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1 **Experimental study of a travelling fire along a cable tray assembly in a mechanically**
2 **ventilated enclosure**

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7 **Highlights:**

- 8 • Large scale fire tests of long cable trays
9 • Flame spread velocity of travelling fire over long cable length
10 • Effect of distance from the ceiling and cable type

11 **Abstract:**

12 This study investigates the behaviour of a fire propagating over a long length of electrical cables,
13 in order to assess the maximum burning length and the associated heat release rate of the travelling
14 fire. It is part of the research work conducted in the framework of the OECD/NEA PRISME 3
15 project for a better assessment of fire propagation over cable trays in nuclear installations. The fire
16 scenario consists of a set of 3 horizontal cable trays 6 m long, positioned in the corridor of a
17 mechanically ventilated large-scale compartment. The parameters of the study are the nature of
18 the cables (thermoset or thermoplastic types) and the distance of the cable trays from the ceiling.
19 The determination of the fire heat release rate (HRR), the total burning length, the velocity of the
20 flame front, the heat release rate per unit area (HRRPUA) and the effective heat of combustion
21 (EHC) of the cable fires are given. For the configuration studied (3 cable trays and a given load),
22 fire HRRs of 160 kW and 520 kW corresponding to burning lengths of 2 m and 3 m and
23 corresponding to velocities of 0.4 mm/s and 0.9 mm/s are obtained for thermoset cables. For
24 thermoplastic type cables (made of polyvinyl chloride), a power of 730 kW corresponding to a
25 burning length of 3.5 m and corresponding to a velocity of 1.9 mm/s is reported. The order of
26 magnitude for HRRPUA and EHC were respectively ranged between 50 kW/m² and 150 kW/m²
27 and 20 MJ/kg and 25 MJ/kg for the two cable types.

28 **Keywords:** cable, travelling fire, burning length, propagation velocity

29 **1 Introduction**

30 Cable trays are widely present in nuclear installations and are therefore considered as a major
31 source of fuel for fire hazards. Many configurations are identified, with multiple horizontal cable
32 trays stacked on top of each other or vertical cable trays against a wall for instance. The
33 characteristics of the cables, the number of cable trays, the arrangement (tight or loose) are
34 important parameters influencing a potential fire scenario. In nuclear installations, the risk of
35 electrical fires is a major concern. Approximately 80 cable fires were identified between the 1980s

36 and 2019 among the fourteen NEA member countries¹ [1]. The study of cable tray fires is thus a
37 major research topic, with the aim of improving our knowledge of the subject and boosting the
38 performance of prediction tools.

39 Since the major fire at Browns Ferry Nuclear Power plant in 1975, many studies have been
40 undertaken to improve the understanding of the risks associated with cable tray fires [2], [3]. Many
41 studies have focused on horizontal cable tray fires. Through the CHRISTIFIRE project, the US
42 NRC carried out a large number of tests to better understand the influence of parameters such as
43 the nature of the cables (thermoset or thermoplastic), the number of trays and the arrangement [4]
44 [5]. These tests led to the development of the FLASHCAT model, which predicts the fire heat
45 release rate of a cable tray fire. The study on this topic was continued as part of the PRISME 2
46 project operated by IRSN, by addressing the effect of containment in a ventilated enclosure and
47 the presence of a wall in particular, which can contribute to increase the intensity of the fire [6],
48 [7], [8]. The various parameters involved were the effects of the cable type (halogenated or
49 halogen-free cables), the cable quantity per tray, the number of trays, the arrangement (loose or
50 tight) and the ventilation type (open atmosphere or confined). The containment and the presence
51 of a sidewall have also been discussed in other contexts [9], [10], [11].

52 One of the limitations of the cited work is that the length of the cable trays does not allow the study
53 of the “travelling fire”, i.e., the propagation of the burning zone with a flame front advancing
54 towards the virgin fuel and an extinguishing front leaving the burnt fuel [12]. With the lengths
55 usually considered of about 2.4 m in the CHRISTIFIRE and PRISME programs, for example, the
56 entire length is ignited before an extinguishing front appears. Thus, these configurations are not
57 fully representative, and it is therefore not possible to quantify the displacement of a burning area,
58 giving a maximum length of the fire and an associated heat release rate. However, a 6.8 m long
59 cable tray configuration was also studied as part of the CHRISTIFIRE program [5]. It consisted of
60 studying the effect of a corridor (in open atmosphere condition) on fire propagation. The length of
61 cable trays was certainly long enough to observe a travelling fire, but this phenomenon was not
62 studied. The motivation of the present study is therefore to access the above-mentioned quantities
63 by considering long cable tray fire experiments.

64 This work is based on the analysis involving a cable length of 6 m carried out as part of the
65 OECD/NEA PRISME 3 project [13]. The study parameters are the nature of the cables using well-
66 qualified² cable (PE-EVA type also named thermoset) and non-qualified cables (PVC also named
67 thermoplastic) and the distance from the ceiling at which the fuel is placed, giving different
68 environmental conditions in terms of temperature and gas concentration. The first part of the paper
69 recalls the experimental set-up, the metrology implemented, and the data processing developed to
70 access the quantities of interest. The second part presents the results, focusing on the specific
71 behaviour of the tests and identifying the maximum lengths on fire, the fire heat release rate and

¹ NEA member countries: Belgium, Canada, Czech Republic, Finland, France, Germany, Japan, Korea, the Netherlands, Spain, Sweden, Switzerland, the United Kingdom and the United States of America.

² The well-qualified cables have passed the IEEE-383 flame spread test contrary to the low qualified cables which are less fire retardancy [34].

72 the associated propagation speeds. The last part concerns discussions highlighting the consistency
73 of the FLASH-CAT model with the experimental results.

74 To complete this experimental study, an initial numerical application of the test with the PVC cable
75 configuration was carried out to validate simulation tools [14].

76 2 Material and Methods

77 2.1 Experimental facility and test configurations

78 The tests were carried out in the IRSN's DIVA facility which is a mechanically ventilated fire
79 installation. It is made of reinforced concrete (400 kg of steel per m³ of concrete) and consists of
80 three identical compartments (3.85x4.86x5.88 = 110 m³ each) and a corridor
81 (3.85x2.50x15.6 = 149 m³) opened to the three rooms in order to bring sufficient air within the fire
82 room (Fig. 1). For thermal protection, a false ceiling is installed, with three layers in all
83 compartments: 13 cm air layer, 1 cm of 'Board Plus LTI' insulated panels and 1.3 cm 'Monalite
84 M1A' calcium silicate panels (Fig. 1). Part of the north wall of the corridor facing the fire source
85 (9.5 m long) was covered with a 2 cm layer of 'Superwool 607 HTC board' insulated panels in
86 order to protect the concrete in front of the cable trays. The material properties are given in Table
87 1. The corridor was chosen as the fire room in order to benefit from its considerable
88 length (15.6 m), appropriate for studying long cable tray fires.

89 Table 1 : Wall and ceiling material properties in the DIVA facility

Materials	Density (kg/m ³)	Thermal conductivity (W.m ⁻¹ .K ⁻¹)	Specific heat (J.kg ⁻¹ .K ⁻¹)
Concrete of DIVA (700°C)	2240	1.5	820
Board Plus LTI (600°C)	350	0.12	-
Monalite M1A (600°C)	970	0.22	970
Superwool 607 HTC board (on the north concrete wall)	360	0.12	840
Superwool 607 HT board (sidewall of the fire source)	350	0.11	840

90

91 The rooms and the corridor were mechanically ventilated by a ventilation network equipped with
 92 intake and exhaust lines, on which the supply and exhaust fans were positioned. The ventilation
 93 configuration was designed to create an oxygen-rich condition, necessary for an efficient
 94 combustion regime, without producing unburned gas in the installation. Thus, the initial intake air
 95 flow rate was set to 1,500 m³/h in each of the three rooms and in the corridor and the exhausts
 96 were set to 3,000 m³/h in the corridor and in room 3, giving an overall, well-ventilated, renewal
 97 rate of about 30 h⁻¹. The ventilation ducts were located just below the ceiling. The flow directions
 98 were north for the intake of the corridor, east for the intakes of the three adjacent rooms, south for
 99 the corridor exhaust and upward for the exhaust of room 3.

