Modelling of Electrical Cabinet Fires based on the CARMELA Experimental Program

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Abstract:
As fire of electrical cabinets causes some hazard to nuclear safety, IRSN has conducted the CARMELA program to investigate this topic. The program was carried out in three stages. The two first stages consisted in analytical experiments where the combustible was simulated by thin plastic pieces and where the different parameters that influence the fire could be easily varied. The third stage involved real relay cabinets. This article first describes the experimental facility and the test matrix. The phenomenology of electrical cabinet fires is then exposed and the most influencing parameters are identified from the analytical experiments: the ventilation comes at first rank but the materials involved are also shown to influence the propagation of the fire. The model developed to represent the fire, and particularly the rate of heat released, is then presented and the comparison of its results with the measurements performed in the experiments shows that its validity is acceptable.

1 INTRODUCTION

The feedback from fire reports in nuclear power plants attests that a large number of fires originate from an electrical or an electronic cabinet. A preliminary Fire-PSA study has shown that the hazard represented by electrical cabinet fires contributed to some extent to the probability of core damage. One reason is that the cabinet can have a safety function that is lost due to the fire: a dysfunction temperature threshold of 40°C is usually assumed. Another cause is the fire hazard itself: heat and toxic smoke are released so that the entire room can quickly become unapproachable to man, which can hinder the safe operations of the facility, for example when the fire occurs in a room devoted to control/command operations. Eventually, adjacent equipments or cables present in the room can also fail due to thermal or chemical agression. Some experiments were already conducted. However, this hazard is not yet precisely quantified and that was the objective of the CARMELA program carried out by IRSN from 2000 to 2003: to give some insight to the mode of combustion of an electrical cabinet and to provide a model that can be used to calculate the scenarii of fire-PSA.

The electrical cabinets present in a NPP are at first characterized by their diversity: the geometry vary from small cubes to large racks of several meters; the ventilation system presents openings covering a large span of sections; the load of electrical components inside the cabinets is highly variable; the electrical components themselves (wires, relays, circuit breakers, transformers...) are in different proportions and present various layouts.

To cope with this diversity, an analytical approach has been chosen. A first step consisted in determining the governing geometrical factors. This led to a first model that was refined during the second step, devoted to the combustible. A third validation step involved real cabinets. Besides, some additional tests were conducted (material characterization, head
loss measurements, study on mixture of materials) to provide the model with closure relationships. The facility and the experiments are first described; a phenomenological overview of the fire of electrical cabinets is then provided; eventually, the modelling is presented and its validation against the CARMELA experimental is discussed.

2 THE CARMELA FACILITY AND TESTS

2.1 Experimental device

The CARMELA program was designed to study the combustion of full-length electrical cabinets. The experiments consisted in a piloted ignition of the combustible material inside the cabinet: a propane burner generally situated at the bottom of the combustible and in the middle of the cabinet provided the pilot flame; it was shut off after ignition was confirmed (usually after 2mn or so). The fire was then allowed to develop freely until its natural extinction. The cabinets were disposed in a large ventilated enclosure so that the influence of the environment on the fire can be supposed to be negligible. Above the cabinet, a 3m diameter hood collected the combustion products for filtering and analysis. The cabinets were out of steel, their dimensions did not vary: 2m high, 0.8m wide and 0.6m deep. Two openings allowed for air admission in the box: the inlet one was situated at the bottom of the front wall and the outlet one was situated either at the center of the roof (first series of experiments) or at the top of the back wall (second and third series). During the fire, the door of the cabinets was locked.

![Electrical cabinet under the hood.](image1)

![Example of layout of the combustible inside the cabinet.](image2)

2.2 Test matrix

The first series of tests investigated the geometrical parameters of the cabinets. A plate of polymethyl-metacrylate was used to simulate the combustible: this material burns easily and
its properties are very well known. The plate was 1.5m x 0.7m x 8mm and was positionned vertically at the center of the cabinet. The table 1 hereunder displays the main features of the first series. In the tests CAA401, CAA402 and CAA403, two steel horizontal plates were located inside the cabinet, partially obstructing the flow. In the tests CAA501, CAA502 and CAA503, two hollow steel volumes were positioned against the lateral walls inside the cabinet. Some of the tests were conducted two times in order to check the repeatability of the results.

