Chapter 7
Research on Fires

7.1. Fire risks at nuclear installations

Fire is a major risk to be taken into account for nuclear installation safety. On March 22, 1975 a cable fire broke out in Unit 1 of the Browns Ferry power plant in the US, as a result of a leaktightness test of a polyurethane foam cable sleeve through a wall, performed by candle. Although the operators involved immediately proceeded to put out the fire, unbeknown to them it spread along the cables on the other side of the wall. It caused a loss of control of some equipment important for the safety not only of Unit 1 but also of the neighboring Unit 2. The operators' reactions to this loss of control contained the incident before it could degenerate into a more severe accident. In October 1989, a turbine blade failure at the Vandellos power plant in Spain (UNGG-type reactor[55]) had multiple consequences: a hydrogen leak and explosion, turbine lubricating oil fire, loss of power and of compressed air for regulating several items of equipment involved in residual reactor heat removal, major basement flooding (including of the reactor building basement), etc. The fire, which lasted for more than four hours, was brought under control with the help of firefighting units from within a 100 km radius around the power plant. If the cooling system had stopped working, the 3000 metric tons of graphite would have caught fire. The reactor has not been restarted, mainly because of the high cost of the modifications necessary to improve safety.

55. Reactor running on graphite-moderated, gas-cooled natural uranium fuel (UNGG: Natural Uranium-Graphite-Gas).

Fires do happen from time to time in French nuclear reactors, with consequences of varying degrees of severity. Some examples are:

- an incident in July 1999 at Bugey nuclear power plant in which a single cause (an electrical fault in a board at the pumping station) was responsible for two electrical faults and two fires in Unit 3, which started almost simultaneously in different, geographically separate fire compartments;
- an electrical cable fire in 2004, caused by overheating in an opening between the turbine hall and the electrical building of Unit 2 at the Cattenom power plant;
- in 2012 an oil fire broke out in the reactor coolant pump of the reactor building for Unit 2 at the Penly nuclear power plant.

These examples demonstrate the vital importance of considering fire risks.

Fire is taken into account in the design of pressurized water reactors as both an internal and an external hazard. As a general rule, hazards of this kind should not lead to reactor accidents or endanger the operation of safety systems designed to manage accidents. As part of the defense in depth principle and the deterministic safety approach, controlling fire risk relies on preventive measures – particularly limiting the heating load in buildings –, on the detection of any fires that do start, and on measures to limit the consequences of fires, particularly by means of the compartmentation[56] of buildings and the installation of extinguishing systems. Moreover, the overall risk of core melt in which an internal fire is the originating event is assessed as part of special level 1 probabilistic safety assessments ("PSA Fire" developed by EDF and IRSN), which take account of scenarios where compartmentation elements fail. This type of assessment is all the more important given that reactor operation can reveal compartmentation anomalies or non-conformities (openings not properly sealed, etc.).

A good knowledge of all the phenomena that can come into play when fire breaks out in a room is therefore necessary: the heat level in the room, the increase in gas pressure in the room, the production of (burned or unburned) hot gases and smoke, transfer to other rooms (particularly if the compartmentation fails), etc.

Analysis of data from the OECD Fire database [1] shows that the majority of fires (around 50%) are caused by electrical sources. Electrical and electronics cabinets are one of the biggest contributors, causing more than 10% of fires, regardless of type (low,

56. Nuclear installations are designed so that fire can be contained within a defined perimeter and that inside this perimeter the consequences of the fire can be controlled. The perimeter is delimited by physical walls, or may even be separated by sufficient space. For the safety demonstration, it is assumed that all equipment within a perimeter on fire has been lost (i.e. is unavailable or has failed). The layout of the buildings, the delimitation of these perimeters and the installation of the equipment are all designed so that, if the equipment in the train of a redundant system is affected by fire, the equipment in the other trains cannot be affected by the fire.

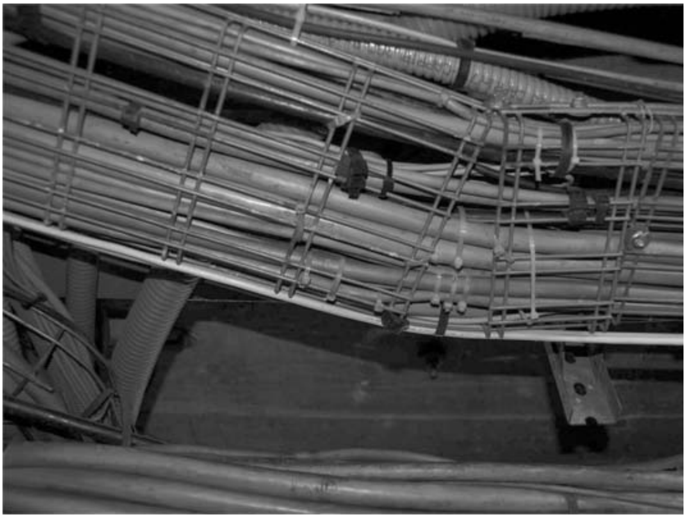

Figure 7.1 Example of a cableway configuration in an installation. @ Georges Goué/IRSN.

