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EXPERIMENTAL STUDY AT REDUCED-SCALE OF FIRE SPREAD BETWEEN ELECTRICAL CABINETS LOCATED OPPOSITE EACH OTHER

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ABSTRACT

The ability of an electrical cabinet fire to spread to neighbouring cabinets is a major concern for fire safety in nuclear power plants. Twelve intermediate-scale fire tests were performed to determine the fire spread conditions (FSCs) from a burning enclosure (BE) to an opposite enclosure (OE) equipped with either a non-combustible (glazed or metallic) or a combustible (poly(methyl methacrylate), PMMA) front panel. The effects on the FSCs of the separation distance (SD) between the enclosures, the target type (electrical component) contained in the OE and overhead electric cable trays were also investigated. Fire spread to the OE equipped with a glazed panel when the total transmitted heat flux led to the spontaneous ignition of the target. This outcome was not obtained for the metallic panel. For the PMMA panel, fire spread when flames coming from the BE reached the flammable gas mixture produced by the panel. For both glazed and PMMA panels, the FSCs were obtained for higher SDs when overhead electric cable trays were used. The tests also revealed that the faster and more powerful PMMA panel fire was not obtained for the minimum SD studied. Finally, total transmittances of the glazed and PMMA panels were assessed.

Keywords: Clear PMMA; Electrical cabinets; Fire spread; Heat flux; Ignition; Overhead electric cable tray; Metal panel; Tempered glass; Transmittance.

NOMENCLATURE

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
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<tbody>
<tr>
<td>AE</td>
<td>Adjacent enclosure</td>
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<tr>
<td>BE</td>
<td>Burning enclosure</td>
</tr>
<tr>
<td>dA</td>
<td>Very small area located at the centre of HFS1 and HFS2 positions</td>
</tr>
<tr>
<td>ECS</td>
<td>Electric cable samples</td>
</tr>
<tr>
<td>FSCs</td>
<td>Fire spread conditions</td>
</tr>
<tr>
<td>F_{dA-BE}</td>
<td>View factor for dA to the flame area of the BE (-)</td>
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<tr>
<td>F_{dA-BW}</td>
<td>View factor for dA to the back wall of the BE (-)</td>
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<tr>
<td>HFS</td>
<td>Heat flux sensor</td>
</tr>
<tr>
<td>HRR</td>
<td>Heat release rate (kW)</td>
</tr>
<tr>
<td>NPPs</td>
<td>Nuclear power plants</td>
</tr>
<tr>
<td>OE</td>
<td>Opposite enclosure</td>
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<tr>
<td>PE</td>
<td>Polyethylene</td>
</tr>
<tr>
<td>PMMA</td>
<td>Poly(methyl methacrylate)</td>
</tr>
<tr>
<td>PVC</td>
<td>Poly(vinyl chloride)</td>
</tr>
<tr>
<td>q_{b,i}</td>
<td>Heat flux measured on the back surface of the front panel by the heat flux sensor i = 1 or 2 (kW/m²)</td>
</tr>
<tr>
<td>q_{c,ig}</td>
<td>Critical heat flux for spontaneous ignition (kW/m²)</td>
</tr>
<tr>
<td>q_{o}</td>
<td>Incident heat flux calculated at the centre of HFS1 and HFS2 positions (kW/m²)</td>
</tr>
</tbody>
</table>
\( q_{0,i} \) \hspace{1cm} \text{Incident heat flux measured without a front panel by the heat flux sensor } i = 1 \text{ or } 2 \text{ (kW/m}^2\text{)}

\( q_r \) \hspace{1cm} \text{Re-radiated heat flux by the front panel (kW/m}^2\text{)}

\( q_t \) \hspace{1cm} \text{Transmitted heat flux through the front panel (kW/m}^2\text{)}

SD \hspace{1cm} \text{Separation distance between the enclosures located opposite each other (m)}

TB \hspace{1cm} \text{Terminal blocks}

\( T \) \hspace{1cm} \text{Flame temperature (K)}

\( T_{F,av} \) \hspace{1cm} \text{Average flame temperature (K)}

XLPE \hspace{1cm} \text{Cross-linked polyethylene}

Greek characters

\( \Gamma \) \hspace{1cm} \text{Transmittance, } q_r / q_o \text{ (\%)}

\( \Gamma_T \) \hspace{1cm} \text{Total transmittance, } q_r / q_o \text{ (\%)}

\( \Gamma_T^T \) \hspace{1cm} \text{Average of the measurements of } \Gamma_T \text{ (%)}

\( \Gamma_A \) \hspace{1cm} \text{Spectral transmittance (-)}

\( \varepsilon_F \) \hspace{1cm} \text{Flame emissivity (-)}

\( \sigma_B \) \hspace{1cm} \text{Stephan-Boltzmann constant (5.67.10^{-8} \text{W.m}^{-2}.\text{K}^{-4})}

1. Introduction

About 500 fire events in Nuclear Power Plants (NPPs) were recorded in the recent version of the OECD FIRE Database [1] for the period from the 1980's to the end of 2017. More than 10 \% of these events involved electrical cabinets. These last ones are indeed a potential source of fire since they contain both combustible materials and live electrical circuits [2]. Nowadays, the ability of a cabinet fire to spread to neighbouring cabinets is still a major concern for fire safety in NPPs. The electrical cabinets in NPPs can commonly be laid out in multiple parallel rows, as found for example in control or switchgear rooms [3]. Several studies [4]-[9] investigated the fire spread between adjacent electrical cabinets. In contrast, little research has addressed a scenario in which electrical cabinets are located opposite each other. One purpose of Mangs et al. [6] was to study the impact of a burning cabinet on a closed-door cabinet located opposite it 1 m away and which represented a row of neighbouring cabinets. The latter cabinet was equipped with a metal door and contained poly(vinyl chloride) (PVC) cable samples, which were attached to the door. In all the tests, the cable samples did not burn. However, even though most electrical cabinets in NPPs have metal doors, some low voltage electrical cabinets are equipped with glazed doors or doors including windows made of poly(methyl methacrylate) (PMMA) [2], e.g., in control rooms.

This work therefore aims at investigating the ability of fire to spread from a burning cabinet to an opposite cabinet equipped with either a non-combustible (glazed or metal) or a combustible (PMMA) door. To that end, this study focuses on determining the fire spread conditions (FSCs) according to the door type. More precisely, in order to study the capability of fire to spread through a glazed or a metallic door, electric components are placed as targets inside the cabinet located opposite the burning cabinet. Thus, the determination of the ignition conditions for the studied targets will provide the FSCs according to the non-combustible door type. Furthermore, to ascertain the FSCs to the opposite cabinet equipped with a combustible (PMMA) door, the ignition conditions of the door are specifically investigated.

The FSCs are studied for a separation distance (SD) between the electrical cabinets facing each other that varies in the 0.4-1 m range, as will be explained in section 2.1. Moreover, the electrical cabinets in NPPs can be connected to each other by overhead electric cable trays, as reported in [2]-[3]. However, the study of their impact on fire spread between cabinets located opposite each other, as recommended by Chavez [4]-[5], had not yet been addressed. This study therefore also proposes to examine this issue.

The first and main goal of this study is therefore to determine the FSCs from a burning enclosure to an opposite enclosure equipped with either a non-combustible (glazed or metallic) or a combustible (PMMA) front panel. The effects on the FSCs of the SD between the enclosures in the 0.4-1 m range, the target type (electrical component) contained in the opposite enclosure and overhead electric cable trays are also investigated.
This study also has two additional objectives. The first one is to characterize the PMMA front panel fire of the opposite enclosure and, in particular, to highlight the impact of the separation distance (SD) on the heat release rate (HRR). The second additional purpose is to assess the total transmittances of the glazed and PMMA front panels.

To this end, a test device comprising primarily of a burning enclosure and a closed enclosure located opposite was used to represent at a reduced-scale two electrical cabinets facing each other. In addition, measurements of the incident and total transmitted heat fluxes for the three front panel types of the opposite enclosure as well as videos were notably made.

The results are intended to provide a better understanding of the FSCs between electrical cabinets facing each other in nuclear installations, as well as in other industrial sectors. The outcomes of this work also target to support the analysis of large-scale electrical cabinet fire tests, which were carried out as part of the OECD PRISME-3 project [10].