<table>
<thead>
<tr>
<th>Test</th>
<th>Inlet [m²]</th>
<th>Outlet [m²]</th>
<th>Inside plate width [mm]</th>
<th>Inside volume width [mm]</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>CAA102</td>
<td>0.1</td>
<td>0.1</td>
<td>-</td>
<td>-</td>
<td>2 tests conducted</td>
</tr>
<tr>
<td>CAA103</td>
<td>0.05</td>
<td>0.1</td>
<td>-</td>
<td>-</td>
<td>2 tests conducted</td>
</tr>
<tr>
<td>CAA104</td>
<td>0.025</td>
<td>0.1</td>
<td>-</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>CAA105</td>
<td>0.0175</td>
<td>0.1</td>
<td>-</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>CAA106</td>
<td>0.025</td>
<td>0.05</td>
<td>-</td>
<td>-</td>
<td>2 tests conducted</td>
</tr>
<tr>
<td>CAA107</td>
<td>0.0075</td>
<td>0.05</td>
<td>-</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>CAA201</td>
<td>0.025</td>
<td>0.1</td>
<td>-</td>
<td>-</td>
<td>Ignition at mid-height</td>
</tr>
<tr>
<td>CAA301</td>
<td>0.025</td>
<td>0.1</td>
<td>-</td>
<td>-</td>
<td>Half plate: 0.7m x 0.75m x 8mm</td>
</tr>
<tr>
<td>CAA401</td>
<td>0.025</td>
<td>0.1</td>
<td>90</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>CAA402</td>
<td>0.025</td>
<td>0.1</td>
<td>150</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>CAA403</td>
<td>0.025</td>
<td>0.1</td>
<td>270</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>CAA501</td>
<td>0.025</td>
<td>0.1</td>
<td>90</td>
<td>-</td>
<td>2 tests conducted</td>
</tr>
<tr>
<td>CAA502</td>
<td>0.025</td>
<td>0.1</td>
<td>184</td>
<td>-</td>
<td>3 tests conducted</td>
</tr>
<tr>
<td>CAA503</td>
<td>0.025</td>
<td>0.1</td>
<td>278</td>
<td>-</td>
<td></td>
</tr>
</tbody>
</table>

**Table 1: Test matrix of the first series.**

The second series of experiments investigated the influence of the combustible. 105 squares of 10cm x 10cm x 8mm each were mounted on steel shafts and positionned inside the cabinet to form the desired layout: a plate (squares disposed side by side to constitute a vertical plate), shelves (see figure 2), cable-tray (15 squares disposed as a vertical narrow band in front of a 90-squares plate) or dispersed (squares disposed uniformly all over the volume of the cabinet). Polymethyl-methacrylate (PMMA), polystyrene (PVC) and polyethylene (PE) were used as combustible materials. The table 2 hereunder displays the characteristics of this second series. The section of the openings were 0.025 m² at inlet and 0.1 m² at outlet, except for test CAB102 where it was 0.05 m².