medium or high voltage). Electrical cabinets and cableways (Figure 7.1) are therefore of specific interest as regards research on fire risks, for several reasons:

- they can cause fires to start;
- they can help fires to spread;
- conversely, they can also be "targets" if a fire breaks out, so their vulnerability should be reduced as far as possible if they are important for reactor safety.

Most of the research on fire aims to assess the characteristics of the fires themselves, particularly estimating heat output, and the consequences for an installation. The consequences of particular interest are the effects of gas pressure and temperature in rooms, transfers of gases (produced by combustion or unburned) and of soot between rooms, through doors or openings, or through ventilation systems, and the effects of these transfers on containment systems and electrical equipment.

Studying the development of fire inside a nuclear installation and its consequences for equipment important for safety is particularly complex because of the confinement of the rooms and the presence of mechanical ventilation. The oxygen concentration in a room on fire decreases then stabilizes, generally at a value where the flow of oxygen being consumed by the fire is balanced by the flow being drawn in by the ventilation. The degree of confinement of installations, the characteristics of ventilation systems (air renewal rate in the rooms, air flow resistance) and how they behave in a fire (shutdown, closure of fire dampers) are decisive in determining the heat output of the fire, how long it burns for and how it spreads to other fire sources, or even to other rooms.

Since the early 1980s, OECD/NEA/CSNI documents [2, 3, 4] have reported international concerns about the safety of power reactors and evolving knowledge of fire risks (including as part of the development of probabilistic safety assessments). Since 2006, IRSN has run programs, particularly the international PRISME[57] projects guided by the OECD/NEA, to improve knowledge of fires in confined, ventilated spaces representative of nuclear installations.

7.2. Organizations involved in research on fire

Research on fire is not unique to the nuclear sector. In France, there are many different organizations conducting research and development related to fire. In particular, the following four university laboratories are helping to run CNRS' fire research group:

- IUSTI[58] (UMR[59] 6595) in Marseille (compartment fires and forest fires),
- P-PRIME (UMR 9028) in Poitiers (combustion of solids, fire and smoke in open and confined spaces),
- CORIA[60] (UMR 6617) in Rouen (metrology of soot),
- LEMTA (UMR 7563) in Nancy (thermal radiation, fuel emissivity measurements).

IRSN, EDF and the French General Directorate for Armament (DGA) are also carrying out research in this field (there are similarities between fires on ships and submarines and nuclear fires), as are French technical centers such as CNPP[61], CTICM[62], INERIS[63], CERIB[64] and CSTB[65], which are conducting technological tests, sometimes on a large scale, particularly for EDF.

The research begun more than 20 years ago by IPSN, then IRSN, concerns fires of internal origin in confined, ventilated rooms similar to those found at fuel cycle laboratories and plants (glove boxes, etc.) and in nuclear reactors. However, we will limit the following discussion to research looking specifically at nuclear reactors.

The experimental resources available to IRSN enable it to run a complete study of a fire in two stages: in the first stage, its main characteristics (heat output of the fire, combustion heat, pyrolysis rate, combustion products, etc.) are determined in an open atmosphere in a device known as a cone calorimeter. Then, in the second stage, tests are run in ventilated rooms representative of those found in nuclear installations. These tests are used to assess the effect of confinement and mechanical ventilation on the development of a fire.

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57. Spread of a Fire for Multi-Room Elementary Scenarios.
58. French University Institute for Industrial Thermal Systems.
59. Joint Research Unit.
60. French Aerothermochemistry Research Complex.
61. French National Center for Prevention and Protection.
62. French Industrial Technology Center for Construction in Metal.
63. French National Institute for the Industrial Environment and Risks.
64. French Concrete Industry Study and Research Center.
65. French Construction Science and Technology Center.

IRSN is conducting or has conducted research with various partners: industrial partners (AREVA, EDF, ENGIE-Tractebel Engineering, Vattenfall, etc.), universities (Aix-Marseille, Rouen, Edinburgh, Ghent, Maryland, Lund, Aalto), research bodies (CNRS, INERIS, DGA, LNE[66], etc.) and international organizations (BelV[67], GRS[68], HSE[69], NRA[70], VTT[71], CNSC[72], CSN[73], etc.).