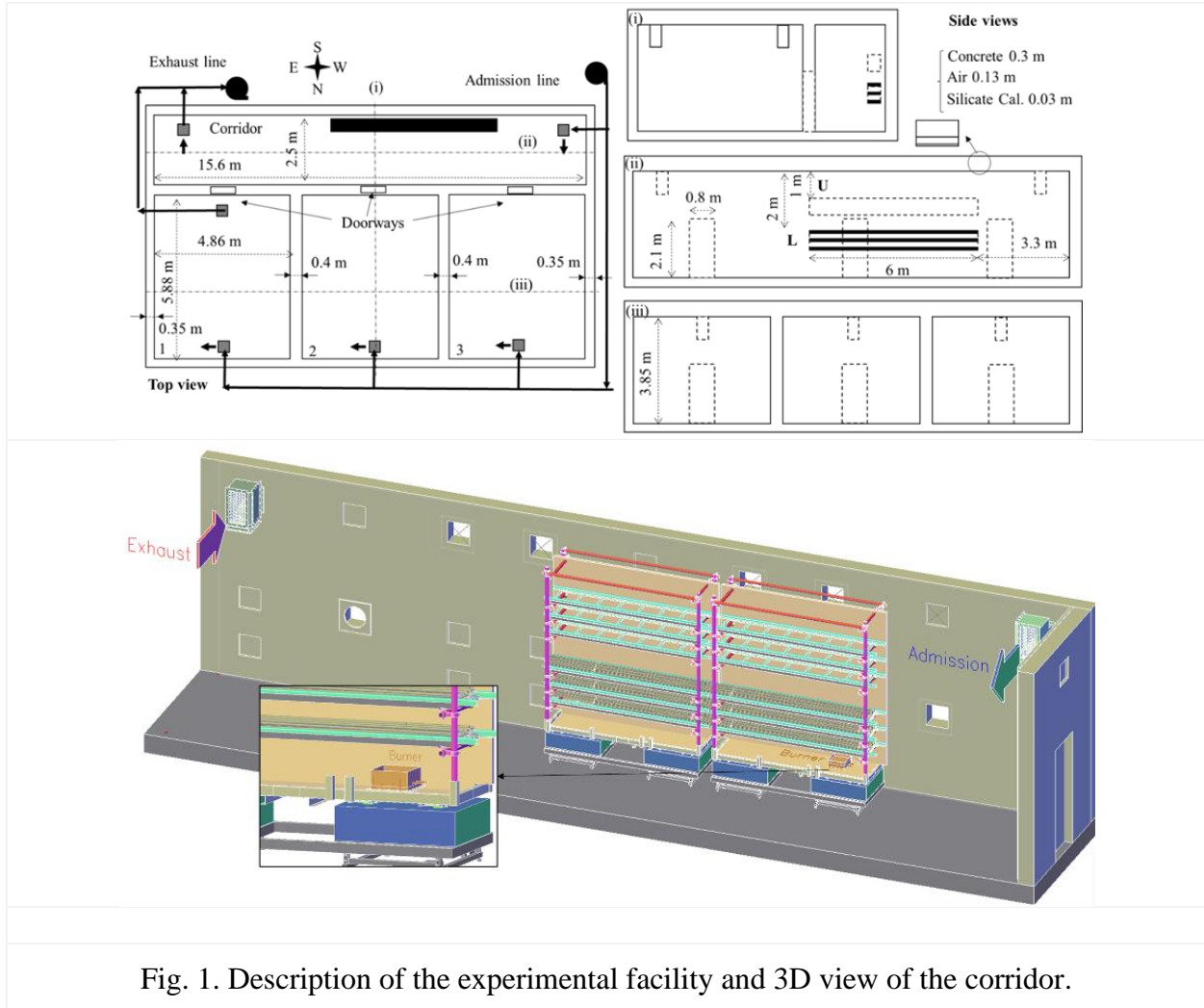


Fig. 1. Description of the experimental facility and 3D view of the corridor.

101 2.2 Characteristics of the fire source

102 The fire source consisted of three stacked horizontal cable trays 6 m long and 0.45 m wide, located
103 in the corridor against the sidewall opposite to the doorways (**Erreur ! Source du renvoi**
104 **introuvable.**). The vertical distance between the trays was 0.3 m. The trays were mounted on a
105 metallic frame protected with rock-wool and set against a 40 mm thick insulated sidewall
106 (Superwool 607 HT Board). Physical properties of this material is reported in Table 1. Two
107 configurations were tested, a cable tray assembly near the floor (index L for lower position) and
108 near the ceiling (index U for upper position) as illustrated in **Erreur ! Source du renvoi**
109 **introuvable.** For the lower configuration, the third tray was located 2 m from the ceiling and 1 m
110 for the upper configuration.

111 Two cable types were considered. The first cable type was a halogen free flame retardant (HFFR)
112 cable. It had a diameter of 20 mm and weighed 0.7 kg/m. The combustible materials were
113 Polyethylene-vinyl acetate (PE-VA) and Polyethylene (PE) and Alumina trihydrate (ATH) was
114 the flame retardant. The proportion of polymer is of 78 % compared with the copper conductors.
115 This cable has very similar characteristics to the one tested at small scale in [15] and at large scale
116 in open atmosphere with five cable trays of 2.4 m long in the framework of the PRISME 2 project
117 [16]. The second cable was a PVC (Polyvinyl Chloride) power cable. It has a diameter of 28 mm
118 and a linear mass of about 1.73 kg/m. The proportion of polymer is of 40 %. The PVC cables also
119 contained PE as combustible material. This cable was also tested at small scale [15] and at large
120 scale in open atmosphere environment in previous studies, conducted within the PRISME 2
121 project [8], [17]. For more information, the composition and the thermo-physical characteristics
122 of both cable types are given in detail in [18].

123 For all tests, the cables were loosely arranged. Each tray respectively contained 32 and 21 samples
124 for the HFFR and PVC cables. The fire was ignited with a gas propane burner (set to 80 kW) at
125 0.5 m from the west end and at 0.2 m below the lower tray. Ignition at one end allows the study of
126 fire spreading over a longer distance, in contrast to ignition at the centre, where the studied length
127 is limited to half of the total length. The ignition procedure was similar for the three tests, i.e the
128 burner was turn-off when the first ignition front (among the three cable trays) reached the half-
129 length of cables (3 m long).

130

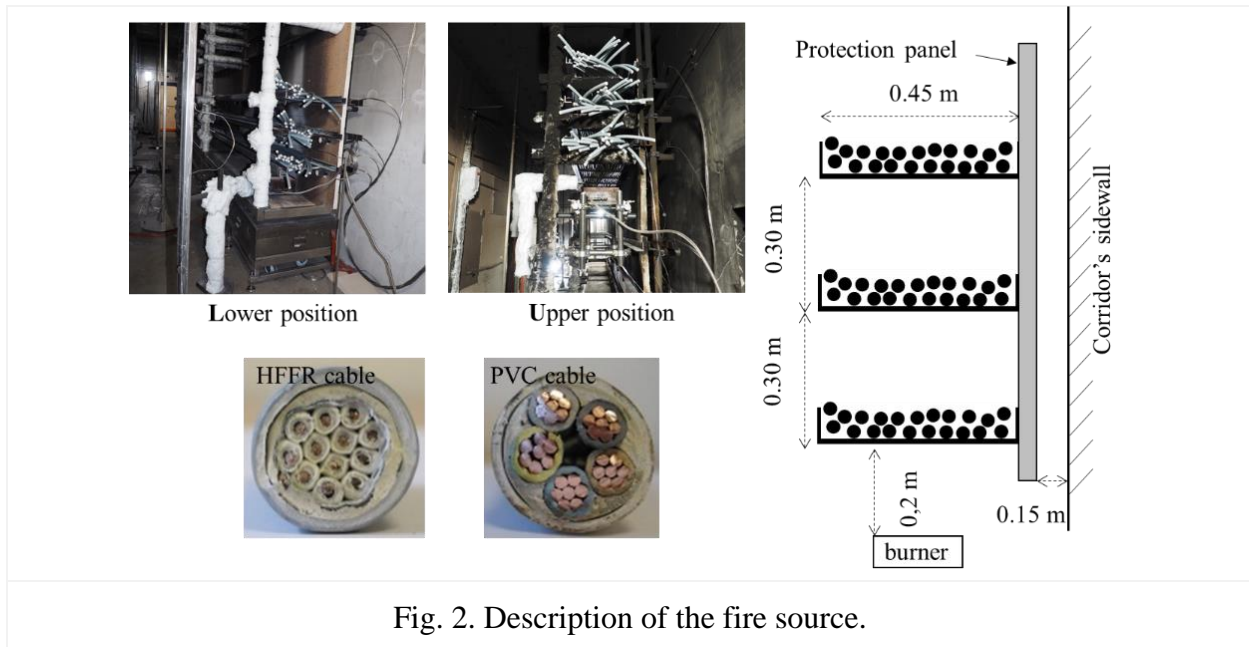


Fig. 2. Description of the fire source.

131 **2.3 Test matrix and experimental procedure**

132 The main objective of the fire tests was to quantify the flame propagation process for a set of long
 133 cable trays. Three large-scale tests were considered, for which the cable type (low-qualified PVC
 134 cables and well-qualified, HFFR cables) and the distance from the ceiling are the
 135 parameters (Table 2).

136 Table 2 : Test matrix

Tests	Cable type	Upper tray position from the ceiling	Comments/objectives
1 (PR3_CFP_D41)	HFFR (well-qualified)	2 m (lower position)	Reference test
2 (PR3_CFP_D61)	HFFR (well-qualified)	1 m (upper position)	Effect of the environment
3 (PR3_CFP_D51)	PVC (low-qualified)	2 m (lower position)	Effect of the cable type

137

138 **2.4 Measurement techniques**

139 Instrumentation was deployed in order to determine the fire heat release rate, the burning length,
 140 the mass loss rate (MLR), the effective heat of combustion (EHC), and the flame spread velocity.
 141 The flame spread velocity and the burning length were determined experimentally from twelve K
 142 type 1.5 mm diameter thermocouples (spaced 50 cm apart), set along each cable tray just above
 143 the cables (without any contact with them before the ignition) to estimate the different flame front
 144 positions on the cable trays. Four 600 kg Mettler type scales were installed under the cable trays
 145 to measure the mass loss and calculate the mass loss rate. The fire heat release rate (HRR) was
 146 experimentally determined by considering the calorimetric approach developed under a hood [19]
 147 and adapted to a mechanically ventilated enclosure [20]. This method requires measurements of
 148 carbon dioxide and carbon monoxide concentrations, measurements of gas temperature and
 149 pressure in the rooms (Fig. 3). The gas temperatures were measured at five positions along the
 150 corridor on vertical masts. For each position, nine thermocouples were distributed over the vertical
 151 distance between 5 cm and 3.8 m. The same number of thermocouples was installed at the centre
 152 of each adjacent room. The gas concentrations were measured at three positions along the corridor
 153 and at the centre of each adjacent room, in both the lower and upper parts. The air flow rate in the
 154 ventilation lines was determined from average pitot probe (annubar type), pressure transducer and
 155 temperature probe. The mass flow rate of the propane at the burner was measured with a Brooks
 156 mass flow sensor.