<table>
<thead>
<tr>
<th>Test</th>
<th>Layout</th>
<th>Vol% PMMA</th>
<th>Vol% PVC</th>
<th>Vol% PE</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>CAB101</td>
<td>plate</td>
<td>100</td>
<td>-</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>CAB102</td>
<td>plate</td>
<td>100</td>
<td>-</td>
<td>-</td>
<td>Outlet section 0.05 m²</td>
</tr>
<tr>
<td>CAB201</td>
<td>shelves</td>
<td>100</td>
<td>-</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>CAB202</td>
<td>cable-tray</td>
<td>100</td>
<td>-</td>
<td>-</td>
<td>Ignition at bottom of the narrow band</td>
</tr>
<tr>
<td>CAB203</td>
<td>dispersed</td>
<td>100</td>
<td>-</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>CAB301</td>
<td>plate</td>
<td>50</td>
<td>50</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>CAB302</td>
<td>shelves</td>
<td>29</td>
<td>71</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>CAB303</td>
<td>plates</td>
<td>29</td>
<td>42</td>
<td>29</td>
<td></td>
</tr>
<tr>
<td>CAB304</td>
<td>plate</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Table 2: Test matrix of the second series.**

The third series of experiments consisted in two tests involving two identical relay cabinets. Their dimensions were 2m high, 0.8m wide and 0.6m deep. The inlet opening was 0.025 m² and the outlet was 0.1 m². The table hereunder depicts the content of the cabinet.
<table>
<thead>
<tr>
<th>Material</th>
<th>Total Mass [kg]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Circuit breaker</td>
<td>0.43</td>
</tr>
<tr>
<td>PVC Jackets</td>
<td>9</td>
</tr>
<tr>
<td>Wire 1.5mm</td>
<td>7.58</td>
</tr>
<tr>
<td>Wire 4mm</td>
<td>12.86</td>
</tr>
<tr>
<td>Terminal box</td>
<td>1.34</td>
</tr>
<tr>
<td>Relay</td>
<td>4.76</td>
</tr>
<tr>
<td>Contactor</td>
<td>10.3</td>
</tr>
</tbody>
</table>

*Table 3: Content of relay cabinets.*

2.3 Instrumentation

The experiments were instrumented so as to allow a full interpretation of the combustion in terms of heat generation, heat exchanges and chemistry. In the exhaust duct downstream of the hood, all the combustion products were sampled and analysed. The measurements included oxygen, carbon monoxide, carbon dioxide and water vapour concentrations. From these data, the method of Janssens\(^5\) allows the determination of the power released by the combustion. Thermocouples were placed inside the cabinets and on the outside walls. Fluxmeters indicated the radiative heat fluxes emitted by the cabinets. Besides, for the second and third series of experiments, an infrared camera gave indications of temperatures, radiated fluxes and emissivities of one side wall. A weighing machine was used to estimate the rate of mass loss of the combustible: during the first series of experiments, it was only weighing the PMMA plate and the measure became pointless as the plate was loosing its geometry; to cope with this problem, for the following series, the weighing machine was supporting the whole cabinet.

3 PHENOMENOLOGY OF ELECTRICAL CABINET FIRES

The combustion of electrical cabinets revealed itself usually remarkably reproducible. This observation opens the way to a phenomenological description of the fire. Generally speaking, once ignited, the fire develops until large involvement of the combustible materials inside the cabinet. As the temperatures increase, the thermal degradation of plastic materials causes large amounts of smoke to be released from the outlet opening; the steel sides of the cabinet become glowing red, a visible sign that temperatures up to 600°C are attained. The rate of heat delivered by the combustion is much dependent on the conditions of the experiments: the range is from tens of kilowatt to megawatt released.

3.1 Chronological description of fires

Five stages can be distinguished during the fire, as is shown for test CAA104 in figure 3 hereunder.

3.1.1 Incubation stage

The incubation stage starts from ignition and is characterized by a relatively low rate of heat release and a slow progression of the fire. The temperatures inside the cabinet increase quickly but the steel walls remain cold.
3.1.2 Fast spread stage
At some point, the spread of the fire increases drastically. This instant can be compared to a flashover phenomenon: the flame that is often visible at the outlet vent as well as increasing wall temperatures indicate that most of the content of the cabinet is surrounded by hot temperatures.

