EFFECTS OF CABLE TRAY CONFIGURATION ON FIRE SPREAD

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ABSTRACT

Fires involving electrical cables are one of the main fire hazards in Nuclear Power Plants (NPPs). The aim of this work is to study the impact of cable tray configuration on fire spread over multiple cable trays. Two real-scale cable tray fire tests were thus carried out as part of the OECD PRISME-2 Project (CORE campaign) for studying the effect of a protected cable tray (CORE-2) and slanted ladder cable trays (CORE-3) on the main fire characteristics. By considering new configurations, these tests completed the preliminary CFSS tests of the PRISME-2 project which involved five horizontal ladder cable trays. The CORE-2 test implemented the same horizontal trays set-up except that the lower tray was a protected cable tray. Compared with the five ladder cable trays set-up, the protected cable tray delayed the ignition of about 16 min and led to decrease the total mass loss (TML). Furthermore, the fire growth rates and the heat release rate (HRR) were slightly higher for the CORE-2 test. The CORE-3 test used five horizontal ladder cable trays 1 m long followed by five slanted ladder cable trays 2 m long with a 30 degree angle. This configuration shortened the ignition of about 4 min, led to similar TML and increased the fire spread over the cable trays meaningfully and the HRR peak compared with the horizontal ladder trays configuration. Finally, the other fire characteristics such as the average effective heat of combustion or the gas and soot yields were not affected by the presence of the lower protected cable tray or the ladder cable trays orientation (horizontal or slanted).

Keywords: Protected cable tray; Slanted ladder cable tray; Ignition; Fire spread

NOMENCLATURE

CDG	Carbon dioxide generation
CO	Carbon monoxide
CO_2	Carbon dioxide
C_{soot}	Mass concentration of soot (kg/m^3)
$\Delta H_{c,eff}$, EHC	Effective heat of combustion (MJ/kg)
E_{CO_2}	Energy produced by mass unit of generated CO_2 (13.3 MJ/kg)
E_{O_2}	Energy produced by mass unit of consumed O_2 (13.1 MJ/kg)
HFFR	Halogen free flame retardant
HRR	Heat release rate (kW)
M_a	Molecular mass of ambient air (0.029 kg/mole)
M_i	Molecular mass of gas species i = CO_2, CO and H_2O (kg/mole)
ML	Mass loss (kg)
MLR, $\dot{m}$	Mass loss rate (kg/s)
$\dot{m}_i$	Mass flow rate of species i = CO_2, CO and soot (kg/s)
$\dot{m}_{O_2}^C$	Mass consumption rate of O_2 (kg/s)
$\dot{Q}$	Heat release rate (kW)
$\dot{Q}_{burner}$	Fire power of the gas burner (kW)
$\dot{Q}_{CDG}$	Heat release rate assessed from the CDG calorimetry method (kW)
$\dot{Q}_{OC}$	Heat release rate assessed from the OC calorimetry method (kW)

OC	Oxygen consumption
O_2	Oxygen
P	Pressure (Pa)
R	Ideal gas constant (8.314 J/mole/K)
t_0	Starting time of the power law equation describing the growth of the fire (s)
t_l	Fire growth characteristic time (s)
T	Gas temperature (K)
TML	Total mass loss (kg)
X_i	Molar fraction of gas species i = O_2, CO_2, CO and H_2O (mole/mole)

Greek characters

α	Fire growth rate (kW/s^2)
ϕ	Oxygen depletion factor
θ	Volumetric expansion factor (1.105)
$\dot{v}$	Volumetric flow rate in the exhaust network (m^3/s)

Superscripts

$\bar{}$	Average
$\dot{}$	Per unit time (s^{-1})
ex	Exhaust network
G	Generated
in	Incoming air

INTRODUCTION

Several hundred kilometers of electrical cables are present throughout nuclear power plants (NPPs). Power cables are used for instance in the process rooms for supplying electricity to the pumps, turbines, transformers or heaters, or in the switchgear room that contains numerous electrical cabinets connected to multiple cable trays[1]. Furthermore, many cable trays containing both instrumentation and control cables are also found in the cable spreading room and in the main control room. Instrumentation cables are used for digital or analogic transmission for various types of transducers, while control cables serve for example for controlling valves or operating relays and contactors.

A serious cable fire occurred at the Browns Ferry NPP in 1975[2] resulting in the loss of the emergency core cooling system of unit 1. Ever since many efforts have been made on the most recent nuclear installations, all over the world, to enhance the prevention of cable fires, for instance by using flame retardant materials in the cable composition. Nevertheless, nearly seventy fire events from NPPs involving electrical cables as fuel were recorded in the current OECD FIRE Database[3] between the late 1980s and the end of 2014. The study of cable fire is therefore a major concern for fire safety analyses in NPPs. Many cable tray fire programmes were carried out over the last decades[4,5,6,7,8,9] and also more recently[10,11,12,13,14,15]. All these last ones implemented ladder cable trays either horizontally or vertically oriented. However, the NPP tray installations may also feature slanted ladder cable trays or protected cable trays. These last ones are used for the fire protection of electrical cables involved in safety trains circuits. Nevertheless, no available programme has yet studied the impact of such cable tray configurations on fire spread.

Two real-scale cable tray fire tests were thus carried out as part of the OECD PRISME-2 Project[16] (CORE campaign) for studying the effect of a protected cable tray (CORE-2) and slanted ladder cable trays (CORE-3) on the main fire characteristics. By considering new configurations, these tests completed the CFSS-1 to CFSS-4 tests[13] (PRISME-2) project which investigated fire spread over five horizontal ladder cable trays according to various cable-types. The CORE-2 test implemented the same horizontal trays set-up except that the lower tray was a protected cable tray. This last one was a metallic non-perforated and covered cable tray. Furthermore, the CORE-3 test involved five horizontal ladder cable trays 1 m long followed by five slanted ladder cable trays 2 m long with a 30 degree angle. The

CORE-2 and CORE-3 tests used the same cable-type, containing a halogen free flame retardant (HFFR), as the CFSS-2 test and they were conducted in open atmosphere under a large-scale calorimeter.

Firstly, this paper gives a description of the cable tray fire sources, the large-scale calorimeter of the SATURNE facility and the instrumentation used for the tests. Then, the assessments of the main fire characteristics of the CORE-2 and CORE-3 tests, such as the mass loss rate (MLR), the heat release rate (HRR) and the effective heat of combustion (EHC) are showed in detail. Furthermore, the evaluations of additional fire characteristics such as the ignition delay, the fire growth rate and the fire duration, all derived from the HRR, are also proposed in this section. In the last part of this paper, the effects of the cable tray configuration are highlighted from comparative analysis of the previous fire properties with the ones obtained for the horizontal ladder trays set-up of the CFSS-2 test. Finally, the evaluation of the gas and soot yields, proposed in this last part, complete the above comparative analysis.