In addition, ETIC[74], a "virtual" laboratory for studying fires in confined spaces, was established in 2010 as a joint venture between IRSN and IUSTI (University Institute for Industrial Thermal Systems, a joint research unit CNRS/Universities of Provence and of the Mediterranean).

7.3. Research facilities, simulation tools

At Cadarache IRSN has the GALAXIE experimental platform, which offers experimental facilities of various capacities. The platform was originally built to conduct research in the 1970s to 1990s on sodium fires, sodium being a coolant used for the PHENIX and SUPERPHENIX fast neutron reactors. The GALAXIE test facilities were modified in the late 1990s and new experimental equipment was added from 2000 to adapt it for research into conventional fires in fuel cycle installations and France's nuclear power reactor fleet.

The GALAXIE platform consists of:

– DANAIDES[75], an installation for performing analytical tests on the separate and combined effects of heat and soot on the operation of different electrical devices (relays, circuit-breakers, etc.);

– a 0.3 MW cone calorimeter for measuring the combustion heat of different materials in open air, and a radiant panel enabling equipment to be subjected to a fixed flow of heat, in order to study its degradation; together the devices constitute the CARINEA facility;

– a larger-scale 3 MW cone calorimeter in the SATURNE tower (2000 m^3), for studying the combustion in open air of equipment from nuclear power plants, such as electrical cabinets and electrical cableways;

66. French National Laboratory for Metrology and Testing.
67. Belgian Federal Agency for Nuclear and Radiological Inspections of nuclear installations (hospitals, universities, radiological facilities, etc.).
68. Gesellschaft für Anlagen – und Reaktorsicherheit (reactor safety organization, Germany).
69. Health and Safety Executive (UK).
70. Nuclear Regulation Authority (Japan).
71. Technical Research Center (Finland).
72. Canadian Nuclear Safety Commission.
73. Consejo de Seguridad Nuclear (Spain).
74. Laboratory for the Study of Fire in a Contained Environment.
75. Analytical Equipment for Studying Electrical Malfunctions caused by Soot during a Fire.

- a controlled-atmosphere calorimeter, CADUCEE, for studying the effect of oxygen depletion on the combustion of different types of fuel, the heat radiated and soot production;
- the 400 m^3 PLUTON box connected to a ventilation system, which can be used for making large fires (up to 5 MW) with different ventilation configurations. The HYDRA device (2.4 m high, 3.6 m long and 2.4 m wide) is currently installed in this box and can be used to study soot movements using laser velocimetry through the opening of a door for different ventilation configurations. Small-scale devices such as NYX and STYX can also be installed in the box; they are designed for studying flows of smoke through openings or doors;
- the DIVA device consists of three rooms of 120 m^3, a 150 m^3 corridor and a first-floor room of 170 m^3, connected to a ventilation system with variable configurations; the device can withstand negative pressures and overpressures within the range − 100 hPa to + 520 hPa.

Figures 7.2-a and 7.2-b show the how the test facilities fit into the different topics being studied; Figure 7.2-c shows the DIVA facility.

All these devices are fitted with significant amounts of instrumentation (up to 800 measuring channels in the case of DIVA) for measuring the main characteristics of fires (temperature, pressure, gas concentrations [combustion and pyrolysis products], soot concentrations, total and radiative flows to the walls) and to take samples to be analyzed after the test (soot composition and granulometry). Video recordings are also made during the tests.

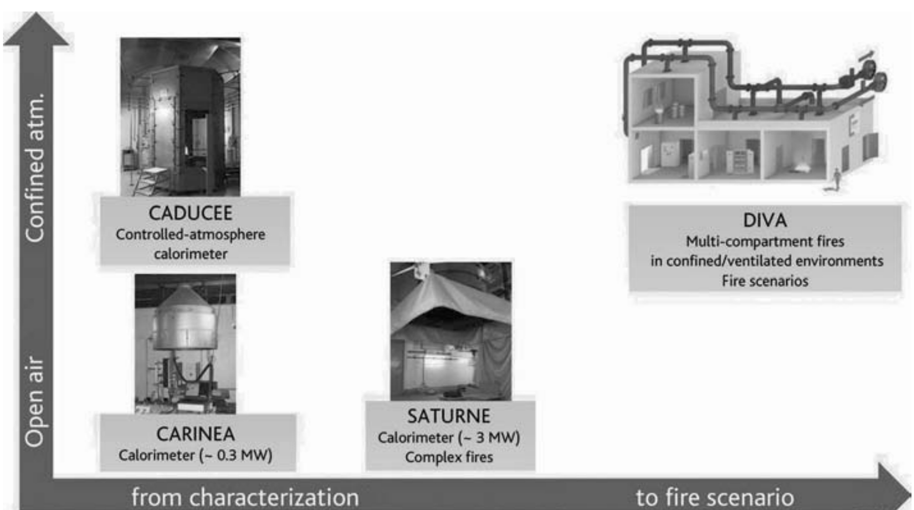

Figure 7.2-a Positioning of the different types of fire characterization test in relation to the test facilities. @ Laurence Rigollet/IRSN.