The experimental setup, the corresponding instrumentation, the fire test matrix and the test protocol are first presented. The results and discussion are then set out in the main part of this work. This part first focuses on the tests that used the enclosure located opposite the burning enclosure without a front panel in order to allow for the measurements of the incident heat flux. The second and third sections of the major part of this work deal with the tests that involved an opposite enclosure equipped with a non-combustible (glazed or metal) and a combustible (PMMA) front panel respectively. Finally, this part ends with the assessment of the total transmittances of the glazed and PMMA front panels. A last portion of this work discusses the representativeness of the performed reduced-scale fire tests.

2. Fire test description

2.1. Experimental setup

The test device (Fig. 1) was composed of two steel enclosures 0.6 m wide, 0.6 m deep and 1 m high, two overhead ladder-type trays and a raised floor. The left-hand enclosure corresponded to a one-quarter scale model of the steel enclosure (1.2 m wide, 0.6 m deep and 2 m high) of the open-door electrical cabinet studied in a previous work [8]. This reduced-scaled enclosure, which is called the burning enclosure (BE), contained a gravel-packed 0.5 m x 0.5 m gas burner located at its bottom (Fig. 2). This gas burner provided a constant fire power of 300 kW for all the tests, which corresponds to one quarter of the maximum HRR of the open-door cabinet [8] studied in open atmosphere conditions [7]. This allowed to obtain the same maximum fire power per unit volume for the reduced and real-scales. Details of the design study of the BE are given in [9], which used this enclosure for a previous work on fire spread between two adjacent enclosures. In addition, as with the open-door cabinet [8], one panel of the BE, located opposite the right-hand enclosure, was removed (Fig. 2).

The right-hand enclosure, which is referred to as the opposite enclosure (OE), was located opposite the BE with a SD that varied in the 0.4-1 m range. This range was used since fire did not spread between enclosures facing each other with a SD of 1 m [6], as commented on in section 1. This specification was also justified by the same order of magnitude of the maximum fire power provided by the burning enclosure (400 kW) in [6] as that used in this study (300 kW). The front panel of the OE, which was located opposite the BE opening, was either a glazed panel (Fig. 3), a metal panel or a panel made of PMMA (Fig. 4), as specified in Table 1. The glazed panel was made of tempered glass and sold under the trademark SECURIT©. The metal panel was a common steel panel. The PMMA panel was made of cast and clear PMMA and sold under the commercial name of PERSPEX©. The thicknesses of the three panel types were similar to those of the corresponding doors that can be fitted to electrical cabinets in NPPs. Large differences in the thicknesses between the steel and both PMMA/glazed panels are reported in Table 1. Indeed, given the high density of steel (7900 kg/m³), the metal walls of the electrical cabinets are usually thin in order to limit the weight. In contrast, considering the significant lower density of PMMA (1190 kg/m³) and glass (about 2500 kg/m³), the corresponding doors can be thicker. This also contributes to increasing their strength. For all the tests, except the first three, electrical components were installed in the OE as targets to potentially highlight their ignition. These targets were composed of either three sets of forty terminal blocks (TB) each (Fig. 3) or a bundle of ten 1-m long electric cable samples (ECS) (Fig. 4). These TB and ECS, as specified in Table 2, can often be found, in similar layouts to those described above, in low voltage electrical cabinets commonly present in NPPs [2],[8].
TB are used to connect the cable wires between electrical components, such as relays, circuit breakers or multi-wire cables. The targets were located close to the front panel of the OE (gap of about 1 cm) and supported by a grid fixed to one of the side walls of this enclosure (Fig. 3). The second side wall of the OE (Fig. 1) was fitted with two ventilation grids, which were closed for all the tests in this study.

In addition, two overhead ladder-type trays were installed for all the tests (Fig. 1). However, these trays were filled with electric cables for only two tests. The types of electric cables used, which will be specified in sections 3.2.1 and 3.3, can be found in NPPs.

Finally, a raised floor, located below the burning and opposite enclosures (Fig. 1), first allowed the two enclosures to be moved and easily positioned. It also allowed for the laying and pulling of all the utilities for the sensors and gas burner (water cooling circuits, instrumentation cables and gas circuit).

The fire tests were carried out in open atmosphere conditions (i.e., in well-ventilated conditions). The test device was placed under a large-scale calorimeter (Fig. 5), which is composed of a 3-m inner diameter large-scale hood connected to an exhaust ventilation network. The latter collects all the combustion products released during the fire tests.

2.2. Instrumentation

One 1.5-mm K-type thermocouple, called TC1, was located at the centre of the burning enclosure (BE) to measure the flame temperature (Fig. 2). The expanded relative uncertainty of this measurement was evaluated in the current test conditions at ± 17 %. For an expansion factor of 2, considered in this study, the expanded uncertainty of the measurement is thus related to two relative standard deviations and the confidence level corresponds to 95 % [11]. Note that the evaluation of the expanded uncertainty, based on the relative one (i.e., ± 17 %), for a given temperature measurement, requires the conversion of this last one in °C. Heat fluxes were measured in the OE using two Gardon water-cooled total heat flux sensors with a measurement range of 0-100 kW/m². The heat flux sensor (HFS) closest to the target (Fig. 3) was labelled HFS1 and the second one HFS2. HFS1 and HFS2 were positioned about 10 mm from the front panel, 250 mm from the ceiling and 175 mm from the support grid and the opposite side wall respectively. The expanded relative uncertainty for the two HFS was estimated in this study to be ± 15 %. This is consistent with the evaluations given in other fire test conditions [9] and [12] for the same type of sensor. Three cameras were used for these tests. One provided a full view of the test device while the other two focused on the burning and opposite enclosures respectively. Carbon dioxide (CO₂) concentration, gas temperature, pressure and volume flow rate were measured in the exhaust ventilation network. These measurements were used to assess the HRR for some of the fire tests in this study. Finally, the acquisition system of all the measurements had a sampling time adjusted to 1 s.

2.3. Fire test matrix

Table 3 provides the fire test matrix of the twelve intermediate-scale fire tests that were conducted to specify the fire spread conditions (FSCs) from a burning enclosure (BE) to an opposite enclosure (OE) equipped with either a non-combustible (glazed or metal) or a combustible (PMMA) front panel. The effects on the FSCs of the separation distance (SD) between the opposite enclosures in the 0.4-1 m range, the target type contained in the OE (sets of TB or a bundle of ten ECS) and overhead electric cable trays were also investigated. These tests were also intended to characterize the PMMA front panel fires and, finally, assess the total transmittances of the glazed and PMMA front panels.

2.4. Test protocol

For tests T4-T12, the controlled fire in the BE was maintained with a constant power of 300 kW, either until ignition of the target contained in the OE or for a maximum fire duration of 25 min. For the first three tests T1-T3, which did not use a target, the controlled fire was maintained for five minutes and provided the same power of 300 kW. Fig. 6 shows the characteristic flame shape obtained for all the tests, as illustrated e.g., for test T6. This flame shape is typical of fire in an enclosure [13].
3. Results and discussion

3.1. Tests without a front panel

The first three tests T1-T3 (Table 3) were conducted with an open opposite enclosure (OE), as illustrated in Fig. 7 for T3. The heat fluxes measured by HFS1 and HFS2 for these tests, \( \dot{q}_{0,1} \) and \( \dot{q}_{0,2} \) respectively, are assumed to be nearly identical to those incident to the front panels of the OE during tests T4-T12. This assumption is justified by the small thickness of the front panels studied (4 mm for the thickest one, Table 4) and the closeness of their back surface to HFS1 and HFS2 (gap of about 1 cm), as compared to the minimum separation distance (SD) of 0.4 m used for these tests. Fig. 8A-C first show \( \dot{q}_{0,1} \) and \( \dot{q}_{0,2} \) for the three S-Ds of 0.4, 0.6 and 0.8 m respectively. After the fast evolutions of these measurements up to about 40 s for all the tests, corresponding to the setting of the fire power at 300 kW, \( \dot{q}_{0,1} \) and \( \dot{q}_{0,2} \) increased more slowly up to the end of the fires. Fig. 8A-C also provide, for the three S-Ds, the incident heat flux calculated at the centre of HFS1 and HFS2 positions \( \dot{q}_o \) as follows:

\[ \dot{q}_o = F_{dA-BE} \varepsilon_F \sigma_B T^4 \]  

