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Original Article

Experimental testing and evaluation of coating on cables in container fire test facility

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A B S T R A C T

Fire tests were conducted on cables using fire-retardant paint employed in nuclear power plants that transmit electrical power, control and instrument signals. The failure criteria of various power and control cables coated with fire retardant coating at three different coating thicknesses (~0.5 mm, 1.0 mm & 1.5 mm) were studied under direct flame test using Container Fire Test Facility (CFTF) based on standard tests for bare cables. A direct flame fire test was conducted for 10 min with an LPG ribbon burner rated at ten by fixing the cable samples in a vertical cable track. Inner sheath temperature was measured until ambient conditions were achieved by natural convection. The cables are visually evaluated for damage and the mass loss percentage. Cable functionality is ascertained by checking for electrical continuity for each sample. The thickness of cable coating on fire exposure is also studied by comparing the transient variation of inner sheath temperature along the Cable length. This study also evaluated the adequacy of fire-retardant coating on cables used for safety-critical equipment in nuclear power plants.

1. Introduction

Electrical cables with flammable insulation material are widely used in Nuclear Power Plants (NPPs) Cable for transmitting electrical power, control and instrument signals. In general, thermosets have a higher heat tolerance than thermoplastics. These cables form a majority of the combustion sources, and most of the past fire incidents involved cables, even in situations where the fire source was not an electrical cable. So, cable safety monitoring is an essential part of safety management [1]. The effect of cable fire was discussed in a cable fire accident at Browns Ferry NPP [2], which resulted in the loss of an emergency core cooling system. To reduce the risk of rapid ignition and fire spread, Fire Retardant Low-Smoke (FRLS) Poly-Vinyl Chloride (PVC) cables and Cross-linked Poly-Ethylene (XLPE) cables are used extensively in the nuclear industry, among other types, for high power cables [3]. Many large-scale cable fire tests were conducted to study cable performance and its flame spread characteristics [4]. Also, the experiments were studied under well-ventilated and vitiated conditions [5]. Even vertical cable tray fire tests were conducted in which cable flame spread characteristics and failure of Cable were discussed [6]. This test carried different cable spacing to influence flame spread and ignitibility [7]. Ignitibility, burning characteristics and other physical properties of the cable materials are dependent on the polymers and additives used in their manufacturing process. Fire protection properties of old cables may start to pyrolyze, which was studied and compared with new cables using FTIR & MCC experiments [8]. While these cables are inherently resistant to fire

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propagation, additional passive safeguards must be provided by coating them with fire retardant coating or paints. Further, fire stops/breaks are installed at central locations along cable trays to prevent fire spread and ensure fire compartmentalization. The fire-retardant colours (FRP) are special formulations to prevent cable damage, ignition and fire spread. Fire retardant coatings were grouped into two types: Non-intumesant and Intumesant. In Non-intumesant type coatings, compounds like Boric acid, antimony trioxide, Zinc oxide did not support combustion [9,10], but intumescent coating swells up upon heating and acts as a protective layer. Largely, water-based intumescent paints are widely used, the effect of fire-retardant characteristics was discussed [11]. In practice, several intumescent paint coatings are applied to individual or grouped cables. However, at higher temperatures, the colour may degrade and lead to insulation. Characterizing the thickness of coating essential for good fire resistance is thus an important research topic [12].

Inference from the previous studies states that the cables coated with intumescent paint when subjected to external fire need to be thoroughly investigated. The focus is on performing tests on the behaviour of bare and coated power and control cables when subjected to fire conditions. Post-fire exposure, the parameters of interest are the swelling rate of coated Cable, decomposition, flame propagation, cable damage, mass loss rates, the effect of coating thickness on cable performance, etc. This work consolidates the detailed description of the cable fire experiments carried out in CFTF. Experiments are carried out using power cables originally used in FBTR and new wires for power, control, and signal transmission [13,14]. The lines were tested in vertical-tray flame test configuration, in uncoated condition, and with several thicknesses of intumescent paint coating. Test samples were prepared, and experiments were conducted loosely based on available bare cables testing. Thermocouples are used to obtain temperatures of sheath materials. Tested samples are assessed using visual inspection and quantitative temperature data.

2. Materials & methods

2.1. Specimen preparation

Sample cables A, B, C and D, made up of copper and aluminium conductors and having 16-, 26-, 19- and 23-mm diameter, respectively was employed for inspection. The cables were armored by G.I. Wire armor having 7, 3, 4 and 13 cores respectively and insulated with a fire-retardant low smoke insulator. A cross-sectional view of all the samples is shown in Fig. 1.