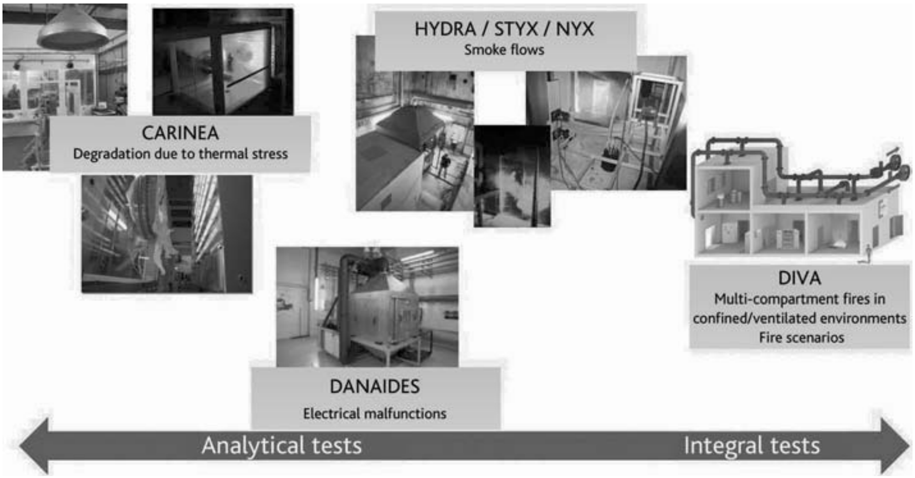

Figure 7.2-b Positioning of the different types of "target" behavior test in relation to the test facilities. @ Laurence Rigollet/IRSN.

As in other nuclear safety fields, assessing the consequences of a fire in a nuclear reactor requires the use of simulation codes incorporating models developed and validated on the basis of tests. Their capacity to simulate real fires in the configurations found in nuclear installations is verified by means of comparisons with large-scale tests performed in facilities reproducing these configurations (confinement, ventilation) as closely as possible. Obviously these tools are essential for analyzing the risks associated with fire and for studying fire scenarios to support IRSN's development of its own "PSA Fire" probabilistic safety assessments for France's nuclear power plant reactors.

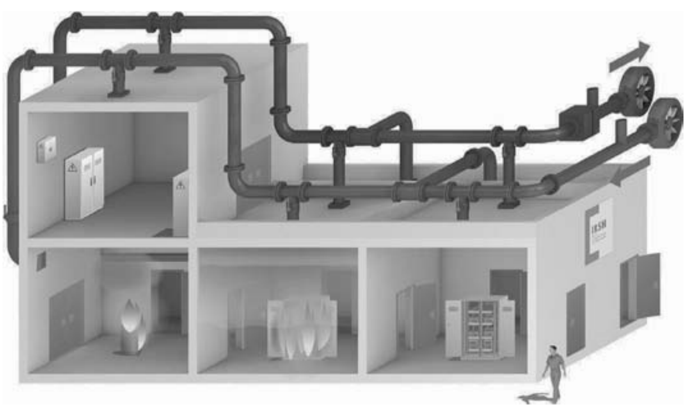

Figure 7.2-c The DIVA installation. © IRSN.

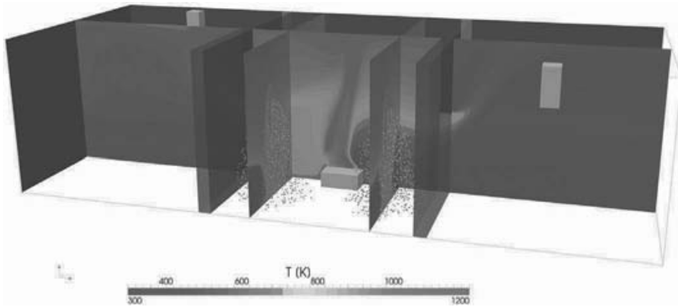

Figure 7.3 Three-dimensional temperature mapping resulting from the simulation of a test at the DIVA facility. © IRSN.

