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# Horizontal cable trays fire in a well-confined enclosure using a two-zone model

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## ABSTRACT

Electrical cable trays are used in large quantities in nuclear power plants (NPPs) and are one of the main potential sources of fire. A malfunction of electrical equipment due to thermal stress for instance may lead to the loss of important safety functions of the NPPs. The investigation of such fires in a confined and mechanically ventilated enclosure has been scarce up to now and has been investigated in the nuclear industry. In the scope of the OECD PRISME-2 project, the Institut de Radioprotection et de Sûreté Nucléaire (IRSN) conducted more than a dozen of fire tests involving horizontal electrical cable trays burning either in open atmosphere under a calorimetric hood or inside mechanically ventilated compartments to investigate this topic. Calorimetric hood experiments in open atmosphere highlighted that the halogenated flame retardant cable tests had shorter ignition time, faster fire growth rate and higher peak of Heat Release Rate (HRR), compared with the mineral flame retardant cables tested. The influence of the enclosure on the fire behavior depends on the temperature of the surrounding gas of the cables, as well as on the oxygen content at the level of cables. The enclosure strongly impacts the pyrolysis of the fuel, decreasing the mass loss rate and the HRR of the fuel, affecting the fire duration. For tests performed at low ventilation level, combustion of unburned gases occurred due to a high production of pyrolysed gas in excess. A semi-empirical model of horizontal cable trays fires in a well-confined enclosure was developed. This model is partly based on the approach used in FLASH-CAT and on experimental findings from the IRSN cables fire tests. It was implemented in the two-zone model SYLVIA. The major features of the compartment fire experiments, such as characteristic HRR and fire duration, could then be reproduced with acceptable error, except for combustion of unburned gases, occurring in the upper part of the fire compartment. The development of such a semi-empirical model is a common practice in fire safety engineering concerned with complex solid fuels.

**Keywords**: Cable trays fire, Enclosure, SYLVIA

## NOMENCLATURE

Acronyms

| | |
|---|---|
| $Al_2O_3$ | Aluminum oxide |
| $Al(OH)_3$ | Alumina trihydrate (ATH) |
| CFS | Cable Fire Spreading |
| CFSS | Cable Fire Spreading Support |
| $CH_4$ | Methane |
| C | Soot |
| CO | Carbon monoxide |
| $CO_2$ | Carbone dioxide |
| FMRC | Factory Mutual Research Corporation |
| $H_2$ | Hydrogen |
| $H_2O$ | Water vapor |
| $HO^{\cdot}$ | Free radical |

| | |
|---|---|
| HX | Hydracids |
| $H^{\cdot}$ | Free radical |
| HRR | Heat release rate |
| IRSN | Institut de Radioprotection et de Sûreté Nucléaire |
| MLR | Mass loss rate |
| NIST | National Institute of Standards and Technology |
| NRC | Nuclear Regulatory Commission |
| NPP | Nuclear Power Plant |
| $O_2$ | Oxygen |
| PVC | Polyvinyl chloride |
| XPE | Cross-linked polyethylene |
| $X^{\cdot}$ | Halogen radical |

Symbols

| | |
|---|---|
| d | Cable diameter [m] |
| $k\rho c_p$ | Thermal inertia of the fuel [$(kW\ m^{-2}\ k^{-1})^2\ s$] |
| h | Tray elevation from the bottom of the lowest tray [m] |
| $L_0$ | Ignition length of cables [m] |
| $m'$ | Mass per unit length [$kg\ m^{-1}$] |
| $\dot{m}$ | Mass loss rate [$kg\ s^{-1}$] |
| $\ddot{m}$ | Surface mass loss rate [$kg\ m^{-2}\ s^{-1}$] |
| n | Number of cables per cable tray [-] |
| p | Total perimeter of the cables in contact with the surrounding gas [m] |
| $\dot{q}''_{bs}$ | Experimental bench scale HRR value [$kW\ m^{-2}$] |
| $\dot{q}''_f$ | Incident heat flux from flames to the fuel surface [$kW\ m^{-2}$] |
| $\dot{Q}$ | Heat release rate [W] |
| S | Burning surface of cables [m] |
| t | Time [s] |
| T | Temperature [K] |
| $v_b$ | Flame spread velocity [$m\ s^{-1}$] |
| $x_b$ | Abscissa of the flame front [m] |
| $x_e$ | Abscissa of the extinction front [m] |

Greek letters

| | |
|---|---|
| $\Delta H_c$ | Effective combustion heat [$J\ kg^{-1}$] |
| $\Delta H_{O2}$ | Heat released per kilogram of consumed oxygen [$J\ kg^{-1}$] |
| $\alpha$ | Correction factor applied of cables surface [-] |
| $\beta$ | Fire spread angle [°] |
| $\chi$ | Oxygen-limiting law [-] |
| $\eta$ | Correction factor [-] |
| $\nu$ | Reaction coefficient [$kg\ kg^{-1}$] |
| $\delta$ | Heated fuel distance [m] |

Subscripts

| | |
|---|---|
| amb | Ambient |
| c | Fuel |
| fs | full-scale |
| i | Cable tray index |
| ign | Ignition |
| n | Number of cable trays |
| $\infty$ | Well ventilated conditions |

## 1 INTRODUCTION

Electrical cable trays, in large quantities in a nuclear facility, are one of the main potential sources of fire. A malfunction of the electrical equipment may lead to the loss of important safety functions of the facility. The investigation of such fires in a well-confined enclosure has been scarce up to now and has been investigated exclusively in the nuclear industry. In the framework of the OECD PRISME-2 program [1], IRSN conducted more than a dozen of fire tests involving horizontal electrical cable trays burning either in open atmosphere under a calorimetric hood or inside mechanically ventilated compartments to investigate this topic. Given the multitude of parameters involved in the definition of this fire source (orientation of cables, length of cables, number of cable trays, spacing between trays, cables loading, flame retardant compounds…), no theory to date has been put forward on how to model all aspects of the problem, if only for the open atmosphere. Some approaches, in the form of experimental studies [2],[3] have nevertheless been carried out and an empirical model (FLASH-CAT) [9] was developed for horizontal cable trays fires in an open atmosphere. Recently, the experiments carried out at IRSN [1] improved the knowledge on this topic. A semi-empirical model of horizontal cable trays fires in a well-confined enclosure could then be developed. This model is partly based on the approach used in FLASH-CAT and on experimental findings from the IRSN cables fire experiments. It was implemented in the two-zone model SYLVIA [5] and is here applied on the IRSN cables fire tests.

