iJRASET
International Journal For Research in Applied Science and Engineering Technology



INTERNATIONAL JOURNAL FOR RESEARCH

IN APPLIED SCIENCE & ENGINEERING TECHNOLOGY

Volume: 14 **Issue:** XI **Month of publication:** November 2026

DOI: https://doi.org/10.22214/ijraset.2026.85594

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International Journal for Research in Applied Science & Engineering Technology (IJRASET)
ISSN: 2321-9653; IC Value: 45.98; SJ Impact Factor: 7.538
Volume 14 Issue XI Nov 2026- Available at www.ijraset.com

PVC Cable Burning Behaviour and Intumescent Protection: Small-Scale Tests and the Browns Ferry Lesson

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Abstract: ***Electrical cables are present in nearly every building and industrial site. In a fire they can act as the starting point, as a path along which flames travel, and as a major producer of smoke. This paper presents laboratory results for a single-core PVC-insulated copper cable and a literature review of passive fire protection (PFP), with attention to intumescent coatings. Two standard tests were run: vertical flame propagation under IEC 60332-1-2, and cone calorimetry at 40 kW/m² under ISO 5660-1. Both vertical specimens passed. Flames died out within 5 s of removing the burner, and charring reached only 80 mm and 160 mm along a 600 mm length. In the cone calorimeter the insulation ignited at 125 s, peaked at 114.89 kW/m², gave a total heat release of 70.81 MJ/m² and a smoke production rate of 0.175 m²/s. The material therefore shrugs off a small flame but, under sustained radiant heating, becomes a long-lived source of heat and smoke. The review part explains how intumescent coatings function, the product families available, how they fail, and how the 1975 Browns Ferry fire reshaped cable-protection rules.***
Keywords: cable fire; PVC insulation; IEC 60332-1; cone calorimeter; passive fire protection; intumescent coating; Browns Ferry.

I. INTRODUCTION

A. Background

Cables usually go unnoticed. They run above ceilings, below floors and through trays, supplying power and signals to everything a facility relies on. Attention arrives only after a failure, and the consequences can be severe. Cable fires rank among the most frequent causes of building fires, and plastic-insulated cable is an underestimated fuel that can both start a fire and help it spread [1,5]. Typical origins are aged or damaged insulation, overheating from overload or a loose connection, an electrical fault, or exposure to a fire elsewhere [1,8]. A burning cable does not remain a local problem, because cable routes are long and continuous through trays, shafts and galleries. Tests on arc-damaged cables suggest an adjacent cable may catch fire in about 40 seconds [5,7], which is faster than many detection and response arrangements can react. Spread along a cable is difficult to forecast. It is governed by the insulation type, the conductor, the bundling arrangement and the surrounding airflow. The metal core may remove heat in one situation and supply it in another [4], so behaviour is non-linear and small tests show only part of the picture. Passive protection is valuable for this reason: barriers, seals, wraps and coatings need no power and no human action. Their value, however, depends on correct selection, installation and maintenance, and evidence on how they perform after years of service is limited.

B. Scope

The work has three parts. First, a short review of cable construction, ignition and flame spread. Second, our own tests on one single-core PVC-insulated copper cable: a vertical flame test (IEC 60332-1-2) and a cone calorimeter test (ISO 5660-1) at 40 kW/m². Third, a review of passive protection centred on intumescent coatings (composition, types, properties, function and hazards), followed by the Browns Ferry fire of 1975 as a case study. Only one cable type and small-scale tests were used. Large tray tests, ageing studies and tests on coated samples could not be carried out and are proposed as future work.

C. Objectives

1) Describe how construction and insulation material affect ignition and flame spread in cables.
2) Measure ignition resistance, flame propagation, heat release, mass loss, smoke and carbon monoxide for PVC cable under standard conditions.
3) Explain how intumescent coatings work, which types exist, and which properties and hazards matter.

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4) Examine a real fire in which the presence or absence of passive protection decided the outcome.
5) Connect the test results to protection requirements and identify gaps in current practice.