DESCRIPTION OF THE FIRE TESTS

Cable tray fire sources

The three cable tray fire sources used for the preliminary CFSS-2 test, the CORE-2 and CORE-3 tests had the same following characteristics:

- Five ladder cable trays 3 m long, 0.45 m wide, spaced from each other by 0.3 m and set up against an insulated side wall (Figure 1),
- Every tray was filled with 32 samples of 2.4 m long of the same cable-type (its mass per unit length is about 570 kg/km). This cable-type contains Poly(ethylene/vinyl acetate) (EVA) and Polyethylene (PE) as polymeric materials and aluminium hydroxide (ATH) as halogen free flame retardant (HFFR),
- The cable samples were packed loosely along the five trays.

The differences between the three fire sources are listed hereafter:

- For the CORE-2 test, the lower cable tray was a metallic non-perforated and covered cable tray (Figure 2),
- For the CORE-3 test, the fire source was composed of five horizontal ladder cable trays 1 m long, followed by five slanted ladder cable trays 2 m long, with a 30 degree angle (Figure 3). The cable samples length was 0.8 m along the first part while the one along the slanted trays was 1.6 m.

Figure 1: The five horizontal ladder cable trays used for the CFSS-2 test.

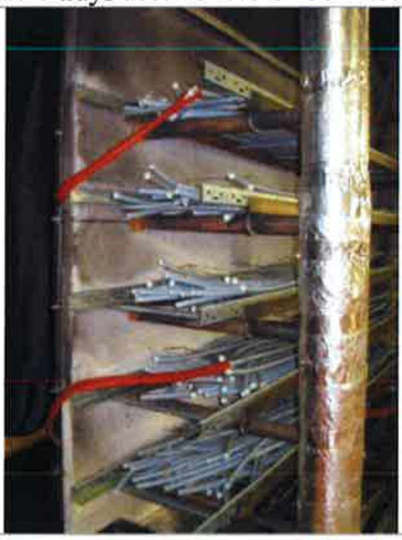


Figure 2: The cable tray set up for the CORE-2 test.

Ignition source

A square sand burner (300 x 300 mm^2), located 0.2 m below the lower tray, was used as an ignition source (Figure 2). This gas burner was supplied with propane gas and its fire power was 80 kW for all the tests. Furthermore, the gas burner was centred under the first cable tray for both the CFSS-2 and CORE-2 tests while it was centred beneath the horizontal part of the lower tray for the CORE-3 test (Figure 3). The ignition source was stopped when the HRR exceeded 400 kW (without taking into account the contribution of the gas burner). Given that, this value is five times higher than the fire power of the gas burner (80 kW), the cable tray fire source is thus considered as ignited and the fire as self-sustained. The ignition delay (t_{ig}) of the cable tray fire source is thus defined as the time to reach a HRR of 400 kW.

Large-scale calorimeter and instrumentation

The tests were carried out under a large-scale calorimeter (Figure 4) located in a facility, named SATURNE. Numerous openings are located at the top of this facility over each wall. They provide enough air to maintain the oxygen concentration at 21 % around the fire source, as in open atmosphere.

Figure 3: The cable tray set up for the CORE-3 test.

Figure 4: The large-scale calorimeter of the SATURNE facility.

The fire source is centred under the large-scale hood (4.5 x 4.5 m^2 side by side with a 3 m inner diameter, Figure 4). This last one is connected to an exhaust ventilation network which collects all the combustion products released by the fire. Gas species concentrations (O_2, CO_2 and CO) as well as soot mass concentrations, gas temperature, pressure and volume flow rate were measured in the exhaust network. Two weighing devices were located below the cable trays (Figure 4) and allowed measuring the mass loss of materials contained in cables during the fire. For all the tests, five thermocouples were positioned along each of the trays directly above the cables (or just above the metallic cover of the lower tray for the CORE-2 test). All the thermocouples were spaced from each other of 0.5 m. In addition, for the CORE-2 test, three thermocouples were also located inside the protected cable tray just above the cables. They were positioned at the centre and at 0.5 m from the centre in both South and North directions.

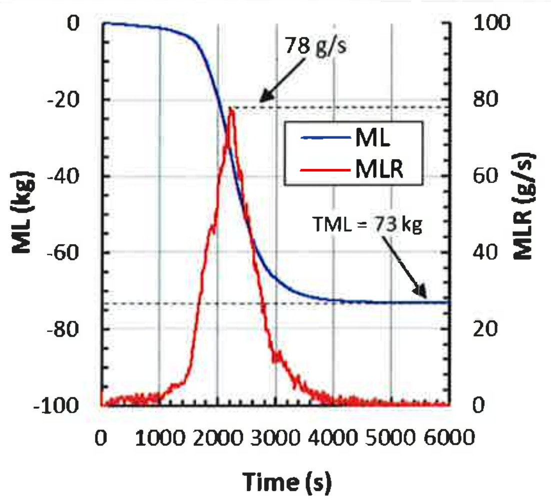
FIRE CHARACTERISTICS

Mass loss and mass loss rate

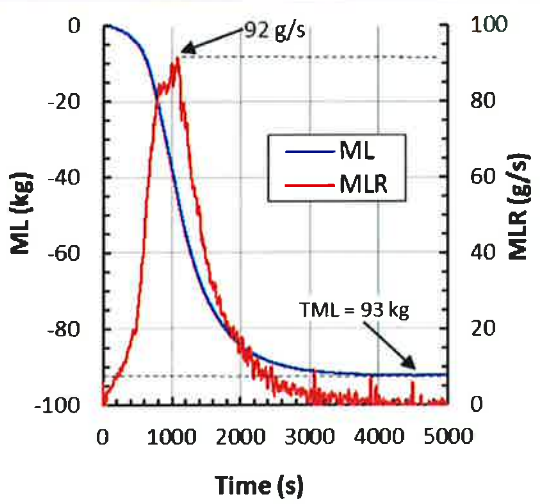
The mass loss (ML) is deduced from the mass measurement carried out with the weighing devices. In addition, the mass loss rate (MLR) is assessed from time derivation of the ML. Both the ML and the MLR are shown in Figure 5 for the CORE-2 and CORE-3 tests. This figure also indicates the total mass losses (TML) of 73 kg and 93 kg as well as the MLR peaks of 78 and 92 g/s, for the CORE-2 and CORE-3 tests respectively.

Figure 5: ML and MLR.

