Experimental investigation of the effects of a sidewall and cable arrangement on a horizontal cable tray fire in an open atmosphere

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Abstract

The work deals with the influence of a sidewall and cable arrangement on the behavior of a fire involving horizontal cable trays in the framework of fire safety assessments in nuclear installations. The analysis is based on large-scale fire tests performed in open atmosphere in the frame of the OECD Nuclear Energy Agency (NEA) PRISME 3 project and on the corresponding simulations applying the FLASHCAT model for predicting the fire heat release rate. The fire configuration consists in five horizontal trays filled with PVC insulated power cables. The parameters investigated are the presence or absence of a sidewall and the cable arrangement (loose or tight bundles). The results show that the presence of a sidewall increases the fire HRR in comparison to a scenario without a sidewall. This effect is due to the increase of the flame spread velocity on the lower trays. Regarding cable arrangement, a tight configuration in bundles reduces the fire HRR in comparison to a scenario with a loose arrangement. This result is due to the reduction of the fire heat release rate per unit of area (HRRPUA) as well as the flame spread velocity. The performance of the FLASHCAT model in predicting the effects of the sidewall and the cable arrangement was also assessed on the basis of the fire tests and satisfactory agreements are reported. The presented analysis demonstrates that the fire scenario with horizontal cable trays against a sidewall and with a loose cable arrangement represents a conservative scenario for fire risk assessment. In addition, on the basis of these experiments, the effect of cable arrangement is more substantial than the sidewall effect.

Keywords: cable tray fire, sidewall, cable arrangement, PVC, FLASHCAT model

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A	Burning area (m^2)
D	Diameter (m)
E	Thickness (m)
H	Height (m)
K	Coefficient (-)
L	Length (m)
$m_c^{''}$	Mass of combustible matter per unit of area (kg/m^2)
m'	Mass of cable per unit of length (kg/m)
n	Number of cables (#)
P	Perimeter (m)
$\dot{q}''$	Heat release rate per unit of area, HRRPUA (kW/m^2)
$\dot{Q}$	Fire Heat release rate, HRR, (kW)
t	Time (s)
Vx	Horizontal flame spread velocity (m/s)
V	Vertical flame spread velocity (m/s)
W	Width (m)
Y_p	Fraction of combustible matter (-)
λ	Thermal conductivity (W/m/K)
Δt	Fire duration of an element dx (s)
ΔH	Combustion enthalpy (J/kg)
ν	Fraction of char (-)

1 Introduction

Electrical cable fires remain one of the key topics in fire safety assessment for industrial facilities and nuclear power plants (NPPs) in particular. Electrical cables are largely encountered in the installations and are considered as a major potential fire source. Many efforts have been made to enhance the prevention of cable tray fires in the most recent NPPs. For instance, flame retardant materials are used in cables [1]. Nevertheless, nearly eighty fire events involving electrical cables were recorded between the late 1980ies and the end of 2019 in NPPs [2]. The safety assessment of such fire events remains a key issue and the performance of the assessment depends on the understanding of the fires and the ability of fire models to predict inherent behavior.

To date, a significant number of research studies have been conducted in order to improve the understanding of electrical cable tray fires. In the 1970ies, after the Brown's Ferry nuclear power plant fire event, numerous projects, supported by the U.S. NRC among other agencies, were initiated focusing on several aspects of cable tray fires as a fire source, detection and suppression [3]. Studies related to key cable characteristics in the understanding of cable fire were then conducted, such as those performed as part of the FIPEC project [4]. More recently, the CHRISTIFIRE project, supported by the U.S. NRC, ran a significant number of fire tests involving cable trays with different features (type of cable, number of trays, confinement and ceiling effect) [5]. This project proposed a global model, FLASHCAT, able to predict the fire HRR of horizontal cable tray fires. These efforts regarding fire tests and modeling have been pursued within the frame of the OECD/NEA PRISME projects conducted by IRSN looking more specifically at practical configurations in mechanically-ventilated compartments [1], [6].

The parameters that influence horizontal cable tray fires in an open atmosphere are the cable characteristics (combustion enthalpy, heat release rate per unit of area, load per unit of length and the fraction of combustible material, as well as the structure of the cable) and the tray assembly characteristics (the number and dimensions of the trays and the vertical distance between trays). Some of these input parameters are well-known and can be introduced into fire models with confidence. However, there are two important features of the cable tray whose influence on fire characteristics and how these features should be introduced into the fire model remain under investigation. These features are the presence of a sidewall and the cable arrangement.

A cable tray set against a sidewall is the most common configuration in NPPs, and in other many industrial sectors, therefore the effects of a sidewall on fire heat release rate is an important issue. Tests performed as part of the CHRISTIFIRE and PRISME projects led to the conclusion that the presence of a sidewall contributes to enhancing the fire HRR. In the CHRISTIFIRE project, only fire tests in corridor environments were performed with a sidewall, whereas for the PRISME project, all fire tests were conducted with a sidewall. A modification of the FLASHCAT model was recently proposed in order to take into account the sidewall effect and a comparison with CHRISTIFIRE and PRISME tests is proposed [7]. However, few fire tests focusing exclusively on changes due to the presence of a sidewall have been performed, which would provide a basis for a strict comparative study [4]. The present contribution proposes to investigate further this question based on new fire tests performed in the frame of the OECD/NEA PRISME 3 project [8] with and without a sidewall, aiming to identify the effect of this feature on the two important parameters in the FLASHCAT model: time to ignition for each tray and flame spread velocities.

A second important parameter is the cable arrangement. Just like the effect of a sidewall, both CHRISTIFIRE and PRISME projects also contributed to identifying the significant influence of the cable arrangement on cable tray fires. A dense or loose arrangement, orderly or disorderly, may significantly change the time to ignition of each successive tray as well as the horizontal flame spread velocity [9], [10]. The dense arrangement slows down the vertical propagation of the flame while the loose arrangement contributes to increasing the burning area of the cables. This feature has also been demonstrated by cone calorimeter tests when investigating the effect of the distance between cables [11]. The larger the distance between cables, the higher the heat release rate per unit of area. The effects of the way the cables are packed densely (in one layer or two layers) have also been investigated, showing the blockage effect of a two-layer configuration [12]. The present contribution proposes to discuss a new dense cable configuration in isolated packages or bundles.

The objectives of the present contribution are therefore to improve our understanding of the effects of a sidewall and the cable arrangement on a given scenario. The study is based on large scale fire tests involving five trays filled with PVC cables and performed in an open atmosphere as well as simulations using the FLASHCAT model. First the fire tests are presented, then the effects of the cable arrangement and the sidewall are analyzed based on large-scale tests. Finally, an analysis of the capability of the FLASHCAT model to predict these two effects is proposed.

2 Fire tests and data processing

Large-scale fire tests in an open atmosphere performed in the frame of the OECD/NEA PRISME 3 project (test campaign named CFP for Cable Fire Propagation, [8]) are considered. The fire source consisted of five horizontal ladder type trays with a width of 450 mm and a length of 3000 mm (see Fig. 1).

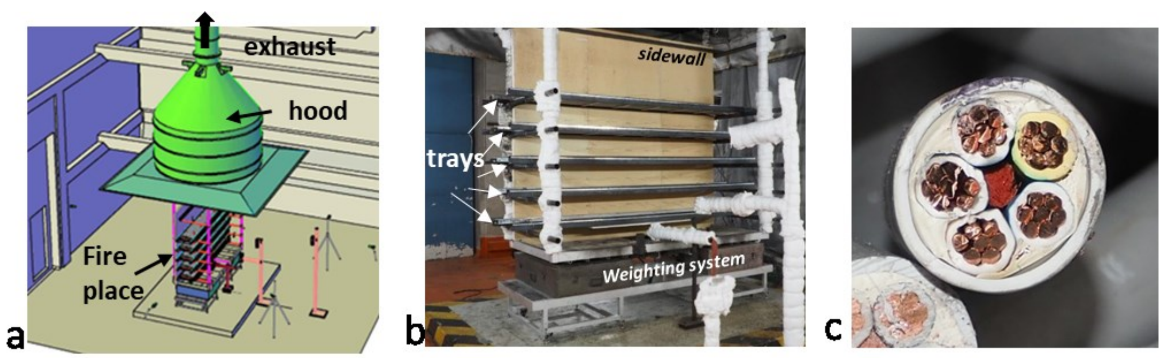

Fig. 1. Pictures of the test set-up (a), the fire location with a vertical stack of five horizontal cable trays (b), and the cable section with five conductors (c).

The vertical distance between the cable trays was 300 mm. The trays were laid on metallic frames with vertical and horizontal round iron tubes thermally insulated with rock-wool. For two tests only, the trays were arranged against a vertical sidewall (e = 40 mm, l = 2600 m, H = 2200 mm) made of insulated material (Superwool 607 HT Board, 350 kg/m^3, thermal conductivity λ = 0.11 W/m/C at 600°C). Each tray was filled with 21 samples of cables with a length of 2400 mm. The cable type was a power cable that contained Poly(Vinyl Chloride) (PVC) in the gray external filler but also polyethylene (PE) in the white inner filler insulation. The cable had an external diameter of 28 mm and a load of 1.75 kg/m (measured onsite before the test) and comprised five conductors with a 25 mm^2 section. This cable had been used in previous studies for studying cable arrangements in [12] or ignition [13] as well as in the PRISME project [6], [14]. The total cable mass represented 442.7 kg and the fraction of combustible matter was estimated at 20 %. The combustible material was ignited by a 80 kW propane square sand burner located 0.2 m below the lowest tray and at the center of the tray. The sand burner was turned off as soon as the total fire HRR reached about 400 kW (about 3 to 4 min after ignition for all tests).

