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Investigating Heat and Smoke Propagation Mechanisms in Multi-Compartment Fire Scenarios

Final Report of the PRISME Project

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Organisation de Coopération et de Développement Économiques
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NUCLEAR ENERGY AGENCY
COMMITTEE ON THE SAFETY OF NUCLEAR INSTALLATIONS

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Acknowledgements

The application of the PRISME Project results to investigate heat and smoke propagation mechanisms in multi-compartment fire scenarios were compiled by Laurence Rigollet (Institut de radioprotection et de sûreté nucléaire – IRSN, France), based on the work carried out by the Writing Group which comprised: Abderrazzaq Bounagui (Canadian Nuclear Safety Commission – CNSC, Canada), Laurent Gay and Bertrand Sapa (Electricité de France – EDF, France), Enrico Gorza (Tractebel-Engie, Belgium), Adrian Kelsey (Health and Safety Laboratory – HSL, United Kingdom), Christine Lallemand (Direction générale de l'armement – DGA, France), Julian Peco (Consejo de Seguridad Nuclear – CSN, Spain), Hugues Prétrel (Institut de radioprotection et de sûreté nucléaire – IRSN, France), Marina Röewekamp (Global Research for Safety – GRS, Germany), Topi Sikanen (Technical Research Centre – VTT, Finland), Susumu Tsuchino (Nuclear Regulation Authority – NRA, Japan), Patrick Van Hees (Lund University, Sweden) and Pascal Zavaleta (Institut de radioprotection et de sûreté nucléaire – IRSN, France).

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List of abbreviations and acronyms

AECL	Atomic Energy of Canada Limited (Canada)
ATH	Aluminium tri-hydroxide
AWG	Analytical Working Group
CFAST	Computer code developed by NIST (United States)
CFD	Computational fluid dynamics
CFS	Cable fire spreading
CFSS	Cable fire spreading support
CNSC	Canadian Nuclear Safety Commission (Canada)
COCOSYS	Containment code system (developed by GRS)
CORE	A PRISME 2 test campaign – see Section 4.2.4
CRIEPI	Central Research Institute of Electric Power Industry (Japan)
CSN	Consejo de seguridad nuclear (Spain)
DGA	Direction générale de l'Armement (France)
DIVA	The multi-room experimental facility used for some PRISME tests
DOOR	One of the PRISME test campaigns – see Section 4.1.1
DTE	Trade mark of the Exxon Mobil Company
EDF	Electricité de France (France)
FDS	Fire dynamics simulator
FES	Fire extinction systems
FD	Factorial design
FHA	Fire hazards analyses
FLASHCAT	A computer model for fires
GER	The ratio between the amounts of oxygen required for the burning of the fire source in open atmosphere and the amount of oxygen blown by the ventilation before ignition
GRS	Global research for safety Gesellschaft für Anlagen- und Reaktorsicherheit (GRS) gGmbH (Germany)
HFR	Halogenated flame retardant
HFFR	Halogen free flame retardant
HRR	Heat release rate
HSE	Health and Safety Executive (United Kingdom)
HSL	Health and Safety Laboratory (United Kingdom)

HTP	Hydrogenated tetra-propylene $C_{12}H_{26}$
I&C	Instrument and control
IRMS	Insulation resistance measurement system
IRSN	Institut de radioprotection et de sûreté nucléaire (France)
ISIS	A computer code used for fire modelling
KEPRI	Korea Electric Power Research Institute
KINS	Korea Institute of Nuclear Safety (Korea)
MAGIC	Computer code developed by EDF (France)
MLR	Mass-loss rate
MOV	Motor operated valve
MW	MegaWatts – this is a unit of power – does it need a definition
NEA	Nuclear Energy Agency
NIST	National Institute of Standards and Technology (United States)
NPP	Nuclear power plant
NRA	Nuclear Regulation Authority (Japan)
NRC	Nuclear Regulatory Commission (United States)
OECD	Organisation for Economic Co-operation and Development
OEIL	Computer code developed by DGA (France)
ONR	Office of Nuclear Regulation (United Kingdom)
PBG	PRISME Benchmarking Group
PE	Polyethylene
PRISME	Propagation d'un incendie pour des scénarios multi-locaux élémentaires (Fire Propagation in Elementary Multi-room Scenarios)
PSA	Probabilistic fire safety analyses
PVC	Poly vinyl chloride
SAFIR	Computer code co-developed by the Aix Marseille University and DGA (France)
SATURNE	A calorimeter facility for open atmosphere PRISME tests
SCDU	Surrogate circuit diagnostic unit
SNL	Sandia National Laboratories
SSCs	Systems, structures, or components
SSM	Strålsäkerhetsmyndigheten (Finland)
SYLVIA	Computer code developed by IRSN (France)
ULB	Free University of Brussels (Université libre de Bruxelles)
VFA	Video fire analysis
VRR	Ventilation renewal rates

VROM-KFD	Ministry of Housing, Spatial Planning and the Environment (Netherlands)
V&V	Validation and verification
VSP	Vertical smoke propagation
VTT	Technical Research Centre (Finland)

Executive summary

Fire hazards analyses (FHA) and probabilistic fire safety analyses (Fire PSA) have demonstrated that fire may be an important contributor to core damage frequency and other major plant damage states of nuclear power plants (NPP).

Several Nuclear Energy Agency (NEA) member countries expressed interest in a new joint international research project on the topic of fire propagation. The PRopagation d'un Incendie pour des Scénarios Multi-locaux Elémentaires (PRISME) projects were proposed by the Institut de Radioprotection et de Sûreté Nucléaire (IRSN) in France with their specially designed facilities in Cadarache to be used to carry out the various fire test scenarios. The first phase of PRISME was formally launched in January 2006 and concluded by June 2011. The second phase launched in July 2011 and ended in December 2016. A total of 12 countries signed the agreement to become PRISME and PRISME 2 members: Belgium (Tractebel-ENGIE and Bel V), Canada (Atomic Energy of Canada Limited – AECL for PRISME and Canadian Nuclear Safety Commission – CNSC for PRISME 2), Finland (Technical Research Centre – VTT), France (IRSN as operating agent and Électricité de France – EDF), Germany (Global research for safety – GRS), Japan (Nuclear Regulation Authority – NRA and Central Research Institute of Electric Power Industry – CRIEPI for PRISME 2), Korea (Korea Institute of Nuclear Safety – KINS for PRISME), Netherlands (Ministry of Housing, Spatial Planning and the Environment – VROM-KFD for PRISME), Spain (Consejo de seguridad nuclear – CSN), Sweden (the future Strålsäkerhetsmyndigheten – SSM), the United Kingdom (Health and Safety Executive – HSE and the Office of Nuclear Regulation – ONR) and the United States (Nuclear Regulatory Commission – NRC for PRISME).

In the first phase of the project, three major research areas were addressed: propagation of heat and smoke from the fire room to adjacent rooms, impact of heat and smoke on safety critical systems and the impact of the ventilation network on limiting heat and smoke propagation. The second phase of the project focused on smoke and hot gas propagation through a horizontal opening between two superposed compartments, fire spread on real fire sources such as cable trays and electrical cabinets and fire propagation from a fire source to another, and fire extinction studies of the performance of various extinguishing systems. In all, 8 experimental campaigns consisting of more than 60 large-scale fire tests were carried out using the facilities at Cadarache. In parallel to the experimental campaigns, PRISME and PRISME 2 partners evaluated the capabilities of various fire modelling codes to simulate fire scenarios based on the PRISME data results. A number of benchmark exercises were conducted within the analytical working group which further advanced the knowledge on the predictive capabilities of the various fire codes being used.

A key accomplishment of the PRISME Project is the enhanced knowledge gained of the phenomena occurring during a fire in a confined mechanically-ventilated installation. Important issues to be considered in safety analysis such as the position of leaks on walls and their effect on smoke and heat propagation in neighbouring compartments have been studied. In the PRISME 2 project, the analysis of the tests also contributed to enhance the understanding of under-ventilated fires including realistic fire sources like electrical cable trays or electrical cabinets. Both projects highlighted the interaction between the fire and the mechanical ventilation.

Another global accomplishment of the PRISME and PRISME 2 projects has been the improvements realised in the use of fire simulation codes to more accurately model fire behaviour. Further, the benchmark exercises conducted by partners have also highlighted to the users the inherent limitations of the models used to predict smoke and heat propagation in certain complex scenarios and fires of electrical cables in confined and ventilated compartment. In general, the PRISME Project has resulted in an improved understanding of heat and smoke propagation from the fire compartment to an adjacent compartment, the effects of under-ventilated conditions on the fire source, the physical phenomena induced by the actuation of water spraying, the behaviour of electrical cables submitted to high thermal stress, the creation of a significant database of experimental data and finally the establishment of an international network on these important topics.

A number of recommendations have been produced by the PRISME 2 project team to address some further phenomena not studied in the current project. These phenomena are smoke stratification and spread, fire propagation from electrical cabinets, and electrical cable tray fires in confined and ventilated conditions. The follow-up PRISME 3 project that is currently underway addresses some specific aspects of all 3 of these phenomena.

This final project report describes the programme of work, high-level results and outcomes of the PRISME and PRISME 2 projects following ten years of experimental research. Further it provides some insights into future areas of research that could further advance the collective understanding of fire propagation scenarios important to the safety analysis for NPP facilities. In all, the PRISME and PRISME 2 projects have provided unique and invaluable information to its members to assist them in better understanding fire phenomena, to improve their predictive capabilities of fire simulations and ultimately to advance system design considerations to reduce overall fire risk to the plants.

1. Nuclear safety issues and background

Fire hazards analyses (FHA) and probabilistic fire safety analyses (Fire PSA) have demonstrated that fire may be an important contributor to core damage frequency and other major plant damage states of nuclear power plants (NPP) (NEA, 2000).

Fire modelling is applied in general by the stakeholders, licensees, technical safety organisation and, in some countries, regulators, to assess the fire consequences and sometimes, to demonstrate the fulfilment of prescriptive requirements for fire protection. One important aspect of this approach of risk informed/performance base fire protection is the availability of verified and validated fire models that can reliably estimate the effects of fires.

Validation and verification (V&V) of fire models in nuclear installations have shown areas where these fire models can be improved, in particular regarding the effect of confinement on the fire behaviour. The PRISME Benchmarking activities highlighted areas where users should have confidence when using the current generation of fire models. As well, the limitations of knowledge and comprehension of some phenomena to simulate more realistically scenarios such as cable tray fire or electrical cabinet fire. Several open questions still remaining, to further enhance fire model predictions, this include but not limited to:

- impact of heat and smoke on systems important to nuclear safety;
- complex fire sources, such as electrical cabinets and cable trays;
- ventilation management for limiting smoke and heat propagation;
- propagation of heat and smoke from the fire room to other rooms;
- effect of water-based extinguishing systems on gas and fire behaviour;
- fire spread on several combustibles materials.

It is important to reduce the uncertainties in the treatment of the above mentioned aspects (NEA, 2000). As such, validated codes to simulate adequately the relevant steps of the fire scenario are needed.

One of the main technical issues in fire safety assessment is related to smoke and hot gases propagation in a nuclear plant and their impact on systems, structures, or components (SSCs) important to safety. The prediction of the fire development in confined and ventilated environment is another challenge, taking into account the strong interaction between the fire and the ventilation conditions, and the behaviour of active fire barrier elements, such as fire dampers, fire doors, etc. Modelling of the most parts of propagation phenomena exists in current numerical tools for fire simulation. However, there is a lack of experimental data suitable for code validation for cases such as coupling natural and mechanical convection.

Moreover, there is a need to understand under which conditions heat and smoke propagation can be simulated by zone models and/or three-dimensional computational fluid dynamics (CFD) codes, so-called field models. This understanding necessitates a well-qualified database obtained in full-scale and under representative experimental conditions. Furthermore, the impact of smoke on safety related equipment, such as the malfunction of electrical panel or of electronic equipment have not yet been modelled but this impact can be tested in real fire experiments (Espargillière et al., 2014).

An important point to underline: fire modelling still suffers from a lack of knowledge on a realistic burning behaviour of several combustibles. Electric cable trays present a significant fire risk in nuclear power plant (NPP) because of the large quantities of electrical cables present in such nuclear facilities, typically hundreds of kilometres of electrical cables. Electrical cabinets are another potential source of fire in NPP. From the FIRE Database (NEA, 2015), a majority of the fire ignitions is due to electrical sources (close to 50%). More specifically, a significant contributor to this electrical fire hazard is attributed to electrical or electronic cabinets, with an occurrence of more than 10% of all fire events recorded, including all types of electrical cabinet (low, medium and high voltage).

Consequently, fire safety analysts need to understand how the fire can spread on complex sources in order to assess the potential fire consequences in NPP.

The PRISME and PRISME 2 projects have contributed to improve knowledge on these different topics. These subjects are not specific of the nuclear domain and concern also the safety in the ships as the analysts have to assess similar fire sources in confined and mechanically-ventilated configurations.

2. Overview of the PRISME and PRISME 2 projects

A number of Nuclear Energy Agency (NEA) member countries participated in the joint international research project on the topic of fire spread and smoke propagation. The PRISME and PRISME 2 projects were operated by *Institut Radioprotection Sûreté Nucléaire* (IRSN) (France) with their facilities in Cadarache to be used to carry out the various fire test scenarios.

The countries who signed the agreement of the PRISME Projects are listed in the following Table 1.

Table 1: PRISME and PRISME 2 project member institutions

Country	**PRISME (January 2006 - June 2011)**	**PRISME 2 (July 2011 – December 2016)**
Belgium	GDF Suez – Tractebel and Bel V	Tractebel-Engie, with the support of ULB (Free University of Brussels), and Bel V, with the support of Ghent University
Canada	AECL	CNSC
Finland	VTT	VTT, with the support of Aalto University
France	IRSN as Operating Agent, with the collaboration of DGA, and EDF	IRSN as Operating Agent, with the collaboration of DGA, and EDF
Germany	GRS, with the support of iBMB of Braunschweig University of Technology	GRS, with the support of iBMB of Braunschweig University of Technology
Japan	JNES (future NRA)	NRA (formely-JNES) and CRIEPI
Korea	KINS, with KEPRI and KOPEC	-
Netherlands	VROM-KFD, with the support of NRG	-
Spain	CSN	CSN
Sweden	SSM (formerly SKI), with the support of Vattenfall and Lund University	SSM, with the support of Vattenfall and Lund University
United Kingdom	HSE/ONR	HSE/ONR
United States	US NRC	-

An overview of the PRISME and PRISME 2 projects is presented in the following paragraphs.

2.1 Purpose of the PRISME Project

The objectives of the PRISME Project are 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) via the following elements (Audouin, 2011; Audouin et al., 2013a):

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

To achieve these objectives, 5 experimental campaigns (see Figure 1) were performed from early 2006 up to mid-2011:

- PRISME SOURCE fire tests devoted to the characterisation of the fire source and the investigation of the fire behaviour in a single compartment in under-ventilated conditions;

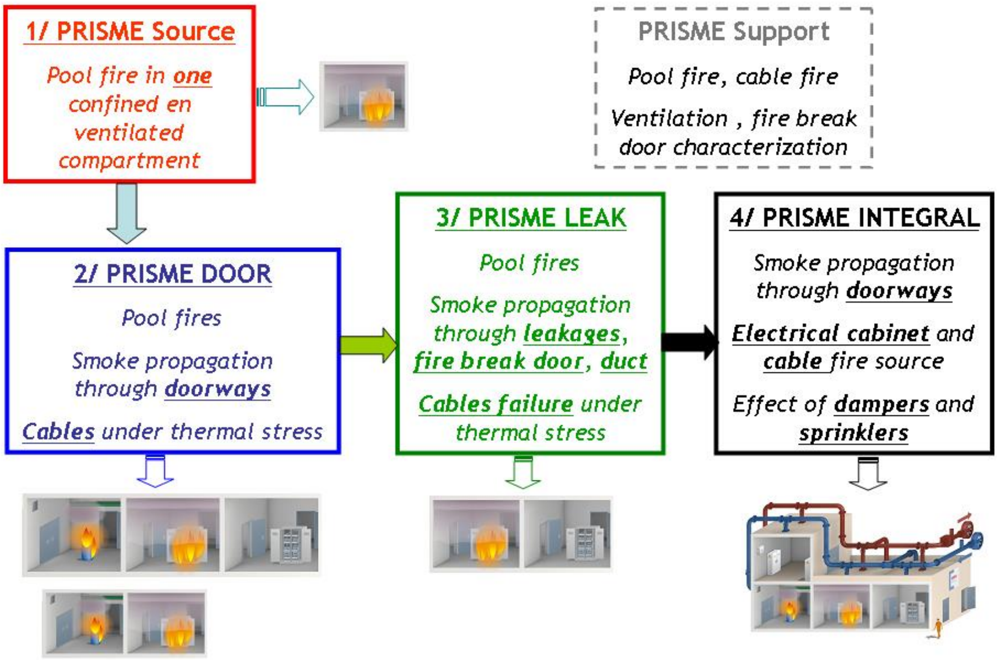
- PRISME DOOR fire tests devoted to the study of the smoke and gas propagation between 2 or 3 rooms through doorway and the effects of thermal stress on Poly Vinyl Chloride (PVC) electrical cables (surrogate and real cables);

- PRISME LEAK fire tests devoted to the investigation of the smoke and gas propagation between 2 rooms through leakages (via 2 openings, a narrow vertical slot, a fire door and a duct running across the fire compartment) and the effects of thermal stress on real electrical cables for which the electrical malfunction was measured;

- PRISME INTEGRAL fire tests devoted to the study of the heat and mass transfer of hot gases and smoke through doorways considering 3 and 4 rooms, with special focus on smoke and heat propagation due to a real fire source (electrical cabinet and cable fire sources); the effects of ventilation management (ventilation and damper effect) or water deluge extinguishing system (sprinkler) on heat and smoke propagation were also studied; and

- PRISME Support: around 10 tests conducted to characterise the fire sources in open atmosphere conditions.

Figure 1: Scheme of the experimental programme carried out during PRISME Project



2.2 Purpose of the PRISME 2 project

The objectives of the PRISME 2 project are to investigate the smoke and hot gas propagation through a horizontal opening between 2 superposed compartments, fire spread on real fire sources such as cable trays and electrical cabinets and fire propagation from a fire source to another, and fire extinction studies of the performance of various extinguishing systems (Audouin et al., 2013b).