CORE-2 test



CORE-3 test



Methods used for the assessment of the heat release rate

The fire heat release rate (HRR) can be assessed with two chemical methods, which are the carbon dioxide generation (CDG) and the oxygen consumption (OC) calorimetry methods.

For the CORE-2 and CORE-3 tests, conducted in open atmosphere, negligible fraction of carbon in the fuel is converted to CO or soot instead of CO_2, as confirmed by their yields assessed in a further section. Consequently, the HRR may be assessed from the CDG calorimetry method ($\dot{Q}_{CDG}$) as follows[17]:

[1] $$\dot{Q}_{CDG} = E_{CO_2}\dot{m}^{G}_{CO_2}$$

- E_{CO_2}: Energy produced by mass unit of generated CO_2 (13.3 MJ/kg);
- $\dot{m}^{G}_{CO_2}$: Mass flow rate of generated CO_2 (kg/s).

In addition, $\dot{m}^{G}_{CO_2}$ is evaluated from:

[2] $$\dot{m}^{G}_{CO_2} = \dot{m}^{ex}_{CO_2} - \dot{m}^{in}_{CO_2}$$

- $\dot{m}^{ex}_{CO_2}$: Mass flow rate of CO_2 in the exhaust network (kg/s);
- $\dot{m}^{in}_{CO_2}$: Mass flow rate of CO_2 in the incoming air (kg/s).

Finally, it is shown that $\dot{m}^{G}_{CO_2}$ may be assessed as follows:

[3]
$$\dot{m}^{G}_{CO_2} = (X^{ex}_{CO_2} - X^{in}_{CO_2})\frac{M_{CO_2}P^{ex}}{RT^{ex}}\dot{V}^{ex}$$

- $X^{ex}_{CO_2}$: Molar fraction of CO_2 in the exhaust network (mole/mole);
- $X^{in}_{CO_2}$: Molar fraction of CO_2 in the incoming air (mole/mole);
- M_{CO_2}: Molecular mass of CO_2 (0.044 kg/mole);
- P^{ex}: Pressure in the exhaust network (Pa);
- R: Ideal gas constant (8.314 J/mole/K);
- T^{ex}: Gas temperature in the exhaust network (K);
- $\dot{V}^{ex}$: Volumetric flow rate in the exhaust network (m^3/s).

Moreover, the HRR is also evaluated from the OC calorimetry method ($\dot{Q}_{OC}$). For negligible fraction of carbon in the fuel converted to CO or soot instead of CO_2, the HRR may be assessed from the OC calorimetry method ($\dot{Q}_{OC}$) as follows[18]:

[4]
$$\dot{Q}_{OC} = E_{O_2}\frac{\phi}{1+\phi(\theta-1)}\dot{m}^{ex}\frac{M_{O_2}}{M_a}(1-X^{in}_{H_2O} - X^{in}_{CO_2})\,X^{in}_{O_2}$$

With

[5]
$$\phi = \frac{X^{in}_{O_2}(1-X^{ex}_{CO_2}) - X^{ex}_{O_2}(1-X^{in}_{CO_2})}{(1-X^{ex}_{O_2}-X^{ex}_{CO_2})X^{in}_{O_2}}$$

and

- E_{O_2}: Energy produced by mass unit of consumed O_2 (13.1 MJ/kg);
- ϕ: Oxygen depletion factor;
- θ: volumetric expansion factor (1.105);
- $\dot{m}^{ex}$: mass flow rate in the exhaust network (kg/s);
- M_{O_2}: Molecular mass of O_2 (0.032 kg/mole);
- M_a: Molecular mass of the ambient air (0.029 kg/mole);
- X^{in}_{i}: Molar fraction of gas species (i = CO_2, H_2O and O_2) in the incoming air (mole/mole);
- X^{ex}_{i}: Molar fraction of gas species (i = CO_2 and O_2) in the exhaust network (mole/mole).

Heat release rate for the CORE-2 test

The HRR assessments from the CDG ($\dot{Q}_{CDG}$) and OC ($\dot{Q}_{OC}$) calorimetry methods are pointed out in Figure 6 (including the gas burner contribution to the HRR) and show very good agreement. So, the final CORE-2 HRR ($\dot{Q}$, Figure 7) is evaluated from the average values of $\dot{Q}_{CDG}$ and $\dot{Q}_{OC}$, minus the fire power of the gas burner ($\dot{Q}_{burner}$), as follows:

[6]
$$\dot{Q} = (\dot{Q}_{CDG} + \dot{Q}_{OC})/2 - \dot{Q}_{burner}$$

The main stages of the CORE-2 fire test are the ignition stage, the fire growth stage, the fully developed fire stage and the fire decay stage. They are described hereafter based on the HRR assessment (Figure 7).

Ignition stage (27 min 34 s)

For the CORE-2 test, the gas burner provided a fire power of 80 kW for 1721 s (28 min 41 s) and led to ignite the cable tray fire source at 27 min 34 s (t_{ig}) when the HRR reached 400 kW (Figure 8).

Fire growth stage (from 27 min 34 s to 35 min 54 s)

It is assumed that the following power law equation can describe the growth of the fire[24]:

[7] $$\dot{Q} = \frac{1000}{t_1^2} \cdot (t - t_o)^2$$

Or

[8] $$\dot{Q} = \alpha \cdot (t - t_o)^2$$

With

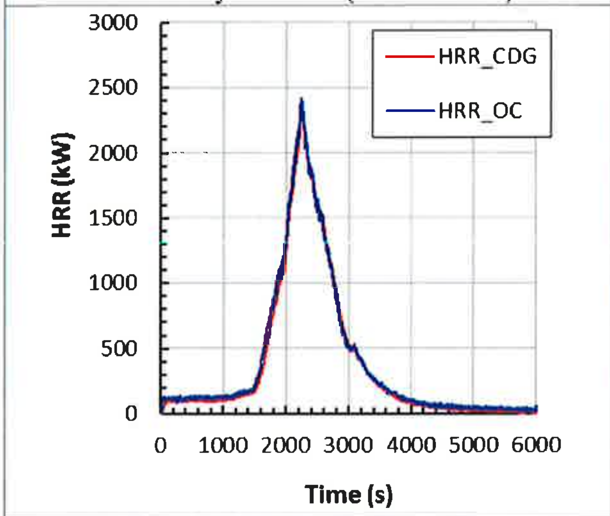
[9] $$\alpha = \frac{1000}{t_1^2}$$

- α: fire growth rate (kW/s^2);
- t_0: starting time of the power law equation describing the growth of the fire (s);
- t_l: fire growth characteristic time (s). t_l is defined as the time necessary after t_0 to reach a HRR of 1000 kW (s).

