.1 Design fire scenarios and needed uncertainty analysis

Furthermore, there is a need to investigate more uncertainties encountered when facing real applications [16]. Experimental uncertainty and model input uncertainty have been identified in current V&V studies. The model input uncertainty originates from the uncertainties of the input parameters such as HRR, material properties and dimension of configurations. In the

V&V study, the model input uncertainty is reduced to a minimum because most of the input comes from experimental data. However, a verified and validated fire model does not guarantee good predictions in real applications. As important as the quality of the fire model is the quality of the design fire scenario, where the HRR-curve and other key parameters are determined. It is possible that a model which gives good predictions in V&V study might give wrong predictions in real application. That is why sensitivity analysis is always an important procedure in applying fire models to real application.

4.2.2 Time aspects of validation process

Another aspect identified that needs attention is the time aspect in the validation process [16]. Metrics are increasingly used for Quantitative Validation ([28], [29]). Single point comparison is used as the criterion for the validation of fire models. For some scenarios, the timing of the fire is also an important attribute. The single criteria of using local single point value comparison ([23], [25]) can be misleading in some circumstances, as shown in the following example. Figure 15 shows model prediction for gas temperature with two different fire models.

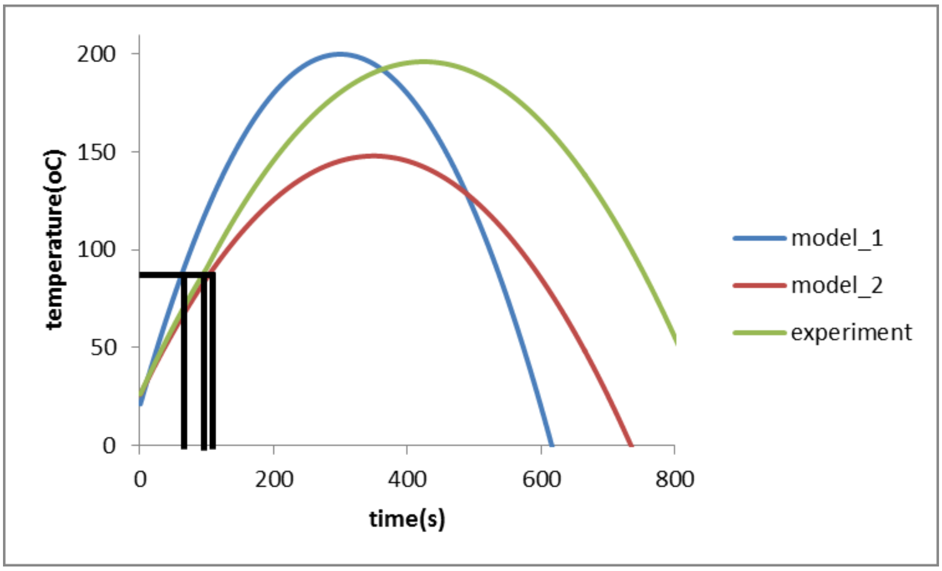


Figure 15: Generic gas temperature prediction by two models

For this generic case, the relative differences for the maximum gas temperature are:

Table 5: Relative differences for maximum value

	Maximum temperature (°C)	Relative difference
Experimental data	196	N/A
Model 1	200	2%
Model 2	148	24%

Model 1 is by far better than model 2 if we only compare the maximum value. However, in some situations it can be the other way around. Now consider situation where the gas temperature prediction is used to determine the time for the activation of sprinkler (activation temperature of 85°C, i.e. black curves on Figure 15). The table below gives the time to for the gas temperature to reach 85°C:

Table 6: Prediction of activation time

	Maximum temperature (°C)	Relative difference
Experimental data	91	N/A
Model 1	61	33%
Model 2	100	10%

In this case model 2 provides a better gas temperature prediction for the activation of sprinkler. This simple example illustrates the fact that the maximum value alone cannot be the perfect criterion for fire model V&V study. The time aspects should also be integrated into the V&V study. However, currently there is no established way to incorporate time aspects into V&V study in a quantitative way. Bonte [20] proposed several normalised metrics for time-dependent comparisons. However, there is still no established method to use those normalised metrics in V&V study. Table 6 also indicates that the relative difference methodology can also be applied to time-related values.

