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FIRE SPREADING FROM A REAL OPEN-DOORS ELECTRICAL CABINET TO OVERHEAD MULTIPLE CABLE TRAYS INTO A CONFINED AND MECHANICALLY-VENTILATED FACILITY

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ABSTRACT

Electrical cabinet fire is one of the main fire hazards in Nuclear Power Plants (NPPs). The ability of the fire to spread beyond the burning cabinet is therefore a major concern for fire safety analyses in NPPs. In the framework of the OECD PRISME-2 programme led by the French "Institut de Radioprotection et de Sûreté Nucléaire" (IRSN), three fire tests, named CFS-5 to CFS-7, involving a real open-doors electrical cabinet and three overhead cable trays, are performed. In this study, the main objectives are to investigate the effects of ventilation and types of electrical cable on the fire spread from the electrical open-doors cabinet to the three overhead cable trays. The fire tests are carried out into a confined and mechanically ventilated facility, named DIVA. Both CFS-5 and CFS-6 tests involve a ventilation renewal rate (VRR, defined as the room volume number renewed per hour) of 15 h^{-1} , while the third CFS-7 test early implements a significantly lower VRR of about 1 h^{-1} . For this last one, fire dampers are indeed shutdown 2 min 30 s after the starting of the cabinet ignition. In addition, the overhead trays are filled with two types of electrical cable used in NPPs, named cable C for the CFS-5 test and cable A for both CFS-6 and CFS-7 tests. These tests highlight that fire spreads from the real open-doors cabinet to the overhead cable trays for a VRR of 15 h^{-1} and whatever the type of cable. However, this last one influences the fire behaviour of the upper cable trays. The cable A trays indeed ignite once and later than the three ignitions highlighted for the cable C trays. Moreover, the cable A tray fire is longer than the three cable C tray fires. The former mainly grows after the cabinet fire while the latter match with the cabinet fire. Finally, for the CFS-7 test, the fire dampers shutdown shortens the cabinet fire and prevents the upper cable trays ignition.

INTRODUCTION

Nearly 400 fire events in Nuclear Power Plants (NPPs) were recorded since the 1980's to the end of 2010 in the current OECD FIRE Database¹. From this last one, Werner² points out that half of these fires are electrical fires since they are ignited from electrical sources. Werner³ also indicates that one of the main contributions to the fire hazard is attributed to electrical cabinets, representing 12 % of all fire events (i.e. 48 cabinet fires). Furthermore, Chavez⁴ mentions that some of these cabinet fires lead to severe damage due to heat, smoke and corrosion. Consequently, the study of electrical cabinet fires and its consequences especially in room for electrical control equipment or in a switchgear-type room of NPPs is a major concern for fire safety analyses. Werner³ indeed points out that a cabinet fire in such room could lead to failure of one NPPs safety train or more, if fire spreads beyond the burning cabinet. Previous investigations focused particularly with:

- Conditions for cabinet to ignite,
- Cabinet fire spread,
- Ability of the fire to spread beyond the burning cabinet,
- Cabinet fire consequences into both fire and adjacent rooms.

Only the main results dealing with the second and third items are discussed in this paper.

During the 1980's at Sandia National Laboratories, Chavez^{4,5} performed fire tests involving several full-scale cabinets. These tests were conducted either in a well-ventilated room of about 300 m³ in volume or in a room with a larger volume of 1400 m³. Only one real (vertical or benchboard) cabinet was internally ignited by fuel or electrical ignition source. The cabinets were most often without door and loaded with IEEE-383 qualified or un-qualified cables. In addition, the cabinets were separated by a double wall (a wall for each cabinet and an air gap of about 2.54 cm between). All these tests highlight that the fire can quickly propagate throughout the internally ignited cabinet without door whatever its type. Moreover, maximal heat release rate (HRR) was measured higher than 1200 kW for vertical open-doors cabinet and for the two cable-types (vs 185 kW for the closed-doors cabinet). However, despite such HRR for the open-doors burning cabinet, fire did not spread to adjacent cabinets. The air gap between the cabinets did not allow the wall temperature of adjacent cabinet to be enough high to lead to auto-ignition of cables fixed to the adjacent cabinet along the wall.

At VTT, Mangs⁶ conducted during the 1990's nine full-scale experiments involving two types of real vertical closed-doors electronic cabinets. All experiments were carried out beneath a large hood which collected all combustion products. They contained either relays or circuit boards but the two types of cabinet also included electrical cables. Finally, an adjacent cabinet was fastened to the burning cabinet. This last one contained Poly(vinyl chloride) (PVC) cables attached to the wall against the burning cabinet. The fire cabinet was ignited in all experiments with a propane gas burner. The higher HRR peaks were measured in the 100-350 kW range for all the experiments leading to flashover inside the cabinet. The highest HRR peak was obtained when the door locking mechanism failed during one of the real cabinet fires. Finally, the adjacent cabinet ignited caused by self-ignition of PVC cables contained inside it.

In the 2000's, Coutin^{7,8} performed eleven real cabinet fire tests in the framework of the PICSEL research program led by IRSN in collaboration with AREVA NC. Four cabinet fires were carried out in open atmosphere (under a large-scale calorimeter) while the seven other were performed in a confined and mechanically ventilated facility. All the fire tests involved the same real twin modules for the electro-technical cabinet. However, two of the cabinets tested in open atmosphere had closed-doors while the nine other cabinets tested had no door. A linear propane burner ignited the fuel load at the base of the cabinet, along its entire width. All the open-doors cabinet fires showed, after the incubation stage, fast fire propagations and significant HRR peaks although they reach higher values in open atmosphere conditions (1200 and 1600 kW) than in the confined conditions (from 400 to 950 kW). Otherwise, the two closed-doors cabinet fires gave HRR lower than 50 kW.

McGrattan⁹ recently performed one hundred and twelve full-scale experiments involving eight electrical cabinets under a medium-scale calorimeter. These cabinets were acquired from a NPP built in the late 1970's but never operated. They were reconfigured with various amounts and types of electrical cable to represent many kinds of cabinet. The main goals were to provide the HRR data for fire models used to assess fire consequences in NPPs. Eleven of the cabinet fires had HRR peaks higher than 100 kW and ten of these last ones had a HRR peak lower than 300 kW. Such HRR peaks were obtained for both open-doors and closed-doors configurations and whatever the cable-type. However, the highest peak HRR measured at nearly 600 kW was obtained for an open-doors cabinet loaded with un-qualified cables and loosely arranged.

