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Review

Degradation Pathways of Electrical Cable Insulation: A Review of Aging Mechanisms and Fire Hazards

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Abstract

Electrical cable insulation, mainly composed of polymeric materials, progressively deteriorates under thermal, electrical, mechanical, and environmental stress factors. This degradation reduces dielectric strength, thermal stability, and mechanical integrity, thereby increasing susceptibility to failure modes such as partial discharges, arcing, and surface tracking—recognized precursors of fire ignition. This review consolidates current knowledge on the degradation pathways of cable insulation and their direct link to fire hazards. Emphasis is placed on mechanisms including thermal-oxidative aging, electrical treeing, surface tracking, and thermal conductivity decline, as well as the complex interactions introduced by flame-retardant additives. A bibliometric analysis of 217 publications reveals strong clustering around material degradation phenomena, while underlining underexplored areas such as ignition mechanisms, diagnostic monitoring, and system-level fire modeling. Comparative experimental findings further demonstrate how insulation aging modifies ignition thresholds, heat release rates, and smoke toxicity. By integrating perspectives from materials science, electrical engineering, and fire dynamics, this review establishes the nexus between aging mechanisms and fire hazards.

Keywords: electrical insulation; aging; fire behavior; degradation pathways; thermal-oxidative aging materials

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1. Introduction

According to U.S. National Fire Protection Association data [1], 32% of home fires involving electrical distribution equipment commence with electrical wires or cable insulation ignition. Cable insulation degradation is recognized as a major contributing factor, with others being overloaded circuits, loose electrical connections, arc faults, short circuits, and faulty appliances or devices. Insulation materials, primarily composed of organic polymers, are susceptible to deterioration over time due to exposure to thermal, electrical, mechanical, and environmental stressors. As these materials degrade, their dielectric and mechanical integrity declines, increasing the likelihood of electrical faults such as partial discharges, arcing, and short circuits–well-established ignition sources for fires.

Numerous studies reveal that many residential electrical fires originate from failures within electrical systems rather than from external ignition sources. For example, NFPA data [2] indicate that in home structure fires, 5% are initiated by electrical wiring and cable insulation igniting first, and these fires account for 4% of related fatalities. In the U.S. only, during the interval 2014–2016, the U.S. Fire Administration reported approximately

24,000 electrical fires annually, causing 310 deaths, 850 injuries, and USD 871 million in property damage, with 31% of these fires first originating from electrical wire or cable insulation [1]. Notably, 43% were attributed to electrical failure or malfunction, including 11% which were directly linked to short-circuit arcs from degraded insulation [1]. A comprehensive review of electrical fires with a large section dedicated to cable fires was conducted by Li et al. [3].

Fires originating from electric cables have been extensively investigated due to their significant role in fire incidents across various sectors. In a comprehensive review, Yu et al. [4] analyzed over 200 publications, systematically examining the key factors that influence cable fire behavior. The review addressed the effects of ambient conditions—such as pressure, oxygen concentration, gravity, and external airflow—alongside electrical parameters, including voltage and current. Furthermore, it explored how wire placement configurations affect critical fire phenomena, including ignition, flame spread, molten dripping, and self-extinction.

The fire hazard posed by degraded insulation arises from multiple mechanisms. Thermal aging can lead to embrittlement and reduced thermal stability; electrical degradation promotes carbonization and local breakdown; and environmental factors such as UV radiation and humidity accelerate chemical changes that reduce fire resistance. Once ignition occurs, the degraded insulation may also serve as a combustible fuel, potentially releasing toxic gases and increasing the rate of flame propagation. Despite advances in flame-retardant formulations and fire-resistant cable design, insulation degradation remains a complex, often overlooked contributor to fire initiation in real-world scenarios.

Degradation of energy materials is a process that unfolds over extended timescales, driven by numerous distinct, interacting, and often nonlinear mechanisms, as stated by French et al. [5]. These mechanisms can trigger isolated or gradual events that ultimately result in material failure. Considerable knowledge gaps remain in the identification, modeling, and reliable prediction of degradation phenomena at the mesoscale, as well as in the implementation of effective long-term monitoring strategies capable of tracking the evolution of degradation processes and preventing failures, particularly those of a catastrophic nature. Establishing a clear connection between mechanistic degradation pathways and their temporal development at intermediate scales is critical for enabling the identification and deployment of improved, long-lived electrotechnical materials under operational conditions.

1.1. Degradation Mechanisms

1.1.1. Thermal Degradation

Thermal degradation involves the irreversible deterioration of dielectric and mechanical properties in insulation materials due to prolonged exposure to elevated temperatures (Salvi et al. [6]). Thermal aging typically increases dielectric permittivity (Li et al. [7]) and may be accelerated by electromagnetic radiation, particularly in the presence of ultraviolet (UV) components (Wanasekara et al. [8], Celine et al. [9]), or other types of electromagnetic radiation (Liu et al. [10]). Flame-retardant additives—either embedded or applied as coatings—can further intensify degradation through complex pathways (Wu et al. [11]). The process is highly dependent on chemical structure; for example, polyamide degrades through a three-stage mechanism: radical formation, propagation, and molecular chain scission (Ren et al. [12]).

1.1.2. Electrical Degradation

Electrical degradation arises from high electric fields, periodic electrical stress, and localized discharge phenomena. Partial discharge, initiated when local fields exceed dielec-

tric strength in voids or defects (Choudhary et al. [13]), leads to erosion, carbonization, and cracking (Salvi et al. [6]). Other mechanisms include electrical treeing (Wang et al. [14]), surface tracking, and corona discharge, which generates reactive species that chemically degrade polymer chains. Material susceptibility is influenced by dielectric properties, molecular structure, and environmental conditions. For instance, XLPE and EPR display differing resistance to electrical treeing due to their distinct morphologies (Chen and Tham et al. [15]). Synergistic effects with thermal or environmental stressors often accelerate failure.

