Horizontal cable tray fire in a well-confined and mechanically ventilated enclosure using a two-zone model

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Summary
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 limited to 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 fire tests involving horizontal electrical cable trays burning either in open atmosphere or inside mechanically ventilated compartments to investigate this topic. A semi-empirical model of horizontal cable tray fires in a well-confined and mechanically ventilated enclosure was developed. This model is partly based on the approach used in FLASH-CAT and on experimental findings from IRSN cables fire tests. It was implemented in the two-zone model SYLVIA. The major features of the compartment fire experiments could then be reproduced with acceptable error, except for combustion of unburned gases. The development of such a semi-empirical model is a common practice in fire safety engineering concerned with complex solid fuels.

KEYWORDS
cable tray fire, enclosure, mechanical ventilation, SYLVIA

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. Since the serious cables fire occurred at the Browns Ferry NPP in 1975 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 performed in the 1980s large scale experiments in an open atmosphere to quantify the combustion...
behavior of cable trays in the nuclear industry. Tests mainly involved 12 ladder-type trays of 2.4 m long and positioned horizontally in two vertical stacks of six trays each, spaced from each other by 0.27 m. A 0.4-m² pan filled with heptane provided a fire power of about 400 kW. Three cable types were used and arranged either loosely or tightly along the trays. Two of the three cable types were compliant with the IEEE-383 standard test.3 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 non-compliant cables.

Large-scale experiments involving cable trays in an open atmosphere were also performed as part of the FIPEC project conducted by Grayson et al10 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 et al5,6 carried out at NIST many cable tray fire tests in order to quantify the burning characteristics in an open atmosphere over a wide range of multiple cable tray configurations found in operating NPPs. Twenty-six multiple tray tests involving horizontal cable trays without wall and ceiling, followed by 10 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 mm²) 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 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 of the spreading fire.

Few experimental programs involving cable tray fires in confined and mechanically ventilated compartments were carried out.7 These ones mainly aimed at studying the failure modes of electrical cables used as a target subjected to fire conditions. Since the investigation of cable tray fires in confined and mechanically ventilated compartments has been scarce up to now, IRSN conducted, in the framework of the OECD PRISME-2 program,8 more than a dozen fire tests involving horizontal cable trays burning either under a calorimetric hood in open atmosphere (CFSS tests campaign9,10) or inside a mechanically ventilated facility (CFS tests campaign11,12) to investigate this topic. These tests aimed at investigating the effects of confined and mechanically ventilated conditions on real-scale cable tray fires. They are representative of fire scenarios in nuclear facilities that are initiated by an electrical fault in a control panel or electrical cabinet, for example.

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, even for only open atmosphere conditions. Some approaches, in the form of experimental studies,2-13 have nevertheless been carried out, and an empirical model (FLASH-CAT)14 was developed for horizontal cable tray fires in an open atmosphere. Recently, the experiments carried out at IRSN8 improved the knowledge on this topic. A semi-empirical model of horizontal cable tray fires in a well-confined and mechanically ventilated 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. Indeed, the horizontal flame propagation along the cable trays is no longer determined by a constant value14 but calculated by means of the Quintiere's correlation,15 mainly depending on the gas temperature and the oxygen volume fraction close to the cables. Concerning the upward fire propagation in the cable tray stack, the FLASH-CAT modeling uses the "minute rule,"14 based on a simple and empirical law providing a time to ignite the next cable tray without any considerations about the nature of cables and the distance between cable trays for instance. In this paper, the ignition of the upper cable tray is performed by the assessment of the thermal stress on it due to the flame located on the lower tray. This new modeling was implemented in the two-zone model SYLVIA16 and is here applied to the IRSN cable fire tests in order to validate properly the SYLVIA software. Such an approach is very useful in fire design of NPPs or some such to predict the fire spread on cable trays including both the thermal properties of cables and the distance separating each tray.