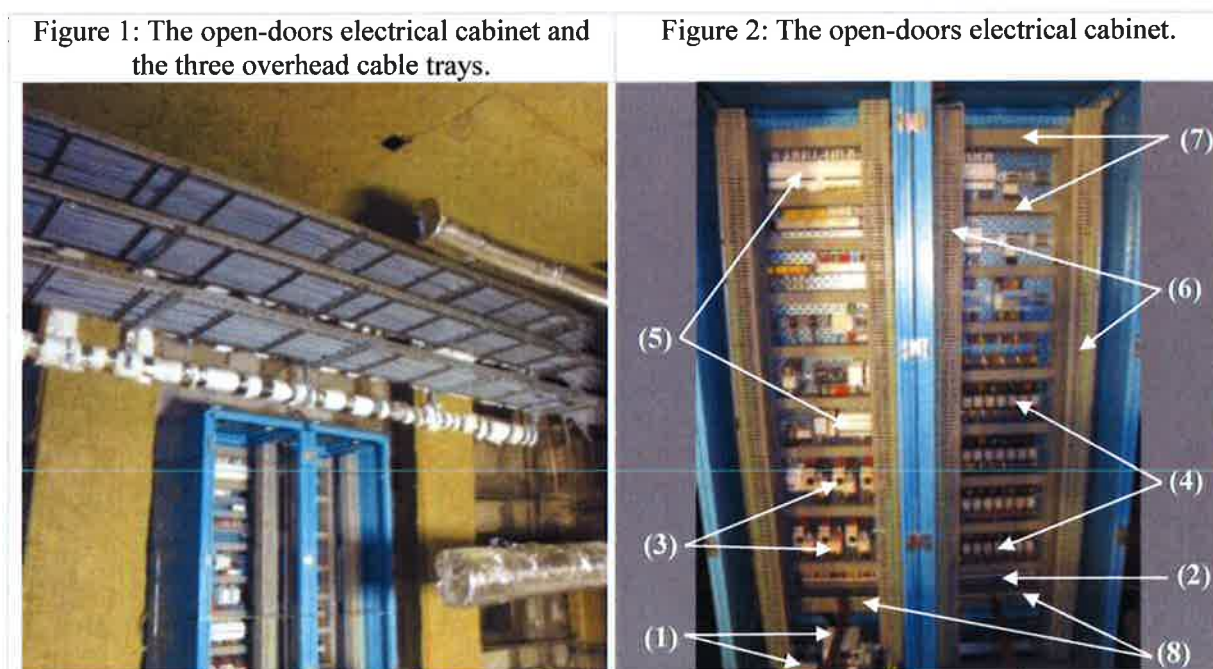
All the previous programmes highlight significant HRR for cabinet fire, in particular for open-doors cabinet configuration. NPPs typically contain hundreds of kilometers of electrical cables which run along cable trays and may be connected to numerous electrical and electronic cabinets. However, no study deals with propagation from a burning cabinet to cable trays located above or below. Only the ability of the cabinet fire to spread to adjacent cabinet was previously investigated and discussed before (Chavez^{4,5} and Mangs⁶). In the framework of the OECD PRISME-2 programme (CFS campaign) led by IRSN (Audouin¹¹), three fire tests, named CFS-5 to CFS-7, involving a real open-doors electrical cabinet and three overhead cable trays, are performed. The goal of this study is to investigate the effects of ventilation and types of electrical cable on fire spreading from the electrical cabinet to the three overhead cable trays. The fire tests are conducted into a confined and

mechanically ventilated facility, named DIVA. Both CFS-5 and CFS-6 tests involve a ventilation renewal rate (VRR, defined as the room volume number renewed per hour) of 15 h^{-1} , while the third CFS-7 test early implements a significantly lower VRR of about 1 h^{-1} . For this last one, fire dampers are indeed shutdown 2 min 30 s after the starting of the cabinet ignition. In addition, the overhead trays are filled with two types of electrical cable used in NPPs, named cable C for the CFS-5 test and cable A for both CFS-6 and CFS-7 tests. Polymeric material contained in these cables is Poly(vinyl chloride) (PVC) for the former and mainly Poly(ethylene/vinyl acetate) (EVA) for the latter. The cable A also includes aluminium tri-hydroxide (ATH) as halogen free flame retardant while the halogenated flame retardant for the cable C is the chlorine included in the PVC polymeric material.

Firstly, this paper gives a description of the experimental set-up as the electrical cabinet fire source, the overhead cable trays and the DIVA facility. Then, analysis of the gas temperature measurements performed along the overhead cable trays gives first results dealing with both cable ignition and fire spreading. Next this paper focuses on HRR assessment based on both thermal and chemical methods. Finally, the last part deals with analyses of both HRR and mass loss rate (MLR) for the three CFS-5 to CFS-7 tests. These last ones highlight the effects of both ventilation and type of cable on the fire spread from the electrical cabinet to the three overhead cable trays.

DESCRIPTION OF THE FIRE TESTS

The real open-doors electrical cabinet and the three overhead cable trays involved for the three tests are shown in Figure 1. The CFS-5 to CFS-7 tests are carried out in the confined, mechanically ventilated and multi-rooms DIVA facility.



The open-doors electrical cabinet



The electrical cabinet used as fire source is a real twin module electro-technical cabinet, as previously used by Coutin^{7,8}. As for this last one, cabinets are without door since this configuration, on one hand, leads to the most critical fire scenario, on the other hand, is taken into account in the NPPs fire safety analyses. The cabinet width, depth and height are respectively of 1.2, 0.6 and 2.2 m. The main components inside the cabinet (Figure 2) are transformers (1), terminal blocks (2), motor circuit breakers and contactors (3), relays (4), circuit breakers (5), vertical trunkings (6), horizontal trunkings (7) and cables. Figure 2 also points out a single pipe (8) with small holes, located at the bottom of cabinet, and used as a propane burner. This last one provides a fire power of about 10 kW for a

duration between 4 and 5 minutes (depending on the test). Because the ignition due to hot shorts is not the purpose of this study, the electrical cabinet is not electrically powered. Finally, the test starts ($t = 0$ s) when the gas burner begins to operate. The starting of the test also matches with the beginning of the cabinet ignition.