1.1.3. Mechanical Degradation

Mechanical degradation results from stresses such as tension, compression, vibration, and abrasion, occurring during installation, operation, or environmental exposure. Manifestations include microcracking, delamination, and polymer rupture, which compromise insulation integrity. Rigid polymers are prone to fatigue cracking, while ductile materials may undergo plastic deformation. Mechanical wear also facilitates moisture ingress, further exacerbating electrical and chemical degradation. Material properties such as elasticity, filler content, and manufacturing quality influence vulnerability. Synergistic effects with thermal or environmental factors are commonly observed in aged cables, as presented by Su et al. [16]. Practical examples of mechanical stress in cables include bending fatigue in flexible power cords and subsea/ROV cables, vibration-induced fatigue in dynamic or transport cables, and abrasion damage in industrial or mining cables where insulation rubs on rough surfaces. For instance, Shah and Niasar [17] (2023) demonstrated that 5000–10,000 bending cycles significantly reduced breakdown strength and increased PD intensity in XLPE insulation. Su et al. [16] further showed that mechanical stresses during cable installation distort polymer microstructure and accelerate degradation. In dynamic marine cables, Ringsberg et al. [18] report that repeated bending and torsional loads reduce mechanical and dielectric lifetimes. In static systems, overloading or bending beyond design limits reduces the cable's mechanical margin, as shown by Plaček et al. [19]. In nuclear installations, while the literature is more limited, the phenomena of stress-induced microcracks and embrittlement align with general cable aging observations have been reported in aging studies of nuclear cables (e.g., NCR/NRC-sponsored reviews of cable aging). Crack initiation due to mechanical strain or bending can act as focal points for partial discharges, surface tracking, or insulation breakdown under subsequent electrical stress.

1.1.4. Environmental Degradation

Environmental degradation is driven by exposure to UV radiation, humidity, oxygen, pollutants, and temperature fluctuations Ghosh and Pattanayak [20]. UV exposure induces photochemical reactions, causing chain scission and surface embrittlement (Venkataraman et al. [21], Wang et al. [22]). Oxygen accelerates oxidative degradation, while humidity increases hydrolysis and partial discharge risk. Pollutants such as ozone and nitrogen oxides contribute to chemical erosion and conductivity changes. These stressors often act synergistically, particularly in coastal or desert environments. Although accelerated aging tests provide insight into degradation kinetics and lifetime prediction, as reviewed by Tayefi et al. [23] or Bensalem et al. [24], they may not fully replicate real-world conditions. Field studies remain essential for validating laboratory findings, as shown in PVC sheath evaluations of synthetic aging, as presented in Liu et al. [25]. Additional real-world observations confirm the severity of environmental stressors: salt-fog exposure in coastal areas rapidly reduces hydrophobicity and increases leakage currents (Zhang et al. [26]); tropical climates with high humidity and biological films enhance surface conductivity and

accelerate flashover events (Fernando & Gubanski [27]); and desert environments intensify UV-driven cracking and embrittlement (Wang et al. [22]). Radiation-induced degradation is particularly critical for nuclear installations, where combined gamma and thermal stresses lead to crosslink scission and dielectric loss (Rajini & Udayakumar [28]). These case studies demonstrate that environmental degradation is highly context-specific, and its interaction with mechanical or thermal stresses often drives premature failure in field applications.

1.2. Literature Search and Selection

To complement the literature review with a systematic and visual exploration of mainstream research themes, a bibliometric analysis was conducted using data extracted from the Scopus database. The query targeted publications addressing the degradation of electrical insulation materials in the context of fire hazards, using the following search expressions:

("electrical insulation" OR "cable insulation" OR "insulation materials") AND (degradation OR aging OR "dielectric breakdown") AND ("fire" OR "fire hazard" OR "fire safety" OR ignition OR "flammability" OR "fire performance" OR "flame retardant").

To visualize the conceptual structure of the literature, a keyword co-occurrence analysis was performed using VOSviewer (v 1.6.20), based on 217 relevant publications retrieved from Scopus. Applying a conservative threshold of 10 keyword occurrences yielded a network of 43 distinct terms connected by 595 co-occurrence links. The resulting clusters, shown in the keyword co-occurrence map in Figure 1 delineate four main thematic domains: thermal and electrical aging, the fire performance of polymeric materials, material degradation and failure mechanisms, and flame retardancy. The keywords with the highest total link strength were "thermal insulation" (292), "insulation" (238), "insulating material" (221), "ethylene" (167), "degradation" (166), and "rubber" (146), indicating a strong emphasis on material-specific degradation phenomena. Notably, terms such as "cable insulation", "thermal aging", and "flame retardants" clustered around these core concepts, reinforcing the interconnectedness between insulation failure, material chemistry, and fire initiation mechanisms.

The presence of 595 links among 43 keywords shows a highly interconnected research landscape, where themes like aging, material properties, and fire behavior are not individually considered but mutually contextualized.

The hierarchy of terms with top positions occupied by "thermal insulation", "rubber", "ethylene", and "insulating material" suggests that the research field is heavily focused on polymeric materials, especially their composition, aging, and thermal properties. This points to a materials science lens being central to fire safety research. The high link strength of "degradation", "thermal aging", and "gamma rays" confirms a major concern with long-term performance degradation, including the impact of radiation, heat, and time on insulation reliability and flammability. While "flame retardants" and "thermal aging" are present, their lower link strengths compared to material-centric terms suggest that fire risk is treated as a secondary effect of material degradation, rather than a standalone area. This highlights a potential gap in integrated fire-risk modeling.

Beyond the identification of four thematic clusters, the co-occurrence network reveals how these themes interlock along a causal pathway from material aging to fire hazard. Terms in the thermal/electrical aging cluster (e.g., "thermal aging," "crosslinking," "electric insulation") connect densely to material composition nodes ("ethylene," "rubber," "cable insulation"), and from there to fire performance nodes ("flammability," "fire protection", "smoke", "degradation"). This bridge structure mirrors the technical chain: polymer chemistry → property drift (tan δ, breakdown strength, k) → fault precursors (PD, treeing, tracking) → ignition and flame spread metrics (CHF, HRR, smoke). The fourth cluster,

flame retardancy, is linked to both composition and fire behavior, indicating a mitigation thread that acts across the pathway rather than as an isolated research stream.