2 | 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: three identical rooms of 120 m³ each in volume (6 × 5 × 4 m³) arranged in a row (referred to as Rooms 1, 2, and 3) and a corridor (Room 0) of 156 m³ in volume (15.6 × 2.5 × 4 m³). Moreover, an upper room (Room 4) of 176 m³ in volume (8.8 × 5 × 4 m³) 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.

Only 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, and was composed of five horizontal ladder-type trays 3 m long, 0.45 m wide, and spaced from each other by 0.3 m (see Figure 3). Each tray was filled with 32 samples of a 2.4-m-long cable. The cable types and characteristics are displayed in 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 m²). 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 mm²). It was centered and located 0.2 m below the lowest cable tray. For all the tests, the sand burner provided an ignition source 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 m³) was 4 h⁻¹. For CFS-1 and CFS-3 tests and 15 h⁻¹ for CFS-2 and CFS-4 tests.

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 Zavaleta and Audouin11 and Zavaleta.12 In support of CFS tests, CFSS tests9 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. These tests constituted reference tests to assess the effect of the confinement on the fire source in the CFS tests.

A semi-empirical model of horizontal cable tray fire in a well-confined and mechanically ventilated enclosure has been developed and implemented in the SYLVIA software. This model is derived from the FLASH-CAT model,14 developed for horizontal cable tray fires in open atmosphere. The implemented model differs from FLASH-CAT in the expressions of the (1) flame spread velocity along cables, (2) upward fire propagation in the cable tray stack, and (3) 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 fire heat release rate.

### 3 Horizontal Cable Tray Fire Modeling

#### 3.1 Heat release rate

A useful correlation for estimating the HRR generated by a burning cable tray is given in NUREG-1805,17 which specifies the 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 Lee18 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

\[
\dot{Q}_{fs} = 0.45 \times S \times \dot{q}_{bs}^{0.25}
\]

where \(\dot{Q}_{fs}\) is the peak full-scale HRR, \(S\), the total burning area of cables involved in the fire at the peak full-scale HRR, \(\dot{q}_{bs}\), the peak bench-scale HRR per unit area, under 60 kW.m⁻² irradiance, and 0.45, an empirical constant.
Due to the lack of available models for the fire spread on large-scale cable trays in the literature, Lee’s correlation, linked with geometric consideration (ie, the assessment of burning area of cables), is used at each instant to simulate the flame propagation on the cable tray. According to Equation 1, the mass loss rate (MLR) of the fuel under well-ventilated conditions is then given by

\[ \dot{m}_{c,'}(t) = 0.45 \frac{q^{\prime \prime \prime}}{\Delta H_{C}} \sum_{i} S_i(t) \]  

(2)

where \( \dot{m}_{c,'}(t) \) is the fuel MLR under well-ventilated conditions, \( \Delta H_{C} \), the heat of combustion under well-ventilated conditions, and \( S_i(t) \), the burning surface area of cables for the cable tray number \( i \).

Fires in confined and ventilated compartments often lead to a significant decrease in MLR (and thus in HRR) compared to the one obtained in open atmosphere (ie, well-ventilated conditions). This decrease is mainly due to the reduced heat transfer from the flame to the fuel surface as the oxygen is depleted in the room, because of the air renewal rate that can be quite low compared to the kinetics of oxygen consumption by the fire source. The under-oxygenation of the fire source is taken into account in the model by applying a correction factor to MLR. In these conditions, HRR is written as

\[ Q(t) = \dot{m}_{c,'}(t) \chi(O_2) \Delta H_{C} \]  

(3)

where \( \Delta H_{C} \) is the effective heat of combustion and \( \chi(O_2) \), a correction factor representative of the rate of decrease of the pyrolysis rate with oxygen depletion (see Section 4.2).