3.1.3 Combustion outside the cabinet
As the fuel involved in the combustion increases, the amount of combustible that is pyrolysed exceeds the quantity that can react with the oxygen available from venting; the combustion becomes under-ventilated. In some experiments (those of the first series with the exception of the test CAA107), the products of combustion leaving the outlet vent are hot enough and rich enough in unburnt fuel vapours to re-ignite as they mix to fresh air; a flame then appears outside the cabinet on the outlet ventilation opening. In the experiments of the second and third series, no such flame was visible but the mass loss measurements show that the combustible was pyrolysed in excess with regard to the oxygen available; the location of the outlet opening could have been responsible of some additional cooling of the combustion products thus inhibiting the ignition outside the cabinet.

3.1.4 Steady stage
The steady-state stage of combustion is closely linked to the relocation of molten materials at the bottom of the cabinet. In the first series of experiments, the combustible was composed of a one-piece plate that falls abruptly, causing the extinction of the flame above the cabinet. During the experiments of the second and third series, the combustible was composed of mechanically independent pieces and the power profile is much smoother.

3.1.5 Decay stage
The fire usually ends by lack of combustible, with the exceptions of the test CAA107 where the fall of the plate caused the fire to extinguish and of the test CAB302 and CAB303 where no ignition could be achieved. In the other experiments, a long and smooth decay of the rate of heat released was observed.

![Graph of heat release rate over time](image)

**Figure 3:** Example of fire chronology. Five stages are distinguished.
3.2 Specific phenomena observed

3.2.1 Fast increase of the outlet temperature
For all experiments, a very fast increase of the outlet temperature was observed: within 100s or 200s, the gases leaving the cabinet reach temperatures well over 100°C. This can be of some importance if one considers that electrical materials cannot stand high temperatures: any component inside a cabinet subject to a fire has much chance to fail almost instantly.

3.2.2 Stratification of the wall temperatures during the steady stage
During the steady stage, the hottest temperatures are measured c.a. 30cm from the bottom of the cabinet walls; at higher elevations, the temperatures stabilize to lower values. The reason is most probably that the materials are relocated on the floor and because the heat is generated where the oxygen is available, that is near the inlet vent. Except for the plume of the fire above the outlet vent, the most hazardous zone for a target component is situated rather low: at 30cm elevation, the temperature is over 600°C and the radiated heat fluxes reach values as high as 30 kW/m².

3.2.3 Oxidation of the hot walls lead to increased emissivity
The observation with the infrared camera allowed the determination of the emissivity of the outside walls as a function of time. For polished stainless steel, it is originally around 0.3; however, as the temperature increases some surface oxidation occurs and the emissivity irreversibly increases up to values around 0.7. It should be noted that the emissivity of the painted real cabinets is much higher, around 0.95.

3.2.4 Occurrence of flash-back
During the test CAB201, the combustion became unstable: the fire apparently extinguished by lack of oxygen for a few seconds, followed by a deflagration after fresh air re-entered inside the cabinet. As this phenomenon was not observed again even for rather near configurations, no estimation could be established concerning the associated risk.

3.3 Influence of the analytical parameters
The goal of the analytical experiments of the first and second series was to facilitate the determination of the most influencing parameters on the combustion of electrical cabinets. Three target values of interest were chosen: the maximum rate of heat release, the steady-state rate of heat release and the time to reach flashover.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Peak HRR</th>
<th>Steady HRR</th>
<th>Time to flashover</th>
<th>Tests concerned(a)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Size of openings</td>
<td>++</td>
<td>++</td>
<td>+</td>
<td>CAA102 to CAA107</td>
</tr>
<tr>
<td>Position of ignition</td>
<td>-</td>
<td>-</td>
<td>?</td>
<td>CAA201</td>
</tr>
<tr>
<td>Amount of combustible</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>CAA301</td>
</tr>
<tr>
<td>Inside elements(b)</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>CAA401 to CAA503</td>
</tr>
<tr>
<td>Position of outlet(c)</td>
<td>++</td>
<td>-</td>
<td>-</td>
<td>CAB101 and CAB102</td>
</tr>
<tr>
<td>Layout of combustible</td>
<td>+</td>
<td>-</td>
<td>+</td>
<td>CAB201 to CAB203</td>
</tr>
<tr>
<td>Nature of combustible</td>
<td>+</td>
<td>-</td>
<td>+&lt;sup&gt;(d)(e)&lt;/sup&gt;</td>
<td>CAB301 to CAB304</td>
</tr>
<tr>
<td>Ignition power/duration</td>
<td>-</td>
<td>-</td>
<td>+&lt;sup&gt;f&lt;/sup&gt;</td>
<td>Reproducibility tests</td>
</tr>
</tbody>
</table>