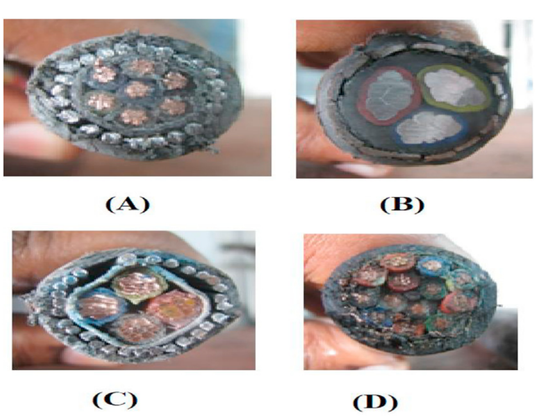

Fig. 1. Cross-sectional view of all the samples.

2.2. Experimental setup

A total of two K-type thermocouples were placed at a spacing of 150 mm (One thermocouple in the flame zone and one above flame zone) along the length of the Cable to record insulation temperature. For this setup, an LPG ribbon burner rated at 20 kW is placed at a distance of 305 mm from the bottom end of the Cable. A flowmeter calibrated to 50 lpm of air is located in the LPG line to control the gas flow to the burner. The flow rate of LPG is adjusted to provide a theoretical heat output of 20 kW. The specimen is exposed to the flame for 10 min at this flowrate specified in the standard. To pass this cable fire performance test, the Cable should self-extinguish when the external flame is removed. Further, the total charred length of the Cable should not exceed 1500 mm. After the burner is put off, the Cable can cool by natural convection heat transfer to ambient air.

3. Results & discussions

This section details the effect of thickness of cable coating on fire exposure of various samples by comparing the transient variation of inner sheath temperature along the Cable length. The test also determines the flame propagation tendency of multi-conductor cables intended for use in cable trays. The tests are carried out following IEEE Standard for Flame-Propagation Testing of Wire and Cable. Four cable samples (600 mm length) in which one is uncoated and the other three are coated with intumescent paint at 0.5 mm, 1.0 mm & 1.5 mm thickness is cut from the spool of each type of Cable. The normal brush method is adapted for coating Intumescent paint, and 24 h of curing time are given for each second and third coat. After curing, two holes of 1 mm diameter at150 mm pitch are drilled over the length of each Cable for fixing thermocouples. The cable samples (4 Nos) of the same type are mounted on a perforated galvanized iron tray of 300 mm width and 2440 mm length. The setup is placed under a 2.4 × 2.4 m exhaust hood equipped with a high-temperature exhaust fan of 1.5 m^3/s capacity for venting smoke and gases generated during the test [15,16].

3.1. Sample A

Sample A in four numbers (A0, A1, A2 and A3) were used in this test. Flames from A0 are seen within the 30s of application of external flame. A yellowish flame of ~150 mm in length is seen intermittently on the exposed portion of the bare Cable while all the other samples remain unaffected, as shown in Fig. 2. After 1 min, a slight bulging of the intumescent paint is observed in the vicinity of the external flame. On the bare Cable, ~300 mm of Cable is seen to be charred and constant yellow flame indicates pyrolysis of the sheath material. Within 2.5 min, the flame of bare Cable is seen to spread to 400 mm length, and deformation of the sheath is observed, whereas the coated cables remain intact with only slight bulging of the F.R. paint (Refer Fig. 2). After 3 min, the sheath material on the bare Cable is completely charred, and flame length is reduced to <50 mm. Due to the thermal expansion of aluminium, protrusion of armor is observed from the top portion of all cable samples. At ~4.5 min, intermittent flashes are seen on coated cable samples during the expansion of the coating material. Meanwhile, as the insulation material starts burning, the flame is seen on A0, and the inner sheath temperature is ~275 °C. During this experiment, sample A2 moved closer to the ribbon burner unexpectedly. This may be attributed to the thermal expansion of armor and the non-uniformity of the external flame. Maximum bulging was noticed in A2. Insulation material in A0 is consumed after 6 min, and armor is exposed. It is also noted that all the coated samples