By inserting Equation 2 in Equation 3, HRR is expressed as

\[ \dot{Q}(t) = 0.45q^{\prime \prime \prime}_0 \chi(O_2) \frac{\Delta H_{C}}{\Delta H_{C}} \sum_{i} S_i(t). \]  

(4)

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

### 3.1.1 Cable burning surface area

For a given cable tray, the surface area of cables in contact with the surrounding gas depends on the number of cables present and on their packing configuration (stacking density). For a small number of cables, this surface area is assumed equal to the total surface area of cables. When the number of cables becomes high, 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 area in contact with the surrounding gas corresponds to the free surface area of the cable sheet. In order to take into account the stacking density of the cables in the estimation of the total burning surface area of cables, a correction factor (\( \alpha \)) is applied to the total surface area of cables when the number of cables becomes high. Thus, the instantaneous burning surface area of cables per cable tray can be written as

\[ S(t) = \alpha \pi n d (x_b(t) - x_e(t)) = p (x_b(t) - x_e(t)) \]  

(5)

where \( n \), the number of cables per cable tray, \( d \), the diameter of cables, \( x_b(t) \), the abscissa of the flame front, \( x_e(t) \), the abscissa of the extinction front, and \( p \) the total perimeter of the cables in contact with the surrounding gas.

The abscissa of the flame front is given by

\[ x_b(t) = L_0 + \int_{t_0}^{t} v_b(t) dt \]  

(6)

and the abscissa of the extinction front is given by

\[ x_e(t) = x_b(t) - \int_{t_0}^{t} v_b(t) dt \]  

(7)

where \( v_b(t) \) is the flame spread velocity, \( t_i (x_e) \) denotes the crossing time of the flame front at the abscissa \( x_e \), and \( t_e (x_e) \) one of the extinction fronts 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

\[ \int_{t_0}^{t_e(x)} \dot{m}_{c,'}(O_2) \chi(O_2) dt = m_{c,\text{unit}} \]  

(8)

where \( \dot{m}_{c,'} \) is the fuel mass loss rate per unit surface and \( m_{c,\text{unit}} \) the mass of the fuel per unit length.

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

### 3.1.2 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 tray fires in an open atmosphere. Indeed, the increase of the temperature of the gas surrounding 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 area of cables. The flame spread velocity can be estimated by dividing the fuel distance heated by the flames by the time to ignition. From the Quintiere formulation of the flame spread velocity in open atmosphere, based on a thermally thick behavior of the material, we apply

\[ v_h(t) = \frac{\Delta H_{C}}{c_m h} \]  

(9)
a time dependence to the ambient gas temperature for confined fires and a correction factor ($\chi$) to the incident heat flux from flames to fuel surface to take into account the decrease of the heat flux with the depletion of oxygen in the compartment:

$$v_b(t) = \frac{4 (\dot{q}_{\infty} \chi(O_2))^2 \delta_c}{\pi (k p_c_\rho) (T_{\text{ign}} - T_{\text{amb}}(t))^2}$$  \hspace{1cm} (9)

where $\dot{q}_{\infty}$ is the incident heat flux from flames to the fuel surface in well-ventilated conditions, $\chi(O_2)$, the oxygen limiting law, $\delta_c$, the heated fuel distance, $k p_c_\rho$, the thermal inertia of cables, $T_{\text{ign}}$, the ignition temperature of cables, and $T_{\text{amb}}$, the ambient gas temperature.

For horizontal cable tray fires in well-ventilated conditions, a value of 70 kW.m$^{-2}$ for the incident heat flux from flames to the fuel surface ($\dot{q}_{\infty}$) and a value between 1 and 2 mm for heated fuel distance ($\delta_c$) are recommended in\textsuperscript{14}. Simulations were performed with a value of 2 mm for $\delta_c$. This value was calibrated to obtain the recommended values given in NUREG/CR-6850\textsuperscript{14} for flame spread velocities of PVC and XPE cables in horizontal cable trays in open atmosphere (0.9 mm.s$^{-1}$ for PVC cables and 0.3 mm.s$^{-1}$ for XPE cables). These values were obtained from PVC cables with a thermal inertia of 0.34 kW$^2$.s.m$^{-2}$.K$^{-2}$ and from XPE cables with a thermal inertia of 0.45 kW$^2$.s.m$^{-2}$.K$^{-2}$.