4.3 Interaction ventilation and fire – more on dynamic confinement in nuclear facilities

In the first study on strategy on fire protection in hot cells, only six fire scenarios (MLR) have been considered. It would be interesting to model the case with different input to see the behaviour of the considered outputs. Also, only two hot cell facilities are studied. It is unknown whether the results from the study are even so applicable to other hot cell configuration. It would be convenient if the same protection strategy used for this study can be applied to several different facilities. Currently it is too soon to conclude if the fire control strategy is case-dependent or not. Additionally, the height of the ventilation openings in the hot cell could also be of importance. Extraction opening in the ceiling or in the floor would result in different extraction temperature, and further influence the pressure behaviour of the hot cell. It is consequently suggested that further research can also focus on different location of the ventilation openings.
Finally, it is today unknown by hot cell type what fail criteria is best to be used for allowable under or overpressure values before structural failing. Also failure temperature criteria for hot cells and filters are not clearly defined. It would thus be very worthy to set up consequent and robust failure criteria for important equipment involved in static and dynamic confinement.

4.4 Cooperation with Ghent University – necessity to conduct more fundamental research

Cooperation between Bel V and Ghent University's Fire Safety Engineering programme is anticipated on for the development of competences in the framework of the PRISME 2 Project. Besides the cooperation with Ghent University in the framework of the International Master of Science in Fire Safety Engineering [15], Bel V decided in 2012 to grant financial support to a post-doctoral researcher in combustion, fire & fire safety of Ghent University. Following paragraphs summarize the intended research (by Tarek Beij [30]):

The scenario of a pool fire in a closed room is of a particular interest in nuclear facilities, where solvents used for nuclear reprocessing might ignite. The subsequent radiant emissions might exert substantial thermal stresses on some targets during the fire (such as cable trays and other pieces of equipment) and trigger a flame spread process.
Although pool fires have been extensively studied over the years, numerous challenges remain. As pointed out in the literature, these challenges are related to soot modelling (and more generally to radiative transfer modelling) as well as to the effect of ventilation conditions on the burning rate. These challenges could be illustrated for example by the statement of Bonte (who conducted a validation study of the CFD code ISIS [20]): "In general, rather low soot behaviour of hydrogenated tetra-propylene can be observed. This was not expected

…TPH is known as a heavily sooty flame". This is in accordance with the statement of Le Saux et al. [31] who stated that: "there is still a need of complementary researches to improve the physical modelling of soot production".

4.4.1 Detailed analysis of soot modelling and subsequent radiation for a pool fire in free-atmosphere

As stated in the literature, soot is the main contributor to radiation in fires. The complexity of interactions between chemistry, radiation, buoyancy and turbulence make soot modelling one of the most challenging topics in fire.
The proposed study will be conducted using the CFD software ISIS. ISIS is a numerical field model mainly dedicated to fire simulations conducted in a confined and ventilated compartment. It has been developed by the IRSN. The validation study of ISIS for radiative transfer and soot modelling [24] involves turbulent gaseous jet flames (i.e. momentum controlled flames with high Reynolds number). It is proposed here to extend this validation study to pool fires where buoyancy effects are important. As a first step, after preliminary laminar calculations, simulations will be carried out for turbulent buoyant fire (e.g. [32], [33]) for which experimental data is available.
In most of the soot models, many parameters need to be numerically calibrated in order to predict correctly the quantities of soot produced by the flame. For example, for the Moss model [34], values are given for common gaseous fuels such as methane and ethylene. If another fuel is used, the model constants need to be adjusted according to its relative sootiness. The approach proposed by Delichatsios and co-workers ([35]-[35]) relies on an experimental measurement of a fuel's propensity to produce soot, namely the laminar smoke point, which is a measurement used in the formulation of a global soot formation rate. Therefore, a one-equation approach is followed as in the Kahn and Greeves model in ISIS. However, in the latter model the laminar smoke point concept is not used. In the proposed work, the several approaches will be tested and compared.
The radiant heat fluxes will be compared and analysed. The effect of the radiative feedback on the pool surface and the subsequent MLR will be investigated for the case of a dodecane pool fire. Furthermore, a validation study using available experimental data of heat fluxes in Single Burning Item (SBI) tests [36] will be performed