The three overhead horizontal cable trays

Three horizontal cable trays of 5 m in length are installed 30 cm above the electrical cabinet and deported beyond its front panel (Figure 1). These trays are ladder-type trays. Spacing between trays is of 30 cm and nearly of 45 cm between the upper tray and the ceiling. Table 1 summarizes the main characteristics of the electrical cables A and C, packed loosely over all the trays. This table also gives the tray filling (i.e. number of cable samples per tray) applied for the CFS-5 to CFS-7 tests. This last one is determined in order to ensure the same cable total surface per tray (i.e. 10 m^2) for the three tests.

Table 1 : Characteristics of the cables and the tray filling used for the CFS-5 to CFS-7 tests.

Cable	Polymeric material	Flame retardant	Outer diameter, linear mass and conductor	Test (Tray filling)
	Poly(vinyl chloride) (PVC)	Chlorine	14.5 mm, 330 kg/km, $8 \times 2 \text{ mm}^2$	CFS-5 (44)
	Mainly Poly(ethylene/vinyl acetate) (EVA)	Aluminium tri-hydroxide (ATH)	20 mm, 540 kg/km, $12 \times 1.5 \text{ mm}^2$	CFS-6&CFS-7 (32)

Set-up of the rooms (DIVA facility) and ventilation

The fire tests involve two rooms (rooms 1 and 2 shown in Figure 3) of a large-scale and mechanically ventilated facility, named DIVA, which contains five rooms in total. The electrical cabinet and the three overhead cable trays are located into the room 1 (fire room) at the centre of the west wall (Figure 3). In addition, rooms 1 and 2 communicating through a doorway are only equipped by one inlet, located at the upper part of room 1, and one outlet, settled at the upper part of room 2 (adjacent room). Open sides of both inlet and outlet are also indicated in Figure 3. Fire dampers are implemented at both inlet and outlet only for the CFS-7 test. For the three tests, the initial VRR (i.e. before the starting of cabinet ignition) involving both rooms 1 and 2 is of 15 h^{-1} . Volume flow rates at both inlet and outlet are therefore initially equal to $3600 \text{ m}^3/\text{h}$. Furthermore, for the CFS-7 test, these last ones strongly decrease from 3600 to about $200 \text{ m}^3/\text{h}$ (i.e. a VRR of about 1 h^{-1}), after the fire dampers shutdown monitored at 150 s after the starting of cabinet ignition.

Figure 3: The rooms 1 and 2 of the DIVA facility used for the CFS-5 to CFS-7 tests.

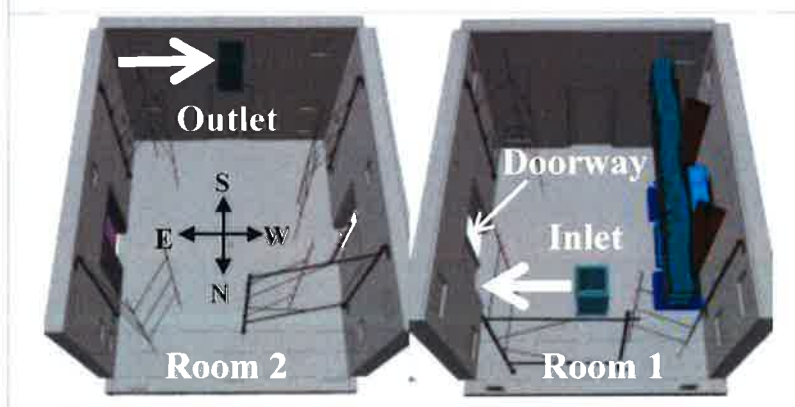
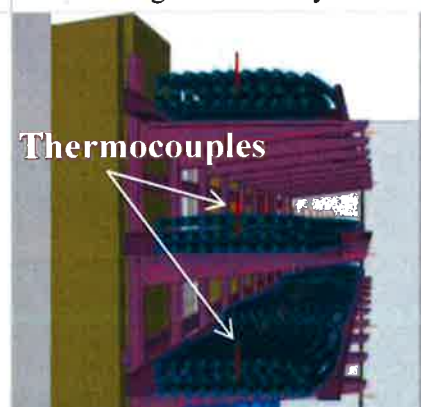


Figure 4: Thermocouples located along the three trays.



RESULTS AND DISCUSSION

Fire spreading over the upper cable trays

Ten thermocouples for measuring gas temperature are located along each of the three cable trays (Figure 4). They measure the gas temperature just above the upper layer of the cable samples and they are separated from each other of 50 cm. Figure 5 shows these measurements for CFS-6, the legends indicating the thermocouple positions from the tray centre (in cm). Fire firstly spreads throughout the cabinet (as illustrated in Figure 6) and leads to a first increase of the gas temperature along the three cable trays up to maximal values of about 500°C (Figure 5). Successive and larger increases of the gas temperature (up to values in the 800-860 °C range, Table 2) are next observed only on the right-hand sides of the cable trays. These results highlight the ignition of the three cable trays. Indeed, as assumed by Drysdale¹², gas temperature higher than 600°C shows the presence of flame. Moreover, this assumption is also used to determine ignition time for each of the three cable trays. Ignition time indeed matches with gas temperature reaching 600°C for the first time along each of the cable trays. Fire thus ignites first at the lower tray (1225 s), then at the mid tray (1725 s) and finally at the upper tray (1850 s), as seen in Figure 5. In the reverse way, it is assumed that cable tray fire is extinguished when gas temperature is 600°C for the last time. So, the cable A tray fire stops to burn at $t = 6000$ s (Figure 5). As this last one starts at 1225 s, fire duration is 4775 s (about 80 min). In addition, Figure 7 also illustrates that fire propagates only over the right-hand side of the three trays. High air volume flow rate (initially of 3600 m³/h), even though being directed towards the opposite wall of the fire source (Figure 3), could influence the fire spreading over the upper cable trays.