II. HOW CABLES ARE BUILT AND HOW THEY BURN

A. Layers and Materials

A power cable consists of concentric layers around a metal conductor (Fig. 1a). In medium- and high-voltage designs the sequence outward is usually conductor, conductor shield, insulation, insulation shield, metallic screen or sheath, and outer jacket [3]. The arrangement varies with voltage and application; the metallic sheath is sometimes omitted where outside ignition risk is low. Our test cable is a far simpler single-core PVC-insulated copper wire.

Conductor. Copper and aluminium are the usual metals. Copper moves heat away from the flaming region efficiently, which keeps the insulation cooler, and published work reports lower heat release for copper than for aluminium conductors [3]. Steel braid or metallic armour adds protection by hindering flame penetration and lowering heat and smoke output [3].

Insulation and sheath. Table 1 summarises three common materials. PVC is a thermoplastic that softens, drips, and burns with dense smoke and hydrogen chloride. XLPE is a thermoset and forms char instead of flowing, which slows the advance of the flame front. LSZH compounds are designed for low smoke and almost no halogen acid gas [7,8]. Material choice is also an electrical decision, since the conductivity of XLPE and EPDM varies strongly with temperature [6], so fire behaviour is only one of several competing requirements.

Table 1. Fire-related comparison of common insulation and sheath materials (values as reported in the reviewed literature [7]).

Material	Class	Behaviour in fire	Smoke index	Flame-front speed
PVC	Thermoplastic	Melts and drips; dense black smoke; hydrogen chloride (HCl)	350	up to 1.9 mm/s
XLPE	Thermoset	Chars instead of melting; halogen-free; slower spread	150	0.4–0.9 mm/s (thermoset cables)
LSZH	Halogen-free compound	Low smoke; essentially no HCl	100	below 1 mm/s (HFFR cables)

B. Routes to Ignition

A wire can be brought to ignition in three ways (Fig. 1b): (a) radiant or convective heating from an outside flame or hot gases; (b) heat conducted into the core from a hot spot or poor joint and passed outward to the insulation; and (c) Joule heating in the core during overload or short circuit [4]. In case (a) the core acts as a heat sink, spreading heat along the wire and possibly quenching a weak flame, so additional external heating may be required before flames spread. In cases (b) and (c) the core is the heat source. Actual faults frequently involve a mixture of the three.

Flame-retardant cables show a further behaviour. When heat flux rises, a PVC sheath over XLPE insulation begins to decompose and swells to about double its diameter as gas gathers beneath the softened layer. Gases from the decomposing XLPE reach the charred layer and ignite with no spark or pilot flame. The sheath surface was near 500 °C at that moment regardless of heat flux; a higher flux only reduced the time to ignition [2].

C. Spread of Flame

After flaming begins, heat travelling forward through the core pre-heats the unburnt insulation, helping the flame advance. Thermoplastic insulation melts, and burning droplets can start new fires below. In stacked trays, hot gas and radiation warm the trays above and the stack behaves like a chimney. The literature describes the second tray igniting about 4 minutes after the first, the third roughly 3 minutes after that, and upper trays at about one-minute intervals [7]. Orientation also matters: horizontal wires can show faster spread than vertical downward spread, owing to differences in heat exchange among flame, core and insulation [4]. If the heat released is too small to decompose the insulation, or the core draws away too much heat, the flame simply goes out.

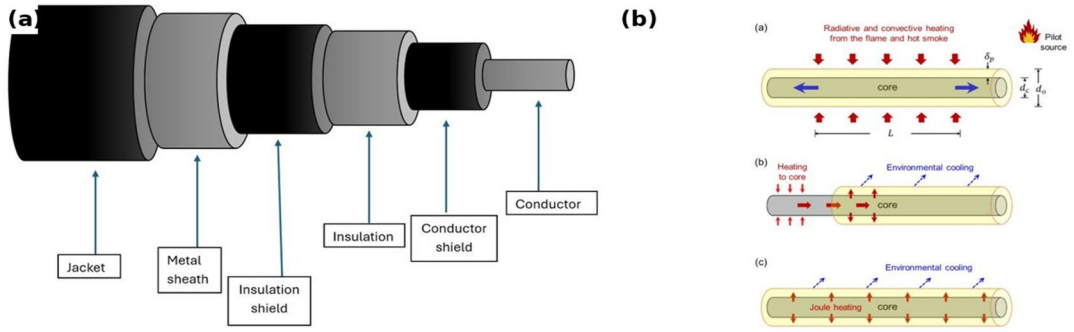


Figure 1. Cable construction and routes to ignition. (a) Basic layers of a power cable; (b) the three heating routes, adapted from [4].