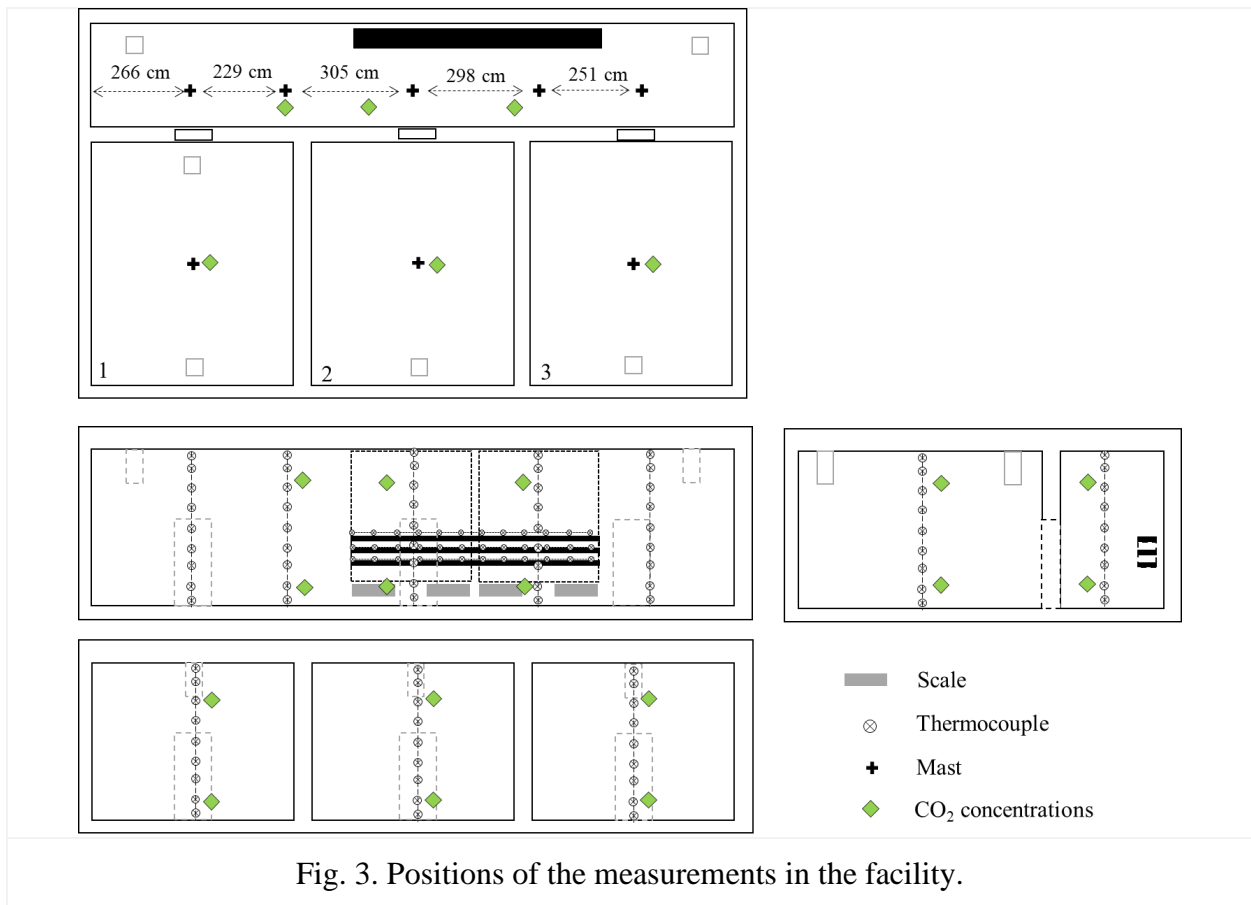


Fig. 3. Positions of the measurements in the facility.

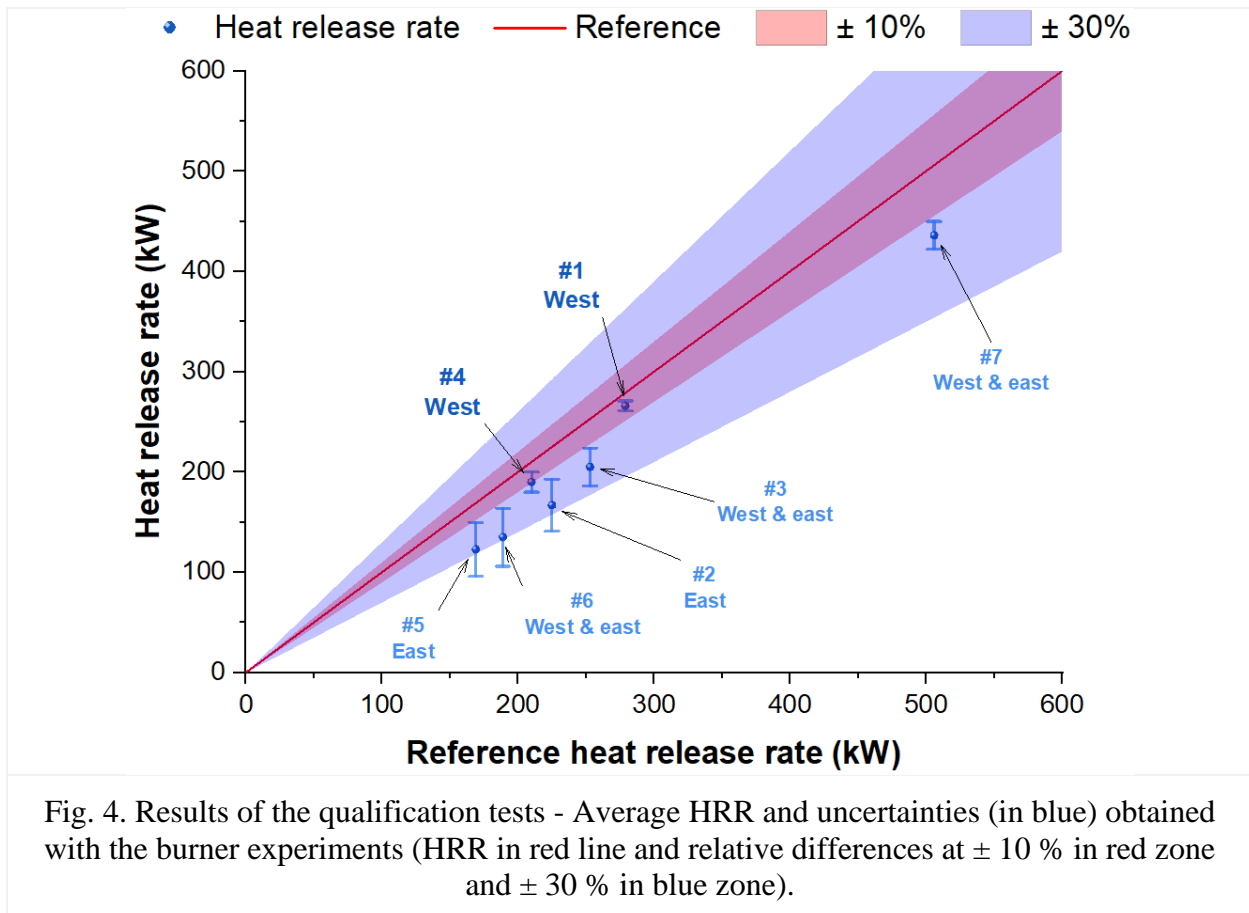
157 The fire heat release rate was determined using the chemical method based on the CO₂ mass flow
 158 rate, generated during combustion [21]. The CO₂ mass flow rate was assessed by means of mass
 159 balances carried out over the entire corridor, according to the approach described in [22]. An initial
 160 qualification phase was conducted, using a gas burner as the reference fire source, to validate the
 161 HRR determination method. Using the gas burner inside the installation, the reference HRR is
 162 determined from the measurement of the propane mass flow rate and the knowledge of the
 163 combustion enthalpy (46 MJ/kg). Qualification tests were carried out with several gas burners
 164 simultaneously placed at both ends of the corridor to assess the effect of the inhomogeneous gas
 165 distribution. The comparison of the average reference HRR $\langle \dot{Q}_{ref} \rangle$ and the average HRR $\langle \dot{Q}_{CDG} \rangle$
 166 determined with the chemical method is presented in Fig. 4.

167 The relative uncertainty $\Delta \dot{Q}^*$ is calculated as follows:

$$168 \quad \Delta \dot{Q}^* = 100 \frac{|\langle \dot{Q}_{CDG} \rangle - \langle \dot{Q}_{ref} \rangle|}{\langle \dot{Q}_{ref} \rangle}$$

169 The uncertainty was comprised between 5 % and 29 %. Compared with the reference HRR the
 170 chemical HRR is always an underestimate.

171



172

173 **3 Results**

174 **3.1 Effect of the cable type (tests 1 and 3)**

175 First, the effect of the cable type on the fire scenario is analysed, considering a low position of the
 176 cable trays inside the corridor. Quantities of interest are the fire heat release rate, the travelling
 177 burning length and the horizontal flame spread velocity.