The fire source was placed under the 3 MW hood of the IRSN Galaxie platform, which was identical to the facility used in [14], equipped with suitable measurement techniques such as computing time variation in the fire HRR from calorimetry methods. The exhaust line downstream of the hood was equipped with a bidirectional velocity probe (or averaging Pitot probe), pressure transducers and thermocouples for mass flow rate measurements and gas analyzers for oxygen, carbon dioxide and carbon monoxide concentrations. The whole fire source including the metallic frame was placed on two weighing systems in order to record variation in mass loss over time. Fourteen K-Type thermocouples were installed uniformly along each of the first four trays and ten along the fifth tray in order to determine the horizontal flame spread velocity.

Three tests were performed with the same configuration except the presence of a sidewall and the cable arrangement (see Table 1). The first test PR3_CFP_S0 is a reference test with a sidewall and disorderly loose cable arrangement as illustrated in Fig. 2. The second test named PR3_CFP_S1 aimed to investigate the effects of the cable arrangement. The arrangement was dense but split into 3 packages or bundles of 7 samples. This configuration simulated a practical situation that mixed an arrangement with packed cables, but also with free passages through the tray. The third test PR3_CFP_S2 test was identical to the test PR3_CFP_S0 except that there was no sidewall in order to investigate the effects of a sidewall.

Table 1: Main features of the fire tests.

Features	PR3_CFP_S0	PR3_CFP_S1	PR3_CFP_S2
Sidewall	YES	YES	NO
Cable arrangement	LOOSE	TIGHT	LOOSE

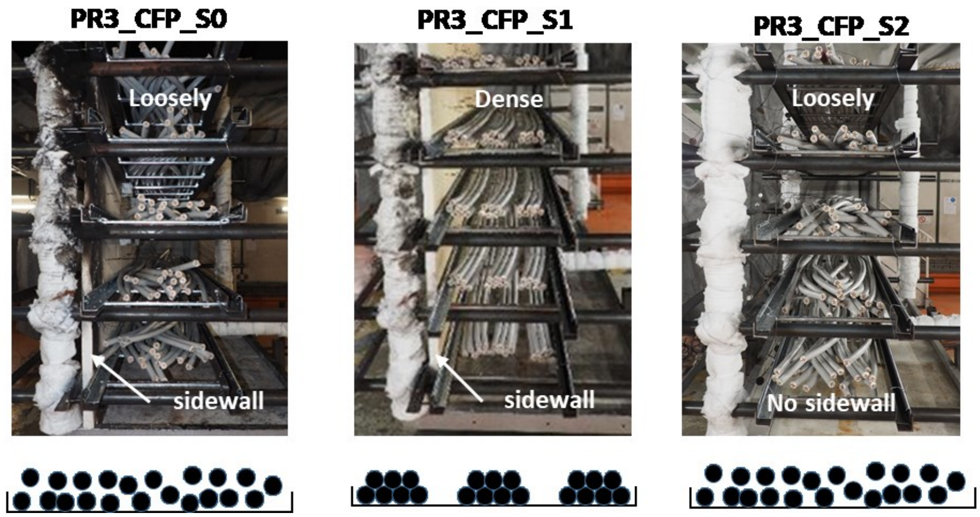

Fig. 2. Pictures of the cable trays illustrating the presence of sidewall and the cable arrangement.

Measurement uncertainties were evaluated from calibration tests, carried out before or after the tests, and from the data provided by the sensor manufacturers. The calibration tests involved obtaining differences between standard values (from specific calibrated sensors or samples) and measured values, read from the data acquisition system. Two levels of uncertainties were defined using the procedure given by Hamins [15]. Standard uncertainties were obtained at room temperature without fire. A second level, expanded uncertainty, took into account the fire test conditions and test repeatability, and was introduced by applying a coverage (or correction) factor to standard uncertainty (Table 2). The relative uncertainty of 7 % applied for air flow rate measurements in the exhaust hood was assessed based on qualification tests.

Table 2: Measurement uncertainties.

Physical variable	Range	Standard Uncertainty	Coverage Factor	Expanded Uncertainty
Mass	(0 - 600) kg	0.002 kg	2	0.004 kg
O2 molar fraction	(0 - 25) %	0.2 %	2	0.4 %
Gas temperature	(0 - 1300) °K	2°K	2	4°K
Plume temperature	(0-1300) °K	8°K	2	16°K

The quantities prepared were estimated from the raw measurements. These included the fire heat release rate from chemical methods (oxygen consumption (OC) and carbon dioxide generation (CDG)), the flame spread velocity and the fire HRR per unit of the area, HRRPUA. The methodology used is described below.

The fire HRR was determined by calculating the oxygen mass loss rate and the carbon dioxide mass flow rate at the hood exhaust according to a methodology promoted by Janssen [16] and widely used in the fire community [17]. The uncertainty determined from the reference propane fire was assessed as 6 % (maximum uncertainty between the two OC and CDG methods).

The vertical and horizontal flame spread velocities were deduced from the temperature measurements above each tray considering the time the flame front is passing over each thermocouple and the distances between thermocouples. Mean horizontal flame spread velocities were then determined for each tray.

The fire HRRPUA versus time was determined as the ratio between the fire HRR and the burning area, both determined experimentally and time dependent. The burning area A(t) was determined from the vertical and horizontal flame spread velocities determined experimentally as mentioned previously. The relationship for the burning area of a tray "i" is approximated with the following relation:

$$A^i(t) = \begin{cases} 0 & t < t_1^i \\ 2k_i w V_x^i (t - t_1^i) & t \in [t_1^i; t_2^i] \\ 2k_i w l_{max} & t > t_2^i \end{cases} \quad \text{with } t_1^i = \frac{i \times h}{v} \quad \text{and} \quad t_2^i = \frac{l_{max}}{V_x^i} + t_1^i \qquad (1)$$

$$A(t) = \sum_{i=1}^{n} A^i(t)$$

The variable w is the width of the cable tray (or the combustible material), V_x^i is the horizontal flame spread velocity determined experimentally for the tray i. The coefficient k expresses the possibility of considering burning on both sides (upper and lower) or on one side only. For instance, for the three tests considered here, it is set to one side for the lowest tray on the basis of video analysis. The length l_{max} is the length of the burning material (here half of the length of the cable tray, 2.4/2 = 1.2 m since ignition occurs at the centre of the cable tray). The times t_1^i and t_2^i are the time the first tray ignites and the time the flame reaches the tray's end. Three stages, depending on time, are identified. In the first stage, the tray has not yet ignited. In the second stage, the flame spreads horizontally at a constant velocity V_x^i (the burning area increases linearly with time). During the last stage, the burning area is constant and equal to the total area of the tray. The total burning area is the sum of the burning area of each tray. The maximum area for one tray can be computed as $2 \times k_i \times w \times l_{max}$. If both sides of the tray are totally burnt, the total area for the five trays is 2×(2× 0.45)×(1.2)×5 = 10.8 m^2. It is worth noting that these relationships are only valid during the propagation phase until the entire surface is burning and do not include the extinction process and thus the reduction in the burning area. This calculation is therefore performed for a limited period of time before tray extinction starts but can still give valuable information regarding the HRRPUA.

As mentioned previously, relation (1) is an approximate of the effective burning area. Different propositions can be made considering the interfacial area in contact with the surrounding air (cases (a) for loose arrangement and (b) for tight arrangement in Fig. 3) In practice, this parameter is difficult to assess due the cable arrangement. The approximation proposed in this analysis is to consider a burning area constant whatever the cable arrangement and equal to the dimension of the tray, no consideration of the cable dimension is introduced (case (c) in Fig. 3. This assumption is also considered in FLASHCAT model. The factor 2 considering the two faces of the trays have been introduced by Zavaleta & al. [14].

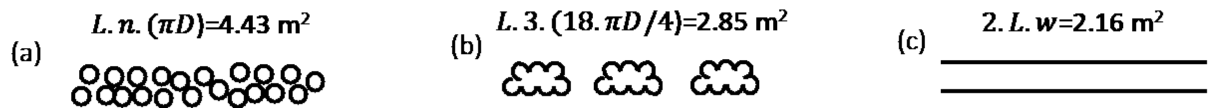

Fig. 3. Illustration of three approaches for estimating the burning area (values correspond to the total area for one tray with 21 2.4 m length cables of 28 mm diameter).

