Identification and characterization of design fires and particle emissions to be used in performance-based fire design of nuclear facilities

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Summary
CERN operates one of the most complex particle accelerator facilities in the world. Several different hazards, including fires, are present and need to be investigated and reduced to a tolerable level. Toward this goal, CERN aims at developing a catalog containing detailed fire dynamics descriptions of combustible items present in its facilities. This paper contributes to this catalog in two ways. First, through the development of a design fire calculator for electrical cabinets that allows the determination of potential design fire curves for any number of electrical cabinets/racks. The second contribution was to experimentally characterize the smoke production rates and smoke particle properties of the most common cables and insulating oils used at CERN by coupling a fast particle mobility analyzer to a cone calorimeter. The two particle size modes (accumulation and nucleation mode) could be linked to the fire properties and heat release rate. Accumulation mode particles (~200 nm) were associated with high heat release rates and high soot emissions from the flame. This study identifies a necessity to consider ultrafine particle emissions with low mass emissions but high number emissions in relation to risk assessments pertaining to nuclear facilities and dispersion of radioactive aerosols to the surrounding environment.

KEYWORDS
CERN, design-fires, DMS500, electrical cabinet fire, particle size distribution, smoke

1 | INTRODUCTION

CERN (French “Conseil Européen pour la Recherche Nucléaire”), or European Organization for Nuclear Research, is the largest particle physics laboratory in the world. As CERN consists of numerous buildings and underground areas, having tens of kilometers of tunnels and other complex constructions, the whole facility represents a great challenge from a technical-scientific standpoint. Having kilometers of wiring, thousands of electrical components and a huge number of various combustible materials present in facilities (electrical cabinets, klystrons, detectors, vehicles, cable trays, racks etc.) - fire safety obviously represents a concern that should be paid special attention to.

Since CERN is such a unique facility, using prescriptive based fire design for research infrastructures is neither always possible nor
recommendable. Therefore, a performance-based fire design is suggested. In comparison to specification-based prescriptive design, the suggested performance-based design has three main advantages:

1. It allows the designer to address the unique features and uses of a building.
2. It allows a better understanding of how a building would perform in the event of a fire.
3. It ensures applying the most effective cost-benefit compensatory measures.

The long-term objective of CERN is to develop a catalog that contains detailed descriptions of combustible items present in its facilities, including their individual and combined heat release curves, as well as the propagation modes and other relevant characteristics (CO and CO2 yields, smoke particle size distributions etc.). This paper presents methodologies for assessing heat release rates in electronic cabinets and for assessing particulate and gaseous emissions. These results can be directly implemented in the CERN catalog.

1.1 | Objective

The first objective of this study was to assess the fire hazard imposed by electrical cabinets and racks used at CERN, and to address them with appropriate design fires. The second objective was to characterize the smoke particles that will be released by fires in diverse CERN facilities. The smoke characterization was performed by conducting fire experiments using the most common cables and insulating oils found at CERN.

To reach these objectives:

1. Representative cabinet types used at CERN were categorized and the most common cabinets were compared to the literature/reference values of electrical cabinets fires.

2. A simple methodology was developed for calculating the expected design fires for any number and distribution of electric cabinets and implemented in a Microsoft Excel® spreadsheet.

3. An experimental set-up was designed to characterize smoke emissions from laboratory scale experiments using oils and cables by connecting a fast particle analyzer to a cone calorimeter.

1.2 | Motivation

Particle accelerator and nuclear facilities are usually complex and unique, with highly extensive and complex equipment installed in their premises. In many cases, standard, off-the-shelf equipment does not fulfill the specific needs of these special facilities. In many of them, most of the equipment used is custom made for unique purposes, which adds extra complexity to assessing all potential hazards, including fire hazards. Cabinets and racks used at CERN vary in geometry, contents, configuration (a single cabinet, 10 cabinets and racks combined in one row, 20 closed cabinets divided in two rows etc. - see Figures 1 and 2) and location (in control rooms above ground or in tunnels 100 m below ground). In case of CERN, as for many other facilities, inspection of most of cabinets is not possible due to operation complexity constraints. Ideally, a design fire gives the heat release rate over time for a certain scenario. When the combustible materials and their heat release rates, and the geometry of the room are known, it is possible to construct a design fire scenario. From these, a conservative "safe" estimate of an envelope case or a worst-case scenario can be evaluated.

The second part of this paper is dedicated to smoke particulate matter analysis of the three most common types of cables used at CERN, as well as two insulating oils used in transformers and klystrons. The term aerosol refers to a suspension of liquid or solid particles in a gaseous medium. Many commonly known phenomena such as dust, suspended particulate matter, fume, smoke, fog, haze, clouds, or smog can be described as aerosols. Smoke from combustion is a mixture of gasses, vapors, and particulates. The particles in smoke include: (a) Nanometer sized nucleation mode particles often in droplet forms, formed from condensed organic vapors, possibly with
an inorganic core and (b) Carbonaceous accumulation mode soot particles formed in the flame with agglomerated structures and consisting of a large number of partly fused spherical primary particles.\(^3\) In fire models, the accurate prediction of aerosol and soot formation (number, mass and size distributions), as well as aerosol and soot deposition thicknesses on surfaces is important for a wide range of applications, including human egress calculations, heat transfer in compartment fires, and forensic reconstructions of fires.\(^4\) In case of a fire in one of CERN tunnels during experiments, it is expected that smoke particles, produced by burning activated materials, will be radioactive too and will further carry and eventually deposit the radiation on surfaces inside the CERN tunnels or lead to radioactive emissions to ambient air. Particle size controls the lifetime of the particles in the air, for example by controlling deposition velocities. This is a serious threat that likely has to be approached from a worst case scenario. For this reason, CERN has a need to obtain detailed knowledge about smoke particle yields and size distributions, which can be used in flame dynamic simulations and aerosol dispersion modeling.