178 To compare the three tests with a same method during the travelling phase, a free period (i.e a
 179 stationary phase during the travelling fire period) is defined during which a quasi-steady HRR is
 180 assessed (Fig. 5). The free period is defined according to the following criteria:

- 181 • the burner must be off,
- 182 • the ignition and extinction fronts must be clearly visible (travelling fire phase),
- 183 • and the L2-norm of the HRR $\|\dot{q}\|_2$ must be lower than or equal to 10 % as explained in
 184 detail below.

185 The method consists in imposing the end of the period t_f just before the edge effect at the end of
 186 cables (defined from the fire visualization with the cameras). Next, the backward iterative
 187 calculation of $\|\dot{q}\|_2$ between the instantaneous and the average HRR ($\dot{q}(t)$ and $\langle \dot{q}(t:t_f) \rangle$)
 188 allows to estimate the begin of the period when $\|\dot{q}\|_2$ reaches 10 %.

189
$$\|\dot{q}\|_2 = 100 \sqrt{\frac{\int_{t-\Delta t}^{t_f} (\dot{q}(t) - \langle \dot{q}(t:t_f) \rangle)^2}{\int_{t-\Delta t}^{t_f} \langle \dot{q}(t:t_f) \rangle^2}} = 10 \% \quad (1)$$

190 With the time step $\Delta t=1$ s.

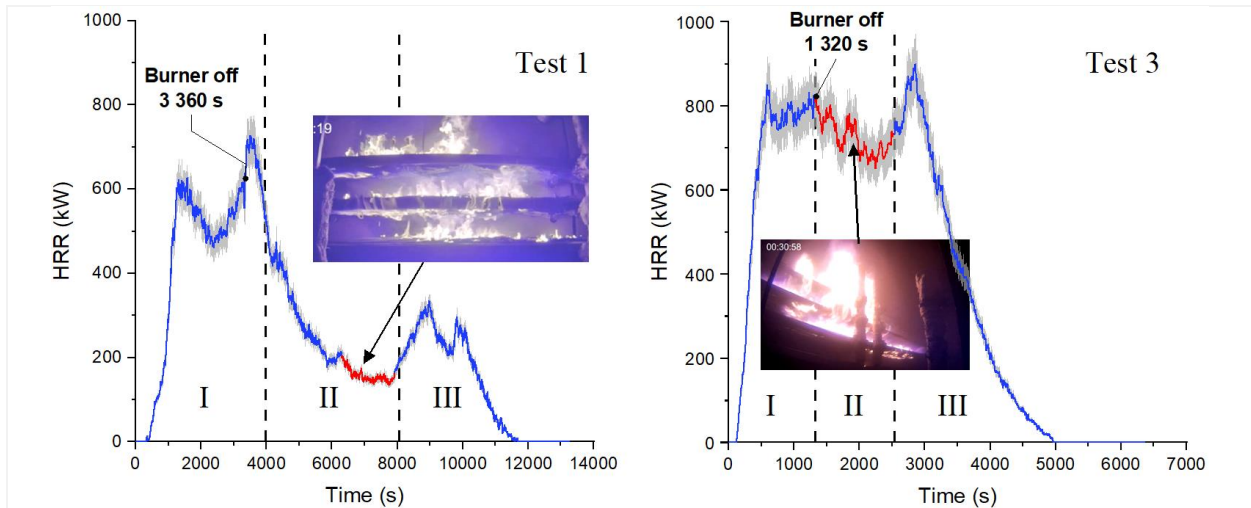


Fig. 5. Time variation of the fire HRR for test 1 (left) and test 3 (right) – HRR in blue, in red the free period during the travelling fire phase (157 kW for test 1 and 727 kW for test 3), uncertainty in shaded zone.

191 3.1.1 Fire heat release rate

192 The time variation of the fire HRR is presented in Fig. 5. For the HFFR cable fire (test 1) about
193 420 s after the burner is switched on, the HRR gradually increases until a first maximum of 600
194 kW after about 1 000 s. Then the HRR decreases slightly and rises again to reach a second
195 maximum of 700 kW. During this first period, the combustion zone remains stabilised in the first
196 3 m of the total cable length where the edge of the cable trays burns and influences the fire HRR.
197 Then, the fire starts travelling as a bounded fire along each cable tray, i.e. an extinguishing front
198 at the rear of the fire (due to lack of combustible) and an ignition front moving towards the unburnt
199 cables. This also means that from this moment the fire propagation is in a self-combustion regime,
200 without being influenced by the cable edges and the burner. Noted that the residual flames
201 observed in the first end of cables did not appear to have any effect on the fire propagation. This
202 propagation phase is defined as a “travelling fire” as already reported in other applications [12],
203 [23], [24]. This second period corresponds to a significant decrease of the fire HRR down to a
204 minimum level at about 157 kW (in average over the free period). This travelling fire is observed
205 until the burning area of the second tray reaches the end of cables. This point coincides with a new
206 increase of the HRR up to 300 kW. This final period corresponds to the burning of the end of the
207 tray. Extinction occurs after 13 200 s.

208 Test 3 aimed at studying the effect of the nature of the cable by repeating test 1 with PVC cables
209 (thermoplastic-type cables). The evolution of the fire HRR shows a rapid propagation, followed
210 by a free period during 20 min at average 727 kW and rapid decay from 3000 s until extinction
211 (Fig. 5 - right). A similar behaviour to that observed for test 1 is reported, with three periods, one
212 of which is intermediate and during which the burning zone propagates over the cable trays without
213 any interaction with the cable edges. The other two periods show maximum HRR, interpreted as
214 related to the edge effect. The main difference between the two tests is the higher HRR amplitude
215 with the PVC cable. This agrees with the results of the literature on the better fire retardancy of
216 HFFR cables. This more intense fire leads to a shorter burning phase duration, in comparison to
217 test 1.

218 It is important to note that the HRR is lower (significantly lower with HFFR cables) during the
219 period of travelling propagation than during the periods when one of the end is burning. Indeed,
220 the cables burn in depth everywhere but this phenomenon could be more pronounced at the edge
221 of the cables as the flame cannot propagate and is stopped. Therefore, the flame feedback on the
222 fuel surface is only concentrated on the fuel area and not preheat potential propagation zone. The
223 results clearly show a difference between the burning of an area with some edge effects and the
224 burning of a travelling area, sufficiently far from the ends. This suggests that tests with too short
225 cable lengths could lead to HRR levels that are higher than those obtained during a travelling
226 propagation. Experiments with longer test lengths allow more realistic quantification of the HRR.

227 3.1.2 Burning length

228 An important quantity of interest is the length of the combustion zone during the travelling fire.
229 Due to the short investigated length, this information is barely reported in the literature for large
230 scale configurations. This length is obtained from the positions of the ignition and extinction
231 fronts, estimated with the temperature measurement considering a criterion of 500°C. The distance

232 between the ignition and the extinguishing fronts gives the burning length for each cable tray. The
 233 overall burning length is defined as the distance between the furthest downstream flame front and
 234 the furthest upstream extinguishing front.

235 The evolution of these burning lengths are respectively presented in Fig. 6 and Fig. 7 for tests 1
 236 and 3. The figures also illustrate the spatial distribution of the burning zone at three instants. Each
 237 tray may not have the same burning length and therefore an overall burning length is also
 238 determined.

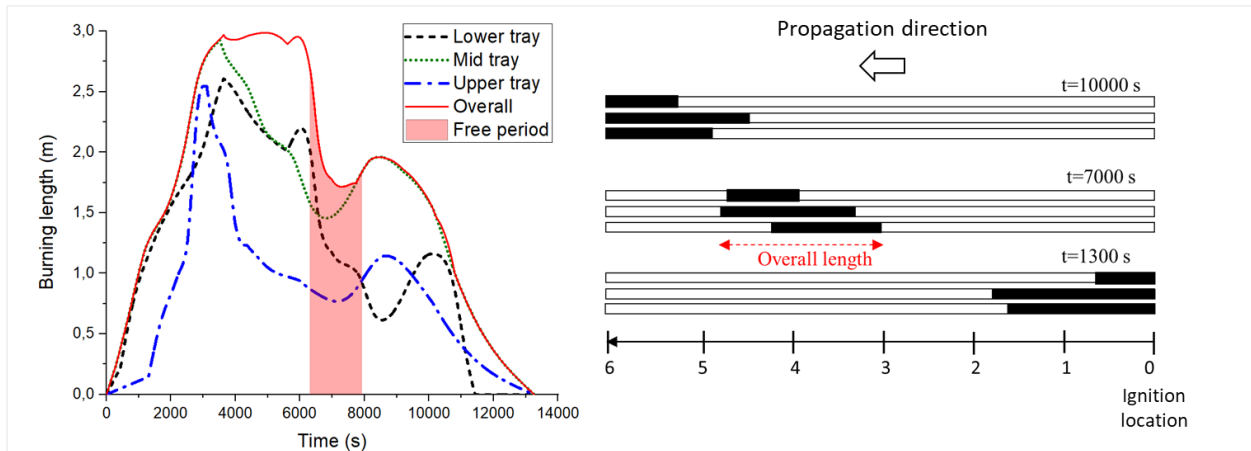


Fig. 6. Time variation of the burning length on each tray and of the overall burning length (left), illustration of the burning length at three distinct times (right) for test 1.

