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FIRE SPREAD FROM AN OPEN-DOORS ELECTRICAL CABINET TO NEIGHBOURING TARGETS IN 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. As part of the OECD PRISME-2 programme, four fire tests were carried out to investigate the fire spread from an open-doors electrical cabinet to overhead cable trays and adjacent cabinets in a confined and mechanically-ventilated facility. These tests, named CFS-5 to CFS-7 and CORE-6, used same both cabinet (fire source) and three overhead cable trays. The trays were filled with a halogenated flame retardant cable-type for CFS-5 and one halogen-free for the three other tests. Moreover, fire dampers were used for CFS-7 test while CORE-6 test implemented two additional cabinets adjacent to the fire source. Measurements such as flame and gas temperature, gas concentration, mass loss rate and heat release rate were performed for investigating the fire spread. Cabinet fire spread to the cable trays for CFS-5 and CFS-6 tests. Three fast and short cable tray fires were showed for CFS-5 while a slow and long cable tray fire was highlighted for CFS-6. In contrast, the fire dampers shutdown for CFS-7 test prevented ignition of the overhead cables. Furthermore, for CORE-6 test, cabinet fire spread to the adjacent cabinets but the upper cables were not ignited.

Keywords: adjacent cabinet; DIVA facility; electrical cabinet; fire spread; overhead cable trays.

NOMENCLATURE

A_i	Specific area associated with the heat flux sensor ‘‘i’’ (m ²).
AR	Adjacent room
ATH	Alumina trihydrate
CDG	Carbon dioxide generation
EVA	Ethylene-vinyl acetate
FR	Fire room
HFR	Halogenated flame retardant
HFFR	Halogen-free flame retardant
PE	Polyethylene
PVC	Poly(vinyl chloride)
CDG	Carbon dioxide generation
C	Soot (considered as pure carbon)
CO	Carbon monoxide
CO ₂	Carbon dioxide
C _n H _m	Unburnt hydrocarbon gases
C_{pc}	Specific heat value of the metallic structures of the cabinet (475 J.kg ⁻¹ .K ⁻¹)
$\frac{d}{dt}m_j$	Mass variation rate of the generated species j = CO ₂ , CO or C in the AR or the FR (g/s)

E_j	Energy produced by mass unit of the generated species $j = \text{CO}_2, \text{CO}$ or C (MJ/kg)
HRR	Heat release rate (kW)
L_v	Latent heat of vaporization of fuel (MJ/kg)
M_{air}	Molar mass of air (kg/mol)
MLR	Mass loss rate (g/s)
m_c	Cabinet mass (kg)
$\dot{m}_j^G$	Mass flow rate of the generated species $j = \text{CO}_2, \text{CO}$ or C (g/s)
$\dot{m}_j^{out}$	Mass flow rate of the generated species $j = \text{CO}_2, \text{CO}$ or C at the outlet of the AR (g/s)
O_2	Oxygen
P	Pressure in the FR and AR (Pa)
P_i	Pressure at the opening i (Pa)
$\dot{Q}$	Heat release rate (kW)
$\dot{Q}_{CDG}$	Heat release rate assessed from the CDG calorimetry method (kW)
$\dot{Q}_{inertia}$	Heat transfers to steel structures of the electrical cabinet (kW)
$\dot{Q}_{inst}$	Energy variation per unit of time within the FR and AR (kW)
$\dot{Q}_{thermal}$	Heat release rate assessed from the thermal method (kW)
$\dot{Q}_{out}$	Convective heat transfers via the inlet and outlet of the FR and AR, respectively (kW)
$\dot{Q}_{pyr}$	Energy per unit of time required for pyrolysis of fuel (kW)
$\dot{Q}_{walls}$	Heat transfers through the walls of the FR and AR (kW)
$\dot{q}_{walls}''$	Heat fluxes measured per unit area through the walls of the FR and AR (kW/m ²)
R	Result of the measurement or assessment
R_g	Ideal gas constant (8.314 J.mol ⁻¹ .K ⁻¹)
R1	Room 1
R2	Room 2
SE	South-East
T_c	Average wall temperature of the metallic structures of the cabinet (K)
TML	Total mass loss (kg)
VRR	Ventilation renewal rate (h ⁻¹)
u	Uncertainty of the measurement or assessment
$\tilde{u}$	Relative uncertainty of the measurement or assessment
U	Expanded uncertainty of the measurement or assessment
$\tilde{U}$	Expanded relative uncertainty of the measurement or assessment
V	Overall volume of the FR and AR (240 m ³)

Greek characters

γ	Isentropic constant (equal to 1.4 for diatomic gases)
$\dot{v}_i$	Volume flow rate at the opening i (m ³ /s)

1 | 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 indicated that one of the main contributions to the fire hazard in NPPs was attributed to electrical cabinets, representing 12 % of all the previous fire events (i.e., 48 cabinet fires). This author also argued that a cabinet fire in a control or switchgear room of NPPs could lead to failure of one safety train or more, if fire spreads beyond the fire cabinet. Consequently, the study of electrical cabinet fires and their consequences in NPPs is a major concern for fire safety analyses. Previous investigations particularly investigated the fire spread within an electrical cabinet and fire ability to spread beyond the cabinet.

Chavez^{3,4} performed fire tests which involved real-scale vertical and benchboard cabinet types. These tests involved a cabinet used as fire source (i.e., a fire cabinet) and neighboring cabinets such as

adjacent cabinets to the fire cabinet. Fire cabinets were most often without door and loaded with IEEE-383⁵ qualified or un-qualified electrical cables. Adjacent and fire cabinets were separated by a double wall (a wall for each cabinet and an air gap of 2.54 cm between). All these tests highlighted that the fire can spread fast throughout the fire cabinet without door and whatever the cable-type. Moreover, maximal heat release rate (HRR) was measured higher than 1200 kW for vertical open-doors cabinets and for the two cable-types while it was assessed at 185 kW for closed-doors cabinets. However, despite such HRR for the open-doors cabinets, fire did not spread to adjacent cabinets. The air gap between the cabinets indeed prevented self-ignition of the electrical cables fixed to the side walls of the adjacent cabinets.

Mangs *et al.*⁶ conducted thirteen experiments which involved two real vertical closed-doors electronic cabinets (nine full-scale tests) and two cabinet mock-ups (four reduced-scale tests). The two electronic cabinets used were relay cabinets and circuit board cabinets. Besides relays or circuit boards, these cabinets contained mainly electrical cables made with Poly(vinyl chloride) (PVC) jacket. The cabinet mock-ups contained only cables loosely attached to a holder at their centerline. All experiments were carried out beneath a large hood which collected all combustion products. The electronic cabinets were 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. Furthermore, for all the nine full-scale tests (real electronic cabinet), an adjacent cabinet, made of 0.5 mm thick steel sheet, was fastened to the fire cabinet. This last one contained samples of PVC cables attached to the wall against the fire cabinet, and also placed at 5 and 30 cm from this last wall. For two full-scale experiments, the adjacent cabinet ignited caused by self-ignition of PVC cables contained inside it.

Coutin⁷ and Coutin *et al.*⁸ performed eleven real cabinet fire tests. Four cabinet fires were carried out in open atmosphere conditions (under a large-scale calorimeter) while seven fire tests were performed in a confined and mechanically ventilated facility. All the fire tests involved the same real electro-technical cabinet and fire scenarios implied both closed and open doors. A linear propane burner ignited the fuel load at the base of the cabinet, along its entire width. All the open-doors electrical cabinet fires showed significant HRR peaks which were higher in open atmosphere conditions (1200 and 1600 kW) than in confined conditions (from 400 to 950 kW). In contrast, the two closed-doors cabinet fires exhibited HRR lower than 50 kW.

McGrattan and Bareham⁹ performed hundred-twelve full-scale experiments under a medium-scale calorimeter. These tests involved eight low voltage control electrical cabinet types which may be found in NPPs. A small propane burner and various size pans of acetone were used as ignition source or preheating source. The main goal of this study was to provide HRR measurements for fire models validation, used in fire safety studies. These numerous experiments confirmed that the cabinet geometry, ventilation, ignition strength (i.e., the amount of energy necessary to start the fire) and combustible loading (i.e., the amount and type of fuel materials) are the key parameters which impact the fire spread and the resulting HRR. 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- and closed-doors configurations. The highest HRR peak, measured at nearly 600 kW, was obtained for open-doors cabinet loaded with IEEE-383 un-qualified cables, and loosely arranged.

All previous programmes highlighted that cabinet fire may produce HRR higher than 100 kW for a large range of cabinet configuration (open-doors or closed-doors, electronic or electro-technical, vertical or benchboard...). These programmes also showed that for such level of HRR generated, fire may spread from a cabinet fire to an adjoined cabinet (i.e., without air gap). Furthermore, electrical cabinets, in real industrial plants as in NPPs, may be connected each other via electrical cables installed along overhead cable trays or placed inside false floors (or raised floors). Such potential fire spread paths to adjacent cabinets therefore also need to be investigated.

As part of two test campaigns of the OECD PRISME-2 programme¹⁰, four fire tests were carried out to study the fire spread from an open-doors electrical cabinet to neighbouring targets in a confined and mechanically-ventilated facility. The targets are three overhead cable trays, two adjacent cabinets and a false floor. Three fire tests, named CFS-5 to CFS-7¹², were carried out in the scope of the cable fire spreading (CFS) test campaign. Fire dampers were set up for CFS-7 test and they were shut down early after the starting of the fire. The fourth test, called CORE-6, was conducted as part of

the last CORE test campaign¹¹ which aimed at COMpleting and REpeating some tests of the previous campaigns.

This paper first presents in detail the experimental set-up used for this study. This part thus describes the electrical cabinet fire source, the overhead cable trays, the adjacent cabinets and the false floor, as well as the facility which hosted the tests and finally the instrumentation. The second and main part of this paper first presents how the HRR is assessed for the four tests. Then, the results of CFS-6 test (reference test), dealing with especially the fire spread from the cabinet fire source to overhead cable trays, are detailed. Finally, the effects on fire spread of the fire dampers shutdown and cable-type (installed along the overhead cable trays and in the adjacent cabinets) are especially discussed from the comparison of the results of the reference test with those of CFS-5, CFS-7 and CORE-6 tests.

2 | DESCRIPTION OF THE FIRE TESTS

Table 1 indicates the main features of CFS-5 to CFS-7 and CORE-6 tests which were carried out in the confined and mechanically-ventilated facility, named DIVA (Fig. 1). These four fire tests used same both open-doors electrical cabinet fire source (Fig. 2), named the fire cabinet, and three overhead cable trays (Fig. 3 and Fig. 4). The cable trays were filled with a halogenated flame retardant (HFR) cable-type for CFS-5 test and a halogen-free flame retardant (HFFR) cable-type for the three other tests. Furthermore, fire dampers were set up for CFS-7 test and they were shut down 2 min 30 s after the starting of the cabinet ignition. Finally, CORE-6 test implemented two additional closed-doors electrical cabinets which were placed against the central electrical cabinet (Fig. 5). These three cabinets were located above a false floor. The two adjacent cabinets only contained PVC trunkings placed against the adjacent side wall and filled with HFFR and HFR cable-types.

Table 1: Main features of CFS-5 to CFS-7 and CORE-6 tests.

Test ID	Open-doors cabinet (fire cabinet)	Cable-type in overhead cable trays	Adjacent cabinet	Fire dampers
CFS-5	Yes	HFR	No	No
CFS-6	Yes	HFFR	No	No
CFS-7	Yes	HFFR	No	Yes*
CORE-6	Yes	HFFR	Yes	No

*Monitored shutdown of the fire dampers at 2 min 30 s after the cabinet ignition.

Abbreviations: CFS, cable fire spreading; CORE, completing and repeating; HFR, halogenated flame retardant; HFFR, halogen-free flame retardant.

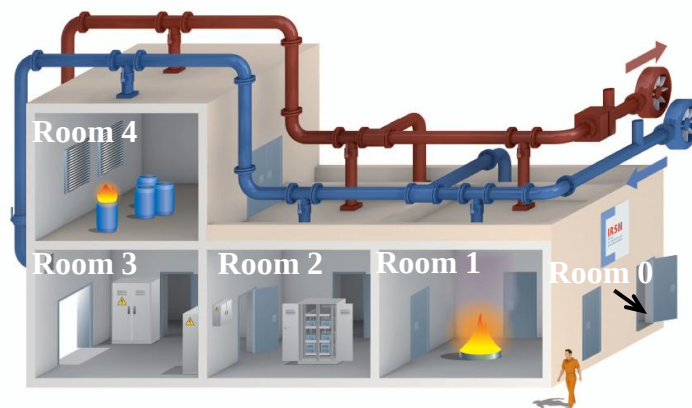


Fig. 1: Perspective view of the DIVA facility¹¹.

2.1 | Fire cabinet

The fire cabinets (Fig. 2) used for the four tests were the same twin modules 400 V electro-technical cabinet, as those previously studied by Coutin⁷ and Coutin *et al.*⁸. These electrical cabinets, which can be found in French nuclear installations, were fully characterised in these previous experimental works. As part of this study, the electrical cabinets were implemented without door since this configuration is considered in fire safety analyses as the most critical fire scenario. The cabinet width, depth and height are respectively of 1.2, 0.6 and 2.2 m. The main components inside the cabinet (Fig. 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 electrical cables. Fig. 2 also points out a single pipe (8) with small holes located at the bottom of the fire cabinet. This last one, completed by a spark system (see the enlarged view in Fig. 6), was used as a propane burner which provided a fire power of about 10 kW for a duration between 4 and 5 minutes (depending on the test). For safety reasons, the electrical cabinet was not electrically powered.