Where \( F_{dA-BE} \) is the view factor for a very small area \( dA \), located at the centre of HFS1 and HFS2 positions, to the flame area of the burning enclosure (BE) (-). Calculations of \( F_{dA-BE} \) are detailed in appendix A. \( \varepsilon_F \) is the flame emissivity (-). \( \varepsilon_F \) is estimated at 0.7 based on the optical flame thickness, as assessed in appendix B. \( \sigma_B \) is the Stephan-Boltzmann constant \((5.67 \times 10^{-8} \text{ W m}^{-2} \text{K}^{-4})\) and \( T \) the flame temperature (K). Fig. 9 gives the flame temperature measured at the centre of the BE for tests T2-T11* \((0 \leq t \leq 300 \text{ s})\). The noticeable differences between the flame temperature measurements can be explained by the uncertainty related to this tricky measurement \((\pm 17 \%, \text{ see section 2.2})\). Accordingly, the average flame temperature \( T_{F,av} \) which is the average of all the measurements provided in Fig. 9, is assumed to be the most suitable flame temperature to be considered in Eq. (1). This last figure also indicates that \( T_{F,av} \) increased from 876 to 989 K over \( 40 \leq t \leq 300 \text{ s} \), leading to the rise of \( \dot{q}_o \), according to Eq. (1), and as seen in Fig. 8A-C. Thus, the clear consistency shown in this last figure between \( \dot{q}_o \) and the heat flux measurements (especially with \( \dot{q}_{0,1} \)) for \( 40 \leq t \leq 300 \text{ s} \), highlights that their rise also resulted from the above increase of the flame temperature (i.e., \( T_{F,av} \)) over the previous time interval. This rise could be explained by the decrease of the flame heat losses to the walls of the BE given the progressive heating of these last ones. Moreover, for a given SD, the fact that \( \dot{q}_{0,2} \) was always moderately lower than \( \dot{q}_{0,1} \) (Fig. 8A-C), could indicate that flames were closer to HFS1 than HFS2, i.e., slightly asymmetric, when they went out of the burning enclosure. This could ensued from interfering minor air flows, as can occur in a large-scale and well-ventilated facility like the one used for this study (Fig. 5). The relative deviations between \( \dot{q}_{0,1} \) and \( \dot{q}_{0,2} \) (i.e., \( \left| \frac{\dot{q}_{0,1} - \dot{q}_{0,2}}{\dot{q}_{0,1}} \right| \times 100 \)) over \( 40 \leq t \leq 300 \text{ s} \), that fall in the 0–20 % range for the three S-Ds studied, confirm that the asymmetric nature of the flames was not very pronounced. Furthermore, note that \( \dot{q}_o \) as evaluated from Eq. (1) did not take into account the contributions of the radiative emissions of surrounding elements, such as that of the back wall of the BE (Fig. 2). The back wall contribution is indeed negligible. Previous research [9] showed that maximum wall temperatures of the BE, for the same fire power of 300 kW, did not exceed 850 K at 300 s. Thus, considering this temperature in Eq. (1), as well as a maximum view factor of 0.145 (SD of 0.4 m) for \( dA \) to the back wall \( F_{dA-BW} \) (see appendix A) and a steel wall emissivity of 0.8, this gives a maximum contribution of 3 kW/m² to \( \dot{q}_o \), before taking into account the flame absorption. Given a global transmittance estimated at 0.3 for the optically thin flames of the BE (see appendix B), the maximum effective contribution of the back-wall to \( \dot{q}_o \) is therefore 1 kW/m². This confirms that the increase of \( \dot{q}_{0,1} \) and \( \dot{q}_{0,2} \) over \( 40 \leq t \leq 300 \text{ s} \) only resulted from the rise of the flame temperature in the BE.

*Flame temperature was not measured for T1 and TC1 was not positioned at the centre of the BE for T12.
3.2. Tests with a non-combustible front panel

This section first deals with tests T4-T7 which used an OE with a tempered glass front panel and then with test T8, which used a metal front panel.

3.2.1 Tests with a glazed front panel

Tests T4-T7 were performed to determine the fire spread condition (FSC) from the burning enclosure (BE) to the opposite enclosure (OE) with a glazed front panel, considering a separation distance (SD) of 0.4 and 0.6 m, two target types (sets of terminal blocks and a bundle of electric cable samples) and overhead trays filled with electric cables for T7 only.

This section first discusses tests T4-T6. SD was 0.4 m for both T4 and T5 and 0.6 m for T6. Fig. 10A-B give for these three tests the heat flux measured on the back surface of the glazed panel by HFS1, \( \dot{q}_{b,1} \) and HFS2, \( \dot{q}_{b,2} \) respectively. These figures first reveal a satisfactory repeatability of these two measurements for T4 and T5 up to the fire stopping at 18 min for the latter test. This stopping occurred shortly after the ignition of the target (bundle of electric cable samples, ECS) in compliance with the test protocol. In contrast, the target (sets of terminal blocks, TB) did not ignite for T4. In this case, the test is stopped after 25 min, which is the maximum test duration, as also specified by the test protocol.

The absence of target ignition for T4 was unexpected since the maximum heat flux measured closest to the target, \( \dot{q}_{b,1} \) (36 kW/m², see Fig. 10A) was higher than the critical heat flux, \( q_{c,ig} \) (31 ± 3 kW/m²) assessed for the spontaneous ignition of this target type [9]. The video analysis for this test indeed revealed that the sets of TB partially melted and then fell to the bottom of the raised floor before \( \dot{q}_{b,1} \) reached previous \( \dot{q}_{c,ig} \). In contrast, the target for T5 (bundle of ECS) spontaneously ignited after about 16 min when \( \dot{q}_{b,1} \) reached the value of 34 kW/m² (Fig. 10A). This value indeed falls in the range for \( \dot{q}_{c,ig} \) assessed for this target type (35.5 ± 3 kW/m², [9]) and also because the bundle of ECS remained fixed to the support grid up until its ignition. Melting of this target type made of PVC and XLPE (Table 2) was indeed not observed during this test. Previous study [9] measured \( \dot{q}_{c,ig} \) for the two above target types. This work investigated the fire spread from the same burning enclosure (BE) to an adjacent enclosure (AE), which was identical to the OE. The location of the targets in the AE and OE were the same. The fire power of the BE was also 300 kW in [9]. The main difference between the test set-up of the previous study and that for T4-T7 tests was the closest panel to the targets which was metallic for the AE and glazed for the OE. Melting of the sets of TB was not observed in the AE for the study [9]. Thermal degradation of this target type made of polyamide (Table 2) could be therefore affected by the impact of the nearby panel on the total transmitted radiative emission. Furthermore, for T6, which used a higher SD of 0.6 m, the bundle of ECS did not ignite since maximum \( \dot{q}_{b,1} \) (22 kW/m², see Fig. 10A) was clearly lower than \( \dot{q}_{c,ig} \) required for such target type (35.5 ± 3 kW/m²).

The incident heat flux \( \dot{q}_a \) is now calculated up to 1200 s for the three SDs of 0.4, 0.6 and 0.8 m, as seen in Fig. 11, which also provides \( \dot{q}_{a,3} \) (HFS1, 0 s ≤ t ≤ 300 s). This figure shows that \( \dot{q}_a \) reached a nearly steady state around 1000 s for the three SDs. This is consistent (given Eq. (1)) with the almost stationary phase attained by the average flame temperature \( T_{F,av} \) at the above same time period (Fig. 12). Furthermore, the \( \dot{q}_a \) increase led to those of the transmitted heat flux through the front panel \( \dot{q}_r \), and of the re-radiated heat flux emitted by the front panel \( \dot{q}_r \) (due to the in-depth energy absorption). The sum of \( \dot{q}_r \) and \( \dot{q}_r \) is the total transmitted heat flux, \( \dot{q}_b \), as stated in [14]:

\[
\dot{q}_b = \dot{q}_r + \dot{q}_r
\]  

Consequently, the rise of \( \dot{q}_a \), as above described, explains the continuous increase of both \( \dot{q}_{b,1} \) and \( \dot{q}_{b,2} \) up to around 1000 s for T4-T6, as seen in Fig. 10A-B. Note that the decrease of \( \dot{q}_b \) beyond 1200 s for both tests T4 and T6 (Fig. 10) was caused by the slow uncontrolled drop in the propane volume flow rate below the setting value (210 l/min) required to get a fire power of 300 kW. This was caused by frost...
formation\(^1\) in the propane supply circuit. However, this phenomenon, which only occurred for T4 and T6, did not impact their outcomes. This event indeed occurred from 1200 s when the ignition conditions for the targets were no longer possible for both T4 (the target melted and fell before 1200 s) and T6 (\(q_b < q_{ci,ig}\)), as previously discussed.