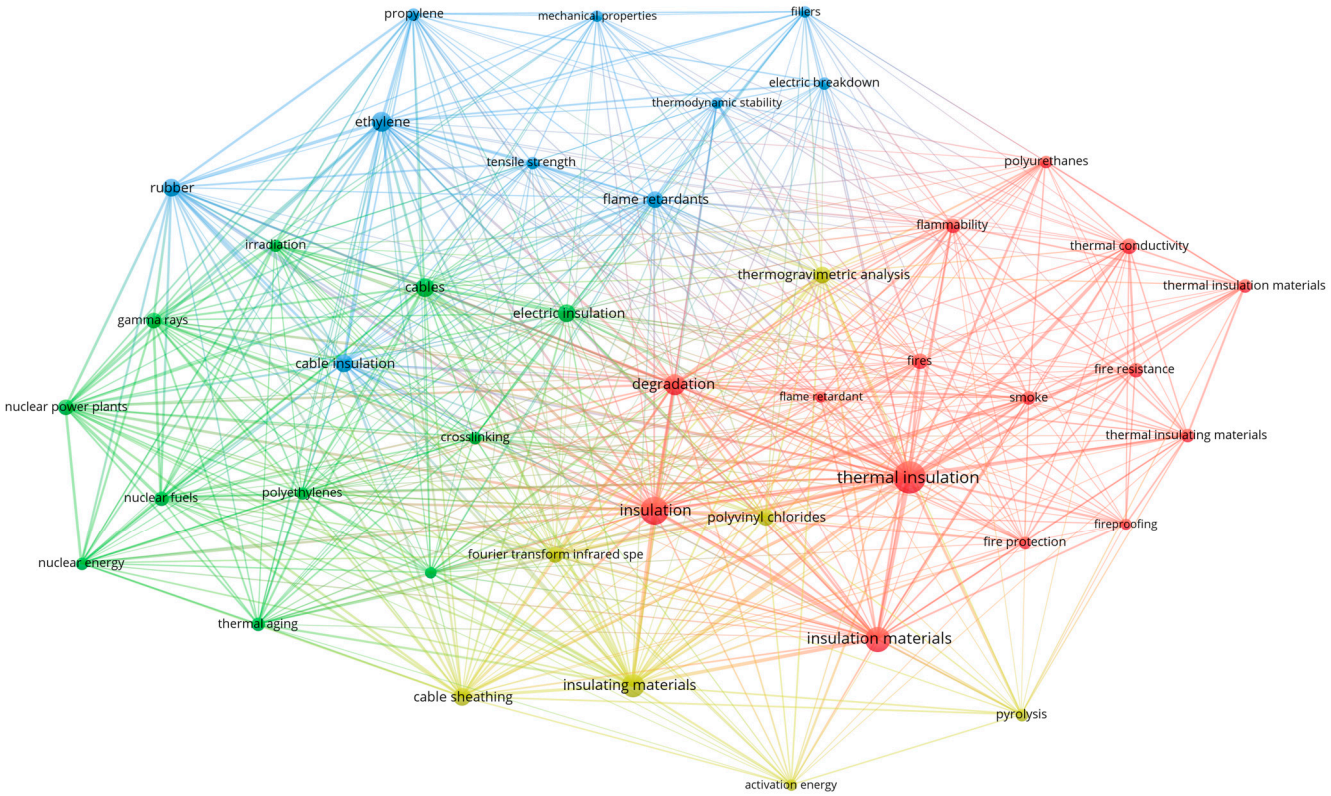


Figure 1. Keyword co-occurrence map. Node size reflects keyword frequency, while link thickness represents co-occurrence strength. Clusters reveal thematic groupings associated with thermal and electrical aging, material composition, fire performance, and flame retardancy.

Network density is high (595 links among 43 keywords; ≈0.66 of a complete graph), indicating that studies rarely address aging, materials, and fire in isolation. At the same time, link thickness (total link strength) is dominated by material-centric terms ("thermal insulation," "insulation," "ethylene," "rubber"), which suggests that the dominant analytical direction remains materials science, while ignition physics and system-level propagation are treated as downstream consequences rather than primary foci.

The peripheral placement or lower connectivity of operational terms such as "electric breakdown" points to a fragmentation between laboratory/materials communities and the power-systems/fire-safety communities. Practically, this implies that degradation descriptors measured in aging studies (e.g., carbonyl index, crystallinity, VLF dielectric spectra) are not yet systematically co-measured with fire performance outputs (e.g., cone calorimeter HRR, CHF) within unified experimental designs.

Two trend implications follow. First, research should focus on integrated test protocols and datasets that pair degradation diagnostics with ignition/combustion metrics (e.g., concurrent VLF $\tan(\delta)$, PD activity, and cone calorimetry on the same specimens across aging states). Second, the position of "flame retardants" as a bridging keyword suggests the need to go beyond simple screening of FR formulations and instead evaluate their long-term durability under service conditions. This includes studying how migration, depletion, or chemical interactions of flame retardants under thermo-oxidative or radiative aging affect system-level outcomes such as cable-tray flame spread or smoke toxicity. Addressing these methodological gaps would support the development of predictive, degradation-informed

fire models capable of linking material condition to ignition probability and propagation in real installations.

1.3. Possible Research Gaps and Trend Implications

Although the network is highly interconnected, its topology reveals specific blind spots that carry practical consequences for the field.

Initiation physics is underrepresented. Terms central to fault-driven ignition ("arc fault," "short circuit," "partial discharge") are peripheral, indicating that ignition mechanisms—despite their centrality in real incidents—are not systematically embedded within material aging studies.

Implication: It is recommended to form joint campaigns where PD/treeing metrics, leakage current, and surface tracking resistance are measured on the same aged specimens that undergo cone calorimetry/MCC, so that degradation descriptors map directly to CHF, HRR, and smoke yields.

Diagnostics-to-risk disconnect. "Monitoring," "detection," and "predictive maintenance" each show a weak presence, suggesting limited translation from laboratory descriptors (e.g., FTIR carbonyl index, VLF $\tan(\delta)$, impedance spectra) to operational risk indicators.

Implication: It is recommended to develop validated surrogates that convert field-measurable diagnostics (VLF dielectric spectra, broadband impedance, and online PD) into probabilistic ignition propensity and flame-spread parameters for trays/shafts.

System-level integration lag: While "flame retardants" and "thermal aging" are connected to fire performance, installations (tunnels, vertical trays, multi-layer bundles) and layout-driven propagation remain weakly integrated with aging/diagnostics.

Implication: Degradation-aware material models should be coupled with geometry-resolved fire simulations (e.g., a Fire Dynamic Simulator with aged-material property sets) and validated against experiments that vary both aging state and installation geometry.

Degradation-aware FR durability. The map anchors fire retardance research to material composition but seldom links it to long-term service evolution (retardant migration/depletion and its effect on ignition/HRR).