At the ignition point of the cable tray, the flame spreads symmetrically on both sides of the ignition region of the cables in the model.

### 3.1.3 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 $35^\circ$ with the vertical direction\textsuperscript{14,19} (see Figure 5). The assumption of the $35^\circ$ 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 a three-conductor XPE cable\textsuperscript{14}.

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:

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

where $h$ is the tray elevation measured from the bottom of the lowest tray and $\beta$ 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 the “minute rule”) is not appropriate since the increase of the temperature of the gas surrounding the cables tends to reduce the preheating time of cables. Moreover, this rule does not take into account the distance between cable trays nor the fuel properties, depending on whether cables are thermoplastic (PVC cables) or thermostat-like (mineral flame-retardant cables). In order to have a more accurate simulation of the upward fire propagation in a cable tray stack, a secondary fire-source model is then used in SYLVIA. Each cable tray is modeled as an independent fire source. A thermally thick target, directed down, whose thickness corresponds to the thickness of cables sheath, is set at the supposed ignition zone of each cable tray. This target exchanges with the surrounding gas by convective and radiative heat transfers and by conductive heat transfer in its thickness (1D Fourier’s equation with an adiabatic internal face). The ignition of the cable tray is then operated on a temperature criterion, corresponding to the temperature of the mesh in contact with internal face of the target. Thus, the ignition time of cables is related to the fuel properties, to the ambient conditions and to the incident heat fluxes.

According to Mowrer and Williamson\textsuperscript{20} a value of 218°C is set for the ignition temperature of PVC cables against 330°C for mineral flame-retardant cables. 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. Thermophysical properties of sheath materials of cables tested in CFS tests are given in Table 2. Properties were only obtained at room temperature by using a helium Pycnometer for density measurement, a Perkin Elmer differential scanning calorimetry for thermal conductivity measurement, a Proceq X1001 for thermal conductivity measurement, a Proceq X1001 for thermal conductivity measurement, a Proceq X1001 for thermal conductivity measurement.

### Table 2 Thermophysical properties of sheath materials of cables (no data available for the cable sample tested in CFS-1 test)

| 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$^{-2}$.K$^{-2}$) |
|-----------------------------|---------------------------------------------|----------------------|-------------------------------|-----------------------------------------------|
| CFS-2                       | 0.156                                       | 1336                 | 1280                          | 0.27                                          |
| CFS-3-4                     | 0.382                                       | 1476                 | 1540                          | 0.87                                          |
specific heat measurement, and a Laser Flash apparatus for heat diffusivity measurement. Measurements were carried out in vacuum. Thermal conductivity was then deduced from values of heat diffusivity, density, and specific heat.

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. The fire spread angle of 35° recommended by the NUREG/CR-685014,18 was not reproduced; values less than 10° were obtained. The difference could be explained by the presence of an insulated side wall supporting the cable trays which tends to reduce the ignition time of the cables by increasing the temperature of the gas surrounding the cables. 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.

3.2 | 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 oxygen diffusion rate in the reactive zone or the heat transfer rate due to the overconsumption of oxygen (flame poisoning).

Halogenated 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 oxygen diffusion rate in the reactive zone or the heat transfer rate due to the overconsumption of oxygen (flame poisoning).

\[
\text{HX} + \text{HO} \rightarrow \text{H}_2\text{O} + \text{X}^- 
\]

Thus, the most energetic free radicals of the flame (HO· and H) are replaced by X radicals of lower energy. Here, X mainly refers to 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 retardants 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:

\[
2\text{Al(OH)}_3 \rightarrow \text{Al}_2\text{O}_3 + 3\text{H}_2\text{O} \quad (+298 \text{kJ.mol}^{-1}) 
\]

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, at 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 heat up of the fuel surface and, then, to a slower flame spread velocity. The mass loss due to the dehydration reaction is not modeled in SYLVIA.

The chlorine contained in the PVC cables causes a reduction of the effective heat of combustion due to the inhibition reactions occurring in the flame that consume oxygen (flame poisoning).