3 Experimental analysis

3.1 Effect of a sidewall

In comparison to a configuration without a sidewall, the sidewall increases the maximum MLR and HRR, but does not modify combustion enthalpy, as shown in Fig. 4 illustrating the variation in MLR, HRR, and combustion enthalpy over time. This effect is mainly reported for the amplitude of the maxima (2160 kW with sidewall and 1900 kW without, which correspond to a reduction of about 12 %). Regarding the global trend, variations in MLR and HRR over time are similar. The reduction in the maximum amplitudes leads to a change in the total mass burned: 81.1 kg (18.3% of the total mass) with sidewall and 77.5 kg (17.5 % of the total mass) without sidewall. The reduction in the MLR without a sidewall is correlated to a longer fire duration (4155 s with sidewall and 5160 s without). The sidewall effect is not reported for combustion enthalpy which shows a progressive increase versus the mass burned from about 15 MJ/kg to 30 MJ/kg. This is explained by the change in the combustible matter. First, the external sheath in PVC (16 MJ/kg) burned and then the insulated thermal filler insulation partially made of PE (40 MJ/kg).

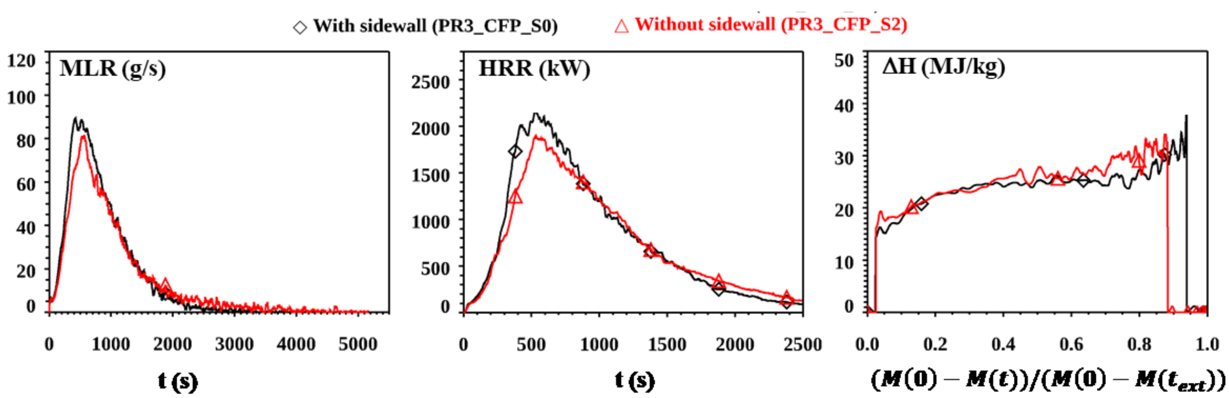

Fig. 4. Effects of the sidewall (with for PR3_CFP_S0 test and without for PR3_CFP_S2 test) on the MLR, HRR and combustion enthalpy.

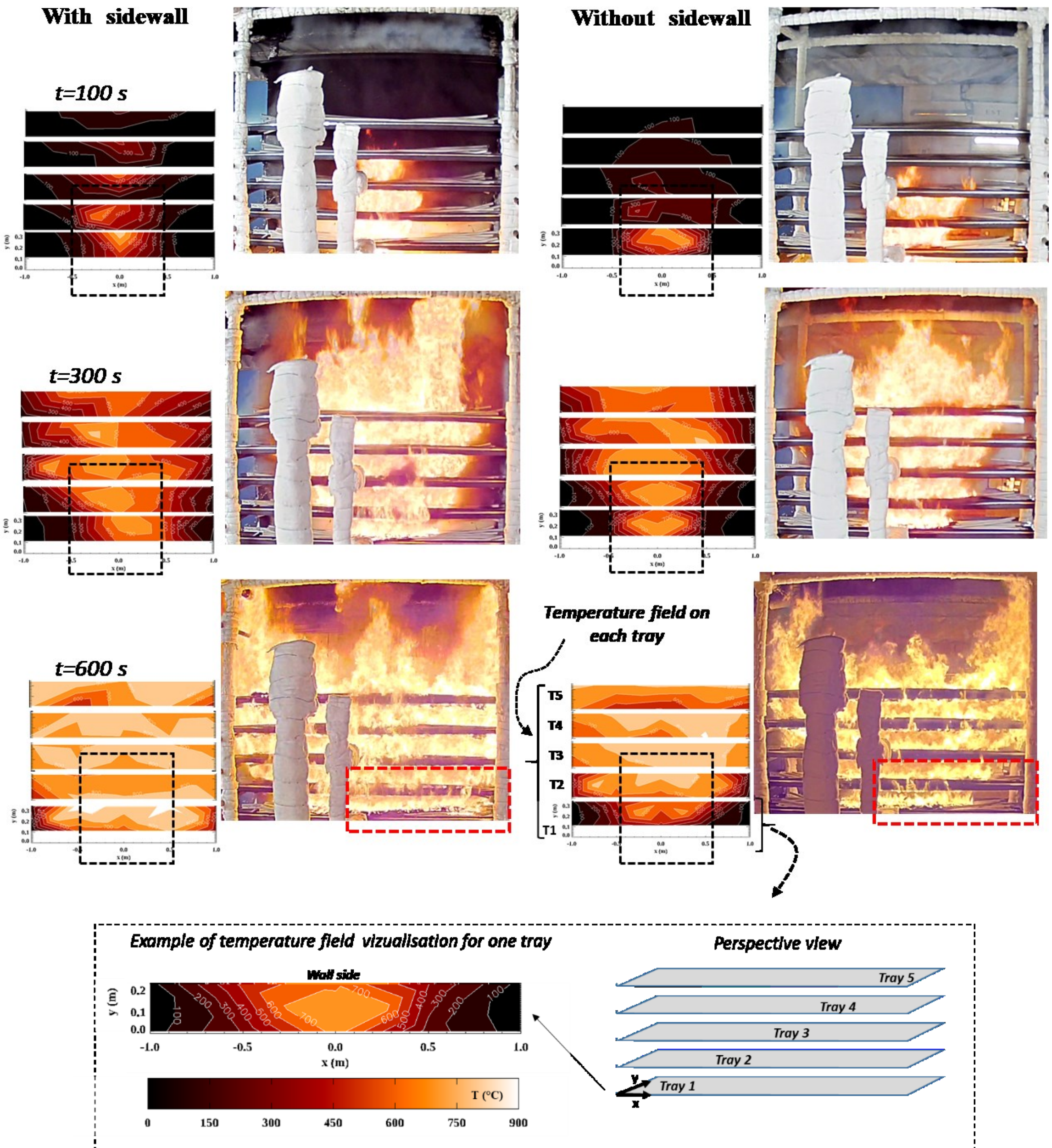

Fig. 5. Effects of the sidewall on the temperature fields for each tray and image of the fire at three instants 100 s, 300 s and 600 s (with a sidewall on the left and without a sidewall on the right).

A qualitative analysis of the temperature above each tray is discussed in order to explain the change in the HRR. First, the temperature fields for each tray and the photographs of the fire are shown in Fig. 5. A gas temperature field is reconstructed above the cables for each of the five trays using the temperature measurements, for each time step. Without a sidewall, the maximum temperature is recorded at the centre of the tray, whereas with a sidewall, the peak temperature moves toward the sidewall (in the y axis direction) as can be seen by the temperature field and the black square on each tray in Fig. 5. A second observation concerns the time delay taken for the flame to propagate on the lowest tray. Without a sidewall, the flame reaches the end of this tray about 400 s later than with a sidewall (see the picture and the red square in Fig. 5).

The effects of the sidewall are also illustrated by variation in the mean temperature over time for each tray. As illustrated in Fig. 6, the main difference between the two tests concerns the temperature of the two first trays, which are much lower without a sidewall (red curve). The sidewall induces a confinement effect mainly seen on the first trays. Without a sidewall, the tray is exposed to an open environment and the temperature is lower. The air entrainment in the flame region along a longer perimeter may also explain this reduction in temperature. On the contrary, regarding the upper trays, the effects of the sidewall are minor. Another explanation is the effect of external radiation from the other trays. The lowest tray is only heated up by its own flame and the presence of sidewall limits the heat loss and consequently increases the heat flux toward the cable. Regarding the upper trays, they are also heat up by their own flame but also by the flame coming from the burning trays situated below. For the fifth tray, the energy coming from the lower trays are significant and the influence of the sidewall because less important.

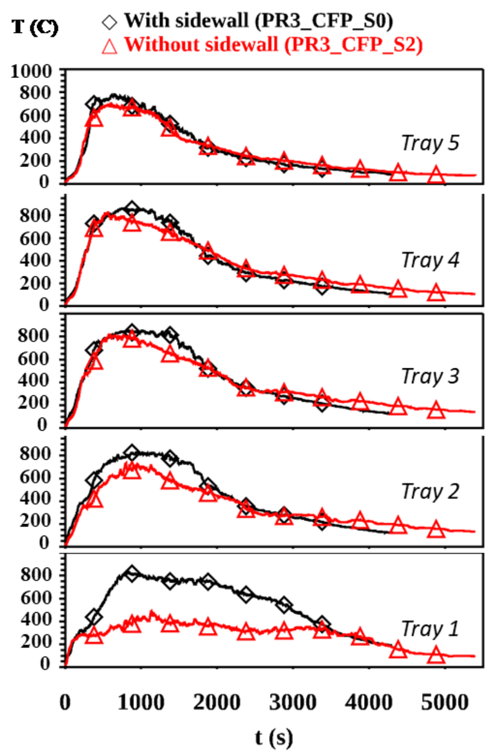

Fig. 6. Effect of the sidewall on the mean temperature of the trays.