For T7 (SD of 0.6 m), as seen in Fig. 13, each of the two overhead ladder-type trays was filled with thirty five electric cables A, as specified in Table 4. The 2.5-m long electric cables were laid tightly along the overhead trays. This test investigated the effect of overhead electric cable trays on fire spread from the BE to the OE. Fig. 14A-B show the test device for T7 one minute after the fire onset and at the fire peak (10 min 30 s) respectively. These figures reveal that the lower electric cable tray directed flames very close to the glazed panel, as occurred with a shorter SD of 0.4 m (T4 and T5). Accordingly, heat fluxes measured on the back surface of the glazed panel for T7 were similar to those for T4 and T5 and higher than those for T6 (SD of 0.6 m). This is illustrated in Fig. 15 which shows \(q_{b,2}\) for all tests T4-T7. Unfortunately, HFS1, which provided \(q_{b,1}\) (measured close to the target), malfunctioned for T7\(^7\). However, it was previously observed that when \(q_{b,2}\) are similar, as obtained e.g. for tests T4 and T5, then \(q_{b,1}\) are also close (Fig. 10). So, given similar measurements of \(q_{b,2}\) for T4, T5 and T7 (Fig. 15), the same outcome can be reasonably assumed for \(q_{b,1}\). This substantiates the fact that the target for T7 (bundle of ECS) also ignited at a similar time (17 min) to T5 (16 min), which used the same target type, as indicated in Fig. 15, and confirmed by video analysis.

Fire spread to the OE equipped with a glazed panel when the total transmitted heat flux was similar to that required for spontaneous ignition of the target. This is the FSC for the glazed front panel which was reached for a bundle of ECS used as the target, a SD of either 0.4 m or 0.6 m when overhead electric cable trays were used.

### 3.2.2 Test with a metallic front panel

The objective of this part is to study the capability of fire to spread through a metallic front panel. The test device is shown in Fig. 16. Only one test (T8) was performed since this last one, which was carried out for the minimum SD of 0.4 m, did not reveal ignition of the target (bundle of electric cable samples, ECS). Fig. 17 provides \(q_{b,1}\) (measured close to the target) for T8 and T5 (glazed panel), both using a SD of 0.4 m. This figure indeed shows that, for a fire duration of 25 min, \(q_{b,1}\) for T8 was clearly lower (maximum value of 25 kW/m\(^2\)) than \(q_{ci,ig}\) (35.5 ± 3 kW/m\(^2\)) required for the spontaneous ignition of the target (bundle of ECS), as occurred for T5 (when \(q_{b,1}\) reached the value of 34 kW/m\(^2\)). This fire spread condition was not reached for the metal panel. This panel reduced the total transmitted heat flux (\(q_b\)) to a greater extent than the glazed panel, as seen in Fig. 17. Indeed, for the opaque metal panel, only \(q_r\) contributed to \(q_b\), while for the glazed panel, both \(q_r\) and \(q_t\) did so. For the glazed panel, \(q_t\) was slightly lower than 10 kW/m\(^2\) at the onset of the fire (Fig. 17). Moreover, \(q_t\) next raised up to the target ignition for T5 since \(q_t\) increased over the same time interval (Fig. 11). This contributed to maintain a gap between \(q_b\) measured for the glazed and metal panels (Fig. 17).

It should be noted that metallic doors of electrical cabinets in nuclear installations (as well as in other industrial sectors) can be equipped e.g. with electrical equipment for monitoring (voltmeter, ammeter, indicator light...). The impact of this door configuration on fire spread is addressed as part of additional investigations [10] which will complete the current outcomes obtained with a full metallic door.

### 3.3 Tests with a PMMA front panel

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\(^1\)This phenomenon can occur when the upstream pressures in the propane supply circuit are no longer sufficiently high to prevent frost (or ice) formation from residual humidity, e.g. in a downstream pressure regulator or mass flow meter. This phenomenon is emphasized when a large propane volume flow rate is required. Two large gas propane bottles (total volume of 36 m\(^3\)) were needed in order to perform 3 or 4 tests.

\(^7\)T7, as well as T12, which both involved overhead electric cable trays, were actually performed last (first T12 and then T7). The calibration test, which was conducted after T7, confirmed the malfunction of HFS1.
This section deals with tests T9-T12, which used the opposite enclosure (OE) equipped with a front panel made of clear PMMA (Table 1), as shown in Fig. 4 e.g. for T9. The prime objective of these tests was to specify the fire spread condition (FSC) from the burning enclosure (BE) to the OE. An additional purpose was to characterize the PMMA front panel fires and, in particular, to highlight the impact of the separation distance (SD) on the heat release rate (HRR). These tests used a SD in the 0.6-1 m range, a bundle of electric cable samples (ECS) as the target in the OE and overhead trays filled with electric cables for T12 only.

For T9 (SD of 0.8 m), the so-called bubbling phenomenon [15] appeared from about 5 min 30 s after the onset of the fire in the upper part of the PMMA panel, as clearly observed one minute later in Fig. 18A. The bubbles were formed from vaporized methyl methacrylate monomer, which was released when PMMA was decomposing [16]. Next, bubble formation occurred over the entire PMMA panel, as shown in Fig. 18B-C after 7 min 30 s and 9 min 30 s respectively. At the same time, bubble bursting at the panel surface led to the release of fuel gases. However, the panel did not ignite. Indeed, given the SD of 0.8 m, flames coming from the BE could not reach the upper part of the PMMA panel to ignite the potentially flammable gas mixture, as depicted in Fig. 18A-E. A porous network-type structure first appeared in the upper part of the panel from about 14 min (Fig. 18D-F), and then progressively developed over the whole front panel of the OE, as illustrated at 17 min 30 s and after this test in Fig. 18E-F respectively. Fig. 19 shows $q_{b,1}$ (HFS1) and $q_{b,2}$ (HFS2) for T9, and first reveals their increase in compliance with the $q_0$ rise. Next, one minute after the starting of bubble formation, i.e., at about 6 min 30 s, both $q_{b,1}$ and $q_{b,2}$ stopped increasing for about 2 min. The scattering of one fraction of the incident radiative energy by the bubble layer located at the PMMA gas interface [17] could contribute to explain such stop of the heat flux evolutions. Next, beyond 8 min 20 s (500 s), both $q_{b,1}$ and $q_{b,2}$ increased again. These evolutions became steep when the porous network-type structure formed in the upper part of the panel from about 14 min (840 s), as previously discussed. This structure did indeed contain plenty of voids (Fig. 18E-F), which clearly enhanced the transmitted heat flux. Furthermore, the target (bundle of ECS), which was placed close to the PMMA front panel, did not ignite. Indeed, maximum $q_{b,1}$ of 15 kW/m$^2$ (Fig. 19) was significantly lower than $q_{c,ig}$ (35.5 ± 3 kW/m$^2$) required for the spontaneous ignition of this target type.

For T10 (SD of 0.6 m), the bubbling phenomenon was also observed first in the upper part of the PMMA panel as of 3 min 30 s. This is illustrated in Fig. 20A at 10 s before the panel ignition, which occurred at 4 min 10 s. Given the lower SD for this test than for T9 (0.8 m), flames coming from the BE occasionally reached the upper part of the PMMA panel. Therefore, when an adequate concentration of fuel gases in the air was reached, flames ignited the flammable gas mixture close to the top of the PMMA panel. Fire then spread downwards and covered two-thirds of the panel 1 min 20 s after ignition (Fig. 20B). Next, ignited PMMA droplets fell to the raised floor, located underneath the panel, from 6 min (Fig. 20C). Flames then covered the whole PMMA panel, as illustrated in Fig. 20D, at the fire peak (7 min 40 s).