IRSN is developing and validating two types of simulation tool:

- the SYLVIA[76] code, which models the burning room as two homogeneous zones with a boundary between them (a flat horizontal surface) that moves over time. The rooms are connected to one another by doors (possibly fire doors), which are open or closed (leaks are modeled), and by the ventilation system. The ventilation system can be modelled in its entirety, with fire dampers, HEPA[77] filters, control dampers, fans, etc. Correlations of the mass and heat exchange between the zones, flames and walls complete the mass and energy balance equations for each zone. Because of its short calculation times, this code is used by IRSN for studies in support of its safety expertise and for its probabilistic safety assessments of fire;
- the ISIS (CFD-type) code, which models three-dimensional, non-stationary, marginally compressible, turbulent, reactive or chemically inert flow fields; it can be used to calculate combustion, thermal transfers and soot transport in large rooms, either ventilated naturally or confined and mechanically ventilated. Only the intake and extraction branches of the ventilation system are modeled (see Figure 7.3 for an illustration of the results achieved with ISIS).

IRSN has coupled the SYLVIA and ISIS codes together, giving it the benefit in a single tool of the precision of ISIS, which performs 3D simulations of fires in rooms, and SYLVIA's ability to describe a whole installation with a complete ventilation system connecting all the rooms. No other coupling of this kind exists anywhere else in the world.

7.4. The main research programs and their contributions

Major progress has been made since 1990 in terms of knowledge of confined, ventilated fires and how to model them, in particular due to research programs run

76. Software System for Analysing the Ventilation of a Fire and Airborne Contamination.
77. High Efficiency Particulate Air.

in collaboration with AREVA on fuel reprocessing plant safety (FLIP[78] program on solvent fires and PICSEL[79] program on electrical cabinet fires). Further progress has also been made through the international PRISME and PRISME 2 programs (2006–2011 and 2011–2016), run by IRSN under the aegis of the OECD/NEA, focusing on nuclear reactor safety.

These programs have been used to validate the ISIS and SYLVIA codes, which are able to a sufficient degree of precision of simulating scenarios involving fire in a confined environment with managed ventilation (shutdown of the air supply followed by air extraction after a certain period of time).

During the large-scale tests, significant variations in gas pressure in the rooms (overpressure when the fire starts, negative pressure when it is extinguished and, in some configurations, wide oscillations) have been observed. These gas pressure variations can subject compartmentation systems (fire doors and dampers) to stresses beyond those they were designed for, enabling fire to spread within an installation. This gas pressure variation is linked to the fire's confinement and the ventilation system's resistivity. The oscillations and instability of combustion are due to the under-oxygenation of the fire, leading to pyrolysis gas combustion. These phenomena could also occur in a nuclear power plant. The tests have also identified the effect of soot on the operation of electrical or electronic equipment.

The PICSEL program run in collaboration with AREVA between 2004 and 2011 studied fires in electrical cabinets and their consequences in experiments in the SATURNE facility (fires in open atmospheres) and the DIVA facility (fires in confined, ventilated rooms), enabling them to be modeled. These results, obtained during a program looking more specifically at the configurations of fuel cycle installations, can be transposed to nuclear reactors.

One of the findings of this program on electrical cabinet fires (Figure 7.4) concerns the heat output of these complex fires (involving multiple components and many different types of material). In particular, the tests showed that the heat output of an electrical cabinet fire with the cabinet doors open was 10 times greater than that of an electrical cabinet fire in which the doors were closed. This difference is due to the fact that soot clogs the door vents, preventing they entry of oxygen and therefore combustion, in the electrical cabinet with its doors closed. These are the first electrical cabinet fire tests run in a confined, ventilated atmosphere; a few tests had been done previously, at the Sandia National Laboratories (SNL) in 1987 and by VTT in 1994, but they had only evaluated the heat output of this type of fire in an open atmosphere.

The PRISME program consisted of 24 tests run in the DIVA facility, plus a further 13 more analytical tests in SATURNE. It produced results on the propagation of smoke and hot gases in the adjacent rooms to a burning one, on how long it would take for the cables in the burning room to malfunction, on how the fire dampers in the ventilation system would work and on how the ventilation system should be managed to prevent pressure effects that might damage the compartmentation system. The PRISME program