Figure 8 points out that the best power law equation that fits with the HRR growth of the CORE-2 fire is $y = 0.0032 \cdot (t - 1320)^2$. So according to equations [7]-[9], the fire growth rate (α) is 0.0032 kW/s^2, t_l = 558 s (9 min 18 s) and t_o = 1320 s (22 min).

Figure 6: HRR assessed from the CDG and OC calorimetry methods (CORE-2 test).

Figure 7: HRR and the main fire stages of the CORE-2 test.



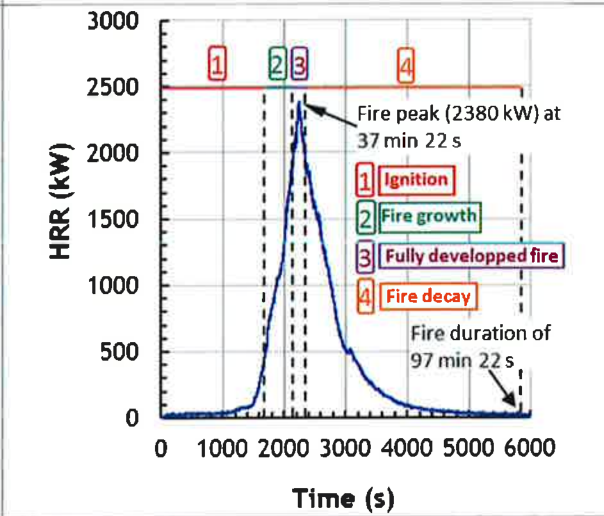
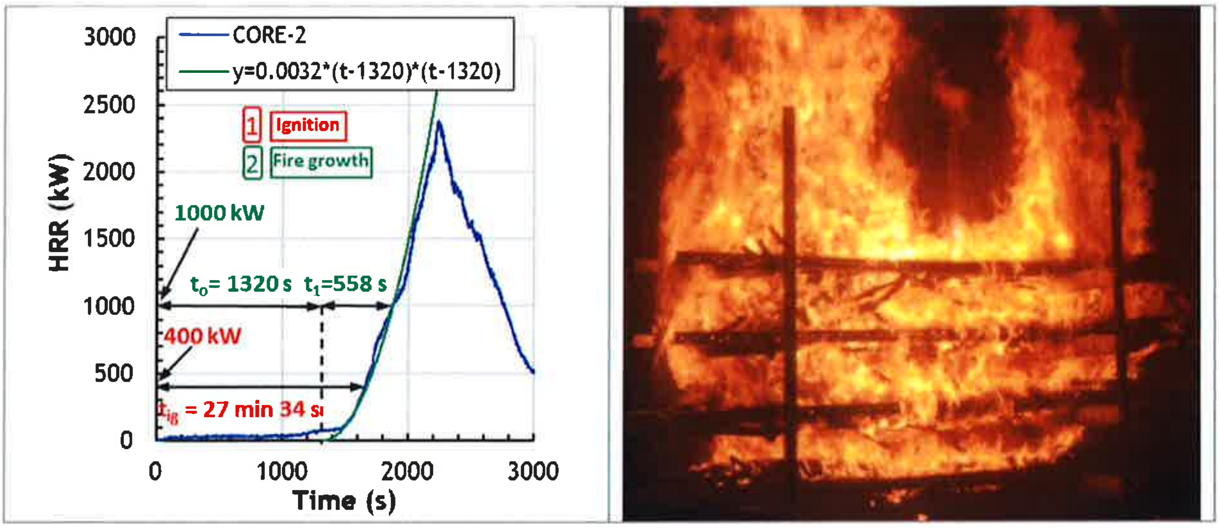


Figure 8: Ignition and fire growth stages of the CORE-2 test.

Figure 9: Start of the fully developed fire stage at about 36 min (CORE-2 test).



Fully developed fire stage (from 35 min 54 s to 38 min 55 s)

It is considered for the CORE-2 test that the fully developed fire stage started when the HRR exceeded the value of 2 MW. Indeed the fire nearly involved all the cable tray surface area for such value of the HRR (Figure 9). Moreover, it is supposed that this stage ended when the HRR reached for the last time the previous value. According to the HRR of the CORE-2 test (Figure 7), the fully developed fire stage thus started at 35 min 54 s (2154 s) and ended at 38 min 55 s (2335 s). The HRR peak (2380 kW) was reached during this stage at 37 min 22 s.

Fire decay stage (from 38 min 55 s to 97 min 22 s)

The fire decay stage for the CORE-2 fire started after the fully developed fire stage at 38 min 55 s (Figure 7). Furthermore, the fire is supposed to be extinguished once its fire power is lower than 25 kW. This value is indeed similar to the uncertainty of the HRR assessed from the chemical methods considered in this study. The CORE-2 fire is therefore extinguished at 97 min 22 s since this time matches with a HRR of 25 kW (Figure 7). As it is considered that the CORE-2 fire starts with the gas burner operation (t = 0 s), then its fire duration is therefore of 97 min 22 s.

Heat release rate for the CORE-3 test

For the CORE-3 test, the HRR evaluations from the CDG ($\dot{Q}_{CDG}$) and OC ($\dot{Q}_{OC}$) calorimetry methods are also very relevant until t = 2000 s (Figure 10). Beyond this time, the two calorimetry methods show different values. In particular, the OC method gives unrealistic values, greater than zero for t > 4077 s, which is the time when the fire is over according to the CDG method (see further for more details). Analysis of the experimental results indicates a slight drift of the oxygen analyzer occurring in the last stage of the CORE-3 test. Indeed, this analyzer pointed out after the test an oxygen concentration in the exhaust duct (20.78 %vol) slightly lower than the one measured before the test (20.91 %vol). This lower oxygen content is therefore interpreted as a continuing fire by the OC method, thus associating it with a fictive heat release.

Thus, it is proposed to evaluate the CORE-3 HRR ($\dot{Q}$, Figure 11) only from the CDG method, minus the fire power of the gas burner:

[10] $$\dot{Q} = \dot{Q}_{CDG} - \dot{Q}_{burner}$$

The same fire stages as for the CORE-2 are now described hereafter for the CORE-3 test (Figure 11).

Ignition stage (7 min 45 s)

For the CORE-3 test, the gas burner provided a fire power of 80 kW for 468 s (7 min 48 s) and allowed the ignition of the cable tray fire source at 7 min 45 s (t_{ig}) when the HRR reached 400 kW (Figure 12).