Implication: Retardant stability trajectories should be included in lifetime assessments (e.g., RTI protocols augmented with FR migration/depletion tracking) and FR effectiveness should be reported as a function of the aging state.

Finally, the current landscape motivates building open, multi-modal datasets where each sample carries (i) aging protocol/state, (ii) dielectric/mechanical descriptors, and (iii) ignition/combustion outputs under standardized conditions. Such datasets would enable explainable or physics-informed machine-learning models that predict ignition thresholds and spread behavior from diagnostics observable in service, accelerating the transition from static material qualification to predictive, degradation-informed fire risk assessment.

2. Fire Initiation and Propagation Due to Insulation Failure

2.1. Ignition Mechanisms in Degraded Insulation

Electrical insulation degradation significantly increases the likelihood of fire ignition due to the emergence of failure modes such as partial discharges, electrical arcing, surface tracking, and short circuits. These phenomena occur when the dielectric properties of the material are compromised, often as a result of long-term exposure to thermal, electrical, mechanical, or environmental stress factors.

Partial discharges (PDs) are localized dielectric breakdowns that occur in voids or defects within the insulation when the electric field exceeds the local breakdown strength.

Repetitive PD activity leads to the formation of carbonized channels, localized heating, and the emission of reactive species, progressively weakening the material and creating ignition-prone zones. PD is favored or triggered by environmental contaminants. Fahami et al. [29] investigated the impact of salt, fly ash, and algae pollutants on polymer insulators and on the susceptibility to PD. It was found that the intensity of partial discharge caused by salt is significantly higher compared to the other contaminants examined. Choudhary et al. [13] experimentally investigated insulation degradation through partial discharge (PD) characteristics using an artificial surface defect to generate phase-resolved partial discharge patterns. A custom tool extracted key PD features, revealing a correlation between electrical stress levels and PD activity. The results showed elevated PD activity at intermediate voltages (9–11 kV), indicated by increased PRR and mean pulse height. Hassan et al. [30] investigated the progression of insulation defects in MV power cables under increasing electrical stress by analyzing PD trends beyond the PD inception voltage. The results show that PD characteristics vary with defect type and voltage, with the Tobit regression model revealing distinct zones for each defect, supporting defect-specific failure risk assessment and maintenance planning.

These studies underscore the critical role of partial discharge activity as both a diagnostic indicator and a degradation driver in electrical insulation. The complex interplay between defect geometry, environmental contamination, and electrical stress highlights the need for defect-specific monitoring strategies to prevent premature failure and reduce fire risk in aging cable systems.

Surface tracking is a degradation-driven phenomenon in which conductive pathways form along the surface of polymeric insulation materials. Typically initiated under conditions of elevated humidity, contamination, or surface oxidation, tracking involves localized electrical discharges that progressively carbonize the surface. These conductive carbonized channels reduce surface resistivity and may lead to thermal runaway, arc formation, and eventual ignition. Surface tracking is particularly hazardous in polluted or high-humidity environments, where it can act as a precursor to flashover and initiate cable fires, especially in aged or partially degraded insulation systems. Güneș [31] conducted surface tracking tests on polyurethane foam under 4 kV stress. An avalanche-type degradation mechanism was revealed, characterized by a sudden surge in partial discharges immediately preceding failure. Initial arcing induced surface roughening, which, combined with the loss of hydrophobicity and void expansion, led to rapid electrical breakdown and compromised insulation integrity. Krirapee et al. [32] investigated the surface tracking resistance of five types of polyethylene-based cable insulation materials, both in unaged and thermally aged conditions. Experimental results showed that HDPE and non-carbon-filled XLPE exhibited superior tracking resistance compared to carbon-filled XLPE, LDPE, and MDPE. Material composition was found to have a greater influence on tracking behavior than thermal aging. These findings highlight surface tracking as a critical failure mechanism in polymeric cable insulation, capable of initiating fire through arc-induced thermal degradation. The susceptibility to tracking is strongly influenced by material composition and surface condition, emphasizing the importance of selecting high-resistance polymers and implementing preventive measures in humid or contaminated environments.

Electrical treeing is a critical degradation process that occurs in polymeric cable insulation under high electric stress, especially in the presence of voids, contaminants, or sharp defects. It is characterized by the formation and gradual growth of microscopic, branch-like discharge channels—resembling tree structures—that originate from localized field enhancements. These partial discharges progressively erode the insulation material, eventually bridging the electrodes and leading to dielectric failure. Electrical treeing not only compromises the long-term reliability of power cables but also plays a significant

role in pre-ignition conditions, as it may lead to localized heating, arcing, and ultimately, insulation breakdown and fire ignition. Understanding the initiation and growth dynamics of electrical trees is thus essential for assessing the fire risk associated with aged or overstressed cables. Bao et al. [33] conducted an experimental study investigating the characteristics of electrical tree growth in XLPE cable insulation under varying frequencies (4–10 kHz), voltages (4–10 kV), and electrode spacings (1–2 mm) using a pin-to-plane configuration. The fractal dimension and growth rate of trees increased with higher frequency or voltage, while greater spacing between electrodes slowed propagation only modestly. Contrary to expectations, increasing the distance from 1 to 2 mm required only a 1–2 kV rise in voltage to produce similar tree structures, often resulting in more complex, double-core formations. A simplified energy threshold model was introduced (Wt) to assess propagation difficulty, showing three distinct regimes of tree energy behavior depending on electrical stress. As shown in Figure 2, the tree morphologies captured during the experiments illustrate the progression from early-stage sparse branches (Figure 2a–c,g,j–n) to dense, bush-type structures (Figure 2d–f,h), confirming the strong influence of electrical stress parameters on the resulting degradation pattern in XLPE.