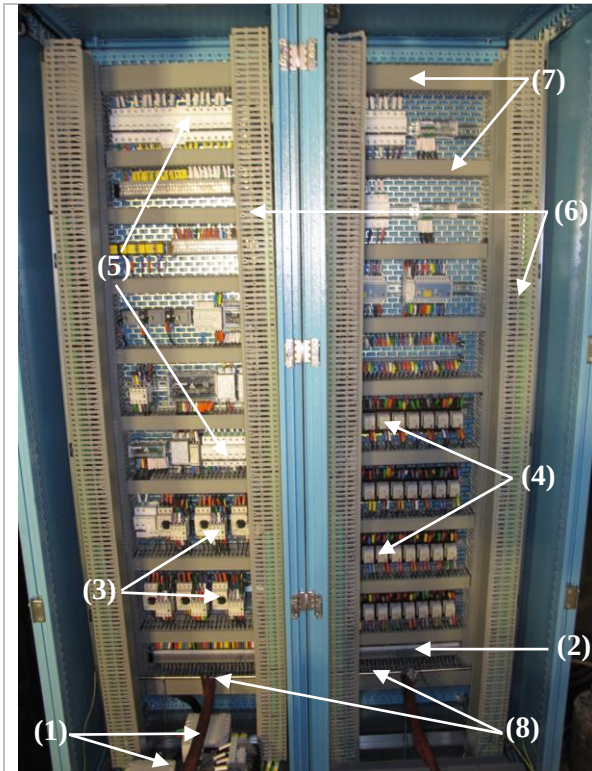


Fig. 2: Open-doors electrical cabinet used for CFS-5 to CFS-7 and CORE-6 tests.

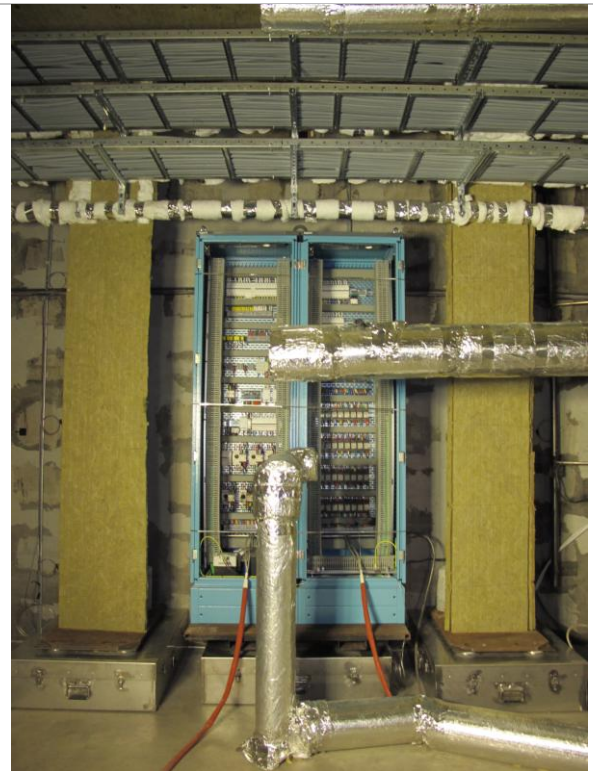


Fig. 3: Open-doors electrical cabinet and overhead cable trays for CFS-5 to CFS-7 tests.



Fig. 4: Overhead cable trays used for CFS-5 to CFS-7 and CORE-6 tests.



Fig. 5: Open-doors electrical cabinet, adjacent cabinets and overhead cable trays (CORE-6).

2.2 | Overhead cable trays

Three horizontal ladder cable trays 5 m long were installed above the fire cabinet and deported beyond its front panel (Fig. 4). The first cable tray was located at 0.3 m from the fire cabinet top. Spacing between cable trays was of 30 cm and the upper cable tray was distanced from the ceiling of nearly 45 cm. The HFFR cable-type which filled the three overhead cable trays for CFS-6, CFS-7 and CORE-6 tests, is named cable A, and the HFR cable-type for CFS-5 test, is called cable B. Cables A and B are control cables found in NPPs and contain four and three main constituent parts, respectively (Fig. 7). Cable A contains Poly(ethylene/vinyl acetate) (EVA) and Polyethylene (PE) as polymeric materials and alumina trihydrate (ATH) as HFFR¹³. Cable B contains plasticized PVC as polymeric material and other loads such as calcium carbonate (CaCO_3)¹⁴. Chlorine included in the PVC material acts as a flame retardant for cable B. Other characteristics of cables A and B are provided in Table 2. Each cable tray was filled with 32 samples of cable A for CFS-6, CFS-7 and CORE-6 tests and 44 samples of cable B for CFS-5 test. The cable samples 5 m long were all packed loosely along the three trays for all the tests (Fig. 4).

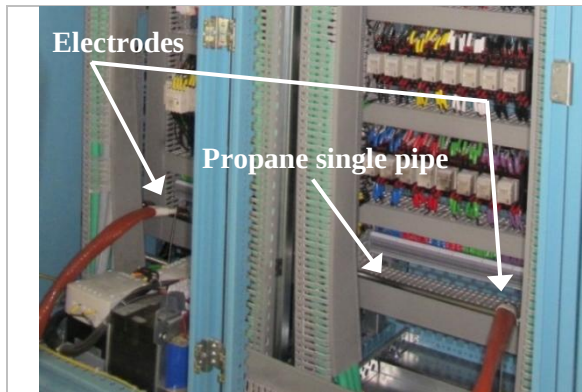


Fig. 6: Zoom on the propane pipe and spark system (metal electrodes) located at the bottom of the fire cabinet.

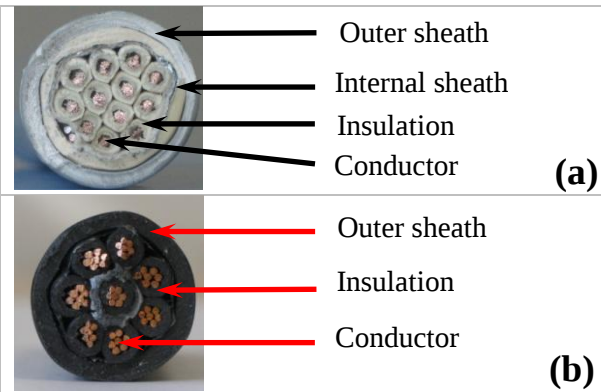


Fig. 7: Cables placed along the upper cable trays. (a) HFFR cable A for CFS-6, CFS-7 and CORE-6 tests. (b) HFR cable B for CFS-5 test.

Table 2: Electrical cables used as targets in CFS-5 to CFS-7 and CORE-6 tests.

Cable ID	Location	Flame retardant	Outer diameter (mm)	Linear mass density (kg/m)	Supplier reference
Cable A	Overhead cable trays (all tests)	ATH (Halogen-free)	20	540	NU-SHX(ST)HX 1kV 12x1.5 mm ²
Cable B		Chlorine	14.5	330	SHCVV 8x2 mm ²
Cable C	In adjacent cabinets (CORE-6)	Chlorine	28	2000	NYM-J 5x25 mm ² RM GRAU
Cable D		Halogen-free	3	21	VARPREN ST 1.5 mm ²
Cable E		ATH (Halogen-free)	37	3670	CST 74C068 3x95 mm ²
Cable F			12	250	CST 74C068 3x2.5 mm ²

Abbreviations: ATH, alumina trihydrate.

2.3 | Adjacent cabinets and false floor (only for CORE-6 test)

Two closed-doors cabinets were placed against the side walls of the fire cabinet only for CORE-6 test (Fig. 5). These adjacent cabinets are cabinet modules identical to the twin modules of the fire cabinet. Each adjacent cabinet was equipped with two trunkings placed against the adjacent side wall (Fig. 8). The trunkings 1 and 2, included in the left-hand adjacent cabinet (Fig. 8 (a) and (b)), contained samples of a HFR (cable C) and HFFR (cable D) cable-type, respectively. In the right-hand adjacent cabinet (Fig. 8 (c)), the trunking 3 included samples of an HFFR cable-type with 2 cable diameters, 37 and 12 mm for cables E and F, respectively. Finally, the trunking 4 only contained samples of cable F. Characteristics of cables C to F, used as targets in the adjacent cabinets for CORE-6 test, are reported in Table 2. A false floor was located below the fire cabinet and the two adjacent cabinets (Fig. 9 (a)). The central part of the false floor communicated with the above fire cabinet through four cable passages (Fig. 9 (b) and (c)).

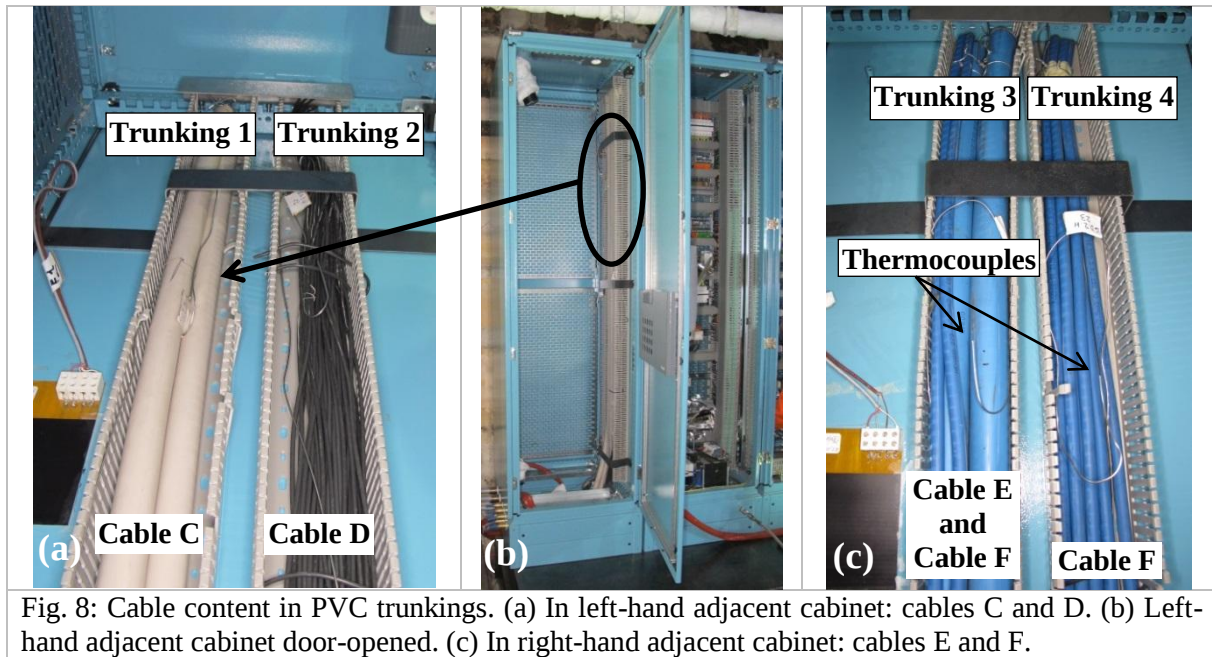


Fig. 8: Cable content in PVC trunkings. (a) In left-hand adjacent cabinet: cables C and D. (b) Left-hand adjacent cabinet door-opened. (c) In right-hand adjacent cabinet: cables E and F.

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

The DIVA facility contains five rooms in total (Fig. 1). The ground floor of this facility first comprises three rooms (room 1 to room 3) of similar size arranged in a row separated by fire doors. Moreover, each room also gives access (through fire doors) to a fourth room which is a corridor (room 0 in the background of Fig. 1). Finally, a fifth room is located at the first floor (room 4).

CFS-5 to CFS-7 and CORE-6 tests used the rooms 1 and 2 of the DIVA facility (Fig. 10). The fire cabinet and the three overhead cable trays were centred against the west wall of room 1 for the four tests. Room 1 was thus considered as the fire room (FR) and room 2 as the adjacent room (AR). These rooms were 4 m high and had a surface area of 30 m² and, they communicated through an open doorway which was 0.79 m wide and 2.17 m high.

The ventilation system of the DIVA facility consists of two separate circuits (one for inlet and one for outlet, respectively shown in blue and red in Fig. 1). For the present study, one inlet duct was implemented in the upper part of the FR and one outlet duct was set up in the upper part of the AR (Fig. 10). For all the tests, before ignition of the cabinet, initial VRR was 15 h⁻¹ for the overall volume of the FR and AR (i.e., initial inlet and outlet flow rates of 3600 m³/h). The flow directions are shown in Fig. 10. Furthermore, for CFS-7 test, fire dampers were set up at the inlet and outlet of the FR and AR, respectively. The monitored shutdown of the fire dampers significantly reduced the VRR from 15 to about 1 h⁻¹.