To answer to these objectives, 4 experimental campaigns were performed from mid-2011 up to 2016:

- PRISME-2 Vertical Smoke Propagation (PR2-VSP) test series investigates the smoke propagation through a horizontal opening connecting 2 rooms mechanically ventilated, the fire room being the lower one;

- PRISME-2 Cable Fire Spreading (PR2-CFS) campaign investigates fire spread on complex fire sources, like horizontal cable trays or electrical cabinet, and fire consequences in a confined and ventilated multi-rooms facility;

- PRISME-2 Fire Extinction Systems (PR2-FES) campaign investigates the effects of water spraying technique, focusing only on fire control and on fire smoke cooling. The suppression of fire source was not studied; and

- PRISME-2 CORE (PR2-CORE) campaign aims at completing and repeating some of the fire tests already carried out during the PRISME 2 project.

About twenty support tests were also performed to characterise the fire sources in open atmosphere conditions. The fuels characterised and applied in the experiments were heptane, oil DTE MEDIUM (ExxonMobil Company) and 5 horizontal cable trays.

3. Description of the experimental facilities and instrumentation

The large-scale experiments performed in the PRISME and PRISME 2 projects have been carried out in a multi-room facility (named DIVA) for the confined and ventilated fire tests and in a calorimeter facility (named SATURNE) for open atmosphere. These experimental facilities are located at Cadarache (France). All compartments of DIVA are representative of nuclear power plants (NPP) with confined rooms connected to a ventilation network.

3.1 The DIVA facility

The DIVA facility is a large-scale multi-room facility (see Figure 6) including 4 compartments (labelled 1 to 4) and a corridor. All the walls are 0.3 m thick and were built with reinforced concrete allowing them to withstand a gas pressure range from 100 hPa to 520 hPa. The compartments labelled 1 to 3 are 6 m in length, 5 m in width and 4 m in height (see Figure 7). Room 4 (length × width × height = 8.8 × 5 × 4 m^3) is designed to study the vertical hot gas propagation from a lower (Room 3) to an upper room (Room 4) through a horizontal opening having a surface of about 1 m². The corridor (length × width × height = 15 × 2.5 × 4 m^3) is located along the Rooms 1 to 3.

All rooms of the DIVA facility can be connected with a mechanical ventilation system by means of inlet and outlet ducts, which can be set up at any height in each room depending of the fire scenarios. The lower rooms (Compartments 1 to 3 and corridor) can be connected through a single doorway or different types of elements (simple openings, fire door, etc.).

Figure 2: Scheme of the DIVA facility and its ventilation network

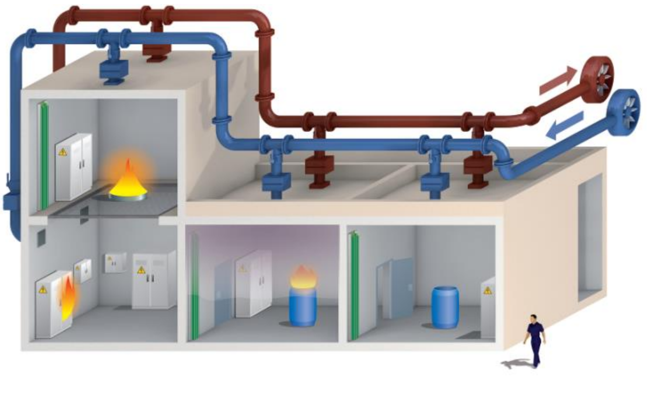
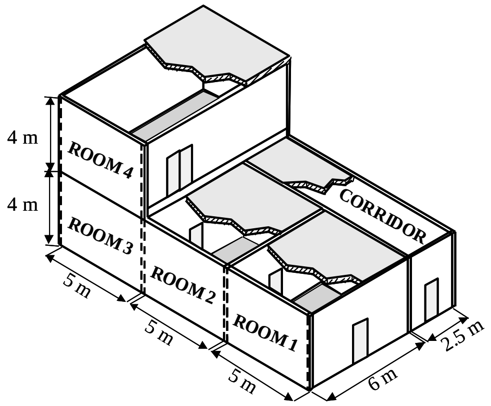


Figure 3: Main geometrical dimensions of the DIVA facility



The DIVA facility can be highly instrumented (up to 800 possible measurement channels on the data acquisition system). The ventilation network of the DIVA facility allows to simulate ventilation configurations representative of nuclear power plant (NPP) as well as nuclear laboratories and nuclear reprocessing plant.

3.2 The SATURNE facility (calorimeter)

The SATURNE facility (see Figure 4) is a large enclosure of 2 000 m^3 (length × width × height = 10 x 10 x 20 m^3), in which a large-scale calorimeter is located. This facility is designed to study fire sources with heat releases up to nearly 3 MW.

The fire tests carried out under the calorimeter hood (see Figure 3 and Figure 4) are devoted to determine the fire behaviour in open atmosphere for simple and complex fuels such as liquid pools, electrical cabinets and cable trays. The main characteristics of the calorimeter are:

- Hood: 3 m in diameter.
- Height from floor: for these tests, the height between the floor and the bottom rim of the hood is approximately 4 m.
- The smoke exhaust system is connected to a ventilation network. Its exhaust flow rate can be varied from 10 000 to 30 000 m^3/h.

Figure 4: Hood of the SATURNE facility (large-scale calorimeter)

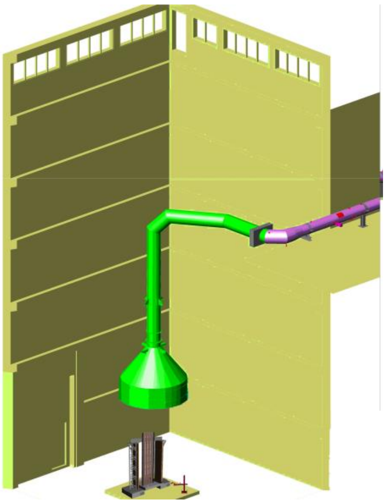
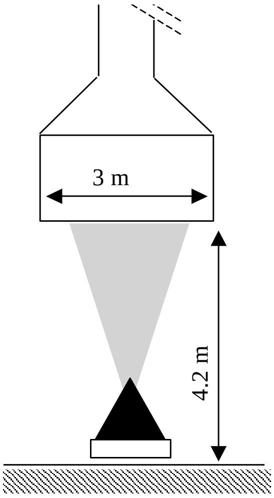


Figure 5: Main geometrical dimensions of the SATURNE facility



3.3 Instrumentation

For most of the PRISME fire tests, more than 500 measurements have been performed in order to fully describe the fire scenarios and to propose a high quality database for code validation. The measurements focus on the following variables: fuel mass-loss rate (MLR), gas and wall temperatures (or others such as inside cables trays), gas species concentrations (CO, CO_2, O_2 and total hydrocarbons), soot concentrations, radiative and total heat fluxes received by the walls or various targets, pressures and flow rates in all compartments and in the ventilation network.

For the SATURNE hood, the measurements available in the exhaust duct are mainly those typically available in calorimeter system such as pressures, gas flow rates, temperatures, gas concentrations of O_2, CO, CO_2 and soot concentration.

Additional values are also determined close to the fire source such as the fuel mass, temperatures, radiative and total heat fluxes (nearby and far from fire source), and video camera recordings.

4. Description of experiments carried out

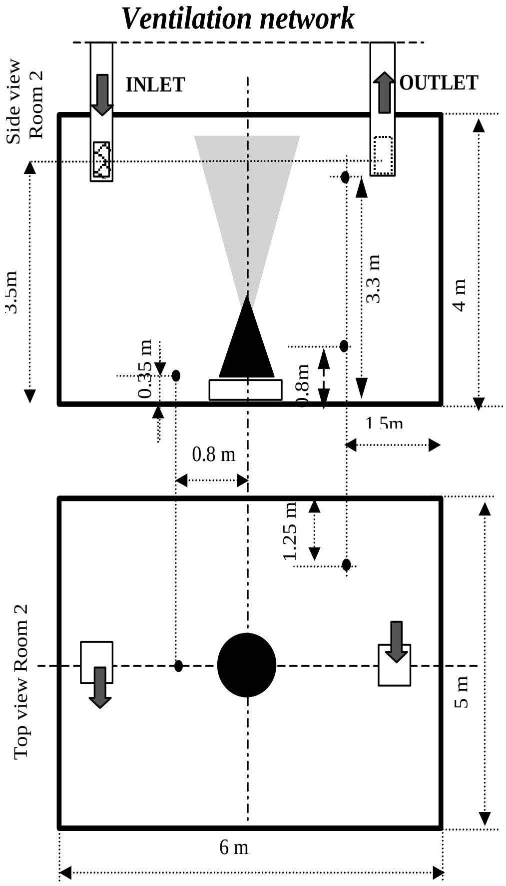
4.1 PRISME Project

The fire sources in the PRISME Project were liquid pool fire and, in the PRISME INTEGRAL campaign, typical real fire sources such as halogenated cables and electrical cabinets. The heat release was in the range from about 200 kW to several MW depending of the fuel nature, the fuel surface, the wall material(s) and the ventilation airflow rate. The fire may be self-extinguished by lack of fuel or lack of oxygen in the fire room.

4.1.1 PRISME SOURCE and DOOR

As a first stage, the PRISME SOURCE fire tests aim to study the fire behaviour of Hydrogenated Tetra-Propylene (HTP) pool fire (HTP = $C_{12}H_{26}$). This liquid fuel was also used as fire source in the PRISME SOURCE and DOOR experimental campaigns. This liquid fuel is tested first in open atmosphere (SATURNE calorimeter) for several fuel surfaces and then in confined and ventilated conditions (single room) in order to investigate the effect of oxygen depletion on the fire source. The experimental matrix of the PRISME SOURCE tests including the main parameters of fire tests (pool area, initial fuel mass, and ventilation flow rate in DIVA) is fully described in Appendix 1 for the confined and ventilated fires and in Appendix 3 for fires in open atmosphere. The PRISME SOURCE fire tests in the DIVA facility were carried out in the Room 2 (see Figure 6).

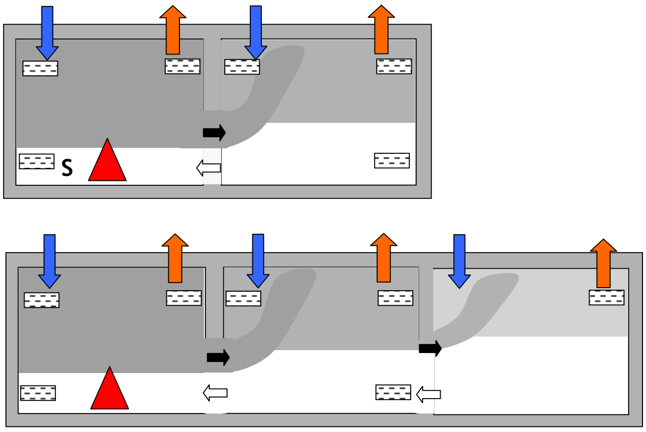
Figure 6: DIVA configurations and tests matrix for PRISME SOURCE



	S (m^2)	VRR (h^{-1})	Inlet position
PRS-SI-D1	0.4	4.7	High
PRS-SI-D2	0.4	8.4	High
PRS-SI-D3	0.4	1.5	High
PRS-SI-D4	0.4	4.7	High
PRS-SI-D5	0.2	4.6	High
PRS-SI-D5a	0.2	1.6	High
PRS-SI-D6	0.4	4.7	Low
PRS-SI-D6a	0.4	1.7	Low

The PRISME DOOR campaign investigated especially the spread of smoke and hot gases through doorways for 2 and 3 room configurations and also the heat transfer to surrogate and real cables. The fire test parameters (as the pool area) were selected based on the previous PRISME SOURCE experiments. In Appendix 1, the experimental matrix of the PRISME DOOR tests is described showing the main parameters of the fire tests such as the pool area, the initial mass of fuel, the ventilation flow rate, the number of compartments and the location of the air inlet. The PRISME DOOR fire tests were carried out in the Rooms 1 and 2 for the two-room scenarios and in the Rooms 1 to 3 for the three-room scenarios (see Figure 7).

Figure 7: DIVA configurations (front view) and tests matrix for PRISME DOOR fire tests



	S (m^2)	VRR (h^{-1})	Number of rooms
PRS-D1	0.4	0	2
PRS-D4	0.4	1.5	2
PRS-D2	0.4	4.7	2
PRS-D3	0.4	8.4	2
PRS-D5	1	4.7	3
PRS-D6	1	4.7	3

4.1.2 PRISME LEAK

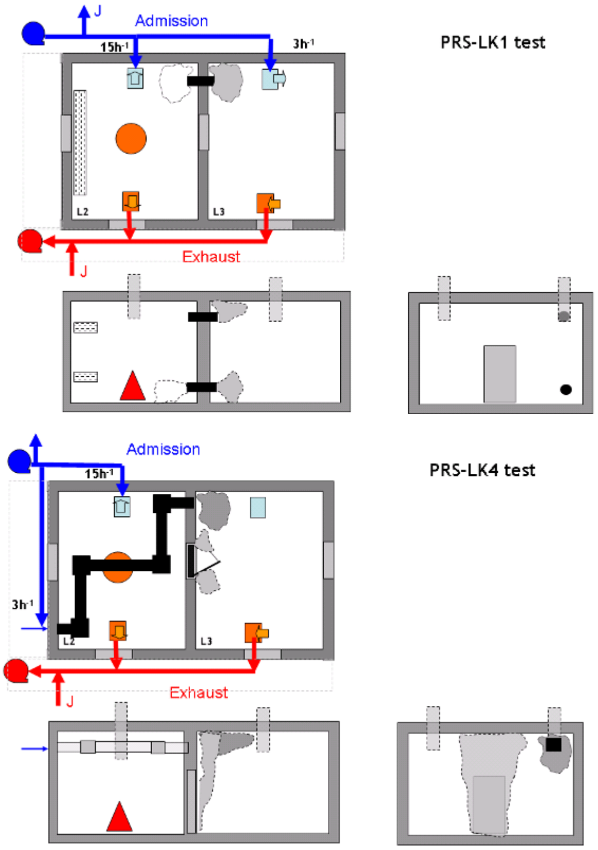
The third campaign, PRISME LEAK, concerned the propagation of smoke and hot gases through leakages (2 openings, narrow slot, fire door) between the fire compartment and the neighbouring room (LEAK 1 to 3, see Figure 8) and the study of the heat transfer coming from a duct crossing the fire compartment and flowing into the adjacent room (LEAK 4, see Figure 8).

More precisely, PRS-LK1 test aimed on investigating the propagation of smoke through 2 circular holes located in the upper and lower part of the wall separating the fire room and the adjacent room. PRS-LK2 test concerned the propagation of smoke through a vertical slot opening. PRS-LK3 test investigated the propagation of smoke through a real fire door. PRS-LK4 test concerned the propagation of smoke through a real fire door as well as the heating of a ventilation duct exposed directly to the fire and the propagation of the blowing heated air into the adjacent room. The experimental matrix of PRISME LEAK is described in Appendix 2.

A second objective was the cable performance testing (as found in a nuclear power plant – NPP) in order to provide additional data to improve the knowledge based on cable fire-induced failure modes and effects. To meet this aim, it was required to reach a gas temperature as high as 430 °C close to cable trays located in the upper part of the fire room in order to induce failure of electrical cable during the fire. For that, all the walls (except the floor) were insulated by rock wool panels of 5 cm in thickness for the ceiling and of 3 cm in thickness for vertical walls.

This study was carried out with the technical support of Sandia National Laboratories (SNL) and sponsored by the US Nuclear Regulatory Commission (NRC) Office of Nuclear Regulatory Research. The equipment and methods used in the PRISME cable performance tests were based directly on those used to support the CAROLFIRE program (Nowlen and Wyant, 2008).

Figure 8: PRS-LK1 (similar for PRS-LK2 and PRS-LK3) and PRS-LK4 fire tests



LEAK Test	Transfer mode
PRS-LK1	Two orifices
PRS-LK2	Vertical slot
PRS-LK3	Fire door
PRS-LK4	Fire door and duct

4.1.3 PRISME INTEGRAL

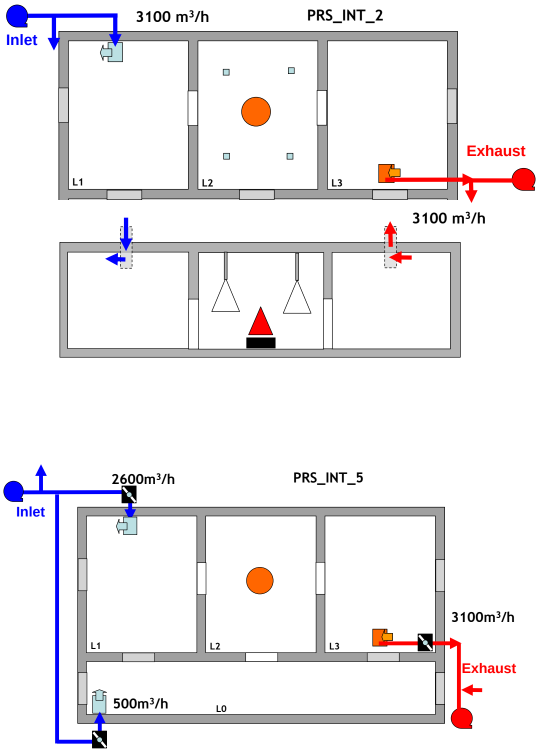
The last stage, PRISME INTEGRAL, aimed at studying practical configurations (see Figure 9) involving various fuels, 3 or 4 rooms connected by doorways, one fire barrier element such as a fire damper and one deluge system such as sprinklers. In these experiments, the air inlet flow goes from Room 1 (and corridor) to the exhaust duct in Room 3 via forced vs. natural air flows through doorways. This last experimental campaign involves 6 fire tests as specified in Appendix 2. The main objectives of this last campaign were to investigate:

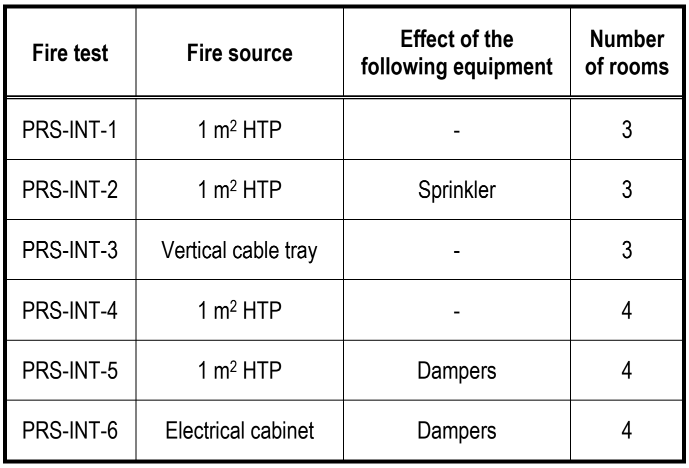
- the propagation of smoke and hot gases through doorways in confined and ventilated rooms;
- the effect of the number of adjacent rooms on the propagation through doorways;
- the effect of sprinkler activation on a fire scenario;
- the effect of fire damper closure on a fire scenario;
- the behaviour of a cable fire in a confined and ventilated fire scenario; and
- the behaviour of an electrical cabinet fire in a confined and ventilated fire scenario.