III. EXPERIMENTAL PROGRAMME

Tests were performed at the National Fire Service College, Nagpur, in September 2026. Two standard methods were chosen because they answer different questions. The vertical flame test shows whether a cable will carry fire after contact with a small flame. The cone calorimeter shows how much heat, smoke and gas the material produces once burning under radiant heat.

A. Specimen

The sample was a single-core PVC-insulated cable with an annealed copper conductor and a total diameter of 12.5 mm. For the vertical test, 600 mm lengths were cut and conditioned for at least 16 hours at (23 ± 5) °C and (50 ± 20) % relative humidity. For the cone test, the PVC was stripped off the copper and used as raw material for a flat plaque (Section 3.3).

B. Vertical flame Propagation (IEC 60332-1-2)

Arrangement. The cable hangs vertically at the centre of an open-fronted steel screen about 1200 mm high, 300 mm wide and 450 mm deep, which shields the flame from draughts (Fig. 2a). The ignition source is a 1 kW pre-mixed propane–air burner [14]. Technical-grade propane (at least 95 % pure) was supplied at about 650 mL/min with roughly 10 L/min of air, and the flame was verified with a copper calibration block before testing (Fig. 2b). The supports were 550 mm apart. The burner was inclined at 45° to the cable, with the tip of the inner blue cone touching the insulation 475 mm below the lower edge of the upper support (Fig. 2c).

Method. For cables of 25 mm diameter or less the standard prescribes 60 ± 2 s of flame application; we used 62 s. The burner was then removed smoothly, the time for any remaining flame to extinguish was recorded, and the cable was allowed to cool. After wiping off soot, the damaged length was measured from the burner contact point. A cable passes if the charred region stays more than 50 mm below the lower edge of the upper support. Two specimens were tested.



Figure 2. IEC 60332-1-2 vertical flame test. (a) Test chamber; (b) 1 kW burner flame during calibration; (c) flame applied to the PVC cable.

Table 2. Vertical flame propagation results (600 mm PVC specimens, 12.5 mm diameter).

Specimen	Flame applied (s)	Burning period (s)	Burning after burner removed (s)	Damaged length (mm)	Unaffected length (mm)	Result
1	62	64	2	80	520	Pass
2	62	67	5	160	440	Pass

C. Cone calorimeter (ISO 5660-1)

Specimen preparation. A cable is round and partly metallic. Tested as supplied, it would present a different exposed area in each run and the copper would conduct heat out of the sample. For this reason the PVC was removed from the conductor, weighed (Fig. 3a), cut into small pieces and pressed in a square mould with a hydraulic press (Fig. 3b) until it fused into a dense flat plaque of 100 mm × 100 mm × 10 mm (0.01 m²). The sides and base were wrapped in aluminium foil so that only the top face received heat and the heat flow stayed one-dimensional.

Apparatus. The cone calorimeter (Fig. 4) works on the oxygen-consumption principle, in which the heat released by most fuels is proportional to the oxygen consumed [15]. A conical electric heater, calibrated with a Schmidt-Boelter gauge, supplied a constant 40 kW/m². The plaque rested on a load cell (0.1 g resolution) 25 mm below the heater, with a spark igniter about 13 mm above the surface. Combustion products were drawn through a hood and duct at 24 L/s. Flow was measured by a bidirectional probe, oxygen by a paramagnetic analyser, smoke by a helium-neon laser photometer, and gases such as CO by an FTIR analyser fed through a line heated to about 180 °C. Data were logged every second. Test conditions are listed in Table 3.