## 2 LITERATURE REVIEW

Since the serious cables fire occurred at the Browns Ferry NPP in 1975 [6] that resulted in a loss of emergency core cooling system of unit 1, many efforts have been made to enhance the prevention of such fires. At the FMRC, Sumitra [2] performed in the 1980s large-scale experiments in an open atmosphere to quantify the combustion behavior of cable trays of the nuclear industry. Tests mainly involved twelve ladder-type trays of 2.4 m long and positioned horizontally in two vertical stacks of six trays each, spaced of 0.27 m from each other. A 0.4 $m^2$ pan filled with heptane provided a fire power of about 400 kW. Three cable-types (two IEEE-383 qualified [7] and one un-qualified) were tested and arranged either loosely or tightly along the trays. The HRR peak and the fire growth rate were affected by the duration of the ignition source. In addition, an increase of the HRR peak was observed with a loose arrangement of cables or with the use of un-qualified cables.

Large-scale experiments involving cable trays in an open atmosphere were also performed as part of the FIPEC project conducted by Grayson [8] in the 2000s. One of the main objectives of this project was to develop an experimental fire data base used for the validation of fire models. Tests showed that both fire ignition and fire spread significantly depend on the cable characteristics. Tests using identical cables indicated that the HRR peak increased with the power of the ignition source, as well as with the partial confinement of the fire source with the presence of walls and ceiling. Moreover, the cable arrangement was also found as one of the most sensitive parameters on the fire growth.

Within the scope of the CHRISTIFIRE program, McGrattan [9],[10] carried out at NIST many cable trays fire tests in order to quantify the burning characteristics in an open atmosphere of a wide range of multiple cable trays configurations found in operating NPPs. Twenty six multiple trays tests involving horizontal cables trays without wall and ceiling, followed by ten corridor tests using horizontal cable trays located near the ceiling were carried out. One to seven horizontal ladder-type trays (2.4 and 3.6 m long) were used, with a tray spacing ranging from 0.23 to 0.45 m and tray width ranging from 0.3 to 0.9 m. Ignition was achieved by means of a sand burner (300 × 300 $mm^2$) providing a fire power of 40 kW. These tests showed that the fire spread depends on the cable-type, cable loading and operating time of the gas burner, as well as on the cable tray geometry in terms of width and spacing. The corridor tests dealt with a horizontal multiple cable trays inside a fully open corridor (2.4 m width × 2.4 m high × 7.3 m long) and located at 0.3 m from the ceiling. A significant increase of the fire growth rate with the presence of the ceiling was observed; the hot gas layer accumulated under the ceiling pre-heated the cables directly upstream the spreading fire.

Few available programs involving cable tray as fire source were carried out in confined and mechanically ventilated rooms as typically encountered in NPPs [11]. Nevertheless, these ones mainly aimed at studying the failures modes of electrical cables used as target submitted to fire conditions. Since the investigation of cable trays fires in confined and mechanically ventilated compartments has

been scarce up to now, IRSN conducted more than a dozen of fire tests involving horizontal cable trays burning either under a calorimetric hood in open atmosphere (CFSS tests campaign [12]-[13]) or inside a mechanically ventilated facility (CFS tests campaign [14]-[15]) to investigate this topic. These tests aim at investigating the effects of confined and ventilated conditions on the fire behavior and on its consequences. Fire tests were carried out under the SATURNE calorimetric hood and in the DIVA facility within the scope of OECD PRISME-2 program [1].

## 3 CONFIGURATION OF THE CFS 1 TO 4 TESTS

CFS tests were carried out in the multi-room large-scale fire test DIVA facility. The DIVA facility (shown in Figure 1) consists of five rooms: 3 identical rooms of 120 $m^3$ each in volume (6 × 5 × 4 $m^3$) arranged in a row (referred to as Rooms 1, 2 and 3) and a corridor (Room 0) of 156 $m^3$ in volume (15.6 × 2.5 × 4 $m^3$). Moreover, an upper room (Room 4) of 176 $m^3$ in volume (8.8 × 5 × 4 $m^3$) is located above Room 3 and part of the adjacent corridor. Rooms can be connected via doors, simple openings and calibrated leak passages (to simulate leaks through an actual closed door and/or through a transfer grid between two rooms). They can also be connected with a ventilation network, with one inlet duct and one exhaust duct per room. The ventilation system of the DIVA facility consists of two separate circuits (one for inlet and one for exhaust), each equipped with fans.

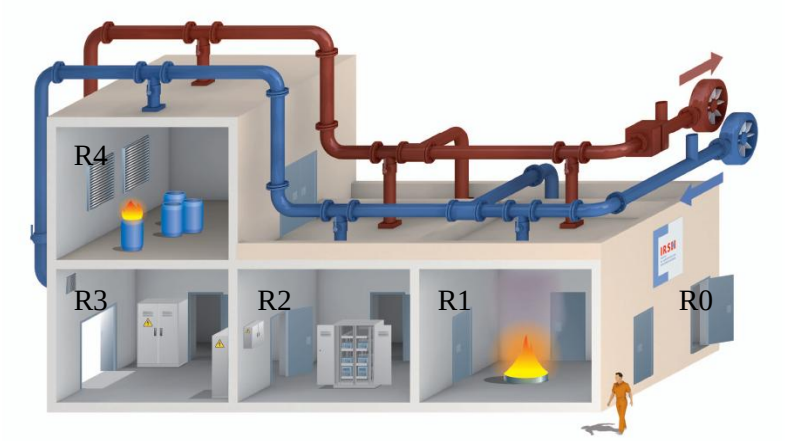



Figure 1: Perspective view of the DIVA facility

Only the Rooms 1 and 2 were used for the CFS 1 to 4 tests. These rooms communicate through a doorway, as shown in Figure 2. The fire source was located in Room 1, against the west wall of the room. This one was composed of five horizontal ladder-type trays 3 m long, 0.45 m wide and spaced each other of 0.3 m (see Figure 3). Each tray was filled with 32 samples of 2.4 m long of a cable-type (see Table 1). For all the tests, the number of cables per tray was determined in order to ensure the same total cable surface for the five cable trays (24 $m^2$). The cable samples were packed loosely along the five trays. In addition, the five trays were set up against an insulated side wall. Ignition was achieved by means of a propane gas burner (300 × 300 $mm^2$). It was centred and located 0.2 m below the lowest cable tray. For all the tests, the sand burner provided a power ignition of 80 kW for 1 minute and 20 seconds for CFS-1 test, 2 minutes and 26 seconds for CFS-2 test and 12 minutes and 24 seconds for CFS-3 and CFS-4 tests. The ignition source was stopped when the HRR exceeded 400 kW considering that for such a value (five times higher than the fire power of the gas burner) the cable tray fire source was ignited. The air inlet was located at the upper part of the fire room while the outlet was set up at the upper part of the adjacent room (see Figure 2). Air renewal rate before ignition for all the volume occupied by the fire and adjacent rooms (240 $m^3$) was 4 $h^{-1}$ for CFS-1 and CFS-3 tests and 15 $h^{-1}$ for CFS-2 and CFS-4 tests.