Chemical reactions occurring during the burning of cables are complex. They depend on the nature of the fuel as well as on the oxygen content in the gas close to the fuel. In SYLVIA, a one-step irreversible combustion reaction, expressed in terms of mass, is used as

\[
1 \text{ kg of fuel} + v_{\text{O}_2} \text{O}_2 \rightarrow v_{\text{CO}_2} \text{CO}_2 + v_{\text{CO}} \text{CO} + v_{\text{H}_2\text{O}} \text{H}_2\text{O} + v_{\text{CH}_4} \text{CH}_4 + v_{\text{C}} \text{C} 
\]

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, due to lack 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. Yields of combustion are obtained experimentally by dividing the mass of the released species by the mass of pyrolysed fuel (see Table 3 for the CFS cable fire tests performed in DIVA). Since the amount of water vapor is not measured experimentally (condensable species), the coefficient related to this species is determined by the mass balance of the reaction. Yield of oxygen consumption is given by

\[
v_{\text{O}_2} = \eta \frac{\Delta H_{\text{O}_2}}{\Delta H_{\text{H}_2\text{O}}} 
\]

where \(\Delta H_{\text{O}_2}\) is the heat released per kilogram of consumed oxygen (set to 13.1 MJ kg\(^{-1}\)) and \(\Delta H_{\text{H}_2\text{O}}\), the effective heat of combustion (user data).

A correction factor, \(\eta\), is applied to the yield of oxygen consumption of PVC cables to take into account the overconsumption of oxygen by inhibition reactions. A coarse estimation of this correction was performed on the CFS tests. For mineral flame-retardant cables, the mean value of the heat of combustion obtained in the DIVA facility with an air renewal rate of 15 h\(^{-1}\) is equivalent to the one obtained in open atmosphere, under the SATURNE 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 not significant at this level of ventilation. For PVC cables, the mean value

| Test  | \(v_{\text{O}_2}\) (g.g\(^{-1}\)) | \(v_{\text{CO}_2}\) (g.g\(^{-1}\)) | \(v_{\text{CO}}\) (g.g\(^{-1}\)) | \(v_{\text{H}_2\text{O}}\) (g.g\(^{-1}\)) | \(\Delta H_{\text{H}_2\text{O}}\) (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             |
of the heat of combustion obtained in the DIVA facility with an air renewal rate of 15 h\(^{-1}\) is lower than the one under the calorimetric hood (12.5 MJ.kg\(^{-1}\) for CFS-2 test against 16 MJ.kg\(^{-1}\) for CFSS-4 test). Assuming that the decrease of the heat of combustion in the DIVA facility is attributed to the action of halogens (no oxygen depletion in open atmosphere due to inhibition reactions), the correction factor to be applied to the yield of oxygen consumption of the combustion reaction is 1.3 (ratio of the heat of combustion under the calorimetric hood to the one obtained in the DIVA facility).

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

4.1 | The two-zone model SYLVIA

The model of horizontal cable tray fire was implemented in the SYLVIA software\(^{16}\) developed at IRSN. This software is designed to predict the behaviors of mechanical/natural ventilation, fire growth, hot gas and smoke propagation, and airborne contamination transfer in confined and mechanically ventilated enclosures. Indeed, it is a simulation tool for calculating the consequences of multi-compartment fires in industrial and nuclear facilities, which are equipped with a full ventilation network (including ducts, room leaks, fire dampers, fans, horizontal/vertical openings, filters ...).