78. Interaction of Liquid Fires with a Wall.
79. Propagation of Solid Fuel Fires in Laboratories and Factories.

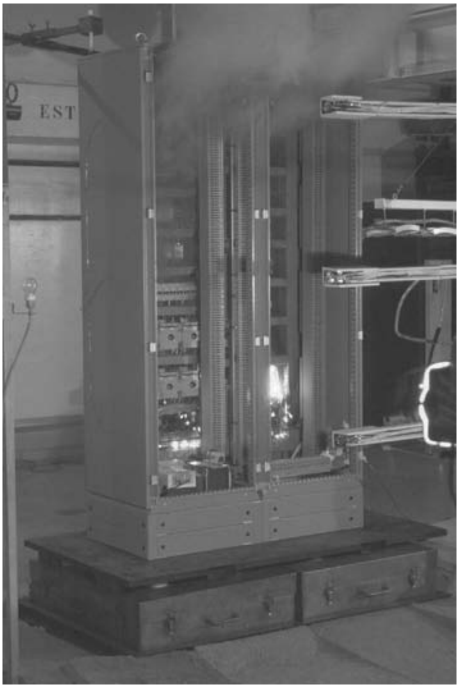

Figure 7.4 Fire in a type of electrical cabinet used in fuel cycle installations, tested at the SATURNE facility as part of the PICSEL program. © Florent-Frédéric Vigroux/IRSN.

provided a better understanding of the effect of ventilation (and therefore under-oxygenation of the fire) on the heat output from a fire breaking out in a confined, ventilated room, and particularly of how long the fire would last. Depending on the air renewal rate, the fire could rapidly go out because of a decrease in the oxygen concentration in the burning room. But the tests run under thePRISME program showed that an equilibrium could be reached between the air coming from the ventilation air supply and the heat output of the fire: in this case, any combustible material would be consumed more slowly than in the open air (lower heat output) and more completely. For example, the same fire could burn 2.5 times longer in a ventilated room with an hourly air renewal rate of 4.7 than in open air. Correlations and analytical models of pyrolysis in a confined, ventilated environment (under-oxygenated fires) have been developed and validated. These models correct the heat output obtained for a fire in open air (measured under the SATURNE hood) by a factor taking into account the under-oxygenation rate of a fire in a confined space.

The PRISME program was also used to quantify the effect on smoke propagation of "mixed" convection, which combines the forced convection created by ventilation with the natural convection induced by the steep vertical temperature gradient of the gaseous atmosphere in a room ("fresh" air on the ground and hot smoke at the ceiling). The mechanical ventilation of the burning room can significantly alter the gas flows that would naturally develop at an open door between two rooms. Depending on the way the ventilation system is adjusted, the mechanical ventilation helps to cause an imbalance in the flows entering and leaving the burning room, and to change the position of the neutral plane (the height where flow rates are zero due to flow reversal) at the door.

All the data collected during this program has been used to assess the ability of computer codes to simulate different fire scenarios. The new models, particularly for pyrolysis, have been integrated into the various partners' codes and validated by means of experimental data obtained during this program.

The PRISME 2 project (2011–2016) was launched for the purpose of studying fire-related themes to complement those studied in the first project (PRISME), such as smoke propagation between rooms on top of one another, the fire propagation between cableways and the performance of sprinkler systems. The PRISME 2 program consists of 22 tests at the DIVA facility and approximately 20 tests in the SATURNE calorimeter.

The tests, involving a simple fire (a pool of liquid) in a ventilated room which is either closed or is connected to an upper room by an opening, revealed a phenomenon of high amplitude and very low frequency oscillations, of the thermodynamic variables in the facility, which suggest combustion instability that is highly correlated with the room's ventilation and with oxygen transfer from the air supply vent to the combustion zone. Understanding these oscillations required further experimental research to identify the configuration and scenario parameters causing them. Results have been obtained for the transfer of smoke in these configurations in relatively stable combustion regimes (i.e. without wide oscillations), providing new data for validating the correlations for smoke transfer through a horizontal opening between closed, ventilated rooms and for validating detailed CFD-type codes.

Several types of cable were tested during the tests in DIVA (following their characterization in an open atmosphere under the SATURNE hood): cables with a halogenated flame retardant and cables with a non-halogenated flame retardant (components reducing the spread of a fire affecting an electrical cable). The integral tests in DIVA revealed that the propagation of fire along five horizontal cableways or from an electrical cabinet to the cableways above it depended heavily on the type of cables and the air renewal rate in the room on fire. The intensity and duration of the fire in a confined, ventilated environment could not be correlated with the degree of fire resistance of the cables. So in certain conditions, supposedly fire retardant cables burned up completely in a fire lasting a long time whereas supposedly non-fire retardant cables caused the fire to go out early on due to a lack of oxygen (in this case, the mass of burned cable was low as a result of the simultaneous consumption of oxygen by the fire in the cabinet and the fire in the electrical cables). This behavior, which may seem paradoxical, is explained simply by the fact that if the runaway of a fire in a confined environment is too sudden, this can cause a drop in the oxygen concentration, which is not compensated for by the air supplied by the ventilation. This produces conditions in which combustion at the flame front stops. These tests also revealed that the sudden reignition can occur (slow deflagration but with a significant peak in gas pressure) of unburned gases that have accumulated in the room. The results are new and original, and underline the importance and value of continuing to study the combustion of cableways in confined, ventilated facilities for the development of combustion models (simplified, such as correlations, and more detailed, such as porous environments for CFD codes), taking account of the specific characteristics of the cableways in question (cable type, size, spacing between cableways, etc.).