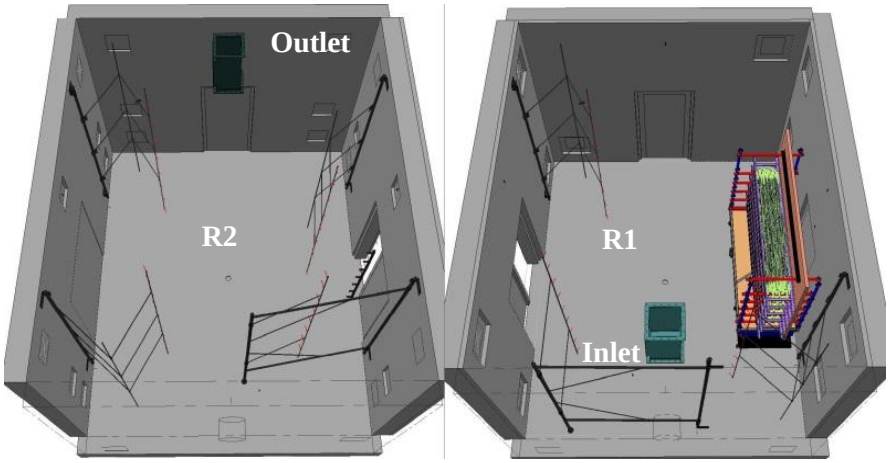



Figure 2: Scheme of the experimental set-up of the CFS tests



Figure 3: Cable trays fire source

About 250 sensors were used to measure heat flux, gas temperature, pressure, gas and soot concentrations mainly in the fire room and the adjacent room, as well as gas velocity through the doorway between the two rooms. Experimental results of CFS 1 to 4 tests are reported in [14] and [15]. In support to CFS tests, CFSS tests [12] were carried out in open atmosphere, under the SATURNE calorimetric hood, and involved the same fire sources as the ones used in the CFS 1 to 4 tests. A comparison between CFS and CFSS tests allows to assess the effect of the confinement on the fire source.

| *Test* | *Flame retardant* | *Number of cables per tray* | *Cable diameter (mm)* | *Total surface of cables ($m^2$)* |
|---|---|---|---|---|
| CFS-1 | Halogenated (chlorine) | 49 | 13 | 24 |
| CFS-2 | Halogenated (chlorine) | 44 | 14.5 | 24 |
| CFS-3-4 | Mineral (ATH) | 32 | 20 | 24 |

Table 1: Characteristics of the CFS 1 to 4 fire sources

## 4 HORIZONTAL CABLE TRAYS FIRE MODELING

A semi-empirical model of horizontal cable trays fire in a well-confined enclosure has been developed and implemented in the SYLVIA software. This model is derived from the FLASH-CAT model [9], developed for horizontal cable trays fires in open atmosphere. The model differs from the FLASH-CAT one, on the flame spread velocity along cables, on the upward fire propagation in the cable tray stack, and on the expression of the fuel mass loss rate, for which a correction is applied to take into account the effect of the oxygen depletion in the fire room on the heat release rate by the fire.

### 4.1 Heat release rate

A useful correlation for estimating the HRR generated by a burning cable tray is available in the NUREG-1805 [16], which specifies state-of-art relevant to fire dynamic equations and correlations for performing fire hazards analysis for the NRC inspection program. This correlation was developed by Lee [17] who showed that the peak full-scale HRR in well ventilated conditions can be predicted according to bench-scale HRR measurements performed on cable samples. This correlation is expressed as:

$$\dot{Q}_{fs} = 0.45\ S\ \dot{q}''_{bs} \tag{1}$$

with:

- $\dot{Q}_{fs}$: peak full-scale HRR (kW);
- S: total burning area of the cable trays involved in the fire at the peak full-scale HRR ($m^2$);
- $\dot{q}''_{bs}$: peak bench-scale HRR per unit area, under 60 $kW.m^{-2}$ irradiance ($kW.m^{-2}$).

In lack of a dynamic model of HRR in the literature, the Lee's correlation is generalized at each instant and adapted to the confinement of the fire source. According to Eq. (1), the Mass loss Rate (MLR) of the fuel under well-ventilated conditions is then given by:

$$\dot{m}_{C,\infty}(t) = 0.45\frac{\dot{q}''_{bs}}{\Delta H_{C,\infty}}\sum_{i}^{n} S_i(t) \tag{2}$$

Fires in confined and ventilated compartments often lead to a significant decrease in the mass loss rate (and thus in the HRR) compared to the one obtained in open atmosphere (i.e. well ventilated conditions). This decrease is mainly due to oxygen depletion in the fire room, because of the air renewal rate that can be quite low compared to the fire power. The under-oxygenation of the fire source is traduced in the model by an oxygen limiting-law applied to the MLR. In these conditions, HRR is written as:

$$\dot{Q}(t) = \dot{m}_{C,\infty}(t)\,\chi(O_2)\,\Delta H_C \tag{3}$$

Introducing Eq. (2) in Eq. (3), HRR is expressed as:

$$\dot{Q}(t) = 0.45\,\dot{q}''_{bs}\,\chi(O_2)\frac{\Delta H_C}{\Delta H_{C,\infty}}\sum_{i}^{n} S_i(t) \tag{4}$$

The difficulty in applying Eq. (4) lies in the estimation of the instantaneous burning surface of cables that depends on the horizontal fire spread along cable trays and on the vertical fire spread from one cable tray to another.

#### *4.1.1 Cable burning surface*

For a given cable tray, the surface of the cables in contact with the surrounding gas depends on the number of cables present on their packing configuration (stacking density). For a small number of cables, this surface is assumed equal to the total surface of the cables ($\alpha = 1$). When the number of cables becomes high, the cables are stacked on top of each other, on several layers more or less

compact. In this case, and for a tight arrangement, the cable surface in contact with the surrounding gas corresponds to the free surface of the cable sheet ($\alpha < 1$). In order to take into account the stacking density of the cables in the estimation of the total burning surface of cables, a correction factor is applied to the total surface of the cables when the number of cables becomes high. Thus, the instantaneous burning surface of cables per cable tray can be written as:

$$S(t) = \alpha\, n\, \pi\, d\, (x_b(t) - x_e(t)) = p\, (x_b(t) - x_e(t)) \tag{5}$$

The abscissa of the flame front is given by:

$$x_b(t) = L_0 + \int_{t_{ign}}^{t} v_b(t)\,dt \tag{6}$$

and the abscissa of the extinction front is given by:

$$x_e(t) = x_b(t) - \int_{t_i(x_e)}^{t_e(x_e)} v_b(t)\,dt \tag{7}$$

$t_i(x_e)$ denotes the crossing time of the flame front at the abscissa $x_e$ and $t_e(x_e)$ the one of the extinction front at the same abscissa.