Table 4: Influence of the analytical parameters.
++ Strong influence ; + influence ; - no influence ; ? not decidable.
The table hereabove summarises these influences in the range of the parameters investigated.

Comments:
 a) The reference test is CAA104.
 b) In the tests CAA501 to CAA503, steel volumes were placed in the cabinet and some influence was observed on the three target parameters: higher rates of heat were released and a faster flashover was observed; however this effect is attributed to an insulation effect of the walls and is not judged directly linked to the presence of dead volumes in the box.
 c) The tests CAB101 and CAB102 are compared respectively to the tests CAA104 and CAA106. In the tests CAB101 and CAB102, besides the difference in the outlet vent, the relocation mode of the combustible was also different because the PMMA squares were allowed to melt and flow down independently one from each other; this certainly participates to the influence noticed in the peak heat release rate.
 d) To complement these experiments, normative ignition tests were performed under a cone calorimeter: the time to ignition of different electrical components submitted to an imposed radiative flux was measured and proved to be highly variable; this time to ignition is thought to influence tightly the time to flashover.
 e) The tests CAB302 and CAB303 did not lead to flashover; obviously, there is a crucial effect of the nature of the combustible on the ease to reach flashover.
 f) The repeatability tests performed often presented very different times to flashover. One reason invoked is the little difference in the ignition but it can also be attributed to an intrinsic variability.

As a conclusion, the analytical experiments demonstrate that the most influencing parameter is the size of the openings. The time to flashover depends on many factors and seems somewhat random with regard to the observable parameters.

4 MODELLING OF ELECTRICAL CABINET FIRES

The objective of modelling electrical cabinet fires is to provide a time-dependent description of the rate of heat released by the combustion and of the temperatures of the steel walls as a function of parameters that can be easily estimated such as: the dimensions of the cabinet, the size of the openings and the estimation of the content of the cabinet (this estimation is often given as a rough percentage, e.g. 25% of what is perceived as a “full” cabinet).

4.1 General relationships

4.1.1 Air entrained by chimney effect

The mass flow-rate of air transiting within the box is induced by buoyancy. Assuming a perfect gas law and letting $T$ be the temperature inside the box (supposed uniform), the momentum balance of the air flow inside the cabinet yields:

$$
\frac{1}{2} k_{in} \frac{q_{in}^2}{S_{in} \rho_c} + \frac{1}{2} k_{out} \frac{q_{out}^2}{S_{out} \rho_c} \frac{T}{T_c} + \frac{1}{2} \left[ \frac{T}{T_c} - 1 \right] \frac{q_{in}^2}{S_c^2 \rho_c} = \left[ 1 - \frac{T_c}{T} \right] \rho_c g H \tag{1}
$$

The two first terms of the left-hand side of equation [1] represent the pressure drops at the inlet and outlet openings of the box; the corresponding coefficients $k_{in}$ and $k_{out}$ were estimated for each configuration by blowing cold air into the box thanks to a fan; a correlation was established, yielding values commonly found for turbulent vent flows$^6$. $k_{in} \approx k_{out} \approx 2.8$. The third term of the left-hand side accounts for the acceleration of the fluid due to its
heating: this term is usually negligible but is kept for generality. The viscous wall friction pressure drops inside the box can be shown to be less than 5% of the pressure drops due to vents. The right-hand side of equation [1] accounts for the pressure head due to the density difference between the inside and the outside of the box.