Method. The analysers were warmed for 30 minutes, and the heat flux was set to 40 kW/m² and checked for uniformity. Exhaust flow was set to 24 L/s, the oxygen analyser was zeroed on nitrogen and spanned on ambient air (20.9 % O_2), and the FTIR was calibrated with zero and span gases. After 60 s of baseline logging, the plaque was mounted at 25 mm separation and the heat shield was withdrawn to begin exposure. The spark igniter stayed on until sustained flaming was recorded, then was switched off, and the test continued until the flame died out. The foil tray and char were taken out after cooling (Fig. 3c).

Table 3. Cone calorimeter test conditions.

Parameter	Value	Parameter	Value
Standard	ISO 5660-1	Specimen size	100 × 100 × 10 mm (0.01 m²)
Incident heat flux	40 kW/m²	Separation from heater	25 mm
Exhaust flow	24 L/s	Calibration factor, C	0.0440
Heat released per kg O_2, E	13.1 MJ/kg	Test date	15 September 2026



Figure 3. Cone calorimeter specimen preparation and residue. (a) Weighing the stripped PVC; (b) hydraulic press used to form the plaque; (c) char left in the foil tray after the test.

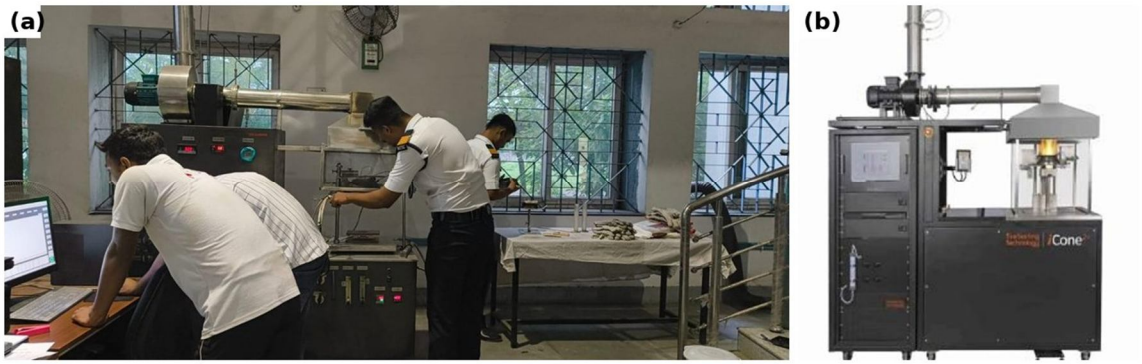


Figure 4. Cone calorimeter used for the ISO 5660-1 test. (a) Set-up in the laboratory; (b) unit with hood.

IV. RESULTS AND DISCUSSION OF TESTS

A. Vertical Flame Test

Both specimens passed (Table 2). Residual flaming ended within 2 s and 5 s of burner removal, and damage was limited to 80 mm and 160 mm of the 600 mm sample, far from the 50 mm limit at the upper support. Some molten material dripped near the lower end. This result fits the chemistry of PVC. It contains roughly half its weight as chlorine, which acts in the gas phase to interrupt combustion reactions, and its limiting oxygen index is only slightly above the 21 % oxygen in air (about 23–30 %, depending on plasticiser). Such a cable does not easily carry fire up a vertical run when touched by a small flame. Two cautions apply. The test uses one cable and a small flame, so it says little about bundled cables in trays, which fall under a different part of the standard series. Also, a cable that passes may still drip burning plastic onto items beneath it.

B. Cone Calorimeter

Measured values are in Table 4 and the heat release and mass curves in Fig. 5. The plaque ignited after 125 s at 40 kW/m². Flaming continued for about 1746 s (29 minutes) and ended at 1871 s.

Table 4. Cone calorimeter results for PVC cable insulation at 40 kW/m².