Furthermore, PRISME partners required getting high thermal stress to the adjacent rooms (i.e. Room 3), which implied a fire (for HTP fuel only) with steady and high fire power. The expected experimental condition was to reach mean gas temperatures in adjacent Room 3 of more than 300°C in the adjacent Room 3. To meet this goal, Room 2 and Room 3 were thermally protected with 5 cm thick rock wool panels (THERMIPAN®) on the ceiling and with 3 cm thick rock wool panels (THERMIPAN®) on the 4 walls.

In Appendix 2, the experimental matrix of the PRISME INTEGRAL tests is described showing the main parameters of the fire tests such as the fire source, the number of compartments and others (fire dampers, sprinkler activation). To determine the fire behaviour of cables in open atmosphere, the PRISME Support tests (see Appendix 3) were carried out under the SATURNE calorimeter before the fire test (PRS-INT-3) inside the DIVA facility.

Figure 9: PRS-INT2 test (similar for PRS-INT1 and PRS-INT3 tests) and PRS-INT5 test (similar for PRS_INT4 and PRS-INT6 tests)





Fire test	Fire source	Effect of the following equipment	Number of rooms
PRS-INT-1	1 m² HTP	-	3
PRS-INT-2	1 m² HTP	Sprinkler	3
PRS-INT-3	Vertical cable tray	-	3
PRS-INT-4	1 m² HTP	-	4
PRS-INT-5	1 m² HTP	Dampers	4
PRS-INT-6	Electrical cabinet	Dampers	4

4.2 PRISME 2 project

4.2.1 PRISME 2 vertical smoke propagation campaign

The PRISME 2 Vertical Smoke Propagation (PR2-VSP) test series investigated the smoke propagation through a horizontal opening connecting 2 mechanically-ventilated rooms, one above the other, the fire room being the lower room. The study focused on the flow at the opening which can undergo complex behaviour. This flow is driven by the competition between the buoyancy force due to the temperature difference, the inertia force due to the pressure difference induced by the mechanical ventilation and the possible local momentum due to fire plume or ceiling jet.

A first stage of tests concerned a single room fire test. The configuration was a one-room test with a given heat release rate and a ventilation rate. Due to unexpected oscillatory phenomenon observed during this first PR2-VSP-1 test, the scenario of this first test was performed 4 times with modified test parameters in order to obtain steady under-ventilated regime (see Table 2). The modified parameters were the pool area (0.4 m^2 or 0.3 m^2), the fuel (heptane or dodecane) and the renewal rate (12 h^{-1} or 16.6 h^{-1}). The 3 first tests (PR2-VSP-1, PR2-VSP1-TER and PR2-VSP-1-QUI) showed oscillatory behaviour. The last test (PR2-VSP-1A) achieved the intended steady under-ventilated combustion regime.

The second phase of tests studied two-room configurations and dealt with smoke propagation towards the adjacent upper room through a horizontal opening. The entire set of the 4 fire tests dealt with a 0.4 m^2 heptane pool fire in 120 m^3 mechanically-ventilated enclosure. Parameters to be investigated were the location of the fire source and the ventilation configurations. For the PR2-VSP-2 test, the fire source was centred in the fire room and located right below the opening. For the PR2-VSP-3, PR2-VSP-4 and PR2-VSP-4-BIS tests, the fire source was off-centred in a corner of the fire room. There were 3 ventilation configurations (see Figure 10):

1. PR2-VSP-2 test favouring one directional flow through the opening with admission in the fire room and exhaust in the adjacent room;
2. PR2-VSP-3 test limiting pressure variation at the opening with admission and exhaust in the 2 rooms;
3. PR2-VSP-4 and PR2-VSP-4-BIS tests representing an intermediate case without exhaust in the fire room. These 2 tests were performed with the same configuration of ventilation but with 2 different renewal rates.

Figure 10: Schematic configuration and tests matrix of the PRS2-VSP fire tests

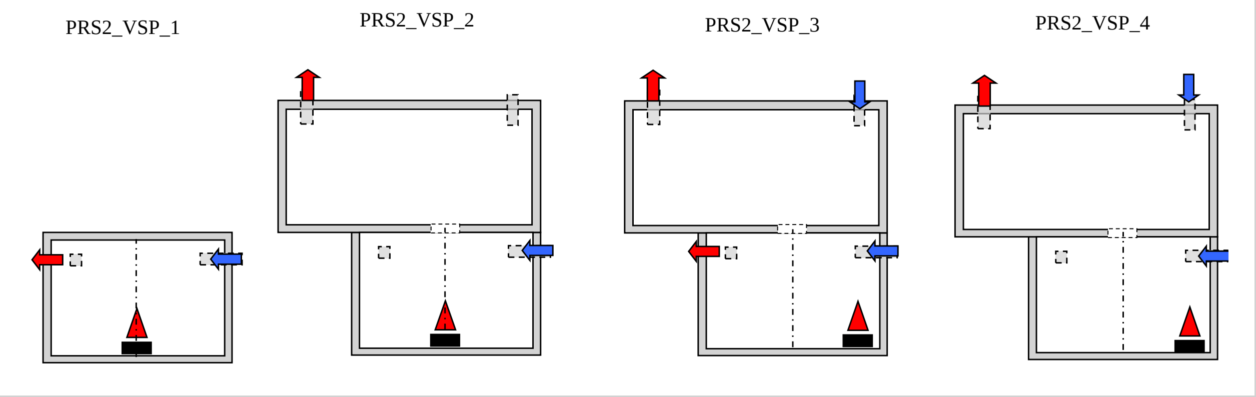


Table 2: Tests matrix of the PRS2-VSP fire tests (see Appendix 4 for more details)

Fire test	Fire source			Ventilation	
	Fuel [-]	Pool area [m²]	Position of the fires source in the room	Lower room (fire room R3)	Upper room (adjacent room R4)
PR2-VSP-1	heptane	0.4	Centre	IN/OUT	-
PR2-VSP-1-TER	heptane	0.4	Centre	IN/OUT	-
PR2-VSP-1-QUI	dodecane	0.4	Centre	IN/OUT	-
PR2-VSP-1A	heptane	0.3	Centre	IN/OUT	-
PR2-VSP-2	heptane	0.4	Centre	-/IN	OUT/-
PR2-VSP-3	heptane	0.4	Off-centre	IN/OUT	IN/OUT
PR2-VSP-4	heptane	0.4	Off-centre	-/IN	IN/OUT

Seven support tests were carried out in the SATURNE calorimeter to characterise the heptane in open atmosphere. The experimental parameters were the pool surface (0.1, 0.2 and 0.4 m^2) and the initial thickness of fuel in the pan.

4.2.2 PRISME 2 CFS campaign

The objectives of the cable fire spreading (CFS) campaign were to investigate fire spreading over complex fire sources and fire consequences in a confined and ventilated multi-rooms configuration.

The PR2-CFS-1 to PR2-CFS-4 fire tests involved a fire source composed of 5 horizontal cable trays. Two rooms of the DIVA facility (the fire and adjacent rooms) were involved in these fire tests and were connected by a doorway (see Table 3). The objectives of these first 4 fire tests were to investigate the effects of confined and ventilated conditions on multiple cable trays fires and fire consequences in the multi-rooms DIVA facility. Three types of electrical cables were involved in the cable trays fire tests (see Appendix 5). The Cable A, a halogen free flame retardant[1] (HFFR) cable, filled the 5 horizontal cable trays for both PR2-CFS-3 and PR2-CFS-4 fire tests. Otherwise, both Cables B and C were halogenated flame retardant[2] (HFR) cables and were respectively installed on all cable trays of the PR2-CFS-1 and PR2-CFS-2 fire tests. The main characteristics of the Cables A, B and C are given in Appendix 5. Both PR2-CFS-2 and PR2-CFS-4 fire tests involved ventilation renewal rates (VRR) of 15 h^{-1}, whereas both PR2-CFS-1 and PR2-CFS-3 fire tests used much lower VRR of 4 h^{-1}.

Table 3: The PR2-CFS-1 to PR2-CFS-4 fire tests carried out in the confined and ventilated DIVA facility

Fire test	Cable	Flame retardant	VRR (h^{-1})
PR2-CFS-1	B	Halogenated (Chlorine[2])	4
PR2-CFS-2	C	Halogenated (Chlorine)	15
PR2-CFS-3	A	Halogen free (ATH[1])	4
PR2-CFS-4	A	Halogen free (ATH)	15

The PR2-CFS-5 to PR2-CFS-7 fire tests involved a fire source composed by a real open-door electrical cabinet and 3 overhead cable trays (5 m in length) (see Table 4). Three rooms of the DIVA facility were involved for these 3 fire tests. The fire room and its adjacent room were connected by an open door, whereas the adjacent room and the third room were separated by a fire door. For the PR2-CFS-7 fire test, fire dampers were implemented at the inlet of the fire room and at the outlet of the adjacent room.

The objectives were to investigate the effects of ventilation rates, fire dampers closure and cable-type on fire spreading for such complex fire sources and related fire consequences in a confined and ventilated multi-rooms facility. Both PR2-CFS-5 and PR2-CFS-6 fire tests used a high VRR of 15 h^{-1}, whereas the third PR2-CFS-7 fire test involved a very low VRR (1 h^{-1}) after fire dampers closure. Indeed, for this latter fire test, fire dampers were closed at both inlet of the fire room and outlet of the adjacent room, 150 s after fire ignition corresponding to the delay of automatic fire detection. In addition, both PR2-CFS-6 and PR2-CFS-7 fire tests used upper trays filled with the HFFR Cable A, whereas PR2-CFS-5 fire test implemented trays filled with halogenated (Poly Vinyl Chloride – PVC) Cable C.

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[1] The halogen free flame retardant for Cable A is aluminum tri-hydroxide, $Al(OH)_3$) (ATH).

[2] The halogenated flame retardant for Cables B and C is chlorine. These cables are made with Poly Vinyl Chloride (PVC) as cable insulation material.

Table 4: Test grid of the PR2-CFS-5 to PR2-CFS-7 fire test

Fire test	Cable-type (see Appendix 5)	VRR [h^{-1}]
PR2-CFS-5	C	15
PR2-CFS-6	A	15
PR2-CFS-7	A	VRR = 15 h^{-1} for t < 150 s VRR ~ 1 h^{-1} after shutdown of fire dampers (t > 150 s)

Four support tests were performed under the large-scale calorimeter of the SATURNE facility to characterise the fire source of 5 horizontal cable trays in open atmosphere (see Table 5) (Zavaleta et al., 2013). Each one of the 4 fire sources involved only a single type of electrical cable supplied by PRISME 2 partners (Technical Research Centre – VTT, Nuclear Regulation Authority – NRA, TRACTEBEL-ENGIE and *Institut Radioprotection Sûreté Nucléaire* – IRSN as indicated in Appendix 5).

Table 5: Test grid of Support tests

CFSS fire test	Types of cables (see Appendix 5)
PR2-CFSS-1	B
PR2-CFSS-2	A
PR2-CFSS-3	Trays 1 and 2 (lower part): D Trays 3, 4 and 5 (upper part): E
PR2-CFSS-4	C

4.2.3 PRISME 2 FES campaign

The objectives of the PRISME 2 fire extinction systems (FES) campaign (test matrix, see Figure 11) were to investigate the efficiency of water sprays for controlling the fire and cooling the smoke in the framework of fire scenarios involved in NPP.

This fire scenario, identical for the 4 tests, consists of a pool fire located in a corner of a 170 m^3 rectangular room, mechanically ventilated at a rate of 15 h^{-1}.

The fire source was a pool fire of preheated lubrication oil MOBILE DTE MEDIUM (Exxon Mobil Company) of 0.7 m^2 surface. It was positioned in a corner of the enclosure in order to avoid direct extinction and to have simultaneously fire and water spraying. The preheated temperature of the oil was about 140 °C and the pool was ignited by means of a gas burner of about 20 kW.

The fire room was connected to a ventilation network equipped with an inlet and an exhaust lines, located in the upper part of the room (0.8 m from the ceiling). The ventilation flow rate corresponds to a renewal rate of 15 h^{-1} or 2 550 m^3/h before ignition.

The water spray system consists of 2 nozzles located at 0.8 m from the ceiling and spraying droplets towards the smoke and away from the pool to avoid extinction.

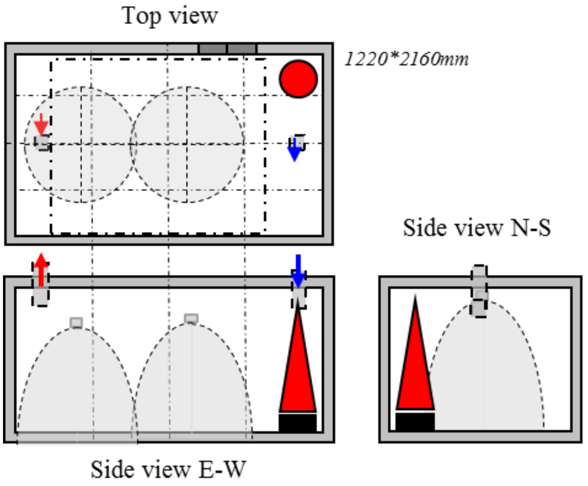
The PR2-FES-1 test was a reference test providing the fire behaviour in under-ventilated conditions in comparison with support tests performed in open atmosphere. The spraying system is actuated late during the combustion phase in order to characterise the behaviour of the fire source without suppression by a water-based fire extinguishing system. The extinguishing system was a spraying deluge system with a water flow rate of 110 l/min. The PR2-CORE-8 test was a repeatability test of PR2-FES-1.

The PR2-FES-2 test aimed at studying the effect of the actuation time in comparison to the PR2-FES-1 test. The same spraying deluge system with the water flow rate of 110 l/min as for PR2-FES-1 test was applied. It was actuated manually in the early stage of the combustion phase based on criterion of 80 °C of gas temperature, nearby the nozzle, in the fire room.

The PR2-FES-3 test aimed at studying the effect of the type of nozzle (and thus the droplet size) on the fire control, in comparison to the PR2-FES-2 test. The spraying deluge system was replaced by a sprinkler system, which was also actuated manually in the early stage of the combustion phase on the same basis as for the PR2-FES-2 test. The water flow rate was identical to PR2-FES-2 test (110 l/min).

The PR2-FES-4 test aimed at studying the effect of the water flow rate on fire control for a given spray system in comparison to PR2-FES-3. The spraying system was a sprinkler with a water flow rate of 157 l/min, actuated manually in the early stage of the combustion phase.

Figure 11: Schematic configuration and tests matrix of the PRS2-FES fire tests (in bolt the modified parameter)



	Fire	Ventilation	Spraying system				
	Pool area (m^2)	Q (m^3/h)	q water (l/min)	Nozzle (*)	DP (kPa)	t A (min)	duration (min)
PR2-FES-1	*0,4*	*2550*	*110*	*D*	*450*	*15*	*11*
PR2-CORE-8	*0,4*	*2550*	*110*	*D*	*450*	*15*	*11*
PR2-FES-2	*0,4*	*2550*	*110*	*D*	*450*	***80°C***	*11*
PR2-FES-3	*0,4*	*2550*	*110*	***S***	***220***	*80°C*	*11*
PR2-FES-4	*0,4*	*2550*	***157***	*S*	***450***	*80°C*	*11*

Support tests were carried out in the SATURNE calorimeter to characterise the preheated lube oil MOBILE DTE MEDIUM in open atmosphere.

4.2.4 PRISME 2 CORE campaign

The last campaign of the PRISME 2 project, called CORE campaign, aimed at completing and repeating some of fire tests already carried out during this project.

The PR2-CORE-1 to PR2-CORE-4 fire tests (test matrix see Table 6) were conducted under the large-scale calorimeter in the SATURNE facility. They completed the investigations performed on 5 horizontal trays configuration in open atmosphere during the cable fire spreading support (CFSS) campaign. These fire tests involved fire stopping, protected tray, slanted trays and PVC cables.

The PR2-CORE-5 to PR2-CORE-8 fire tests (test matrix see Table 7) were performed in the DIVA facility. For these tests, the fire source is lubricant oil used during the FES campaign, as well as an electrical cabinet and 5 horizontal trays used during the PR2-CFS campaign. The objectives are to assess consequences of these fire sources on targets of interest. The targets studied are radiation shield screen, 2 electrical adjacent cabinets and 3 horizontal trays not powered and 3 electrical cabinets powered. The behaviour of a fire door between 2 rooms of the DIVA facility is also studied.