The fire design of the SYLVIA software belongs to the well-known two-zone fire modeling.\(^{24,25}\) In such software, each compartment is described with two Lagrangian control volumes separated by a thermal interface (see Figure 6). Mass and energy balances are performed in each zone: the lower zone simulating the fresh gas and the upper zone, simulating the combustion products and the gas entrained by the plume. In a two-zone approach, a plume feeds the upper zone of the fire room, whose volume increases, which has the effect of lowering the interface and leading to the under-oxygenation of the fire source 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. The features of ambient quantities (pressure, temperature, mass fraction of species) in each control volume are assumed to be uniform at a given time. These control volumes can be connected by various ventilation components representing either natural or mechanical ventilation. The convective/conductive/radiative heat transfers inside the compartments and in the ventilation network (walls, gas phase) are fully modeled and play a major role for predicting temperature and pressure, especially in rooms and ventilation ducts near the fire. The fire itself is described by correlations (plume, flame height...) available in the literature.\(^{24,25}\) Furthermore, the SYLVIA software has additional specific models for simulating a water spray system, the condensation/adsorption of gaseous species (as water vapor) on walls, and the transport and deposition of aerosol particles (soot, dust) on solid surfaces as ventilation ducts, room walls, or high efficiency particulate air filters.

The design of ventilation network is based on the node-and-branch method.\(^{26}\) A node is a point (no volume) or a simple zone (with a fixed volume) in the ventilation network, where the different physical quantities (pressure, temperature, particle, and gaseous species mass fractions...) are considered uniform. A point can be considered as a simple junction between two or more ducts or linked with an exterior environment (boundary condition node). A zone, which leads to inertial effects under transient conditions due to the fixed volume, may involve a single room (as the fire compartment) or a node between two branches. A branch represents a passive element of the network (for instance, pipe, filter, fire damper, leak...) or an active element (for instance, fan, motor-driven valve...). A mass flow rate is assumed to be uniform in OD branches and is a function of the pressure difference at its boundaries (nodes). A given branch is always connected to two nodes, but there is no limit on the number of branches connected to a given node. Pure aeracual simulations in connection with the ventilation requirements (design of ventilation networks, aeracual balancing, studies of the wind effect on airborne contamination transfer and their release to the environment ...) are possible with the SYLVIA software.\(^{27}\) For more details about the SYLVIA modeling, see Plumecocq et al.\(^{16}\)

4.2 | Input data of the model

A modeling of the ventilation network of the DIVA facility was performed with SYLVIA in order to reproduce at best the experimental aeracual resistivity of the ventilation network of the CFS tests in the simulations (see Figure 7). The various nodes and branches of the modeled ventilation network correspond to aeracual elements for which one or more experimental measurements were performed (pressure, temperature, volume flowrate). In order to prevent some errors for the dataset of the ventilation network, the characteristic of the DIVA ventilation network is processed by means of the experimental data obtained from tests in operating conditions, just before the fire ignition. Of course, the fire scenario definition is achieved in SYLVIA by defining the compartment equipment, the fire source, and the wall properties (possible presence of insulation layers), these features being specific for each test.

The plume model of Heskestad\(^{28}\) was used in the simulations, including the mirror effect to take into account the effect of the side wall in support of cable trays in the CFS tests on the plume flow rate.
According to Hasemi,\textsuperscript{29} plume modeling by a quasi-circular fire source approach is reasonable as long as the ratio length of the fire source/width of the fire source < 3. Given the mirror effect, the width to be considered is twice the width of the cable tray, i.e., 0.9 m. It is deduced that the approach taken in the paper is reasonable up to $3 \times 0.9$ m, i.e., 2.7-m length of cable tray under the flames, which represents a value greater than the total length of the cable tray considered in the CFS tests (2.4 m). Moreover, given the flame spread, the extinction front, starting from the central zone of the path, generally appears before the flame front reaches the ends of the cable tray. Thus, the quasi-circular fire source approach remains reasonable throughout the simulation.

Simulations of the CFS tests have been performed using the oxygen-liming law, $\chi(O_2)$, proposed by Peatross and Beyler.\textsuperscript{30} This law is a linear function of the fuel MLR according to the oxygen volume fraction available for combustion close to the fuel (see Figure 8). In SYLVIA, the oxygen volume fraction available for combustion is evaluated according to the flame height, the elevation of fire source in the compartment, and the interface between the fresh gases of the lower zone and the combustion gases of the upper zone. The flame is supplied by oxygen volume fraction available in the zone where the flame is located. In the case where the interface height is in the flame area, this oxygen volume fraction is calculated from the oxygen fractions of the two zones, by a weighting ratio of the flame lengths crossing the lower and upper zones. However, no extinction modeling is used in this work.