Fire growth stage (from 7 min 45 s to 13 min 38 s)

Figure 12 also exhibits that the best power law equation which fits with the HRR growth of the CORE-3 fire test is $y = 0.0073 \cdot (t - 255)^2$. So according to equations [7]-[9], the fire growth rate (α) is 0.0073 kW/s^2, t_l= 371 s (6 min 11 s) and t_o = 255 s (4 min 15 s).

Fully developed fire stage (from 13 min 38 s to 20 min 53 s)

As for the CORE-2 test, it is assumed that the fully developed fire stage started when the HRR exceeded the value of 2 MW. Indeed the fire spread almost over all the cable tray surface area for such value of the HRR (Figure 13). This stage is also supposed ended when the HRR was lower than 2 MW. Given the HRR of the CORE-3 test (Figure 11), this stage therefore started at 13 min 38 s (818 s) and finished at 20 min 53 s (1253 s). The HRR peak (2550 kW) was achieved during this stage at 17 min 23 s.

Fire decay stage (from 20 min 53 s to 66 min 57 s)

The fire decay stage for the CORE-3 fire test started after the fully developed fire stage at 20 min 53 s and ended at 66 min 57 s (Figure 11). The fire is assumed to be extinguished once its fire power is lower than 25 kW (as for the CORE-2 test). The CORE-3 test is thus over at 66 min 57 s since this time matches with a HRR of 25 kW (Figure 11). As it is considered that the CORE-3 fire starts with the gas burner operation (t = 0 s), then its fire duration is therefore of 66 min 57 s.

Figure 10: HRR assessed from the CDG and OC calorimetry methods (CORE-3 test).

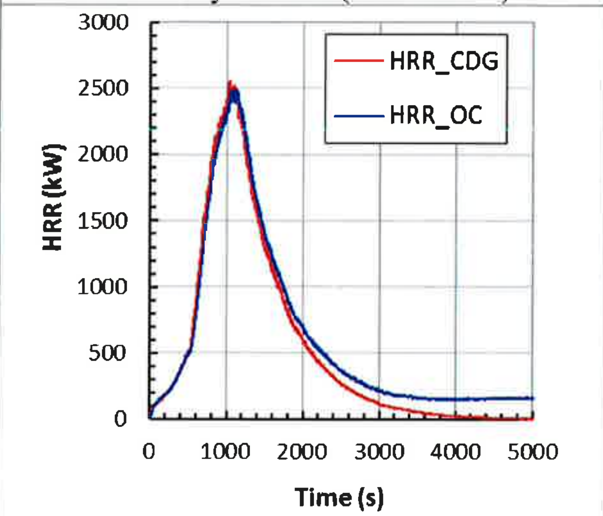


Figure 11: HRR and the main fire stages of the CORE-3 test.

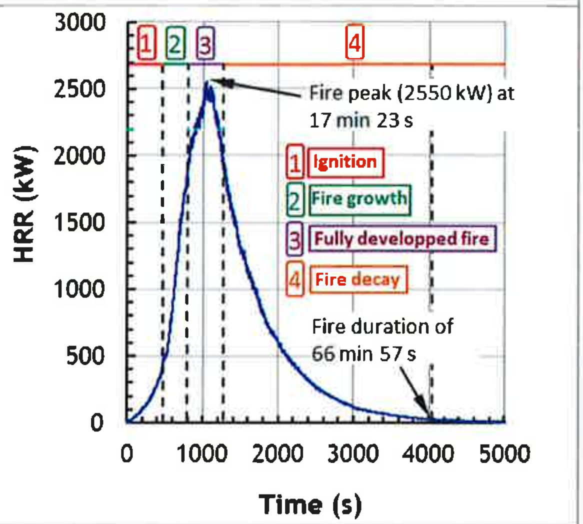
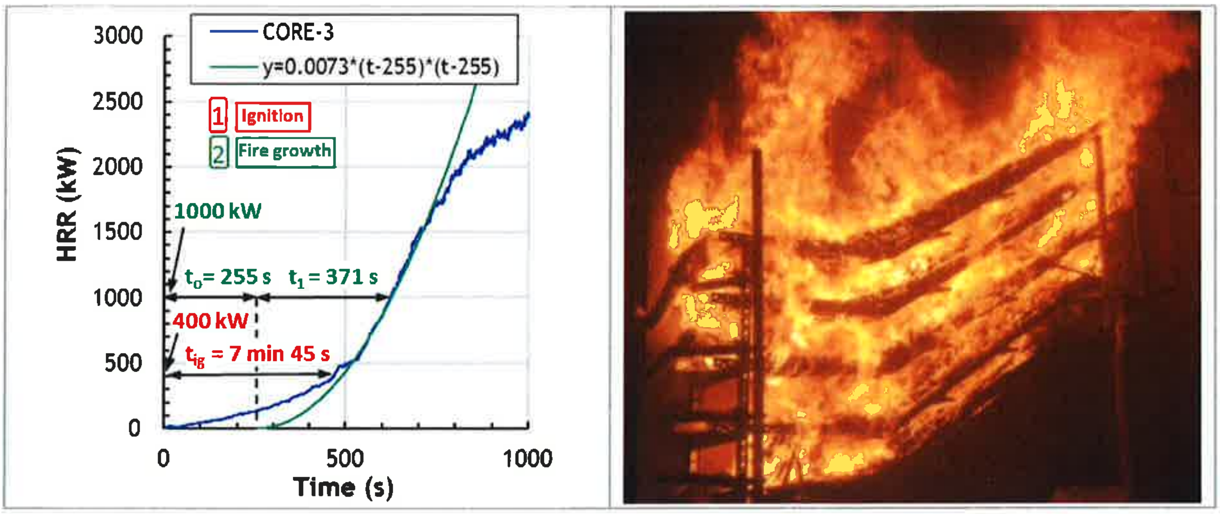


Figure 12: Ignition and fire growth stages of the CORE-3 test.

Figure 13: Starting of the fully developed fire stage at about 13.5 min (CORE-3 test).