As it was noticed by Mangs & Al, the dependence of equation [1] on T is weak once T>200°C. Therefore a representative value of T = T_f = 800°C is imposed, and one can estimate a steady-state mass flow-rate within the box with an error less than 10%:

\[ q^* = \rho_{\infty} \sqrt{2 g H} \frac{1 - \frac{T_c}{T_f}}{\frac{k_{in}}{S_{in}^2} + \frac{T_f}{S_{out}^2} + \frac{T_f}{S_{out}^2} - 1 \frac{1}{S_{in}^2}} \]  

One should note that \( q^* \) is representative of the flow inside the box as soon as the gas temperature rises at the outlet. In the experiments, this rise occurs very quickly, well before flashover: the gas burner used for ignition is enough to rise the outlet temperature to about 300°C.

4.1.2 Energy balance of the cabinet

An energy balance equation of the cabinet allows the determination of the gas and cabinet walls temperatures:

\[ C_w \frac{d T_w}{dt} = \dot{Q}_c - q^* \epsilon g (T_g - T_w) - (\dot{Q}_c + \dot{Q}_{out}) \frac{\Delta H_{vap}}{\Delta H_c} - S_w h_w (T_w - T_s) - S_w \epsilon w \sigma (T_w^4 - T_s^4) \]  

where the left-hand term represents the thermal inertia of the cabinet; the first term of the right-hand side represents the power released within the cabinet; the second term represents the heat convected out of the cabinet; the third term is the heat necessary for the pyrolysis of the combustible; the fourth term is the heat exchanged by natural convection at the external walls of the cabinet and the fifth term is the energy radiated out by the cabinet walls. Some of the terms of equation [3] are determined according to further physical modelling: depending on the combustion mode (over- or under-ventilated) the gas temperature \( T_g \) is related either to the convected flux as in the open or to the temperature of the cabinet \( T_w \) by considering that an horizontal thermal equilibrium is achieved.

Eventually, a time-solution of the equation [3] is provided by an implicit first-order solver. As the system is represented by a single temperature whatever the elevation, the results are to be interpreted as indicative of the temperature levels achieved.

4.1.3 Mass balance of combustible material

As the fire is assumed to stop when all the combustible has burnt, the amount of combustible material must be calculated. Assuming a constant heat of combustion, the mass balance of the combustible writes:

\[ \frac{dm_{comb}}{dt} = - \frac{\dot{Q}_c + \dot{Q}_{out}}{\Delta H_c} \]  

4.2 Modelling of the rate of heat release

4.2.1 Empirical formulation of fire growth in over-ventilated conditions
The fire spread in the two first stages of the combustion is modelled by a t-squared law, which is a simple but practical way for complex fires\(^7\).
During the first stage (incubation period):
\[
\dot{Q}_c(t) = \alpha_1 t^2 \tag{5}
\]
During the second stage (fast spread):
\[
\dot{Q}_c(t) = \alpha_2 (t - t_i)^2 + \alpha_1 t^2 \tag{6}
\]
Where the incubation time \(t_i\) is the instant separating the first from the second. \(\alpha_1\) and \(t_i\) revealed to be extremely variable and must be provided as an input of the model. Some empirical correlation established from the experiment gives:
\[
\alpha_2 = \beta q^{n/2} \tag{7}
\]
with \(\beta=1800 \text{ W/kg}^2\) for the tests involving PMMA and \(\beta=100 \text{ W/kg}^2\) for real cabinets.