For T11 (SD of 0.7 m), bubbles started to form before 5 min (Fig. 21A) and spread to almost all of the PMMA panel before its ignition that occurred at 8 min 30 s (Fig. 21B). Fire then clearly spread faster over the whole panel than for T10, as illustrated in Fig. 21C-D which show, for T11, the panel fire barely 10 and 30 s respectively after the panel ignition. This could be substantiated by a larger degraded surface of the PMMA panel before ignition for T11 compared with T10 (SD of 0.6 m). Indeed, given the higher SD for T11, the piloted ignition occurred about four minutes later than for T10 when bubbles covered nearly the whole panel while they spread over only the upper half of the panel for T10. Furthermore, the higher PMMA panel temperature before ignition for T11 than for T10, due to the longer heating period, also likely contributed to faster fire spread for the former test. Fig. 22 provides the HRR of the PMMA front panel fires for T10 and T11, which was evaluated using the carbon dioxide generation calorimetry method, as detailed in [18]. The gas burner contribution (300 kW) was subtracted from these assessments. This figure first indicates, for T10, the PMMA panel ignition (1) and a first HRR peak of 270 kW (2). The latter corresponds to the relatively fast downward fire spread over two-thirds of the PMMA panel as previously described. Moreover, Fig. 22 also shows for T10 a maximum HRR peak of 380 kW (3), which was reached about 3 min 30 s after ignition. This event corresponds to the fire spread over the whole PMMA panel. For T11, there was only one significant HRR peak (760 kW, (5)) which was obtained very fast when fire spread over nearly the entire PMMA panel barely 30 s after its ignition
(4), as commented above. This HRR peak was twice as high as the maximum peak obtained for T10. This confirms that the PMMA panel fire for T11 was faster and more powerful (i.e., more severe) than for T10, despite the slightly higher SD for T11 (0.7 m) than for T10 (0.6 m).

Finally, for T12 (SD of 1 m), as seen in Fig. 23, each of the two overhead trays was filled with seventeen electric cables B, as specified in Table 4. The 2.5-m long electric cables were laid tightly along the overhead trays. Shortly after the start of T12, the lower electric cable tray directed flames, coming from the BE, up to the upper part of the OE front panel. This is illustrated a few minutes later in Fig. 24A. Ignition of the PMMA panel was next piloted at 4 min 50 s by flames coming from the BE. Fire then spread downwards and covered one third of the panel 1 min 40 s after ignition (Fig. 24B). Next, as with T10, drippings of ignited PMMA (Fig. 24C) fell to the raised floor. Shortly afterwards, this led to a pool fire on the raised floor which was concomitant with the PMMA panel fire. Accordingly, flames spread from the raised floor to the whole PMMA panel (Fig. 24D).

Fire propagated to the OE when flames, coming from the BE, reached the flammable gas mixture produced by the PMMA panel (i.e., the panel ignition was piloted by flames coming from the BE). This is the FSC for the PMMA front panel which was reached for a maximum SD of 0.7 m or 1 m when overhead electric cable trays were used. For a SD of 0.8 m and without an overhead electric cable tray, no FSC was achieved either by the PMMA panel ignition or by ignition of the target (bundle of ECS) contained in the OE. Finally, the fire severity clearly increased for T11 (SD of 0.7 m) compared to T10, although T11 did not use the lowest SD.

3.4. Transmittance

This section focuses on the assessment of the total transmittance $\Gamma_T$ of the glazed and PMMA front panels. $\Gamma_T$ can be assessed based on the ratio of the total transmitted heat flux to the incident heat flux $q_b/q_o$, as proposed in [14].

3.4.1. Glazed front panel

$\Gamma_T$ is assessed for the 4-mm thick tempered glass panel and the SDs of 0.4 and 0.6 m. In addition, for each SD, $\Gamma_T$ is evaluated from HFS1 ($q_{b,1}$, $q_{o,1}$) and HFS2 ($q_{b,2}$, $q_{o,2}$) measurements. Fig. 25 shows, for $40 \, s < t < 300 \, s$, that the four assessments of $\Gamma_T$ are similar. This first confirms the consistency of the measurements provided by HFS1 and HFS2 and also shows that a moderate change in the heater panel distance has no significant impact on $\Gamma_T$ for $40 \, s < t < 300 \, s$. This last outcome is also reported in [19]. The average of these four measurements of the total transmittance $\Gamma_T$ is then evaluated and shows a continuous increase from 30 to 50% between 40 s and 300 s. Furthermore, $\Gamma_T$ ($q_b/q_o$) is also calculated up to 1200 s for the SDs of 0.4 and 0.6 m from the corresponding $q_{b,1}$ for T4 and T6 (Fig. 10) and $q_o$ (Fig. 11), as shown in Fig. 26. This figure also provides the four previous measurements of $\Gamma_T$ over $40 \, s < t < 300 \, s$ which show a satisfactory agreement with the calculated $\Gamma_T$ over this time period. Fig. 26 also shows that the two calculated $\Gamma_T$ are fairly similar for $40 \, s < t < 1200 \, s$, as confirmed by their relative deviations assessed lower than 20% over this time interval. Finally, Fig. 27 provides $\Gamma_T$ (40 s < t < 300 s) and the average of the two calculations of $\Gamma_T$ (40 s < t < 1200 s). This figure first confirms their similarity over 40 s < t < 300 s and also reveals that the average of the two calculations of $\Gamma_T$ increased from about 30 to 60 % over 10 min before reaching a nearly constant value of about 60 % for about 10 min.

3.4.2. PMMA front panel

$\Gamma_T$ (i.e., $q_b^*/q_o^*$) is assessed for the 3-mm thick clear PMMA panel and the SDs of 0.6 and 0.8 m. Moreover, for each SD, $\Gamma_T$ is evaluated in the same way as for the glazed panel. These evaluations used heat fluxes measured for T9 (SD of 0.8 m), that were previously discussed (section 3.3), and those for

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§Given the setting of the fire power (300 kW) for about 40 s, as commented in section 3.1, $q_b^*/q_o^*$ was evaluated for $t \geq 40 \, s$. Moreover, as the fire stopped at $t = 300 \, s$ for the three tests T1-T3, the measured total transmittance was not assessed beyond that time.
T10 (SD of 0.6 m) which are given in Fig. 28. This figure indicates first sharp rises of $q_{b,1}$ and $q_{b,2}$ as of 260 s. These evolutions, which followed the PMMA panel ignition, did not allow to assess $\Gamma_T$ beyond the above time. Fig. 29 shows, for $40 \leq t \leq 260$ s, that the four assessments of $\Gamma_T$ are close. This is consistent with the outcomes obtained for the glazed panel. $\Gamma_T$ is evaluated based on the four previous measurements, and shows a continuous increase from 15 to 30 % between 40 and 260 s.

Initial $\Gamma_T$ (when $\dot{q}_0 = 0$) is equal to the transmittance $\Gamma$ (i.e., the transmitted to incident heat flux ratio, $\dot{q}_T/\dot{q}_0$). Initial $\Gamma_T$ of 15 %, as above calculated, can therefore be compared to $\Gamma$ measured at 10 % by Linteris et al. [20] for the same type of clear 3-mm thick PMMA sample, but exposed to a black body emitter at 873 K in the spectral range 1.5-10 μm. The two previous values for $\Gamma$ can be considered as fairly similar given that the deviation could be attributed to the heater type. Indeed, although the temperatures of the black body emitter [20] and of the flames in the burning enclosure (BE) at the start, were both close to 873 K, the spectral intensity emitted by the two radiative sources cannot be considered as identical since the flames in the BE were characterized as optically thin (see appendix B). This could explain the slight discrepancy between the two above evaluations of $\Gamma$.