For the CFS-7 test, maximal gas temperatures are lower than 600°C (Table 2). So no cable trays ignition is considered.

Figure 8 shows the gas temperature measured along the three cable trays for the CFS-5 test. As for the CFS-6 test, fire firstly spreads throughout the cabinet (as illustrated in Figure 9) and leads to a first increase of the gas temperature up to maximal values of about 400 °C (Figure 8). Sharp peaks of gas temperature, exceeding 600 °C (Table 2), are then observed and therefore show ignitions of the cable trays. The two first ones only involve the upper tray and occur at respectively 837 s and 949 s (times corresponding to a gas temperature of 600°C for the first time, Figure 8). On the other hand, the third ignition involves all the trays since it occurs in nearly same time in the lower (1086 s), the mid (1096 s) and the upper (1097 s) trays (Figure 8). Three short cable tray fires then followed these ignitions. They indeed extinguished at respectively 854, 982 and 1156 s (times corresponding to a gas temperature of 600°C for the last time, Figure 8), showing fire duration around one minute (respectively of 17, 33 and 70 s). Furthermore, Figure 8 also points out that fire mainly involves the right-hand sides of the three trays. However, for the upper tray, fire also spreads over its left-hand side. This last outcome is confirmed by Figure 10.

Table 2 : Maximal gas temperature measured along the three cable trays, just above the cables.

Test	Lower tray	Mid tray	Upper tray
CFS-5	700	770	730
CFS-6	800	810	860
CFS-7	560	410	540

Methods used for assessment of heat release rate

Heat release rates (HRR or \dot{Q}) for the CFS-5 to CFS-7 tests in the DIVA facility are determined from a thermal method and the carbon dioxide generation (CDG) calorimetry method. The former was developed by Coutin¹³ for assessing HRR of a cabinet fire by establishing an energy balance inside a single fire room.

Figure 5: Gas temperature measured along the three overhead cable trays (CFS-6).

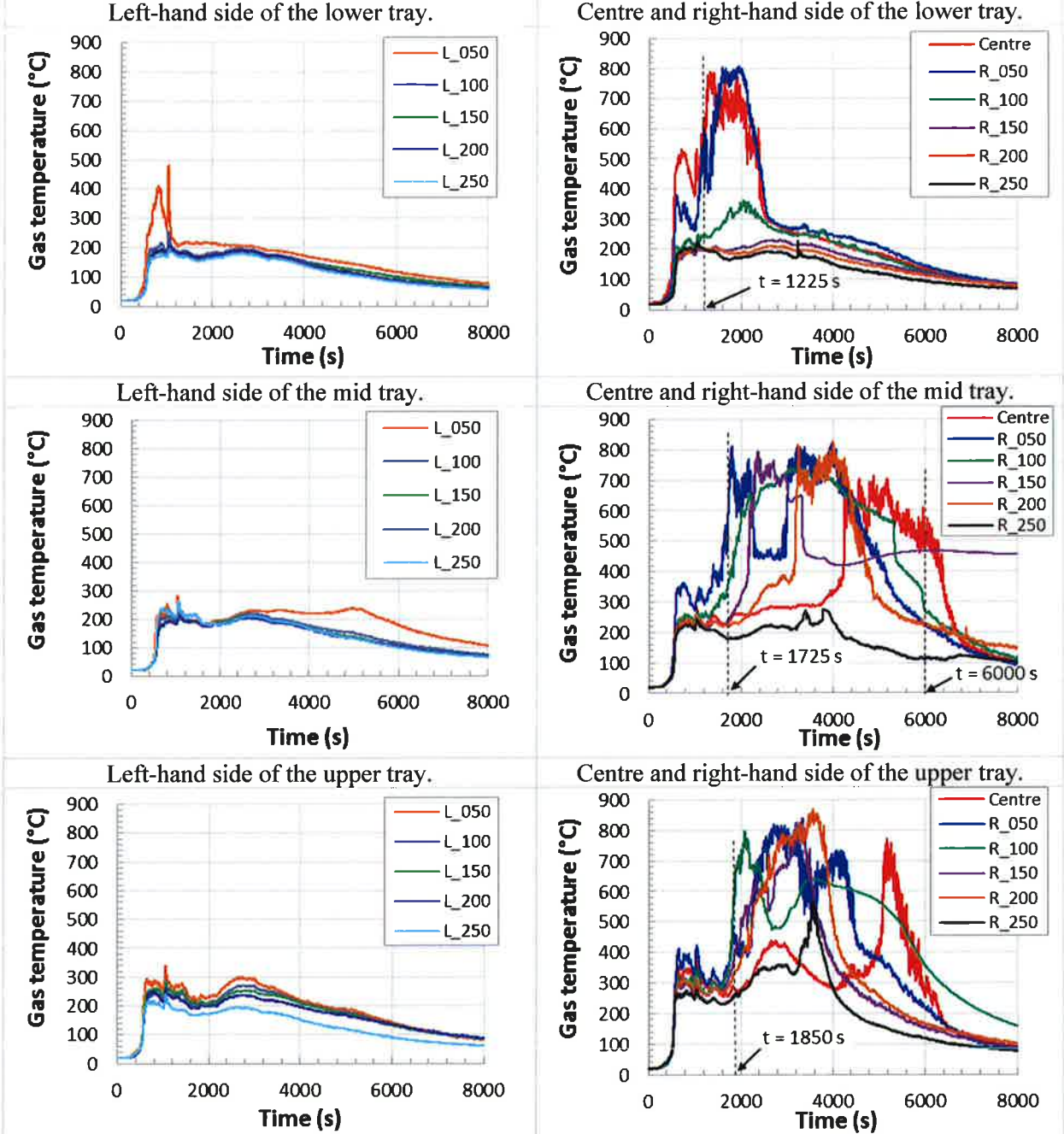


Figure 6: Cabinet after CFS-6.



Figure 7: Cable trays after CFS-6.

Left-hand side.

Right-hand side.



Figure 8: Gas temperature measured along the three overhead cable trays (CFS-5).