At a given abscissa x, from the ignition time of this area, the extinction time corresponds to the moment when the whole fuel mass in this region is consumed. It is given by:

$$\int_{t_i(x)}^{t_e(x)} p\, \dot{m}''_{c,\infty}\, \chi(O_2)\,dt = m'_c \tag{8}$$

A scheme of the modeling of the cables burning surface is shown in Figure 4.

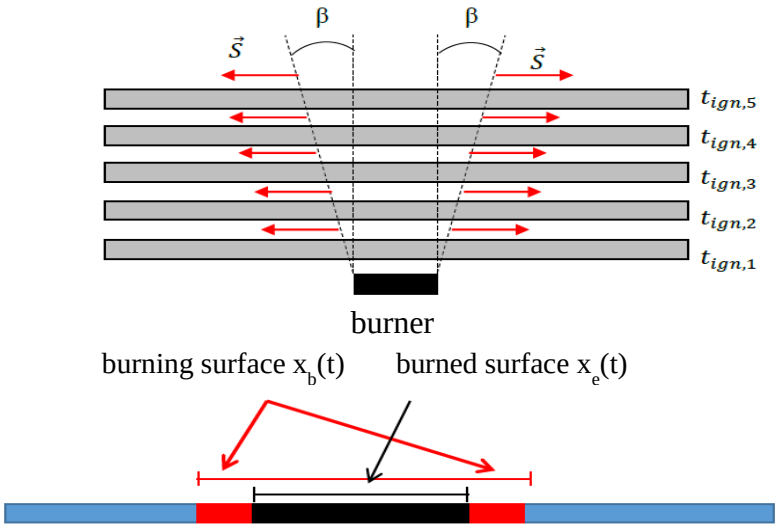



Figure 4: Scheme of the modeling of the burning surface of cables

### *4.1.2 Horizontal flame spread velocity along the cable trays*

In a confined enclosure, the flame spread velocity along the cable trays is not constant contrary to the assumption made in FLASH-CAT for cable trays fires in an open atmosphere. Indeed, the increase of the temperature of the surrounding gas of the cables tends to increase the flame spread velocity while the decrease of the oxygen content at the level of the cables tends to reduce this velocity, by reducing

the heat flux transmitted by the flames to the surface of the cables. The flame spread velocity can be estimated by dividing the fuel distance heated by the flames by the time to ignition. Mathematically, Quintiere [18] leads to the following formulation of the velocity, based on a thermally-thick behavior of the material, on which a correction factor ($\chi$) is applied to the incident heat flux from flames to the fuel surface to take into account the decrease of this heat flux with the decrease of the oxygen content:

$$v_b(t) = \frac{4\left(\dot{q}''_{f,\infty}\,\chi(O_2)\right)^2 \delta_c}{\pi\left(k\rho c_p\right)\left(T_{ign} - T_{amb}(t)\right)^2} \qquad (9)$$

For horizontal cable trays fires in well ventilated conditions, a value of 70 kW.m$^{-2}$ for the incident heat flux from flames to the fuel surface ($\dot{q}''_{f,\infty}$) and a value between 1 and 2 mm for heated fuel distance ($\delta_c$) are considered [4].

At the ignition point of the cable tray, the flame spreads symmetrically on either side of the ignition region of the cables. The flame spread velocity is then multiplied by two to take into account this effect in the model. When one of the flame fronts reaches the end of the path, one returns to the unmodified formulation of the flame spread velocity given by Eq. (9).

### *4.1.3 Vertical fire spread in a cable tray stack*

An empirical model for upward fire propagation in a cable tray stack is used in FLASH-CAT. This model assumes a V-shaped burning pattern forming an angle of 35° with the vertical direction [9] (see Figure 5) [19]. The assumption of the 35$^o$ angle of fire spread is based on results from a fire test performed in an open atmosphere involving 14 filled horizontal cable strays in a two-tray-wide by seven-tray-high array. Cable trays were filled with 3-conductor XPE cable [20].

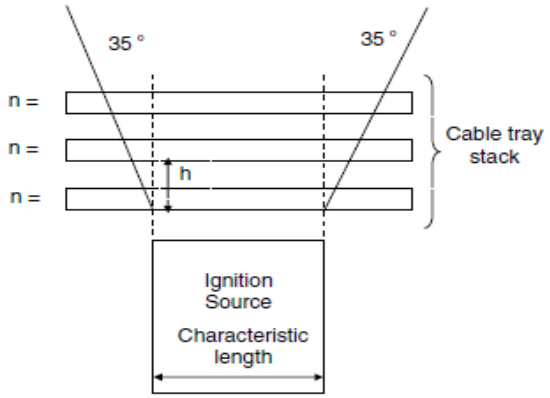



Figure 5: Model for fire propagation in a cable tray stack

The lowest tray in the stack has the burning length of the characteristic length of the ignition source (see Figure 5). The burning length of the trays above is calculated using the following equation:

$$L_{0,i+1} = L_{0,i} + 2\,(h_{i+1}\tan(\beta)) \qquad (10)$$

where h is the tray elevation measured from the bottom of the lowest tray and β the fire spread angle.

Assuming that the first cable tray in a stack of horizontal cable trays is within the zone of influence of a given ignition source, the spread of the fire within the stack is assumed as follows in FLASH-CAT:

- exposure source to the first tray: tray ignites at time to damage;
- first tray to second tray: 4 minutes after ignition of first tray;

- second tray to third tray: 3 minutes after ignition of second tray;
- third tray to fourth tray: 2 minutes after ignition of third tray;
- for next trays: 1 minute after ignition of the previous tray.

In a confined enclosure, this rule (known as "minutes rule") is not appropriate since the temperature increase of the surrounding gas of the cables tends to reduce the preheating time of cables. Moreover, this rule does not take into account the fuel properties, depending on whether cables are thermoplastic (PVC cables) or thermoset-like (mineral flame retardant cables). In order to have an accurate simulation of the confined configuration, a secondary fire-source model is then used in the SYLVIA software for the fire spread within the stack. This model consists in placing a thermally thick target, whose thickness corresponds to the thickness of the cable sheath, at the supposed ignition zone of each cable tray. Thus, the ignition time of cables is related to the fuel properties, to the ambient conditions and to the incident heat fluxes (convective and radiative). The ignition of the cable tray is then operated on a temperature criterion given in 5.1 and taken from the data of CHISTIFIRE experiments [26]. Thermal physical properties of cable samples tested in CFS tests are given in Table 2.

| *Cable-type used in CFS tests* | *Thermal conductivity* ($W.m^{-1}.K^{-1}$) | *Density* ($kg.m^{-3}$) | *Specific heat* ($J.kg^{-1}.K^{-1}$) | *Thermal inertia* ($kW^2.s.m^{-4}.k^{-2}$) |
|---|---|---|---|---|
| CFS-2 | 0.156 | 1336 | 1280 | 0.27 |
| CFS-3-4 | 0.382 | 1476 | 1540 | 0.87 |

Table 2: Thermal physical properties of cable samples (no data available for the cable sample tested in CFS-1 test)

An estimation of the fire spread angle from a video analysis was performed on the CFSS tests performed under a calorimetric hood in open atmosphere [21]. The fire spread angle of 35° recommended by the NUREG/CR-6850 [4] was not reproduced, values less than 10° were obtained. The difference could be explained by the presence of an insulated side wall in support of cable trays which tends to reduce the ignition time of the cables by increasing the temperature of the surrounding gas. Depending on the distance between walls and cable trays, the fire spread angle may vary. Hence, the fire spread angle is an input data of the model.