Another interesting result concerns the periods during which all cables burn together. This information is obtained from the temperature measurements presented in Fig. 7. For each tray, four critical times are identified corresponding to initial ignition, the ignition of the entire tray (all thermocouples give a temperature above a threshold limit set to 500 °C in this case), initial extinction and the full extinction of the entire tray (all thermocouples give a temperature below the threshold limit). Plots highlight three phases experienced by the trays and reported on the figures with three colors (orange, blue and grey). The first phase (orange) corresponds to the flame spreading over the tray. During this period, the thermocouple positions are progressively covered by flame conditions. The second phase (in blue) corresponds to full burning where all temperatures are above the threshold criterion for burning (500°C). The entire tray is burning. The last phase (in grey) corresponds to progressive extinction at the thermocouple location (gas temperatures progressively decrease below the burning criterion). The tray progressively extinguished.

As previously observed, the duration of the flame spreading period differs between trays and decreases with tray elevation; the higher the tray, the shorter the flame spreading period. This is explained by cable pre-heating induced by the burning of the lower trays, which contributes to warming up the upper trays and then accelerating flame spread. These plots also enhance the effect of the sidewall. With the sidewall, there is a significant period (t = [600 , 1200] s) during which all trays are burning simultaneously. Peak HRR is reached during this period. Without a sidewall, there is no period during which all trays are burning simultaneously; only one period is identified with the four upper trays burning simultaneously. This is due to the low flame spread velocity on the lower two trays, meaning that this tray never burned entirely simultaneously; local extinction happens before the whole tray has ignited.

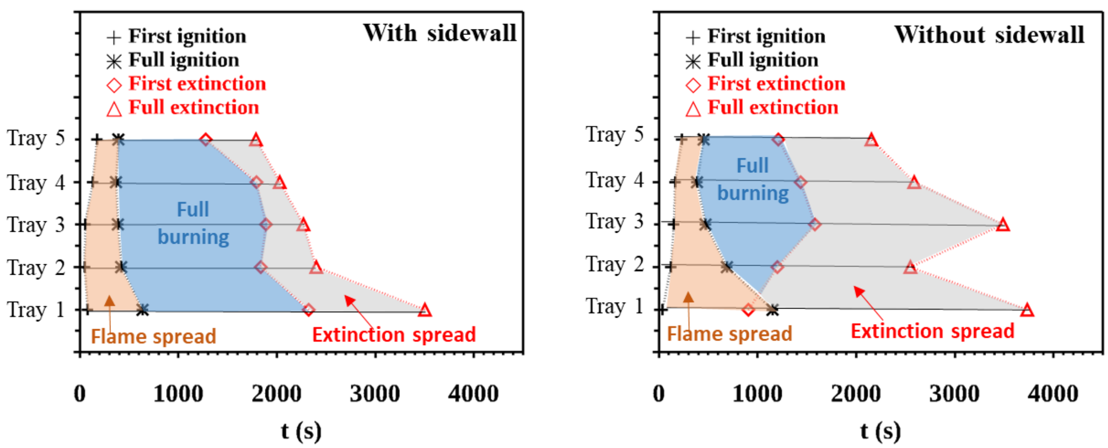

Fig. 7. Critical times (of ignition and extinction) on each tray for the two tests with and without a sidewall.

In order to quantify more precisely the effects of a sidewall, the time to ignition for each tray and the horizontal flame spread velocity are assessed using measurements. Mean vertical flame propagation is very similar for both tests. The 5th tray ignition occurs after about 180 s in both tests and there is nearly no difference in terms of ignition time for the two configurations. On the other hand, regarding the horizontal flame spread velocity, differences are mainly reported for the lowest two trays as illustrated in Fig. 8. With a sidewall, the vertical flame spread velocity increases with the tray index from 1 mm/s up to 5 mm/s for the upper tray. This increase is induced by the preheating of the upper trays caused by the plume generated by the lower tray. Without a sidewall, the only modification is a reduction in the velocity of the lower trays. This result is in agreement with visual observations. The flame propagates slowly over the lowest two trays without a sidewall. The sidewall contributes to promoting flame spread, mainly for the first two trays. It is worth noting that the flame spread velocities measured are consistent with amplitudes recommended for FLASHCAT -model for PVC (between 3 and 6 mm/s) [14] as well as those measured from a similar experiment (5 trays with PVC cable), between 2 and 5 mm/s [18].

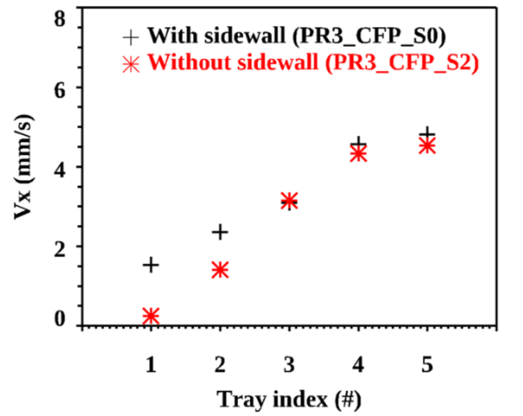

Fig. 8. Effects of the sidewall on the horizontal mean flame spread velocity for each tray.

Another important variable is the fire HRRPUA for which an assessment is proposed based on the HRR and the burning area, both computed from measurements as detailed in the previous section. The results for the burning area, presented in Fig. 9, show that the burning area grows more slowly without a sidewall because of the lower flame spread velocity for the two lower trays. The fire growth rate is larger with a sidewall than without.

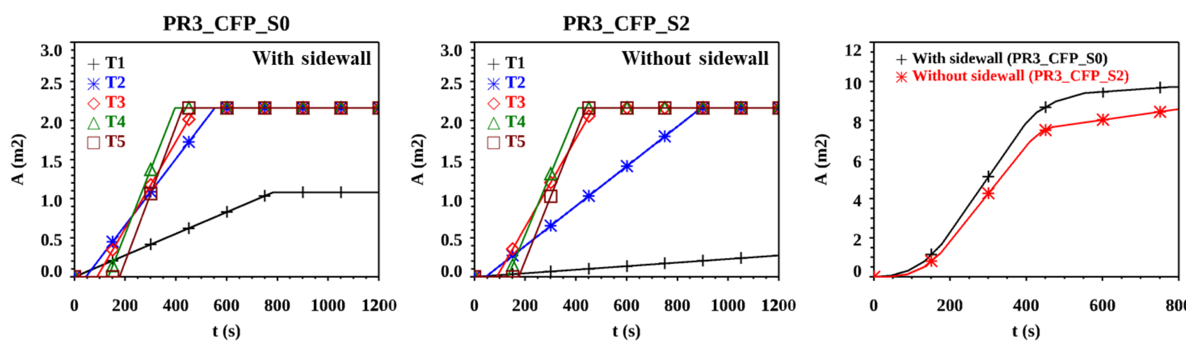

Fig. 9. Effects of the sidewall on variations in the burning area for each tray over time (with a sidewall on the left and without a sidewall in the center) and variation in the total burning area over time for the two tests (right).

HRRPUA results are presented in Fig. 10 and compared to cone calorimeter test results. HRRPUA for both tests are very similar and do not appear to be influenced by the sidewall. The mean value over a given period is about 175 kW/m^2 (174 kW/m^2 for tests with a sidewall and 177 kW/m^2 for tests without a sidewall) with a maximum value at 250 kW/m^2. This experimental outcome differs from the proposal made by Huang & al. [7], who suggest that the HRRPUA varies with the sidewall effect. According to these results, the sidewall modifies the flame spread velocity of the two lower trays but does not affect the fire HRRPUA. The comparison with the cone calorimeter tests on a sample of cables under 77 kW/m^2 of irradiance gives similar trends with maximum amplitude (220 kW/m^2) and progressive decay with time.

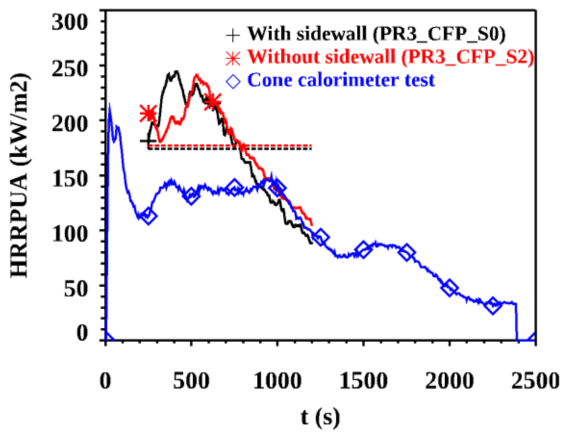

Fig. 10. Variation in HRRPUA over time for the two tests with and without a sidewall and comparison with cone calorimeter tests (the doted lines correspond to the mean amplitude during the period of calculation).