Quantity	Value	Quantity	Value
Time to ignition (flame-in)	125 s	Total heat release, THR	70.81 MJ/m²
Time to flameout	1871 s	Mass loss rate, MLR	8.55 g/m²·s
Peak heat release rate, qA,max	114.89 kW/m²	Total mass loss, TML	3870 g/m²
Mean HRR, first 180 s, qA,180	14.82 kW/m²	Smoke production rate, SPR	0.175 m²/s
Mean HRR, first 300 s, qA,300	23.69 kW/m²	CO peak	0.70 [unit to be confirmed]
Max. average rate of heat emission, MARHE	35.90 kW/m²		

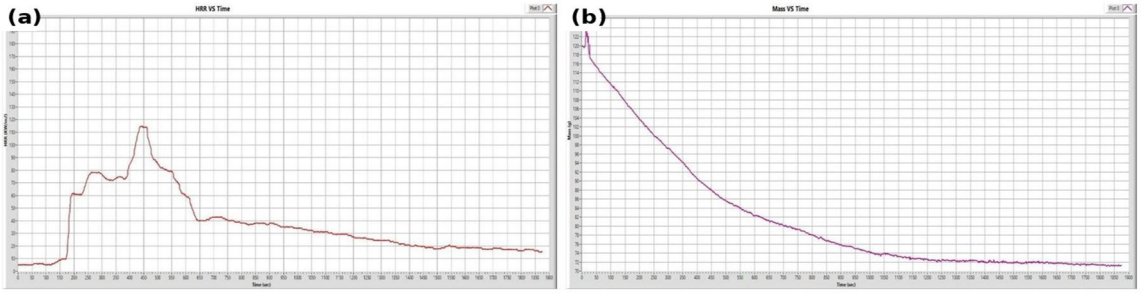


Figure 5. Cone calorimeter output for PVC cable insulation at 40 kW/m². (a) Heat release rate against time; (b) specimen mass against time.

Heat release. The curve climbs sharply at about 175 s to near 60 kW/m², then holds a shoulder of 70–80 kW/m². It later rises to the peak of 114.89 kW/m² at around 450 s and falls to roughly 40 kW/m² by 650 s, after which it tails off slowly for about twenty minutes. The trace begins to rise somewhat later than the logged flame-in time of 125 s. The peak is moderate, but the burning is prolonged: the total of 70.81 MJ/m² is the heat a PVC layer of this thickness would contribute to a compartment. From the reported values we calculated a fire performance index (time to ignition divided by peak HRR) of 125/114.89 ≈ 1.09 s·m²/kW and a growth rate (peak HRR divided by time to peak) of about 0.26 kW/m²·s.

Mass loss. Mass falls steadily at first and then levels off near 1100 s (Fig. 5b), when pyrolysis is largely complete. The total loss was 3870 g/m². Low-level flaming continued until 1871 s, sustained by the last volatiles and the char. The mass loss rate of 8.55 g/m²·s kept fuel flowing to the flame through the main burning period.

Smoke and gases. A smoke production rate of 0.175 m²/s agrees with the familiar picture of PVC as a dense smoke producer, one that would rapidly cut visibility in a closed space such as a cable gallery. The FTIR recorded a clear CO peak, indicating incomplete combustion. Hydrogen chloride is the other principal hazard of PVC, but it did not appear in the test printout, so no value can be reported here.

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C. The Two Tests Together

The results are consistent. PVC cable resists ignition by a small flame and does not carry fire far along a single vertical cable. Under sustained radiant heat, however, it ignites within a couple of minutes and goes on releasing heat, smoke and CO for around half an hour. This matches conditions in a cable gallery, where the main threat is heat from a nearby fire rather than a small flame. There are three limitations: only one cable type was tested, the cone specimen was a pressed plaque without the copper heat sink, and no coated samples were examined. The findings should be treated as a baseline.

V. PASSIVE PROTECTION AND INTUMESCENT COATINGS

A. Passive Protection for Cables

Passive protection confines a fire to its origin and buys time for critical circuits, without sensors, power or human action. For cables it takes several forms: fire-rated seals where cables pass through walls and floors; boards, barriers and enclosures around trays; wraps and blankets; fire-retardant or intumescent coatings; circuit-integrity cable such as mineral-insulated types; and the selection of low-smoke halogen-free cable from the start. PFP does not replace detection and suppression. It slows the fire and limits its size so that active systems have a chance to work. Studies on coated PVC cables and cables in trays report that fire-retardant coatings delay insulation failure [9–11].