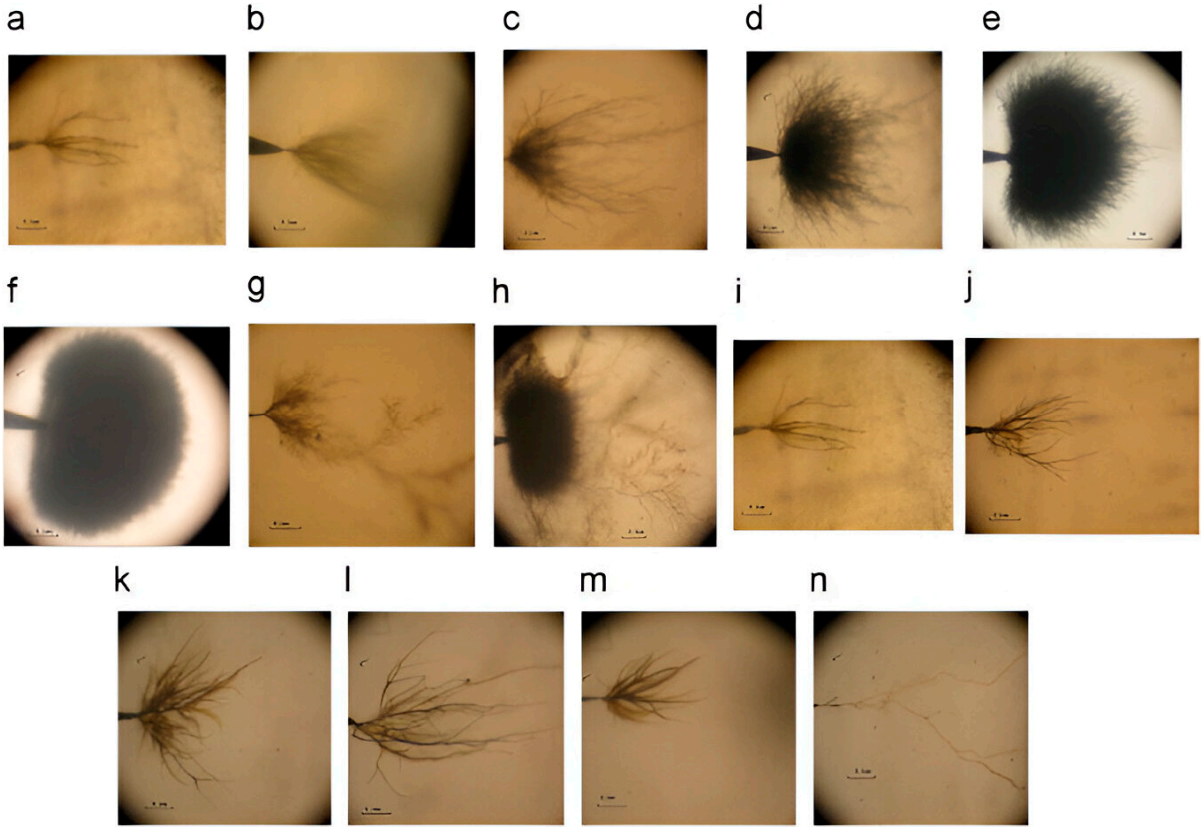


Figure 2. Electrical tree morphologies in XLPE showing progression from sparse branching to dense bush-type structures: (**a**–**f**) at frequency of 4 kHz and AC voltages: 4, 5, 6, 7, 8, and 12 kV, electrodes distance of 1 mm; (**g**,**h**) at frequency of 4 kHZ, voltage of 6 and 8 kV, electrodes distance of 2 mm, (**i**–**l**) at constant voltage of 4 kV and different frequencies: 4, 5, 6, and 10 kHz, electrodes distance of 1 mm, (**m**,**n**) at constant ac voltage of 4 kV, frequency of 7 and 10 kHz, with the electrodes distance of 1 mm. Reproduced from [33] with permission from Elsevier.

2.2. Fire Spread Dynamics in Cable Systems

The dynamics of fire spread in cable installations are governed by a complex interplay of material properties, installation geometry, ventilation conditions, and external heat sources. Once ignition occurs—often as a consequence of insulation failure—the configura-

tion of bundled cables, the vertical or horizontal routing, and the presence of combustible sheathing materials can significantly accelerate flame propagation. Polymeric insulation and jacketing materials, particularly those lacking adequate flame retardancy, can act as continuous fuel sources, supporting rapid flame spread through melt dripping and the release of flammable volatiles. Moreover, confined spaces such as cable trays or shafts can promote chimney effects, thereby increasing the intensity of heat and mass transfer and enabling multi-cable ignition. Understanding these mechanisms is essential for assessing fire hazard in critical infrastructure and for developing fire-resistant cable designs and installation standards.

Qin et al. [34] experimentally investigated the effect of cable spacing on the combustion behavior of horizontally arranged thermoplastic-insulated cables. Their study identified a critical spacing of 2.5 mm that maximized flame spread and mass loss rates, with enhanced flame interaction observed at intermediate spacings. The results underscore cable spacing as a key parameter influencing fire growth and provide important guidance for fire safety design in electrical installations.

In case of complex cable installations and layouts, the flame propagation velocity depends on a complex of factors. In vertical cable trays, the spread rate can reach values as high as 50 m/h, 15 times higher than in horizontal cable trays (McGrattan et al. [35,36]). The orientation of cable installations—horizontal versus vertical—plays a pivotal role in governing flame propagation dynamics. Li et al. [3] systematically analyzed these configurations and observed that, in typical horizontal layouts, flame spread often halts upon removal of the ignition source due to the gravitational opposition to lateral fire growth and the predominantly upward direction of heat transfer. Consequently, cables positioned laterally or below the flame path experience limited thermal exposure. However, in complex configurations such as multi-layer horizontal trays, sustained fire propagation can occur even after ignition ceases, particularly due to radiative heat feedback from burning upper layers. Notably, upper cable trays tend to exhibit faster flame spread, as the heat they generate promotes ignition in the lower layers through downward radiative transfer.

An experimental, laboratory-scale study was conducted by Zhang et al. [37], analyzing the fire behavior of densely and loosely arranged cables on ladder-type trays with the objective of revealing contrasting combustion dynamics driven by thermal mass and airflow exposure. Densely packed cables exhibited reduced combustion efficiency, with lower peak temperatures, radiation, and HRR, while loosely arranged cables promoted stronger convective heat transfer and significantly higher HRR values. An improved HRR prediction model was proposed by redefining the width parameter as the total cable base circumference, thereby enhancing prediction accuracy. Densely packed cables over ladder-type trays exhibit delayed ignition due to thermal shielding and low convective exposure, resulting in the formation of a characteristic “U”-shaped flame confined to the tray’s geometry. In contrast, loosely arranged cables promote faster and more intense combustion, supported by enhanced convective and radiative heat transfer. At the microscale, inter-cable heat exchange mechanisms differ markedly between configurations: dense layouts favor conduction and localized radiation, while loose arrangements amplify convective flow and surface-to-surface radiation, accelerating flame spread and increasing heat release.