### 4.2 Combustion specificities according to the nature of flame retardants

Depending on the nature of the compounds used in flame retardants, a different behavior of the flame retardant with respect to the fire is observed. Halogens contained in flame retardants act by the action of the corresponding halohydric acid, by capturing the hot flame radicals (flame poisoning). Their efficiency is shown by a reduction of the combustion rate which also depends on external factors, such as the oxygen diffusion rate in the reactive zone or the heat transfer rate from the flame to the surface of the polymer. The reactions of inhibition of the free radicals by the corresponding hydracids are the following [22]:

$$HX + HO^{\cdot} \rightarrow H_2O + X^{\cdot} \quad (11)$$

$$HX + H^{\cdot} \rightarrow H_2 + X^{\cdot} \quad (12)$$

Thus, the most energetic free radicals of the flame ($HO^{\cdot}$ and $H^{\cdot}$) are replaced by $X^{\cdot}$ radicals of lower energy. Here, X designates the chlorine contained in PVC cables.

The number of mineral compounds used as flame retardants is relatively small since they have to be decomposed at a relatively low temperature, which is not common for minerals. Alumina trihydrate

($Al(OH)_3$) is one of the most common mineral flame retardant because it is inexpensive and easy to incorporate into plastics. Alumina trihydrate is decomposed in a temperature range between 180 °C and 200 °C, as follows [21]:

$$2\ Al(OH)_3 \rightarrow Al_2O_3 + 3\ H_2O\ \ (+\ 298\ kJ.mol^{-1}) \tag{13}$$

Alumina trihydrate is cooled by the reaction of dehydration (endothermic reaction), which involves less volatile products released by the fuel. Moreover, aluminum oxide resulting from its dehydration forms, on the fuel surface, a protective crust against a subsequent degradation of the material. Finally, water vapor released by the reaction dilutes the gaseous phase and decreases the amount of oxygen at the fuel surface.

In terms of modeling, effects of mineral flame retardants on combustion are taken into account in the thermal inertia of the fuel. According to Table 2, thermal inertia of mineral flame retardant cables tested in CFS-3 and CFS-4 tests is three times higher than the one of PVC cables tested in CFS-2 test. This results in a delay in the heating of the fuel and then, to a slower flame spread velocity. The mass loss of cables due to the dehydration reaction is not modeled.

Chlorine contained in PVC cables results in a decrease of the effective heat of combustion due to the inhibition reactions occurring in the flame. To the under-oxygenation of the fire source with its confinement is added the one due to the action of the hydrogen chloride. Chemical reactions occurring during the burning of cables are complex. These depend on the nature of the fuel as well as the level of oxygenation of the fire source. In the SYLVIA software, a simplified combustion reaction (one step, irreversible) expressed in terms of mass is used as:

$$1\ kg\ of\ fuel + \nu_{O2}\,O_2 \rightarrow \nu_{CO2}\,CO_2 + \nu_{CO}\,CO + \nu_{H2O}\,H_2O + \nu_{CH4}\,CH_4 + \nu_C\,C \tag{14}$$

It is assumed that the fuel is homogeneous and that chemical reactions occur simultaneously with the same kinetics. This equation does not take into account the release of hydrogen chloride from PVC cables, in the absence of available experimental data. Averaged values of the reaction coefficients over the fire duration are used, although these could change, depending on the level of oxygenation of the fire source. They are obtained experimentally from the mass of released species and the pyrolysed mass of fuel (mass ratio, see Table 3 for the CFS cable fire tests performed in confined conditions). Since the amount of water vapor is not measured experimentally, the coefficient related to this species is determined by the mass balance of the chemical reaction. Oxygen consumption is given by:

$$\nu_{O2} = \eta \frac{\Delta H_C}{\Delta H_{O2}} \tag{15}$$

where $\Delta H_{O2}$ is the heat released per kilogram of consumed oxygen, set to 13.1 MJ $kg^{-1}$ [23].

| *Test* | $\nu_{CO2}$ $(g.g^{-1})$ | $\nu_{CO}$ $(g.g^{-1})$ | $\nu_{CH4}$ $(g.g^{-1})$ | $\nu_C$ $(g.g^{-1})$ | $\Delta H_c$ $(MJ.kg^{-1})$ |
|---|---|---|---|---|---|
| CFS-1 | 1.12 | 0.12 | 0.09 | 0.017 | 13 |
| CFS-2 | 1.14 | 0.16 | 0.14 | 0.054 | 12.5 |
| CFS-3 | 1.77 | 0.08 | 0.08 | 0.008 | 19 |
| CFS-4 | 2.14 | 0.04 | 0.02 | 0.007 | 26 |

Table 3: Yields of combustion products and effective heat of combustion for the CFS tests

A correction factor is applied to the oxygen coefficient of the combustion reaction of PVC cables to take into account the overconsumption of oxygen due to inhibition reactions. A coarse estimation of this correction was performed on the CFS cables fire tests. For the mineral flame retardant cables tested, the mean value of the combustion heat obtained in the DIVA facility with an air renewal rate of 15 $h^{-1}$ is equivalent to the one obtained under the calorimetric hood (26 MJ $kg^{-1}$ for CFS-4 test, against 27 MJ $kg^{-1}$ for CFSS-2 test). The under-oxygenation of the fire source with the confinement is then negligible at this level of ventilation. For the PVC cables tested, the mean value of the combustion heat obtained in the DIVA facility with an air renewal rate of 15 $h^{-1}$ is lower than the one obtained under the calorimetric hood (12.5 $MJ.kg^{-1}$ for CFS-2 test against 16 $MJ.kg^{-1}$ for CFSS-4 test). Assuming that in an open atmosphere, the oxygen diffusion rate in the reactive zone is greater than the oxygen consumption rate by inhibition reactions, and assuming that the higher fire growth rate of PVC cables compared to mineral flame retardant cables does not impact significantly the oxygen change in the fire room at this level of ventilation, the difference found on the combustion heat between the open atmosphere and the confined one is then attributed to the action of halogens. In this case, the correction factor to be applied to the oxygen consumption is 1.3, that corresponds to the ratio of the combustion heat obtained under hood to the one obtained in DIVA.