2 | PROPOSED DESIGN FIRE FOR MULTIPLE ELECTRICAL CABINETS AND RACKS

Several experimental campaigns on fires in open and closed electrical cabinets have been performed in France, Finland, and the USA. The results of the experiments are presented in References 5-10. The goals of the mentioned experiments were to examine the potential for a cabinet fire to ignite, the rate of development of a fire in a cabinet, the resulting room environment produced by a fire and the potential for a fire to spread to other cabinets. The effects of the following variables on fire development were investigated:

- Different ignition sources
- Cabinet styles
- Cabinet ventilation
- Fuel types, amounts and configuration

In experiments when the cabinets were attached to each other, fire could propagate to adjacent cabinets. If the cables in the adjacent cabinet were attached to the wall, the predominant mode of propagation was conduction. In situations when separation between the wall and cables existed, predominant modes of propagation were conduction and radiation. The experiments conducted by Chavez\(^5\) effectively showed that the fire did not propagate between the cabinets separated by an air gap of 1 in. (ie, 2.54 cm). The key role of ventilation conditions in peak heat release rate (HRR) values reached is shown. The sizes of inlet and outlet openings determined the amount of oxygen available for combustion, which had the greatest effect on peak HRR. Ventilation conditions had much greater impact to peak HRR in comparison to other parameters of the cabinets that were investigated - namely ignition location, amount of fuel, special arrangement in the cabinet and the cabinet filling. Each of the experimental campaigns resulted in models for peak HRRs where the only variables are inlet and outlet sizes and vertical distance between them.

At CERN facilities, the electrical cabinets and racks can be distributed from a single closed cabinet to a set of two rows consisting of any number of columns of combined racks and open and/or closed cabinets (Figures 1 and 2). Therefore, in order to cover the common and possible fire scenarios a simple methodology for calculating the expected design fires for any number and distribution of electric cabinets was developed and implemented in a Microsoft Excel© spreadsheet.

As the highest HRR values for cabinets are obtained with open doors, and the racks have similar content as the cabinets, estimation is made that racks and cabinets with open doors will burn in the same manner. In other words, racks and open-door cabinets are treated, as they were the same in calculations.

In theory, obtaining the accurate heat release rate for a single cabinet is possible only if exact contents and specifications are known, as well as the precise geometry limits of the cabinet. Nevertheless, in
practice we know from tests\textsuperscript{9} that unexpected events in the combustion process can occur (internal combustible failing, moving parts...), and affect the outcome HRR. Therefore, this further reinforces the necessity of making conservative conclusions when estimating electrical cabinet design fires. As seen in Figures 1 and 2, cabinets and racks with their contents are custom made, and the contents, specifications, and geometry vary from case to case. Therefore, estimation of the heat release rates were based on values found in the literature.

Electric Power Research Institute (EPRI) and U.S. Nuclear Regulation Commission (U.S.NRC)\textsuperscript{10} made a summary of the state of the art in nuclear power plant fire safety in the US, including the analysis of all the fire experiments done up to the moment of publishing. They gave values for peak HRR for open and closed cabinets, obtained as a 98th percentile from the previous experiments. The results represent an envelope case for all the fire experiments done on electrical cabinets. The values found in this paper are used to develop the Excel calculator for CERN, and they will be compared with values obtained by models from experimental campaigns conducted in France and Finland. Exact values are: 1004 kW for open and 464 kW for closed cabinets, but values of 1000 kW and 500 kW are taken for the sake of simplicity.

Additional documents have been published by EPRI and U.S. NRC, namely “Heat Release Rates of Electrical Enclosure Fires (HELEN-FIRE)\textsuperscript{11} and “Refining And Characterizing Heat Release Rates From Electrical Enclosures During Fire (RACHELLE-FIRE)”.\textsuperscript{12} This pair of documents presents and analyzes 112 tests of eight types of cabinets. New methods and data have been developed in areas of classification of electrical enclosures in terms of function, size, contents, and ventilation conditions, and determination of peak HRR probability distributions considering specific electrical enclosure characteristics. The mentioned documents for example show that large open thermoplastic cabinet with default fuel load has a 98th percentile HRR of 1000 kW, while the same cabinet with very low fuel load has a 98th percentile HRR of 75 kW. Following guidelines given in these documents would certainly result in using more realistic HRR values, and consequently having more realistic risk estimations. Nevertheless, it is impossible for CERN to inspect every single cabinet, and also equipment used in CERN is often custom made, as it was explained in motivation Section 1.2. Therefore, following the precautionary principle adopted by CERN, the extreme values proposed in these documents were used in order to simulate scenarios to be used in a conservative risk assessment.