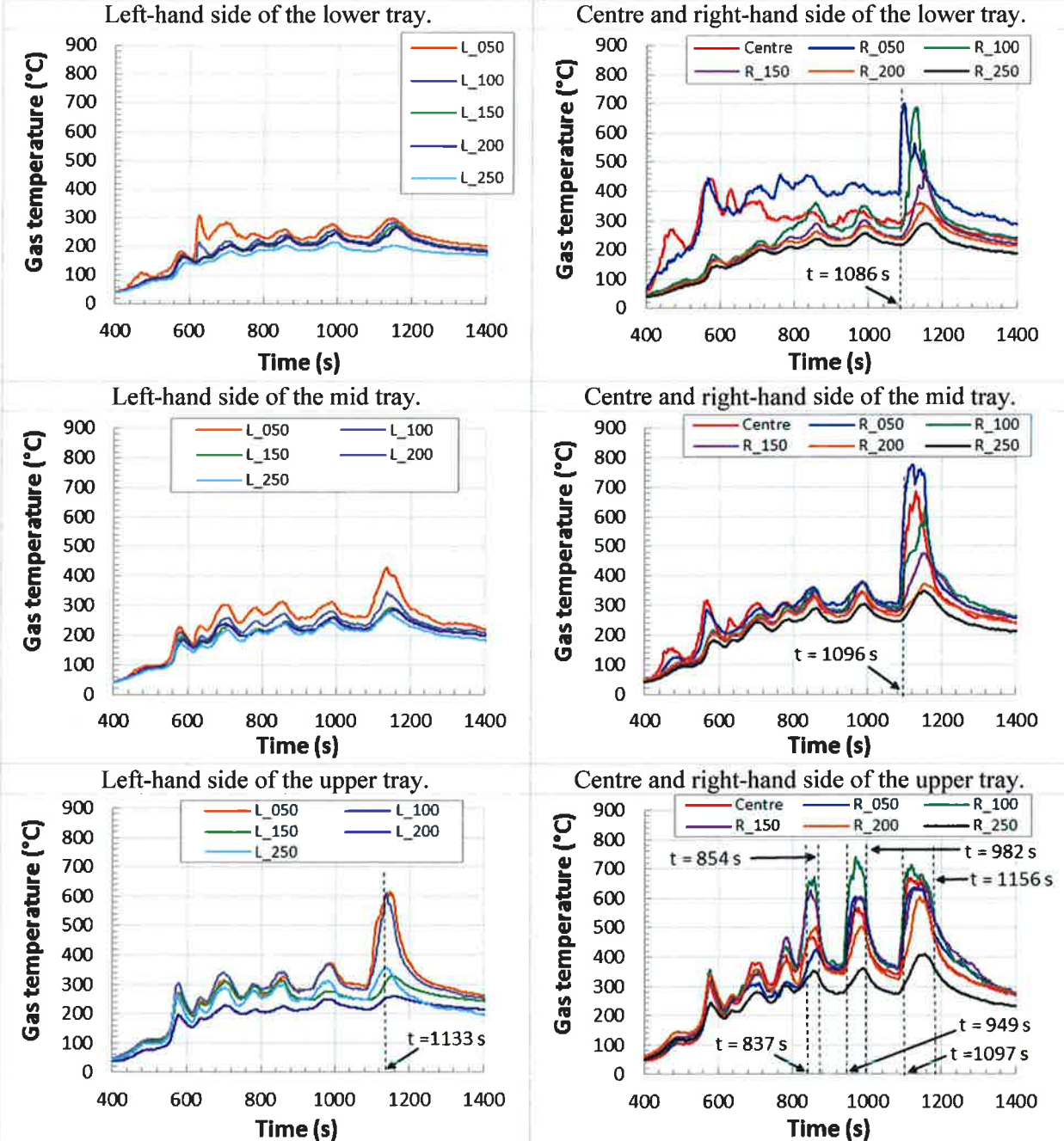


Figure 9: Cabinet after CFS-5.



Figure 10: Cable trays after CFS-5.

Left-hand side.

Right-hand side.



This method may be extended to test configuration involving several rooms and to other complex fire sources as for the CFS-5 to CFS-7 tests. In this case, the energy balance is carried out inside both fire and adjacent rooms (i.e. rooms 1 and 2, see Figure 3). The heat released by the fire is mainly distributed in four main parts:

- heat transfers to steel structures of the electrical cabinet (for the three ladder-type cable trays, this term is assumed to be negligible compared to the one for the cabinet) ($\dot{Q}_{inertia}$),
- energy per unit of time required for pyrolysis of fuel materials contained in the electrical cabinet and the three cable trays (\dot{Q}_{pyr}),
- heat transfers through the walls of both fire and adjacent rooms (\dot{Q}_{walls}),
- convective heat transfers through inlet (fire room) and outlet (adjacent room) ducts of the ventilation network (\dot{Q}_{out}).

The fire HRR from the thermal method ($\dot{Q}_{thermal}$) is therefore assessed thanks to the following relationship:

$$\dot{Q}_{thermal} = \dot{Q}_{inertia} + \dot{Q}_{pyr} + \dot{Q}_{walls} + \dot{Q}_{out} \quad [1]$$

Alternatively, the fire HRR can also be evaluated from the carbon dioxide generation (CDG) calorimetry method. For fires with large amount of CO and soot (considered as pure carbon), Tewarson¹⁴ and Brohez¹⁵ proposed to assess the HRR from the CDG calorimetry method (\dot{Q}_{CDG}) as follows:

$$\dot{Q}_{CDG} = E_{CO_2} \dot{m}_{CO_2}^G + E_{CO} \dot{m}_{CO}^G + E_C \dot{m}_C^G \quad [2]$$

- E_{CO_2}, E_{CO}, E_C : energy produced by mass unit of respectively CO₂, CO and soot generated (kJ/g);
- $\dot{m}_{CO_2}^G, \dot{m}_{CO}^G$ and \dot{m}_C^G : Mass flow rate of respectively CO₂, CO and soot generated (g/s).