Effective heat of combustion

The combustion behaviour of a fire may be characterized by the effective heat of combustion (EHC or $\Delta H_{c,eff}$) defined as the ratio of HRR ($\dot{Q}$) to MLR ($\dot{m}$)[18]:

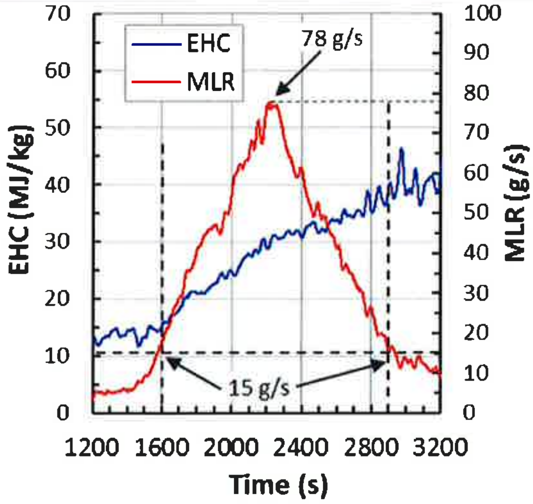
[11] $$\Delta H_{c,eff} = \frac{\dot{Q}}{\dot{m}}$$

Figure 14 therefore points out the EHC evaluated from equation [11] and also the MLR assessed above for the CORE-2 and CORE-3 tests. First, this figure highlights that the EHC is quite low in the early stage of these two tests. Indeed, the highly endothermic dehydration of the flame retardant ATH[19,20], contained in the cable-type studied, delays the burning of the polymeric materials (EVA and PE blend) in particular during the first stage of the tests. Then the EHC continuously increases given the fire spread over all the cable trays area which leads to the progressive consumption of the ATH flame retardant. The EHC after the fire peak (ranging from 30 to about 40 MJ/kg) is indeed consistent with the EHC of the EVA (about 35 MJ/kg[21,22]) and the PE (43 MJ/kg[23]).

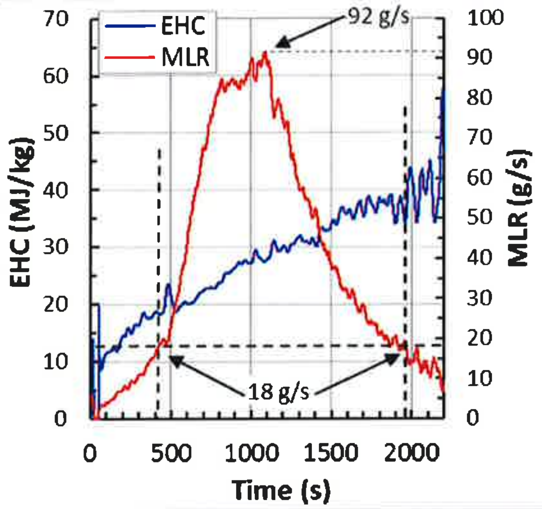
Figure 14 indicates that the EHC shows fast and steep fluctuations for the CORE-2 test when t > 3000 s and for the CORE-3 test when t > 1920 s. These variations are caused by non-negligible fluctuations of the MLR as well as rather low values of this last one (lower than 15 g/s and 18 g/s for the CORE-2 and CORE-3 tests, respectively). Indeed, the EHC is evaluated according to the inverse of the MLR (equation [11]). So it is suggested to assess the average EHC ($\overline{\Delta H_{c,eff}}$) for 1600 s < t < 3000 s when MLR > 15 g/s for the CORE-2 test and for 425 s < t < 1920 s when MLR > 18 g/s for the CORE-3 test (Figure 14). These MLR values are higher than 20 % of the MLR peak for the two tests since these last ones are of 78 g/s for the CORE-2 test and of 92 g/s for the CORE-3 test (Figure 14). The average EHC is thus assessed at 28.6 MJ/kg for the former test and at 29.2 MJ/kg for the latter test.

Figure 14: EHC and MLR

CORE-2 test



CORE-3 test



EFFECT OF THE CABLE TRAY CONFIGURATION

The effect of the cable tray configuration on the fire characteristics previously determined are highlighted from comparison with the ones obtained for the CFSS-2 test[13] (five horizontal ladder cable trays). These last ones are summarized in Table 1.

This table firstly indicates similar TML for the CORE-3 (93 kg) and CFSS-2 (97 kg) tests. Indeed, for these two tests the fire involved entirely the five ladder cable trays which were filled with the same cable loading (32 cable samples per tray). By contrast, the TML is lower for CORE-2 (73 kg). For this test, the three gas temperatures measured inside the lower protected cable tray are clearly lower (Figure 15) than the maximal temperatures measured along the burning upper trays (as seen further in Figure 19). Indeed, the cable samples contained inside the lower protected tray showed damages only over a limited portion (Figure 16). These outcomes suggest that the mass loss for this first tray is significantly lower than for the first ladder cable tray of the CORE-3 and CFSS-2 tests, thus leading to the lower TML pointed out above for the CORE-2 test.

The HRR as well as the ignitions delays of CORE-2, CORE-3 and of CFSS-2 tests are summarized in Figure 17. This figure and Table 1 firstly highlight that the protected cable tray delays of about 16 min the ignition of the CORE-2 fire source compared with the five ladder cable trays (CFSS-2). The non-perforated and covered lower tray, located just 0.2 m above the gas burner (Figure 2), acted as a protection screen for the upper ladder cable trays. Compared with the CFSS-2 test (five horizontal ladder cable trays), the average gas temperatures measured along each of the four upper cable trays were indeed significantly lower before the ignition of the CORE-2 cable tray fire source occurring at 27 min 34 s (Figure 19). These temperatures are evaluated as the average of the measurements carried out by the five thermocouples located along each cable tray.

By contrast, the slanted cable trays configuration shortened by about 4 min the ignition of the CORE-3 fire source (Figure 17) compared with the five horizontal ladder cable trays (CFSS-2). The total heat required for the ignition of the cable tray fire source is obtained from the product of the fire duration of the ignition source by its fire power (80 kW). A total heat of 37 MJ was therefore required to ignite the CORE-3 fire source vs 60 MJ for the CFSS-2 test (about one and a half times higher) and 138 MJ for the CORE-2 test (nearly four times larger).

Table 1: Main fire characteristics of the CFSS-2, CORE-2 and CORE-3 tests.

Test	CFSS-2 (horizontal ladder cable trays)	CORE-2 (protected cable tray)	CORE-3 (slanted ladder cable trays)
TML (kg)	97	73	93
Peak of MLR (g/s)	78	78	92
Ignition delay	11 min 57 s	27 min 34 s	7 min 45 s
Fire growth rate (kW/s^2)	$2.2 \cdot 10^{-3}$	$3.2 \cdot 10^{-3}$	$7.3 \cdot 10^{-3}$
Peak of HRR (MW)	2.20	2.38	2.55
Fire duration (min)	72	97	67
$\overline{\Delta H_{c,eff}}$ (MJ/kg)	28	28.6	29.2

Figure 15: Gas temperature inside the lower protected tray (CORE-2 test).