Several models have previously been proposed for obtaining the peak HRR of closed-door cabinets.\textsuperscript{6,8,13} First, in Reference 6, a simple cabinet flow model assuming small vents and thus unidirectional flow is analyzed and a dimensional equation for peak HRR ($\dot{Q}$) in the following form is developed:

$$\dot{Q} = 4.3 \times \frac{H}{\sqrt{A_i + A_e}} \text{ [MW]}$$

where $H$ (m) is the vertical distance between the vents of the cabinet, while $A_i$ (m$^2$) and $A_e$ (m$^2$) are areas of inlet and outlet openings respectively.

After a new series of similar experiments, 10 years later, in 2004, Mangs\textsuperscript{13} proposed a similar but improved version of Equation (1), including the combustion efficiency $\chi$ that takes into account incomplete combustion:

$$\dot{Q} = 7.4 \times \chi \times \frac{H}{\sqrt{A_i + A_e}} \text{ [MW]}$$

Finally, in 2011 IRSN\textsuperscript{8} have considered cabinets with vent areas that are non-negligible in comparison to the cabinet size, and also taken into account acceleration of the fluid due to its heating. Bernoulli equation yielded the following equation for the steady state mass flow rate ($q^*$):

$$q^* = \rho_{\text{air}} \sqrt{2gH} \times \frac{1 - (\frac{H}{L})}{\left(\frac{a}{b}ight) + \left(\frac{A_e}{A_i}\right) + \left(\frac{S_{\text{out}}}{S_{\text{in}}}ight) - 1} \times \left(\frac{1}{\chi}\right)$$

where $\rho_{\text{air}}$ (kg·m$^{-3}$) is ambient air density, $g$ (m·s$^{-2}$) is the gravity acceleration, $H$ (m) is the vertical distance between the vents of the cabinet, $T_{\infty}$ and $T_i$ (°C) are respectively ambient and cabinet temperatures, $k_{\text{in}}$ and $k_{\text{out}}$ are pressure loss coefficients at inlet and outlet (taken to be $=2.8$ as it is the value commonly found for turbulent flows\textsuperscript{14}) and $S_{\text{in}}, S_{\text{out}}$ (m$^2$) are sectional areas of inlet, outlet and of cabinet \footnote{Correction added on 5 August 2020, after first online publication: T has been amended to $T_{\infty}$ in Equation 3.}.

The peak HRR in the cabinet is determined from the oxygen available, that is, from $q^*$:

$$\dot{Q} = q^* \times \Delta H_{\text{O}_2}$$

where $\Delta H_{\text{O}_2} = 3.144$ MJ·kg$^{-1}$ is a constant valid over a large range of fuels at standard conditions of pressure and oxygen concentration.\textsuperscript{8}

In all three proposed equations, values of HRR strongly depend on the cabinet height. Largest cabinets at CERN are 3 m high, which can be seen as an envelope case when determining HRR according to these equations. Peak heat release rates for a 3 m high cabinet are calculated according to all three equations proposed, for variety of vent size ratios and the results are shown in Table 1. \footnote{Correction added on 5 August 2020, after first online publication: Table 1 citation has been added.} The peak HRR value for majority of inlet/outlet ratios is obtained using Equation (2) - referred to as Mangs 2004. When using Equation (2), combustion efficiency is taken to be $\chi = 0.7$, which is seen as a conservative assumption as fires in closed cabinets are virtually certain to be under-ventilated. As it can be seen in summary of cabinet experiments in Reference 8, the most extreme case of ventilation sizes was $A_{\text{in}} = 0.1$ m$^2$ and $A_{\text{out}} = 0.1$ m$^2$. In general vent sizes were much smaller. Thus, peak HRRs were analyzed for the vent areas ratio of up to that size. It can be seen that even for the most extreme case when both inlet and outlet areas are equal to 0.1 m$^2$, the peak HRR value is 494 kW, which is still below the 500 kW, which was the value taken as
a peak HRR value for closed cabinets proposed by Reference 10 and used in the Excel calculator. This validates the assumption of peak HRR for closed cabinets and further validates the excel calculator.

The equations supporting Table 1 presume that the fire size is limited to the combustion air entering the target. However, external burning could occur at the top vent allowing for larger HRR if sufficient pyrolysis can occur inside the cabinet. This limitation should be kept in mind. Nevertheless, it seems that test data, which shows HRRs <500 kW suggests that ventilation does not support significant excess pyrolysis.

In real, growing and ventilated fires, the initial fire development is nearly always accelerating, in comparison to for example smoldering decay phase, \( t_d \) is the time at the start of the decay phase, and Peak HRR values for various inlet/outlet ratios are presented in Figure 3A,B.

The decay phase HRR curve can be characterized according to the following exponential function

\[
\dot{Q} = \dot{Q}_0 \exp \left[ -\left( \frac{t - t_d}{\tau} \right) \right]
\]

where \( \dot{Q}_0 \) is the heat release rate at the time of the start of the decay phase, \( t_d \) is the time at the start of the decay phase, and \( \tau \) is the decay time constant. In Reference 13, the decay time constants used to fit the exponential functions that describe the decay were in the range between 13 and 23 minutes. As no additional data is available, it was decided to take the mid value, that is, \( \tau = 18 \) minutes. Using a decay time constant \( \tau = 18 \) minutes gives a decay time of approx. 50 minutes. Decay time is defined as the time from when the fire starts decreasing from the peak value, until the fire dies out. Comparing the adopted value of 50 minutes to decay times between 18 and 40 minutes found in Reference 5, proves that our assumption is conservative.