3.2 Effect of the cable arrangement

A second important cable tray fire parameter that needs to be better understood for the purposes of fire HRR predictions is the cable arrangement. In the present configuration, the effect of this parameter on MLR, HRR and combustion enthalpy is reported in Fig. 11.

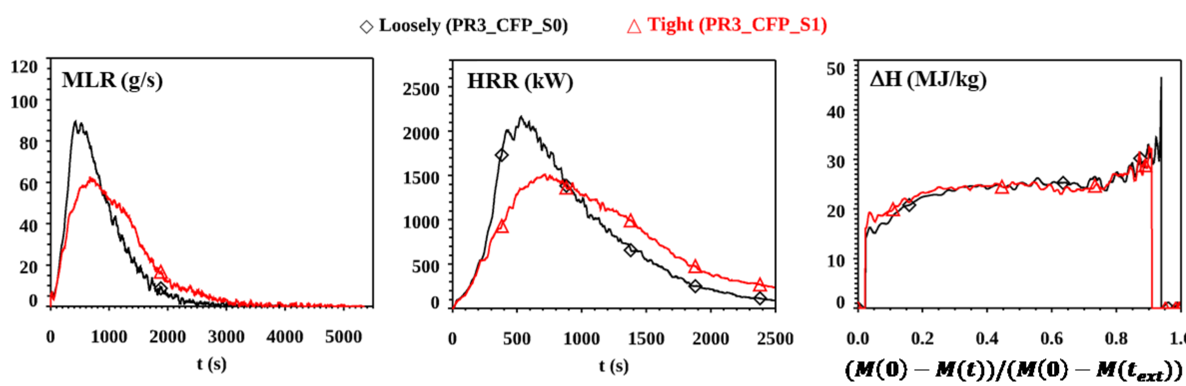

Fig. 11. Effects of the cable arrangement (loose for PR3_CFP_S0 test and tight for PR3_CFP_S1 test) on MLR, HRR and combustion enthalpy.

A change in cable arrangement from a loose to a tight bundle configuration contributes to reducing MLR and fire HRR but does not modify combustion enthalpy. The effects of a tight arrangement on HRR consists in a reduction of the maximum amplitude (2160 kW with a loose arrangement to 1511 kW with a tight arrangement or a reduction of 30 %) as well as a time shift and an increase in HRR in the later stages of the combustion period. The total fire duration increases (4155 s for loose and 5360 s for tight arrangement) as well as the total mass loss

(81.1 kg for loose and 84.8 kg for tight arrangement) and the total heat release (2047 MJ for loose and 2176 MJ for tight arrangement).

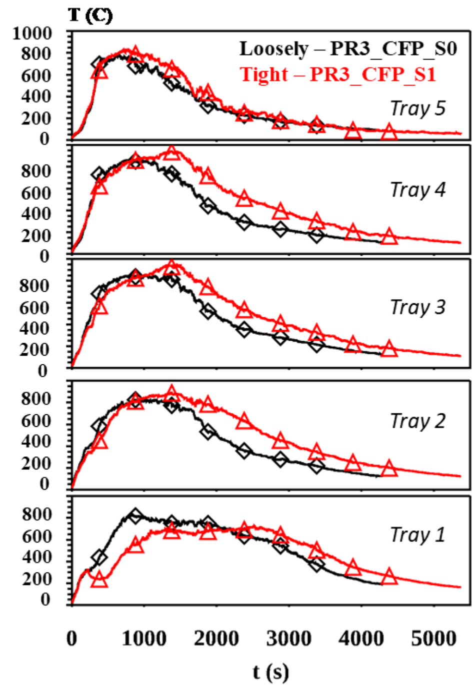

Fig. 12. Effects of the cable arrangement on mean temperature over the tray.

The analysis of the average temperature over each tray (presented in Fig. 12) confirms the time shift in maximum intensity, especially for the lower tray. The amplitude of the maximum average temperature is similar for the two arrangements.

The mean horizontal flame spread velocity along each tray is also modified because of the cable arrangement. Using the tight arrangement rather than the loose one contributes to reducing its amplitude by about 24 % on average (see Fig. 13). The increase in the inertia of the combustible material (tightly packed cables) as well as the decrease in interfacial cable area in contact with the environment with the tight bundle arrangement explain this reduction.

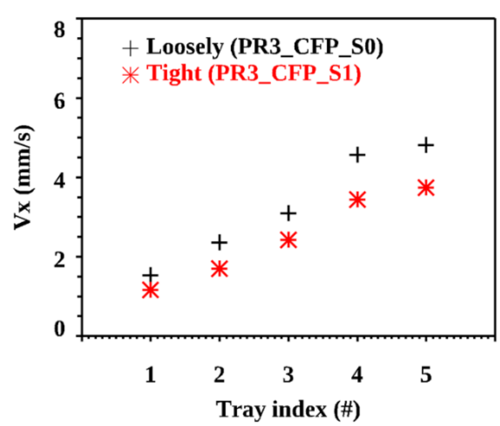

Fig. 13. Effects of the cable arrangement on horizontal flame spread velocity.

The analysis of the burning area of each tray shows a similar behavior except the rate of growth that is higher with the loose arrangement (Fig. 14). With a tight cable arrangement, the growth rate of the burning area is lower (because of a lower flame spread) and therefore it takes longer to ignite the entire tray area. This observation agrees with the time shift for the maximum HRR reported previously.

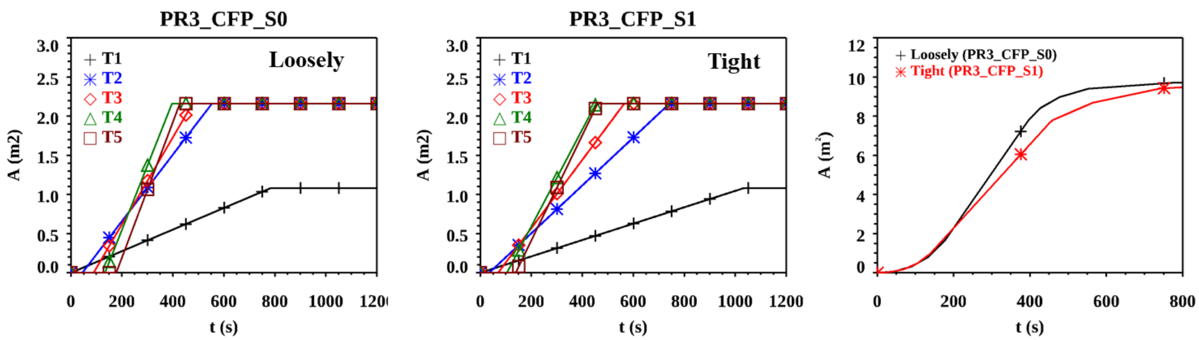

Fig. 14. Effects of the cable arrangement on the variations over time in the burning area for each tray (loose on the left and tight arrangement in the center) and variation over time in the total burning area for the two tests (right).

The HRRPUA can be experimentally determined by identifying the burning area and the fire HRR in the same way as presented in Fig. 15. The HRRPUA computed over a given period is reduced with a tight cable arrangement (174 kW/m^2 for a loose arrangement and 149 kW/m^2 for a tight arrangement). This is explained by a reduction in the cable interfacial area in contact with the environment in case of a tight arrangement, in particular with a bundle configuration. The comparison with a cone calorimeter test show similar trends with a maximum at the beginning of the combustion phase followed by a progressive decay.

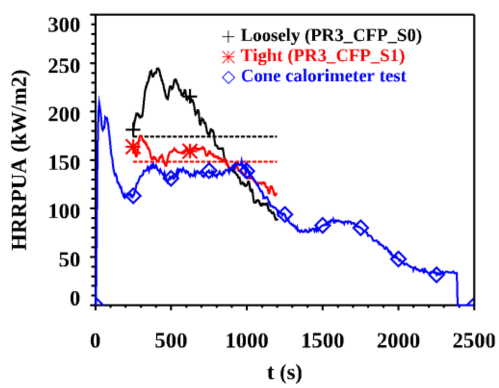

Fig. 15. Variation in HRRPUA over time for the two tests with two cable arrangements and comparison with the cone calorimeter test.

The present results are compared to literature data and especially those of the OSKAR fire tests [12], [19], which investigated a tight arrangement in layers. The present bundle arrangement aims to investigate an intermediate tight configuration without a complete blockage of the vertical flow because of the tray. The T1 OSKAR fire test configuration was almost identical to the PR3_CFP_S0 test configuration (same cable load with 21 samples per tray) except the tray width, which was slightly smaller (400 mm instead of 450 mm) and the cable arrangement. The T1 OSKAR test cable arrangement involved distributing the 21 samples over two layers as illustrated in Fig. 16.

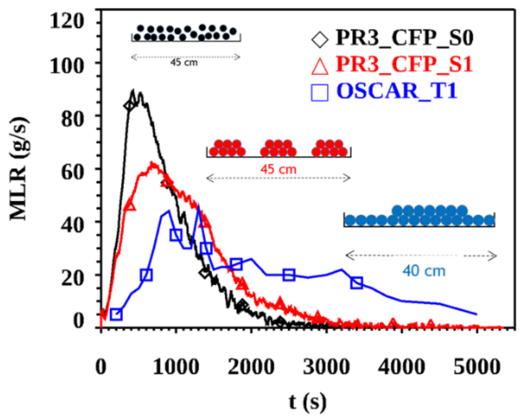

Fig. 16. Comparison of the MLR for the present tests with OSCAR fire tests [12].