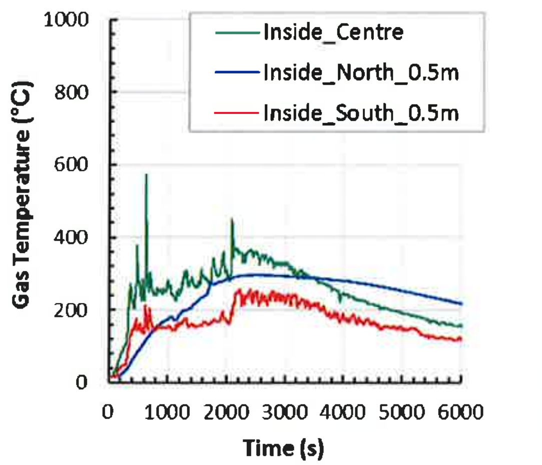


Figure 16: cable samples contained in the protected lower cable tray after the CORE-2 fire.

In addition, the best power law equations fitting with the HRR of these three tests are also summarized in Figure 18. This figure and Table 1 indicate that the fire growth rate of the CORE-2 test (0.0032 kW/s^2) is lightly higher than for the CFSS-2 test (0.0022 kW/s^2). It means that the fire spreads slightly faster over the four upper ladder cable trays for the CORE-2 test than over the five ladder cable trays for the CFSS-2 test. Furthermore, Figure 18 points out that the slanted cable tray configuration leads to clearly increase the fire growth rate. This last one is indeed more than three times higher for the CORE-3 test (0.0073 kW/s^2) than for the CFSS-2 test (0.0022 kW/s^2). This outcome is consistent with the faster increase of the average gas temperatures for the CORE-3 test compared with the CFSS-2 test, except for the lower cable tray (Figure 20). Compared with the horizontal cable tray configuration (CFSS-2 test), the slanted tray orientation (30° angle) of the second part of the CORE-3 fire source could indeed favors the pre-heating of the cables by the plume. This effect is indeed supposed to increase the spread rate of the fire as pointed out by previous cable tray fire experiments[12]. In addition, compared with the CFSS-2 test, the slight increase of the fire growth rate for the CORE-2 test could also be due to a higher pre-heating of the cables before they ignite, as a consequence of the much longer operation of the gas burner for the latter test (28 min 41 s vs 12 min 24 s for the former test).

Figure 17: Ignition delays (t_{ig}) for the CFSS-2, CORE-2 and CORE-3 tests.

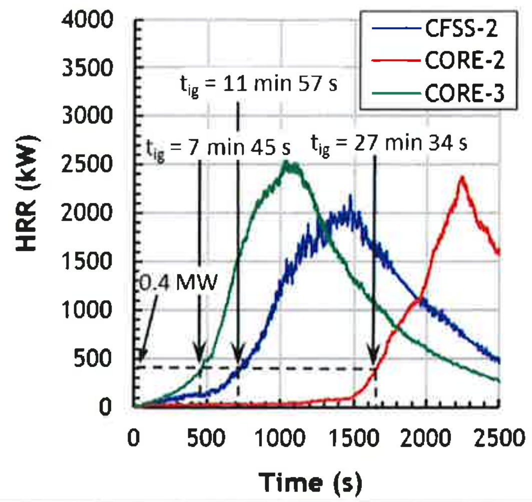


Figure 18: Fire growth rates for the CFSS-2, CORE-2 and CORE-3 tests.

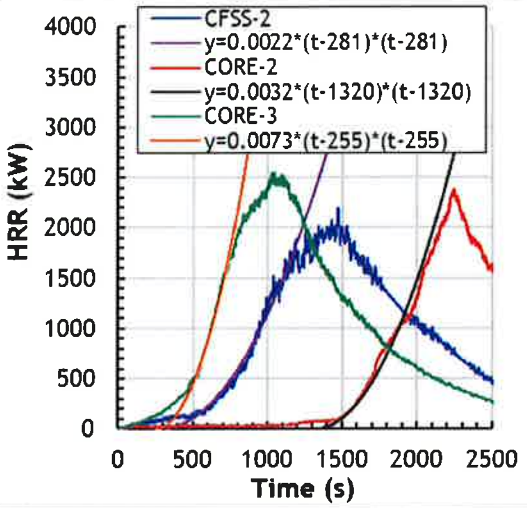


Figure 19: Average gas temperatures along the cable trays (CORE-2 and CFSS-2 tests).

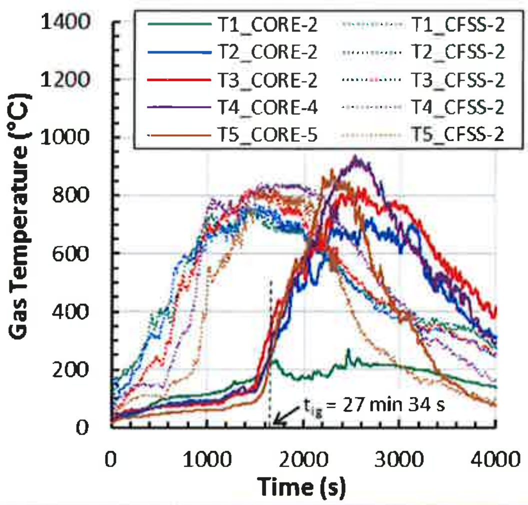
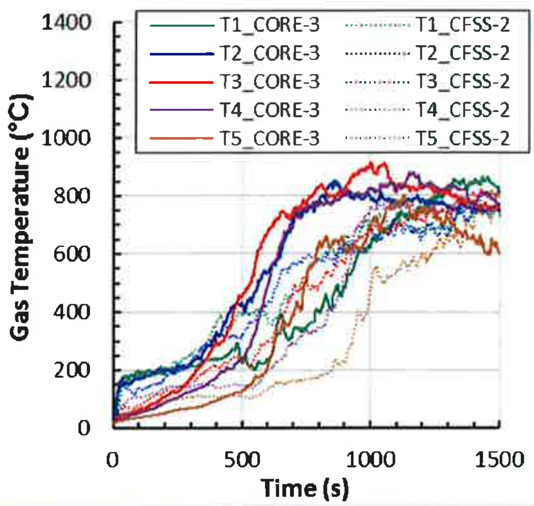


Figure 20: Average gas temperatures along the cable trays (CORE-3 and CFSS-2 tests).



In addition, the HRR peak for the CORE-2 test (2.38 MW, Table 1) is slightly higher than for the CFSS-2 test (2.20 MW, Table 1) and the one obtained for the CORE-3 test (2.55 MW, Table 1) is the highest compared with the former tests. This last outcome suggests for these tests that the HRR peak may increase slightly when the fire growth rate increases (Table 1). Moreover, the fire duration, that includes the gas burner operation time, is equivalent for the CORE-3 fire (about 67 min, Table 1) and the CFSS-2 fire (about 72 min, Table 1). Otherwise the fire duration is significantly higher for the CORE-2 fire (about 97 min) due to the much higher time needed by the gas burner for its ignition.