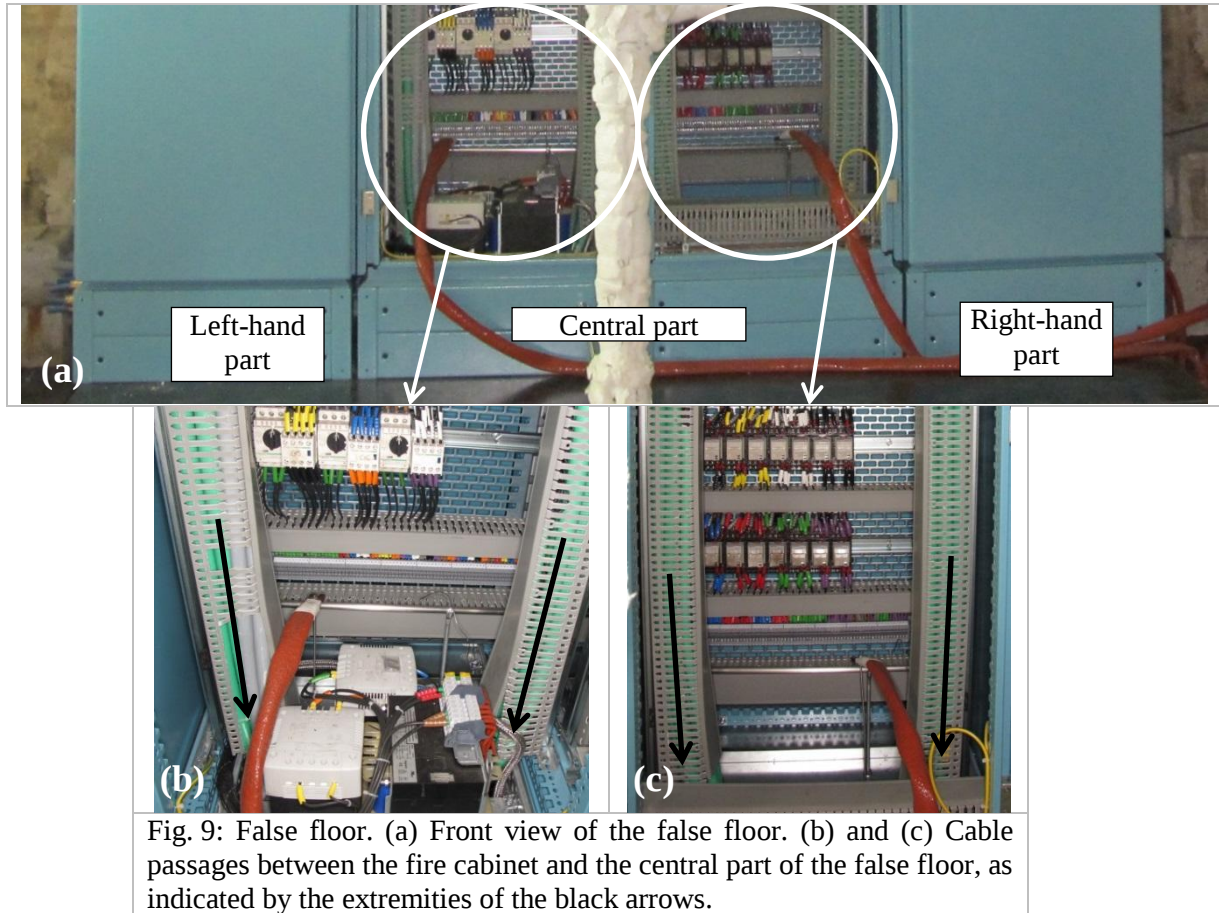


Fig. 9: False floor. (a) Front view of the false floor. (b) and (c) Cable passages between the fire cabinet and the central part of the false floor, as indicated by the extremities of the black arrows.

2.5 | Instrumentation

This section presents the measurements carried out as part of CFS-5 to CFS-7 and CORE-6 tests and discussed in this study.

2.5.1 | Common measurements for the four tests

Eleven thermocouples, separated from each other of 50 cm, were located along each of the three cable trays (Fig. 11). These thermocouples were positioned just above the cables and thus measured either gas temperature or flame temperature when the cables were ignited. Furthermore, twenty-four specific thermocouples were brazed on the walls of the fire cabinet. Six thermocouples were implemented on each of the two side walls and twelve on the rear wall. Two electronic scales were located below the two supports of the three cable trays and thus measured their fuel mass loss (Fig. 3). For same measurement dealing with the cabinets, one electronic scale was positioned below the fire cabinet for CFS-5 to CFS-7 fire tests (Fig. 3) and two were used for the three cabinets involved for CORE-6 test (Fig. 12). Three gas probes, supported by a vertical tree in the south-east (SE) corner and located at 0.7, 2.2 and 3.3 m from the floor (Fig. 13), allowed the oxygen (O_2) concentration measurement in the lower, mid and upper parts of the FR, respectively. In addition, unburnt hydrocarbon gases (C_nH_m) concentration was also measured in the upper part of the FR (Fig. 13).

2.5.2 | Specific measurements for CORE-6 test

Three thermocouples were located along each of the four trunkings at 50, 100 and 150 cm from the bottom of the adjacent cabinets. Fig. 8 (c) indicates for instance the two upper thermocouples located along the two trunkings (3) and (4) contained in the right-hand adjacent cabinet. Furthermore, one

thermocouple was placed at the centre of the false floor and cameras were placed in each of the two adjacent cabinets.

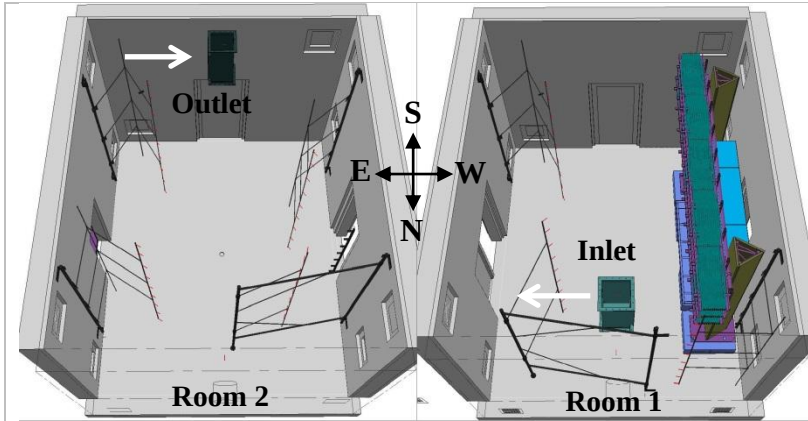


Fig. 10: Room 1 (FR) and room 2 (AR) of the DIVA facility used for CFS-5 to CFS-7 and CORE-6 tests. The white arrows indicate the flow directions at the inlet and outlet.



Fig. 11: Thermocouples located just above the cables (circles pointing out their extremity).

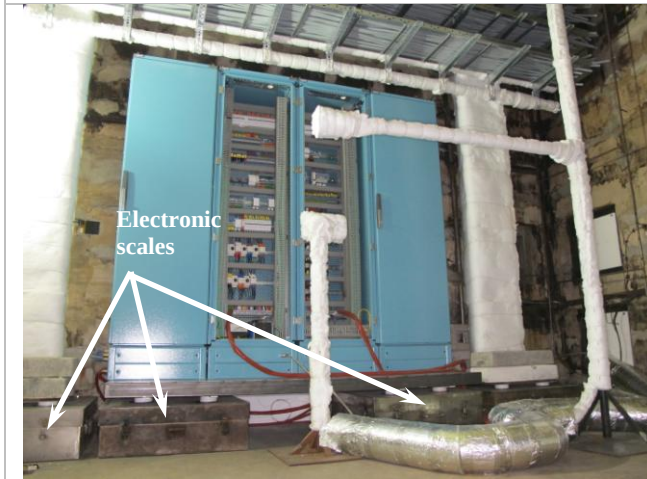


Fig. 12: Electronic scales used for CORE-6 test (two below the cabinets and two beneath the supports of the three cable trays).

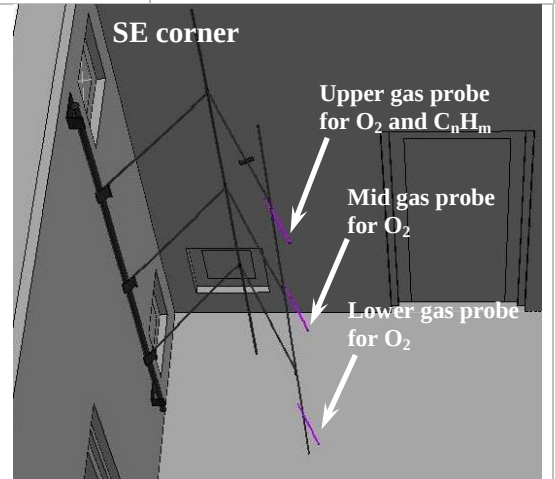


Fig. 13: Gas probes in the South-East (SE) corner of the FR for measurement of O_2 and C_nH_m concentrations.

2.5.3 | Measurement uncertainty

The relative uncertainty of a measurement, $\tilde{u}$, may be defined as followed:

$$\tilde{u} = \frac{u}{R} \quad (1)$$

Where u is the uncertainty (or standard deviation) of the measurement and R its result (expressed in the corresponding unit). u is estimated by combining the individual uncertainties, such as the instrument uncertainty and the repeatability, using the usual method called the “law of propagation of uncertainty”^{15,16}. Furthermore, the uncertainty is often expressed in terms of an expanded uncertainty, in which the confidence level that the measurement falls within the expanded bounds is high¹⁵. For an expansion factor (or coverage factor) of 2, considered in this study, the expanded relative uncertainty of the measurement, $\tilde{U}$, is thus related to two relative standard deviations (i.e., $2 \cdot \tilde{u}$) and the confidence level corresponds to 95%. Table 3 gives $\tilde{U}$ evaluated for the measurements which were carried out as part of CFS-5 to CFS-7 and CORE-6 fire tests and discussed in this paper.

Table 3 : Expanded relative uncertainty, $\tilde{U}$, of the measurements discussed in this study.

<i>Measurement (unit)</i>	<i>Sensor type</i>	$\tilde{U}$ (-)
Flame temperature (°C)	1.5 mm K-type thermocouple	0.07
Gas temperature in the FR (°C)	1.5 mm K-type thermocouple	0.05
Gas temperature in the cabinets (°C)	1.5 mm K-type thermocouple	0.02
Wall temperature of the fire cabinet (°C)	0.5 mm K-type thermocouple	0.08
Oxygen concentration (%Vol)	Oxygen analyzer	0.02
Unburnt hydrocarbon gases concentration (%Vol)	Unburnt hydrocarbon gases analyzer	0.1
Mass (kg)	Electronic scale	< 0.01

3 | RESULTS AND DISCUSSION

This section first presents how the HRR is assessed for the four tests. Then, the second part focuses on the results of CFS-6 test (Table 1) which is considered as the reference test. The third part aims at comparing the results of CFS-7 test with those of the reference test for showing the effect of the fire dampers shutdown on fire spread. Next, the effects on fire spread of the cable-type installed along the overhead cable trays are highlighted from simile between the outcomes of CFS-5 test and those of the reference test. Finally, the results of CORE-6 test, regarding the cabinet fire spread to both adjacent cabinets and false floor, are given in detail. This last part also discusses the effect of the adjacent cabinets (CORE-6 vs CFS-6) on fire spread to overhead cable trays.

3.1 | Heat release rate assessment

The HRR (or $\dot{Q}$) assessment for CFS-5 to CFS-7 and CORE-6 tests in the confined and mechanically-ventilated DIVA facility was determined by the thermal method and carbon dioxide generation (CDG) calorimetry method.

The thermal method was developed by Coutin *et al.*¹⁸ for assessing the HRR of a cabinet fire by establishing an energy balance inside a single room. This method may be extended to test configuration involving several rooms and to other complex fire sources such as the ones implemented for these four tests. In this case, the energy balance is carried out inside the FR and AR of the DIVA facility (Fig. 10). The heat released by the fire was mainly distributed in five main parts:

- heat transfers to steel structures of the electrical cabinet (thermal inertia of the three ladder cable trays is negligible compared with that of the cabinet) ($\dot{Q}_{inertia}$);
- energy per unit of time required for pyrolysis of fuel contained in the electrical cabinet and the three cable trays ($\dot{Q}_{pyr}$);
- heat transfers through the walls of the FR and AR ($\dot{Q}_{walls}$);
- energy variation per unit of time within the FR and AR ($\dot{Q}_{inst}$);
- convective heat transfers via the inlet and outlet of the FR and AR, respectively ($\dot{Q}_{out}$).

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

$$\dot{Q}_{thermal} = \dot{Q}_{inertia} + \dot{Q}_{pyr} + \dot{Q}_{walls} + \dot{Q}_{inst} + \dot{Q}_{out} \quad (2)$$

Where:

$$\dot{Q}_{inertia} = m_c C_{p_c} \frac{dT_c}{dt} \quad (3)$$

With m_c the cabinet mass (kg), C_{p_c} the specific heat value representative of the metallic structures of the cabinet ($475 \text{ J.kg}^{-1}.\text{K}^{-1}$), T_c the wall temperature of the metallic structures of the cabinet (K). This last one is obtained as the average of the twenty-four wall temperature measurements of the cabinet.

$$\dot{Q}_{pyr} = L_{v,cabinet} MLR_{cabinet} + L_{v,cable} MLR_{cable} \quad (4)$$

With $L_{v,cabinet}$ and $L_{v,cable}$ the latent heat of vaporization of fuel contained in the cabinet and the three cable trays, respectively (both assumed equal to 2.4 MJ/kg), $MLR_{cabinet}$ and MLR_{cable} the mass loss rate of the cabinet and the three upper cable trays, respectively (g/s).

$$\dot{Q}_{wall} = \sum_i^{FR} \dot{q}_{wall_i}'' \cdot A_i + \sum_i^{AR} \dot{q}_{wall_i}'' \cdot A_i \quad (5)$$

With $\dot{q}_{wall_i}''$ the measured heat fluxes per unit area through the walls of the FR and AR (kW/m^2) and A_i the specific area (m^2) associated with the heat flux sensor ‘‘i’’. For all the tests, thirty heat flux sensors were stuck over all area of the concrete walls inside the FR and additional thirty ones on walls of the AR.

$$\dot{Q}_{inst} = \left(\frac{1}{\gamma - 1} \right) V \frac{dP}{dt} \quad (6)$$

With γ the isentropic constant (equal to 1.4 for diatomic gases), V the overall volume for the FR and AR (240 m^3) and P the pressure in the FR and AR (Pa).

$$\dot{Q}_{out} = -\dot{Q}_{inlet} + \dot{Q}_{outlet} \quad (7)$$

Assuming that the specific heat (C_p) and molar mass of air (M_{air}) remain constant ($M_{air} C_p = 29.2 \text{ J.mol}^{-1}.\text{K}^{-1}$), the HRR through the opening i = inlet and outlet can be given by:

$$\dot{Q}_i = \frac{M_{air} C_p}{R_g} \dot{v}_i \cdot P_i \quad (8)$$

With $\dot{v}_i$ the volume flow rate at the opening i (m^3/s), R_g the ideal gas constant ($8.314 \text{ J.mol}^{-1}.\text{K}^{-1}$) and P_i the pressure at the opening i (Pa).