# 5 SIMULATIONS OF THE CFS 1 TO 4 TESTS USING THE TWO-ZONE MODEL SYLVIA

The model of horizontal cable trays fire was implemented in the two-zone model SYLVIA. The SYLVIA software [5] [4] is developed at the Institut de Radioprotection et de Sûreté Nucléaire (IRSN) to simulate a full ventilation network, fire scenarios in a highly confined and ventilated facilities, and airborne contamination transfer inside nuclear installations. This software is based on a zone approach which consists in calculating mass and energy balances in each of two zones, separated by an interface, which constitutes the enclosure (fire room or not): the lower zone simulating the fresh gas and the upper zone, simulating the combustion products and the gas entrained by the plume. In a zone approach, a plume feeds the upper zone of the fire room, whose volume increases, which has the effect of lowering the interface if the gas flow in the exhaust duct or at the level of openings of the fire room is not sufficient to remove all gases supplied by the plume.

## 5.1 Input data of the model

CFS tests simulations have been performed using the oxygen-limiting correlation ($\chi(O_2)$) proposed by Peatross and Beyler [24]. This correlation is a linear function of the fuel mass loss rate according to the oxygen volume fraction available for combustion close to the fuel (see Figure 6).

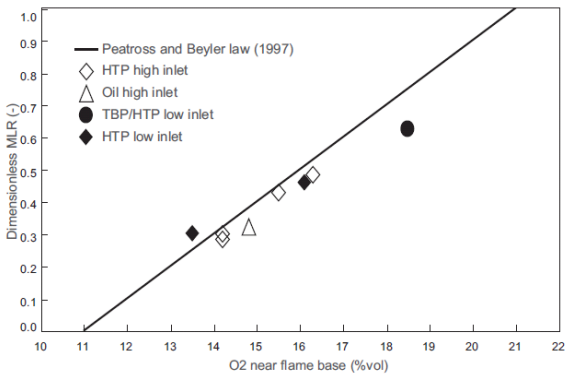



Figure 6: Development of the steady-state fuel mass loss rate with oxygen concentration near the flame base [25]

The cable samples being packed loosely along the trays, no correction factor is applied to the total burning surface of the cables to take into account the staking density of the cables ($\alpha = 1$) . The mass per unit length of the cable components are reported in Table 4.

| *Cables* | *Total* ($g.m^{-1}$) | *Metal* ($g.m^{-1}$) | *Sheath* ($g.m^{-1}$) | *Filler* ($g.m^{-1}$) | *Insulation* ($g.m^{-1}$) |
|---|---|---|---|---|---|
| CFS-1 | 235 | 85 | 85 | 35 | 30 |
| CFS-2 | 320 | 140 | 100 | - | 80 |
| CFS-3-4 | 570 | 155 | 155 | 125 | 135 |

Table 4: Mass per unit length of the cable components

Bench-scale HRR measurements performed on cable samples and full-scale effective heat of combustion in open atmosphere are reported in Table 5.

| *Cables* | $q_{bs}$ ($kW.m^{-2}$) | $\Delta H_{c,\infty}$ ($MJ.kg^{-1}$) |
|---|---|---|
| CFS-1 | 270 | 22 |
| CFS-2 | 234 | 16 |
| CFS-3-4 | 184 | 27 |

Table 5: Bench scale HRR and full scale effective heat of combustion under well ventilated conditions

Thermal inertia of the cable samples tested in CFS-1 test is not known. This one has been fitted in a way to reproduce the kinetics of the gas temperature increase in the fire room (see Figure 9). A value of 0.10 $kW^2.s.m^{-4}.k^{-2}$ was set in the simulation.

Data related to the ignition temperature of the cables are taken from the CHISTIFIRE experiments [26]. According to these experiments, a value of 218 °C is set for a PVC cable against 330 °C for a mineral flame retardant cable. Since the ignition of the lowest cable tray was achieved by means of a propane gas burner in the CFS experiments, a gas burner model is used in SYLVIA for the ignition of the first cable tray.

### 5.2 Results and discussion

Results of the CFS tests simulations with a comparison to experimental data for the heat release rate, the pressure and the mean gas temperature in the fire room are shown in Figures 7 through 9. The comparison of the predicted HRR with the experimental data shows a good agreement for the CFS-2 test (except for the fire duration) and deviations for the three other tests, as shown in Figure 7. Several explanations for theses deviations are put forward. First, in absence of a specific law to solid fuels, the oxygen limiting law of Peatross and Beyler is used, whereas this law was established on liquid fuels. Second, the set up of the cable trays against an insulated side wall contributes to a lesser heat removal at the vicinity of cables, leading to a decrease of the heating time of cables. This wall is not taken into account in the calculations (zone model limitation). Third, in a two-zone model approach, an interface separates the hot gas layer from the cold one. For CFS-4 test performed at high renewal rate (15 $h^{-1}$) with mineral flame retardant cables, the interface is located at mid-height of the fire room. For this

test, only the highest cable tray is predicted in the hot gas layer, explaining the high underestimation of the HRR. Fourth, the large dispersion of the fuel inside the fire room is favorable to a production of pyrolysed gases in excess. For CFS 1 to 3 tests, the effect of the inhibition reactions for halogenated cables and the effect of the low renewal rate for CFS-3 test led to a significant production of pyrolysed gases in excess and their combustion in the upper part of the fire room. These instabilities of combustion are not reproduced by the calculations, the pyrolysed gases in excess not being modeled.
The delay in the power rise due to the effect of the reaction of dehydration occurring in mineral flame retardant cables is not reproduced by the calculations for CFS-3 and CFS-4 tests, as seen in Figure 7. More, no fire extinguishing criteria was used in the simulations, explaining the overestimation of the fire duration for CFS-1 and CFS-3 tests performed at low air renewal rate. For CFS-4 test, the overestimation of the fire duration is due to an under-estimation of the HRR, while the under-estimation of the fire duration for CFS-2 test is attributed to a slight overestimation of the HRR.