To integrate different experimental approaches and findings, the main characteristics and results of several relevant and recent studies are summarized in Table 1.

Table 1. Summary of experimental studies on fire behavior of electrical cables under various configurations and conditions.

Cable/Insulation Type	Layout/Configuration	Main Findings/Results	Ref
110 kV cable Flame-retardant cross-linked PE insulation corrugated aluminum sheath and armored polyethylene sheath.	Horizontal cable above horizontal floor structure. Inclined Cable Above Horizontal Floor Structure Inclined Cable Above Inclined Floor Structure	Flame spread is sustained only within an optimal cable-to-floor distance (0.75 d–2 d). Spread rates were highest for inclined layouts with lower ignition; cable geometry significantly influenced fire behavior.	Xu et al. [38]
Thermoplastic insulation PVC or generic cable insulation 10 kV cable with large-section (ZC-YJLW03-Z) Halogen-free telecom cables Polyurethane foam insulation XLPE, LDPE, MDPE, HDPE	Parallel, horizontal cables with varying spacing Horizontal cable above horizontal floor, inclined cable above horizontal floor, inclined cable above inclined floor Grouped halogen-free telecom cables under varying spacing and cable density Inclined plane setup with 4 kV applied voltage under ASTM D2303 conditions Dip setup using Nichrome wire electrode and 0.1% ammonium chloride solution, tested under ICEA S-66-524	Max flame spread at 2.5 mm spacing due to strong flame interaction. Vertical layouts favor spread; horizontal trays limit it unless heat radiates from upper layers. Stable spread at optimal spacing; too close or distant spread reduces combustion. Heat flux controls ignition; sheath thickness delays peak burning; layout influences HRR. Tracking on PU foam shows abrupt failure after roughening and arc-induced loss of hydrophobicity. HDPE and XLPE resist tracking best; aging has little effect; composition is a key factor.	Magalie et al. [39]
Copper-core polyethylene-coated (Cu-PE) wires	Dual parallel wires with variable spacing and inclination angle	Flame spread rate shows a rise-then-drop trend with increasing wire spacing; oxygen depletion at narrow spacing limits flame. Inclination affects molten PE droplet behavior—downward spread is enhanced by a sliding effect, and upward spread by thermal buoyancy.	Lu et al. [40]
Generic cable types in interlayer setups; focus on smoldering and initial fire stages.	Full-scale interlayer platform simulating tunnel-like, narrow and long cable installations.	Temperature decays exponentially in early fires. CO spreads steadily in smoldering but slows in flaming. Cable-contact detectors had the fastest response (up to 82% faster). Point-temp detector failed. High alarm thresholds delayed detection by 10–20%.	Zhu et al. [41]
HDPE-sheathed parallel-wire cable under mechanical load.	Horizontal cable under tension, exposed to open-air pool fire; combined FDS-FEA numerical and full-scale experimental study.	Surface and pool fire interacted, raising cable surface temps to 400 °C. Sheath first insulates, then supports combustion post-ablation. Distinct radial and axial temp gradients appear after HDPE burnout. Cable deformation has 3 stages; failure occurs at 0.055 mm/s deformation rate. Fire resistance is influenced by cable diameter, sheath, and prestress. The FDS-FEA model effectively simulates fire response and deformation.	Wan et al. [42]

The studies reviewed in this section, and summarized in the comparative Table 1, highlight the diversity of cable configurations, insulation types, and experimental conditions used to investigate fire behavior. Despite the variability, consistent trends can be observed—such as the influence of insulation composition, layout geometry, and environmental conditions on flame spread and heat transfer dynamics. The comparative synthesis offers a structured perspective on the main experimental findings, providing a valuable reference point for further analysis, modeling, or design improvements in fire-safe cable systems.

Despite the diversity of experimental conditions, a consistent pattern emerges: cable spacing and orientation dominate flame spread, often outweighing the effect of insulation chemistry alone. Vertical configurations are universally associated with higher spread velocities, while horizontal configurations tend to self-extinguish once ignition ceases. However, contradictory findings exist regarding the role of cable density, with Zhang et al. [37] reporting reduced HRR in dense bundles due to shielding, whereas other studies highlight enhanced flame spread under intermediate spacing. These inconsistencies underline the need for standardized protocols that capture both geometric and material contributions to cable fire development.

3. Influence of Aging on the Combustion Characteristics

3.1. Heat Release Rate and Smoke Generation of Aged Cables

Aging significantly alters the fire behavior of electrical cables by degrading the insulation material, which directly affects the heat release rate (HRR) and smoke production, Xie et al. [43]. Experimental studies have shown that thermal aging, UV exposure, and radiation can lead to increased brittleness, reduced flame retardancy, and micro-cracking in cable jackets. These changes tend to lower the ignition threshold and increase the peak HRR due to more efficient combustion of the deteriorated insulation. Furthermore, aged cables often produce denser and more toxic smoke, posing greater hazards during fire events. The altered thermal decomposition pathways in aged polymers also influence the rate of heat generation and the composition of smoke, necessitating updated fire risk assessments for in-service cables with significant aging exposure.

The comparative analysis of fire behavior between new and aged electrical cables reveals significant differences in ignition dynamics, combustion intensity, and smoke generation. As insulation materials deteriorate due to thermal, electrical, or environmental aging, their resistance to ignition decreases, leading to shorter ignition times and higher peak heat release rates. Aged cables tend to exhibit faster flame spread and greater smoke production, often exceeding the performance boundaries observed in new, flame-retardant cable constructions. These changes underscore the critical impact of material aging on fire risk and emphasize the importance of accounting for insulation degradation in fire safety assessments and predictive modeling. A comparison of the combustion parameters for new and aged cables is presented in Table 2.

Table 2. Comparison of combustion parameters for new and aged cables.

Property	New Cable	Aged Cable	Ref
Ignition time	Longer (due to intact insulation and flame retardants)	Shorter (due to surface cracks, oxidation, and degradation)	Kim et al. [44] Wang and Wang [45]
HRR	Lower peak HRR	Higher peak HRR	Bai [46] Wang and Wang [45] Tang et al. [47]
Smoke generation	Reduced, often within regulatory limits	Increased, due to incomplete combustion and altered chemistry	Shi et al. [48] Liu et al. [49]
Flame spread rate	Slower, more predictable	Faster, enhanced by microcracks and polymer breakdown	Wang and Wang [45]
Combustion efficiency	Slower	More complete	Xie et al. [43]

Comparisons across multiple studies converge on the conclusion that aging consistently lowers ignition time and raises peak HRR. However, the magnitude of this effect varies considerably: Kim et al. [44] report moderate increases in HRR, while Tang et al. [47] describe much stronger acceleration. This divergence likely arises from differences in aging protocols (natural vs. accelerated) and insulation chemistries (PVC vs. XLPE). These contrasts point to the importance of harmonized test conditions if aging's effects on fire behavior are to be generalized.