Table 6: Test Matrix for the CORE-1 to CORE-4 fire tests (SATURNE facility)

Test	Objective	Fire source
PR2-CORE-1	Effect of PVC cables (provided by GRS, Cable G in Appendix 5)	Five horizontal cable trays (same design as CFS-Support tests)
PR2-CORE-2	Effect of protected tray (Cable A described in Appendix 5)	PR2-CFSS-2 fire scenario with the lowest tray protected
PR2-CORE-3	Effect of slanted trays (Cable A described in Appendix 5)	Five horizontal cable trays inclined with 30° angle
PR2-CORE-4	Effect of fire stopping (Cable A described in Appendix 5)	Three horizontal cable trays (4 m in length) with fire barriers

Table 7: Test Matrix for PR2-CORE-5 to PR2-CORE-8 fire tests (DIVA facility)

Test	Objectives	Fire source	Target (location)
PR2-CORE-5	Lubricant oil fire and fire consequences on targets (renewal rate of 15 h^{-1})	1 m^2 pool PR2-FES oil	Radiation shield screen (Room 1) Three electrical cabinets powered (Room 2) Fire door (between Rooms 2&3)
PR2-CORE-6	Effect of cabinet fire on targets (renewal rate of 15 h^{-1})	Electrical cabinet without door	Adjacent modules of cabinet Overhead 3 Cable A trays (see Appendix 5) Fire door (between Rooms 2&3)
PR2-CORE-7	Effect of lower renewal rate (4 h^{-1}) on fire spreading over trays filled with type-C halogenated cables and fire consequences	Five cable trays (like PR2-CFS-2 fire test)	Fire door (between Rooms 2&3)
PR2-CORE-8	Repeatability of PR2-FES-1	0.4 m^2 pool FES oil	-

5. Major findings from the PRISME Projects

The main experimental results of the PRISME and PRISME 2 projects concern the following issues:

- smoke and hot gas propagation through vertical (doorways) or horizontal openings, between the fire compartment and the adjacent rooms;
- smoke and hot gas propagation through leakages (openings, narrow slot, fire door) between the fire compartment and an adjacent one;
- the heat transfer coming from a duct crossing the fire compartment and blowing into the adjacent room;
- water extinguishing systems actuation on the fire development;
- fire damper closure on the fire development;
- cable fire in open atmosphere and in confined and ventilated fire scenarios; and
- fire propagation from an electrical cabinet fire to different targets.

The following sub-sections present some outstanding results from the PRISME and PRISME 2 experimental campaigns this includes:

- the effect of oxygen depletion on the fuel mass-loss rate (MLR), with discussions on limitations of the literature correlations;
- the relative effects of heat and mass transfer from the fire compartment to an adjacent room;
- smoke propagation from the fire compartment to adjacent compartments;
- the behaviour of cable fires in confined and ventilated fire scenarios;
- the behaviour of an electrical cabinet fire in confined and ventilated fire scenarios;
- cable performance testing;
- the effect of damper closure on the fire development;
- actuation of a sprinkler system; and
- the efficiency of cable protection or of fire barriers.

5.1 Effect of under-ventilated conditions on the fire behaviour

A topic of interest of both PRISME and PRISME 2 projects was the understanding of an under-ventilated fire. During the PRISME Projects, various effects of under-ventilation on the fire behaviour were observed:

1. the effect on the fuel MLR and on the fire duration due to oxygen depletion;
2. the production and the accumulation of unburnt gases, which ignite suddenly, inducing a peak of pressure in the facility; and

3. the oscillatory behaviour of the fuel MLR.

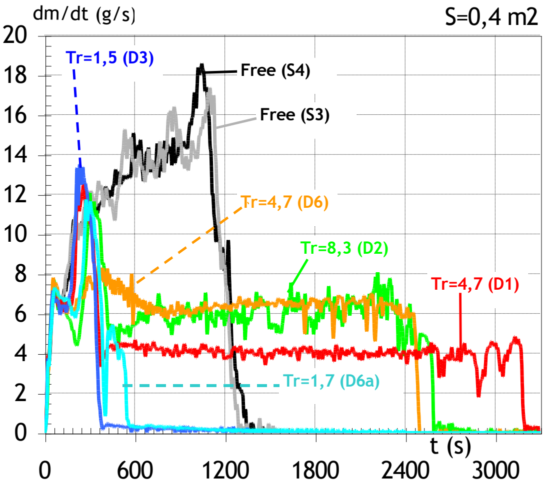
5.1.1 Dependency of mass-loss rate on the oxygen concentration

In case of confined and ventilated fires, the ventilation flow rate may be not high enough to remove the combustion products from the fire compartment (depending of course on the heat release rate (HRR) of the fire source). Consequently, these products quickly fill up the fire compartment contributing to oxygen depletion. As a result, the mass-loss rate (MLR) of the fire source is significantly reduced until the fires self-extinguishes due to the lack of fuel or of oxygen (see Le Saux et al., 2009; Melis and Audouin, 2008; Nasr et al., 2011; Prétrel et al., 2005; Prétrel et al., 2014; Prétrel et al., 2013b; Suard et al., 2011b; and Suard et al., 2011c).

In fact, the fire duration may be either shorter because of short-term self-extinguishing by lack of oxygen, or drastically longer because of the MLR decreases under steady state conditions (i.e. without flame extinction) involving more time to burn the entire fuel available in the pan. For example, in the PRISME SOURCE experiments, the fire duration for a renewal rate of 4.7 per hour was around 2.5 times longer compared to the same pool fire in free atmosphere. This phenomenon was observed for pool fire, e.g. in PRISME SOURCE campaign (see Figure 12) or in PRISME DOOR campaign (see Figure 13). Knowledge of the fire duration is an important parameter for the analysis of fire hazards and its effects on the systems, structures, or components (SSCs) important to safety for nuclear power plants (NPP).

Figure 12: PRISME SOURCE

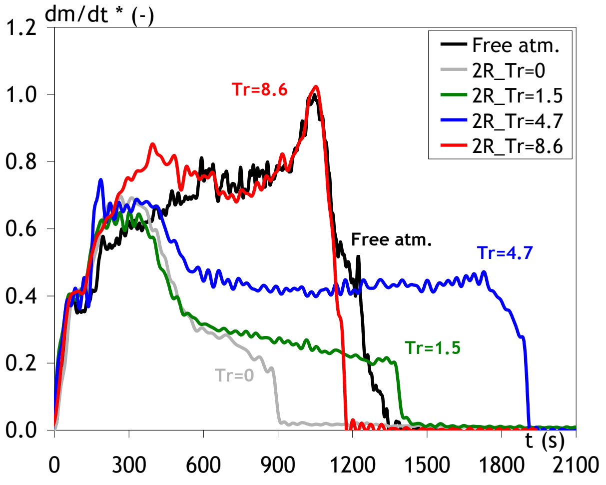
(1 room; S = 0.4 m^2)



Source: Audouin et al., 2013a.

Figure 13: PRISME DOOR (D1 to D4)

(2 rooms; S = 0.4 m^2)



Source: Audouin et al., 2013a.

The effect of the air flow rate on the MLR is strongly depending on the oxygen concentration within the fire compartment. The analysis of the PRISME SOURCE experiments consolidated the correlation of Peatross and Beyler (1997) for liquid combustible. It also confirmed that the oxygen concentration considered in the correlation must be representative of the concentration near the flame base (see Figure 14 and for PRISME SOURCE data, see Melis and Audouin, 2008; Nasr et al., 2011; Suard et al. 2011b). This approach can be used if the liquid pool fire compartment looks like a well-stirred reactor.[3]

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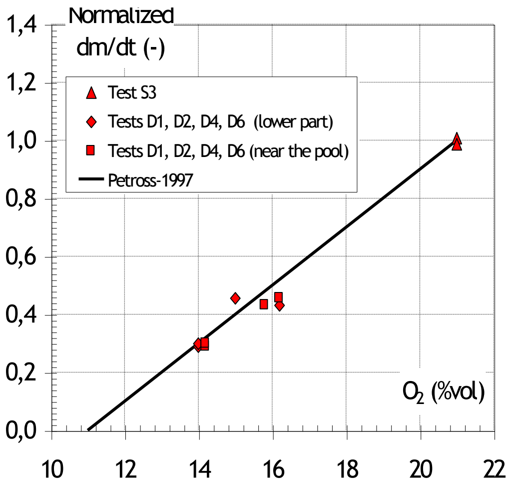
[3] A well-stirred reactor is an ideal reactor in which perfect mixing is achieve inside the control volume.

Figure 14: PRISME SOURCE data compared to Peatross and Beyler correlation

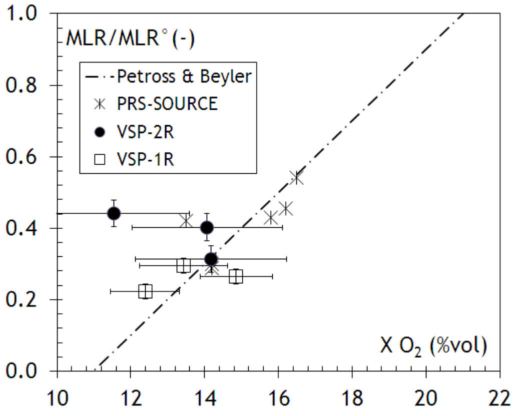


$$\boxed{\frac{\dot{m}_c}{\dot{m}_c^O} = 0{,}1\ X_{O_2} - 1{,}1}$$

Source: Peatross and Beyler, 1997; Melis and Audouin, 2008; Nasr et al., 2011; Suard et al. 2011b.

The PR2-VSP (vertical smoke propagation) test results were compared to the PRISME SOURCE data on Figure 15. For this comparison, a mean value (obtained from the 3 oxygen concentrations) is considered in the PR2-VSP. The bars of uncertainties correspond to the deviations between 3 sample points. The comparison shows that on average there is indeed a dependency between the MLR and the level of oxygen concentration in the room. In these experiments, the gas in the compartment is not well-mixed and the spatial variation of the oxygen concentration induced by the ventilation is significant. The expected linear relationship is no more observed.

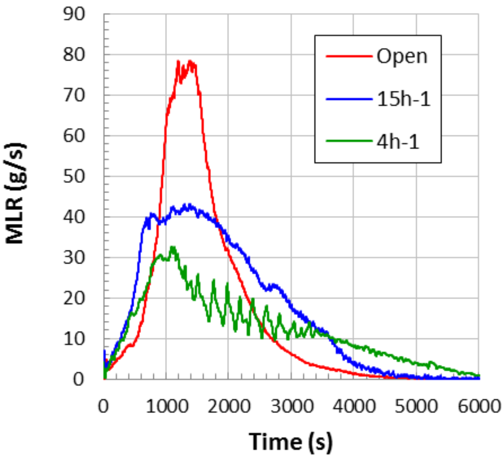
Figure 15: Dependency between MLR and oxygen for PR2-VSP and PRS-SOURCE tests



The PRISME LEAK and INTEGRAL tests show situations where the external heat fluxes are significant, in particular because of the compartment wall thermal insulation, and compensate the effect of oxygen depletion. For such fire tests, the fire power is very similar to the power expected in open atmosphere although the level of oxygen was very low. This type of fire is similar to flashover behaviour where the flames move all over the volume of the compartment. Consequently, the Peatross and Beyler (1997) correlation is no more valid and a new modelling has been proposed to take into account the effect of oxygen depletion and the radiative heat flux from ambient gases (see Suard et al., 2011c; and Nasr et al., 2010).

The effect of under-ventilation on the MLR was also observed for complex fire sources, such as electrical cable trays in the PR2-CFS (cable fire spreading) tests. The MLR of the 5 horizontal halogen free flame retardant (HFFR) cable trays decreased with the ventilation renewal rate due to the oxygen depletion in the room (see Figure 16). However, in this case, the Peatross and Beyler (1997) correlation is not appropriate because it was built on pool fire experiments. So, additional tests are needed to propose such correlation for complex fire sources.

Figure 16: MLR for the CFSS-2 (open), CFS-4 (15 h^{-1}) and CFS-3 (4 h^{-1}) fire tests



5.1.2 *Flash ignition process*

In some PRISME 2 tests, the under-ventilated conditions induce a production and an accumulation of pyrolysis gases, which auto-ignite suddenly. This behaviour occurs after extinction by lack of oxygen of a previous phase of combustion, with hot liquid fuel remaining in the pan or with a hot excess of pyrolysis gases produced. This phenomenon leads to high over-pressure peaks. It was observed for liquid fuel (heptane) fires during 2 tests, PR2-VSP-1-TER and PR2-VSP-1-QUI, and for cable tray fires during 2 tests, PR2-CFS-1 and PR2-CORE-7.

During the PR2-VSP tests, auto-ignition of a premixed flammable mixture of evaporated fuel and oxygen was observed after the final extinction. This auto-ignition phenomenon occurred about 3 min after a continuous evaporation of 3.3 kg of fuel and resulted in a short fire (1 min) of about 1.6 MW. An over-pressure peak of about 60 hPa was measured with flow inversions in the ventilation. This phenomenon occurred after extinction of an under-ventilated fire (first extinguishing by lack of oxygen) where fuel still continue to evaporate.

Concerning the cable trays fire tests, the ignitions of pyrolysis gases leading to the highest over-pressures occurred in case that the fire source was a halogenated flame retardant cable (B-type or C-type, see Appendix 5) and with a low ventilation renewal rate (4 r.h^{-1}). The production of unburned hydrocarbons increased compared to those ones obtained for the corresponding well-ventilated fires (CFSS fire tests). Thus, accumulation of unburnt gases under the ceiling of the fire room is favoured during these under-ventilated fires, leading to rapid combustion of these gases in the upper part of the fire room. These ignitions resulted in to HRR peaks of around 1 MW and pressure peaks of more than 130 hPa.

This phenomenon of sudden ignition of unburnt gases may cause severe consequences with respect to system, structure, or components (SSCs) important to safety, such as a loss of confinement. These results highlight the necessity to improve the understanding of this phenomenon to enable the analysts to model it and to be able to assess it adequately. Indeed, it is still difficult to estimate the amount of unburnt gases and the conditions that can induce their ignition.

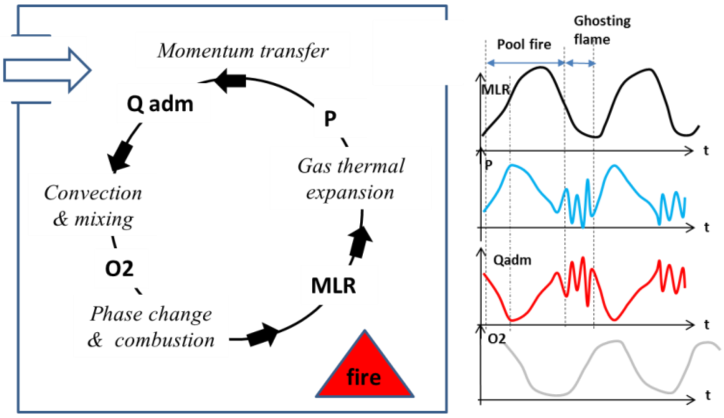
5.1.3 Oscillatory behaviour of fire

During the PR2-VSP campaign, the fire scenario showed oscillatory behaviour of the fuel MLR (Prétrel et al., 2016).

The frequency was between 5.10^{-3} and 7.10^{-3} Hz (period of 150-200 s) with amplitude of about twice the average level of burning rate. A period of oscillation was composed of 2 successive phases with the flame attached to the pool during the first 2/3 of the period followed by a “ghosting flame” phase with the flame detached from the pool and going in the direction of the inlet ventilation branch. The period of ghosting flame phenomenon was characterised with a second dominant frequency of about 0.1 Hz. The gas pressure in the room, the inlet and exhaust ventilation flow rates, the gas species (oxygen and carbon dioxide) concentrations and the gas temperature were also oscillating at the same frequency. The oscillation of the inlet ventilation flow leads to variations in the amount of oxygen entering the enclosure. The burning rate, pressure and ventilation flow rate oscillated without time shift. The burning rate and the species concentration within the enclosure oscillated with time shift because of the time for advection in the enclosure.

These phenomena could be described as follows (see Figure 17). The increase in the fuel MLR and thus of the HRR leads to an increase of pressure in the compartment because of the thermal expansion of the gas. This pressure change then has a direct effect on the inlet and exhaust flow rates in the ventilation network due to momentum transfer. The increase of pressure reduces the flow rate at the inlet branch and thus diminishes the amount of oxygen entering the compartment. A decrease in oxygen concentration induces a drop in the burning rate which leads to a cooling down of the gas and therefore a decrease of the compartment gas pressure. Finally, the inlet flow rate increases again with an increase in the oxygen concentration and in the fuel MLR. The period of stable flame above the pool corresponds to the increase in the burning rate due to well-ventilated conditions and the period of ghosting flame corresponds to under-ventilated conditions close to the extinction limit.

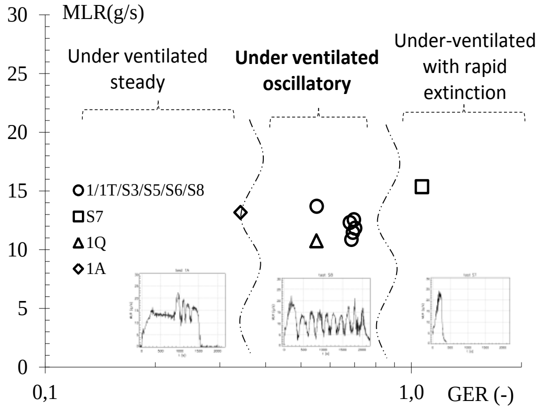
Figure 17: Illustration of the cycle process explaining the oscillatory behaviour



Some tests were performed in order to identify the main influential parameters. The results showed that the oscillations are not due to the nature of the liquid fuel or to the thermal insulation of the enclosure.

The most influential parameters on the oscillations are the pool fire dimension and the ventilation flow rate. The combination of these 2 parameters through the GER[4] parameter is used to identify a GER range of occurrence of the oscillatory phenomenon. The analysis of the fire tests shows also that the oscillatory behaviour occurs for high enough gas temperature and low-oxygen concentration close to extinction limit.

Figure 18: Average MLR versus the GER



The same phenomenon was observed in the cable trays fire test, PR2-CFS-3, with HFFR cables and a low air renewal rate (4 r.h^{-1}) (see Figure 16). Like for liquid fuel, the oscillatory behaviour was due to the combustion of unburnt gases in the upper part of the fire room. This phenomenon leads to oscillatory behaviour of pressure, inlet and outlet flow rates, HRR and both species concentrations and gas temperatures in the upper part of the fire room.

These fire scenarios, inducing significant fluctuations, are identified as a major concern for fire safety assessments due to a possible loss of the dynamic confinement and the current uncertainty of the prediction capabilities of numerical tools. The loss of dynamic confinement is a major fire hazard in case of oscillatory fire due to the risk of gas release at each cycle of oscillations where high pressure level in the room is achieved.

