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# Testing of the fire-proof functionality of cable insulation under fire conditions via insulation resistance measurements

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ABSTRACT

Two different designs for low-fire-hazard cables were tested under conditions similar to those of the fire test specified in IEC 60331-21. In addition to the other standard requirements, an insulation resistance meter was connected directly to the measurement circuit to monitor the actual state of the cable insulation during the fire tests. The suitability of this measurement of the insulation resistance was demonstrated by testing cables with fire barriers made from mica glass tape and from ceramifiable silicone rubber. The results showed that insulation resistance is sensitively affected by the melting of the organic components of insulation, by the decomposition of the fire retardant, by the ignition of the core insulation and by the formation of a silica layer during a fire test. The results also helped to reveal the importance of flame conductivity in performing such tests. The initial observations are supported by thermogravimetry and differential scanning calorimetry, which are beneficial as a first step towards understanding the mechanisms of fire-proof functionality in cables. The suggested procedure can assist in the comparison of the fire-proof functionalities of different cable designs, in the analysis of their failure mechanisms and in cable design optimisation.



## 1. Introduction

Polymers are an essential part of our world and lives. Their properties can be modified considerably, which has led to their widespread application in many industrial fields. The cable industry is no exception, and many types of polymers play important roles in this field. Unfortunately, one of their weaknesses in various applications is their flammability. Statistics collected by Keski-Rahkonen et al. [1,2] in nuclear power plants confirm that cables can be a major source of fire ignition. Moreover, once a flame is ignited, a cable can further contribute to its propagation [3]. Considering that cable lines must often be installed in link areas and across fire walls, their usage may be rather hazardous in many cases. Cable design, insulation and sheathing materials together determine the effectiveness of cables against flame ignition and propagation [4]. Special care must be taken when cable lines are installed in areas with increased risk of fire or increased incidence of people. Fire-resistant cables, so-called low-fire-hazard cables (LFHCs), have been developed to satisfy the requirements of low flame spread and heat release together with very low emission of smoke and dangerous gases [5,6] and should be used in such situations. The functionality and duration of reliable operation of fire-resistant cables must be confirmed to ensure the safety of all individuals [7] and to guarantee the functionality of safety and emergency systems. The necessary time of operation is determined based on the length of the escape route from a burning building to a safe place. The highest-quality materials are required, particularly for cables that are used directly for fire-safe facilities, e.g., in fire alarm systems, fire-extinguishing devices and fire water pumps.

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Fire-proof functionality is achieved by using both organic and inorganic flame retardants as cable compounds, thereby reducing flammability, delaying combustion or inhibiting fire spread. Large quantities (60–70%) [8,9] of inorganic filler materials such as metal hydroxides (aluminium trihydroxide, $Al(OH)_3$, or magnesium hydroxide, $Mg(OH)_2$) are widely used. Their interaction with fire has previously been described by many authors [9–12] and can be briefly summarised as follows:

- retardants slow the thermal decomposition of the overall material by releasing a significant amount of water in an endothermic reaction and hence absorb energy from the combustion zone, and
- retardants produce char and a metal oxide coating that can act as a protective layer during combustion.

Together with the aforementioned retardants, the fire-proof functionality of cables can be further improved by incorporating a special fire-protective layer (fire barrier) within the cables (such as glass tape, mica glass tape or ceramifiable silicon rubber).

The fire-proof functionality and other fire-test parameters of cables are practically tested in conformity with many industrial standards [13]. The global standard IEC 60331-21 (tests for electric cables under fire conditions — circuit integrity) [14] is perhaps the most common standard for this purpose; it specifies a test procedure and performance requirements, including a recommended flame-application period, for cables with rated voltages up to and including 600/1000 V. The standard is intended to cover low-voltage power cables and control cables with rated voltages. In addition, IEC 60331-11 [15] specifies the test apparatus to be used for testing cables required to maintain circuit integrity when subjected to fire alone, in which the test conditions are based on a flame with a controlled heat output corresponding to a temperature of at least 750 °C. The test period is determined based on the length of the longest escape route from a burning building and should be equal to 30, 60, 90 or 180 min, followed by a 15-min cooling period, at a rated voltage. According to IEC 60331-21, circuit integrity is defined as the "ability to continue to operate in the designed manner whilst subjected to a specific flame source for a specified period of time". The voltage must be maintained (i.e., no fuse failures or circuit-breaker interruptions), and the conductor must not rupture over the defined period. Cables that maintain their circuit integrity and consequently satisfy the performance requirements specified in the standard can be denoted, for example, "IEC 60331-21 (90)", where "90" indicates 90 min of flame application.