We now know the HRR peak values for both closed and open cabinets and the way to describe both the fire growth and decay fire stages. It now remains to determine the duration of the HRR peak. In the case where the amount of fuel is not known, the duration of burning at the peak HRR (steady stage burning time - \( t_s \)) needs to be determined. Kassawara\(^{10}\) recommends \( t_s = 8 \) minutes to be taken. Following the precautionary principle adopted by CERN a 50% higher \( t_s \) (\( t_s = 12 \) minutes) is used. In the case of closed cabinets, as their peak HRR is 50% smaller than peak HRR of open cabinets, it is assumed that duration of steady burning \( t_d \) will be 2 times longer than \( t_s \) of open cabinets. Thus, \( t_s \) for closed cabinets is taken to be \( t_s = 24 \) minutes. This is decided according to the engineering estimation that the same amount of fuel will take twice as long to burn if the peak HRR is 2 times smaller. The final HRR curves for closed and open cabinets are presented in Figure 3A,B.

Once that the burning behavior of a single cabinet is completely addressed (growth stage, peak HRR, duration and decay stage), we only need to describe the fire spread between the adjacent cabinets in order to obtain a complete methodology to assess the HRR of a fire of multiple electrical cabinets. Fire spread to the adjacent cabinet occurs in 11-16 minutes according to the experiments done in References 6 and 13. To be on the safe side, it is assumed that the fire will spread to the adjacent cabinet after 10 minutes. The mode of fire spread are conduction and radiation. The walls of the fire cabinet heat up, then conduct the heat to the adjacent cabinet wall, which finally heats up it’s contents which then catch fire. In the experiments, the bundle of cables with outer sheaths coated in PVC

### Table 1 Peak HRR values for various inlet/outlet ratios

| Peak HRR (kW) | A inlet (m²) | 0.01 | 0.02 | 0.03 | 0.04 | 0.05 | 0.06 | 0.07 | 0.08 | 0.09 | 0.1 |
|--------------|-------------|------|------|------|------|------|------|------|------|------|-----|
| A inlet (m²) | 0.01 | 49 | 71 | 80 | 90 | 105 | 116 | 125 | 133 | 138 | 143 |
|              | 0.02 | 56 | 99 | 126 | 143 | 153 | 160 | 165 | 181 | 196 | 210 |
|              | 0.03 | 58 | 108 | 148 | 178 | 199 | 214 | 226 | 234 | 240 | 245 |
|              | 0.04 | 58 | 112 | 159 | 198 | 228 | 252 | 271 | 286 | 298 | 307 |
|              | 0.05 | 59 | 114 | 165 | 209 | 247 | 278 | 304 | 326 | 343 | 357 |
|              | 0.06 | 59 | 116 | 169 | 217 | 259 | 296 | 328 | 355 | 379 | 398 |
|              | 0.07 | 59 | 116 | 171 | 221 | 268 | 309 | 346 | 378 | 406 | 431 |
|              | 0.08 | 59 | 117 | 172 | 225 | 273 | 318 | 359 | 395 | 428 | 457 |
|              | 0.09 | 59 | 117 | 173 | 227 | 278 | 325 | 368 | 408 | 445 | 477 |
|              | 0.1 | 59 | 117 | 174 | 229 | 281 | 330 | 376 | 419 | 458 | 494 |

[Correction added on 5 August 2020, after first online publication: “Mangs 2004” and “IRSN 2011” have been removed from Table 1.]
was attached to the wall of the cabinet adjacent to the fire cabinet, as it is the worst-case scenario and results in the fastest fire spread. It is assumed that the cables ignite when they reach a temperature of 250 °C. This temperature was taken as it was the maximum temperature at which the cable partially burned and partially deformed, indicating an approximate ignition level. This ignition temperature is in accordance with the range of decomposition of polyvinyl chloride, 200 °C to 300 °C.\textsuperscript{13}

The worst-case scenario is when a fire starts in a middle cabinet. In a simple one-row case, fire would spread to two adjacent cabinets every 10 minutes. In a more complicated case with 2 rows, after ignition of the first adjacent cabinets, further cabinets in the row opposite from the "fire cabinet" row would be heated by 2 cabinets at a time, thus it would take less than 10 minutes for each of them to ignite. An approximation of the time until the ignition of each of the cabinets is given in Figure 4. Numbers represent the time (min) at which each of the cabinets starts to burn - 0 being the initial "fire cabinet," and in this case 50 being the last cabinet to ignite. The values shown are pure engineering approximations, with being cautious of staying on realistic "safe" side. It is observed that regardless of the number of cabinets, after 50 minutes, there will be no difference between the time of burning in adjacent cabinets in each row, meaning that next two cabinets would ignite after 60 minutes, then next 2 after 70 minutes etc.