4.4.2 Quantitative study of the interaction between a single-room fire and mechanical ventilation

In a single-room fire, ventilation conditions play an important role in the fire development. For under-ventilated fires, the Heat Release Rate (HRR) is limited by the amount of oxygen available. Furthermore, vitiation has an influence on the sootiness of the flames and the subsequent radiative feedback and pyrolysis rate. Therefore, there are two major parameters that need to be considered: (i) oxygen concentration, and (ii) radiation on the pool surface. In [36] the analysis was focused on the oxygen depletion effect by considering cases where gas temperatures are low enough so that radiation feedback can be ignored. However, as pointed out in [31], "radiation on the pool could be an important parameter". Therefore, a special attention will be given to the latter aspect for a set of several mechanical ventilation conditions.

5 REFERENCES

[1] NEA/CSNI, „Fire Risk Analysis, Fire Simulation, Fire Spreading and Impact of Smoke and Heat on Instrumentation Eletronics - State of the Art Report," R(99)27.

[2] Institute for Energy, „Fire Protection in the operatinal safety of nuclear installations - Current trends and isseus," DG JRC – Institute for Energy, 2006.

[3] B. Metzger, „Achieving Compliance - Fire Protection at U.S. Nuclear Power Plants," *Fire Protection Engineering,* nr. 55, 3rd Quarter 2012.

[4] WENRA Reactor Harmonisation Working Group, „Harmonisation of safety approaches in Europe," 2006. [Online]. Available: http://www.wenra.org.

[5] ibz, „Royal Decree on the safety prescriptions for nuclear facilities," *Belgisch Staatsblad - Moniteur Belge,* nr. BS 21 december 2011, 30 November 2011.

[6] NFPA 805, „Performance-Based Standard for Fire Protection for Light Water Reactor Electric Generating Plants," National Fire Protection Association, Quicy, MA, 2010.

[7] The International Association of Fire Safety Science, „IAFSS," 2012. [Online]. Available: http://www.iafss.org/.

[8] Society of Fire Protection Engineers, „SFPE," [Online]. Available: http://www.sfpe.org/.

[9] Fire Protection Network, „Firepronet," 2012. [Online]. Available: http://www.firepronet.eu/.

[10] Department of Flow, Heat and Combustion Mechanics, „Combustion, fire & fire safety," Ghent University, 2012. [Online]. Available: http://www.ugent.be/ea/floheacom/en/research/groups/fire.

[11] NEA/CSNI, „OECD/NEA PRISME Project Application Report," R(2012)14.

[12] H. Butafuoco, Practical Application of Validated Computer Models for Fire Hazard Analysis in Nuclear Power Plants, IMFSE - Ghent University, Faculty of Engineering, Department of Flow, Heat and Combustion, 2012.

[13] IRSN, „ISIS 3.0.0 - Physical Modelling," Direction de la préventijon des accidents majeurs - Service d'Etude et de Modélisation de l'Incendie, du corium et du Confinement, 2012.

[14] Kevin McGrattan, Randall McDermott, Simo Hostikka, Jason Floyd, „Fire Dynamics Simulator (Version 5) - User's Guide," National Institute of Standards and Technology in cooperation with VTT, 2010.

[15] International Master of Science in Fire Safety Engineering, „IMFSE," Erasmus Mundus framework, 2012. [Online]. Available: http://www.imfse.ugent.be/index.asp.

[16] F. Xu, Application of Zone- and Field codes to model heat and smoke propagation in support of Fire Hazard Analyses of Nuclear Power Plants, IMFSE - Ghent University, Faculty of Engineering, Department of Flow, Heat and Combustion, 2012.

[17] Feng Xu, Frederick Bonte, „Simulation of PRISME Integral 4 and Integral 6 Fire Tests with Sylvia," Bel V Internal R&D report, Brussels, 2012.

[18] IRSN, „Users guide of the SYLVIA v1.5 code," Pôle Sûreté des installations et systèmes Nucléaires - Service Agressions Internes et risque Industriels, 2012.

[19] Feng Xu, Frederick Bonte, „Strategy of Fire Protection in Hot Cells," Bel V Internal R&D report, Brussels, 2012.

[20] F. Bonte, Validation of Zone and Field Models to Support Fire Hazard Analysis and Fire PSA review of Fire Scenarios encountered in Nuclear Power Plants, Internal document Bel V & PGFSE - Ghent University, Faculty of Engineering, Department of Flow, Heat and Combustion, 2011.