Furthermore, $\Gamma_T$ ($\dot{q}_b/\dot{q}_0$) is also calculated up to 1200 s for the SD of 0.8 m (the PMMA panel did not ignite for this value) from the corresponding $q_{b,1}$ for T9 (Fig. 19) and $q_{b,2}$ (Fig. 11), as shown in Fig. 30. This figure also provides $\Gamma_T$ over $40 \leq t \leq 260$ s and first highlights its consistency with the calculated $\Gamma_T$. This last one is next revealed relatively constant with a value around 30 % for about 8 min. This stage started when bubbles formed from about 5 min 30 s and ended shortly before the porous network-type structure developed from 14 min (section 3.3). However, $\Gamma_T$ slightly decreased to 25 % from about 7 min before slowly regaining the value of about 30 %. This decrease matched with the substantial formation of bubbles in the upper part of the PMMA panel (Fig. 18B) that stopped temporarily the $q_b$ increase (section 3.3). Finally, $\Gamma_T$ increased from 30 % up to above 50 % from 13 min, as a result of the rise of the transmitted heat flux through the porous network-type structure. In short, $\Gamma_T$ first increased from about 15 to 30 % over 5 min before reaching (only for the SD of 0.8 m) a relatively constant value of about 30 % for about 8 min up to the formation of the porous network-type structure. Glass and PMMA are classified as semi-transparent materials since these two materials partially transmit the radiative emission. However, glass could be considered as a relatively transparent material in the visible and near infrared ranges (i.e., in the 0.3-2.4 μm range), as stated in [21] and confirmed by the high value of the spectral transmittance $\Gamma_\lambda$ (> 0.8) in the above wavelength ranges [22]. This could be consistent with the higher $q_b$ (see T6 in Fig. 10 and Fig. 28) and $\Gamma_T$ obtained for the glazed panel than for the PMMA one. Furthermore, the scattering of the incident radiative energy by the bubble layer (section 3.3) could also emphasize the above differences of both $q_b$ and $\Gamma_T$ between the two panel types.

4. Representativeness of the reduced-scale fire tests

Table 5 gives the incident heat fluxes obtained at reduced-scale (i.e., $\dot{q}_0^*$) at 300 and 1000 s as well as the maximum ones estimated for real-scale electrical cabinet fires [13], for three distances from the cabinets of 0.4, 0.6 and 0.8 m. The real-scale electrical cabinet was used to design the reduced-scale enclosures (section 2.1). Table 5 first shows that for each of the three above distances the reduced-scale $\dot{q}_0^*$ at 300 s is lower than the real-scale incident heat flux. Indeed, while flame temperatures at real (973 K, [13]) and reduced-scales (989 K, Fig. 9) are close, the view factors and flame emissivity are higher at real-scale. This is obvious for the view factors due to the scale reduction and also verified for the flame emissivity set at 0.7 at reduced-scale (section 3.1) versus 1 at real-scale [13]. In contrast, Table 5 also shows that for each of the three above distances the reduced-scale $\dot{q}_0^*$ at 1000 s can be higher than or similar to the real-scale incident heat flux. The reduced-scale $\dot{q}_0^*$ increase (Fig. 11) resulted from the flame temperature increase from 989 K at 300 s to 1122 K at 1000 s (Fig. 12), in accordance with Eq. (1). The controlled fire duration of the reduced-scale tests up to about 20 min can therefore lead to similar incident heat fluxes as those obtained at real-scale [13]. Accordingly, the fire spread conditions (FSCs) and the total transmittances, in particular, as determined in this work, are thus assumed to be not specific of the considered reduced-scale test device.

5. Conclusion
The first and main goal of this study was to determine the fire spread conditions (FSCs) from a burning enclosure (BE) to an opposite enclosure (OE) equipped with either a non-combustible (glazed or metallic) or a combustible (PMMA) front panel. The effects on the FSCs of the separation distance (SD) between the opposite enclosures in the 0.4-1 m range, the target type (electrical component) contained in the OE and overhead electric cable trays were also investigated. These tests were also intended to characterize the PMMA front panel fires and, finally, to assess the total transmittances of the glazed and PMMA front panels.

The tests first revealed that fire spread to the OE equipped with a glazed panel when the total transmitted heat flux was similar to that required for the spontaneous ignition of the target. This is the FSC for the glazed front panel which was reached for a bundle of electric cable samples (ECS) used as a target, a SD of either 0.4 m or 0.6 m when overhead electric cable trays were used. The lower electric cable tray indeed directed flames very close to the glazed panel, as occurred for a shorter SD of 0.4 m. Furthermore, fire did not spread to the OE equipped with a 1.5-mm thick metal panel and the minimum SD of 0.4 m. The metal panel reduced the total transmitted heat flux to a greater extent than the glazed panel. The last tests showed that fire propagated to the OE fitted with a PMMA front panel when flames, coming from the BE, reached the flammable gas mixture produced by the PMMA panel (i.e., the panel ignition was piloted by flames coming from the BE). This is the FSC for the PMMA front panel which was reached for a maximum SD of 0.7 m or 1 m when overhead electric cable trays were used. This last outcome confirms the fact that the presence of overhead cable trays favoured the fire spread from a burning enclosure to an enclosure located opposite and equipped with either a PMMA or a glazed front panel. Moreover, characterizations of the PMMA front panel fires also showed that the faster and more powerful fire (i.e., the more severe fire) was not obtained for the minimum SD studied. Finally, the assessments of the total transmittances for the 4-mm thick glazed panel (and a SD of 0.4 and 0.6 m) and 3-mm thick clear PMMA panel (and a SD of 0.8 m) revealed their increase from 30 and 15 % respectively up to nearly steady values of around 60 and 30 % respectively (over about 10-13 min).

The above FSCs and total transmittances, in particular, are assumed to be not specific of the reduced-scale test device considered in this study since the related test conditions provided incident heat fluxes similar as those obtained at real-scale. The results of this study are intended to provide a better understanding of the fire spread issue between electrical cabinets located opposite each other in nuclear power plants as well as in other industrial sectors.

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Appendices.

Appendix A: calculation of the view factors

Fig. A.1 provides the geometric configuration for the calculations of the view factor \( F_{dA-BE} \) for the very small area \( dA \), located at the centre of HFS1 and HFS2 positions, to the flame area related to the burning enclosure (BE). The flame shape (Fig. A.1a) suggests considering a lower vertical flame area \( BE1 \) (height \( b1 \) and width \( 2a \)) and an upper 45° angle inclined flame area \( BE2 \) (length \( b3 + b4 \) and width \( 2a \)). Accordingly, the view factors for \( dA \) to the lower vertical flame area \( F_{dA-BE1} \) (Fig. A.1b) and to the upper inclined flame area \( F_{dA-BE2} \) (Fig. A.1c) are calculated as follows:

\[
F_{dA-BE1} = 2f \left( X = \frac{a}{c1}, Y = \frac{b1 + b2}{c1} \right) - 2f \left( X = \frac{a}{c1}, Y = \frac{b2}{c1} \right)
\]

\[
F_{dA-BE2} = 2f \left( X = \frac{a}{c2}, Y = \frac{b3}{c2} \right) + 2f \left( X = \frac{a}{c2}, Y = \frac{b4}{c2} \right)
\]

Where \( f(X,Y) \) is expressed as follows [23]:

\[
f(X,Y) = \frac{1}{\pi} \left( 1 - \frac{X^2 + Y^2}{4} \right) \]

\[
f(X,Y) = \frac{1}{\pi} \left( 1 - \frac{X^2 + Y^2}{4} \right)
\]
\[ f(X, Y) = \frac{1}{2\pi} \left( \frac{X}{\sqrt{1 + X^2}} \tan^{-1} \left( \frac{Y}{\sqrt{1 + X^2}} \right) + \frac{Y}{\sqrt{1 + Y^2}} \tan^{-1} \left( \frac{X}{\sqrt{1 + Y^2}} \right) \right) \] 

(A.3)

And \( c_1 \) and \( c_2 \) are the distances from \( dA \) to the lower and upper flame areas, respectively, \( b_2 \) is the height difference between the \( dA \) height (0.75 m) and the lower vertical flame area height \( b_1 \), and \( a \) is half of the enclosure width (0.3 m). The geometric configuration parameters \((a, b_1, b_2, b_3, b_4, c_1, c_2)\) and view factors \( F_{dA-BE1} \) and \( F_{dA-BE2} \), calculated for the three SDs of 0.4, 0.6 and 0.8 m (tests T1-T3, respectively), are given in Table A.1. Finally, \( F_{dA-BE} \) is obtained as follows:

\[ F_{dA-BE} = F_{dA-BE1} + F_{dA-BE2} \] 

(A.4)

Regarding the calculations of the view factor for \( dA \) to the back wall of the burning enclosure \( F_{dA-BW} \), the following relationship is used:

\[ F_{dA-BW} = 2f \left( X = \frac{a}{c_3}, Y = \frac{b_5}{c_3} \right) + 2f \left( X = \frac{a}{c_3}, Y = \frac{b_6}{c_3} \right) \] 

(A.5)

Where \( c_3 \) is the distance separating the back wall of BE and the front panel of the opposite cabinet (sum of the BE depth and SD), \( b_5 \) and \( b_6 \) are the distances from \( dA \) to the opposite enclosure floor and ceiling respectively (same as those for HFS1 and HFS2). The geometric configuration parameters \((a, b_5, b_6, c_3)\) and the view factor \( F_{dA-BW} \), calculated for the SDs of 0.4, 0.6 and 0.8 m are given in Table A.2.