The calculations presented in this chapter are based on the assumption of burning in an open compartment for example large experimental halls or facilities equipped with heat and smoke extraction. In confined enclosures, the heat feedback (re-radiation) from the enclosure surfaces back to the fuel source would have a strong impact on overall burning behavior. Therefore, the proposed calculator would not be applicable to confined enclosures.

It is observed that cabinets sometimes have glass facing (Figure 1). In case the cabinet has plastic or glass facing, it is advised to consider it as an open cabinet due to the conservative assumption that the facing would inevitably fail leading to unlimited oxygen supply inside of the cabinet.

Also, the proposed calculation methodology is valid only for adjacent cabinets, that is, cabinets that have the walls touching each other. This is the most common case in CERN, as it was shown in Figures 1 and 2. Spread to opposite cabinets is not covered in this work.

A schematic of the Excel calculator for design fires in electrical cabinets in CERN facilities is presented in Figure 5. The user is required to specify the number of rows and columns of cabinets, and to specify for each position if the cabinet is open or closed. In case the amount of combustibles inside of the cabinet is known, the user can specify the amount of combustibles in order to get a more precise estimation of the duration of burning. As the final output, the design fire for any number of cabinets is given, as well as the total amount of combustible load for the specified set of cabinets. The assumptions and boundaries of the calculator are the following:

- The mode of heat transfer for spread to adjacent cabinets is assumed conduction.
- The cabinets are assumed to be adjacent (ie, next to each other without air gaps).
- If the amount of fuel is known, combustible fraction will determine the duration of the steady burning.
- Combustible fraction (0-1) indicates how much of fuel is expected to burn where 0 = none; 1 = all.
- If the amount of fuel is unknown, the default values of steady burning duration are 12 minutes for open cabinets, and 24 minutes for closed cabinets.

![](A.png)  \( Q \) open [kW]  \( Q \) closed [kW]

**FIGURE 3** Single open A, and closed B, cabinet HRR curves

![](B.png)

**FIGURE 4** Time (min) for fire spread to adjacent cabinets
Peak HRR value is 1 MW for open cabinets and 500 kW for closed cabinets regardless of the combustible fraction.

Effective heat of combustion $\Delta H_c$ is assumed to have a fixed value of 24 MJ/kg, as it is the worst-case value obtained in experiments found in literature.\(^8\)

Integration of the HRR curve and division by the effective heat of combustion results in the total amount of combustible load for the specified set of cabinets.

3 | PARTICULATE MATTER ANALYSIS

3.1 | Methodology

The goal of the experimental campaign was to assess relationships between HRR, smoke production rates, and smoke particle size distributions for a set of specimens commonly used at CERN (three type of cables and two types of oils). In order to capture the transient combustion and particle emissions, the standard Cone Calorimeter (Fire Testing Technology FTT) set-up was interfaced with a Fast Particulate Mobility Analyzer (DMS500; Cambustion Ltd., Cambridge, UK) to analyze the particle concentration and size distribution with high time-resolution.

Outputs from the cone calorimeter are heat release rate (HRR), mass loss rate (MLR), effective heat of combustion, CO and CO\(_2\) yields and smoke production rate (SPR). These values are calculated according to the equations proposed in the standard.\(^{17}\) Heat release rate is calculated by carbon dioxide generation (CDG) method. Smoke obscuration is measured as the fraction of laser light intensity ($\lambda = 633$ nm) that is transmitted through the smoke in the exhaust duct. This fraction is used to calculate the extinction coefficient. Finally, the product of the volumetric flow rate ($m^3/s$) of smoke and the extinction coefficient ($1/m$) of the smoke gives the smoke production rate (SPR) in units of $m^2/s$.

The DMS500\(^{18}\) measures the Particle Number concentration (PN) [1/cm\(^3\)] and the particle size distribution in the size range 5-1000 nm at up to 10 Hz time resolution. The smoke is first diluted a factor 1:5 upon extraction from the cone calorimeter, then the sample is transported through a heated sample line (150°C) to avoid condensation and nucleation of vapors in the sampling system. The sample was finally cooled to room temperature by further dilution in the range of 1:12-500 down to optimal concentration for the measurement using an internal rotating disk diluter in the instrument. The DMS500 works on the following principle: a high voltage corona discharge is used to charge particles approximately proportionally to their surface area. The charged particles are introduced into a classification section with a strong radial electrical field. This field causes particles to drift through a sheath flow toward a set of electrometer detectors (at different distance from the entrance of the classification section) on to which the particles are detected in terms of an electrical current. The measured electrical currents and the known charge distribution as function of particle size is used as input to an inversion matrix that provides the number based particle size distribution. The data reported here are fitted using two lognormal size modes, a smaller nucleation mode and a larger accumulation mode. Fire smoke particles may have complex shapes and the definition of particle size is not trivial. As the particle sizing in the DMS is based on electrical mobility, the size measure is the equivalent mobility diameter. The mass concentration and mass weighted particle size distribution were estimated using assumptions of the particles mass-mobility relationship as discussed below.