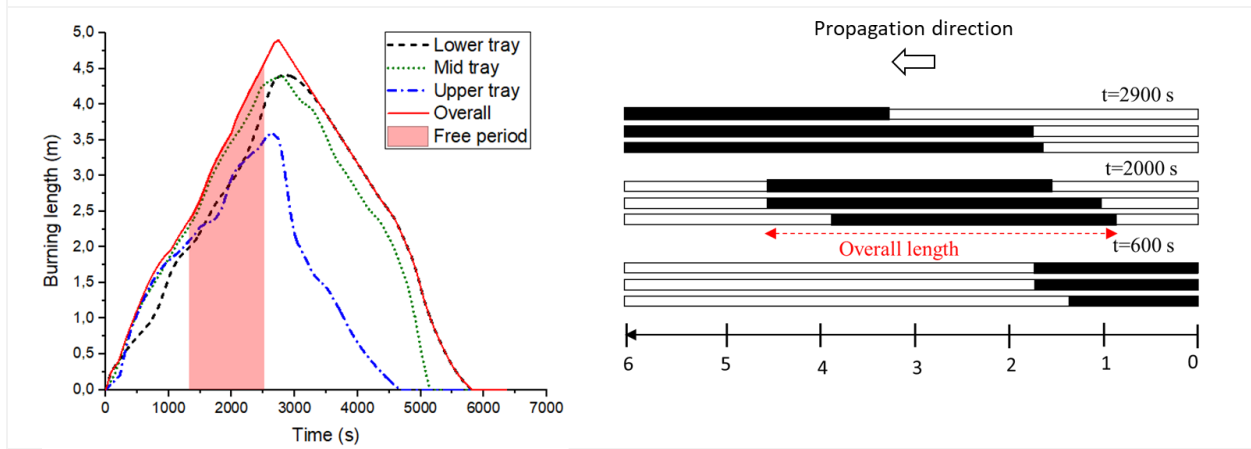


Fig. 7. Time variation of the burning length on each tray and the overall burning length (left), illustration of the burning length at three given times (right) for test 3.

239 For the test with the HFFR cable (test 1 in Fig. 6), the intermediate cable tray has most of the time
 240 the longest burning length. During the free period, the overall burning length ranges between 1.7 m
 241 and 2.7 m. Regarding the test with the PVC cable (test 3 in Fig. 7), the burning length is greater
 242 with the range between 2.4 m and 4.6 m. The estimation of the burning length for PVC cables was
 243 subject to uncertainties due to difficulties in accurately estimating the position of the extinction
 244 fronts with thermocouples. This explains the differences in variations between burning length and
 245 HRR (Fig. 5). Nevertheless, the burning length of PVC cables provides qualitative information on

246 the overall behaviour of flame front propagation. A notable difference between the two types of
247 cable concerns the position of the flames. Indeed, for the HFFR cable, the burning lengths were
248 slightly offset from one cable tray to the other, whereas they occupied similar positions with similar
249 flame lengths for the PVC cable.

250 3.1.3 Effective heat of combustion and HRRPUA

251 The measurement of the mass loss and the chemical HRR allow the effective heat of combustion
252 (EHC) to be determined versus time. For the HFFR cable (Fig. 8-left), the EHC remains nearly
253 constant throughout the test between 18.7 MJ/kg and 23.4 MJ/kg with an average of 20.7 MJ/kg
254 during the free period. The amplitude agrees with measurements made in an open environment for
255 an experiment involving five cable trays of 2.4 m in length [25]. However, these literature tests
256 showed a continuous increase in EHC, whereas in these tests the value seems relatively stationary
257 over time. Regarding the PVC, the EHC is about 21 MJ/kg and is similar to the value obtained for
258 HFFR cable. This value agrees with the values obtained for other configurations (5 horizontal
259 cable trays 2.4 m long [8]).

260 An attempt to determine the HRRPUA (heat release rate per unit of area) from the HRR and the
261 burning surface is proposed. The latter is evaluated using the sum of the lengths on fire on each
262 tray, taking into account both areas of the cable tray (top and bottom). The burning width is
263 supposed equal to the cable tray width (45 cm) because the cable loose arranged were stuck
264 between them. For the HFFR cable, the HRRPUA shows a maximum of 275 kW/m² during the
265 first combustion period and then decreases rapidly over the following periods to reach values
266 below 100 kW/m² (Fig. 8-right). During the free period, the HRRPUA varies between 43 kW/m²
267 and 64 kW/m², with an average of 53 kW/m². The values obtained during the free period are low
268 compared to those measured with the same cable in other studies [4]. One explanation is the low
269 HRR measured for a rather significant burning area. However, these values are consistent with
270 those obtained by Meinier et al. [15] in a cone calorimeter under an irradiance of 40 kW/m².
271 Regarding the PVC cable, the HRRPUA is higher than that obtained with the HFFR cable, with
272 an average value of about 120 kW/m². This value is still lower than the 250 kW/m² value
273 recommended for thermoplastic cable for use in the FLASHCAT model [4].

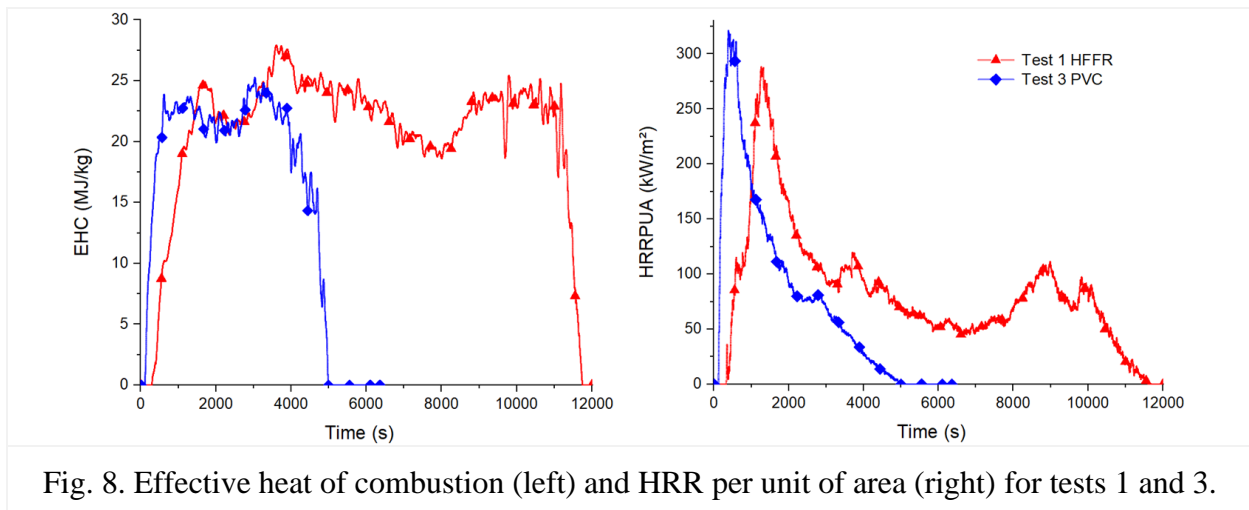


Fig. 8. Effective heat of combustion (left) and HRR per unit of area (right) for tests 1 and 3.

274 3.1.4 Horizontal flame spread velocity

275 Along each cable tray, from 0.5 m to 6 m long, thermocouples were spaced of 0.5 m. The
 276 horizontal ignition fronts x_f^i along each cable tray "i" were detected at the time where the
 277 temperature reached a threshold temperature value of 500°C. To obtain a continuous value, the
 278 ignition positions are interpolated with a polynomial law. The velocity spread of the ignition fronts
 279 \dot{x}_f^i in each tray "i" is calculated as the time derivation of the ignition position x_f^i . The flame spread
 280 velocity over the three trays versus time is presented for both tests in Fig. 9. For test 1 with HFFR
 281 cables, during the first period, the propagation velocities are the highest (about 0.75 mm/s and up
 282 to 3 mm/s). Then they decrease to 0.4 mm/s during the free period, which is lower than those
 283 obtained with five cable trays 2.4 m long in open environment (0.8, 1.1, 2.7, 3.0 and 6.4 mm/s for
 284 five trays [17]). This result shows that the flame spread velocity of a travelling fire over a long
 285 cable length is probably lower than that obtained in tests involving short cable lengths and with a
 286 greater number of trays. These results emphasize the effect of the configuration on the horizontal
 287 flame spread velocity. This value is also slightly lower than those recommended for the
 288 FLASHCAT model (higher than 1 mm/s).

289 The propagation velocity obtained for test 3 with PVC cables is greater, with 1.9 mm/s during the
 290 free period. The dehydrate ATH in HFFR cables releases water vapor. This process cools the
 291 cables and decreases the oxygen concentration at the cable surface which reduces the preheating,
 292 slows the combustion and attenuates the gas temperature contrary to the PVC cables. The velocities
 293 of PVC cables agrees with those obtained in the literature for shorter lengths (1.5, 2.4, 3.1, 4.6 and
 294 4.8 mm/s for five trays [8]) but remains on the lower side of the expected range.