As indicated by the foregoing discussion, based on the obtained results, a tested cable can either pass or fail a test in accordance with IEC 60331-21. In addition, we presume that every cable producer would desire answers to the following questions. How exactly does the internal structure of cable insulation respond to high temperature? Why does a cable fail during testing? Which cable design is better? Where is the weakest point in the construction of a tested cable? Typically, the standard test method cannot provide such information because the determination of these properties is not related to the primary purpose of IEC 60331-21. However, as our results show, the testing procedure can be modified by including a suitable insulation resistance meter connected directly to the measurement circuit. Previously, Wang et al. [16] also used an insulation resistance meter to determine the failure times of polyvinyl chloride (PVC) insulated power cables under fire conditions similar to those of the ISO 834 standard (horizontal fire resistance test furnace) [17]. Their results proved that measurements of the insulation resistance between insulated cable cores can indicate the actual state of the cable insulation throughout the entire fire test. Wang et al. [16] focused only on the identification of the "failure point" (the beginning of the rapid deterioration of the cable insulation) and the "breakdown point" (the point at which a short circuit occurs between the insulated cable cores). Nevertheless, an analysis of the insulation resistance behaviour between these two points can also be very interesting and should be explored in detail. Consequently, such an analysis can provide important insight into the processes that accompany the burning of cable insulation and thus can assist in the comparison of the fire-proof functionalities of different cable designs, in the analysis of their failure mechanisms and in cable design optimisation.

For these reasons, in our study, we attempted to gain a detailed understanding of the behaviour of the insulation resistance of low-fire-hazard cables under fire conditions. To demonstrate the complexity of our findings, we tested the performance of cables with two different designs (a cable with a fire barrier made from mica glass tape and a cable with a fire barrier made from ceramifiable silicone rubber) that were subjected to conditions similar to those of the test specified in IEC 60331-21, utilising the modified test apparatus detailed in IEC 60331-11. The measurement set-up was adapted to enable insulation resistance measurements. The cables were not under load; however, the insulation resistance meter remained connected throughout the entire fire test. Herein, we hope to provide a detailed overview of the behaviour of these types of cables during a fire based on measurements of their insulation resistance in the time domain. To support and interpret our initial observations, two thermocouples were placed near the cable sheath and between the insulated cable cores during testing. Moreover, the cable insulation compounds were examined via thermogravimetric analysis (TGA) and differential scanning calorimetry (DSC).

## 2. Experimental

### *2.1. Description of tested cables*

Power cables with two different designs were tested: a cable with a fire barrier made from mica glass tape (henceforth referred to as "Cable 1", Fig. 1a) and a cable with a fire barrier made from ceramifiable silicone rubber (henceforth referred to as "Cable 2", Fig. 1b).

The central copper conductor of Cable 1 was protected by two layers of mica glass insulation tape (1) based on mica paper (phlogopite), reinforced with glass fibre fabric. Mica glass tape allows for the creation of an inorganic, fire-resistant insulating layer under fire conditions. The core insulation (2) was composed of cross-linked polyethylene (XLPE). In addition to its excellent dielectric properties, XLPE allows cables to operate safely at temperatures above those allowed by thermoplastic materials (e.g., PVC) because of its cross-linking structure. The tested cable consisted of five insulated conductors wrapped together in a "Z" configuration with polyester film tape (PET) (3), thereby providing separation of the conductors from the inner cable bedding. The bedding (4) was