3.2 | Samples and preparation

Three types of electrical cables were studied; labeled as C01, C02 and C04 (blue, black and brown cables respectively), as they were for previous experiments conducted by CERN (CERN Cable Fire Tests, CERN-CFT). C01 (Blue) and C02 (black) cables were regular multi conductor cables with thermoset insulation. The C04 (brown) cable type...
was a coaxial cable with tight metal shield and a thermoplastic dielectric insulator around the core conductor. Detailed specifications of the tested cables are given in Table 2:

The tested oils were the most common ones used as electric insulating oils in transformers and klystrons present at CERN. The oils were synthetic ester transformer oil MIDEL 7131 and Shell Diala S4 ZX-I having their flash points at 260 °C and 191 °C, respectively. Figure 6 shows all 3 types of cables, while Figure 7 shows photos of prepared samples of cables and oils right before starting the test.

In the first test attempt, C01 cables (blue) did not ignite under the 25 kW/m² of imposed heat flux. Therefore, it was decided to test all the cables under heat flux of 50 kW/m². On the other hand, oils were in the first trial tested under 30 kW/m², but due to quite aggressive burning that caused boiling and spills especially for the Shell Diala oil, it was decided to conduct further tests on oils under an incident heat flux of 20 kW/m².

### 3.3 Results

3D plots of the evolution of the particle size distributions over time are shown for Shell Diala oil and Midel oils on Figure 8A,B respectively. The time series show two distinct modes, a nucleation mode at approximately 20 nm, and an accumulation mode at approximately 200 nm. Accumulation mode particles were dominant with Shell Diala oil during the whole period of burning (Figures 8A and 9A). For the Midel oil test, the accumulation mode dominates throughout most of the burning, with a sudden peak in nucleation mode particles toward the end of the experiment (Figures 8B and 9B).

The nucleation and accumulation modes apparent from Figure 8 were determined by lognormal fits to the data. The time evolution of HRR, nucleation mode and accumulation mode particle number concentrations are shown in Figure 9A,B for Shell Diala oil and Midel oils respectively. These figures clearly illustrate the dominating accumulation mode particles, but also show that a substantial fraction of the emitted particles in Midel oil are small nucleation mode particles. It is likely that the nucleation mode is caused by small ash particles possibly followed by growth by condensation of organic matter as the emissions cool down. These nucleation mode particles are likely formed throughout the combustion, but will rapidly coagulate on to larger particles due to the high concentration of accumulation mode soot particles. A trend of accumulation mode particles concentration correlating with HRR, and nucleation mode particles concentration peaking during lower HRR can be observed for Midel oil. Shell diala oil did not show significant release of ultrafine particles, but a correlation between HRR and larger particles is still obvious (Figure 9 a).

The Midel oil was when compared with the Shell Diala oil associated with: 1. Lower HRR and a longer duration of the experiment 2. Lower accumulation mode concentration and smoke production rate (SPR) and 3. A burst of nucleation mode particles as the HRR dropped strongly near the end of the experiment. It is possible that this is associated with the higher flash-point of Midel oil (260 °C compared to 191 °C for the Shell Diala oil) leading to slower fire dynamics and a higher fraction of oil left for smoldering that led to nucleation mode emissions at the end of the experiment.

### TABLE 2  Cable specifications

| CFT-1 | C01 | C02 | C04 |
|-------|-----|-----|-----|
| Sample color | Blue | Black | Brown |
| Cable diameter (mm) | 9.3 | 11 | 4.8 |
| Inner conductor | Stranded tin plated copper wires, 7 x 0.20 mm, diameter 0.6 mm | Stranded tinned copper wires, 32 x 0.19 mm, diameter 1.3 mm | Stranded copper wires, 7 x 0.32 mm, diameter 0.96 mm |
| Insulation | PE, diameter 1.05 mm | PE - LE, diameter 2.70 mm | Foam-PE, diameter 2.6 mm |
| Wrappings | Al-PET-Al foil | PET foil | Al-PETP-Al-foil + copper braid, tinned + Al-PETP-Al-foil |
| Sheath | FRNC | Halogen free flame retardant compound (HFFR/LSZH/LSOH/FRNC) - Megolon S534 | FRNC |
| Linear mass (kg/km) | 131 | 157 | 38 |

[Correction added on 5 August 2020, after first online publication: Table 2 title has been corrected.]
**FIGURE 7** C01 (blue) cables and oil in their specimen holders

**FIGURE 8** Number Concentration vs Mobility Diameter vs Time - Oil: Shell Diala A, and Midel B, average from all 3 tests
The 3D plot in Figure 10 shows the evolution of particle size distributions over time for C01 cables (blue). In the cable example, the nucleation and accumulation modes are apparent for different burning modes of the cable. 3D plots for the remaining fuel types - C02 (black) cables and C04 (brown) cables are shown in Appendix A.

Figure 11 a-c shows time series of the heat release rate (HRR) and the nucleation and accumulation mode particle number concentrations from a single test with each of the three tested specimens. Looking at C01 (blue) cable results in Figure 11A, upon ignition, a short period of moderate HRR and bimodal size distribution is visible. After this follows a longer period (200-400 seconds) with reduced HRR, where nucleation mode particles are dominant. We interpret this as the outer sheath burning. In the time period 400 to 900 seconds the HRR is increased and accumulation mode particles became dominant. We interpret this as burning when fire caught the inner sheath. Thus, nucleation mode particles observed in the first part of burning represent burning of the outer sheath of cable.