Alternatively, the fire HRR can also be evaluated from the CDG calorimetry method. For fires with large amount of CO and soot (considered as pure carbon), Tewarson¹⁹ and Brohez *et al.*²⁰ proposed to assess the HRR from the CDG calorimetry method ($\dot{Q}_{CDG}$) as follows:

$$\dot{Q}_{CDG} = E_{CO_2} \dot{m}_{CO_2}^G + E_{CO} \dot{m}_{CO}^G + E_C \dot{m}_C^G \quad (9)$$

where E_j is the energy produced by mass unit of the generated species $j = \text{CO}_2, \text{CO}$ or C (i.e., soot) (kJ/g) and $\dot{m}_j^G$ is the mass flow rate of the generated species $j = \text{CO}_2, \text{CO}$ or C (g/s). Pretrel *et al.*²¹

proposed to evaluate the fire HRR in multi-rooms facility from Eq. (2) and the mass conservation of CO₂, CO and soot carried out in such facility. This evaluation applied for CFS-5 to CFS-7 and CORE-6 tests in the FR and AR (Fig. 10) may be thus written as follows:

$$\begin{aligned} \dot{Q}_{CDG} = & E_{CO_2} \left[\dot{m}_{CO_2}^{out} + \frac{d}{dt} m_{CO_2}^{FR} + \frac{d}{dt} m_{CO_2}^{AR} \right] \\ & + E_{CO} \left[\dot{m}_{CO}^{out} + \frac{d}{dt} m_{CO}^{FR} + \frac{d}{dt} m_{CO}^{AR} \right] + E_C \left[\dot{m}_C^{out} + \frac{d}{dt} m_C^{FR} + \frac{d}{dt} m_C^{AR} \right] \end{aligned} \quad (10)$$

where $\dot{m}_j^{out}$ is the mass flow rate of the generated species $j = \text{CO}_2, \text{CO}$ or C at the outlet of AR (g/s) and $\frac{d}{dt} m_j^{FR}$ and $\frac{d}{dt} m_j^{AR}$ are the mass variation rates of the generated species $j = \text{CO}_2, \text{CO}$ or C , in the FR and AR, respectively (g/s). The average values of E_{CO_2} and E_{CO} are 13.3 and 11.1 MJ/kg, respectively, according to Brohez²⁰, and that for E_C is 15.8 MJ/kg according to Pretrel²¹.

Fig. 14 shows for CFS-5 to CFS-7 and CORE-6 tests the HRR assessments from both CDG and thermal methods.

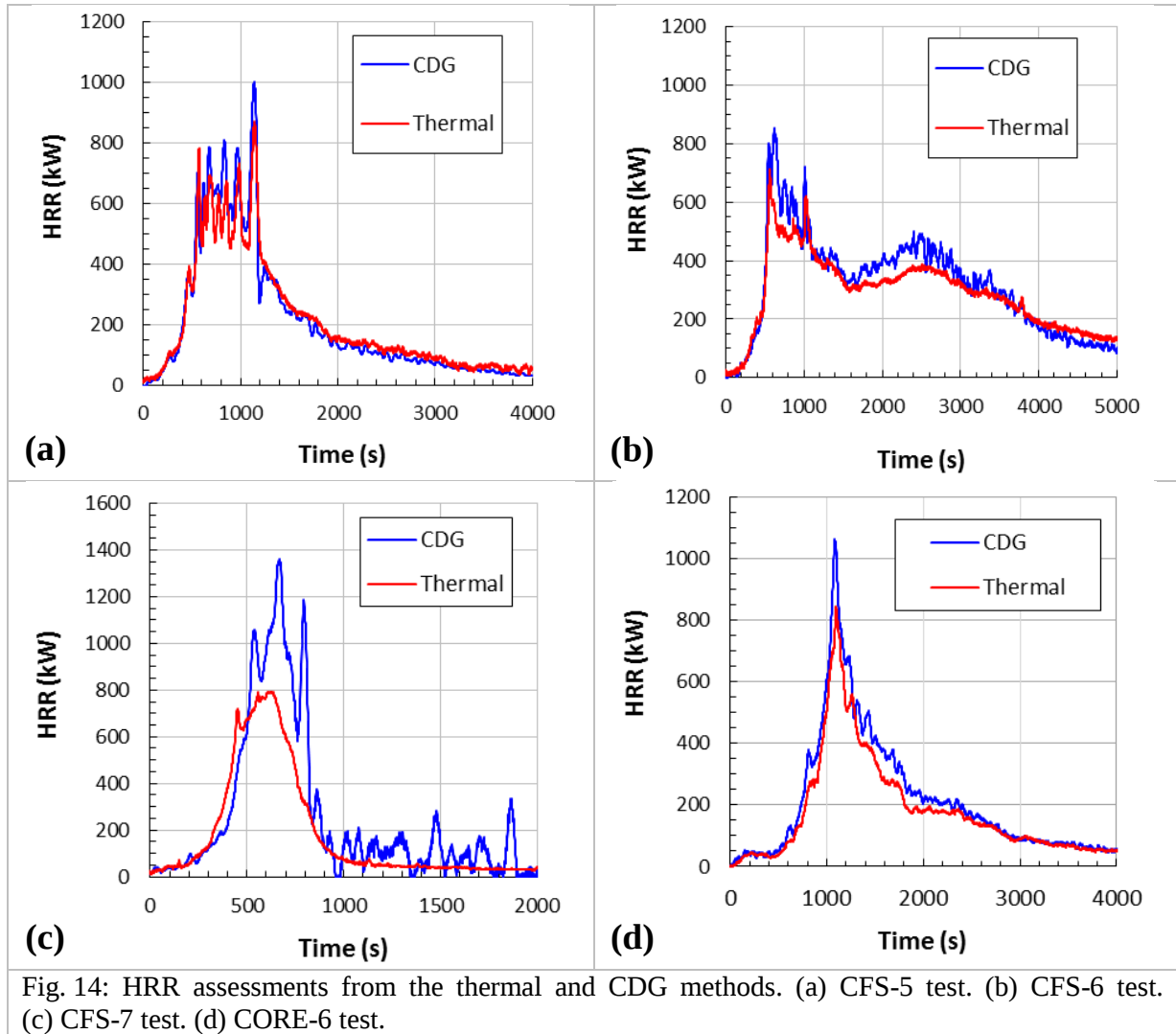


Fig. 14: HRR assessments from the thermal and CDG methods. (a) CFS-5 test. (b) CFS-6 test. (c) CFS-7 test. (d) CORE-6 test.

These two methods give consistent results for all the tests except for CFS-7 test. Uncertainty of the HRR, assessed from CDG method, is acceptable when mass flow rates of the generated species at the outlet of the AR (i.e., $\dot{m}_j^{out}$ terms in Eq. (10)) are larger than mass variation rates of the generated

species in the FR and AR (i.e., $\frac{d}{dt}m_j^{FR}$ and $\frac{d}{dt}m_j^{AR}$ terms in Eq. (10)). Indeed, these last ones give significant fluctuations especially at early stage of the fire when the gas species are filling the rooms and mass flow rates of the species at the outlet are low. For CFS-7 test, the monitored fire dampers shutdown led to nearly zero mass flow rates of the species at the outlet of the AR. Consequently, the HRR evaluation from the CDG method for CFS-7 test gives too large fluctuations (Fig. 14 (c)) and only the thermal method is therefore used for the HRR assessment of this test. In contrast, for each of the three other CFS-5, CFS-6 and CORE-6 tests, final HRR was obtained from the average of the HRR evaluated from the CDG and thermal methods.

The relative uncertainty, $\tilde{u}$, of the final HRR for CFS-5, CFS-6 and CORE-6 tests is estimated from the relative standard deviation of the two HRR assessments obtained from the CDG and thermal methods for each of these three tests (see Fig. 14). In same way as for the measurements, an expanded relative uncertainty, $\tilde{U} = 2 \cdot \tilde{u}$, is considered for these assessments and provided in Table 4. For the HRR of CFS-7 test, which was only evaluated from the thermal method, as previously detailed, $\tilde{U}$ is taken equal to the maximal value estimated for the previous tests (i.e., 0.3).

Table 4 : Expanded relative uncertainty, $\tilde{U}$, of the HRR assessed for CFS-5 to CFS-7 and CORE-6 tests.

Test ID	$\tilde{U}$ (-)
CFS-5	0.2
CFS-6	0.3 for HRR < 100 kW and 0.2 for HRR ≥ 100 kW
CFS-7	0.3
CORE-6	0.15

3.2 | Fire spread for CFS-6

CFS-6 test (reference test, Table 1) involved an initial VRR of 15 h⁻¹ and used the HFFR cable A (Table 2) installed over the three overhead cable trays. Fig. 15 (a) exhibits, after CFS-6 test, the fire cabinet and three overhead cable trays and Fig. 15 (b) shows an enlarged view of the right-hand side of the cable trays, between the mid and upper cable trays. These figures point out that the fire fully involved the cabinet and also spread to the upper cable trays. Total mass loss (TML) was measured at 35.5 and 39 kg for the cabinet and overhead cable trays, respectively. Furthermore, Fig. 16 indicates that fire only spread on the right-hand sides of the three cable trays.

Fig. 17 shows the measured temperatures along the three cable trays for CFS-6 test, just above the cables, the legends indicating the thermocouple positions from the tray centre (in cm). The fire propagation throughout the cabinet led to a first increase of these temperatures up to about 500°C (Fig. 17 (b3)). Next, higher temperatures up to around 800°C are measured (Fig. 17 (b1) to (b3)) showing that the cable trays were ignited. The presence of flame is indeed assumed for a minimal temperature of 600°C according to Drysdale¹⁷. However, given $\tilde{U}$ equal to 0.07 for the flame temperature measurement (Table 3), the ignition is certainly obtained when a temperature measurement indicates 645°C for the first time. Indeed, the true temperature, corresponding to this measurement, is ensured to be higher than 600°C since it ranges from 600°C (i.e., 645 - 645×0.07) to 690°C (i.e., 645 + 645×0.07) with a confidence level of 95 % (section 2.5.3). Therefore, considering the 645°C threshold, fire is first ignited at the lower tray at 1237 s (Fig. 17 (b3)), then at the mid tray at 1729 s (Fig. 17 (b2)) and finally at the upper tray at 1878 s (Fig. 17 (b1)).

In the reverse way, it is assumed that cable tray fire is extinguished as soon as all temperatures along the three cable trays are lower than 600°C. However, given $\tilde{U}$ equal to 0.07, as previously considered, the extinction is thus certainly achieved as soon as all temperature measurements indicate values lower than 561°C. Indeed, the true temperature, corresponding to this measurement, is surely lower than 600°C since it varies from 522°C (i.e., 561 - 561×0.07) to 600°C (i.e., 561 + 561×0.07)

with a confidence level of 95 %. Considering this 561°C threshold, measurements indicate that the cable tray fire ended at 6073 s (Fig. 17 (b2)). This extinction may be corroborated by the other temperature measurements along the cable trays (Fig. 17 (b1), (b2) and (b3)) which are all lower than 400°C when $t \geq 6073$ s and the MLR of the cable trays which is very nearly zero around 5000 s (Fig. 18). Finally, the fire duration is evaluated as the time difference between the first ignition (i.e., 1237 s) and the extinction time (i.e., 6073 s), which gives 4836 s (about 80 min).

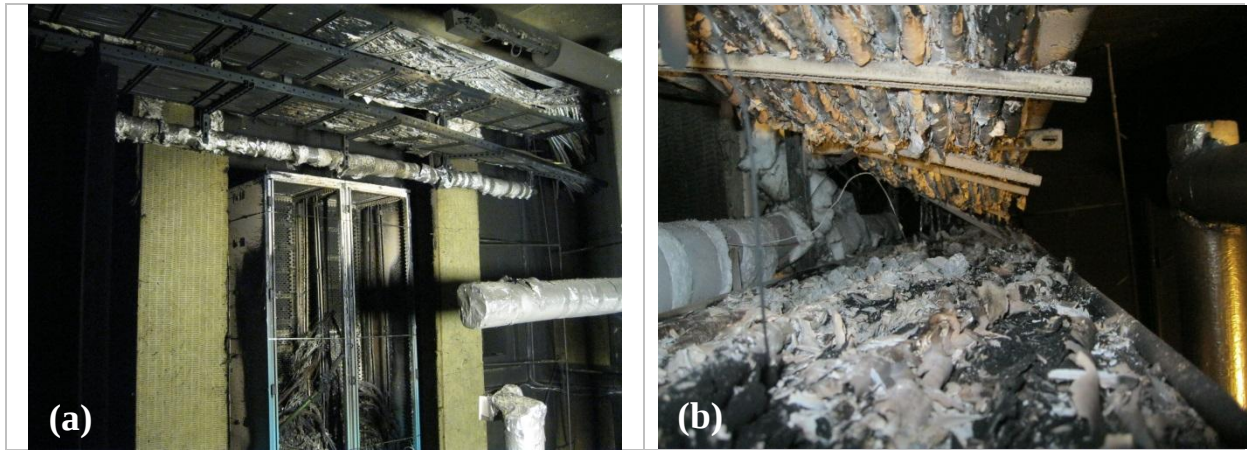


Fig. 15: After CFS-6 test. (a) Fire cabinet and the three overhead cable trays. (b) Enlarged view of the right-hand side of cable trays, between the mid and upper trays.