B. Working principle of Intumescent Coatings

"Intumescent" means swelling on heating. A typical coating combines an acid source (commonly ammonium polyphosphate), a carbon source or char former (commonly pentaerythritol), a blowing agent (commonly melamine) and a polymer binder [12,13]. On heating:

- The binder softens and starts to melt;
- Ammonium polyphosphate decomposes to polyphosphoric acid, which dehydrates the carbon source and converts it into carbonaceous char;
- Melamine breaks down and gives off non-flammable gases (ammonia, nitrogen, water vapour) that inflate the soft char into a thick, multi-cellular foam; and
- The foam hardens into an insulating layer of low thermal conductivity, often quoted as 10 to 100 times the thickness of the original film.

On a cable the coating therefore delays heating of jacket and insulation, blocks direct flame contact, limits spread along the run and, in seals and wraps, expands to fill gaps left when cable jackets melt.

C. Product Types

Intumescent coatings are usually grouped by carrier into water-based, solvent-based and epoxy-based types (Table 5). They can also be classed by the char they form: a soft, light char from the phosphate–carbon–melamine system, or a harder char from systems based on sodium silicate or graphite [12]. For cables, products also come as flexible wraps, composite sheets, and firestop putties and pillows for penetrations.

Table 5. Main intumescent products used for cable protection.

Type	Typical features	Advantages	Limitations
Water-based	Single-pack, vinyl or acrylic binder, thin film	Low VOC, easy clean-up, suited to indoor trays and bundles	Sensitive to moisture; usually needs a topcoat
Solvent-based	Thin film, quick drying	Fast cure, good film properties	Solvent vapour is a flammability and inhalation hazard during application
Epoxy-based	Two-pack, thermoset binder, hard char	Durable in harsh or outdoor service (offshore, process plant)	Swells only a few times its thickness, so more material is needed; higher cost
Wraps, sheets and firestop devices	Intumescent layer on a flexible or rigid carrier	Self-sealing; good for penetrations and irregular shapes	Installation quality decides performance; must match the seal design

D. Properties that Decide Performance

- Thermal resistance: how long the coating holds the cable surface below its critical temperature (about 140–160 °C for thermoplastic jackets) in the design fire.
- Char strength and adhesion: the char must resist erosion by hot gas flow and thermal shock, and the coating must remain bonded to the jacket.
- Compatibility with the cable: it must activate before the jacket softens, must not draw plasticiser out of PVC, and must stay flexible enough to follow cable movement without cracking.
- Durability: fire performance must survive years of humidity, UV, temperature cycling and handling.
- Maintainability: inspection and repair must be easy enough that they actually take place.

E. Hazards and limitations

- Ageing and weathering. Moisture is regarded as the chief enemy. Water can leach out ammonium polyphosphate and melamine, and in one accelerated weathering study a coating lost 39.8 % of its fire resistance after 480 hours and almost all of it after 600 hours. A suitable topcoat reduces the damage, and UV resistance and water repellence deserve as much attention as flame retardancy.
- Cracking and delamination. A coating thicker than about 1.5 mm can crack when the cable moves, and a coating that cracks or lifts exposes the jacket directly to flame. Differences in thermal expansion between coating and jacket add to the stress.
- Mismatch with real fires. Many products are certified against the cellulosic ISO 834 curve, yet hydrocarbon pool and jet fires can reach 240–350 kW/m², and under such loads a coating may degrade quickly. Test standards for these fires (ISO 22899-1, UL 1709) differ from one another, and the cable-specific classification (EN 13501-3, based on EN 1366-11) is not applied uniformly. Data from properly aged in-service installations is scarce.
- Application and side effects. A trained applicator is needed to achieve even thickness, solvent-based products carry vapour hazards, and any covering on a cable can reduce its ability to shed heat, so current rating should be rechecked. The coating also releases gases as it reacts, one reason formulations without halogenated additives are preferred.