A comparison of the variation in the MLR over time is presented in Fig. 16. As expected, the tight bundle arrangement leads to an intermediate configuration between loose and tight arrangements in layers. Maximum MLR and the time required to reach this maximum value are compared quantitatively (see Table 3). With respect to the reference test with a loose arrangement (PR3_CFP_S0), the T1 OSKAR fire test gives the lowest maximum MLR (45 g/s) and the longest time to reach this maximum (900 s). The PR3_CFP_S1 fire test with tight bundle arrangements shows an intermediate ranking, lower than the loose arrangement but higher than the T1 OSKAR fire test.

Table 3: Maximum MLR and time to reach the maximum value, geometrical parameters and coefficients k for the present tests and the OSKAR fire test T1.

Variables	PR3_CFP_S0	PR3_CFP_S1	OSKAR T1
MLR_{max}(g/s)	89.4	62.7	45.0
T(MLR_{max}) (s)	425	672	900

In order to interpret these results, a specific analysis based on geometrical considerations is proposed. Two parameters are defined: the cable interfacial area in contact with air (with parameter k_A), which enhances the pyrolysis and the free area on the tray (with parameter k_B) that allows the flame to flow through trays and avoids flame blockage. With a loose cable arrangement, the cable interfacial area is maximum and the blockage effect minimum. With a tight cable arrangement in layers (OSKAR configuration), the cable interfacial area is reduced, and the blockage effect is maximum, which reduces the flame propagation. The tight cable bundle arrangement is an intermediate configuration; the cable interfacial area is also reduced, but the blockage effect is mitigated due to free paths between the bundles. A parameter k is then introduced to sum up both effects of interfacial area and blockage. This parameter quantifies the effects of tight arrangements with respect to loose arrangements for which k = 1 with the following relationship:

$$k = k_A(1 - 0.9k_B) \quad \text{with } k_A = p/p_o \text{ and } k_B = w_c/w \tag{2}$$

p is the perimeter of the cable in contact with the surrounding air, p_o is the maximum perimeter of the cable in contact with the surrounding air in case of a loose arrangement, w_c is the width of the tray covered by cable and w is the effective tray width (450 mm for CFP tests and 400 mm for the OSKAR T1 test).

The coefficient k combines the two effects of the interfacial area with coefficient k_A and the blockage effect with coefficient k_B. A constant of 0.9 is introduced in order to weight the effect of the blockage with respect to the effect of the interfacial area. For loose arrangements, $k_A = 1$ and $k_B = 0$ and therefore k = 1. For the OSKAR T1 test tight arrangement, $k_B = 1$, indicating that the blockage effect is maximum. The values of k_A and k_B for the tests are computed as indicated in Table 4 from geometrical considerations.

Table 4: Expression of p and w_c for the present tests and the OSKAR fire test T1.

Test	Perimeter p	Width w_c
PR3_CFP_S0	$21\pi D$	W
PR3_CFP_S1	$\pi D(7\times(1/2)+4\times1/4)\times3=27/2\ \pi D$	$(D\times4)\times3$
OSKAR T1	$\pi D(1/2)\ (14+7+6+1)=14\pi D$	W

Table 5: Geometrical parameters and coefficients k for the present tests and the OSKAR fire test T1.

Variables	PR3_CFP_S0	PR3_CFP_S1	OSKAR T1
p (mm)	1846	1187	1231
L (mm)	0	336	400
k_A	1	0.643	0.667
k_B	0	0.747	1
K	1	0.211	0.067

The calculations shown in Table 5 confirm the ranking established on the basis of the maximum MLR and the time taken to reach this maximum. Coefficient k_A is almost the same for the two tight configurations, but differences are identified for coefficient k_B as illustrated by the different blockage effect for the two tests (PR3_CFP_S1 and OSKAR T1). Combining the two coefficients shows that the two-layer arrangement of the OSKAR T1 test gives the lower value of k, which is in good agreement with the ranking observed for the MLR.

4 Modeling approach using the FLASHCAT model

4.1 Recall of the model

The FLASHCAT model was proposed as part of the CHRISTIFIRE project [5] and predicts the fire HRR based on the integration of variation over time in the heat release rate per unit of area $\dot{q}''(t)$ over the entire length of the cable, as illustrated in Fig. 17. This integration is then totalled for all trays n_t. The fire heat release rate $\dot{Q}(t)$ is expressed as [5]:

$$\dot{Q}(t) = \sum_{i=0}^{i=n_t} w\left\{2\int_{L_b^i/2}^{L/2} \dot{q}''(t - t_{ign}^i)dx\right\} \quad (3)$$

HRRPUA $\dot{q}''(t)$ is input to the model that can be obtained either experimentally from cone calorimeter tests, for instance, or assumed with a pre-design shape. The ignition of each tray is specified with time t_{ign}^i. The tray geometry is characterized by width w and length L. Length L_b^i characterizes the initial length that burned instantaneously at ignition.

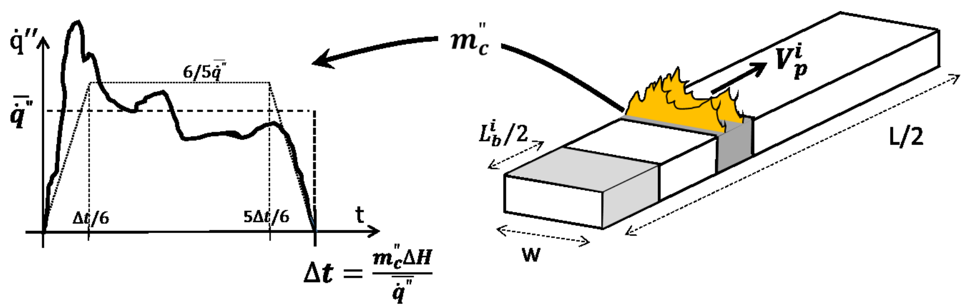

Fig. 17. Illustration of the FLASHCAT model.

The extinction time of an element of cable dx, which corresponds to the total duration of the signal $\dot{q}''(t)$, is introduced as:

$$\Delta t = \frac{m_c^{"}\Delta H}{\dot{q}^{"}} \quad \text{with} \quad m_c^{"} = \frac{nY_p(1-\nu)m'}{w} \quad (4)$$

ΔH is combustion enthalpy and $\bar{\dot{q}}^{"}$ average HRRPUA over the period Δt. $m_c^{"}$ is the mass of combustible matter per unit of area with m' the mass of cable per unit of length, n the number of cableq, Y_p, the fraction of burning material and ν the fraction of char that does not contribute to combustion. The horizontal flame spread velocity over the distance x is introduced in the relationship between the time t and the position x over the tray. $t_{j+1} = t_j + dx/V_x^i$ (index j is the time incremental and i is the tray index). The flame spread velocity is a constant for each tray.

Several model parameters may be discussed in order to adapt the prediction to practical cases. One influential parameter is variation in HRRPUA over time $\dot{q}''(t)$. Test data or pre-design shape can be considered. In the original model [5], a trapezoidal shape was proposed simulating three typical phases as illustrated in Fig. 17: a growth phase that lasts a period of $1/6\Delta t$, a steady phase that lasts a period of $4/6\Delta t$ and finally a decay phase that lasts a period of

1/6Δt. With this assumption, the mean HRRPUA in the relationship for Δt is $\overline{\dot{q}''} = 5/6\dot{q}''_{avg}$ where the variable $\dot{q}''_{avg}$ is average amplitude during the steady phase (4/6 of the total duration). This explains why some authors explicitly write the ratio as 5/6 in the expression for Δt. Another fitting parameter is the width of the burning material that can be considered as the product of the cable diameter and the number of cables (Huang & al. [20]) or that can be taken as the width of the tray and can be doubled to incorporate the burning of the two sides (upper and lower) of the tray (Zavaleta & al. [14]).

4.2 Sidewall effect predictions

In order to assess how the sidewall effect can be introduced in the FLASHCAT model, predictions of fire HRR are proposed for the two fire tests. The following parameters remain identical for the two simulations: number of trays, 5; tray width 0.45 m; height difference between trays, 0.3 m; cable length, 2.4 m; number of cables per tray, 21; cable mass per unit of length, 1.75 kg/m; fraction of combustible matter, 0.25 and fraction of char 0.26. Ignition is started at the center of the cable length and combustion enthalpy is 25 MJ/kg (mean value obtained from these fire tests). No finite initial length of burning is considered. Regarding the profile shape of the HRRPUA, the approach that best fits the fire test results is to consider the experimental profile obtained at small scale with the irradiance of 77 kW/m^2 (presented in Fig. 10) instead of considering the trapezoidal assumption shape. This profile is corrected such that the average value of the HRRPUA over the duration Δt is equal to the value measured experimentally during the cable tray fire tests (175 kW/m^2). Fig. 18 illustrates this adjustment of the cone calorimeter results (in black) into the HRRPUA profile required for the FLASHCAT model (mean value of 175 kW/m^2 and duration ΔT of 2275 s) in red. For these experiments, the fire duration for an element of cable ΔT is ΔT = 15.925×25000/175 = 2275 s with m''_c = 21×0.26×(1-0.25)×1.75/0.45 = 15.925 kg/m^2. In addition, as recommended by Zavaleta & al. [14], the two sides of each tray are considered, except for the first tray, for which the video has shown that only the upper side is burning. The only parameters that differ from the two simulations are the time to ignition for each tray (determined from the vertical flame spread velocity) and the horizontal flame spread velocities (both measured from the test data) (see Table 6).