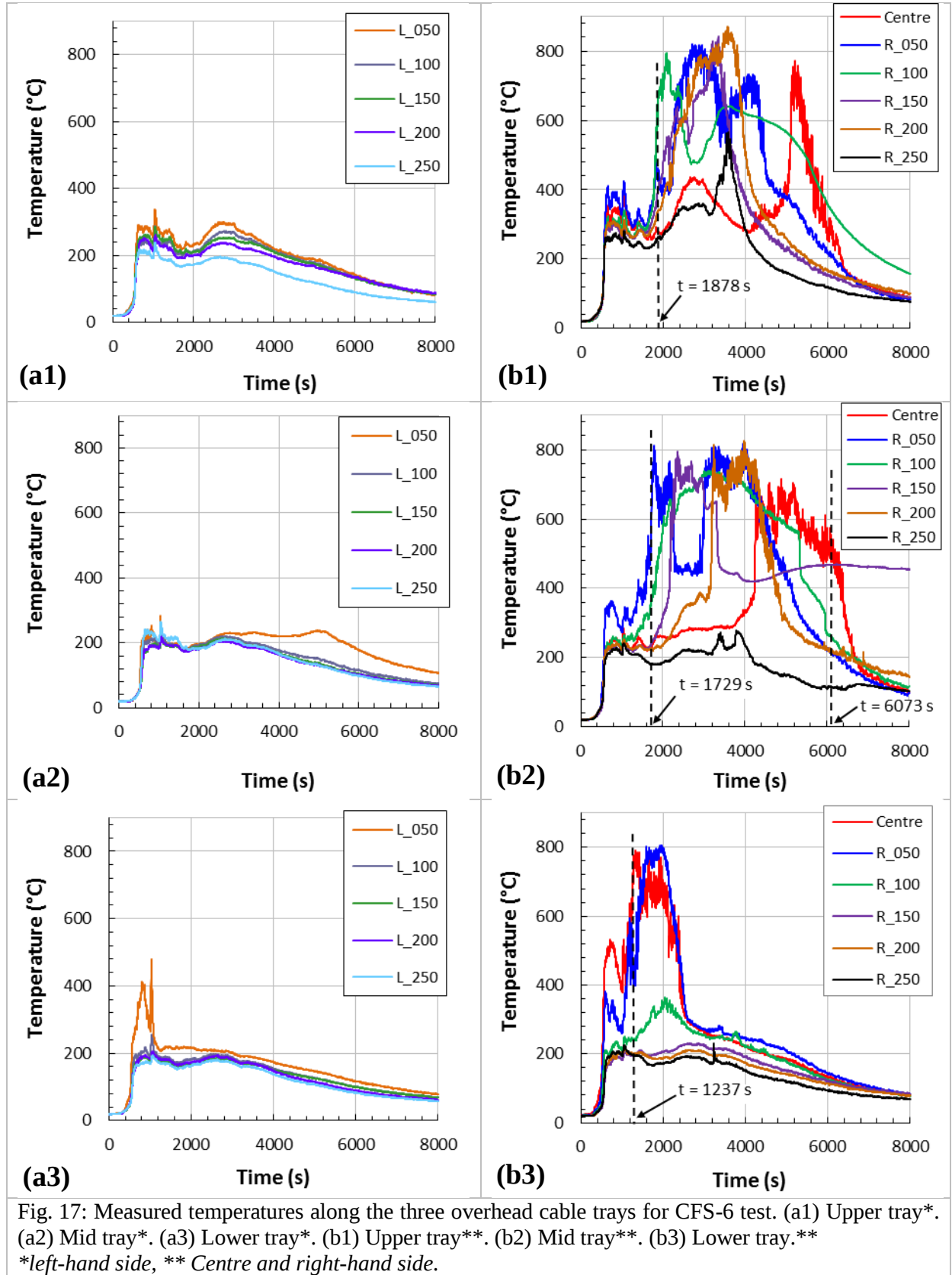
Fig. 16: Global view of the three overhead cable trays after CFS-6 test.

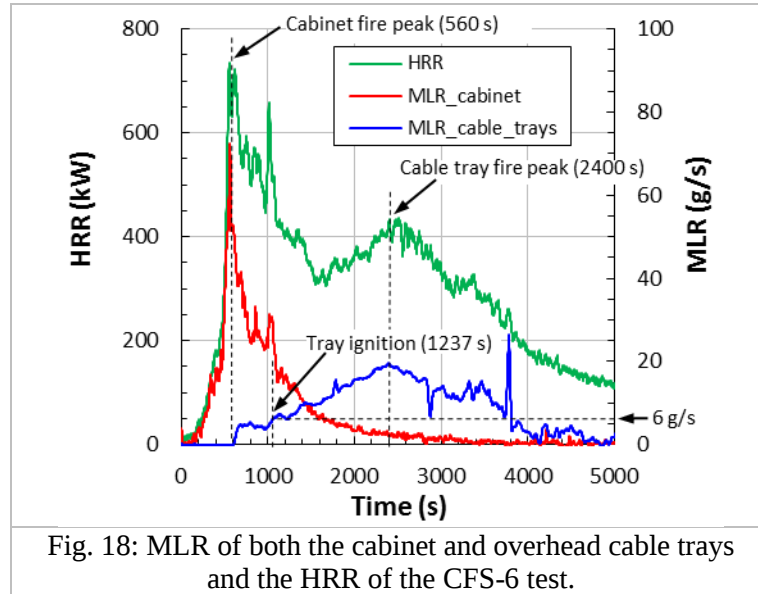
Fig. 17 also confirms that fire did not spread over the left-hand sides of the cable trays since measured temperatures along these last ones were clearly lower than 600°C (Fig. 17 (a1) to (a3)). This atypical propagation might have been influenced by the important air volume flow rate (nominal value of 3600 m³/h), even if it was directed towards the opposite wall of the fire source (Fig. 10).

Fig. 18 presents the mass loss rate (MLR) for both the fire cabinet and three overhead cable trays as well as the HRR of CFS-6 fire test. The MLR is obtained from time derivation of the mass losses measured separately for the fire cabinet and the three cable trays as early commented (section 2.5.1). The expanded relative uncertainty evaluated for the MLR is 0.3 for $\text{MLR} \leq 10$ g/s, 0.23 for $30 \text{ g/s} \geq \text{MLR} > 10$ g/s and 0.15 for $\text{MLR} > 30$ g/s.

The first and higher HRR peak of 735 kW at 560 s was only caused by the fire cabinet since the MLR for the cable trays was zero at the same time (Fig. 18). Ignition of the overhead cable trays, as above determined, occurred at 1237 s, i.e., 677 s after the cabinet fire peak, when the cable trays MLR reached a value of about 6 g/s (Fig. 18). Furthermore, the last HRR peak of 440 kW at 2400 s was mainly due to the cable tray fire. Indeed, at this time, the cabinet MLR was nearly zero while that of

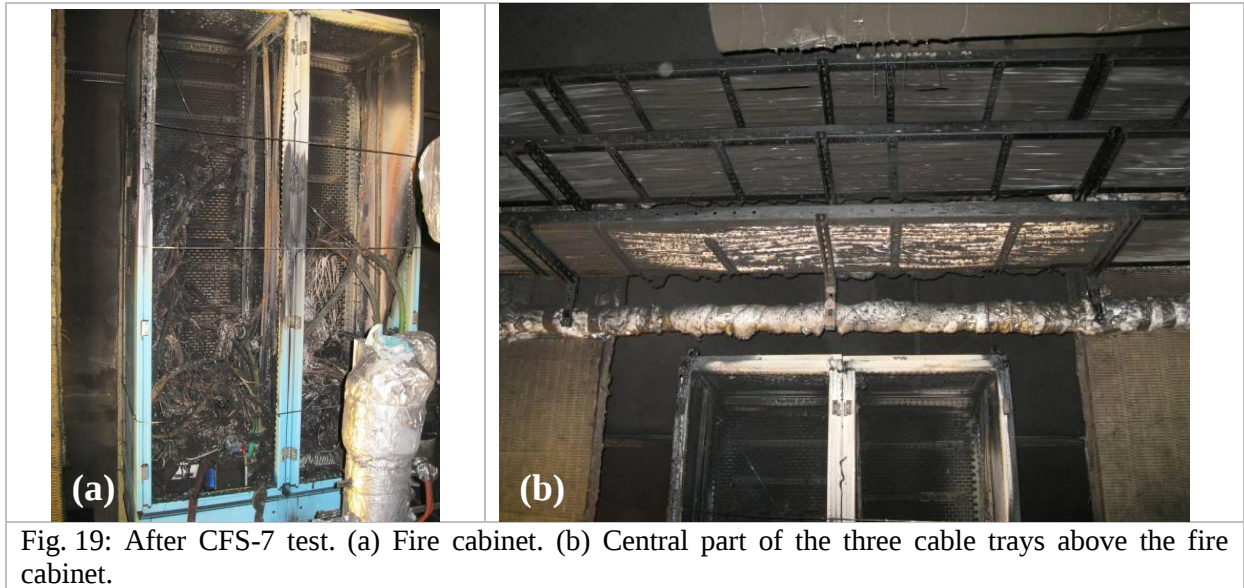
the cable trays reached its maximal value of 19 g/s (Fig. 18). Thus, it takes about 20 min (1175 s) for the cable tray fire to reach its peak. These outcomes show that the cable tray fire for CFS-6 test mainly grew at the end of the cabinet fire.





3.3 | Fire dampers shutdown effects (CFS-7 test vs CFS-6 test)

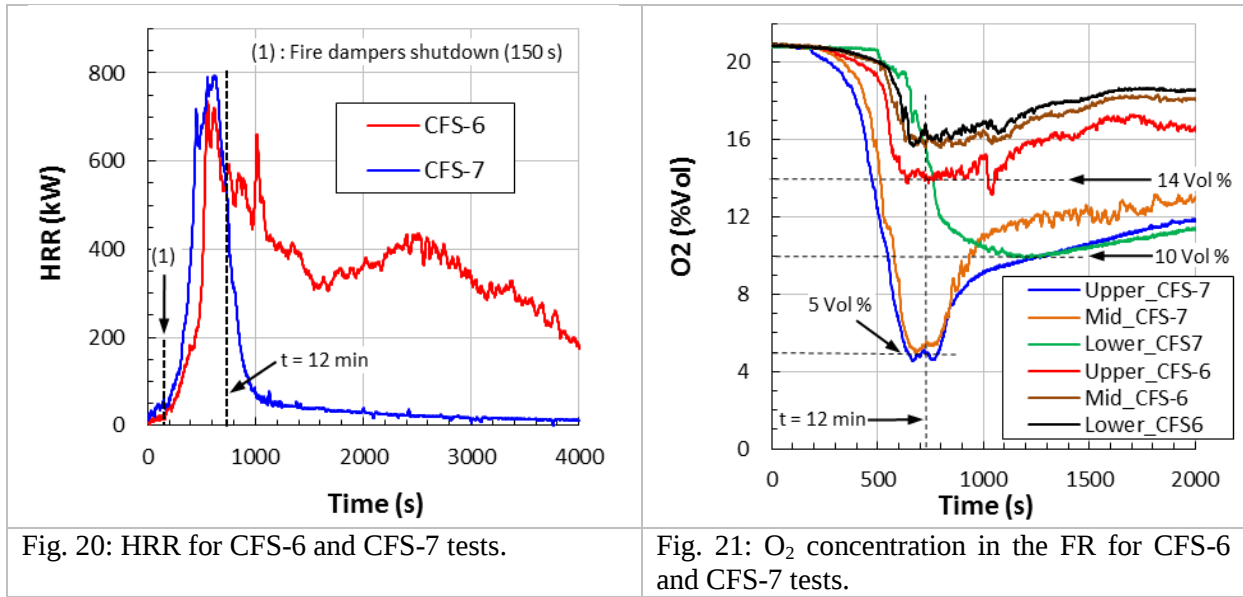
Both CFS-6 and CFS-7 tests (as for all the tests) used initial VRR of 15 h^{-1} . For CFS-7 test, the fire dampers were shut down at 2 min 30 s after the cabinet ignition, that led to decrease the VRR to about 1 h^{-1} . Fig. 19 (a) shows that the fire entirely involved the fire cabinet for CFS-7 test but, unlike CFS-6 test, it did not spread to the overhead cable trays (Fig. 19 (b)). This last figure indeed shows limited impact of the cabinet fire which was focused below the central part of the lower cable tray.