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

Bench-scale HRR measurements performed on cable samples\textsuperscript{32} and full-scale heat of combustion in open atmosphere are reported in Table 5.

Thermal inertia of PVC cable samples tested in CFS-1 test is not known. This one was fitted in a way to reproduce the kinetics of the

| TABLE 4 | Mass per unit length of the cable components |
|---------|---------------------------------|
| **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 5 | Bench scale HRR and full-scale heat of combustion under well-ventilated conditions |
|---------|---------------------------------|
| **Cables** | $q_{in}$ (kW.m$^{-2}$) | $\Delta H_{foc}$ (MJ.kg$^{-1}$) |
| CFS-1 | 270 | 22 |
| CFS-2 | 234 | 16 |
| CFS-3-4 | 184 | 27 |
gas temperature increase in the fire room (see Figure 10). A value of 0.10 kW².s⁻¹.m⁻⁴.K⁻² was found.

4.3 Results and discussion

The results of the CFS test simulations for the heat release rate, pressure, and mean gas temperature in the fire room are presented in Figures 9–11. These results are compared to experimental data, including experimental uncertainties.

The relative uncertainty of the measurement, \( \tilde{u} \), of a temperature, pressure ... or that of the assessment of a fire characteristic, such as the heat release rate, may be defined as followed:

\[
\tilde{u} = \frac{u}{R}
\]

(16)

where, \( u \) is the uncertainty (standard deviation) of the measurement or assessment and \( R \) its result expressed in the corresponding unit. \( u \) is estimated by combining the individual standard uncertainties, such as the instrument uncertainty and the repeatability, using the usual method called the “law of propagation of uncertainty.” Furthermore, the uncertainty is often expressed in terms of an expanded uncertainty, in which the confidence level that the measurement or the assessment falls within the expanded bounds is high. For an expansion factor (or coverage factor) of 2, here considered, the expanded relative uncertainty of the measurement or assessment, \( \tilde{u} \), is thus related to two relative standard deviations (2\( \tilde{u} \)) and the confidence level corresponds to 95%. Table 6 gives the expanded relative uncertainty evaluated or assessed for some measurements and assessments carried out as part of the PRISME-2 CFS test campaign. The evaluation of the uncertainty for the HRR is detailed in Zavaleta and Audouin for the CFS-3 and 4 fire tests and in Zavaleta for the CFS-1 and CFS-2 fire tests.

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 9. Several explanations for these deviations are put forward. (1). The Peatross and Beyler’s oxygen-limiting law used in the simulations was established for liquid fuels. For pool fires in a highly under-ventilated environment, the flame tends to move away from the horizontal fuel surface when it is close to extinction (ghosting flame). For solid fuel fires, buoyancy forces force the flame to stay close to fuel materials because of their vertical distribution. In addition, due to their high thermal inertia, the pyrolysis rate of solid fuels decreases more slowly than liquid fuels when the heat flux from the flame to the fuel surface decreases. (2). The setup 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). (3). In a zone model approach, an interface separates the hot gas layer from the cold one. For CFS-4 test performed with mineral flame-retardant cables at high renewal rate (15 h⁻¹), the interface stabilizes 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 HRR. (4). The large dispersion...
FIGURE 10  Pressure predictions in the fire room for CFS tests

FIGURE 11  Mean gas temperature predictions in the fire room for CFS tests
of the fuel inside the fire room is favorable to a production of pyrolysed gas in excess. CFS-1 to CFS-3 tests led to a significant production of pyrolysed gas in excess and its combustion in the upper part of the fire room. These instabilities of combustion are not reproduced by the calculations in lack of a model of pyrolysed gas in excess in SYLVIA.

The delay in the power rise due to the effect of the reaction of dehydration for mineral flame retardant cables is not reproduced by the calculations for CFS-3 and CFS-4 tests, as shown in Figure 9 for the initial increase in HRR. Add to this, 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 mainly 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.

