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Fire behavior of halogen-free flame retardant electrical cables with the cone calorimeter

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HIGHLIGHTS

- Halogen-free electrical cables are studied using cone calorimeter tests.
- The influence of external heat flux and spacing is highlighted.
- Time-to-ignition is only dependent on the sheath properties.
- A critical heat flux corresponds to a significant change in fire hazard.
- Spacing between cables has a variable effect on fire properties.

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ABSTRACT

Fires involving electrical cables are one of the main hazards in Nuclear Power Plants (NPPs). Cables are complex assemblies including several polymeric parts (insulation, bedding, sheath) constituting fuel sources. This study provides an in-depth characterization of the fire behavior of two halogen-free flame retardant cables used in NPPs using the cone calorimeter. The influence of two key parameters, namely the external heat flux and the spacing between cables, on the cable fire characteristics is especially investigated. The prominent role of the outer sheath material on the ignition and the burning at early times was highlighted. A parameter of utmost importance called transition heat flux, was identified and depends on the composition and the structure of the cable. Below this heat flux, the decomposition is limited and concerns only the sheath. Above it, fire hazard is greatly enhanced because most often non-flame retarded insulation part contributes to heat release. The influence of spacing appears complex, and depends on the considered fire property.

1. Introduction

Several thousand kilometres of electrical cables are present throughout the nuclear power plants (NPPs). Power cables are used for instance for supplying electricity to the pumps, turbines, transformers, heaters, or to the numerous electrical cabinets contained in NPPs [1]. Furthermore, many cable trays also contain instrumentation and control cables. The former are used for digital or analogic transmission for various types of transducers while the latter serve for example for controlling valves or operating relays and contactors.

A serious cable fire occurred at the Browns Ferry NPP in 1975 [2] resulting in loss of the emergency core cooling system of unit 1. Ever since, many efforts have been made on the most recent nuclear installations all over the world to enhance the prevention of cable fires, for instance by using flame retardant materials in cables. Nevertheless, nearly seventy fire events from nuclear power plants (NPPs) involving electrical cables as fuel were recorded in the current OECD FIRE Database between the late 1980s and the end of 2010 [3].

Cable fires are therefore one of the main fire hazards which may affect the safety of NPPs. The assessment of such fire hazard and of their consequences largely relies on the use of fire models able to forecast the fire spread over cable trays. Experimental research programmes on cable fires were conducted over the past four decades for providing data at both small and large scale in order to develop and to validate some fire models. For instance, the Lee correlation [4] was built from the results of large-scale horizontal cable tray fire tests [5] and the ones on fire behavior of cable samples obtained at small-scale [6]. This correlation thus aims at assessing the peak

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of heat release rate (HRR) of horizontal cable trays fires by using the HRR peak per unit area for cable samples measured in the fire propagation apparatus [7] or in the cone calorimeter [8] under an irradiance of 60 kW/m^2. In addition, the engineering FLASH-CAT model [1] was proposed to assess the time evolutions of the HRR of a fire spreading over horizontal ladder cable trays located away from wall and ceiling. This model needs as input parameters the physical and thermal properties of the electrical cables as well as its main fire characteristics (ignition delay, HRR per unit area...), all determined at small-scale. The FLASH-CAT model was validated in the scope of the CHRISTIFIRE programme [1] which involved both large-scale horizontal cable trays fires in open atmosphere conditions and small-scale characterizations. Furthermore, small scale characterizations of the electrical cables [9] are also essential for the development of pyrolysis models [10,11]. These last ones are currently implemented in fire field models for a detailed forecasting of the fire spread over cable trays.

In the scope of the OECD PRISME-2 project [12], additional real-scale cable tray fire tests were carried out in open atmosphere [13,14]. These fire tests involved new configurations such as horizontal and slanted cable trays, both supported by a wall and filled with halogen-free flame retardant (HFFR) cable-types used in NPPs. These cable-types showed a strong impact on the fire characteristics such as the ignition delay, the fire growth rate and the effective heat of combustion (EHC) [13,14]. These original experimental results clearly highlighted the need of complementary fire tests at small and large-scale to a better understanding of HFFR cable fire behavior and to perform a complete validation of fire models. Moreover, the cable arrangement, which is an important parameter in NPPs [15], was not taken into account in the scope of these fire tests. So there is also a particular interest for investigate the effect of cable spacing on the fire characteristics.