4.2.2 Modelling the under-ventilated heat release rate
The maximum power released in the cabinet is determined from the oxygen available, \(i.e.\) from \(q^*\). The heat released by the combustion of a fuel with a given amount of oxygen is known to be weakly dependent on the nature of the fuel. This leads to the formulation of the ventilation limit in term of power:
\[
\dot{Q}^* = q^* \Delta H^\text{air}_c \tag{8}
\]
where \(\Delta H^\text{air}_c = 3.144 \text{ MJ/kg}\) is a constant valid for the ambient conditions of pressure and oxygen concentration.
During the third and fourth stages (steady-state combustion), the oxygen limitation simply gives:
\[
\dot{Q}_c = \dot{Q}^* \tag{9}
\]
During the third stage, the amount of pyrolysed combustible is linked to the radiated fluxes inside the cabinet, as this mode of thermal transfer predominates during this period. Based on this consideration, the following correlation for the heat released outside the cabinet was derived:
\[
\dot{Q}_{\text{out}} = \left(\dot{Q}_{\text{max}} - \dot{Q}^*\right) \frac{T_g^4 - T_{\text{pyr}}^4}{T_f^4 - T_{\text{pyr}}^4} \tag{10}
\]
However, as was already noted, the occurrence of a flame outside the cabinet is thought to be specific to the tests involving PMMA.
4.3 Practical modelling

4.3.1 Content of the cabinet and “mean” combustible
The investigation of the content of electrical cabinets show that the mass of combustible materials can be represented as:

\[ m_{\text{comb}} = \tau_v f_{\text{comb}} \rho_{\text{comp}} V_c \]

where

- \( V_c \) is the volume of the cabinet.
- \( \rho_{\text{comp}} \) is the density of components inside the cabinet. A value of 80 kg/m\(^3\) is a good compromise for many types of cabinets.
- \( f_{\text{comb}} \) is the combustible mass fraction of the electrical components. The tests performed on each component yield a mean value of 36%.
- \( \tau_v \) is a coefficient describing how full is the cabinet: \( \tau_v=100\% \) for full cabinets and \( \tau_v=50\% \) for the relay cabinets used in the CARMELA program.

The characteristics of the “mean” combustible (characterized by the average properties deduced from the real material contents of the cabinet) were estimated from the values measured for each component with a cone calorimeter. The mean value of the heat of combustion \( \Delta H_c=14.3\text{MJ/kg} \) is in agreement with those measured in the experiments which vary in the range 10-20 MJ/kg.

4.3.2 Incubation stage
The incubation stage for real cabinet fires is quite difficult to represent as it is much dependent on the ignition conditions. A compromise can be taken in the range \( t_i=10\text{-}15\text{mn} \) and \( \alpha_i=0.06\text{ W/s}^2 \).

4.4 Comparison to real cabinet fires
The figure 4 hereunder displays an overview of the validation matrix of the model: the steady-state heat release rate is compared to the model prediction. For the experiments where outside combustion occurred (i.e. the analytical experiments involving only PMMA), the HRR values were taken after the fall of the fuel plate. Experiment CAA102 is represented by an uncertainty bar because steady-state combustion is short and cannot be estimated with precision. The maximum HRR measured during experiments carried out at VTT\(^4\) and involving real electronic cabinets are also represented on the figure. It should be noted that for electrical cabinets experiments, some error compensation could have occurred. On one hand, some additional openings due to thermal stress (particularly at the door) in the box have been reported in VTT experiments\(^3\); this contributes to a higher ventilation and therefore to higher HRR peak. On the other hand, the theory of post-flashover compartment fire is applied here assuming ideal combustion (i.e. perfect mixing of the pyrolyzed fuel and the available oxygen); this tends certainly to over-estimate the theoretical heat released. Eventually, some of the experiments conducted at VTT did not lead to a flashover (i.e. to a full involvement of all the combustible in the cabinet); the corresponding points fall well below the theoretical line; up to now, this issue is still unresolved.
Nevertheless, most of the experimental points gather near the theoretical line: the model is therefore a valuable approach for estimating the maximum power released by the combustion of electrical cabinets.