VI. CASE STUDY: BROWNS FERRY NUCLEAR PLANT, 1975

On 22 March 1975, at the Browns Ferry nuclear plant near Decatur, Alabama, workers were hunting for air leaks in the cable spreading room beneath the control room, where cables for Units 1 and 2 pass through wall penetrations into the reactor building. They used a lit candle to detect draughts. The flame was drawn into a penetration seal made of non-fire-rated polyurethane foam, and the foam ignited [16,17]. Fire travelled through the penetration into the reactor building. Early attempts with rags and portable extinguishers failed, and the fire burned for almost seven hours [16,17].

More than 1,600 cables were damaged, 628 of them important to plant safety, and power, control and instrument circuits needed for reactor cooling were affected [16]. The key point is the route the fire took: through a penetration whose seal was itself combustible. A rated penetration seal, a non-combustible fire stop or a protective barrier at that opening would have prevented spread from the cable spreading room to the reactor building. Afterwards the NRC issued NUREG-0050 in February 1976, which led to Branch Technical Position 9.5-1 and later to the fire-protection rules in 10 CFR 50 Appendix R. These call for fire-rated barriers or adequate separation between redundant safe-shutdown cables, and for tested penetration seals [17–19]. The NRC records that since Browns Ferry no fire at a US commercial nuclear plant has compromised safe reactor operation [16].

There is a second lesson. When the NRC later ran full-scale fire tests, some cable-protection materials did not perform as designed [16]. Protection that is installed but not properly qualified gives false comfort. Other incidents point the same way: at the Hinsdale telephone exchange (1988) the fire grew in an overfilled cable tray and acid fumes from burning PVC cable damaged almost all switching equipment, and at the Ostankino tower in Moscow (2000) the fire ran down the cable core and burned through improvised barriers.

VII. OVERALL DISCUSSION

The tests and the literature agree that cable fire behaviour comes from the interplay of material, geometry, electrical loading and environment, not from any single factor. The PVC cable did well in the small-flame test, yet a pass in IEC 60332-1 should not be read as proof of good performance in an installation. In the cone calorimeter the same material ignited in about two minutes and burned for nearly half an hour at 40 kW/m², emitting smoke and CO throughout. In a real tray the heat source is more likely to be a nearby fire than a small flame, so the cone result is closer to that picture.

This suggests a practical way to think about coating performance. The 125 s ignition time at 40 kW/m² is roughly the delay a coating must extend: it has to keep the jacket well below ignition and below its critical failure temperature for the entire design exposure, with its char staying in place. We did not test coated cable, so we cannot state how much delay any particular coating would add. Published work indicates that coatings can delay insulation failure [9–11], with results depending on thickness, adhesion, ageing and the fire exposure. The weaknesses in Section 5.5, together with Browns Ferry, mean that selection, installation quality and inspection matter as much as the product itself.

Material choice remains the most direct passive measure. Switching from PVC to XLPE or LSZH cable removes much of the HCl and smoke at source, and coatings or barriers then deal with the remaining heat. The study has clear limits: small-scale tests, a compressed-plaque cone specimen, only two vertical-test specimens, and missing CO unit and HCl values in the test output. Future work should include IEC 60332-3 bundled-cable tests, coated and uncoated specimens in the cone calorimeter, accelerated ageing of coatings, and exposure to higher heat fluxes.

VIII. CONCLUSIONS

1) The PVC cable passed the IEC 60332-1-2 vertical flame test. Residual flame lasted no more than 5 s and damage was limited to 80 mm and 160 mm of a 600 mm specimen.

2) At 40 kW/m² in the cone calorimeter the PVC ignited at 125 s, peaked at 114.89 kW/m², released 70.81 MJ/m², lost 3870 g/m² of mass and burned for about 29 minutes, with a smoke production rate of 0.175 m²/s and a clear CO peak.

3) PVC is hard to ignite with a small flame but is a long-lasting source of heat, smoke and CO under sustained heating. In confined cable galleries this supports passive protection, low-smoke halogen-free cable, or both.

4) Intumescent coatings protect by swelling into an insulating char. Their performance depends on type, thickness, adhesion and ageing, and they are vulnerable to moisture, cracking and fires harsher than those they were certified for.