3.2. Ignition Behavior and Flame Spread in Aged Cables

The ignition characteristics and flame propagation dynamics of electrical cables are significantly influenced by insulation aging processes to a variable degree, depending mainly on the nature of the insulation and exposure type. As polymeric materials degrade

over time- through thermal exposure, UV radiation, moisture ingress, or electrical stress—their physical and chemical properties evolve in ways that affect their flammability. Aging can lower the ignition threshold by introducing surface cracks, reducing thermal inertia, and facilitating the release of flammable volatiles. In some cases, aged insulation ignites more rapidly and sustains flame spread over longer distances compared to fresh material. Conversely, in other scenarios, oxidative crosslinking or embrittlement may inhibit ignition but promote unpredictable flame propagation paths. This section examines how various aging mechanisms alter the ignition delay, flame spread rate, and burning behavior of cables under controlled and real-world fire scenarios. Several studies relating the cable insulation aging to the ignition parameters are presented in Table 3.

Table 3. Ignition delay and flame spread rate.

Cable	Aging Method	Ignition Delay	Flame Spread Rate	Main Findings	Ref
XLPE	Thermal aging	Decreased by 30%	Accelerated by 20%	Aging reduced ignition resistance; lower decomposition temperature led to earlier ignition	Kim et al. [44]
PVC XLPE	Thermal Xenon arc Ozone Hydrothermal	Increased to values depending on the aging method	Not provided	XLPE showed a reduced fire hazard compared to PVC-insulated cables from the ignition time point of view	Zhang et al. [50]
PVC	Naturally aged cables (>10 years)	Slightly decreased ignition temperature. Aged sheath ignites earlier under MCC and TG conditions	Increased combustion rate (faster heat release and prolonged flame behavior)	Aged PVC sheaths show reduced fire protection; higher peak heat release; earlier and longer HCl evolution; and stronger overall combustion intensity	Xie et al. [43]

3.3. Aging-Induced Thermal Conductivity Degradation in Cable Insulation

While the thermal degradation of cable insulation is most often associated with a decline in thermal conductivity due to oxidation, void formation, and molecular scission, this general trend is not universally monotonic. In particular, certain stages of the aging process—especially under thermal and thermo-oxidative stress—may give rise to structural reorganizations and chemical transformations that lead to a temporary or localized increase in thermal conductivity. These changes are typically overlooked in simplified lifetime or ampacity models, yet they may significantly impact the internal thermal field distribution and the cable's overall thermal management strategy. Understanding the conditions under which thermal conductivity increases during aging, and their implications for operational safety, is essential for constructing accurate predictive models of insulation performance. Moreover, the mismatch between internal heat generation and dissipation capacity—particularly when accompanied by conductivity anomalies—can initiate thermal instabilities that promote self-accelerating degradation. The following section provides a comprehensive examination of the mechanisms responsible for this conductivity increase, supported by recent experimental and computational findings.

3.3.1. Mechanisms Leading to Increased Thermal Conductivity with Cable Aging

Despite the prevalent observation that thermal conductivity (k) typically decreases during aging, certain aging-induced phenomena can increase k under specific conditions. The

mechanisms listed below, while less common, play critical roles in the complex evolution of aged insulation.

Thermal Crosslinking and Crystallinity Enhancement

Additional crosslinking can occur post-manufacture, particularly in XLPE, leading to increased crystallinity or more ordered polymer domains. Molecular dynamics and experimental studies confirm that a higher crosslink density correlates with improved phonon transport pathways and, thus, higher k values (Choudhary et al. [51], Huang et al. [52], Liu et al. [53]). However, excessive aging eventually destroys these crystalline regions, eventually reversing the trend.

Polymer Densification

Early-stage aging may induce densification via loss of volatile plasticizers, chain reorganization, or oxidative by-products filling voids. Such densification reduces the boundary scattering of phonons, enhancing k slightly before oxidative degradation dominates (Liu et al. [54]).

Conductive Filler Rearrangement

Filled polymer systems—such as those containing graphite, boron nitride, or carbon fibers—can undergo filler realignment or agglomeration during aging, forming improved thermal pathways. Pleşa et al. [55] reviewed high-voltage polymer composites and demonstrated that filler size, shape, and distribution critically influence thermal conductivity, with better-oriented fillers yielding quantifiable and statistically significant k increases.

Carbonaceous Char Formation

During pyrolytic or high-temperature aging, polymer insulation may develop carbon-rich char networks with enhanced phonon/electron transport. Studies on intumescent coatings show char morphology changes—especially reduced porosity and bubble size—lead to elevated thermal conductivity in aged char layers (Wang et al. [56]).

Although early-stage aging phenomena such as crosslinking or filler alignment can temporarily increase thermal conductivity and stabilize temperature gradients, these are typically followed by irreversible degradation mechanisms that lead to a decline in k. Once thermal conductivity begins to drop, heat accumulation accelerates internal degradation, initiating a positive feedback loop that can result in thermal runaway.

For a circular section conductor, the transient conduction equation can be written as follows:

$$\rho c_p \frac{\partial T}{\partial t} = \frac{1}{r}\frac{\partial}{\partial r}\left[rk(t,T)\frac{\partial T}{\partial r}\right] \quad (1)$$

where $\rho\left[\frac{\mathrm{kg}}{\mathrm{m}^3}\right]$ is the material density, $\mathrm{c_p}\left[\frac{\mathrm{J}}{\mathrm{kg\cdot K}}\right]$ is the specific heat capacity, T[K] is the temperature, r[m] is the radial coordinate, $\mathrm{k}\left[\frac{\mathrm{W}}{\mathrm{m\cdot K}}\right]$ is the thermal conductivity, and t[s] is the time variable.