The comparison between the CFS-1 and CFS-3 experimental data and numerical results (Figure 9) appears to be satisfactory about up to 1000 and to 5000 s for CFS-1 and CFS-3, respectively. Beyond these times, the HRR are significantly overestimated because no modeling is used to predict the fire extinction due to a lack of oxygen, as observed during the fire tests (see Table 7). Indeed, this extinction can be explained by the low ventilation rate of the fire compartment. Moreover, only 82% and 73% of mass loss were burned during the CFS-1 and CFS-3 experiments, respectively, while all the mass of combustible is consumed in the simulations.

Pressure rise in the fire room mainly depends on the ratio between the fire heat release rate and the dissipated and evacuated heat rates. At the beginning of the fire, heat dissipation by walls is low because of their inertia, which results in a rise in pressure of the fire room. The resulting pressure peak is quite well reproduced by the calculations for CFS-1 and CFS-3 tests, as shown in Figure 10. The highest pressure peak value is predicted for CFS-1 test (23 hPa in the simulation against 14 hPa experimentally), this test involving cables with the highest 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 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. This test involved halogenated cables and was performed at high air renewal rate (15 h⁻¹). Although the chemical reaction module of the SYLVIA software was activated in the calculations to simulate the combustion of unburned gases, given the production of methane in the combustion reaction (see Equation 14), no combustion of unburned gases was predicted in lack of a model of pyrolysed gas in excess in SYLVIA.

The hot column of gas 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 remove all the gases supplied by 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 11. Deviations are mainly due to the combustion of pyrolysed gas in excess, not reproduced by the calculations. For CFS-4 test, the more important deviation is mainly explained by the deviation on the predicted HRR.

### 5 | CONCLUSION

IRSN cable tray fire tests were carried out both in open atmosphere and into the confined and mechanically ventilated DIVA facility. 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 flames to the surface area of the fuel. 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 production of pyrolysed gas and their consequences.

A semi-empirical model of horizontal cable tray fires in a well-confined and mechanically ventilated enclosure has then been developed. This model is partly based on the approach used in FLASH-CAT and on experimental findings from the IRSN tests. The model was implemented in the two-zone model SYLVIA. Except for the instabilities of combustion (CFS-3) and for the fire duration due to the extinction by lack of oxygen (CFS-1 and CFS-3), the major features of the compartment fire experiments, such as characteristic HRR, pressure, and mean gas temperature could then be reproduced with in general acceptable errors. Indeed, CFS test predictions have

### TABLE 6
Expanded relative uncertainty, ū, of the pressure and gas temperature measurements and HRR assessment of the PRISME-2 CFS experiments

| Measurement                                      | Sensor Type                    | ū (%) |
|-------------------------------------------------|--------------------------------|-------|
| Gas temperature in the fire room (°C)            | 1.5-mm K-type thermocouple     | 5     |
| Differential pressure between rooms and outside (pa) | Pressure transmitters           | 1     |

### TABLE 7
Extinction of fire source

| Test    | Air Renewal Rate [h⁻¹] | Mass Loss [%] | Fire Extinction  |
|---------|------------------------|---------------|-----------------|
| CFS-1   | 4                      | 82            | Lack of oxygen  |
| CFS-2   | 15                     | 100           | Lack of fuel    |
| CFS-2   | 4                      | 73            | Lack of oxygen  |
| CFS-4   | 15                     | 100           | Lack of fuel    |
shown up to 30% error on the maximum value of the mean gas temperature for halogenated and mineral flame-retardant cables, 50% error on the pressure peak for mineral flame-retardant cables against 20% error for halogenated cables (outside instabilities of combustion), and are in the range of experimental uncertainties of the HRR peak for halogenated cables against a factor 2 for mineral flame-retardant cables.

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 cable tray 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. Moreover, the modeling of fire extinction should be considered in the simulations of fire scenarios with low ventilation rate in order to predict properly the fire duration, the HRR, and the mass loss of fuel.

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