3.3.1 | Fire cabinet

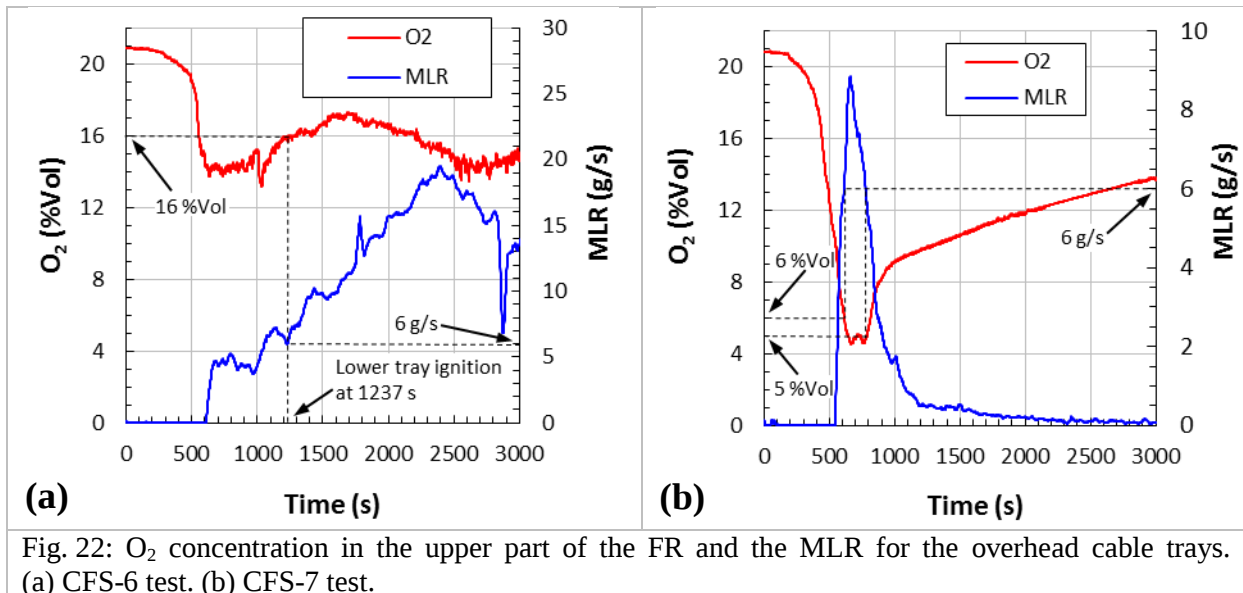
Fig. 20 presents the HRR for CFS-6 and CFS-7 fire tests. The time when fire dampers are shut down is also indicated in this figure. Compared to CFS-6 test, Fig. 20 shows that the HRR of CFS-7 test fast decreased to nearly zero for $t \geq 12 \text{ min}$. Indeed, Fig. 21 first points out that oxygen (O_2) concentrations in all the FR were always higher than 14 %Vol for CFS-6 test while those measured in both mid and upper parts were about 5 %Vol around $t = 12 \text{ min}$ for CFS-7 test. Moreover, O_2 concentration in the lower part of the FR for CFS-7 test was lower than that for CFS-6 test as soon as $t \geq 12 \text{ min}$ and then decreased fast down to 10 %Vol (Fig. 21). The fire dampers shutdown thus shortened the cabinet fire

for CFS-7 test compared with CFS-6 test, due to such critical O_2 concentrations. For that reason, the cabinet TML for the former test (23.9 kg) was lower than for the latter test (35.5 kg).



3.3.2 | Overhead cable trays

Fig. 22 (a) and (b) give both the O_2 concentration in the upper part of the FR and MLR of the cable trays for CFS-6 and CFS-7 tests, respectively. Vertical location of this O_2 concentration (3.3 m) is close to the height of the mid cable tray. The lower cable tray ignited at $t = 1237$ s for CFS-6 test for a MLR at 6 g/s and O_2 concentration in the upper part of the FR at 16 %Vol (Fig. 22 (a)). In contrast, Fig. 22 (b) indicates for CFS-7 test that for the MLR higher than 6 g/s the O_2 concentration in the upper part of the FR ranged from 5 to 6 %Vol. Such O_2 concentration did not allow the ignition of the CFS-7 cable trays and the MLR decreased to zero after its peak (9 g/s, Fig. 22 (b)).



Furthermore, the fast decrease of the cabinet fire for $t \geq 12$ min as earlier discussed (Fig. 20) also contributed to the steep MLR decrease of the cable trays located above. The fire dampers shutdown therefore prevented ignition of the overhead cable trays, due to very low O_2 concentration in the upper part of the FR. In contrast, a VRR of 15 h^{-1} , as used for CFS-6 test, led to suitable O_2 concentration for the ignition of the overhead cable trays.

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

The features of CFS-5 test (Table 1) were identical than those of CFS-6 test, except the cable-type installed along the three overhead cable trays. The HFR cable B (Table 2) was indeed used for the former test instead of the HFFR cable A involved in the latter test. Fig. 23 (a) and (b) exhibit the fire cabinet and an enlarged view of the right-hand side of the cable trays (between the mid and upper cable trays) after CFS-5 test, respectively. These figures show that the fire fully involved the cabinet and spread to the upper cable trays. TML was measured at 36.9 and 16.3 kg for the cabinet and the upper cable trays, respectively. Moreover, Fig. 24 indicates that fire spread more over the right-hand sides of the three cable trays.



Fig. 23: After CFS-5 test. (a) Fire cabinet. (b) Enlarged view of the right-hand side of the cable trays, between the mid and upper trays.



Fig. 24: Global view of the three overhead cable trays after CFS-5 test.

Fig. 25 shows for CFS-5 test the measured temperatures along the three overhead cable trays, just above the cables. Like for CFS-6 test, the fire propagation throughout the cabinet led to a first increase of these temperatures up to about 400 °C (Fig. 25 (b3)). Next, steep peaks of these temperatures up to around 700°C were measured (Fig. 25 (b1) to (b3)). It is assumed, as for CFS-6 test (section 3.2), that when a temperature measurement along a cable tray reaches the 645°C threshold for the first time, the ignition is certainly obtained. After each ignition, it is also considered that as soon as all the temperature measurements of a cable tray indicate values lower than 561°C then the extinction is very likely achieved. Fig. 25 (b1) points out that the temperature measurements reach the 645°C threshold at 843, 953 and 1100 s. This figure also indicates that after each ignition, all temperature

measurements are lower than the 561°C threshold at 866, 998 and 1176 s. Three successive stages of ignitions and extinctions thus occurred at 843/866 s, 953/998 s and 1100/1176 s for the upper cable tray, showing three fire stages.

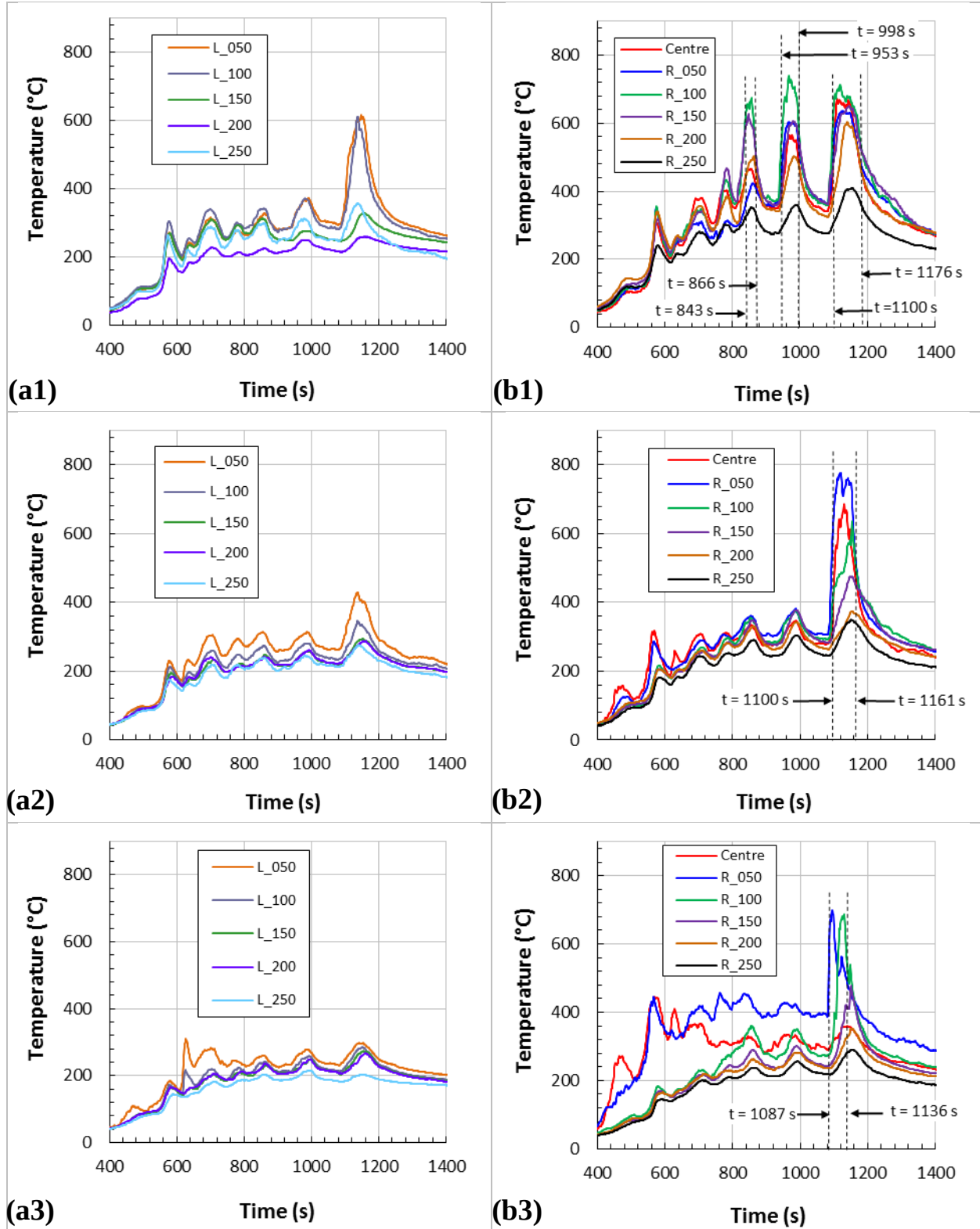


Fig. 25: Measured temperatures along the three overhead cable trays for CFS-5 test. (a1) Upper tray*. (a2) Mid tray*. (a3) Lower tray*. (b1) Upper tray**. (b2) Mid tray**. (b3) Lower tray**.

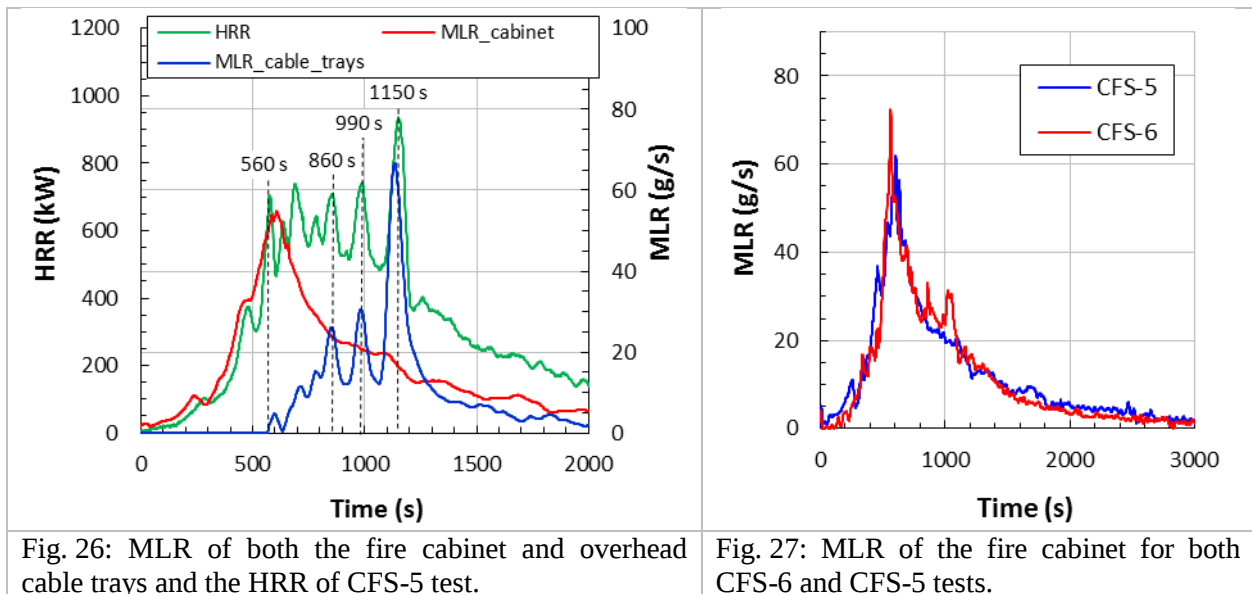
*left-hand side, ** Centre and right-hand side.

Next, Fig. 25 (b1) to (b3) point out that the third fire stage involved all the cable trays since ignition (determined as previously) occurred in nearly same time in the upper (1100 s), mid (1100 s) and lower (1087 s) trays (Fig. 25 (b1), (b2) and (b3), respectively). The durations of the three cable tray fire stages are deduced from the differences between times to ignition and extinction. This gives fire durations of around 1 min (23, 45 and 89 s for the first, second and third fire stages, respectively), showing three successive short cable tray fires for CFS-5 test.

Fig. 26 points out the MLR of both the fire cabinet and overhead cable trays and the HRR of CFS-5 test. Like for CFS-6 test, the first HRR peak at 560 s (700 kW) was only caused by the cabinet fire since the MLR of the cable trays was zero at the same time. This figure next exhibits three successive HRR peaks which match with the three MLR peaks of the overhead cable trays, while the cabinet MLR was in the 15-25 g/s range. These observations corroborate the occurrence of three successive cable tray fires for CFS-5 test and also show that they overlapped with the cabinet fire. These outcomes also exhibit that these fires were fast since their peaks were reached at 860, 990 and 1150 s (Fig. 26) while their ignition occurred at 843, 953 and 1087 s as above determined.

Fig. 27 and Fig. 28 point out for CFS-5 and CFS-6 tests the MLR of the cabinet and the HRR of both the cabinet and overhead cable tray fires, respectively. Given similar MLR of the cabinet for the two tests (Fig. 27), it is thus deduced that the differences showed in the HRR (Fig. 28) confirm two specific cable tray fire behaviors depending on the cable-type as previously discussed; three fast and short CFS-5 cable tray fires (HFR cable B) which overlapped with the cabinet fire and a significantly slower and longer CFS-6 cable tray fire (HFFR cable-type) which mainly grew at the end of the cabinet fire. Clarifications regarding these distinct fire behaviors are discussed hereafter.