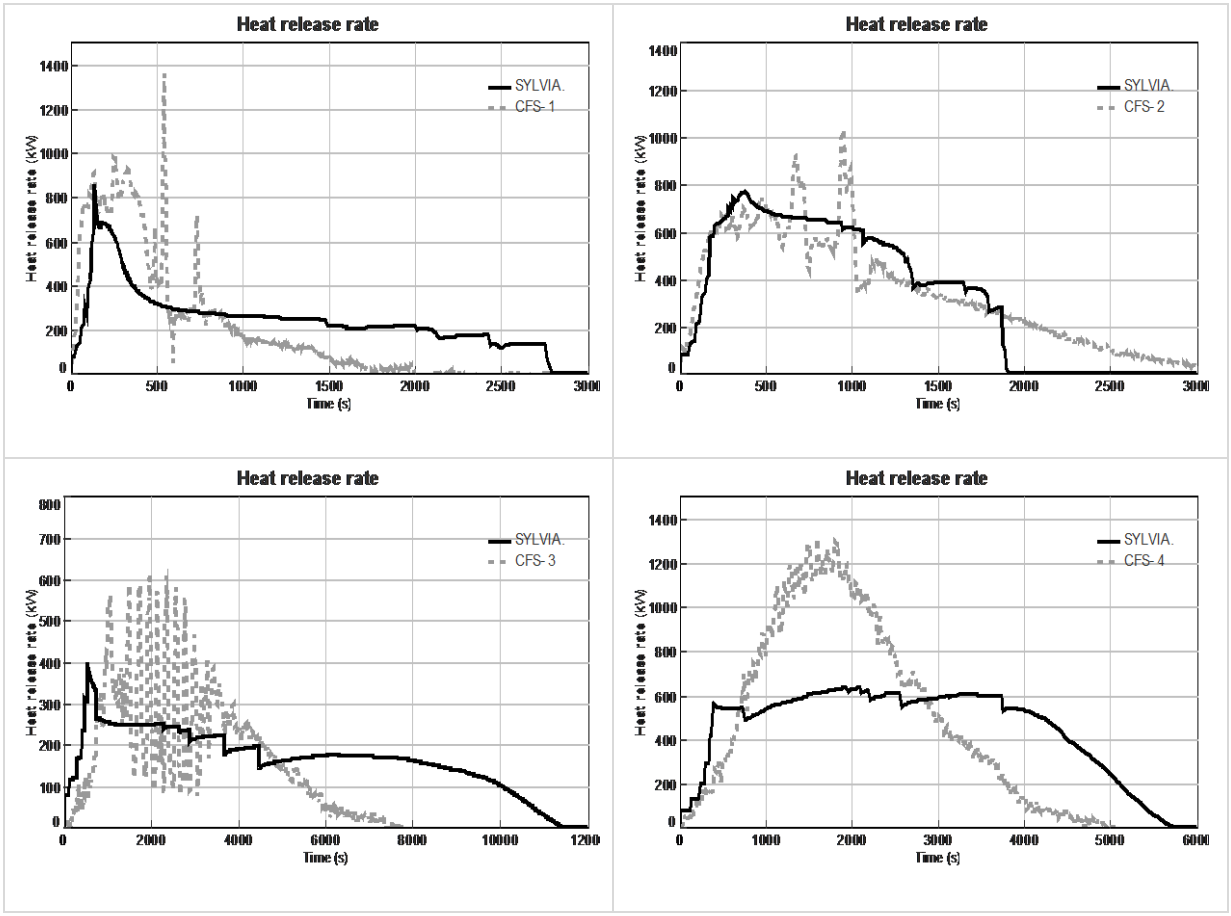



Figure 7: HRR predictions for the CFS tests

The kinetics of the rise in pressure of a fire room mainly depends on the ratio between the kinetics at which the heat production by the fire source increases and the kinetics at which this heat is dissipated or evacuated. At the ignition of the cable trays, the heating of the walls (main source of heat dissipation) not being instantaneous, it results in a rise in pressure of the fire room. The resulting pressure peak is quite well reproduced by the calculations for the four tests, as shown in Figure 8. The highest pressure peak value is predicted for CFS-1 test (23 hPa against 14 hPa experimentally), this test involving cables with a high fire growth rate (0.14 $kW.s^{-2}$). The following pressure peaks observed in CFS 1 to 3 tests, and not reproduced by the calculations, are due to the combustion of pyrolysed gas in excess, mainly in the upper part of the fire room where the highest gas temperatures are met. A pressure peak as high as 145 hPa occurred during CFS-1 test.

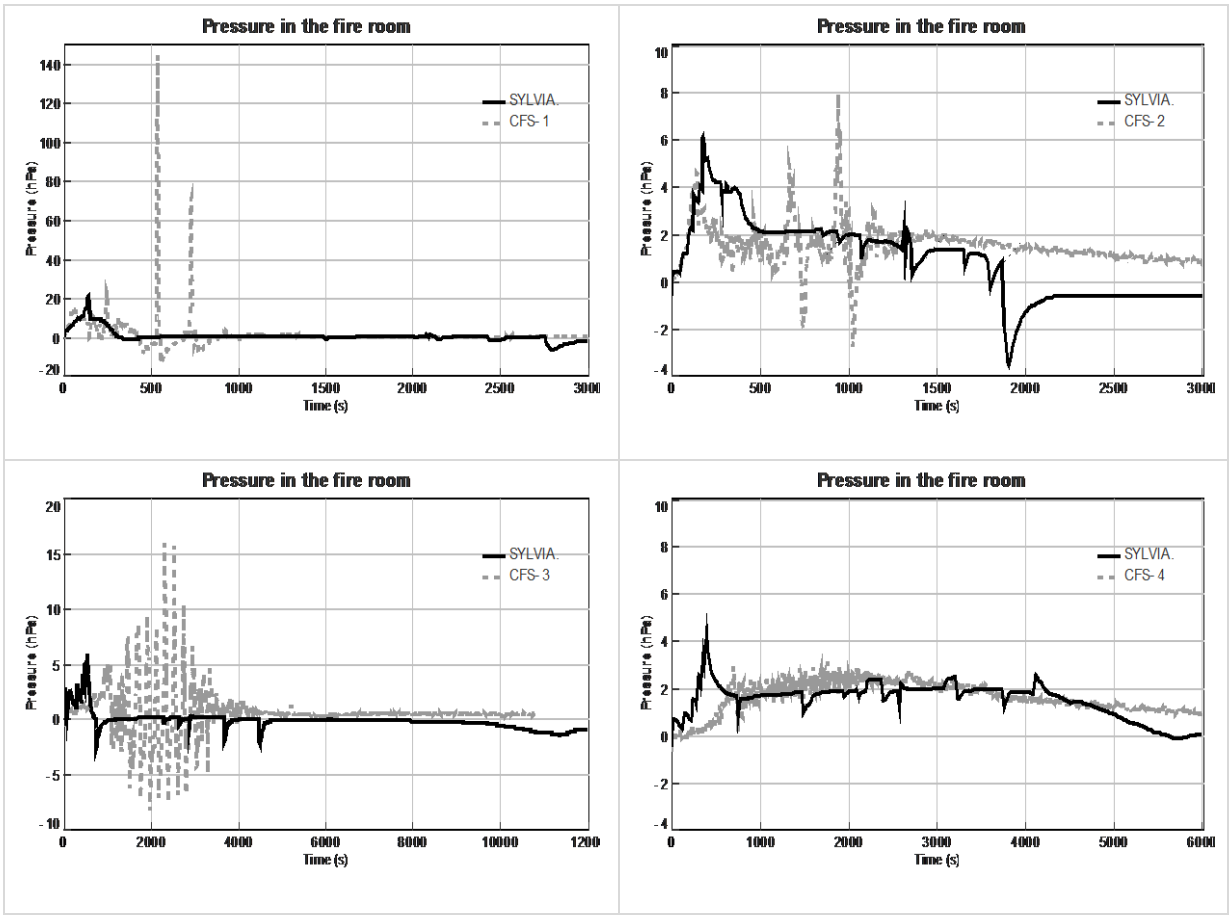
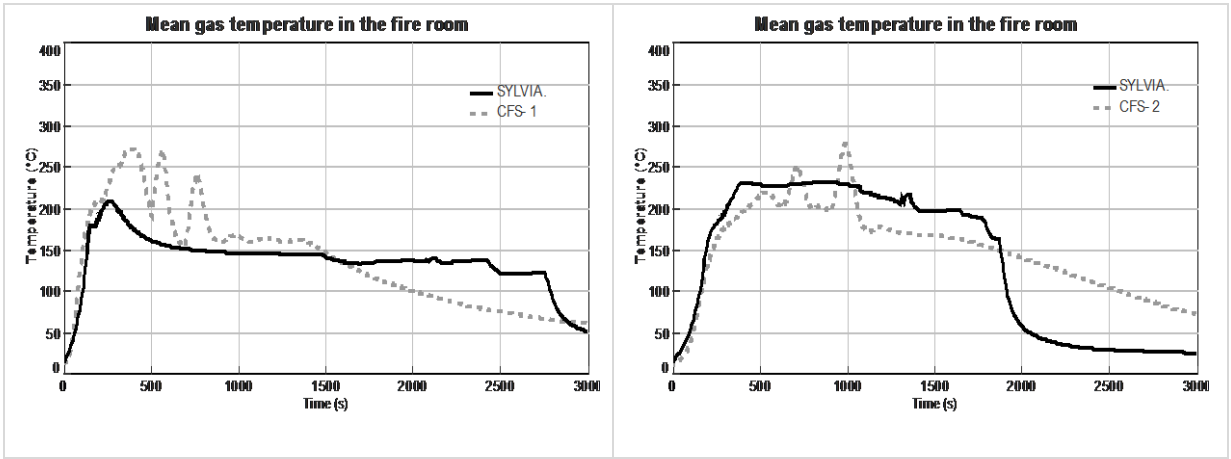