Consequently, the current study first aims at investigating the role of the different cable components on the main fire characteristics in the case of HFFR cables based on ethylene-vinyl acetate copolymer and polyethylene (EVA-PE) matrix. The structure and composition of cables were analysed in detail and the thermo-physical and flammability properties of the outer sheath were determined. Then the burning behavior of the two cables was studied using the cone calorimeter. Time-to-ignition, HRR and EHC were measured for different external heat fluxes. An attempt was made to relate these parameters to the properties of the cable component and more especially the outer sheath. Lastly the effect of cable spacing on the time-to-ignition and the fire characteristics was investigated.

2. Experimental approaches

2.1. Materials

Two halogen-free flame retardant cables are used in the present study. The first, named cable A, has an external diameter and a mass per unit length of 12 mm and 0.21 kg/m respectively. The second one (cable B) has an external diameter of 21 mm, and a mass per unit length of 0.67 kg/m. SEM-EDX (scanning electron microscopy coupled energy-dispersive X-ray spectroscopy) observations carried out on sheath materials evidence the presence of aluminum. The decomposition of sheath (the outer layer) under nitrogen flow starts at 200 °C. This outcome confirms that the mineral flame retardant is probably aluminum hydroxide (ATH), the most used metallic hydroxide in wire and cable industry [16]. Considering the weight residue obtained from anaerobic pyrolysis in thermogravimetric analysis (around 40 wt%) it is possible to assess the fillers content: between 60 and 62 wt% for both cable-types. Indeed, polymer is fully decomposed and ATH leaves a residue of 35 wt%. This is typical of sheath formulations for such cable-type. A more detailed description of the cables is provided in the results section.

2.2. Cone calorimetry

Fire behavior was studied using a cone calorimeter [8]. There have been a large number of studies that characterized cables under such fire test equipment [1,17–21]. The first question arising when testing cables is the preparation of specimens. Recommendations from ISO 5660 standard were followed except the use of a grid. Cables were cut in pieces of 10 cm long. These cable samples were arranged one against one other without space as shown in Fig. 1. 8 and 5 cable samples were used respectively for cables A and B. Specimen were wrapped in aluminum foil and insulated by rock wool. The samples were exposed to various heat fluxes in well-ventilated conditions (air volume flow rate of 24 L/s) in the presence of a spark igniter to force the ignition. The distance between the cable samples and the cone was fixed to 25 mm. The HRR was determined by oxygen depletion according to Huggett's relation (1 kg of consumed oxygen corresponds to 13.1 MJ of released energy) [22]. In some experiments, the temperature of the upper surface of the samples was measured during cone calorimeter test using an infrared camera (Optris) to assess the temperature at ignition. For these experiments, the distance between the cable samples and the cone was fixed to 60 mm (instead of 25 mm) to allow a correct measurement (The inclination of the infrared camera must be of few degrees relative to the perpendicular position).

The use of a grid is recommended to avoid the distortion of cables during the test [8]. However, a grid reduces the heat flux absorbed by the sample and will, for instance, influence the time-to-ignition. The data on this last parameter are intended to be used in simple models for forecasting of real cable fire. Therefore in this work, the grid was removed.

2.3. Pyrolysis-combustion flow calorimetry

The flammability of each component of cables was investigated using a pyrolysis combustion flow calorimeter (PCFC from Fire Testing Technology, UK) which was developed by Lyon and Walters [23]. The sample (3 ± 0.5 mg) was heated from 80 to 750 °C at 1 °C/s

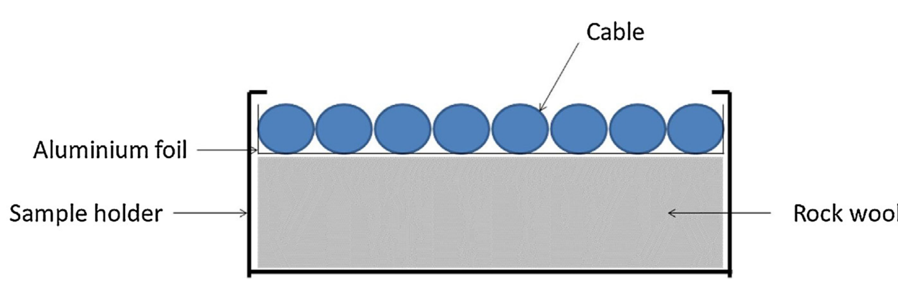

Fig. 1. Positioning of cables into the sample holder.