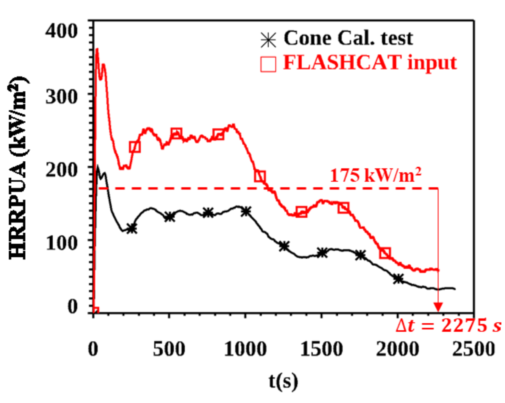

Fig. 18. Variation in HRRPUA over time considered as input parameters for FLASHCAT

calculations

Table 6: FLASHCAT input parameters that differ between the two tests with and without a sidewall.

Test	Vz (m/s)	Vx (T1) (m/s)	Vx (T2) (m/s)	Vx (T3) (m/s)	Vx (T4) (m/s)	Vx (T5) (m/s)
PR3_CFP_S0 (with sidewall)	6.8	1.5	2.4	3.1	4.6	4.8
PR3_CFP_S2 (without sidewall)	6.9	0.2	1.4	3.1	4.3	4.5

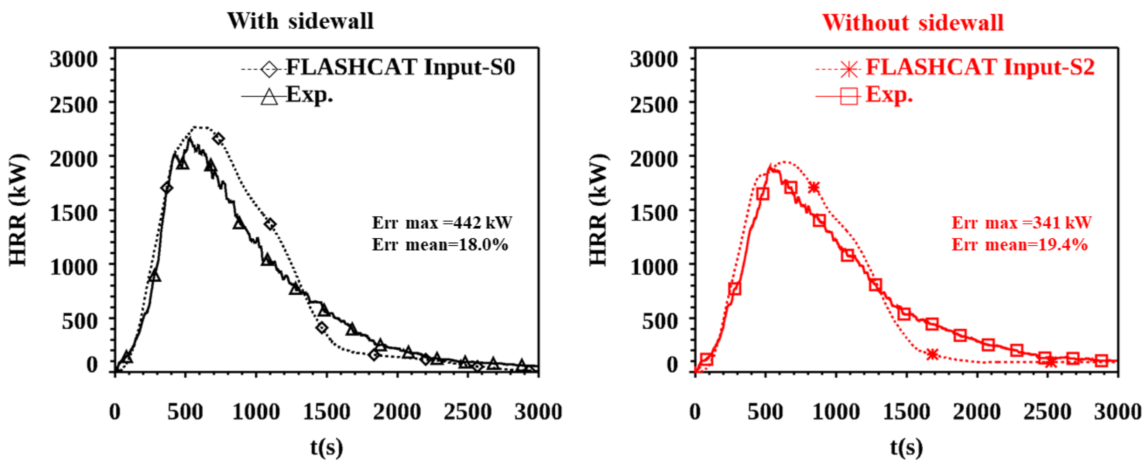

Fig. 19. Comparison of the HRR obtained from the fire test (plain lines) and the HRR predicted using the FLASHCAT model (dotted lines) for the two tests with and without a sidewall.

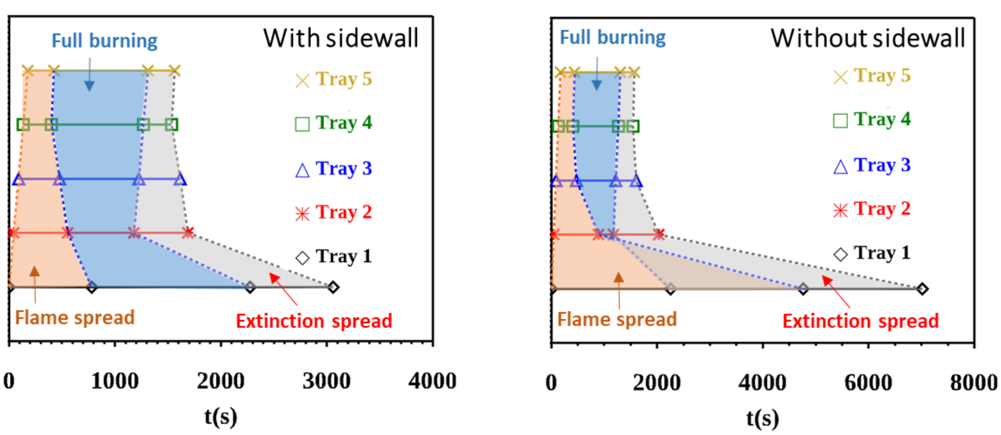

Fig. 20. Critical times (of ignition and extinction) deduced from the FLASHCAT predictions for the two tests with and without a sidewall.

Fig. 18 compares the predictions of the model and the results of the experimental fire tests. The results show a fairly good estimation of the fire test. The model's ability to predict the reduction in HRR because of the absence of a sidewall is attributable to the horizontal flame spread velocity of the first two lower trays without a sidewall. An analysis of the effects of the flame spread velocity is proposed in Fig. 20 with a similar representation as in Fig. 7. The plots show the predicted critical times (ignition time, propagation stop time, extinction start time, final extinction time) for the five trays. As performed with the experimental results in Fig. 7, these instants highlight the three typical periods of flame propagation, full burning of the entire tray and progressive tray extinction. Quantitatively, the simulations (Fig. 20) and the experimental results (Fig. 7) look very similar. The main difference concerns the lower tray (Tray 1) that never burns entirely (no full burning period) without a sidewall whereas a period of full burning is reported (experimentally and numerically) with a sidewall. With the absence of a sidewall, the horizontal flame spread velocity is slower and no period of full burning is reported; the burning area never covers the entire tray area. The presence of a sidewall mainly contributes to increasing the flame spread velocity of the two lower trays, which consequently increases the fire HRR.

4.3 Effects of cable arrangement

A FLASHCAT simulation is also run for the test with a tight arrangement and a comparison with the loose cable arrangement fire test (reference test PR3_CFP_S0) as presented in Fig. 21. The input parameters are identical to those considered for the loose arrangement and indicated in the previous section (effects of a sidewall). Only, the HRRPUA and the flame spread velocities are changed with the experimental values: HRRPUA =148 kW/m^2 and Vx is equal to 1.16, 1.70, 2.43, 3.44 and 3.73 m/s for the five trays (see Table 7). The effect of the reduction in the two parameters leads to the expected results reported for the fire tests. The amplitude of the maximum HRR is reduced with the tight arrangement as well as time shift. It is worth noting that the agreement between the FLASHCAT predictions and the test results is better with the loose than with the tight arrangement. This is possibly due to the experimental determination of the fire HRR, which is overestimated for the tight arrangement. Nevertheless, the results demonstrate that the change in the cable arrangement from loose to tight can be taken into account with the FLASHCAT model in reducing both the HRRPUA and flame spread velocities.

Table 7: FLASHCAT input parameters that differ between the two tests with two cable arrangements.

Test	$\bar{\dot{q}}''$ (kW/m^2)	Vz (m/s)	Vx (T1) (m/s)	Vx (T2) (m/s)	Vx (T3) (m/s)	Vx (T4) (m/s)	Vx (T5) (m/s)
PR3_CFP_S0 (loose)	175	6.8	1.5	2.4	3.1	4.6	4.8
PR3_CFP_S1 (tight)	148	8.7	1.2	1.7	2.4	3.4	3.7

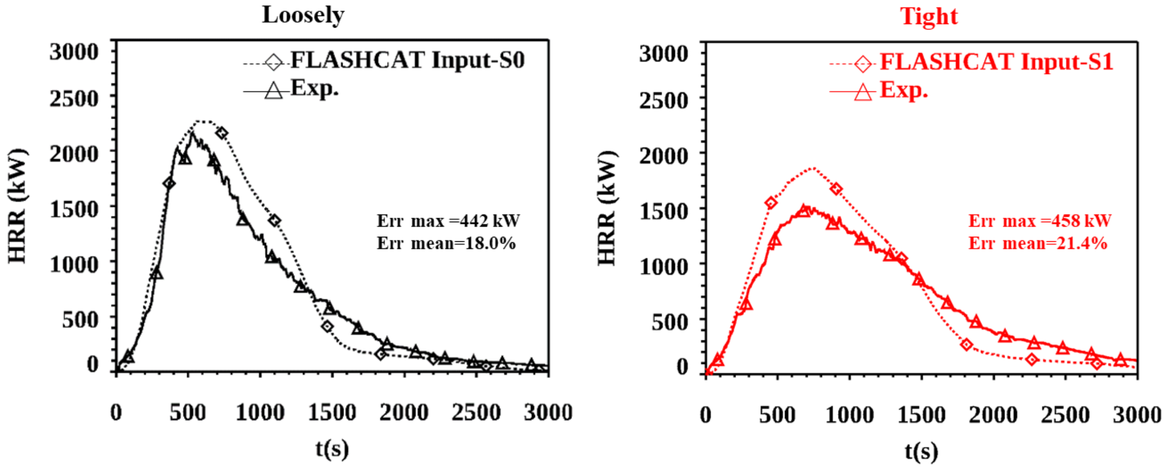

Fig. 21. Comparison of the HRR obtained from the fire tests (plain lines) and the values predicted using the FLASHCAT model (dotted lines) for the two tests with two cable arrangements.