Accumulation mode particles present in second part of burning represent burning of inner wires' sheath. Accordingly, the main (outer) cable sheath and inner wire sheath are made of different materials. The inner sheath produces larger particles, which is most likely connected to the significantly higher burn ratio (higher HRR) and formation of soot in the flame. This also suggests that while the outer sheath shows some positive fire rating, the inner sheath contribution worsens the global performance. Therefore, peaks in aerosol emissions and smoke production rates in cable fires can be expected when the fire reaches the inner wires' sheath and the soot formation rate increases with the HRR.

When comparing these results with the other two cable types, the main features of the HRR and particle concentration trends with time were similar. However, a few differences are worth pointing out. The length of the experiment increased with increasing cable diameter, with C02 (black) cables showing the longest experiments (~ 2500 seconds) and C04 (brown) cables showing...
the shortest experiments (~700 seconds). Both C02 (black) and C04 (brown) cables showed a stronger burst of nucleation mode particles early in the experiment compared to the C01 (blue) cables. This may be related to different thicknesses of outer sheath material, with high releases of non-combusted pyrolysis gasses being a possible origin of these short-lived peaks of nucleation mode particles.

Particle number and mass concentration graphs, obtained using an estimation of the particle effective density vs size, from a single test on C01 cables (blue) are shown on Figure 12. Figure 12A shows the number weighted particle concentration (average and all the time points) demonstrating bimodal particle distribution.

The smaller particles are more likely to be spherical while the larger ones might be highly irregular as they often consist of an agglomeration of smaller primary particles. In Reference 20, an aerosol particle mass analyzer was used to measure the mass of diesel exhaust particles as function of mobility diameter. They determined the effective density and found that it decreases as the particle size increases. By observing TEM (transmission electron microscopy) images, they realized that this phenomenon occurs because the particles become more highly agglomerated as size increases. Later data has shown that this phenomenon is similar for a range of soot particle sources.

By using effective densities, $\rho_{\text{eff}}$ [Equation (7)], of diesel exhaust particles, the number concentration, $N_i$, in each size channel was converted to the mass concentration, $m$, in the size channel for our tests and the result is shown in Figure 12B. It is important to have in mind that the mass concentration results are uncertain, as mass of smoke particles and their effective density for cables and oils used were not known, thus the values of diesel exhaust were used as an

![Figure 11](image-url)
approximation. Also, when comparing Figure 12A,B, it is interesting to note how nucleation mode particles (smaller than 100 nm), even though high in number concentration (Figure 12A), have negligible contribution to the size distribution based on total mass concentration (Figure 12B). This is because of the low mass of the smaller nucleation mode particles. Mass is calculated according to the Equation (7).\(^{20}\) As this equation gives mass of one size channel at the time, every variable has an index i. Mass being dependent on diameter in power of 3 explains why nucleation mode particles give a negligible contribution in Figure 12B (even though \(\rho_{\text{eff}}\) is higher for the nucleation mode). At the peaks their diameter varies by \(\sim 1\) order of magnitude, thus the mass is almost 3 orders of magnitude smaller than the mass of accumulation mode particles. Approaches in the literature\(^{18}\) to convert DMS number distributions from diesel exhaust to mass concentrations have used higher effective densities than those used here, this would even further decrease the mass fraction in the nucleation mode.

\[ m_i = N_i \rho_{\text{eff},i} d_i^3 \pi / 6 \]  

(7)

A very interesting phenomenon is observed when comparing results for smoke production rate (SPR) measured with cone calorimeter with the particle concentrations from the DMS. SPR (\(m^2/s\)) is obtained as a product of the volumetric flow rate of smoke (\(m^3/s\)) and the extinction coefficient (\(1/m\)) of the smoke at the point of measurement. The extinction coefficient is given as natural logarithm of the ratio of incident light intensity to transmitted light intensity, per unit light path length.\(^{17}\) Thus, greater attenuation of the laser light corresponds to greater smoke production values. When comparing particle concentration values from the DMS and smoke production rates for cables, it is observed that SPR almost perfectly correlates with the accumulation mode concentration particles (Figure 13A). On the other hand, SPR and nucleation mode concentration particles correlates poorly (Figure 13B). The nucleation mode particles, although sometimes having extremely high number concentrations, were practically "invisible" on smoke production rate measurements. Light attenuation depends on scattering and absorption and these phenomena are dependent on particle size, mass, shape, refractive index and on the incident wavelength of the light. Ultrafine particles (<100 nm) are much smaller than the cone calorimeter red laser wavelength (\(\lambda = 633\) nm) and thus have very low scattering efficiency. Additionally, the mass absorption cross section per particle mass may be higher for the soot rich accumulation mode particles, compared to nucleation mode particles. This results in a fundamental limitation of the cone calorimeter to detect small particles. The same phenomena were observed for the other cables tested.

### 3.4 | Repeatability of the tests

Overall, the repeatability of the tests had proven to be high. Figure 14A shows HRR plot for 3 repeats on Midel oil, while Figure 14B shows 3 repeats for total particulate concentration (nucleation + accumulation) for the same oil.

Figure 15 shows HRR and total concentration repeatability for C04 (brown) cables. Even though the cables are complex specimens, made of numerous different materials, and thus possessing several modes of degradation, repeatability was shown to be high in all three tests.