The PRISME 2 program also provided data on the use of extinguishing systems. During these sprinkler tests, contact between the droplets and the flame zone above the tray of burning oil and walls was avoided so that the effect of the sprinkler on controlling the fire could be studied without directly extinguishing it and avoiding the edge effects associated with the walls. This data can be used to validate simulation codes and to assess the codes' ability to simulate the phenomena identified during the tests, e.g. cooling of the gases in the room due to contact with the water droplets and their vaporization, vigorous mixing of the gases in the room producing a uniform gas distribution and therefore temperature and oxygen concentration and a significant increase in combustion of the burning liquid (measured by loss of mass by the pool of liquid over time).

Industrial protection aimed at preventing the spread of fire along a cableway was installed and tested under the SATURNE hood on a set of three cableways, one on top of the other (Figure 7.5). The fire did not cross the barrier created by this protection, but the demonstration at this stage is not fully established because there was some pyrolysis of the cables downstream of the protection and the flames could have crossed the barriers if there had been more cableways present or if the fire had been in a confined environment so that the cables downstream of the protection had been preheated.

The speed of propagation along inclined cableways was measured and compared with the speed along horizontal cableways.

Figure 7.5 An experiment involving a fire in a set of cableways, one on top of the other. © Florent-Frédéric Vigroux/IRSN.

A test of fire propagation from an electrical cabinet with open doors to adjacent cabinets and to cableways passing above the electrical cabinets was performed in the DIVA facility. The test revealed that the fire spread to one of the cabinets adjacent to the burning cabinet but that the spread of the fire was less intense than during a similar test in a previous campaign, without cabinets adjacent to the electrical burning cabinet.

The results of the tests are being analyzed by the international bodies involved in the PRISME and PRISME 2 programs (Germany, Belgium, Canada, Spain, Finland, France (IRSN, EDF, DGA, Marseille University), Japan, Sweden, the UK, South Korea, the USA, and the Netherlands, though the last three only for PRISME). Code benchmark exercises have been organized by IRSN in the context of a working group related to the PRISME and PRISME 2 programs: the various partners have compared the results of fire simulations with the experimental data. A sensitivity study carried out with six different simulation codes, involving six input parameters (heat release rate of the fire, radiative fraction of the flame, thermal properties of the walls, etc.) revealed that the fire's heat release rate is always the dominant parameter, showing that efforts to improve its modeling need to continue.

In another example of assessment of the relevance of simulation codes, the CNRS fire research group organized a benchmark exercise of multi-dimensional computer codes that use fields (ISIS code mentioned above, SATURNE code developed by EDF, and FDS[80] code developed by NIST[81] in the United States), based on a fire test in a hotel room. The exercise showed that results produced by the different codes were very widely dispersed as regards the values measured during the test. Experts attributed this dispersal in particular to the difficulty of choosing an appropriate combustion model for calculating the fire's instantaneous heat release rate.

These results demonstrate the need to continue the research in order to achieve better modeling of the characteristics of fires by developing pyrolysis and combustion models in under-oxygenated and complex fire conditions. It is also necessary to increase knowledge particularly of the instability of combustion as a result of the production and ignition of unburned gases, as observed during the study of cable fires in an under-oxygenated environment[82] in the PRISME 2 program, and of about the sudden pressure variations caused by this, so that the predictive capabilities of the simulation tools can be improved. The layout of cableways (horizontal, vertical, mixed, near a wall, etc.) and the cables they carry (loose, tight, etc.), as well as the type of cables, constitute a set of parameters with effects on flammability and the propagation of fire that are complex to model and require new experimental data. The effectiveness of measures to protect cables from catching fire (wrapping in fire-resistant tape, enclosure, etc.) is also worth studying experimentally. The first tests on fire-resistant taping were run during the PRISME 2 program. They acquired data on the fire resistance of this taping under realistic conditions.

80. Fire Dynamics Simulator.
81. National Institute of Standards and Technology.
82. Situation arising as a result of a confined, ventilated atmosphere; the phenomenon can also occur as a result of the accidental heating of cables, e.g. through the Joule effect, causing the release of pyrolysis gases.