Fig. 29 provides for CFS-5 test the O_2 concentration in the upper part of the FR and the MLR for the overhead cable trays. The three successive CFS-5 cable tray fires were short (about 1 min) since the O_2 concentration was fairly low when they occurred (lower than 14 %Vol, Fig. 29), due to the cabinet fire and the fast growth of these fires (HFR cable B). These fast fires indeed led to quick decreases of the O_2 concentration below 13 %Vol (Fig. 29) and such concentration is supposed to extinguish them. In contrast, the CFS-6 cable tray fire was much longer (80 min) since it ignited later (than the CFS-5 cable trays) and grew when the O_2 concentration was higher than 16 %Vol (Fig. 22 (a)), caused by the less powerful cabinet fire and slower growth of this fire (HFFR cable A). Indeed, for this slow fire, and given the air renewal (VRR of 15 h^{-1}), the O_2 concentration was still higher than 16 %Vol nearly up to its fire peak (Fig. 22 (a)), which allowed its development. Such differences of cable tray fire behavior, due to the cable-type, finally led to lower TML of the cable trays for CFS-5 test (16 kg) compared with CFS-6 test (39 kg).



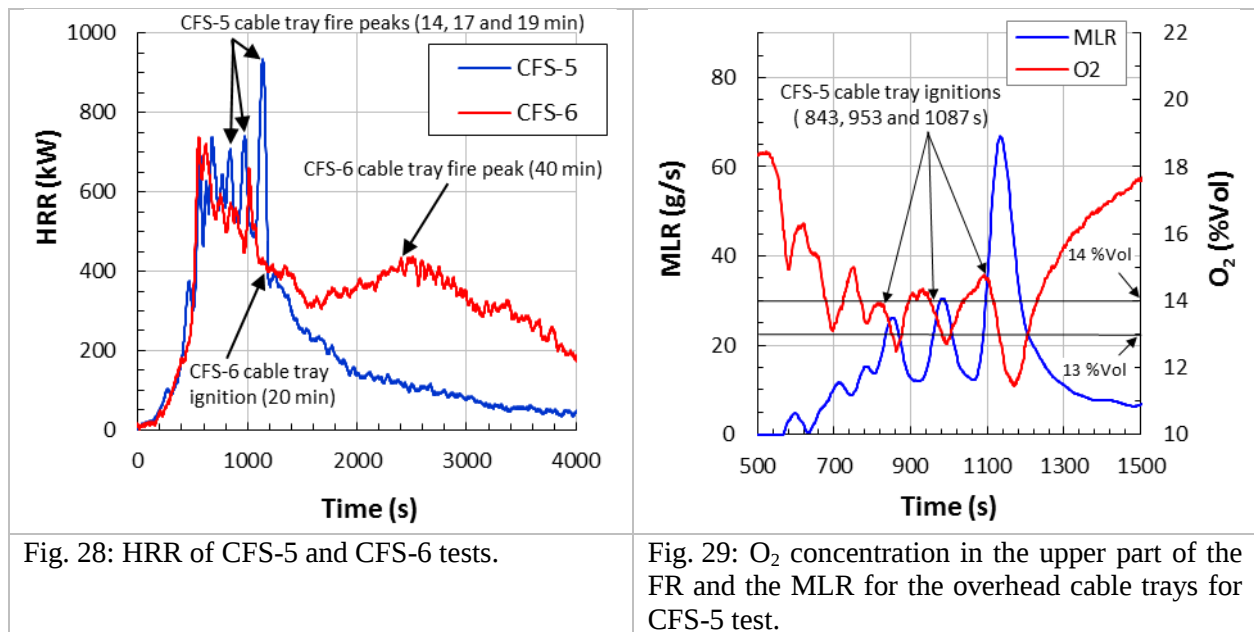


Fig. 28: HRR of CFS-5 and CFS-6 tests.

Fig. 29: O₂ concentration in the upper part of the FR and the MLR for the overhead cable trays for CFS-5 test.

3.5 | Fire spread for CORE-6

Compared with CFS-6 test, CORE-6 test also implemented two adjacent cabinets placed against the side walls of the fire cabinet (Fig. 5). These adjacent cabinets contained HFFR and HFR cable-types (Table 2) which were installed along PVC trunkings placed against the adjacent side wall (Fig. 8 and Fig. 31 (a)). The results of CORE-6 test highlighted that the fire fully spread within the fire cabinet (Fig. 30), to the two adjacent cabinets and false floor. However, unlike CFS-6 test, fire did not propagate to the three overhead cable trays. The TML was measured at 46.2 and 2.3 kg for the three cabinets and upper cable trays, respectively.

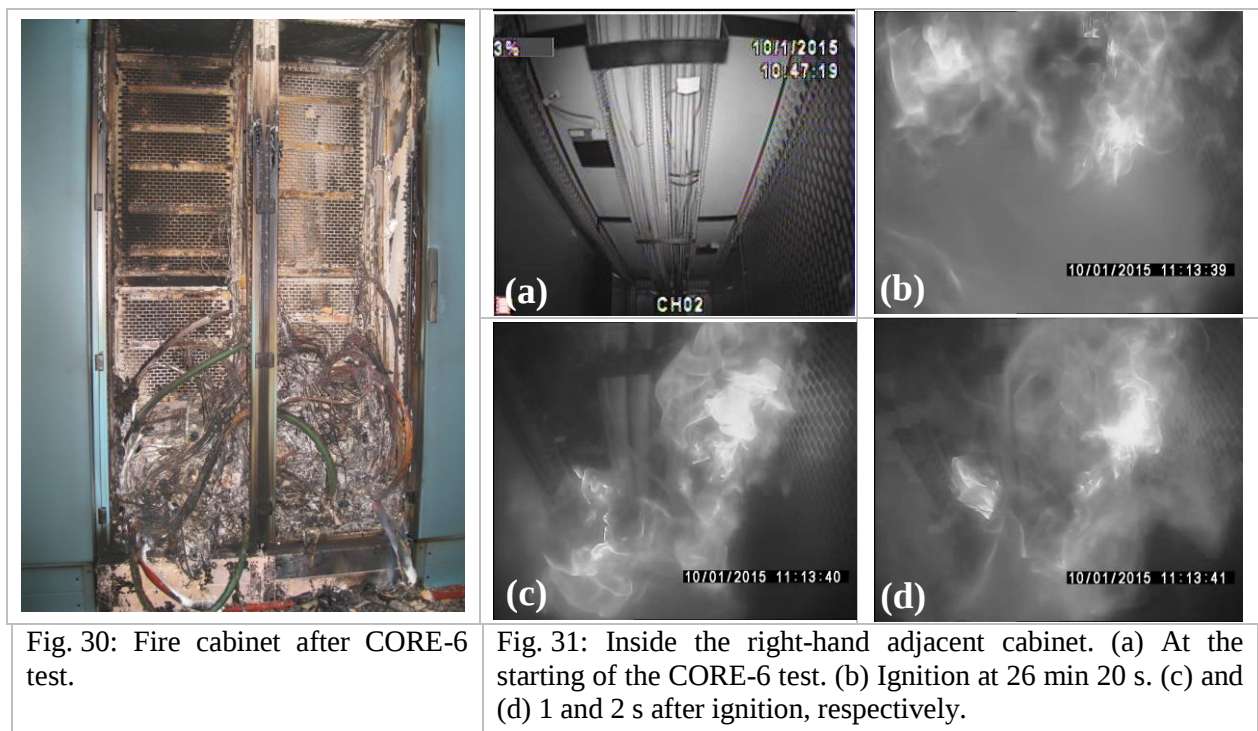


Fig. 30: Fire cabinet after CORE-6 test.

Fig. 31: Inside the right-hand adjacent cabinet. (a) At the starting of the CORE-6 test. (b) Ignition at 26 min 20 s. (c) and (d) 1 and 2 s after ignition, respectively.

3.5.1 | Adjacent cabinet

Fire was first observed at 26 min 20 s after the cabinet ignition in the right-hand adjacent cabinet (Fig. 31 (b), (c), and (d)). Fire was next identified at 38 min 35 s in the left-hand adjacent cabinet from a temperature measurement carried out along the PVC trunking 1 as it will be discussed hereafter. Fig. 32 (a) and (b) show the upper part of the left- and right-hand adjacent cabinets, respectively, after the CORE-6 test.

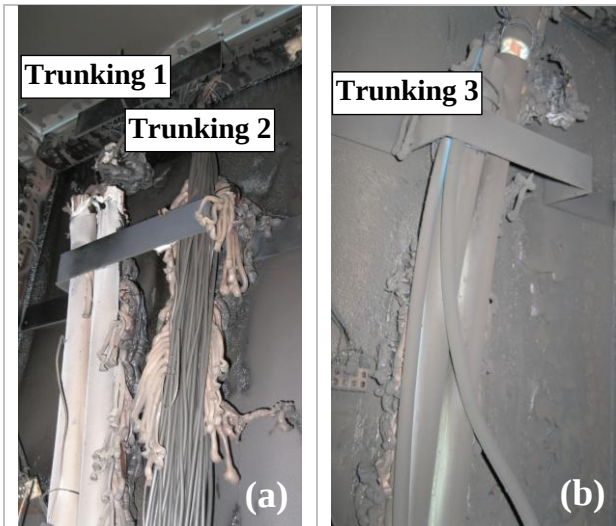


Fig. 32: (a) Upper part of the left-hand adjacent cabinet (b) Upper part of the right-hand adjacent cabinet.

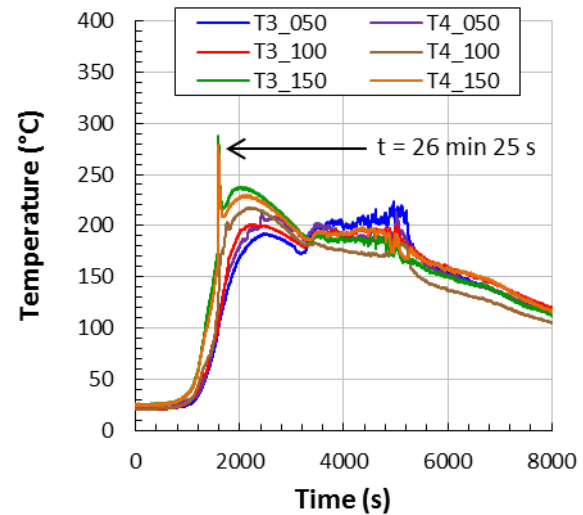


Fig. 33: Measured temperatures along the PVC trunkings 3 and 4 of the right-hand adjacent cabinet.

Visual comparison between Fig. 8 (c) and Fig. 32 (b) first points out that the trunking 4 and its cable content were removed from their initial location. Indeed, this trunking burnt and its charred part, as well as the samples of cable F contained inside, fell in bottom of this cabinet. Fig. 32 (b) also shows that the trunking 3, which contained the samples of cables E and F, burnt. In contrast, all these samples and also those which fell in bottom of the cabinet (all of same HFFR cable-type) did not burn. Fig. 33 gives the measured temperatures along the trunkings 3 and 4. The results show a steep increase at 26 min 25 s of these measurements at 150 cm high from the bottom of the right-hand adjacent cabinet. At this time, temperatures over the right-hand side wall of the central cabinet (except at the bottom) exceeded 600°C (Fig. 34). Similar wall temperatures are thus assumed on the adjoined side wall of the right-hand adjacent cabinet where the PVC trunkings were fixed. Given that self-ignition of PVC polymeric material may occur when its temperature reaches 400 °C²²⁻²³, it is thus highly probable that the fire that occurred in this cabinet at 26 min 25 s was caused by the self-ignition of PVC trunkings 3 and 4.

Fig. 35 shows the temperature measurements carried out along the trunkings 1 and 2 contained in the left-hand adjacent cabinet. The fast increase of the measurement along the trunking 1 at 100 cm high from the bottom of this cabinet shows that ignition occurred at 38 min 35 s after the CORE-6 test starting. Moreover, Fig. 32 (a) and Fig. 36 show respectively that the PVC trunkings 1 and 2 and the three samples of PVC cable C contained in the trunking 1 (Fig. 8 (a)) partially burnt. In contrast, the smaller samples of cables D (HFFR cable-type) contained in the trunking 2 did not burn.

Works carried out by Chavez^{3,4} showed that an air gap of 2.54 cm may prevent fire spread from a cabinet fire to adjacent cabinet. In contrast, the study conducted by Mangs *et al.*⁶ highlighted that fire may spread to an adjoined cabinet (i.e., without air gap) if samples of PVC cables are implemented in this cabinet. The results of the CORE-6 test are thus consistent with the latter work, but they also show that the samples of HFFR cable-types, located inside the PVC trunkings placed against the adjacent side wall of the adjoined cabinets, were not ignited. Fire spread from a fire cabinet to an adjacent cabinet not only depends on the air gap but also on the material type contained inside.