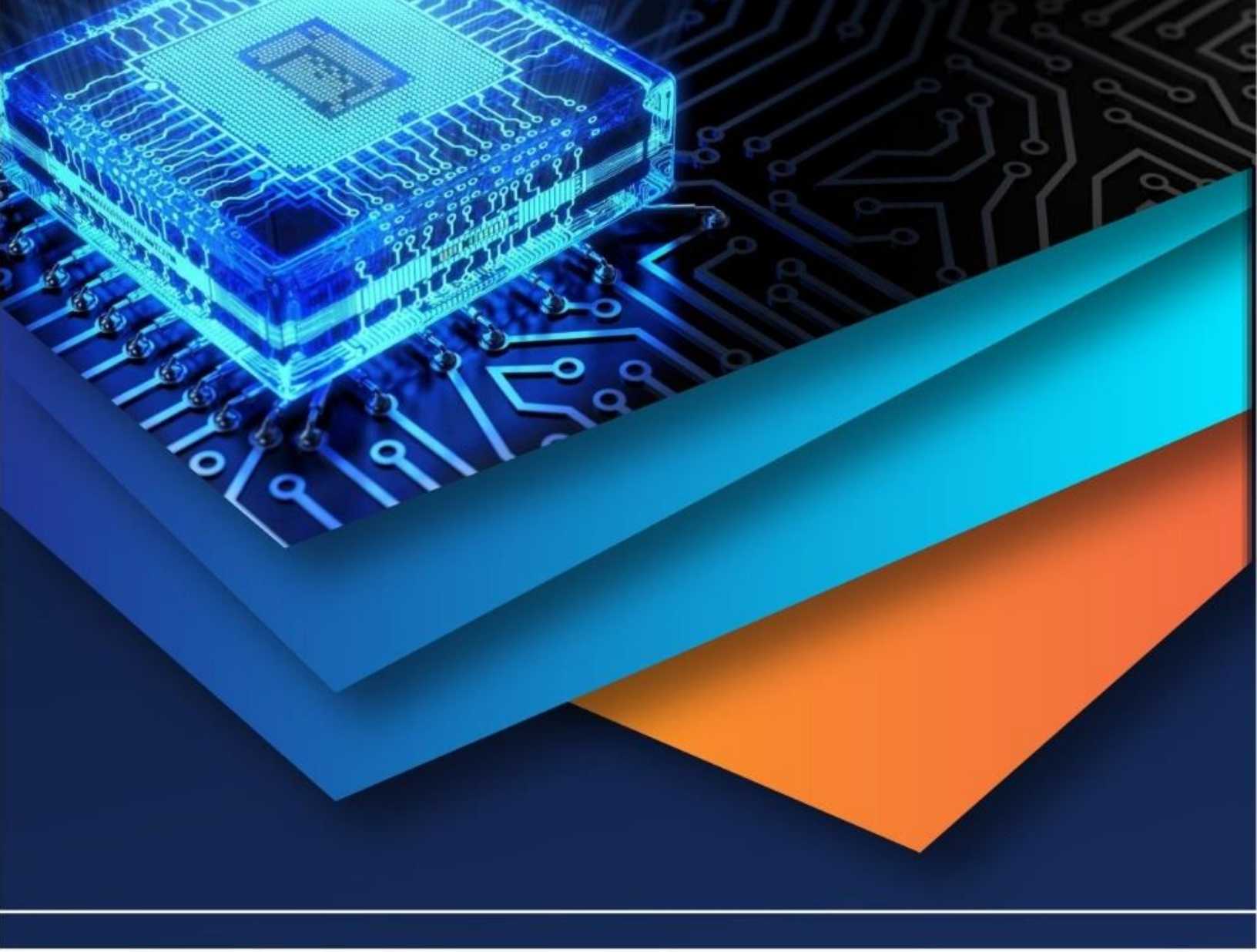
5) Browns Ferry shows that one combustible penetration seal can undo an otherwise sound design, and that protection must be properly rated and tested at full scale.

Cable fire safety is a joint problem of materials, electrical design, fire dynamics and regulation. Passive protection should match the real fire exposure, be installed with care, and be inspected throughout the life of the facility, with detection and suppression working alongside it.

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