Furthermore, the gas and soot yields (Y_i) are given in Table 2 for the CFSS-2, CORE-2 and CORE-3 tests. Y_i is defined as the ratio of m_i^G to TML:

[12] $$Y_i = \frac{m_i^G}{TML}$$

- m_i^G: Total mass of gas or soot species (i = CO_2, CO and soot) generated by the cable tray fire (kg).

For CO_2, $m_{CO_2}^G$ is evaluated according to:

[13] $$m_{CO_2}^G = \int_{t=0}^{t_{end\_fire}} (\dot{m}_{CO_2}^G - \frac{\dot{Q}_{burner}}{E_{CO_2}}) dt$$

Where $\dot{m}_{CO_2}^G$ is obtained from equation [3]. The mass flow rate of CO_2 generated by the gas burner ($\frac{\dot{Q}_{burner}}{E_{CO_2}}$) is removed from $\dot{m}_{CO_2}^G$ for proper evaluation of the total mass of CO_2 only generated by the cable tray fire ($m_{CO_2}^G$).

Furthermore, for CO and soot, as their generation by the gas burner is supposed negligible, m_i^G is therefore assessed as follows:

[14] $$m_i^G = \int_{t=0}^{t_{end\_fire}} \dot{m}_i^G dt \qquad \text{for i = CO and soot}$$

Moreover, these species are also assumed negligible in the incoming air ($\dot{m}_i^{in} = 0$, for i = CO and soot). So, $\dot{m}_{CO}^G$ is obtained from equation [15]:

[15] $$\dot{m}_{CO}^G = \dot{m}_{CO}^{ex} = X_{CO}^{ex} \frac{M_{CO} P^{ex}}{R T^{ex}} \dot{V}^{ex}$$

and $\dot{m}_{soot}^G$ from equation [16]:

[16] $$\dot{m}_{soot}^G = \dot{m}_{soot}^{ex} = C_{soot}^{ex} \dot{V}^{ex}$$

With:

- X_{CO}^{ex}: Molar fraction of CO in the exhaust network (mole/mole);
- M_{CO}: Molecular mass of CO (0.028 kg/mole);
- C_{soot}^{ex}: Mass concentration of soot in the exhaust network (kg/m^3).

Table 2 first points out that the CO_2 yields are much higher than the CO and soot yields for the three tests. This outcome validates the assumptions considered for the HRR assessment from the CDG and OC calorimetry methods, as previously discussed. In addition, the CO_2, CO and soot yields are similar for the three tests (Table 2). Finally, the evaluations of the average EHC for the CFSS-2, CORE-2 and CORE-3 fires give close values (from 28 to 29 MJ/kg, Table 1). The CO_2, CO and soot yields as well as the average EHC are thus not affected by the presence of the lower protected cable tray or the ladder cable trays orientation (horizontal or slanted).

Table 2: CO_2, CO and soot yields for the CFSS-2, CORE-2 and CORE-3 tests.

Test	Y_{CO_2} (g/g)	Y_{CO} (mg/g)	Y_{soot} (mg/g)
CFSS-2	2.23	27	15
CORE-2	2.17	34	19
CORE-3	2.20	21	12

CONCLUSION

Two real-scale cable tray fire tests were thus carried out as part of the OECD PRISME-2 Project (CORE campaign) for studying the effect of a protected cable tray (CORE-2 test) and slanted ladder cable trays (CORE-3 test) on the main fire characteristics. These tests completed the preliminary CFSS-1 to CFSS-4 tests of the PRISME-2 project which investigated fire spread over five horizontal ladder cable trays according to various cable-types. The CORE-2 and CORE-3 tests used the same cable-type, containing a halogen free flame retardant (HFFR), as the CFSS-2 test and they were conducted in open atmosphere under a large-scale calorimeter.

The CORE-2 test implemented the same horizontal trays set-up as for the CFSS-2 test except that the lower tray was a metallic protected cable tray. This last one was a non-perforated and covered cable tray which delayed the ignition of about 16 min compared with the CFSS-2 test. This lower cable tray indeed acted as a protection screen for the upper ladder cable trays. In addition, the total mass loss (TML) was lower for the CORE-2 test (73 kg) than for the CFSS-2 test (97 kg). Indeed, the cable samples contained inside the lower protected cable tray showed damages only over a limited portion. Furthermore, the fire growth rate (0.0032 kW/s^2) for the CORE-2 test was slightly higher than for the CFSS-2 test (0.0022 kW/s^2). The longer gas burner operation (about 29 min for the CORE-2 test vs about 12 min for the CFSS-2 test) could indeed lead to a greater pre-heating of the electrical cables before they ignite. This effect is indeed supposed to increase the spread rate of the fire.

The CORE-3 test involved the same horizontal cable trays set-up 1 m long as for the CFSS-2 test, followed by five slanted ladder cable trays 2 m long, with a 30 degree angle. Compared with the horizontal trays set-up (CFSS-2 test), the slanted trays configuration shortened by about 4 min the ignition of the multiple cable trays and also clearly increased the fire growth rate. This last one is indeed assessed as more than three times higher for the CORE-3 test (0.0073 kW/s^2) than for the CFSS-2 test (0.0022 kW/s^2). The slanted cable trays orientation (30° angle) of the second part of the CORE-3 fire source could indeed favor the pre-heating of the cables by the plume and therefore the spread rate of the fire. The heat release rate (HRR) peak was also shown higher for this test (2.55 MW) compared with the CFSS-2 test (2.2 MW). This outcome, also observed for the CORE-2 test, suggests for these tests that the HRR peak may increase when the fire growth rate increases. Furthermore similar TML was obtained for the CORE-3 test (93 kg) and the CFSS-2 test (97 kg). Indeed, for these two tests, the fire involved entirely the five ladder cable trays which were filled with the same cable loading (32 cable samples per tray).

Finally, the other fire characteristics such as the average effective heat of combustion or the gas and soot yields were not affected by the presence of the lower protected cable tray or the ladder cable trays orientation (horizontal or slanted).

Further experiments involving similar cable tray fire sources will be characterized in a confined and mechanically-ventilated facility. These investigations will allow for highlighting the effect of confined and ventilated conditions on fire spread over these fire sources.

ACKNOWLEDGMENT

This work was performed by IRSN in the framework of the OECD PRISME-2 project with the support of the partners: ENGIE and Bel V (Belgium), CNSC (Canada), VTT (Finland), DGA and EDF (France), GRS (Germany), NRA and CRIEPI (Japan), CSN (Spain), SSM (Sweden) and ONR, an agency of HSE (United Kingdom).

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