Where the average values of $E_{CO_2} = 13.3$ kJ/g according Tewarson¹⁴ and $E_{CO} = 11.1$ kJ/kg and $E_C = 15.8$ kJ/kg according Brohez¹⁵. Recently, Pretrel¹⁶ proposed evaluations of HRR for fires in multi-rooms facility based on the previous equation [2] and mass conservation of CO₂, CO and soot in such facility. This evaluation applied for the CFS-5 to CFS-7 fire tests is therefore based on the mass conservation of these species performed in both fire room (R1) and adjacent room (R2) and is written as follows:

$$\begin{aligned} \dot{Q}_{CDG} = E_{CO_2} \left[\dot{m}_{CO_2}^{out} + \frac{d}{dt} m_{CO_2}^{R1} + \frac{d}{dt} m_{CO_2}^{R2} \right] \\ + E_{CO} \left[\dot{m}_{CO}^{out} + \frac{d}{dt} m_{CO}^{R1} + \frac{d}{dt} m_{CO}^{R2} \right] + E_C \left[\dot{m}_C^{out} + \frac{d}{dt} m_C^{R1} + \frac{d}{dt} m_C^{R2} \right] \end{aligned} \quad [3]$$

Where:

- \dot{m}_j^{out} : Mass flow rate of species j = CO₂, CO or soot at the outlet of R2 (g/s);
- $\frac{d}{dt} m_j^{Ri}$: Mass variation rate of species j = CO₂, CO or soot in the room i, i = 1 or 2 (g/s).

Figure 11 and Figure 12 show respectively for the CFS-6 and CFS-5 tests that the HRR assessments from both CDG and thermal methods are consistent. The final HRR for these tests is thus obtained from average of the two previous HRR evaluations (Figure 13 for CFS-6 and Figure 17 for CFS-5).

The mass variation rates of the species (see the $\frac{d}{dt} m_j^{Ri}$ terms in equation [3]) show significant fluctuations when the masses of the species in the rooms quickly change. If the former are larger than the mass flow rates of the species at the outlet of the room 2 (see the \dot{m}_j^{out} terms in equation [3]) then the assessed HRR from the CDG method (see equation [3]) gives large uncertainty. In this case this method cannot be considered. The fire dampers shutdown for the CFS-7 test leads to nearly nil mass flow rates of the species at the outlet of the Room 2. Moreover, it also gives quicker variations of the masses of the species in particular in the fire room than the ones obtained for both CFS-5 and CFS-6 tests. Consequently, HRR evaluation from the CDG method for the CFS-7 gives too large uncertainty. For this test, HRR assessment is only based on the thermal method (Figure 14).

Fire spread for CFS-6

Two weighing devices are used to measure mass loss of the three cable trays and one for the cabinet. Mass loss rate (MLR) is obtained from time derivation of mass loss. Figure 13 indicates for the CFS-6 test MLR for both cabinet and three cable trays and also HRR. The first and higher HRR peak at 560 s (735 kW) only arises from the cabinet fire since MLR for the cable trays is nil at the same time. Ignition of the cable A trays, previously identified at about 20 min, therefore occurs at about 11 min after the cabinet fire peak (about 9 min). Furthermore, the last HRR peak at 2400 s (440 kW) is mainly caused by the cable A trays fire. Indeed, at the same time, MLR for the cabinet is nearly nil while MLR for the cable A trays reaches its maximal value (19 g/s). So, the peak of the cable A tray fire occurs about 30 min after the peak of the cabinet fire. The cable A tray fire therefore mainly grows after the cabinet fire.

Figure 11: HRR assessments from the thermal and CDG methods (CFS-6).

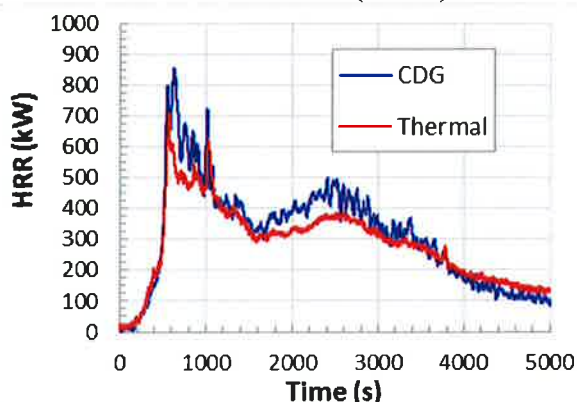


Figure 12: HRR assessments from the thermal and CDG methods (CFS-5).

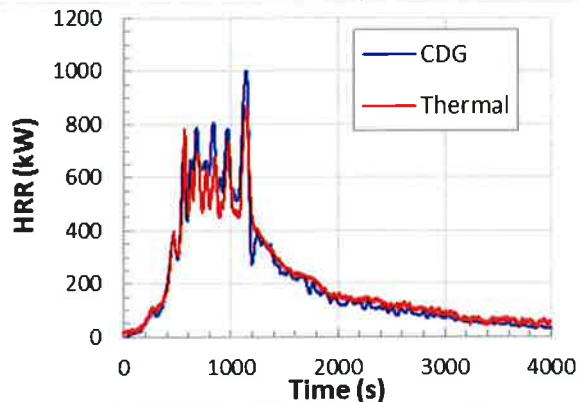


Figure 13: MLR for both cabinet and cable trays and HRR (CFS-6).

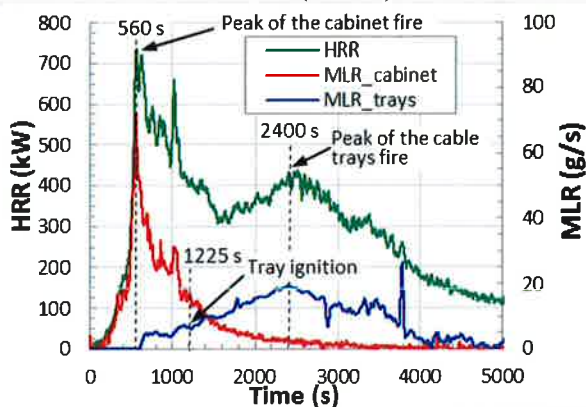
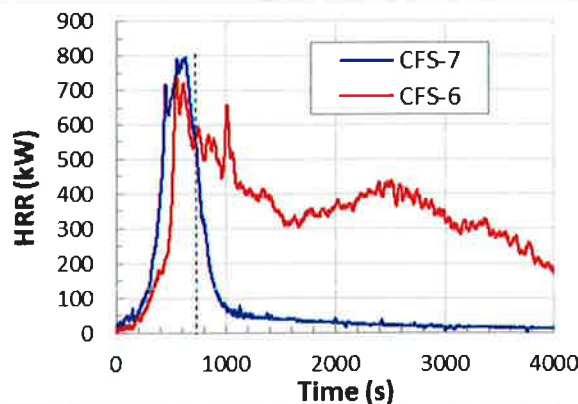


Figure 14: HRR for both CFS-6 and CFS-7 tests.