In addition to these research programs using integral tests, academic research is also being carried out on the modeling of pyrolysis, a phenomenon strongly linked to conditions around the fire, soot production and radiation from the flames. The models, developed particularly at the ETIC joint research laboratory, have been validated in medium-scale tests, especially in the CADUCEE controlled-atmosphere calorimeter. For this validation, appropriate instrumentation was developed to cover different aspects, particularly flowmeters and non-intrusive methods using a laser (LII[83], PIV[84], etc.). Laser velocimetry techniques and PIV (visualization of the movement of particles in a moving fluid) can be used to find out the velocity fields of flows and to measure the local intensity of turbulence. These measurements are essential to validate the airflow calculations and therefore the calculations for smoke and heat transport within the rooms. The PIV technique has been used to measure the velocity fields of flows through a door in the HYDRA device and at an opening in the STYX device.

Research being conducted on fires is looking at the effects of a fire on equipment important for safety, in particular compartmentation components such as doors and fire dampers, and electronic and electrical equipment.

As far as the compartmentation components are concerned, airflow tests are performed in IRSN's STARMANIA facility at the Saclay research center. In particular this allows measurement of the effects of pressure on fire protection components (doors, dampers).

Electrical equipment malfunctions due to heat and soot were studied during the analytical test programs CATHODE (2007–2009) in an oven named SCIROCCO, then DELTA (2014–2015) using the DANAIDES device (Figure 7.6); the criteria deduced from these tests can be used to predict the operational limits of the tested equipment[85] when a fire breaks out in the room where it is located. The tests have identified three general zones (in terms of temperature and soot concentration): one zone where the equipment remains operational, one zone where malfunctions occur that are reversible, and one zone where the malfunctions are irreversible. During tests on circuit boards, the damage from soot appears to be significant from a soot concentration of 1.5 g/m^3, reducing the zone in which the equipment functions properly.

EDF is also performing analytical tests on the MILONGA experimental platform at the Chatou center. In particular these tests consist of taking measurements using a small cone calorimeter coupled with a Fourier transform infrared spectrometer and an electrical low pressure impactor, of the gases and soot released by the combustion of different materials, particularly those used in cables. Malfunctions of electrical and electronic equipment exposed to heat and smoke are also being studied in the MAFFé

83. Laser Induced Incandescence. LII is used to measure soot concentration and to validate soot production models in an under-oxygenated environment. This measurement technique is not currently used in fire tests because it is the subject of academic research.
84. Particle Image Velocimetry.
85. Tested equipment: D125 circuit-breakers, MICOM P921 and VIGIRACK A326E electronic relays, LOREME.

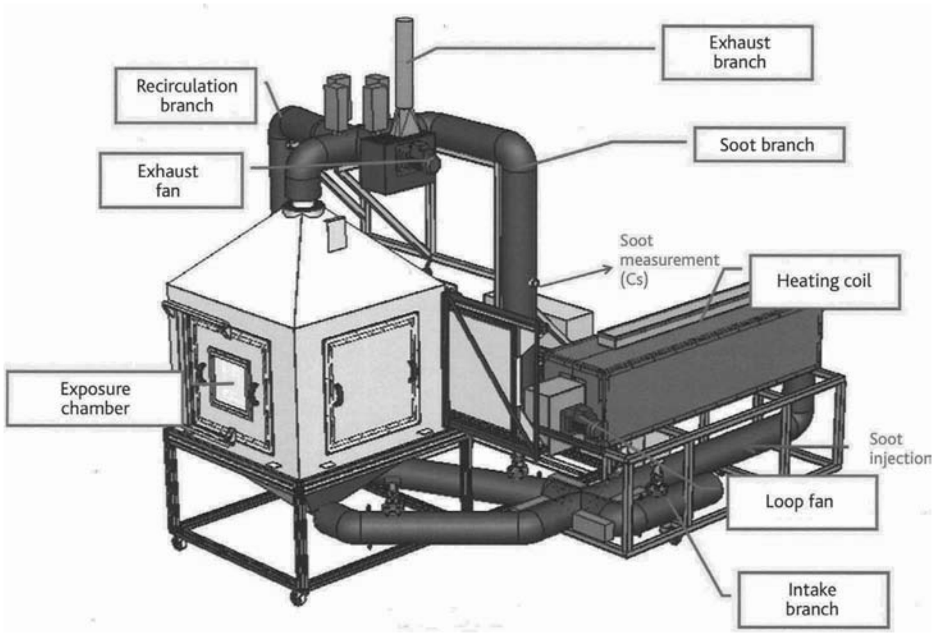

Figure 7.6 The DANAIDES facility used for the DELTA program. @ Marc Piller/IRSN.

furnace. The results of these tests are used by EDF in its safety demonstrations, subject to assessment by IRSN.

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