5 Conclusions

This study investigates the effects of two characteristics of cable tray fires: the sidewall supporting the trays and the cable arrangement. The fire scenario comprises five 3 m long superposed horizontal trays filled with PVC cables. The discussion is based on the analysis of large-scale fire tests performed in the frame of the OECD/NEA PRISME 3 Project and fire HRR predictions conducted using the FLASHCAT model. The test parameters correspond to the presence of a sidewall and two cable arrangement configurations: loose and tight bundles. The main outcomes are as follows:

- The presence of a sidewall increases the fire HRR (approx. 12 % increase in the maximum HRR according to the present tests) in comparison to the configuration without a sidewall. This effect is mainly due to the increase in the flame spread velocity on the first two lower trays (first and second for the present configuration with 5 trays). The presence of a sidewall increases the pre-heating of the cable as well as the flame spread velocity. For the upper trays (fourth and fifth for the present configuration with 5 trays), the influence of the sidewall is less significant. For these trays, the cable pre-heating is mainly due to the plume induced by the lower trays and the sidewall has little influence. The results also show that the HRRPUA and the combustion enthalpy were not modified by the presence of a sidewall. The study highlights that the FLASHCAT model can predict the effects of the sidewall in terms of the increase in flame spread velocities for the first two lower trays in comparison to simulations without a sidewall. It is worth noting that the importance of the side wall effect may depend on other parameters as the type of cable and possibly its diameter. With a smaller diameter and then less inertia this effect can be stronger as it has been reported for cable fire experiments in the OCDE PRISME-2 project [14] and in the FIPEC project [4].
- The tight bundle arrangement reduces the amplitude of the fire HRR (reduction of about 30% for the maximum HRR) and also delays the time the maximum HRR is

reached in comparison to the loose arrangement. This effect is caused by both a reduction in the fire HRRPUA and the flame spread velocity. Comparisons with other tests involving tight cable arrangement in layers (OSKAR fire tests [12]) show that the tight bundle arrangement is an intermediate configuration, which avoids the blockage effect induced by a tight layered arrangement. A specific analysis shows that the cable arrangement can be described as a combination of two features: the interfacial area of the cable in contact with air and the free area of the tray that limits the blockage and allows flames to propagate towards the trays.

- In view of a fire risk assessment, the scenario of a horizontal cable tray against a sidewall with a loose cable arrangement is conservative. The absence of a sidewall or a tighter cable arrangement leads to a less powerful fire. In addition, on the basis of these experiments, the effect of cable arrangement is more substantial than the sidewall effect. The FLASHCAT model can be used to predict the fire HRR with a good agreement provided the appropriate input parameters are used. The present study proposes the adequate set of input parameters for a typical PVC insulated power cable implemented in nuclear installations.

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6 References

[1] P. Zavaleta, S. Suard, and L. Audouin, "Cable tray fire tests with halogenated electric cables in a confined and mechanically ventilated facility," *Fire Mater.*, vol. 43, no. 5, pp. 543–560, 2019, doi: 10.1002/fam.2717.

[2] "Organisation for Economic Co-operation and Development (OECD) Nuclear Energy Agency (NEA), Committee on the Safety of Nuclear Installations (CSNI): OECD FIRE Database Version 2019:01, Paris, France, April 2021 (limited to FIRE Database Project members)."

[3] S. P. Nowlen, "Nuclear power plants: A unique challenge to fire safety," *Fire Saf. J.*, vol. 19, no. 1, pp. 3–18, 1992, doi: 10.1016/0379-7112(92)90003-U.

[4] S. J. Grayson, P. Van Hees, A. M. Green, H. Breulet, and U. Vercellotti, "Assessing the fire performance of electric cables (FIPEC)," *Fire Mater.*, vol. 25, no. 2, pp. 49–60, 2001, doi: 10.1002/fam.756.

[5] K. Mc Grattan, A. Lock, N. Marsh, M. Nyden, S. Bareham, and M. Price, "Cable Heat Release, Ignition, and Spread in Tray Installations During Fire (CHRISTIFIRE) Phase 1 Horizontal Trays," 2012.

[6] S. Suard, P. Van Hees, M. Roewekamp, S. Tsuchino, and R. Gonzalez, "Fire development in multi-compartment facilities: PRISME 2 project," vol. 43, no. September, pp. 433–436, 2019.

[7] X. Huang, H. Zhu, L. He, L. Peng, C. Cheng, and W. Chow, "Improved model for estimating sidewall effect on the fire heat release rate of horizontal cable tray," *Process Saf. Environ. Prot.*, vol. 149, pp. 831–838, 2021, doi: 10.1016/j.psep.2021.03.040.

[8] S. Suard, P. Zavaleta, and H. Prétrel, "Overview of the OECD PRISM3 Project," in *in Roewekamp, M. and Berg, H.P. (Eds) : Proceeding of SMiRT 25, 16th International Seminar on Fire Safety in Nuclear Power Plants and Installations, Kolen, Germany, December,* 2019.

[9] X. Huang *et al.*, "Burning behavior of cable tray located on a wall with different cable arrangements," *Fire Mater.*, vol. 43, no. 1, pp. 64–73, 2019, doi: 10.1002/fam.2669.

[10] X. Huang, Y. Wang, W. Zeng, L. Peng, A. C. H. Cheng, and W. K. Chow, "Compartment temperature estimation of a multiple-layer cable tray fire with different cable arrangements in a closed compartment," *J. Fire Sci.*, vol. 37, no. 4–6, pp. 303–319, 2019, doi: 10.1177/0734904119860410.

[11] R. Meinier, R. Sonnier, P. Zavaleta, S. Suard, and L. Ferry, "Fire behavior of halogen-free flame retardant electrical cables with the cone calorimeter," *J. Hazard. Mater.*, vol. 342, pp. 306–316, 2018, doi: 10.1016/j.jhazmat.2017.08.027.

[12] M. Siemon, O. Riese, B. Forell, D. Krönung, and W. Klein-Hessling, "Experimental and numerical analysis of the influence of cable tray arrangements on the resulting mass loss rate and fire spreading," *Fire Mater.*, vol. 43, no. 5, pp. 497–513, 2019, doi: 10.1002/fam.2689.

[13] R. Meinier, M. Fellah, R. Sonnier, P. Zavaleta, S. Suard, and L. Ferry, "Ignition and Charring of PVC-Based Electric Cables," *Fire Technol.*, vol. 58, no. 2, pp. 689–707, 2022, doi: 10.1007/s10694-021-01168-0.

[14] P. Zavaleta, R. Hanouzet, and T. Beji, "Improved Assessment of Fire Spread over Horizontal Cable Trays Supported by Video Fire Analysis," *Fire Technol.*, vol. 55, no. 1, pp. 233–255, 2019, doi: 10.1007/s10694-018-0788-x.

[15] A. Hamins and K. Mc Grattan, "Verification and Validation of Selected Fire Models for Nuclear Power Plant Applications Vol 2 - Experimental Uncertainty," *Nureg-1824 -EPRI 1011999 Final Rep.*, 2014.

[16] M. Janssens, "Calorimetry," in *SFPE Handbook of Fire Protection Engineering*, National Fire Protection Association, Quincy- Massachusetts, USA, 2002, pp. 46–48.

[17] H. Prétrel, W. Le Saux, and L. Audouin, "Determination of the heat release rate of large scale hydrocarbon pool fires in ventilated compartments," *Fire Saf. J.*, vol. 62, no. PART B, pp. 192–205, 2013, doi: 10.1016/j.firesaf.2013.01.014.

[18] T. Beji, S. Verstockt, P. Zavaleta, and B. Merci, "Flame Spread Monitoring and Estimation of the Heat Release Rate from a Cable Tray Fire Using Video Fire Analysis (VFA)," *Fire Technol.*, vol. 52, no. 3, pp. 611–621, 2016, doi: 10.1007/s10694-015-0538-2.

[19] M. Siemon, "Ein Pyrolysemodell zur Prognose der Brandausbreitung - A pyrolysis model to predict fire spread - PhD Thesis," Institut für Baustoffe, Massivbau und Brandschutz (iBMB) Braunschweig, Germany, 2016.

[20] X. Huang *et al.*, "An improved model for estimating heat release rate in horizontal cable tray fires in open space," *J. Fire Sci.*, vol. 36, no. 3, pp. 275–290, 2018, doi: 10.1177/0734904118769810.