Although, the analysis of the fire tests enables to propose an explanation of the phenomenon, there is a lack of knowledge for a complete understanding of the oscillatory behaviour and thus for performing predictive numerical simulations. The issues concern the processes of fuel pyrolysis, low-oxygen combustion with extinction phenomena and gas mixing inside the compartment.

5.2 Hot gas propagation from the fire room to the adjacent room

In order to assess the relative effect of heat and mass transfers in the PRISME DOOR, PRISME LEAK and PRISME 2 VSP campaigns, the mass flow rate (MFR) and the convective heat flux (CHF) between the fire compartment and the adjacent compartment are presented in the Figure 19 and Figure 20.

Mean MFR: $MFR[kg/s] = \frac{1}{\Delta t} \int_{\Delta t} \dot{m}(t)\, dt$ and $\dot{m}(t)[kg/s] = C_d \int_S \rho(t) \times u(t) \times dS$

Mean CHF: $CHF[kW] = \frac{1}{\Delta t} \int_{\Delta t} \dot{m}(t) \times C_p \times T(t) \times dt$

---

[4] The definition of the GER is the ratio between the amount of oxygen required for the burning of the fire source in open atmosphere and the amount of oxygen blown by the ventilation before ignition: $GER = \frac{r\, \dot{m}_f^o}{Y_{O2}^o\, \dot{m}_{v,in}^o}$

with ρ the mass density of gas, u the velocity profile through the doorway, S the doorway area, Δt the integrating time during steady period, C_p the specific heat capacity at constant pressure, T the temperature profile through the doorway and C_d the doorway coefficient (depending on the type of opening).

The propagation of hot gases is obviously larger through doorways than through leakages showing a ratio of nearly 5 to 10 times for MFR and of nearly 3 to 10 times for CHF. As expected from the PRISME LEAK fire experiments, the CHF decreases from PRS-LK1 to PRS-LK3 corresponding to openings, a narrow slot and a fire door. Nevertheless, the MFR from the fire compartment to the adjacent room is similar for these 3 fire tests indicating that the mass transfer of gas depends weakly on the type of leakages in the fire scenarios investigated.

This result strengthens the fact that a high level of confinement remains the best way to limit the propagation of hot gases in a nuclear facility and the consequences due to fire (ignition of target, malfunction of electrical components, etc.). It has to be noticed that such a high level of confinement could exacerbate the pressure effects particularly during the fire ignition (over-pressure peak) and fire extinguishing (under pressure peak) transient periods that can lead to possible damage of confinement equipment.

The PR2-VSP tests illustrate the key effect of the ventilation configuration on the smoke propagation through a horizontal opening and show the capability of the ventilation as a potential tool to reduce the impact and the potential consequences of the fire. The complex bi-directional flows through a horizontal opening show 3 different behaviours with dominant effect of the ventilation (PR2-VSP-2 test with flow mainly one directional upwards), dominant effect of the buoyancy (PR2-VSP-3 test with flow mainly bi-directional) and intermediate configuration (PR2-VSP-4 and PR2-VSP-4-BIS tests). The position of the fire source under the vent or off-centre also modifies the flow features. In the case of forced convection in the PR2-VSP tests, the MFR is of the same order of magnitude that the one through a doorway but the CHF is 2 times higher.

Figure 19: Mass flow rate from the fire compartment to the adjacent room

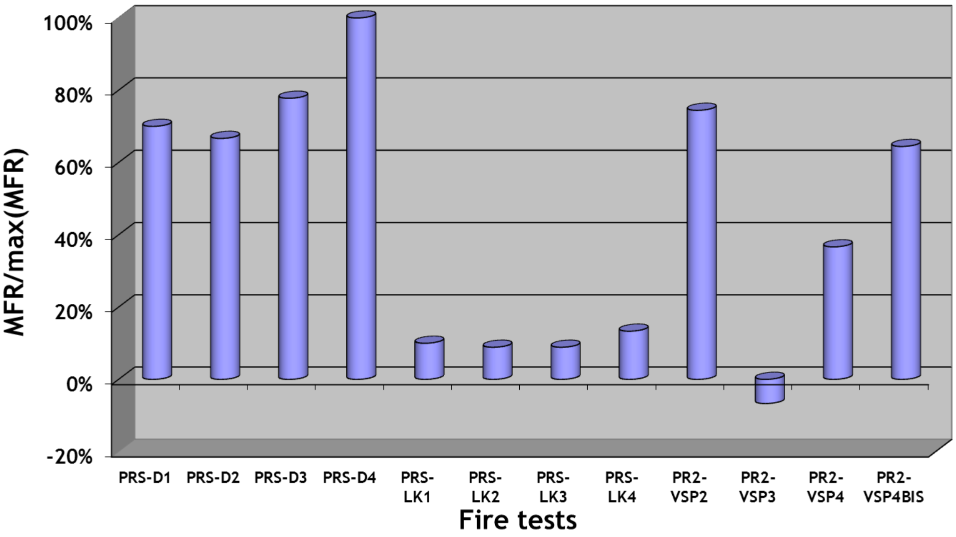
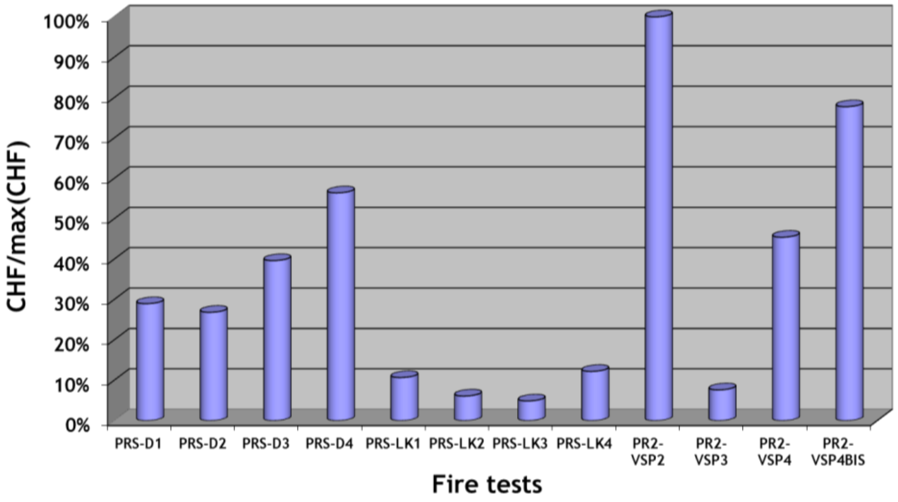


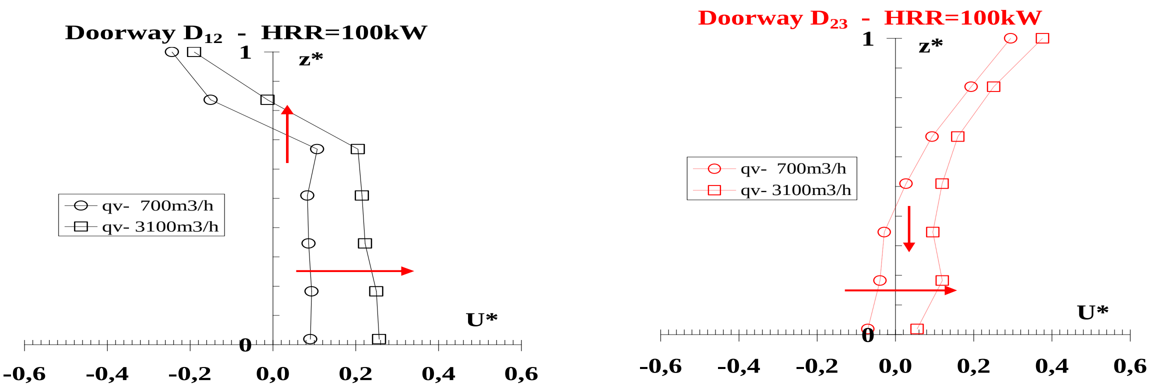
Figure 20: Convective heat flux from the fire compartment to the adjacent room

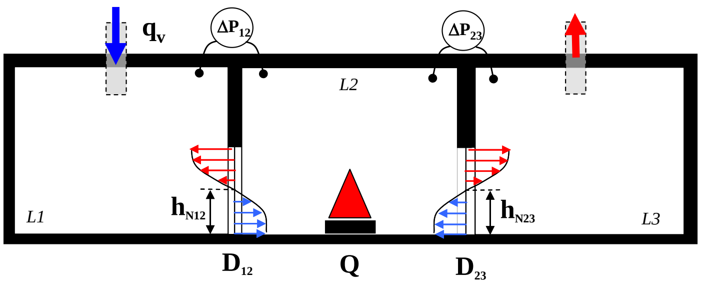


5.3 Smoke propagation in ventilated installations

The PRISME Project has pointed out the combined effects of forced and natural convection in the process of smoke propagation in confined and ventilated compartments (Prétrel and Audouin, 2011). Natural convection is induced by the high smoke temperature and forced convection by the effect of the ventilation. The prediction of smoke movement and its propagation required a proper understanding of the coupling between these 2 physical mechanisms. A typical example of this combined effect is presented in Figure 21. It shows the velocity profiles at 2 doorways located upstream and downstream the fire compartment during a support test of the INTEGRAL campaign implementing gas burner as fire source. The mechanical ventilation of the fire compartment scenario can significantly modify the typical bi-directional flow at a doorway compared to what is expected in open atmosphere. It contributes to unbalance the in- and out-flow rate and to change the position of the neutral plane. For multi-room scenarios, the ventilation layout and the location of the fire compartment have a significant impact on the doorway flow. The effect of the ventilation strongly modifies the natural convection flow induced by the fire. The PRISME Project contributes to improve the knowledge on such flow conditions during a fire scenario.

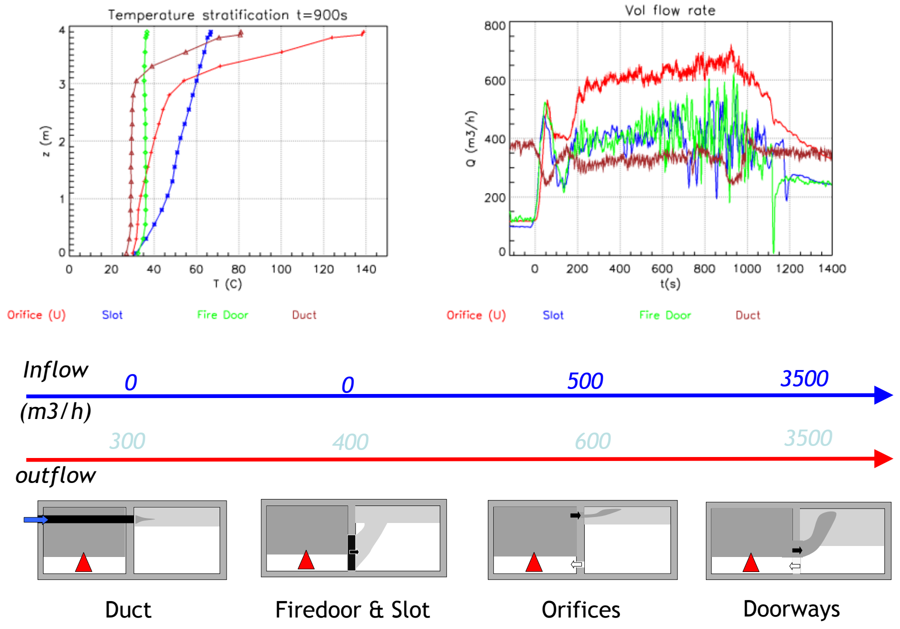
Figure 21: Velocity profiles at the doorways in the PRISME INTEGRAL configuration





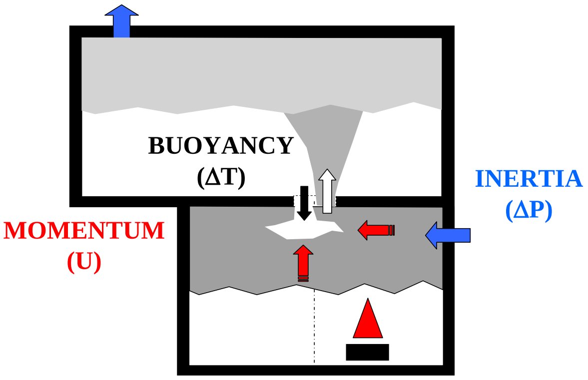
The different modes of smoke propagation tested within the PRISME Projects can be ranked according to smoke temperature and flow rate (see Figure 22). The smoke propagation through doorways, and in some circumstances through a horizontal opening, gives the largest rates. For the PRISME configurations, the 4 other modes give the following ranking according to temperature and flow rate of the smoke: orifices, closed fire door, slot and duct (Prétrel and Audouin, 2010). The tests results demonstrate the impact of each mode and the way it influences the readings in the adjacent compartment.

Figure 22: Illustration of the ranking for smoke propagation configuration (PRISME LEAK)



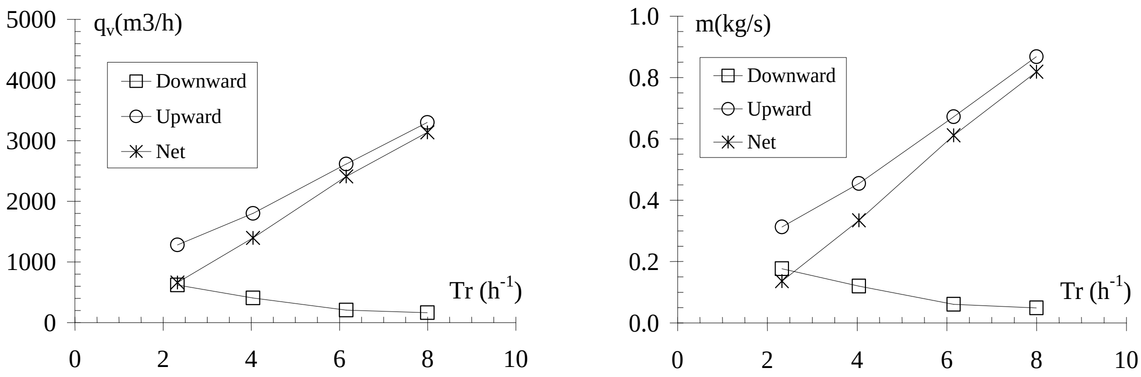
The effect of the ventilation flow rate on the vent flow was also investigated within the PR2-VSP-2 configuration. In this campaign, the study focused on the spreading of smoke through a horizontal vent with various ventilation configurations. A specific study (Prétrel et al., 2013a), before the pool fire tests, was performed with a gas burner and the ventilation configuration with one inlet line in the fire room and one exhaust line in the upper adjacent room (see Figure 23). With this configuration, the effect of the pressure difference with buoyancy can be investigated. The vent flow is affected by 3 dynamic phenomena: buoyancy from the heat release from the fire, inertia due to the mechanical ventilation and local momentum from the local smoke flow, e.g. from a ceiling jet for instance.

Figure 23: Configuration of smoke movement in confined and ventilated compartments in the PR2-VSP2 fire scenario



The analysis of the volume and MFR shows (see Figure 24) that the increase in the ventilation flow rate increases the net flow rate towards the adjacent room and reduces the reverse downward flow in the fire room.

Figure 24: Volume and mass flow rate at the vent versus the renewal rate



For this specific ventilation configuration, with the inlet at the lower fire room level and the outlet in the upper room, the experimental results were compared to the Cooper formulas (see Cooper, 1989; and 1994). It correctly predicts the regime of the flow and the flow rate of the downward flow. The predictions of the upward flow yield different conclusions according to the formulation considered.

Three configurations of ventilation were studied in experimental VSP campaign: only admission in the fire room and exhaust in the adjacent room (PRISME2-VSP-2 test), admission and exhaust in both rooms (PRISME2-VSP-3 test) and no exhaust in the fire room (PRISME2-VSP-4 and PRISME2-VSP-4-BIS tests). The results show 3 different behaviours with dominant effect of the ventilation (PRISME2-VSP-2 test with flow mainly one directional upward), dominant effect of the buoyancy (PRISME2-VSP-3 test with flow mainly bi-directional through the horizontal opening) and intermediate configuration (PRISME2-VSP-4 and PRISME2-VSP-4-BIS tests). These tests illustrate the key effect of the ventilation configuration on the smoke propagation. The observed phenomena still remain complex to numerically predict such flows through horizontal openings. The experimental analysis of the PRISME 2 VSP tests shows the need of additional configurations to establish confident vent flow model for zone calculations and a complete validation for fire field models.

5.4 Cable fire

During the PRISME Projects, several types of cable tray configurations were tested: one vertical cable tray in the PRS-INT-3, 5 horizontal cable trays in the PRISME 2 CFS campaign and 5 slanted cable trays in the PR2-CORE-3 test.

5.4.1 Vertical cable tray in confined and ventilated fire scenario

The vertical cable tray fires show 2 very different behaviours, depending on if it occurs in open atmosphere (maximum 800 kW and 1 h duration, see Appendix 3) or in confined and ventilated rooms (maximum 200 kW and 20 min duration, see Appendix 2). The ignition and flame spreading process is modified by the environment and particularly by the flow induced by the doorways. For solid materials such as cables, the ignition and flame spreading process is very sensitive to the flows around the combustible material and to the ignition conditions (location and HRR of the gas burner which ignites, cable arrangement); these 2 parameters can strongly affect the flame propagation process.

5.4.2 Five horizontal cable trays in confined and ventilated fire scenario

Three cables trays fire sources, as used in the PRS2-CFS-1 to PRS2-CFS-4 fire tests, were initially characterised in open atmosphere (see Table 5). These preliminary tests highlighted the effects of the nature of cables, especially of the flame retardant on the fire propagation in open atmosphere. They showed faster growth fires and higher peak of HRR for halogenated flame retardant cables than for halogenated free flame retardant cables (Zavaleta, 2013). These tests were also used for the application of a video flame analysis (VFA) in order to estimate the lateral flame spread rate (Beji et al., 2016). It has been found that this flame spread rate was substantially higher (between 2 and 5 mm/s) than the value recommended for thermoplastic due to the presence of a support insulated wall.