[21] ASTME, „Standard Guide for Evaluating the Predictive Capability of Deterministic Fire Models," nr. E1355-05a, 2009 .

[22] ISO, „Fire Safety Engineering – Assessment, verification and validation of calculation methods," nr. ISO 16730, 2008.

[23] NUREG-1824 and EPRI 1011999, „Verification and Validation of Selected Fire Models for Nuclear Power Plant Applications, Volume 1: Main Report," U.S. Nuclear Regulatory Commission, Office of Nuclear Regulatory Research (RES), Rockville, MD and Electric Power Research Institute (EPRI), Palo Alto, CA, 2007.

[24] IRSN, „ISIS 3.0.0: Validation," Direction de la prévention des accidents majeurs - Service d'Etude et de Modélisation de l'Incendie, du corium et du Confinement, 2011.

[25] NUREG-1934 and EPRI 1023259, „Nuclear Power Plant Fire Modeling Application Guide (NPP FIRE MAG)," U.S. Nuclear Regulatory Commission, Office of Nuclear

Regulatory Research (RES), Washington, DC, 2010 and Electric Power Research Institute (EPRI), Palo Alto, CA, 2011.

[26] OECD/NEA, „OECD/NEA PRISME-2 Project," 2011. [Online]. Available: http://www.oecd-nea.org/jointproj/prisme-2.html.

[27] EPRI TR-1011989 and NUREG/CR-6850, „EPRI/NRC-RES Fire PRA Methodology for Nuclear Power Facilities: Volume 2: Detailed Methodology," Electric Power Research Institute (EPRI), Palo Alto, CA, and U.S. Nuclear Regulatory Commission, Office of Nuclear Regulatory Research (RES), Rockville, MD, 2005.

[28] L. Audouin et al., „Quantifying differences between computational results and measurements," *Nuclear Engineering and Design,* nr. 241, pp. 18-31, 2011.

[29] Suard, S., Vaux, V., Rigollet, L., „Fire code benchmark activities within the international research PRISME program – Discussion on metrics used for validation and on sensitivity analysis," *SMIRT 21, 12th International Post-Conference Seminar on Fire Safety in Nuclear Power Plants and Installations,* München, 2011.

[30] Ghent University, Bel V, „Project description," in *Agreement for scientific research*, internal reference, 2012.

[31] W. Le Saux, H. Prétrel, C. Lucchesi, P. Guillou, „Experimental study of the fire mass loss rate in confined and mechanically ventilated multi-rooms scenarios," *Fire Safety Science,* nr. 9, pp. 943-954, 2008.

[32] Y. Xin, J.P. Gore, „Two-dimensional soot distributions in buoyant turbulent fires," *Proceedings of the Combustion Institute,* vol. 30, nr. 1, pp. 719-726, Januari 2005.

[33] S.R. Tieszen, „Comparison of simulation and experiment for soot concentration in a 2M diameter JP-8 fire," *Proceedings of the ASME Summer Heat Transfer Conference,* vol. 1, pp. 747-750, 2005.

[34] J. B. Moss, C. D. Stewart, and K. J. Young, „Modeling soot formation and burnout in a high temperature laminar diffusion flame burning under oxygen-enriched conditions," *Combustion and Flame,* nr. 101, pp. 491-500, 1995.

[35] M.A. Delichatsios, *Combust. Sci. Technol.,* nr. 100, pp. 283-298, 1994.

[36] T. Beji, J.P. Zhang, W. Yao, M.A. Delichatsios, „A novel soot model for fires: Validation in a laminar non-premixed flame," *Combustion and Flame,* nr. 158, pp. 281-290, 2011.

[37] T. Beji, Theoretical and Experimental Investigation on Soot and Radiation in Fires. PhD dissertation., University of Ulster (UK), 2009.

[38] Melis, S. and Audouin, L., „Effects of vitiation on the heat release rate in mechanically-ventilated compartment fires.," *Fire Safety Science,* nr. 9, pp. 931-942, 2008.

[39] W. Yao, J. Zhang, A. Nadjai, T. Beji, M.A. Delichatsios, „Global soot model developed for fires: Validation in laminar flames and application in turbulent pool fires," *Fire Safety Journal,* nr. 46, pp. 371-387, 2011.