**Appendix B: assessment of the flame optical thickness**

Considering the radiation emitted by the flames of the burning enclosure to be that from a homogeneous and isothermal equivalent medium, the spectral intensity emitted by the radiative source \( I_\sigma \) can be given as follows [24]:

\[ I_\sigma = (1 - \Gamma(\sigma)) I_{bb}(T) \] 

(B.1)

Where \( \sigma \) is the wavenumber (cm\(^{-1}\)), \( \Gamma \) is the flame transmittance (-) and \( I_{bb}(T) \) is the blackbody intensity at the equivalent flame temperature \( T \) (W.m\(^{-2}\).sr\(^{-1}\).cm) [25]. \( \Gamma \) can be related to the optical thickness of the flame \( \tau \) as proposed in [24]:

\[ \Gamma(\sigma) = \exp(-\tau(\sigma)) \] 

(B.2)

Accordingly, \( I_\sigma \) can now be written as follows:

\[ I_\sigma = (1 - \exp(-\tau(\sigma))) I_{bb}(T) \] 

(B.3)

Thus, according to the values of \( \tau \), the flames of the burning enclosure (BE) can be either optically thick (\( \Gamma \approx 0 \) and their emission is similar to that of a blackbody) or thin (\( \Gamma \neq 0 \) and surrounding emission can be partially transmitted through the flame thickness). \( \tau \) can be assessed according to [24] using the following relationship:

\[ \tau(\sigma) = \beta_o \left( \frac{\sigma}{\sigma_o} \right)^{a} L \] 

(B.4)
Where $\beta_0$ is the extinction coefficient at a reference wavenumber $\sigma_0$ ($\sigma_0=4000 \text{ cm}^{-1}$ as chosen in [24]) expressed in m$^{-1}$, $\alpha$ is the non-integer exponent (-) and $L$ the geometrical thickness of the flames (m). The characteristic flame shape of the BE (Fig. 6) suggests considering for $L$ minimum and maximum values of 0.6 and 1 m respectively. The former value corresponds to the BE depth while the latter corresponds to that reached at the top of the BE (Fig. 6). Furthermore, in accordance with [24], $\beta_0$ is taken to be 1.74 and 2.1 m$^{-1}$ and $\alpha$ 1.07 and 1, for $L$ set at 0.6 and 1 m, respectively. $\tau$ is calculated from Eq. (B.4) in the 2000 - 5000 cm$^{-1}$ wavenumber range where the main part of the radiation energy emitted by the flames from the burning enclosure is expected to be found. Table B.1 reports that the calculated values of $\tau$ and those for the related flame transmittance $\Gamma$, deduced from Eq. (B.2), fall in the 0.5 - 2.65 and the 0.05 - 0.65 ranges, respectively. Accordingly, the flames of the BE, whose geometrical thickness varies between 0.6 and 1 m, are therefore optically thin (i.e., $\Gamma \neq 0$). Surrounding emission, such as that from the back wall of the BE, can therefore be partially transmitted through the flame thickness. Based on the values provided in Table B.1, an average transmittance can be calculated for $L = 0.6 \text{ m} (0.42) \text{ and } L = 1 \text{ m} (0.19)$. Finally, a global transmittance of 0.3 for the flames in the BE can be deduced from the average of the two previous values. This gives a global flame emissivity $\varepsilon_F$ of 0.7 which is considered for the calculations of the incident heat flux to the front panel of the opposite enclosure (section 3.1).

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Table 1: Specifications of the opposite enclosure front panels.

<table>
<thead>
<tr>
<th>Front panel</th>
<th>Trademark</th>
<th>Specific features</th>
<th>Density (kg/m³)</th>
<th>Length (mm)</th>
<th>Height (mm)</th>
<th>Thickness (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Glazed</td>
<td>SECURIT©</td>
<td>Tempered</td>
<td>2500</td>
<td>600</td>
<td>1000</td>
<td>4</td>
</tr>
<tr>
<td>Metallic</td>
<td>- Steel</td>
<td></td>
<td>7900</td>
<td>600</td>
<td>1000</td>
<td>1.5</td>
</tr>
<tr>
<td>PMMA</td>
<td>PERSPEX©</td>
<td>Cast and clear PMMA</td>
<td>1190</td>
<td>600</td>
<td>1000</td>
<td>3</td>
</tr>
</tbody>
</table>

Abbreviations: PMMA, poly(methyl methacrylate).
Table 2: Specifications of the electrical components which composed the targets contained in the opposite enclosure.

<table>
<thead>
<tr>
<th>Electrical component</th>
<th>Supplier specification</th>
<th>Material composition</th>
</tr>
</thead>
<tbody>
<tr>
<td>ECS</td>
<td>U1000R02V 3x2.5 mm²</td>
<td>PVC (sheath material) and XLPE (insulation material)</td>
</tr>
<tr>
<td>TB</td>
<td>TB 4/6 1SNA 115 116 R0700</td>
<td>Polyamide</td>
</tr>
</tbody>
</table>

Abbreviations: ECS, electric cable samples; PVC, poly(vinyl chloride); TB, terminal blocks; XLPE, Cross-linked polyethylene.
Table 3: Fire test matrix.

<table>
<thead>
<tr>
<th>Test ID</th>
<th>Front panel type</th>
<th>SD (m)</th>
<th>Target type</th>
<th>Overhead electric cable trays (Y/N)</th>
</tr>
</thead>
<tbody>
<tr>
<td>T1</td>
<td>Without</td>
<td>0.4</td>
<td>Without</td>
<td>N</td>
</tr>
<tr>
<td>T2</td>
<td>Without</td>
<td>0.6</td>
<td>Without</td>
<td>N</td>
</tr>
<tr>
<td>T3</td>
<td>Without</td>
<td>0.8</td>
<td>Without</td>
<td>N</td>
</tr>
<tr>
<td>T4</td>
<td>Glazed</td>
<td>0.4</td>
<td>Sets of TB</td>
<td>N</td>
</tr>
<tr>
<td>T5</td>
<td>Glazed</td>
<td>0.4</td>
<td>Bundle of ten ECS</td>
<td>N</td>
</tr>
<tr>
<td>T6</td>
<td>Glazed</td>
<td>0.6</td>
<td>Bundle of ten ECS</td>
<td>N</td>
</tr>
<tr>
<td>T7</td>
<td>Glazed</td>
<td>0.6</td>
<td>Bundle of ten ECS</td>
<td>Y</td>
</tr>
<tr>
<td>T8</td>
<td>Metallic</td>
<td>0.4</td>
<td>Bundle of ten ECS</td>
<td>N</td>
</tr>
<tr>
<td>T9</td>
<td>PMMA</td>
<td>0.8</td>
<td>Bundle of ten ECS</td>
<td>N</td>
</tr>
<tr>
<td>T10</td>
<td>PMMA</td>
<td>0.6</td>
<td>Bundle of ten ECS</td>
<td>N</td>
</tr>
<tr>
<td>T11</td>
<td>PMMA</td>
<td>0.7</td>
<td>Bundle of ten ECS</td>
<td>N</td>
</tr>
<tr>
<td>T12</td>
<td>PMMA</td>
<td>1</td>
<td>Bundle of ten ECS</td>
<td>Y</td>
</tr>
</tbody>
</table>

Abbreviations: ECS, electric cable samples; PMMA, poly(methyl methacrylate); SD, separation distance; TB, terminal blocks.
Table 4: Specifications of the electric cables installed along the overhead trays (T7 and T12 tests).

<table>
<thead>
<tr>
<th>Cable ID</th>
<th>Related test</th>
<th>Supplier specification</th>
<th>Material composition</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cable A</td>
<td>T7</td>
<td>Power cable ALSECURE 0.6/1 kV 3x2.5 mm²</td>
<td>Polyolefin, XLPE and halogen-free flame retardant</td>
</tr>
<tr>
<td>Cable B</td>
<td>T12</td>
<td>Power cable NYM-J 5x25 mm² RM GRAU</td>
<td>PVC and PE</td>
</tr>
</tbody>
</table>

Abbreviations: PE, polyethylene; PVC, poly(vinyl chloride); XLPE, Cross-linked polyethylene.
Table 5: Incident heat flux obtained for the reduced and real-scale cabinet fires.