The specific behaviours of cable trays fire in confined and ventilated environment are discussed in Section 5.1. The tests highlighted the fact that the fire propagated over the entire trays in the confined and ventilated conditions. The effect of under-ventilation on this complex fire source is a longer duration of the fire tests and a lower maximal value of HRR than those of the corresponding tests in open atmosphere (see explanations in Section 5.1). Another interesting result for fire study of these tests is the fact that the fire growth rates in confined environment in the most cases were lower than in open atmosphere according the ISO standard (ISO, 2014) (see Table 8).

Table 8: Fire growth rate of cable fires depending on the type of cable and the environmental conditions

Type of cables (see Appendix 5)		A	B	C
Fire growth [kW/s^2]	In open atmosphere	0.0022	0.1	0.028
	In confined environment	0.0008/0.0005	0.14	0.015
	Classification of fire according ISO standard (ISO, 2014)	Slow $\alpha < 0.011$ kW/s^2	Fast 0.044 kW/s^2 $\leq \alpha <$ 0.178 kW/s^2	Medium 0.011 kW/s^2 $\leq \alpha <$ 0.044 kW/s^2

Source: ISO, 2014.

The PR2-CFS tests highlight that fire spread on the 5 horizontal cable trays in a confined compartment depend on the ventilation conditions and on the nature of cables. These tests also show the need to enhance the knowledge of the main parameters governing the fire spread on horizontal cable trays in order to improve models for such fire. The analysis of cable fire in open atmosphere shows that the main spread parameters are the horizontal velocity of the flame along a burning cable tray, the ignition time of cable tray and the angle of the front flame with the vertical axis. These parameters depend on cables composition and arrangement on the trays, the space between 2 trays and the environmental conditions (confinement or not, the proximity of a wall or of a ceiling). Other configurations of interest have to be studied in order to develop a physical modelling able to predict the HRR of cables fire scenario.

5.4.3 Five slanted cable trays in open atmosphere

The effect of slanted trays on fire spread was studied by comparison to the same fire with horizontal trays in open atmosphere. The same type of cable, HFFR Cable called A (see Appendix 5), was used in the 2 tests. The fact that the cable trays were slanted induced a shorter ignition delay and an increase of the fire growth rate. While the horizontal cable trays configuration is classified as a slow fire according the ISO standard (ISO, 2014) (see Table 8), the slated cable trays configuration fire may be classified as a medium fire. This is due to the chimney effect of the slanted cable trays configuration that facilitates the preheating of cables and then their ignition.

5.5 Electrical cabinet fires

One test was performed in the PRISME Project, PRS-INT6, to study an electrical cabinet fire with fire damper closure. The electrical cabinet fire leads to an under-ventilated combustion regime inducing self-extinguishing of the fire by lack of oxygen. The HRR time history shows a period of slow propagation phase (incubation phase) followed by a large peak at nearly 1 MW. This behaviour is very different from the pool fire, which generally shows a steady phase. The electrical cabinet fire is an unsteady fire typical of fires involving solid materials.

5.6 Electrical cabinet fire propagation

In the PRISME 2 project, the objectives of 4 tests were to study the fire propagation from an electrical cabinet to various targets: overhead cables in the PR2-CFS-5 to PR2-CFS-7 tests, adjacent modules of the cabinet and cables in the PR2-CORE-6 test.

The PR2-CFS campaign highlighted the effect of cable-type on ignition and fire spreading over upper trays. In case of halogenated cables, the electrical cabinet fire spread rapidly to cables and led to a reduction of the oxygen concentration in the room until fire extinction by lack of oxygen. Inversely, the HFFR cables ignited later than the electrical cabinet. The upper oxygen concentration was sufficient for the combustion of a larger quantity of HFFR cables than during tests with halogenated cables.

In the PR2-CORE-6 test, the electrical cabinet fire did not spread to overhead cable trays (contrarily to the PR2-CFS-6 fire test). Ignition occurred in the adjacent modules and the fire spreads down to the base of the cabinet involving the entire cables contained inside.

All these results demonstrate the need to continue research in order to explain why in one case the fire propagated to the overhead cables, in the PR2-CFS-5 to PR2-CFS-7 tests, and why not in another case, in the PR2-CORE-6 test. It can be assumed that the 2 adjacent modules played the role of heat sinks and there was not sufficient energy to ignite overhead cables.

5.7 Cable functional performance

The cable functionality tests were performed during within the PRISME LEAK campaign (see Section 4.1.2). The objective of the cable performance testing was to provide additional data to complete the available knowledge based on cable fire-induced failure modes and effects. One or more electrical cables routed in open ladder style cable trays were exposed to fires and monitored for electrical performance using 2 different electrical monitoring systems. One system, the insulation resistance measurement system (IRMS), monitors conductor-to-conductor and conductor-to-ground insulation resistance for various conductor pairs. The second system, the surrogate circuit diagnostic unit (SCDU), is nominally configured to simulate a typical motor operated valve (MOV) control circuit but was also deployed in a more simplistic mode in which specific conductors were electrically energised and various modes of cable failures monitored (e.g. intra-cable short circuits versus shorts to an external ground).

The test results provided the relationship between environmental gas temperature and electrical cable failures. These data (Dreisbach et al., 2010) were consistent with those obtained in laboratory tests under controlled radiative heat sources (Nowlen and Wyant, 2008).

5.8 Effect of damper closure on the fire scenario

The damper closure (at both air inlet and exhaust ventilation branches) leads to weaken the fire HRR. In the PRISME Projects, several experiments studied the effect of dampers closure on the behaviour of fire source: a pool fire in the PRS-INT-5 test, an electrical cabinet in the PRS-INT-6 test, and a complex fire source, composed by an electrical cabinet and 3 overhead cable trays, in the PR2-CFS-7 test.

For an under-ventilated liquid pool fire (PRS-INT-5 test), the damper closure was followed by rapid extinction, the level of oxygen being already low at the time of closure. No pressure rise was noticed but a significant under pressure peak (- 46 hPa) resulting from the combined effect of the closure of the ventilation and the sudden stop of the fire HRR (extinction).

For an under-ventilated electrical cabinet fire (PRS-INT-6 test), the damper closure was not followed by extinction. The combustion slowed down but still proceeds and a significant increase of pressure is measured (+ 15 hPa). At extinction due to lack of oxygen, there was still a under pressure peak (-6 hPa) which was however significantly lower than for a pool fire test.

The PRISME INTEGRAL tests (PRS-INT-5 and PRS-INT-6) highlight that the dampers closure effect is more pronounced for a liquid pool fire than for an electrical cabinet fire.

Comparative analysis of tests with damper closure (PRS2-CFS-7 test) and without dampers closure (PRS2-CFS-6 test) highlights the effect of ventilation on cabinet fire and also the ability of fire to spread from the cabinet to overhead trays. Both fire tests show similar growth stage of cabinet fire. However, the fire dampers closure (2 min 30 s after fire ignition) leads to reduce cabinet fire duration and to limit the ignition of upper cables trays. Indeed, the shutdown of the fire dampers induces low-oxygen concentrations in the upper part of the fire room for ignition of the halogenated free flame retardant cables.

The effect of the damper closure is therefore depending on the HRR history and the nature of the fuel. The time of closure, in relation to the HRR history, is also an important parameter.

5.9 Behaviour of activation of sprinkler system in a fire scenario

The PRISME Projects investigated the effect of the activation of a sprinkler system during one representative large-scale fire test, PRS-INT-2 test, and the efficiency of water spray systems on the fire control in the fire extinction systems tests PR2-FES campaign, with a repeatability test (PR2-CORE-8 test).

The activation of the sprinkler system during a pool fire scenario in confined and ventilated compartment leads to rapid extinction. For the only test performed in the PRISME Project, the water spray system activation induces no over-pressure peak but a under pressure peak, which is the result of the combined effects of the gas cooling by water and fire extinguishing.

The actuation of water spraying, like deluge or sprinklers, in the PRISME 2 FES tests, induces 4 typical physical mechanisms. The first one is the cooling of the gas phase that is the straightforward consequence of the heat transfer exchange between the water droplets and the gas. The second effect is the process of gas mixing and homogenisation induced by the water spraying. The gas concentrations in the upper and lower parts of the room tend to the same level. The third effect is the significant increase of the fire HRR (from 400 kW to 500 kW) when the water spraying is activated. This behaviour is a consequence of the change of the gas property in the vicinity of the fire that enhances the burning rate. Then, the last important effect is the occurrence of gas pressure peaks when the water spraying is activated or shut off, consequence of sudden change of gas temperature. The processes of gas cooling and fire HRR increase are the main causes to these variations of gas pressure.

Three water spray system parameters have been investigated: the time of activation, the type of nozzle (deluge and sprinkler) and the water flow rate. An earlier activation favours the cooling process in preventing the increase of gas temperature. It allows a better efficiency in reducing the gas temperature. The difference between the deluge and sprinkler nozzles (at the same water flow rate) is an enhancement of the gas dynamic within the room and then an increase of the burning rate. However, this result may depend on the tests operating conditions (110 l/min and the corresponding operating pressure). It is possible that for other operating conditions, the difference on the process burning rate enhancement vanishes. The increase of the water flow rate, whatever the type of nozzle, improves the gas cooling as well as the gas dynamic (and thus the burning rate enhancement). In term of smoke control, the most efficient design would be an earlier activation with larger flow rate. However, in term of fire control, these tests points out the effect of burning rate enhancement that can be considered as negative effect induced by a water system.

The repeatability study shows a good accordance between the 2 tests, PR2-FES-1 and PR2-CORE-8 test. The general trend and the critical events (as peaks) are observed at the same time and with the same amplitude for both tests. Based on a set of 53 sensors, the average difference between sensors is about 13% for the global signal and 5% for critical events.

5.10 Efficiency of cable protection or of fire barriers

Two types of fire barrier were tested in the PR2-CORE campaign in open atmosphere.

In the PR2-CORE-2 test, the first tray of the 5 horizontal ones was protected with a metallic non-perforated cover. The comparison with the same tests without protection shows a significant delay of the cable trays ignition.

The objective of the PR2-CORE-4 test was to study the efficiency of fire barriers, made in mineral wool linked by a specific adhesive (see Figure 25 and Figure 26). This test shows the efficiency of the fire barriers to stop the fire. Nevertheless, this test also highlights 2 weaknesses dealing with these fire barriers. The first one concerns the cloth wrapping the barrier that ignites several times. The second one deals with the multiple ignitions of gases occurring within the space between the fire barriers. Partial degradation of the outer sheath of the cable samples located downstream of the fire barriers are observed as consequences of the previous ignitions.

<table>
<tr><th>Figure 25: Wrapping of the cables by layers of mineral wool linked by a specific adhesive</th><th>Figure 26: Wrapping of the fire barriers by a cloth</th></tr>
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6. Major findings from the PRISME Benchmarking Group and the PRISME 2 Analytical Working Group

In parallel to the experimental programmes, the partners have performed simulations in order to evaluate the capabilities of fire codes to simulate fire scenarios based on the PRISME and PRISME 2 tests.

A group of partners, named PRISME Benchmarking Group (PBG) and PRISME 2 Analytical Working Group (AWG), meet with the scope of:

- analysing results of pre and post-tests calculations;
- analysing results of benchmark exercises; and
- discussing improvements in understanding key phenomena in relation to real fire source in under-ventilated conditions.

The fire codes generally used by the group, composed by users and developers, are the following:

- zone codes: CFAST developed by the US National Institute of Standards and Technology (NIST), MAGIC developed by *Electricité de France* (EDF), OEIL developed by the French *Direction générale de l'Armement* (DGA), and SYLVIA developed by the French *Institut Radioprotection Sûreté Nucléaire* (IRSN);
- lumped code: COCOSYS developed by the German Global research for safety (GRS); and
- computational fluid dynamics (CFD) codes: Fire Dynamics Simulator (FDS) developed by the NIST (FDS website), ISIS developed by IRSN (ISIS collaborative website) and SAFIR co-developed by the Aix Marseille University and DGA (France).

In the following paragraphs, the main improvements of fire models are presented as well as the benchmark exercises performed in conjunction of PRISME and PRISME 2 projects.

6.1 Improvements of fire models and of fire codes validation

The experimental outcome obtained within the PRISME and PRISME 2 projects provides a better understanding and an increase of knowledge with respect to fire development in confined and ventilated large-scale compartments representative of nuclear installations. In particular, the PRISME and PRISME 2 tests highlighted the interaction between the fire and the mechanical ventilation. Moreover, the experimental results are used to improve fire modelling and form a huge experimental database useful to validate fire simulation codes (zone models, lumped-parameter codes and CFD codes).

The results of the PRISME tests have been used by developers to improve the ventilation models in the fire codes (e.g. OEIL, MAGIC and FDS) and to validate the calculation of the pressure for mechanically-ventilated fires. For example, the main outcome for MAGIC V4.1.3 is the confidence and quality of the MAGIC pressure calculations for confined fires as a supplement to the previous validation files for natural fires that had demonstrated the code ability to predict gas and wall temperatures, gas concentrations, heat fluxes and targets features. Another example is given by the Swedish partner who validated the ventilation module of FDS on PRISME experiments and derived a correlation useful for fire safety engineers (see Van Hees et al., 2011 and Chapter 7). In several codes, such as SYLVIA, MAGIC, OEIL, ISIS and FDS, the ventilation network is described and the effect of the fire on the ventilation flow rate can be calculated. For example, inverse flows at the inlet branch, due to the fire ignition, can be simulated with the SYLVIA and ISIS codes (Vaux and Prétrel, 2013; Suard et al., 2013c).

Based on the PRISME tests, some developers increased the predictability of their codes, e.g. Containment Code System (COCOSYS), SYLVIA or ISIS. Predictive pyrolysis models, based on the Peatross and Beyler (1997) correlation or developed by partners (Suard et al., 2011b; 2011c), had been implemented in the fire codes and validated on the PRISME tests. In COCOSYS, the pyrolysis model has been extended to consider the radiative feedback of hot gases and soot on the pyrolysis rate (Klein-Heßling et al., 2010; Pelzer et al., 2011; Pelzer and Klein-Heβling, 2013). The oscillatory combustion regimes observed in some PRISME 2 tests are the subject of research for some partners to develop pyrolysis models able to simulate this phenomenon.

The simulations of flows through a horizontal opening can be validated on the vertical smoke propagation (VSP) fire tests. The Cooper's correlation (Cooper, 1989; and 1994) is implemented for example in the MAGIC, CFAST and SYLVIA codes. The SYLVIA validation shows that this correlation gives relatively satisfactory agreement in case that the mechanical ventilation facilitates the direction of flow. The discrepancy between experimental results and the correlation values is important for flow regimes close to natural convection or for downward flow rates. There is still work to better estimate the part of upward and downward flows in particular for natural convection scenarios which are closer to realistic nuclear power plant (NPP) configurations. This is part of PRISME 3 proposal. The simulations of flows through leakages with CFD codes were also validated on PRISME Leak tests (Xu and Bonte, 2013).

The PRISME 2 cable fire tests in open and in confined environment provide a large experimental database, which can be applied for assessing simplified or detailed cable fire models. For example, the constants used in the FLASHCAT model, based on CHRISTIFIRE tests (McGrattan et al., 2012), had to be modified in the cable fire spreading support (CFSS) PR2-CFSS configuration. Indeed, the support wall of trays contributes to preheat the cables, inducing higher flame spread velocities than the ones measured in the CHRISTIFIRE tests. With respect to this topic, detailed models or engineering approaches were discussed, using FDS or ISIS (see Section 6.2.2.2). These issues are still under development.

The fire suppression models will be validated on the fire extinction systems tests PR2-FES and the effect of the droplets size and flow rate of the water sprays systems could be evaluated. The increased pyrolysis rate during water spraying was not simulated by fire codes. The recently implemented momentum exchange between spray droplets and atmosphere in COCOSYS (Klein-Heßling et al., 2010) may improve the results.

The AWG has, from the users' point of view, helped in better understanding the fire simulation codes outputs as well as in analysing their strengths and weaknesses. This complements the analysis performed in the validation and verification (V&V) document presented in NUREG 1824 (Najafi et al., 2006), with respect to later versions of fire codes. Therefore, the AWG has enabled the analysts to carry out a comparative analysis of results obtained with different fire codes (Audouin et al., 2011; Siemon and Riese, 2013).

The benchmark exercises (see Section 6.2) carried out also highlight some significant user-effects. Discussions between users allow for an identification of differences in input, geometry, mesh size and post-processing methods.

6.2 Benchmark exercises

Both groups, PBG as well as AWG of PRISME 2 project, were composed by developers and users of fire simulation codes from the member countries. In order to facilitate effective exchanges on the use of fire codes, benchmark exercises were proposed to the PRISME partners and managed by IRSN.

6.2.1 The PRISME Benchmarking Group

Three benchmark exercises were performed in conjunction with the PRISME Project by members of the PBG.

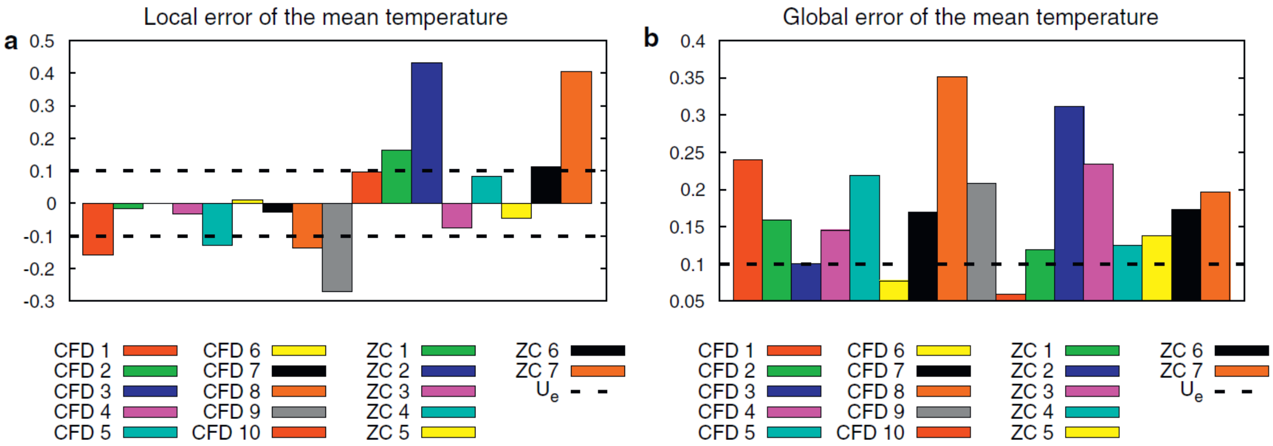
6.2.1.1 BENCHMARK EXERCISE #1

The major goal of the first exercise was to provide a more quantitative process to compare fire models with experimental data (Rigollet and Röwekamp, 2009; Suard et al., 2011a; and Suard et al., 2011d).