Figure 8: Pressure predictions in the fire room for the CFS tests

The hot gas column which rises above the cable trays leads to important convective movements inside the fire room. Since the gas flow through the exhaust line is not sufficient to instantaneously evacuate all the gases contained in the plume, it results in an accumulation of these gases in the upper part of the room and a vertical stratification of the gas temperature. Predictions of the mean gas temperature in the fire room are in agreement with the ones obtained experimentally for CFS 1 to 3 tests, as shown in Figure 9. The deviations are mainly due to the combustion of pyrolysed gas in excess, not reproduced by the calculations. For CFS-4 test, the deviation is more important and is mainly explained by the deviation on the predicted HRR.



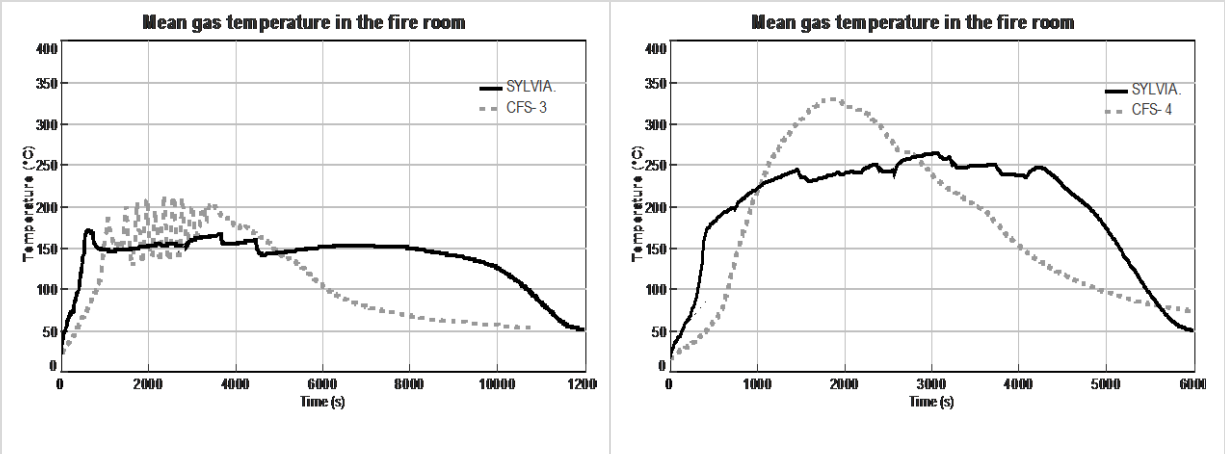



Figure 9: Mean gas temperature predictions in the fire room for the CFS tests

## 6 CONCLUSION

Cable trays fire tests were carried out both in open atmosphere and into the confined and mechanically ventilated DIVA facility of IRSN. These tests were performed in the framework of the OECD PRISME-2 program and helped to investigate the different phenomena arising in such fires. In particular, the effect of the confinement on the flame spread velocity was highlighted. Indeed, the increase of the ambient gas temperature with the confinement of the fire source tends to increase the flame spread velocity while the under-oxygenation of the fire source tends to decrease this velocity, by reducing the heat flux transmitted by the flame to the surface of the cables. CFS 1 to 4 tests also evidenced the importance of the production of pyrolysed gases in excess observed in fully developed enclosure fires. These pyrolysed gases in excess represent a hazard because they can lead to their combustion inside the fire room with a possible pressure effect on fire equipment. Different characteristic parameters of the ventilation network (air renewal rate, but also the position of the inlet and exhaust ventilation ducts in the fire room) also play an important part on the pyrolysed gases production and their consequences. A semi-empirical model of horizontal cable trays fires in a well-confined enclosure has then been developed. This model is partly based on the approach used in FLASH-CAT and on experimental findings from the CFS tests.

The model was implemented in the two-zone model SYLVIA. Apart from the instabilities of combustion, the major features of the compartment fires experiments, such as characteristic HRR, pressure and mean gas temperature could then be reproduced with acceptable error. However, additional compartment fire experiments are required for the improvement and the full validation of the model, given the multitude of parameters involved in the definition of the fire source. The development of such a semi-empirical model is a common practice in fire safety engineering concerned with complex combustibles. It opens the way to parametric studies.

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