Repeatability graphs for remaining specimens (shell diala oil, C01 (blue) and C02 (black) cables) are given in Appendix B.

Errors associated with cone calorimeter are explained in detail in ISO 29473:2010 - Fire tests — Uncertainty of measurements in fire tests - Annex C.\(^{22}\) As shown above there was a relatively high repeatability for the particle concentrations measured with the DMS. Much of the variability in Figures 14B and 15B appear to be driven by small variations in HRR and combustion conditions between the experiments. This shows that the precision in the DMS measurements is very high.

However, the charge level for a given particle size in the DMS depends on particle shape, especially for larger particle sizes.\(^{18}\) Since particle shape was not known for the fire smoke, this introduces
uncertainties in the size distribution and number concentration measurements. Highly agglomerated soot particles are detected with a smaller equivalent mobility diameter and higher number concentration in instruments based on unipolar charging\textsuperscript{23} such as the DMS\textsuperscript{18} compared to a scanning mobility particle sizer based on bipolar charging.

**FIGURE 13** A, Smoke production rate vs accumulation mode concentration and B, Smoke production rate vs nucleation mode concentration - CO2 (black) cables
4 | CONCLUSIONS AND FUTURE WORK

4.1 | Summary and conclusions

In the first part of this paper, an Excel calculator that provided design fires for electrical cabinets and racks present in CERN was developed. Findings from experiments conducted in the USA, Finland and France were used to obtain an envelope case covering the worst possible conditions. The user can specify any combination between the most basic one - a single cabinet, to the most severe one - 2 rows containing 10 cabinets each.

In the second part, an experimental campaign was conducted on three types of the most common cables used at CERN, as well as on two of the most common insulating oils used at CERN. Our results demonstrate that in these cable fires, nucleation mode particles were emitted during low heat release rates primarily during burning of the outer sheath of the cable or at the final stage when nearly all material had been combusted. Accumulation mode particles were dominating the particle emissions (ie, smoke) at high heat release rates in later stages of burning when the sheath of inner wires was burning. Accumulation mode particles were always dominating the particle mass emissions, and their concentration correlated well with the smoke production rates derived from obscuration measurements. Nucleation mode particles were often found to dominate the particle number emissions. Particle emissions, both number and mass, from the oils were dominated by accumulation mode particles. However, a burst of nucleation mode particles was observed toward the end of combustion for the high flash-point oil sample, suggesting that nucleation mode particles may also be important emissions from fires in the klystron and transformers.

It is instructive to compare our results to recently published data on rich biomass combustion emission and fire properties investigated with a combination of a modified cone calorimeter and the DMS500. In addition, that study showed a bimodal size distribution, with the fraction of accumulation mode particles increasing with increasing HRR.24

4.2 | Future work

The literature on fires in electrical cabinets is existing, but limited. To the author's knowledge, only five experimental campaigns on cabinet fires have been performed up to today. Making conclusions and using the models presented in the mentioned papers is seen as the only feasible and sufficiently precise way of dealing with cabinet fires in CERN facilities. Nevertheless, as the sizes of cabinets change over time, as well as their contents, new experimental campaigns on modern electrical cabinets (such as those used in CERN) would be of great use to the whole field of fire safety engineering. On top of that only a single short campaign conducted at IRSN dealt with cabinets burning in confined areas (under-ventilated conditions) thus this condition also deserves more attention in future works. The calculator developed for electrical cabinets and racks can if needed be further developed and extended to more cabinets.

The goal of the experiments was to obtain detailed smoke characterization data of key specimens, which is required to initialize and further develop CFD modeling software that can resolve aerosol agglomeration and deposition to better model particle dispersion. Particle accelerators and nuclear facilities might be interested in these results; smoke particles are expected to carry radiation further away from the seat of a fire of activated material, which is a potential hazard both for the facility and for the environment. Our results show that the nucleation mode particles observed with the DMS500 did not contribute significantly to the total aerosol particle mass nor to the aerosol light extinction. However, our measurements reveal that these ultrafine particles (<100 nm) can dominate the particle number emissions from cable fires. With respect to fires in environments susceptible to ionizing radiation, our measurements show that consideration of these ultrafine particle emissions may be crucial for accurate fire-propagation and aerosol dispersion models. In particular, chemical and elemental analysis of these particles can reveal whether they have high probabilities of containing radioactive isotopes during or after exposure to ionizing radiation. Smoke emissions from various sources to ambient air are also of relevance for adverse health impacts and effects on global climate.25 The adverse effects can be related to the particle properties such as size and chemical composition.

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APPENDIX A. 3D PLOTS FOR C02 (BLACK) CABLES AND C04 (BROWN) CABLES

FIGURE A1  Concentration vs Mobility Diameter vs Time - C02 (black) cables - average from all 3 tests

FIGURE A2  Concentration vs Mobility Diameter vs Time - Brown Cables (C04) - average from all 3 tests

APPENDIX B. REPEATABILITY GRAPHS

FIGURE B1  Repeatability of HRR A, and total concentration B, for shell diala oil
**FIGURE B2**  Repeatability of HRR A, and total concentration B, for C02 (black) cables

**FIGURE B3**  Repeatability of HRR A, and total concentration B, for C01 (blue) cables