The use of metrics to assess the level of agreement between experimental data and fire code results 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 analyse. In the case of time-dependent curves (unsteady conditions) the estimate of the agreement between 2 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 metrics are built on the relative difference (often normalised) between model predictions and experimental measurements, on which some mathematical norms (e.g. Euclidean and Hellinger norms) from functional analysis are applied. These norms permit the measurement of average curve separation or of curve shapes.

The work in the PBG was devoted to investigate different metrics to compare experimental data with numerical results and to evaluate their use in the validation process of fire codes.

Figure 27: Local (a) and global (b) errors for the mean gas temperature



Source: Audouin et al., 2011.

This benchmark exercise involved seventeen participants using 8 fire simulation codes (3 CFD or field codes and 5 zone codes). The calculations were qualified as “open” (as opposed to “blind”). Therefore, wall and fuel properties were specified as well as the fuel burning rate, the ventilation conditions and the test data. Despite this guidance, the so-called “user-effect” was important for both field and zone models. The main objective of this work was, however, to investigate the possibility of using metrics in a validation process of a real large-scale fire scenario involving several participants with different fire simulation tools.

For the validation process, 6 quantities were compared during the whole fire duration: the gas temperature, the oxygen concentration, a wall temperature, the total heat flux to a wall, the compartment pressure and the ventilation flow rate at the inlet branch. Compared to the proposals of the literature, 2 metrics were used for quantifying the evaluation of the models (see Figure 27). The first metric, also used by the US Nuclear Regulatory Commission (NRC) and Electric Power Research Institute (EPRI) in the validation work on fire models (Najafi et al., 2006), considers the relative difference of numerical and experimental results expressed in terms of the difference between an extreme value and its baseline. The first metric considers only instantaneous values and behaves as a measurement of a local error. The second metric, called the normalised Euclidean distance, considers the differences between computational results and measurements during the entire fire duration. This metric behaves as a global error and gives an overview of code capabilities. To be able to define criteria for acceptance of simulation results, the interpretation of differences must be possible. As it was shown on simple exemplary model results, several other metrics, tested for this benchmark, could not be used due to these difficulties.

However, it appears that it is important to consider more than one metric for the validation process of computer codes. The definition of the purpose of the validation process is also a critical issue in assessing numerical models. Obviously, the compared quantities and the metrics selected in a validation process directly depend on its intended use. In this work (Audouin et al., 2011), the assessment of metric capabilities in case of fire in a confined compartment has shown that the unsteady behaviour of the phenomenon is as significant as peak values.

6.2.1.2 BENCHMARK EXERCISE #2

A sensitivity analysis was performed on several fire models using a factorial fractional experimental design (Suard et al., 2013a). The computer codes involved were: FDS, CFAST, MAGIC, OEIL, SAFIR, SYLVIA and COCOSYS. The influence of 6 factors was tested on 9 responses including gas and wall temperature, oxygen concentration, wall heat flux and over or under pressure peaks in the fire compartment. These responses were selected due to their importance in fire safety studies. The factors to be considered were the fuel mass-loss rate (MLR) and radiative fraction, thermo-physical properties of the compartment (conductivity, heat capacity and emissivity of concrete walls) and the air mass flow rate (MFR) through the ventilation network.

Globally, the ranking factor was identical for most numerical tools. These major results help to quantify the importance of the different factors for each response with a high level of confidence. For this purpose, a qualitative three-colour coding scheme was used to highlight the most important factors for the considering responses and Table 9 gives an overview of the analyses performed. The results show that the main factor for each response is the fuel MLR. The oxygen concentration seems to be affected by the ventilation MFR whereas the thermo-physical quantities such as temperature, heat flux or pressure in the room are primarily affected by the wall emissivity and by the fuel radiative fraction. These results are both original and very important for the fire community in that they provide us with clear orientations for future research of high relevance and thus contribute to the improvement of databases, mandatory for fire models.

Initially, different methods to generate samples were compared. The effects of factors were studied in the case of a Monte Carlo method, a full and a fractional factorial design (FD). For each response, the methods used gave similar results with the same ranking factor. This result is also important both for experimental studies as well as for numerical simulations performed with fire field models, given the fact that fractional FD with 8 runs provides the same information as a Monte Carlo method with 200 runs or a full FD with 64 runs. Since it drastically reduces the number of runs to perform, fractional FD makes sensitivity analyses easier for industrial applications.

Table 9: Qualitative overview of the most important factors for the selected responses

Responses	*Mass loss rate*	*Radiative fraction*	*Wall conductivity*	*Wall heat capacity*	*Wall emissivity*	*Ventilation flow rate*
Maximum mean temperature	🟥	🟧	🟩	🟩	🟥	🟩
Average mean temperature	🟥	🟩	🟧	🟧	🟥	🟩
Wall temperature	🟥	🟩	🟥	🟥	🟩	🟩
Oxygen concentration	🟥	🟩	🟩	🟩	🟩	🟧
Wall total heat flux	🟥	🟩	🟩	🟩	🟧	🟩

Red: the factor has a significant influence (> 0.8) for most of the codes.
Orange: the factor has a relative influence (≈ 0.5) for most or for some codes.
Green: the factor has a small influence (< 0.25) for most of the codes.

6.2.1.3 BENCHMARK EXERCISE #3

The aim of the last exercise, based on one PRISME DOOR test, was to assess the fire model ability to predict thermal stratification in 2 connected rooms, in particular the behaviour of the flow rate through the door. The experimental results show that the mechanical ventilation of the fire compartment scenarios can significantly modify the typical bi-directional flow at a doorway compared to what is expected in open atmosphere. It contributes to unbalance the in- and out-flow rate and to change the position of the neutral plan (see Section 5.3). These phenomena are difficult to model with CFD codes.

The results of simulations obtained with CFD codes show that the temperature and velocities profiles at the door are quite good in the upper and lower parts. The estimation of the gradient and the range of temperature or velocity are not as good in the intermediate zone, around the neutral plane.

This exercise highlights the need to properly estimate the gradient of pressure between the 2 connected rooms in mechanically-ventilated configuration.

6.2.2 The Analytical Working Group of PRISME 2

Two benchmark exercises were performed in conjunction with the PRISME 2 project by members of the AWG.

6.2.2.1 BENCHMARK EXERCISE #1

The aim of the first benchmark exercise was to validate fire codes on 2 PRISME INTEGRAL tests:

- PRS-INT-4: a pool fire in a four-room configuration; and
- PRS-INT-6: an electrical cabinet fire in a four-room configuration with dampers closure.

Ten partners validated their codes: the zone codes, MAGIC and CFAST, the lumped-parameter code, COCOSYS, and the CFD codes, FDS, SAFIR and ISIS.

This first benchmark exercise has highlighted some aspects that need to be taken into consideration to further improve fire safety analysis:

- Definition and use of the main input data have to be carefully chosen as these have an impact on the results. The engineering analysis is essential to estimate the best time-dependent of uncertain parameters. Based on the experimental test results for heterogeneous fire sources, such as an electrical cabinet, the heat release rate (HRR) peak value (and time) is not reproducible; the MLR can be erroneous due to the fact that some components reached the bottom of the cabinet during the fire. Since there is no way to identify which material burns at each time, the heat of combustion is also difficult to estimate unless a linear behaviour between the HRR and the MLR is considered. The choice of the burning rate (directly or corrected from the experimental estimates) significantly affects the main parameters such as pressure, temperatures, etc.

- The over-pressure peak is well simulated, if damper closure modelling takes into account leaks.

- Considering both the INTEGRAL-4 and the INTEGRAL-6 tests, it has to be mentioned that even if global trends are well obtained by computer codes, some difficulties remain.
  - For the pool fire, large HRRs can lead to discrepancies between numerical and experimental results similar to those observed for uncertain fire sources.
  - For complex fire sources, such as an electrical cabinet fire, the following recommendations need to be considered in order to better estimate the fire behaviour:
    - considering a vertical fire spread within the electrical cabinet; a time dependent spatial distribution of the MLR;
    - considering a set of combustion reactions and a set of MLRs depending on the material. The first step is to assume that an electrical cabinet consists mainly of PE and Poly Vinyl Chloride (PVC) with a certain ratio. The different pyrolysis rates for a given heat flux can lead during each time step to a calculated time dependent heat of combustion; and
    - considering improved turbulence modelling to couple the combustion.

6.2.2.2 BENCHMARK EXERCISE #2

The aim of the second exercise was to assess the ability of fire modelling to predict a cable tray fire in confined and ventilated compartments.

The first step of this exercise was to perform blind calculations of a cable fire test, the PR2-CFS-1 test. Performing blind simulations can be compared of the fire code use for fire safety analysis, by using available data coming from a previous characterisation of cable tray fire in open atmosphere.

The second step with open calculations aimed at comparing the different models chosen by the partners to simulate cable tray fires.

The computer codes involved were: FDS (5.5.3 and 6.1.2 versions), ISIS 4.2, MAGIC, SYLVIA 1.7 and COCOSYS. Several theoretical approaches are used to simulate the fire propagation over cable trays. Depending of the users and the fire models (CFD, two-zone, lumped parameter), the cables fire source is simulated in a variety of ways:

- the direct use of experimental data fuel mass-loss rate (MLR), heat of combustion) obtained from the fire characterisation under a large-scale calorimeter in open atmosphere (FDS, SYLVIA, ISIS);

- several analytic approaches considering simple correlations (modified FLASHCAT or simple cable burning modelling for instance) for fire propagation determined by previous fire tests (COCOSYS, SYLVIA, MAGIC, ISIS); and
- detailed pyrolysis modelling based on a multilayers approach (Matala and Hostikka, 2011; Matala, 2013) and a kinetic chemical model for the degradation of solid material (FDS).

The main outcomes of this exercise show some significant discrepancies between the different approaches and that further investigations are necessary to simulate properly such complex fire source. Nevertheless, 2 encouraging and complementary ways are drawn now:

- the analytic approach, which is at an early stage, requesting more modelling and experiments at medium and large scale to improve and strengthen the first simple models available (especially the FLASHCAT model) (McGrattan et al., 2012);

- the detailed pyrolysis approach requesting more modelling to take into account the complexity of cables (materials, geometry, charring and intumescence effect for fuel materials) and more characterisation of thermo-chemical properties for additive and polymeric materials (sheath, filler…) constituting the cables during the fire.

7. Application of the PRISME and PRISME 2 projects results to fire safety analysis

PRISME and PRISME 2 projects aimed first of all at providing technical information and the underlying science to better understand behaviour of complex fire sources, like electrical cables or cabinets, in a confined environment, smoke propagation, the effect of network ventilation and the resulting thermal stresses to sensitive safety equipment, furthermore at validating fire models. To achieve this goal, the test campaigns were designed as close as possible to the real configurations and validation activities were performed.

The PRISME and PRISME 2 projects results will be useful in the fire safety analysis and can be viewed from 4 different angles:

- to evaluate the code capabilities to simulate fire in confined and ventilated environment;
- to determine the limits of fire codes use in fire safety analysis;
- to extend the knowledge basis and to highlight some phenomena which can occur in case of fire in nuclear power plants (NPP): these phenomena have to be taken into account in fire safety analysis but need, in some cases, further research;
- to share analysis of the fire tests to enhance fire risks analysis.

7.1 Fire code capabilities

The first angle at which the PRISME and PRISME 2 projects have added value to the safety analysis is the improvement of mastering and use of fire simulation computer codes. The benchmark exercises conducted as part of the PRISME Benchmarking Group (PBG) and the PRISME 2 Analytical Working Group (AWG) helped to highlight some important aspects which were shared with the partners of the PRISME and PRISME 2 projects. In particular, participation in such exercises allowed to better identify the limitations of the models used.

Several fire codes (zone models, lumped-parameter codes or computational fluid dynamics – CFD codes) have been validated on the PRISME and PRISME 2 results. These validations highlight the limits of some codes to simulate accurately the interaction between fire and mechanical ventilation, observed in the tests (Bonte et al., 2013; Gay et al., 2013; Le Saux et al., 2008; and Prétrel et al., 2012). A lot of partners improved their fire models used to assess fire consequences in order to take into account the effect of the depletion of oxygen on the fire heat release. The PRISME tests were also used to validate the ventilation module of Fire Dynamics Simulator (FDS) by Sweden (Wahlqvist and Hees, 2013) and the fire codes like ISIS (Suard et al., 2013b) and MAGIC (Gay et al., 2013) in France. The simulation of the PRISME tests also showed that the prediction of gas pressure in the fire compartment is not so easy for some models (Bonte et al., 2013). Another models validated on the PRISME 2 tests are the spraying models. For example, for the French *Direction générale de l'Armement* (DGA), the validation of ŒIL and SAFIR was completed with the PRISME 2 tests. These tests allow in particular the validation of the model of droplets vaporisation. Having a validated spraying model in order to design the spraying system installed in the ships is particularly important point for DGA.

Based on the PRISME tests, some models were developed. For example, the Swedish partner developed a simple model for predicting the temperature in a room adjacent to the fire room, derived from computer simulations results. This correlation reduces the number of time-consuming simulations when investigating e.g. the functional performance of electrical components and cables (Van Hees et al., 2011). Global research for safety (GRS) intends to evaluate PRISME fire experiments together with other published compartment fire experiments to derive generic data on the combustion efficiency and the efficiency of oxygen depletion under conditions of limited oxygen supply. The data is intended to help describing source terms for the heat release rate (HRR) in nuclear power plant (NPP)-like compartments.

The partners worked on the validation procedure and highlighted the need to use several metrics to quantitatively measure the agreement between numerical and experimental results (Audouin et al., 2011). The use of different metrics should be a new aspect of the future requests for a code validation procedure.

So, the work performed by partners allowed enlarging the validation domain of several fire codes. This point leads to accept the use of some computer codes in an application domain close to the PRISME and PRISME 2 validation domain.

7.2 Use of fire codes in fire risks analysis

Exchanges between users highlighted some difficulties encountered in simulating fire scenarios. As a lesson learnt, simulation results used in fire risk analysis have to be considered with caution.

One important aspect which has also been demonstrated through the PRISME and PRISME 2 projects is the influence of the HRR used. The sensitivity analysis of the results of fire simulation codes for a single-compartment experiment has been performed. The effect was quantified for pool fires based on the variation of different input parameters on the results analysed. Those quantifications are deemed particularly useful in performing safety analyses. This sensitivity analysis confirmed that the HRR is the most important input parameter to evaluate the fire consequences in an installation. In case of a “blind simulation”, the real HRR is unknown and must be estimated. Given the high sensitivity of this parameter on the results, the use of a HRR as close to the real value as possible is crucial for accurate modelling. If the HRR is unknown, a sensitive analysis based on this parameter could highlight the worsted-case fire scenario to frame the main fire consequences. This needs to be particularly considered for assessments of fire simulations carried out by the operator (Suard et al., 2013a).

The latest benchmark exercise of the PRISME 2 project highlights the difficulty to simulate complex fire sources like cables trays. Fire codes are not yet mature enough to predict the behaviour of such fire but several promising ways are investigated by several partners.

7.3 Significant increase of knowledge

The PRISME and PRISME 2 projects have extended significantly the knowledge basis of fires in confined and mechanically-ventilated installation. The tests results and their analyses improve the understanding of the phenomena occurring during such fire. In this context, analyses and exchanges with other partners during the PRISME and PRISME 2 meetings were particularly useful. Even if the rooms to be analysed in nuclear power plants (NPP) are not necessarily identical to those of the DIVA installation, in which the PRISME and PRISME 2 tests have been performed, some phenomena for which additional studies are needed have been highlighted. Partners used these data to improve their fire models or to initiate complementary research.

The different configurations show various regime of combustion in under-ventilated conditions. The conditions inducing the different regimes of combustion have a significant impact on the correct assessment of the consequences. Indeed, the estimation of the consequences of the sudden ignition of unburnt gases or of the oscillatory regimes, observed in the PR2-VSP (vertical smoke propagation) and cable fire spreading (CFS) campaigns, is important. On these specific topics, some countries like Belgium or France have initiated research studies to develop models able to simulate such phenomena.

Another topic refers to realistic fire sources which were implemented in PRISME 2. In particular, the cable fire tests results have mainly been used as validation tests for developing detailed cable pyrolysis models for FDS or for ISIS. The application of video fire analysis (VFA) allows a reconstruction of the HRR profile based on the estimated temporal evolution of flame and extinction fronts at the level of each cables tray (Beji et al., 2016). The results of this research can be also used to improve analytical model such as the FLASHCAT model (McGrattan et al., 2012) proposed by the US Nuclear Regulatory Commission (NRC). And in the future, such an easy-to-use model could help fire brigades to evaluate the development and the spread of a cable fire in a building. In France, the results of the PRISME 2 CFS campaign are used by *Institut Radioprotection Sûreté Nucléaire* (IRSN) to assess the consequences of cables trays fires in nuclear plants. Additional research studies are committed in France and in Finland to develop detailed pyrolysis models to simulate cables trays fires.

Other subjects studied during the 2 projects give information about important issues to be considered in safety analyses like smoke propagation through leakages or cables malfunction induced by fire. The PRISME LEAK campaign showed the influence of the position of leaks in the walls connecting 2 neighbouring rooms on hot gases propagation. Leaks located near the ceiling will be more detrimental for the propagation of heat in an adjacent room than leaks in the lower part of the wall. The tests of the PRISME LEAK campaign concerning the propagation of heat through a pipe crossing the fire compartment has also highlighted the possible impact that this configuration might have on equipment located in the compartment adjacent to the fire compartment. These particular smoke propagation phenomena observed during test campaigns of the PRISME Project are meanwhile considered by some PRISME partners in their fire safety analysis (Hosser and Hohm, 2013). Moreover, the cable functionality tested during the PRISME tests has given some insights for fire safety analysis on the critical cable temperature and on the failure modes for instrument and control (I&C) cables used (Berchtold et al., 2011).