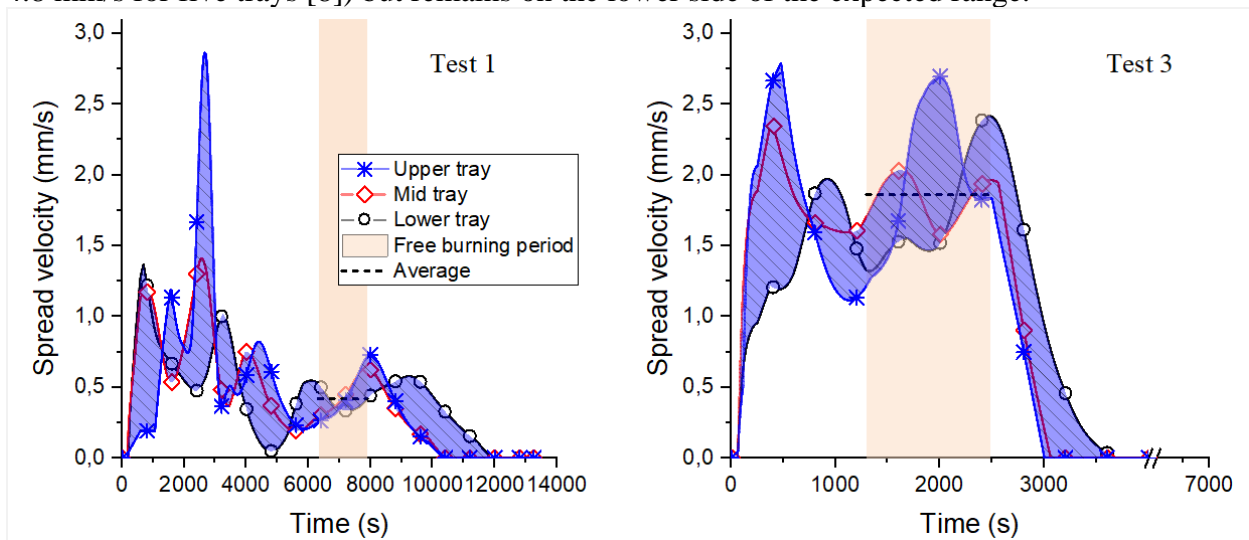


Fig. 9. Horizontal flame spread velocity of the flame front for test 1 (left) and test 3 (right).

295 The values obtained according to the NUREG recommendations [26] are 0.3 mm/s for thermoset
 296 or well-qualified cables (HFFR) and 0.9 mm/s for thermoplastic or non-qualified cables (PVC).
 297 The values of the present tests are higher than these recommendations.

298

299 **3.2 Effect of the environment**

300 Test 2 (HFFR cable in the upper location) aims at investigating the effect of the environment of
301 the cable trays on the fire HRR, the burning length and the flame spread velocity during the
302 travelling fire. The evolution of the fire HRR shows, in the first instants, similar behaviour to that
303 of test 1, with a gradual increase up to a maximum value of about 600 kW (Fig. 10). Then, contrary
304 to test 1, the HRR is maintained at this level during the travelling phase for the three trays. When
305 the flame front reaches the other edge of the trays, a slight re-increase is observed. As in test 1, the
306 burning period of both ends results in higher HRR. On the other hand, the free period of travelling
307 fire along the cables gives a higher HRR than that noted in test 1: about 522 kW over a period of
308 about 29 minutes. In comparison to test 1, the increase of HRR is explained by the ceiling effect,
309 which preheated the cable and then promoted burning.

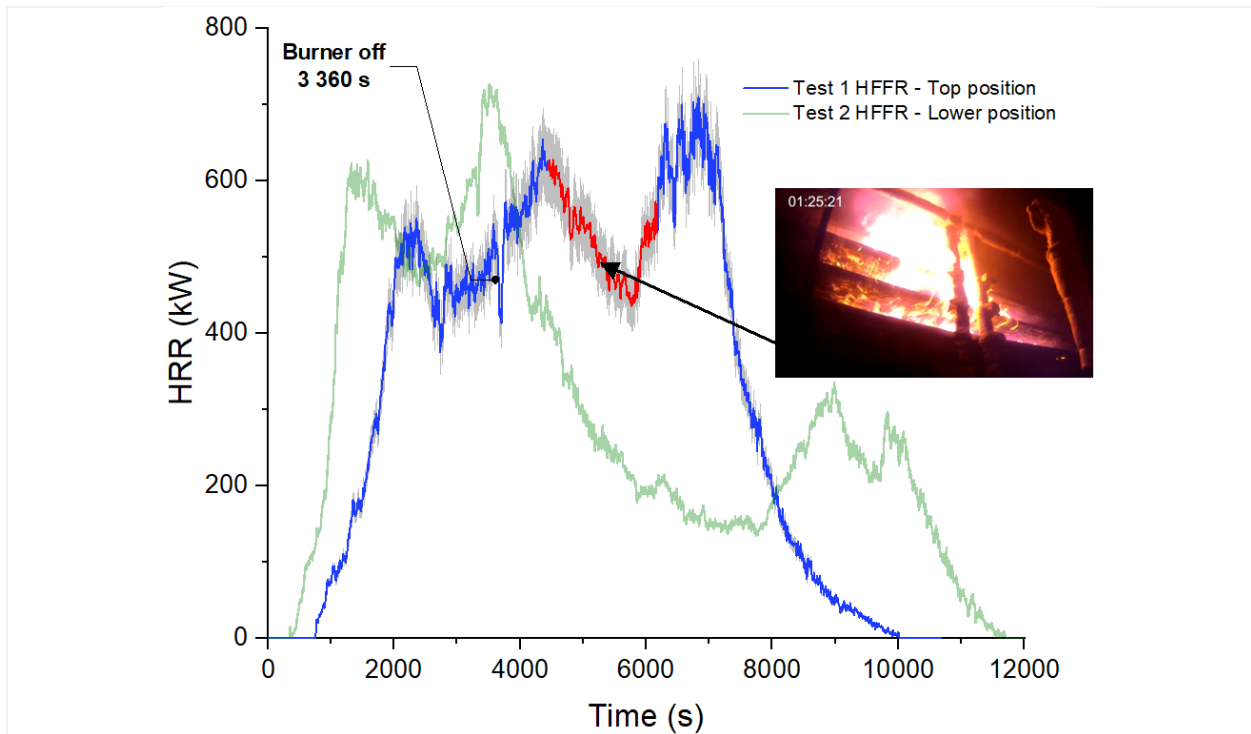


Fig. 10. Time variation of the fire HRR for test 2 (HFFR cable and upper position) – HRR in blue, HRR during the travelling phase in red, uncertainty in shaded zone.

310

311 For this purpose, the temperature of the unburned cables downstream of the flame front is
312 investigated. Fig. 11 shows the horizontal temperature profiles of the cables in the unburnt area in
313 front of the fire for the three cable trays and at four instants. The results show a higher cable
314 temperature for the upper position (test 2) compared to the lower position (test 1). An average
315 difference of 85 °C confirms the higher preheating of the cables with the elevation of the fire. The
316 average temperature of the cables at 1.5 m downstream of the flame front is between 40°C and
317 130°C for the low position test and between 130°C and 230°C for the upper position test.

318

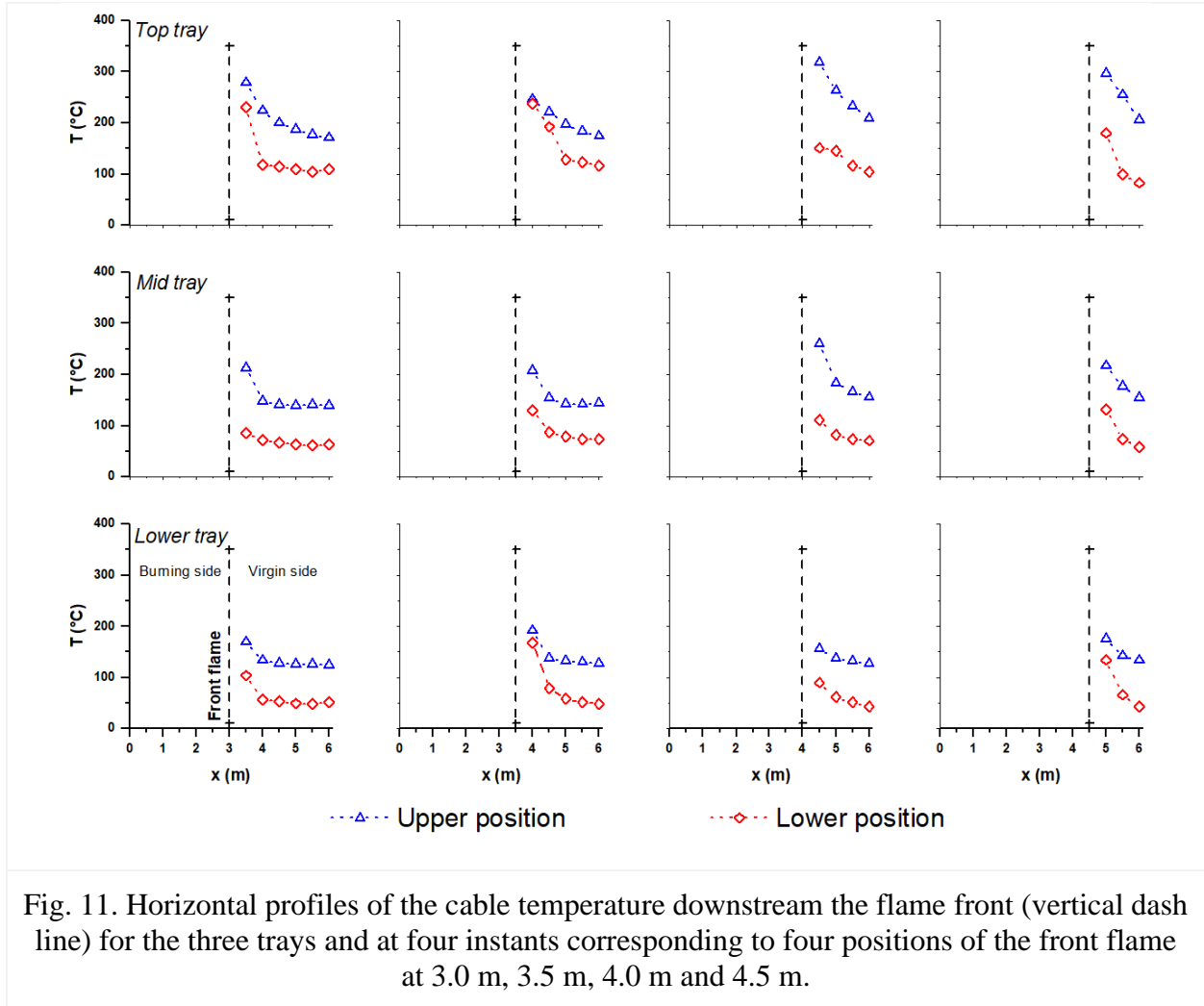


Fig. 11. Horizontal profiles of the cable temperature downstream the flame front (vertical dash line) for the three trays and at four instants corresponding to four positions of the front flame at 3.0 m, 3.5 m, 4.0 m and 4.5 m.