![Graph showing HRR vs Steady-state mass Flow-Rate](image)

**Figure 4: Overview of the validation matrix of the model. The tests performed at VTT are included.**

The figure 5 hereunder represents the time response of the model with the input values described in §4.2 and the power estimated from the two experiments of the CARMELEA program involving real cabinets. The two experiments were identical to check the repeatability of the phenomena observed. During the first experiment, some smoke escaped out of the hood during the fast increase stage; as the oxygen measurement is performed in the exhaust duct, the experimental power showed on figure 5 is certainly under-estimated during this period. The modelling agrees correctly even though a trend to over-estimate the power released is noticed. This tendency is attributed to the hypothesis of the modelling which were voluntarily maximizing the risk; in particular the value $\Delta H^\text{ref} = 3.144MJ/kg$ was chosen as the upper bound of what is reported in the literature; similarly, the expression of $q^*$ is evaluated at a high temperature.
5 CONCLUSION

With more than thirty experiments carried on over three years, the CARMELA program provided a valuable investigation of the combustion of electrical cabinets. The analytical approach presented many advantages, besides its lowered price, as it allowed a parametric study of the most influencing parameters. From this point of view, the importance of the size of the ventilation openings was demonstrated. Based on the experimental program, a model was developed to predict the evolution of the power released and of the temperatures of the cabinet. Its validation against the experiments proved correct, particularly concerning the steady-state heat release rate. Though, the research concerning the fire of electrical cabinets is not closed and the PICSEL program, interested in studying the influence of a confined environment—a ventilated room-on the combustion, is actually going on at IRSN.

6 NOMENCLATURE

Acronyms
HRR  Heat Release Rate
PE   Polyethylene
PMMA Polymethyl Methacrylate (e.g. Plexiglas®)
PSA  Probabilistic Safety Assessment
PVC  Polyvinyl Chloride
NPP  Nuclear Power Plant
Symbols

$C_p$  Heat capacity of air (J.kg$^{-1}$.K$^{-1}$)
$C_w$  Thermal inertia of the cabinet (J/K)
$g$  Acceleration of gravity (m.s$^{-2}$)
$h_w$  Convective heat exchange coefficient (W.m$^2$.K$^{-1}$)
$H$  Cabinet height (m)
$k_{in}$  Pressure drop coefficient of the inlet vent (-)
$k_{out}$  Pressure drop coefficient of the outlet vent (-)
$L_v$  Latent heat of vaporization (J.kg$^{-1}$)
$\dot{Q}_c$  Rate of heat released inside the cabinet (W)
$\dot{Q}_{out}$  Rate of heat released outside the cabinet (W)
$\dot{Q}_{D_2}$  Ventilation limit HRR (W)
$q_p$  Inlet mass flow rate (kg.s$^{-1}$)
$q$  Steady-state mass flow rate (kg.s$^{-1}$)
$Re$  Reynolds number (-)
$S_c$  Flow cross-section inside the cabinet (m$^2$)
$S_{in}$  Area of the inlet vent (m$^2$)
$S_{out}$  Area of the outlet vent (m$^2$)
$S_w$  External exchange surface of the cabinet (m$^2$)
$T_r$  Flame temperature (K)
$T_a$  Temperature of ambient (K)
$T_g$  Temperature of gas at outlet (K)
$T_w$  Temperature of the cabinet walls (K)
t  Time (s)
$\alpha$  Growth factor (W.s$^{-2}$)
$\Delta H_{air}$  Heat of combustion of air (J.kg$^{-1}$)
$\Delta H_c$  Heat of combustion of the combustible (J.kg$^{-1}$)
$\Delta H_{vap}$  Latent heat of vaporization of the combustible (J/kg)
$\varepsilon_w$  Emissivity of the cabinet walls (-)
$\rho$  Density (kg/m$^3$)

7 REFERENCES

2. Mangs, J., Keski-Rahkonen, O., Full scale fire experiments on electronic cabinets, VTT Publications 186, 1994