Additional investigations were also led in the PRISME and PRISME 2 tests. For example, Sweden partner asked to implement a radiation screen in a PRISME 2 CORE test in order to complete their study with full-scale test in a confined environment. The radiation screens are often used as a cheaper and more flexible way to separate and protect sensitive equipment. They investigate radiation screens using relatively simple experimental setup and also evaluate the performance of numerical models to predict their behaviour. The PRISME 2 CORE test contributed thus to extend the validation domain of the numerical models.

7.4 Sharing of the fire test analysis to enhance fire risk analysis

In order to enhance the use and accuracy of fire simulation models in fire risk analysis, some partners believe that the participation in the PRISME and PRISME 2 projects and, in particular to the "benchmarking" exercise, were of paramount importance. Several issues requiring additional research have been highlighted. Extending the investigations with respect to these issues is needed to enhance deterministic as well as probabilistic fire safety analyses.

The publication of special issues allows sharing the acquired knowledge on fire in confined and mechanically environment with the fire community.

In conclusion, the added value of the PRISME and PRISME 2 projects results in safety analysis is considered as an important part to the process of understanding the phenomena of confined fire in under-ventilated compartments as for the development of applicability and application limits of fire simulation codes.

8. Recommendations

The main outcomes of the PRISME Project concerned smoke movement from the fire compartment to adjacent rooms, the effects of under-ventilated conditions on the fire source, mainly liquid, and the electrical cable behaviour exposed to high thermal stress.

The PRISME 2 project completed studies on smoke movement from the fire compartment to adjacent rooms through a horizontal opening, fires of complex sources such as cable trays, the fire spread from an electrical cabinet to targets, such as cable trays or electrical modules, and the efficiency of water-based fire extinguishing systems for fire control.

Both projects have mainly contributed to building up a large experimental database and establishing an efficient international network on the various research topics.

Based on the discussion with the PRISME 2 partners, 3 main topics need further research:

- Smoke propagation in a facility by investigating other configurations of interest with natural convection flows through a doorway and an horizontal opening or studying an elevated fire source.

- Fire propagation from an electrical cabinet to targets such as cable trays or adjacent cabinets: some tests were already performed on this subject within the PRISME 2 project and the results highlighted that the fire spread on complex fire sources depends on the heat sinks as well as on the cable-type. Fire spread from an electrical cabinet to other targets is a fire safety analysis issue currently under investigation; more data on this subject are strongly needed for fire hazard analysis as well as probabilistic fire safety analyses (Fire PSA).

- Electrical cable tray fires in confined and ventilated atmosphere: the need is to investigate the significance of some parameters on the fire development in order to improve the existing models for cable fires. Another need is to study a cable fire scenario in a specific configuration, representative of a service gallery.

Based on these topics, a follow-up PRISME 3 project has been defined. The test configurations will be close as possible to the real situations encountered in nuclear facilities. The new project will cover the cable fire propagation, the fire spread from an electrical cabinet to another one and the smoke stratification and spread.

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APPENDIX 1

APPENDIX 1: SUMMARY OF FIRE TESTS (SOURCE, DOOR) IN THE PRISME PROGRAMME IN THE DIVA FACILITY

Test name	Facility [-]	Fuel [-]	Pool area [m²]	Initial fuel [kg]	Fuel burned [kg]	Fire extinction [-]	Fire duration [s]	Air inlet location [-]	Ventilation flow rate [m³/h]	Ventilation renewal rate [h⁻¹]	Number of rooms [-]	Comments
PRS-SI-D1	DIVA	HTP(1)	0.4	15.0	13.2	O2	3 190	High	560	4.7	1	
PRS-SI-D2	DIVA	HTP	0.4	15.7	15.7	Fuel	2 580	High	1 020	8.4	1	
PRS-SI-D3	DIVA	HTP	0.4	16.0	2.9	O_2	360	High	180	1.5	1	
PRS-SI-D4	DIVA	HTP	0.4	15.7	13.3	O_2	2 895	High	565	4.7	1	
PRS-SI-D5	DIVA	HTP	0.2	7.2	7.2	Fuel	2 552	High	555	4.6	1	
PRS-SI-D5a	DIVA	HTP	0.2	7.8	4.5	O_2	1 978	High	190	1.6	1	
PRS-SI-D6	DIVA	HTP	0.4	16.0	12.0	O_2	2 495	Low	560	4.7	1	
PRS-SI-D6a	DIVA	HTP	0.4	15.8	3.4	O_2	575	Low	200	1.7	1	
PRS-D1	DIVA	HTP	0.4	14.9	6.8	O_2	883	High	0	0	2	One doorway PVC rods + cables
PRS-D2	DIVA	HTP	0.4	17.7	9.1	O_2	1 410	High	180	1.5	2	One doorway PVC rods
PRS-D3	DIVA	HTP	0.4	16.3	16.3	Fuel	1 910	High	560	4.7	2	One doorway PVC rods
PRS-D4	DIVA	HTP	0.4	15.1	15.1	Fuel	1 160	High	1 030	8.4	2	One doorway PVC rods + cables
PRS-D5	DIVA	HTP	1.0	15.9	15.9	Fuel	1 310	High	560	4.7	2	One doorway PVC rods + cables
PRS-D6(2)	DIVA	HTP	1.0	25.1	13.0	O_2	420	High	560	4.7	3	Two doorways PVC rods + cables

(1). HTP = Hydrogenated Tetra-Propylene ($C_{12}H_{26}$).

(2). PRS-D6: N_2 injection in fire room at 405 s after ignition because of safety reasons.

APPENDIX 2

APPENDIX 2: SUMMARY OF FIRE TESTS (LEAK, INTEGRAL) DURING THE PRISME PROGRAMME IN THE DIVA FACILITY

Test name	Facility [-]	Fuel [-]	Pool area [m²]	Initial fuel [kg]	Fuel burned [kg]	Fire extinguishing [-]	Fire duration [s]	Air inlet location [-]	Ventilation flow rate [m3/h]	Number of rooms [-]	Comments
PRS-LK1	DIVA	HTP	0.6	17.5	17.5	Fuel	1 120	High	1 760	2	Two circular ducts
PRS-LK2	DIVA	HTP	0.6	18.1	18.1	Fuel	1 180	High	1 760	2	Narrow vertical slot
PRS-LK3	DIVA	HTP	0.6	17.6	17.6	Fuel	1 120	High	1 760	2	Real fire door
PRS-LK4	DIVA	HTP	0.6	17.7	15.2	O_2	1 000	High	1 760	2	Real fire door + Internal duct
PRS-INT1	DIVA	HTP	1.0	98.9	80.9	O_2	2 035	High	3 100 (L1)	3	Two doorways
PRS-INT2	DIVA	HTP	1.0	52.3	23.6	O_2	622	High	3 100 (L1)	3	Two doorways Sprinkler activation
PRS-INT3	DIVA	Cables	- (1)		4.7	Fuel (2)	1 500	High	3 100 (L1)	3	Two doorways
PRS-INT4	DIVA	HTP	1.0	52.1	52.1	Fuel	1 610	High	2 500 (L1) + 600 (L0)	4	Three doorways
PRS-INT5	DIVA	HTP	1.0	53.5	26.0	O_2	750	High	2 500 (L1) + 600 (L0)	4	Three doorways Dampers
PRS-INT6	DIVA	Electrical cabinet	- (3)	44.0	35.0	O_2	1 950	High	2 500 (L1) + 600 (L0)	4	Three doorways Dampers

(1). 4 cable trays of 3 m in length.

(2). Self-extinguishing of fire (limited flame propagation).

(3). Electrical cabinet dimensions: 1.2 m in width, 2.0 m in height, 0.6 m in depth.

APPENDIX 3

APPENDIX 3: SUMMARY OF SUPPORT FIRE TESTS (SOURCE, CAB) IN THE PRISME PROGRAMME UNDER THE SATURNE CALORIMETER

Test name	Facility [-]	Fuel [-]	Pool area [m²]	Initial fuel [kg]	Fuel burned [kg]	Fire extinguishing [-]	Fire duration [s]	Air inlet location [-]	Ventilation flow rate [m3/h]	Number of rooms [-]	Comments
PRS-SI-S1	Hood	HTP	0.2	7.8	7.8	Fuel	3 190	-	Open	-	
PRS-SI-S2	Hood	HTP	0.2	7.7	7.7	Fuel	1 510	-	Open	-	
PRS-SI-S3	Hood	HTP	0.4	14.9	14.9	Fuel	1 295	-	Open	-	
PRS-SI-S4	Hood	HTP	0.4	15.1	15.1	Fuel	1 350	-	Open	-	
PRS-SI-S5	Hood	HTP	0.1	3.7	3.7	Fuel	1 945	-	Open	-	
PRS-SI-S6	Hood	HTP	0.1	3.8	3.8	Fuel	1 940	-	Open	-	
PRS-SI-S7	Hood	HTP	0.1	6.1	6.1	Fuel	2 928	-	Open	-	
PRS-CAB-1	Hood	Cables	- (1)	≈ 47.0 (2)	19.7	Fuel	4 200	-	Open	-	First cable test
PRS-CAB-2	Hood	Cables	- (1)	≈ 47.0 (2)	28.8	Fuel	3 300	-	Open	-	Improvement of the fire propagation along the cables
PRS-CAB-3	Hood	Cables	- (1)	≈ 47.0 (2)	27.2	Fuel	3 390	-	Open	-	Repeatability of PRS-CAB-2

(1). 4 cable trays of 3 m in length.

(2). In the CAB fire tests, the total mass of PVC power cables was about 173 kg including 104 kg of copper wire and 69 kg of plastic materials. From latter materials, only 47 kg of plastic materials (mainly PVC and Polyethylen including in both additive materials as $CaCO_3$) could be ignited during the fire tests.

In addition to the PRS-INT2 fire test (including activation of sprinklers), a hydrodynamic characterization of the droplets flow was performed for one sprinkler head. These tests measured the water flow rate spatial distribution on the floor for five heights of sprinkler nozzle (1.0, 1.5, 2.0, 2.5 and 3.0 m) for average flow conditions of 42.6 l/min and 2.65 bars.

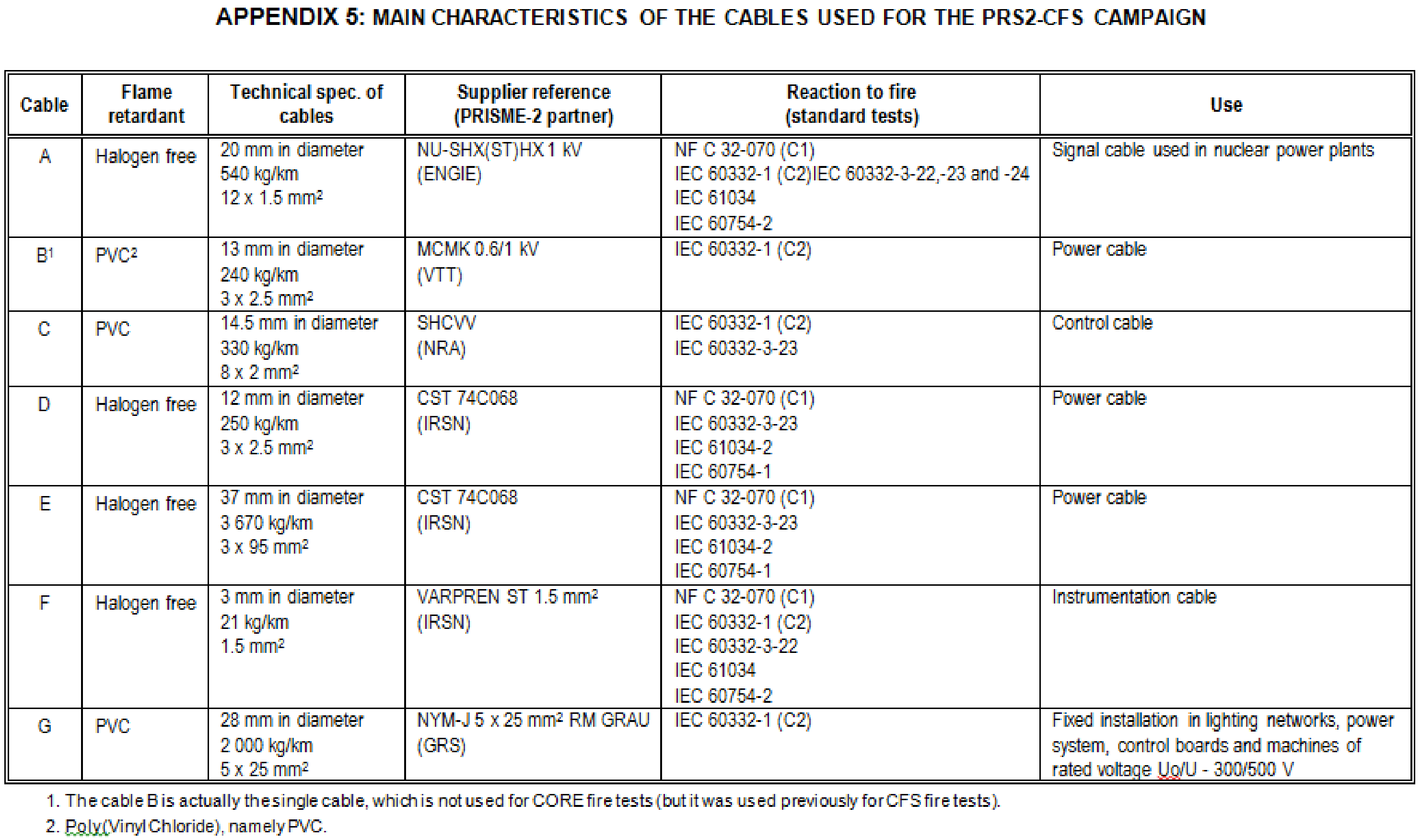
During the PRISME campaigns, the whole DIVA facility was checked just before the first fire test by carrying out one or more simple fire experiments by mean of a gas burner (PYROS) or a small liquid pool fire. Some of these additional experiments can be used to investigate some research topics (as the forced vs. natural flow through doorway in the PRISME INTEGRAL campaign see Pretrel and Audouin, 2011).

APPENDIX 4

APPENDIX 4: SUMMARY OF VSP FIRE TESTS IN THE PRISME 2 PROJECT IN THE DIVA FACILITY

	Fire source			Ventilation					Main results			
Test name	**Fuel [-]**	**Pool Area [m²]**	**Position of the fires source in the room**	**Admission of the lower room (R3) [m³/h]**	**Exhaust of the lower room (R3) [m³/h]**	**Admission of the upper room (R4) [m³/h]**	**Exhaust of the upper room (R4) [m³/h]**	**Ventilation renewal rate [h⁻¹]**	**Initial fuel [kg]**	**Fuel burned [kg]**	**Fire extinction [-]**	**Fire duration [s]**
PR2-VSP-1	heptane	0.4	Centre	1 437	1 446			12	27.2	17.4	O_2	1 520
PR2-VSP-1-TER	heptane	0.4	Centre	1 414	1 430			12	27.3	16.6	O_2	1 405
PR2-VSP-1-QUI	dodecane	0.4	Centre	1 417	1 445			12	30.2	21.4	O_2	1 985
PR2-VSP-1A	heptane	0.3	Centre	1 939	2 036			16.6	20.5	20.5	Fuel	1 555
PR2-VSP-2	heptane	0.4	Centre	2 359	-	-	2 377	8.3	27.2	27.2	Fuel	1 310
PR2-VSP-3	heptane	0.4	Off- centre	990	1 048	1 450	1 464	8.5	27.2	12.6	O_2	755
PR2-VSP-4	heptane	0.4	Off- centre	947	-	1 373	2 375	8.1	27.5	5.3	O_2	335
PR2-VSP-4BIS	heptane	0.4	Off- centre	1 548	-	1 333	2 978	10.1	21.5	11.0	O_2	530

APPENDIX 5



APPENDIX 5: MAIN CHARACTERISTICS OF THE CABLES USED FOR THE PRS2-CFS CAMPAIGN

Cable	Flame retardant	Technical spec. of cables	Supplier reference (PRISME-2 partner)	Reaction to fire (standard tests)	Use
A	Halogen free	20 mm in diameter 540 kg/km 12 x 1.5 mm²	NU-SHX(ST)HX 1 kV (ENGIE)	NF C 32-070 (C1) IEC 60332-1 (C2)IEC 60332-3-22,-23 and -24 IEC 61034 IEC 60754-2	Signal cable used in nuclear power plants
B[1]	PVC[2]	13 mm in diameter 240 kg/km 3 x 2.5 mm²	MCMK 0.6/1 kV (VTT)	IEC 60332-1 (C2)	Power cable
C	PVC	14.5 mm in diameter 330 kg/km 8 x 2 mm²	SHCVV (NRA)	IEC 60332-1 (C2) IEC 60332-3-23	Control cable
D	Halogen free	12 mm in diameter 250 kg/km 3 x 2.5 mm²	CST 74C068 (IRSN)	NF C 32-070 (C1) IEC 60332-3-23 IEC 61034-2 IEC 60754-1	Power cable
E	Halogen free	37 mm in diameter 3 670 kg/km 3 x 95 mm²	CST 74C068 (IRSN)	NF C 32-070 (C1) IEC 60332-3-23 IEC 61034-2 IEC 60754-1	Power cable
F	Halogen free	3 mm in diameter 21 kg/km 1.5 mm²	VARPREN ST 1.5 mm² (IRSN)	NF C 32-070 (C1) IEC 60332-1 (C2) IEC 60332-3-22 IEC 61034 IEC 60754-2	Instrumentation cable
G	PVC	28 mm in diameter 2 000 kg/km 5 x 25 mm²	NYM-J 5 x 25 mm² RM GRAU (GRS)	IEC 60332-1 (C2)	Fixed installation in lighting networks, power system, control boards and machines of rated voltage Uo/U - 300/500 V

1. The cable B is actually the single cable, which is not used for CORE fire tests (but it was used previously for CFS fire tests).
2. Poly(Vinyl Chloride), namely PVC.