Ventilation effects on fire spread (CFS-6 vs CFS-7)

Figure 14 points out that the fire dampers shutdown leads to shorter fire for the CFS-7 test than for the CFS-6 test (VRR of 15 h^{-1}). Furthermore, Figure 15 and Figure 16 show oxygen (O_2) concentration in the upper part of the fire room and MLR for the cable trays respectively for the CFS-6 and CFS-7 tests. Vertical location of this O_2 concentration (3.3 m) is close to the height of the mid tray. The lower cable tray ignites at $t = 1225 \text{ s}$ for the CFS-6 test when O_2 concentration in the upper part of the fire room is of 16 %Vol and MLR for cable trays is of 6 g/s (Figure 15). Otherwise, for the CFS-7 test, O_2 concentration in the upper part of the fire room ranges from 5 to 7 %Vol while MLR for the cable trays is higher than 6 g/s (Figure 16). O_2 concentration is thus too low for allowing ignition of the cable trays for the CFS-7 test. Consequently, MLR for the CFS-7 cable trays quickly decreases to zero after its peak (9 g/s), as seen in Figure 16. The fire dampers shutdown prevents ignition of the three

cable trays for the CFS-7 test. Otherwise, the high VRR of 15 h^{-1} used for the CFS-6 test leads, on one hand, the open-doors cabinet fire to ignite the lower cable tray, on the other hand, the cable tray fire growth. Total mass loss (TML) of the CFS-7 cable trays is therefore very low (lower than 2 kg) compared with the TML (39 kg) of the CFS-6 cable trays.

Figure 15: Upper O₂ concentration and MLR for the CFS-6 cable trays.

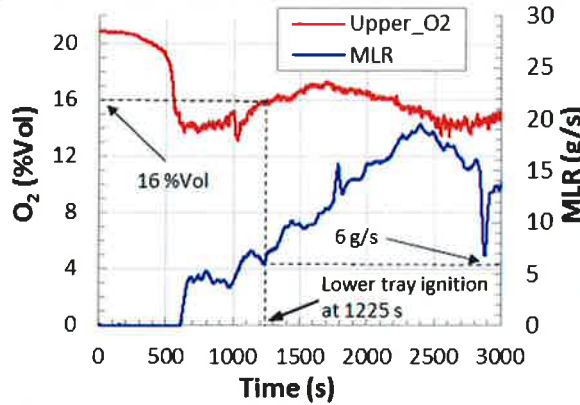


Figure 16: Upper O₂ concentration and MLR for the CFS-7 cable trays.

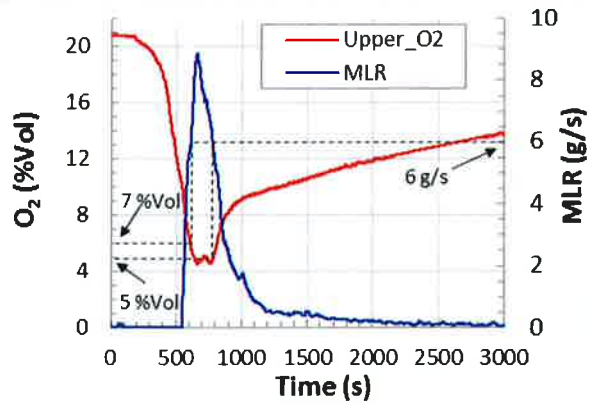


Figure 17: MLR for both cabinet and cable trays and HRR (CFS-5).

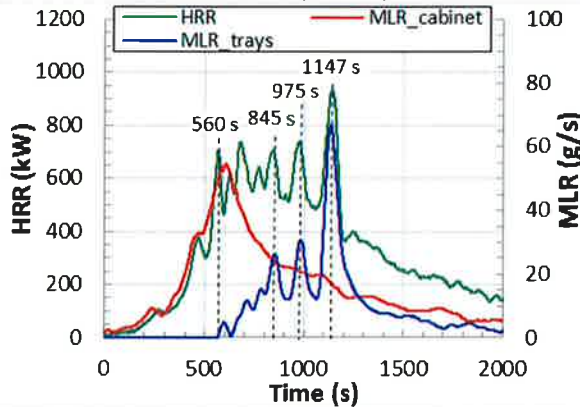


Figure 18: Cabinet MLR for both CFS-6 and CFS-5 tests.

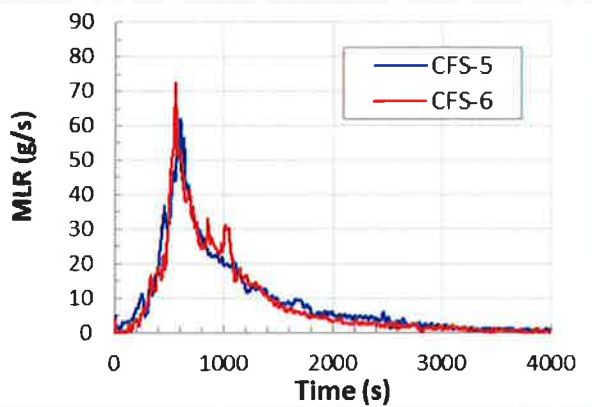


Figure 19: HRR for both CFS-6 and CFS-5 tests.