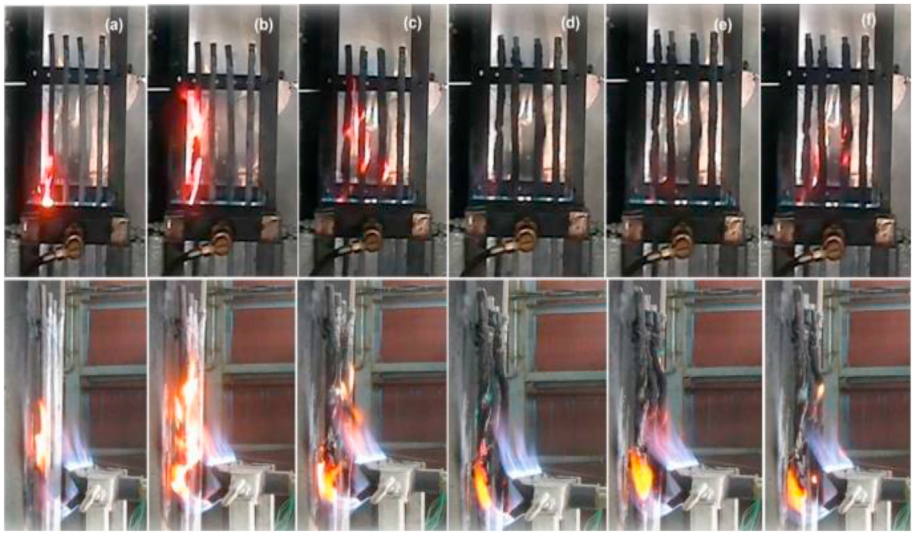

Fig. 2. Photographic view of cables sample A at different time intervals.

have bulged in the exposed region. The expanded coating acts as temporary protection and insulates the cables from external flame. The temperature of the uncoated Cable reaches 300 °C, whereas the temperature of A3 is ~130 °C. Char from the intumescent paint protects the rest of the experimental duration (~4 min). Peak temperature at 10 min is 425 °C in A0 and 180 °C in A3. Post-inspection, it is seen that the back portion of coated cables is completely intact without any discolouration or damage, whereas the bare Cable is completely damaged.

3.2. Sample B

Sample B in four numbers (B0, B1, B2 and B3) were used in this test. The cable sheath of B0 is ignited after 15 s of external flame application, as shown in Fig. 3. The flame propagates steadily, and a length of 300 mm is seen to ignite within 1 min. This Cable is ignited much earlier than other samples as the sheath material is PVC. Consequently, the fire's intensity and growth rate are higher than earlier experiments using FRLS cables. Flashes of flame are also observed on the coated cables. After 2.5 min, a significant bulging of the intumescent paint is seen on all cables. Since the cable material is not fire-resistant, gases from the pyrolysis diffuse through the paint and ignite at the surface. The degradation of the expanded paint commences, and an external flame has directly impinged on the cable surface. After 3 min, all cables except B3 are burning [17]. The inner sheath temperature reached 300 °C within 3 min of the test. However, temperatures at this location are significantly lower in coated samples. The intumescence reaches a maximum of 4 min, and the coating surface is 3 mm away from the ribbon burner. This causes the paint to be exposed to more severe

Fig. 3. Photographic view of cables sample B at different time intervals.

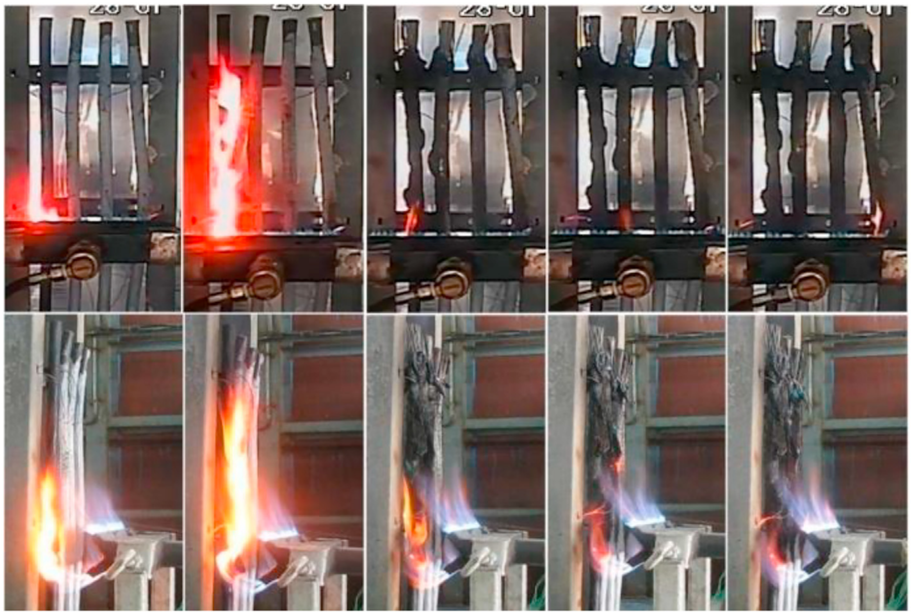

Fig. 4. Photographic view of cables sample C at different time intervals.

conditions. Total flame length is seen to exceed 1 m for this experiment. Cable B3 is noted to be relatively unaffected in this duration. The fire continues for 7 min until the sheath material in B0 is exhausted.