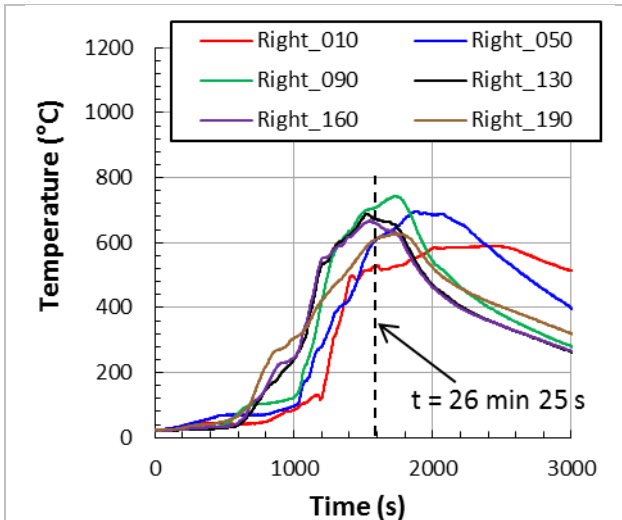


Fig. 34: Wall temperatures over the right-hand side wall of the central cabinet.

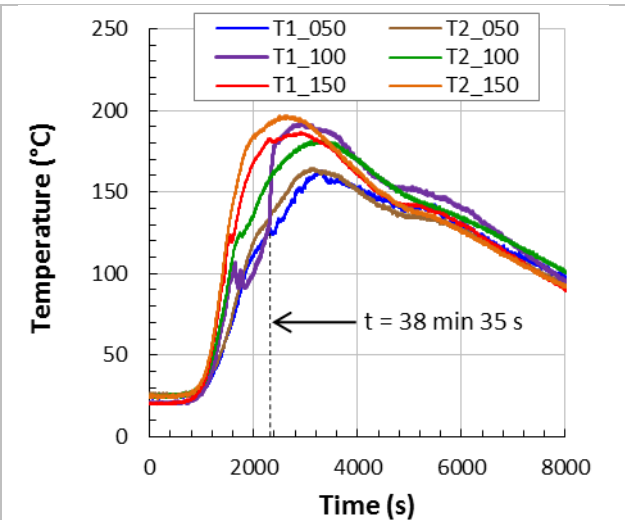


Fig. 35: Measured temperatures along the PVC trunkings 1 and 2 of the left-hand adjacent cabinet.

3.5.2 | False floor

Fire spread from the fire cabinet to the false floor (Fig. 9 (a)) via the cables passages (Fig. 9 (b) and (c)) and fully burnt all the cables contained in its central part (Fig. 37). Fig. 38 provides the temperature measurement located in the central part of the false floor. According to this measurement and the minimal temperature criterion of 600 °C, assumed revealing the presence of flame, it is therefore deduced that fire spread to the false floor at 61 min 50 s and was extinguished at 102 min 22 s. The long fire duration (about 40 min) contributed to consume the total amount of cable fuel mass contained in the central part of the false floor.



Fig. 36: Samples of cable C (HFR cable-type) contained in the trunking 1 (left-hand adjacent cabinet) after CORE-6 test.



Fig. 37: Central part of the false floor. Arrows showing cable conductors coming from the fire cabinet through the cable passages.

3.5.3 | Overhead cable trays

For CORE-6 test, temperature measurements carried out along the three overhead cable trays were lower than 600 °C, confirming that fire did not spread over these last ones, unlike CFS-6 test. These two tests were identical except the two adjacent cabinets only implemented for CORE-6 test. Fig. 39 exhibits the HRR of CFS-6 and CORE-6 tests. This figure shows that the cabinet fire growth was slower for CORE-6 test than for CFS-6 test. A plausible explanation of this experimental observation could come from a higher thermal inertia generated by the presence of the three adjoining cabinets in CORE-6 test. Therefore, the heat transferred to the overhead cable trays was lower for CORE-6 test

compared with CFS-6 test. As a consequence, the measured temperatures along the cable trays in CORE-6 test were lower compared with those measured in the CFS-6 test (Fig. 40). Pyrolysis of the CFS-6 cable trays therefore started earlier than for CORE-6 test (Fig. 41) when temperatures just above the cables exceeded 400 °C (at 580 s, Fig. 40). This condition was reached later for CORE-6 test but only in the upper cable tray (1080 s, Fig. 40) when unburnt hydrocarbon gases (C_nH_m), accumulated under the ceiling, were ignited in same time as the cabinet fire reached its peak (1080 s, Fig. 42). These two concomitant fire events led to decrease the O_2 concentration in the upper part of the FR below 12 %Vol (Fig. 43). Such O_2 concentration was too low for the cable trays ignition, which was highlighted at 16 %Vol for CFS-6 test (section 3.3.2). The higher HRR peak obtained for CORE-6 test (950 kW) compared with that of CFS-6 test (735 kW) was due to the overlapping of the cabinet fire with the C_nH_m combustion under the ceiling of the FR.

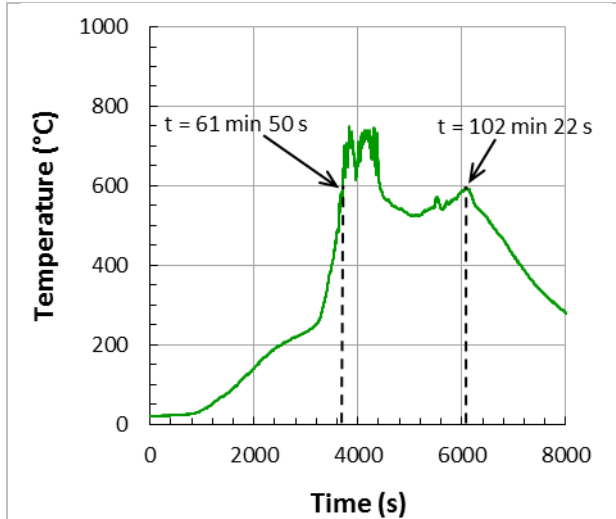


Fig. 38: Measured temperature in the central part of the false floor.

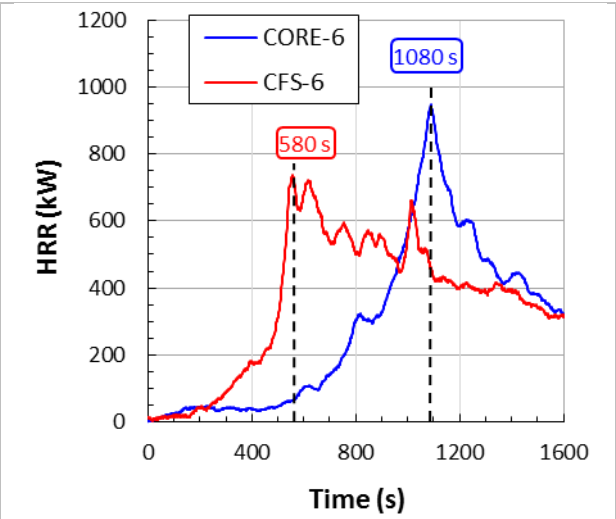


Fig. 39: HRR of the CFS-6 and CORE-6 tests.

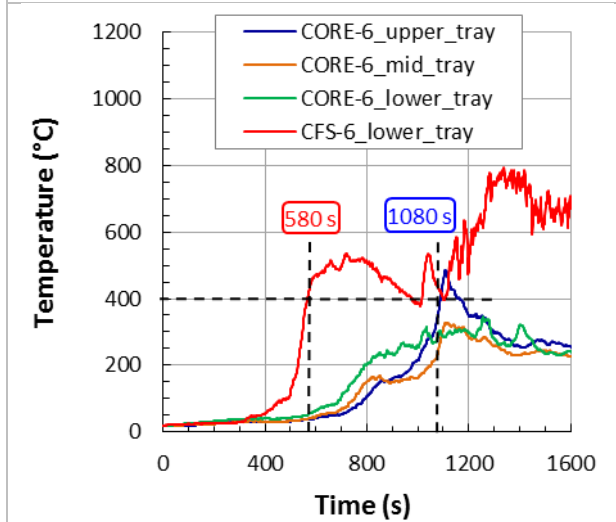


Fig. 40: Measured temperatures at the centre of the lower tray for CFS-6 test and at the centre of the three trays for CORE-6 test.

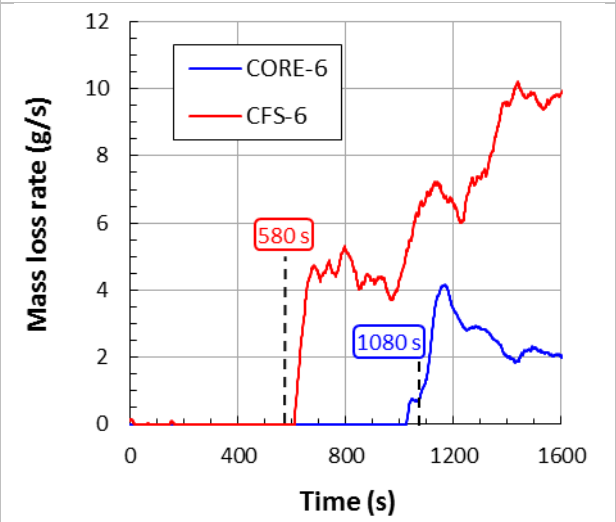
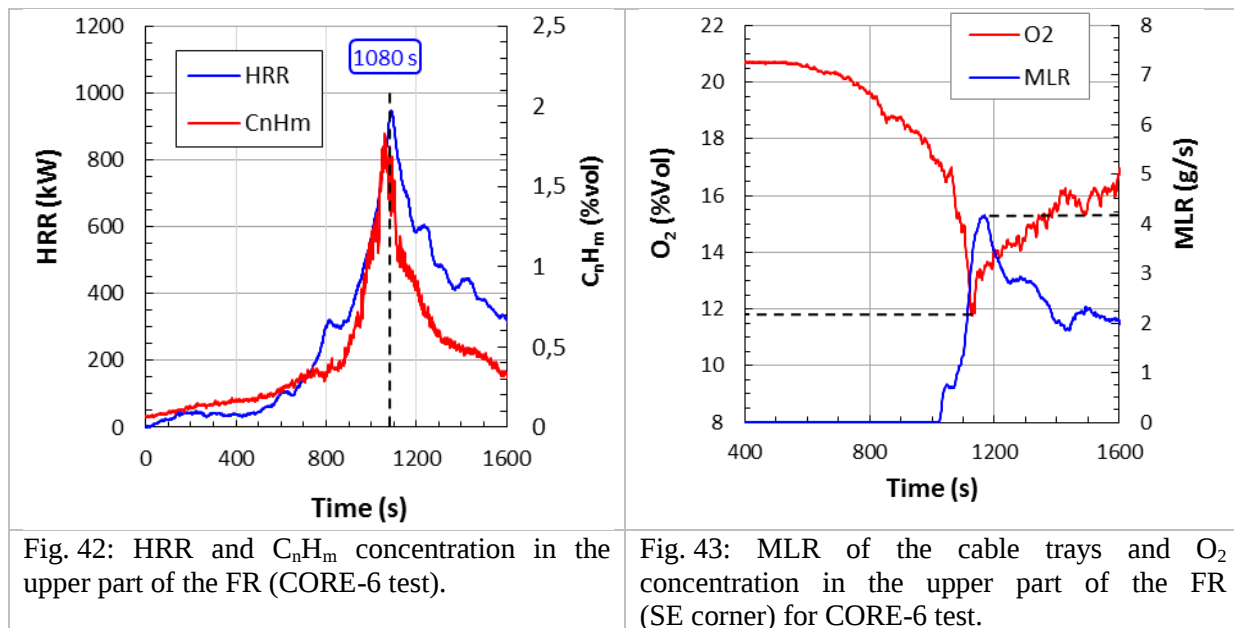


Fig. 41: MLR of the CFS-6 and CORE-6 tests.



4 | CONCLUSION

As part of the OECD PRISME-2 programme, four tests were carried out to study the fire spread from an open-doors electrical cabinet to neighbouring targets in a confined and mechanically-ventilated facility. The targets are three overhead cable trays, two adjacent cabinets and a false floor. These tests, named CFS-5 to CFS-7 and CORE-6, used same both open-doors electrical cabinet (fire cabinet) and three overhead cable trays. Moreover, fire dampers were set up for CFS-7 test while CORE-6 test implemented two additional closed-doors adjacent electrical cabinets placed against the fire cabinet, all located above a false floor.

The cabinet fire spread to overhead cable trays only for CFS-5 and CFS-6 tests which involved a VRR 15 h^{-1} . However, two specific cable tray fire behaviors depending on the cable-type were showed; three fast and short cable tray fires for CFS-5 test (HFR cable B) which overlapped with the cabinet fire and a significantly slower and longer cable tray fire for CFS-6 test (HFFR cable-type) which mainly grew at the end of the cabinet fire. These fires for CFS-5 test were short (about 1 min) since the O_2 concentration was fairly low when they occurred, due to the cabinet fire and the fast growth of these fires (HFR cable B). In contrast, the cable tray fire for CFS-6 test was much longer (80 min) since it ignited later (than the CFS-5 cable trays) and grew when the O_2 concentration was higher, caused by the less powerful cabinet fire and slower growth of this cable tray fire (HFFR cable A).

In contrast, cabinet fire did not spread to overhead cable trays for CFS-7 and CORE-6 tests. Indeed, the early fire dampers shutdown for CFS-7 test prevented ignition of overhead cable trays, due to very low oxygen concentration. Moreover, the slower growth of the CORE-6 cabinet fire compared with CFS-6 test, caused by the higher thermal inertia of the three adjoined cabinets, led to lower temperatures of the upper cable trays than the ones required for their ignition (obtained for CFS-6).

Finally, cabinet fire spread to the two adjacent cabinets and false floor for CORE-6 test. Indeed, trunkings, made in poly(vinyl chloride) (PVC), placed against the adjacent side walls and samples of HFR cables (made in PVC) contained inside, had self-ignited. In contrast, all samples of the various HFFR cable-types placed along the trunkings did not burn. These outcomes reveal that the fire spreading to an adjoined cabinet depends on the material-type installed inside. Finally, the long fire duration (about 40 min) in the central part of the false floor led to burn all the cables contained inside.

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