<table>
<thead>
<tr>
<th>Distance from the cabinet (m)</th>
<th>0.4</th>
<th>0.6</th>
<th>0.8</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reduced-scale incident heat flux ($q_0$) at 300 s (kW/m²)</td>
<td>33</td>
<td>22.5</td>
<td>16</td>
</tr>
<tr>
<td>Reduced-scale incident heat flux ($q_0$) at 1000 s (kW/m²)</td>
<td>55</td>
<td>37</td>
<td>26</td>
</tr>
<tr>
<td>Maximum real-scale incident heat flux [13] (kW/m²)</td>
<td>45</td>
<td>37</td>
<td>30</td>
</tr>
</tbody>
</table>

Abbreviations: $q_0$, incident heat flux calculated at the centre of HFS1 and HFS2 positions.
Table A.1: Geometric configuration parameters used to assess $F_{dA-BE1}$ and $F_{dA-BE2}$ view factors.

<table>
<thead>
<tr>
<th>Test ID</th>
<th>a (m)</th>
<th>b1 (m)</th>
<th>b2 (m)</th>
<th>b3 (m)</th>
<th>b4 (m)</th>
<th>c1 (m)</th>
<th>c2 (m)</th>
<th>$F_{dA-BE1}$</th>
<th>$F_{dA-BE2}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>T1</td>
<td>0.3</td>
<td>0.65</td>
<td>0.1</td>
<td>0.36</td>
<td>0.21</td>
<td>0.4</td>
<td>0.21</td>
<td>0.197</td>
<td>0.688</td>
</tr>
<tr>
<td>T2</td>
<td>0.3</td>
<td>0.65</td>
<td>0.1</td>
<td>0.5</td>
<td>0.15</td>
<td>0.6</td>
<td>0.35</td>
<td>0.150</td>
<td>0.439</td>
</tr>
<tr>
<td>T3</td>
<td>0.3</td>
<td>0.65</td>
<td>0.1</td>
<td>0.63</td>
<td>0.13</td>
<td>0.8</td>
<td>0.5</td>
<td>0.112</td>
<td>0.302</td>
</tr>
</tbody>
</table>
Table A.2: Geometric configuration parameters used to assess $F_{dA-BW}$ view factor.

<table>
<thead>
<tr>
<th>Test ID</th>
<th>a (m)</th>
<th>b5 (m)</th>
<th>b6 (m)</th>
<th>c3 (m)</th>
<th>$F_{dA-BW}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>T1</td>
<td>0.3</td>
<td>0.75</td>
<td>0.25</td>
<td>1</td>
<td>0.145</td>
</tr>
<tr>
<td>T2</td>
<td>0.3</td>
<td>0.75</td>
<td>0.25</td>
<td>1.2</td>
<td>0.108</td>
</tr>
<tr>
<td>T3</td>
<td>0.3</td>
<td>0.75</td>
<td>0.25</td>
<td>1.4</td>
<td>0.083</td>
</tr>
</tbody>
</table>
Table B.1: Optical length of the flames of the BE and the related flame transmittance

<table>
<thead>
<tr>
<th>( \sigma ) (cm(^{-1}))</th>
<th>( L = 0.6 ) m</th>
<th>( L = 1 ) m</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>( \tau(\sigma) ) (-)</td>
<td>( \Gamma(\sigma) ) (-)</td>
</tr>
<tr>
<td>2000</td>
<td>0.50</td>
<td>0.61</td>
</tr>
<tr>
<td>3000</td>
<td>0.77</td>
<td>0.46</td>
</tr>
<tr>
<td>4000</td>
<td>1.04</td>
<td>0.35</td>
</tr>
<tr>
<td>5000</td>
<td>1.33</td>
<td>0.27</td>
</tr>
</tbody>
</table>

Abbreviations: BE, burning enclosure; \( L \), geometrical flame thickness; \( \sigma \), wavenumber; \( \Gamma \), flame transmittance; \( \tau \), optical thickness of the flame.
Overhead ladder type trays
Closed ventilation
2 grids
Burning enclosure
Opposite enclosure
Raised floor
SD
Front panel
Fig. 1: Test device.
Fig. 2: View of the BE with the gravel-packed gas burner located at its bottom and the front panel removed. BE, Burning enclosure.
Fig. 3: View of the OE equipped with a glazed front panel and three sets of terminal blocks used as target. HFS, Heat flux sensor. OE, Opposite enclosure.
Fig. 4: View of the OE equipped with a PMMA front panel and a bundle of ten electric cable samples used as target. HFS, Heat flux sensor. OE, Opposite enclosure.
Fig. 5: Overview of the test device positioned under a large-scale calorimeter.
Fig. 6: Characteristic flame shape obtained for all the tests, as illustrated e.g., for test T6 (SD of 0.6 m).
Fig. 7: Test device for T3.
Fig. 8: Measured and calculated incident heat fluxes.  
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C. SD = 0.8 m (T3).
Fig. 9: Flame temperature measured at the centre of the BE (TC1) for tests T2-T11 and the average flame temperature ($0 \leq t \leq 300$ s). BE, burning enclosure.
Fig. 10: Back surface heat flux for the glazed front panel and for the SDs of 0.4 and 0.6 m (T4-T6). A. HFS1. B. HFS2.
Fig. 11: Measured (HFS1, $0 \leq t \leq 300$ s) and calculated ($0 \leq t \leq 1200$ s) incident heat fluxes.
Fig. 12: Flame temperature measured at the centre of the BE (TC1) for tests T2-T11 and the average flame temperature ($0 \leq t \leq 1200$ s). BE, burning enclosure.
Fig. 13: Test device for T7.
Fig. 14: Overview of the test device for T7. A. Fire start (1 min). B. Overhead cable fire peak (10 min 30 s).
Fig. 15: Back surface heat flux (HFS2) for all the tests (T4-T7) which used a glazed front panel.
Fig. 16: Test device for T8.
Fig. 17: Back surface heat flux (HFS1) for T5 (glazed panel) and T8 (metallic panel), SD = 0.4 m.
Fig. 18: View of the opposite enclosure for T9. A, B and C. bubble formation at 6 min 30 s, 7 min 30 and 9 min 30 s, respectively. D, E and F. Porous network-type structure at 14 min, 17 min 30 s and after the test, respectively. BE, burning enclosure.
Fig. 19: Back surface heat flux for the PMMA front panel and a SD of 0.8 m (T9).
Fig. 20: View of the opposite enclosure for T10. A. 10 s before the panel ignition (4 min). B. End of the downward fire spread step (5 min 30 s). C. Drippings of ignited PMMA (6 min). D. Fire peak (7 min 40 s).
Fig. 21: View of the opposite enclosure for T11. A. At 5 min. B and C. 10 s before (8 min 20 s) and 10 s after (8 min 40 s) the PMMA panel ignition, respectively. D. At the fire peak (9 min).
Fig. 22: Heat release rate of the PMMA panel fires for T10 and T11 (without the gas burner contribution).
Fig. 23: Test device for T12.
Fig. 24: View of the opposite enclosure for T12. A. 10 s before the panel ignition (4 min 40 s). B. End of the downward fire spread step (6 min 30 s). C. Ignited drippings of PMMA (7 min). D. Fully-developed fire (8 min 30 s). OE, opposite enclosure.
Fig. 25: Measurements ($40 \, s < t < 300 \, s$) of the total transmittance for the tempered glass panel.

Fig. 26: Measurements ($40 \, s < t < 300 \, s$) and calculations ($40 \, s < t < 1200 \, s$) of the total transmittance for the tempered glass panel.

Fig. 27: Average of the measurements ($40 \, s < t < 300 \, s$) and of the calculations ($40 \, s < t < 1200 \, s$) of the total transmittance for the tempered glass panel.
Fig. 28: Back surface heat flux for T10.
Fig. 29: Measurements ($40 \leq t \leq 260$ s) of the total transmittance for the clear PMMA panel.

Fig. 30: Calculation ($40 \leq t \leq 1200$ s) and average of the measurements ($40 \leq t \leq 300$ s) of the total transmittance for the clear PMMA panel.
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- **A** located at the centre of HFS1 and HFS2.