319

320 The burning length variation for each tray and the overall length are presented in Fig. 12. As in
 321 test 1, the burning length in the intermediate tray is the longest. During the free period, the overall
 322 burning length of the fire reaches about 3.2 m, which is significantly longer than in test 1. The
 323 proximity of the ceiling contributes to increase the maximum travelling fire length.

324 The effect of the ceiling is also reported for the flame spread velocities. An average of 0.9 mm/s
 325 was measured during the free period, compared with the mean of 0.4 mm/s for test 1 (Fig. 13).
 326 This result is consistent because the increase of the environment temperature under the ceiling
 327 increased the horizontal spread velocity U_h . This result is consistent with the Quintiere correlation
 328 [27]:

329

$$U_h(t) = \frac{4 \Delta \dot{q}_f''^2}{\pi k \rho C_p (T_{ig} - T_{amb}(t))^2} \quad (2)$$

330 where U_h is the horizontal fire spread velocity, \dot{q}_f'' the incident heat flux from flames to the fuel
 331 surface, Δ the heated fuel distance, $k\rho C_p$ the thermal inertia of cables, T_{ig} the ignition temperature
 332 of cables (500°C for the three tests) and T_{amb} the ambient temperature. Indeed, the ambient
 333 temperature near the cables was hotter for the test 2 (upper position) in contrast to the test 1 (lower
 334 position). Therefore, the temperature difference $T_{ig} - T_{amb}(t)$ in the denominator of the Quintiere
 335 was lower for the test 2 leading to higher speed.

336 As part of the CHRISTIFIRE program, Mc Grattan et al. [5] obtained velocity propagations
 337 comprised between 2 mm/s and 10 mm/s for thermoset and thermoplastic cables. These values are
 338 more significant because the tests were performed in a well-ventilated corridor (in open
 339 atmosphere) and the upper tray was located 30 cm just under the ceiling. Nevertheless, the
 340 travelling fire propagation was not studied during this program.

341

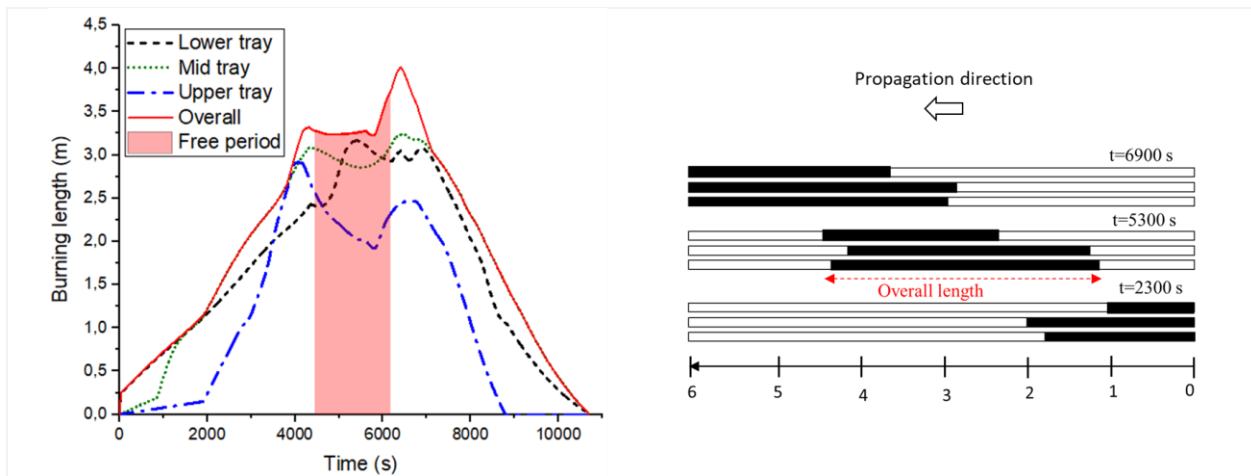


Fig. 12. Time variation of the burning length for each tray and the overall burning length (left), illustration of the burning length at three given times (right) for test 2.

342

343

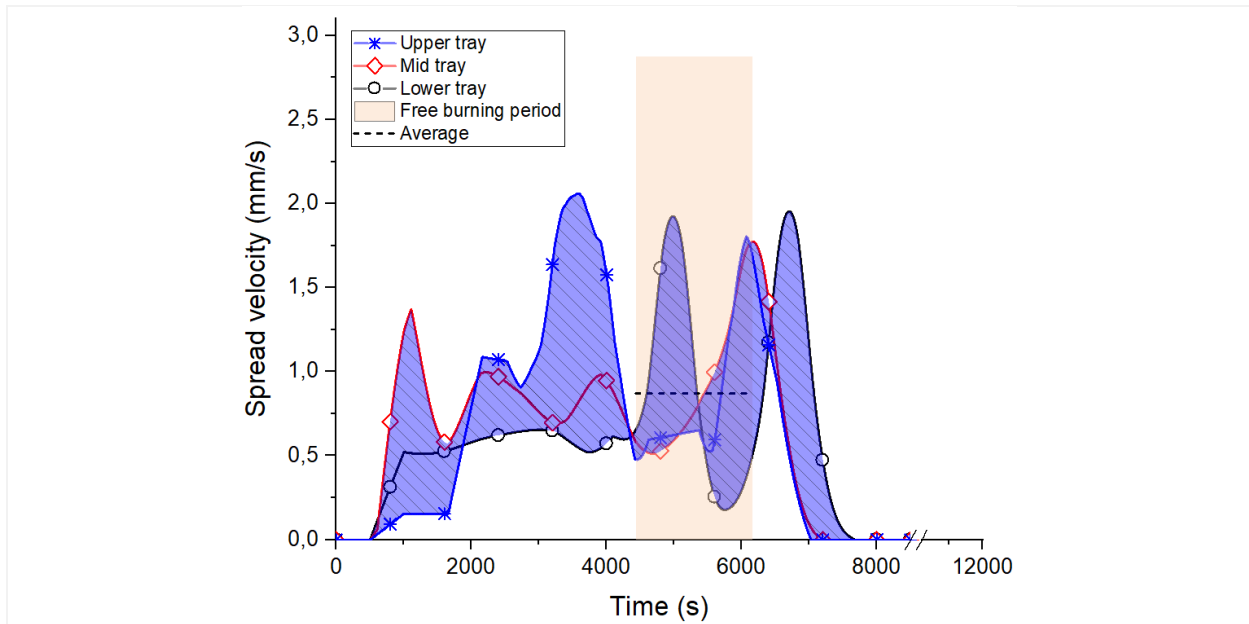


Fig. 13. Horizontal flame spread velocity of the flame front for test 2 (HFFR cable and upper position U).

344 3.3 Discussion

345 A comparative analysis of the three tests is proposed, focusing on the free period during the
 346 travelling fire and thus discounting both the specific burning of the cable ends and the presence of
 347 the burner (see Table 3). The travelling fire phase lasted 20 min with the PVC cable. During this
 348 period, the average heat release rate was on the order of 730 kW, the overall length of fire was
 349 3.5 m with propagation speeds of approximately 1.9 mm/s. This makes the burning during this test
 350 the most powerful, fastest and longest of the three tests. In contrast, the free period with the HFFR
 351 cable (in the low configuration) was the least powerful (157 kW), with the shortest overall burning
 352 length (1.8 m) and propagation velocities of less than 1 mm/s. This reduction in propagation speed
 353 leads to a longer duration of the free period (26 min). The effect of the elevation of the HFFR
 354 cables below the ceiling was to increase the heat release rate, the burning length and the mean
 355 velocity to 522 kW, 3.2 m and 0.87 mm/s respectively. These values are still lower than those
 356 obtained with the PVC cable.

357

358 Table 3 : Main results during the free period of the travelling fire phase (the mean burning length
 359 is the total burning length divided by the number of trays, the mean velocity is the average over
 360 the number of trays).