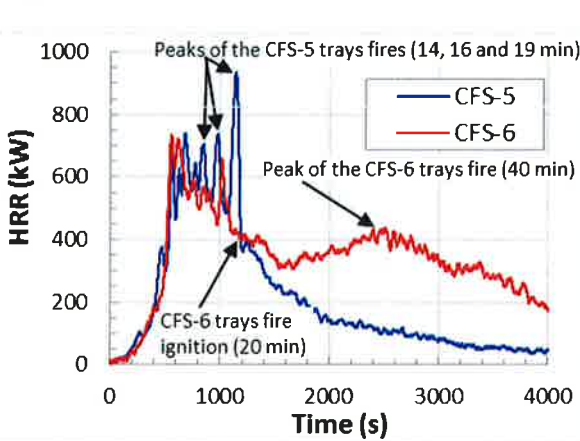
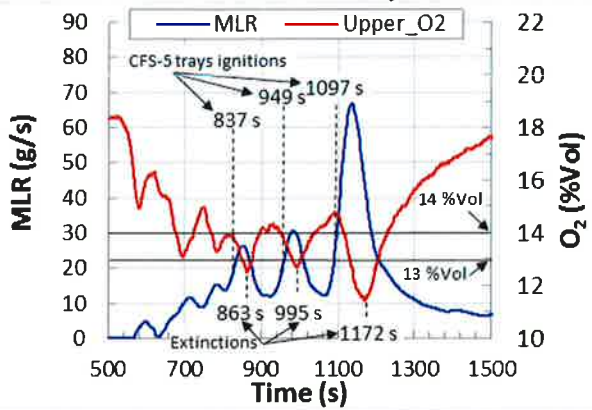


Figure 20: Upper O₂ concentration and MLR for the CFS-5 cable trays.



Cable-type effects on fire spread (CFS-6 vs CFS-5)

Figure 17 points out, for the CFS-5 test, MLR for both cabinet and three cable trays and also HRR. The first HRR peak at 560 s (700 kW) only arises from the cabinet fire since MLR for the CFS-5 trays is nil at the same time. Three successive HRR peaks match with the three peaks of MLR for the trays at 845, 975 and 1147 s (Figure 17), showing the effect of the three cable C tray fires on HRR. Their

contributions to the total HRR peaks are respectively of about 150, 200 and 450 kW and are reached quickly after the cable ignitions. Indeed, these last ones were previously identified at 837, 949 and 1097 s (i.e. at about 5, 7 and 9 minutes after the cabinet fire peak). The third HRR peak is the higher since the corresponding cable tray fire involves the three trays. Furthermore, when the cable C trays ignites three times (between 837 and 1097 s), MLR of the cabinet is in the 15-25 g/s range, showing that the three fast cable C trays fires match with the cabinet fire (Figure 17).

As the CFS-6 and CFS-5 cabinet fires are similar (Figure 18), the differences between the CFS-5 and CFS-6 fires (Figure 19) confirm the cable-type (cable A or cable C) effects on the fire behaviour of the three cable trays. The long cable A tray fire mainly grows after the cabinet fire while the three short cable C tray fires match with the cabinet fire. Indeed, as the cable A trays ignite later than the cable C trays, the air renewal inside the fire room (VRR of 15 h⁻¹) leads to higher O₂ concentration before the ignition of the former (16 %Vol, Figure 15) than for the latter (14 %Vol, Figure 20). In addition, after the ignition of the CFS-6 lower tray, O₂ concentration still increases up to 17 Vol% for about 10 min (Figure 15), favoring the cable A tray fire growth. On the contrary, the three CFS-5 cable tray fires lead to the quick decreases of the O₂ concentration below 13 Vol% (Figure 20). Such O₂ concentration level is supposed to extinguish the cable fire. The ends of these fires are taken at respectively 863, 995 and 1172 s when O₂ concentration is minimal (Figure 20). Considering the times of ignition for the CFS-5 cable trays, fire durations are thus of about 1 min. These last ones are consistent with the previous evaluation based on the analysis of the gas temperatures measurements carried out along the trays.

CONCLUSION

Electrical cabinet fire is one of the main fire hazards in Nuclear Power Plants (NPPs). The ability of the fire to spread beyond the burning cabinet is therefore a major concern for fire safety analyses in NPPs. In the framework of the OECD PRISME-2 programme led by the French "Institut de Radioprotection et de Sûreté Nucléaire" (IRSN), three fire tests, named CFS-5 to CFS-7, involving a real open-doors electrical cabinet and three overhead cable trays, are performed. In this study, the main objectives are to investigate the effects of ventilation and types of electrical cable on the fire spread from the electrical open-doors cabinet to the three overhead cable trays. The fire tests are carried out into a confined and mechanically ventilated facility, named DIVA. Both CFS-5 and CFS-6 tests involve a ventilation renewal rate (VRR, defined as the room volume number renewed per hour) of 15 h⁻¹, while the third CFS-7 test early implements a significantly lower VRR of about 1 h⁻¹. For this last one, fire dampers are indeed shutdown 2 min 30 s after the starting of the cabinet ignition. In addition, the overhead trays are filled with two types of electrical cable used in NPPs, named cable C for the CFS-5 test and cable A for both CFS-6 and CFS-7 tests.

These tests highlight that fire spreads from the real open-doors cabinet to the overhead three cable trays for a VRR of 15 h⁻¹ (i.e. for both CFS-5 and CFS-6 tests) and whatever the type of cable (cable A or cable C). However, this last one influences the fire behaviour of the cable trays. Indeed, the cable C trays (CFS-5) ignite three times and earlier than the single ignition of the cable A trays (CFS-6). The former actually ignite at about 5, 7 and 9 min after the peak of the cabinet fire while the latter ignites 11 min after this peak. Moreover, the cable A tray fire is longer (fire duration of about 80 min) than the three cable C tray fires (fire duration of about 1 min for each one). The former mainly grows after the cabinet fire thanks to oxygen concentration higher than the one available for the latter which match with the cabinet fire. Total mass loss (TML) is higher for the CFS-6 cable trays (39 kg) than for the CFS-5 cable trays (16 kg). Furthermore, the two first CFS-5 cable trays ignitions only occur in the upper tray while the third ignition involves at nearly same time the three trays. Otherwise, for the CFS-6 test, the lower cable tray first ignites and then the fire reaches the mid tray before spreading over the upper tray. In addition, for both CFS-5 and CFS-6 tests, fire mainly involves the right-hand sides of the three cable trays. High air volume flow rate (initially of 3600 m³/h), even though being directed towards the opposite wall of the fire source could influence the fire spreading over the cable trays. Finally, for the CFS-7 test, the fire dampers shutdown shortens the cabinet fire and prevents the upper cable trays ignition since O₂ concentration is too low.

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