3.3. Sample C

This experiment is carried out using cable samples C0-C3. The surface area of C0, which is exposed to external flame, is ignited after 30 s of external flame application and is shown in Fig. 4. The fire-retardant PVC sheath resists flame propagation, and a flame of approximately 25 cm in length is observed following the cable ignition. After 1.5 min, the sheath of C0 begins to bulge, and char starts to form. Within 2 min, most of the outer sheath material is ignited, and almost 500 mm of the Cable is seen to be engulfed in flame. However, the other cables are unaffected, and swelling of coating is not observed. At this point, the temperature of the inner sheath of coated cables is seen to be ~100 °C, whereas the bare Cable reaches ~175 °C. The sheath material on C0 burns for approximately 4.5 min, and the flame is exhausted. However, flame from the cable sheath during this duration causes localized swelling of a segment of paint on C1 [18]. Inner sheath temperature of C0 near the flame location reaches 300 °C. The temperature at the flame location of C2 and C3 are below 150 °C. No consistent flames are seen on any cables after 5 min. Intermittent flames at around 8 min in C2 and C3 cause swelling of the paint. However, no flame propagation or smoke is observed from any cables [19,20].

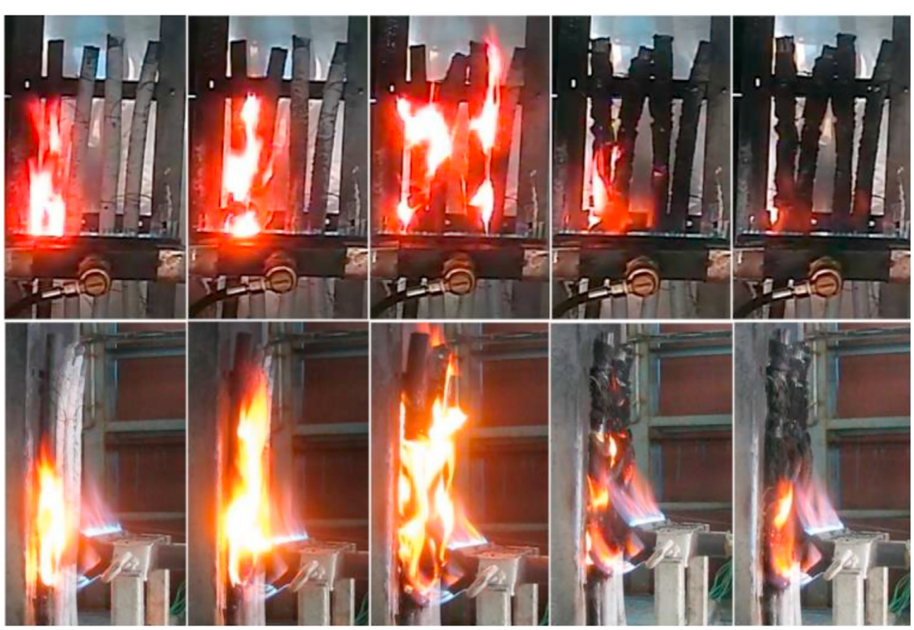

Fig. 5. Photographic view of cables sample D at different time intervals.

3.4. Sample D

This test is carried out using samples D0-D4. D0 starts Ignition after 30 s of external flame application. At 2 min, thermal expansion of the armor and conductor causes D1 to bend and move towards D0, as seen in Fig. 5. For the rest of the experimental duration, a portion of D1 is seen to remain in contact with D0. This causes the coating on D1 to bulge excessively and cause intermittent flames at 3 min. The coating on the other cables gradually bulges as the inner sheath temperature increases [21]. However, no flames are seen on D2 and D3 until ~4.5 min. After this point, the inner sheath temperature of D2 and D3 increase above 150 °C and maximum bulging is observed at 6 min. Within this period, flames are observed on these cables. In this test, sheath materials on cables D0 and D1 constantly burn for the first 8 min following Ignition until sheath material is exhausted [22, 23]. However, cables D2 and D3 remain unaffected until 5 min, following which intermittent flames are observed, only in the presence of external flame. As the external flame is removed at 10 min, all flames are self-extinguished, and no afterburn is observed.

4. Conclusion

This work analyzed the tests on coated and cable samples coated with intumescent fire-retardant paint. Galvanized iron ladder and perforated trays were installed in a vertical flame test configuration to mount the cable specimens. On visual inspection, physical damage of Cable due to fire is found to be more on uncoated Cable whereas coated Cable has minimum physical damage. After exposure to the fire, electrical continuity in most cores within the bare cables was lost without affecting its continuity. The peak temperature of bare cables near the flame region was 350–500 °C. The peak temperature of cables coated with three coatings was less than 220 °C in all cases and decreased with coating thickness. Further, the percentage of reduction in weight shows that coated cables have a lesser percentage than coated cables. Hence, it is concluded that a thickness of ~1.5 mm is adequate for shielding the power and control cables from external fires up to 10 kW when exposed for 10 min and shall be employed in nuclear power plants.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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