Name	HRR (kW)	Overall burning length (m)	Mean burning length (m)	U (Tray1/Tray2/Tray3) (mm/s)	Mean velocity (mm/s)
1 (HFFR-L)	157	1.8	1.2	0.39 / 0.45 / 0.43	0.42
2 (HFFR-U)	522	3.2	2.7	0.89 / 0.90 / 0.83	0.87
3 (PVC-L)	727	3.5	3.0	1.71 / 1.83 / 2.03	1.86

361
 362 The experimental determination of the fire heat release rate, the mean burning length and the flame
 363 spread velocity independently (chemical method for the HRR, video and temperature measurement
 364 for the burning length and temperature measurement for the velocities) allowed us to analyse their
 365 meaning based on the theoretical approach developed in the FLASHCAT model [4]. This model
 366 considers two important relationships that are recalled below:

$$367 \quad Q = n_T L w \dot{q}'' \quad \text{and} \quad L = U_h \Delta t \quad \text{with} \quad \Delta t = m'' \frac{\Delta H}{\dot{q}''} \quad \text{and} \quad m'' = \frac{n Y_p (1-\nu) m'}{w} \quad (3)$$

368 where Q is the fire HRR, L the mean burning length, n_T the number of trays, \dot{q}'' the heat release
 369 rate per unit of area (HRRPUA), U_h the horizontal flame spread velocity and Δt the burning time
 370 corresponding to the time for in-depth burning material. Δt depends on the effective heat of
 371 combustion ΔH , HRRPUA and the mass of combustible per unit of area m'' computed from the
 372 mass of cable per unit of length m' , the fraction of burning material Y_p , the char yield ν , the number
 373 of cables n and the width of trays w . The model shows therefore that the variation of the fire HRR
 374 with the burning length and the burning length with the flame spread velocity are linear and that
 375 the coefficients depend on the cable properties.

376 Considering the equations above and the slope of the curves in Fig. 14, it is possible to respectively
 377 compare the theoretical and the experimental HRRPUA.

378

379 Table 4 provides the input parameters to assess the HRRPUA with the two laws $Q=f(L)$ and
 380 $L=f(U_h)$ as illustrated in Fig. 14. Each part of the cables has been weighted to obtain the lineic
 381 mass m' (0.70 kg/m for HFFR cables and 1.73 kg/m for PVC cables) and the fraction of burning
 382 material Y_p (31 % for HFFR cables and 19 % for PVC cables). This last parameter does not take
 383 into account the metal conductors amount and the non-combustible materials in polymers. For
 384 HFFR cables, the fraction of ATH flame retardant is of 60 % [15]. The PVC cables are actually
 385 only composed of 50% combustible material (PVC and phthalates) from TGA (thermogravimetric
 386 analyse) technics presented in [28].

387 Using the first law $Q=f(L)$, the theoretical HRRPUA for the three tests are respectively of 97 kW/m²,
 388 143 kW/m² and 180 kW/m². Thanks to the slopes of the curves, the experimental HRRPUA are
 389 assessed at 104 kW/m², 156 kW/m² and 192 kW/m². The theoretical and experimental results are
 390 consistent with a relative difference comprised between 7 % and 9 %. Using the second law
 391 $L=f(U_h)$, the theoretical HRRPUA are equal to 90 kW/m², 105 kW/m² and 214 kW/m² instead of
 392 83 kW/m², 106 kW/m² and 216 kW/m². It is also consistent with a relative difference of 8 % for
 393 the test 1 and 1 % for the others. The values obtained with the two laws are consistent, in agreement
 394 with the expected trend (higher value for PVC) and with the order of magnitude recommended for
 395 instance in the FLASHCAT model (150 kW/m² for thermoset cables as HFFR cables and
 396 250 kW/m² for thermoplastic cables as PVC cables).

397 In addition, the results show that a cable preheating process [29], [30], [31], [32], [33] (as discussed
 398 in [5]) because of the vicinity of the ceiling contributes to increase the HRRPUA.

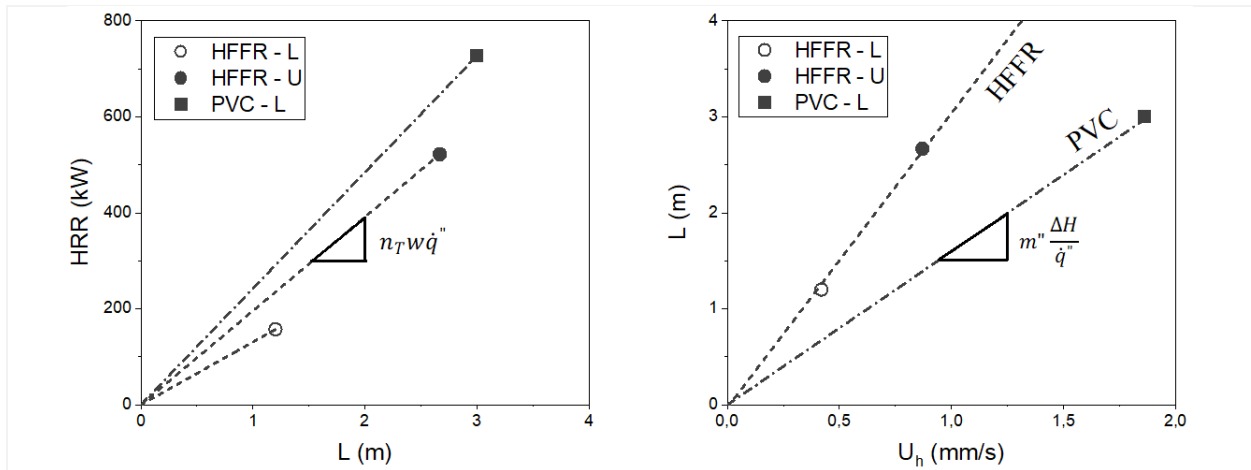


Fig. 14. Heat release rate versus the burning length (left) and total burning length versus the flame spread velocity (right).

399

400

401
402

Table 4 : HRRPUA assessment from the two laws $Q=f(L)$ and $L=f(U_h)$ and comparison between theoretical and experimental results.

	Parameters	Test 1 (HFFR-L)	Test 2 (HFFR-U)	Test 3 (PVC-L)
Input parameters	n_T	3	3	3
	n	32	32	21
	Y_p	0.31	0.31	0.19
	ν	0.25	0.25	0
	m' (kg/m)	0.70	0.70	1.73
	w (m)	0.42	0.42	0.42
	m'' (kg/m ²)	12.4	12.4	16.4
	L (m)	1.2	2.7	3.0
	Q (kW)	157	522	727
	U_h (mm/s)	0.42	0.87	1.86
	ΔH (MJ/kg)	20.7	26.3	21.0
	First law $\dot{q}_{th}'' = \frac{Q}{n_T L w}$	\dot{q}_{th}'' (kW/m ²)	97	143
$Slope = n_T w \dot{q}''$ (kW/m)		131	196	242
$\dot{q}'' = \frac{Slope}{n_T w}$ (kW/m ²)		104	156	192
Second law $\dot{q}_{th}'' = \frac{m'' \Delta H}{L} U_h$	\dot{q}_{th}'' (kW/m ²)	90	105	214
	$Slope = \frac{m'' \Delta H}{\dot{q}''}$ (m/mm.s ⁻¹)	3.1	3.1	1.6
	$\dot{q}'' = \frac{m'' \Delta H}{Slope}$ (kW/m ²)	83	106	216

403

404 The second relationship linking the burning length and the flame spread velocity allows to assess
405 experimentally the burning time. The values are 2368 s for HFFR cable at the low position (test 1),
406 2759 s for HFFR cable at the upper position (test 2), and 1756 s for PVC cable. The burning time
407 is shorter for PVC cable compared to HFFR cable because of a higher HRRPUA; the PVC cable
408 burns faster than the HFFR cable.

409 It is worth noting that the relation $L = f(U_h)$ does not depend on the number of trays.

410 **4 Conclusions**

411 The objective of this work was to investigate the propagation of the combustion area over
412 horizontal cable trays. For this purpose, three large-scale experiments on long length cable trays
413 were conducted. The test configuration consisted of three horizontal cable trays with a total length
414 of 6 m ignited by a gas burner at one end. The parameters were the type of cable (PVC as a non-
415 qualified cable and HFFR as a well-qualified cable) and the distance between the cable tray and
416 the ceiling (far or close).

417 Experiments on long cable trays showed a travelling combustion zone with a leading front of flame
418 propagation and a trailing front of fire extinction. To the authors' knowledge, this type of large-
419 scale travelling fire on a cable tray assembly has barely been presented in the literature. These
420 experiments allowed the quantification of the travelling burning length, the corresponding fire
421 HRR and the horizontal fire spread velocity.

422 For tests with HFFR cables (thermoset-type), the overall burning length of a set of three cable trays
423 is between 1.8 m and 3.2 m and the associated fire HRR is between 157 kW and 522 kW. The
424 difference between the two tests is the influence of the proximity of the ceiling on the heating of
425 the cables. The test with PVC cable gives higher burning length, HRR and propagation speeds than
426 the tests with HFFR cables. Indeed, the maximum burning length during the propagation phase is
427 3.5 m for an associated power of 727 kW and a propagation speed of 1.9 mm/s (inferior to 1 mm/s
428 with HFFR cables).

429 This study also demonstrated the effect of the environmental conditions on the fire. The vicinity
430 of the ceiling leads to an increase in the preheating of the cable and therefore increases the fire
431 HRR and the flame spread velocity.

432 These tests also showed that the short-length tests usually given in the literature tend to maximize
433 the HRR and the flame spread velocity. Long length fire tests provide lower amplitudes and more
434 realistic results. This study allowed us to determine the burning length of the travelling fire and to
435 correlate it with the fire HRR and the flame spread velocity. These relationships have never been
436 reported for large-scale fire tests and it seems important to continue long-length cable tray
437 experiments in order to confirm the trends related in this study.

438

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