The following boundary conditions apply:

A. Inner boundary (conductor–insulation interface, Neumann-type boundary condition):

$$-k(t,T)\left.\frac{\partial T}{\partial r}\right|_{r=r_{cond}} = q''_{cond}(t) \quad (2a)$$

where $q''_{cond}\left[\frac{\mathrm{W}}{\mathrm{m}^2}\right]$ is the heat flux density at the conductor–insulation interface.

The superficial heat flux density at the boundary of the metallic conductor:

$$q''_{cond}(t) = \frac{P(t)}{2\pi r_{cond} L} = \frac{I^2 R(t)}{2\pi r_{cond} L} \tag{2b}$$

where P[W] is the electrical power, I[A] is the current intensity, R[Ω] is the electrical resistance, L[m] is the length of the conductor, and r_{cond}[m] is the conductor radius.

Due to the high *k* of the metallic conductor, it is safe to assume that no significant radial temperature gradient occurs in the metallic conductor mass, meaning that the resistance can be expressed as a function of temperature:

$$R(T) = R_0\left[1 + \alpha\left(T_{cond} - T_{ref}\right)\right] \tag{3}$$

B. Outer boundary (insulation–air interface; Robin boundary condition)

$$-k(t,T)\left.\frac{\partial T}{\partial r}\right|_{r=r_{out}} = k(T_{out} - T_\infty) + \varepsilon\sigma\left(T_{out}^4 - T_\infty^4\right) \tag{4}$$

where $\varepsilon[-]$ is the emissivity of the material and $\sigma\left[\frac{W}{m^2 \cdot K^4}\right]$ is the Stefan–Boltzmann constant.

The thermal conductivity degradation can be modeled as described in [57]:

$$k(t,T) = k_0 exp[-a(T)\cdot t] \tag{5}$$

where *a* is the temperature-dependent degradation rate constant, given by:

$$a(T) = A\cdot\exp\left(-\frac{E_a}{RT}\right) \tag{6}$$

A is the pre-exponential factor, reflecting the frequency of molecular-scale events (e.g., vibration, diffusion) that can result in degradation. In polymer degradation models, *A* typically lies in the range 10^5–$10^{12}s^{-1}$, depending on the insulation chemistry and degradation mechanisms.

R is the universal gas constant.

E_a[kJ/mol] is the activation energy, which characterizes the sensitivity of the degradation rate to temperature. A higher value is equivalent with a slower degradation at moderate temperatures, but also faster acceleration at high temperatures. Reported values for cable insulation materials are provided in Table 4.

Table 4. Activation energy for common cable insulation materials.

Material	E_a**[kJ/mol]**	**Ref**
XLPE	~160 (thermo-oxidative aging)	Lv et al. [58]
EPR	~100 (thermo-oxidative aging)	Blivet et al. [59]
PVC	Three stages of the thermal degradation process were observed under the oxygenated atmosphere: 130–175 stage 1 145–510 stage 2 75–190—stage 2	Yang et al. [57]

The thermal runaway in aged cable insulation arises from a nonlinear feedback loop between internal temperature, material degradation, and declining thermal conductivity. As the cable operates, heat generated in the conductor (see Equation (1)) is transferred radially through the insulation (see Equations (2a) and (2b)), whose thermal conductiv-

ity decreases over time due to thermally activated degradation processes, as shown in Equation (6). This reduction in conductivity impairs the insulation's ability to dissipate heat toward the surface, causing a progressive increase in internal temperature. Since both the thermal conductivity degradation rate and the conductor's electrical resistance are temperature-dependent, the rising temperature accelerates the loss of conductivity and simultaneously increases the heat flux entering the insulation. Although the outer surface dissipates more heat via convection and radiation at elevated temperatures, these mechanisms cannot fully compensate for the growing internal thermal resistance. The result is an accelerating cycle in which higher temperatures lead to faster degradation and lower conductivity, further elevating the temperature and culminating in thermal instability. This runaway process depends critically on the degradation kinetics of the insulation material, the heat flux imposed by the conductor, and the efficiency of external cooling. As the thermal conductivity decreases, the Bi number $Bi = hL/k$ increase, so the insulation body becomes internally conduction-limited and the external cooling is ineffective. As the thermal conductivity decreases, the thermal diffusion length $l_T = \sqrt{\alpha t}$ drops, which causes heat to accumulate locally and trigger pyrolysis hot spots. Delayed redistribution causes steeper internal thermal gradients, contributing to nonuniform decomposition and heterogeneous ignition behavior. Reduced k traps degradation heat, accelerating the transition from solid-state degradation to gas-phase pyrolysis, increasing flammable volatiles. In multi-cable installations, one ignited cable can transmit heat to neighboring cables. Degraded insulation with low k resists lateral heat conduction; that is, more heat is available at the surface, promoting horizontal flame spread. This is especially relevant in cable trays, tunnels, or vertical risers, where flame propagation is geometry sensitive.

Figure 3 shows the evolution of thermophysical properties of cross-linked polyethylene (XLPE) insulation during thermal aging, based on data from Liu et al. [60]. The thermal conductivity shown in Figure 3d remains stable initially but shows a visible decline after 80–100 h at elevated temperature. This behavior coincides with a sharp increase in density as shown in Figure 3a and a marked drop in thermal diffusivity, as shown in Figure 3c, suggesting significant structural degradation—likely due to oxidation and micro void formation. Although the absolute reduction in conductivity is moderate (from ~0.39 to ~0.35 W/m·K), it can meaningfully affect the cable's ability to dissipate heat, especially under a load or in confined environments. These results offer direct experimental confirmation of a degradation mechanism that is often assumed but rarely measured, highlighting the importance of including time-dependent thermal properties in aging and reliability models for cable insulation. As thermal conductivity decreases—particularly in low-density, porous, or microcracked insulation—radiative heat transfer within the material can become a significant component of its overall thermal response. Experimental studies on open-cell foams and porous insulations have shown that radiation contributes substantially (up to ~30–50%) to effective thermal conductivity, especially at elevated temperatures or in thicker samples (Zhang et al. [61], Venkataraman et al. [62]). This is equivalent to saying that, although conductive pathways are increasingly disturbed during degradation, infrared radiation across internal voids and cracked regions can partially offset conductive losses—yet they can also trap additional heat, further elevating the internal temperature and escalating the thermal confinement, Blazejczyk et al. [63]. In fire exposure scenarios, this shift toward radiative heat transfer can accelerate insulation pyrolysis and ignition, even as surface convective and radiative losses remain relatively unchanged.

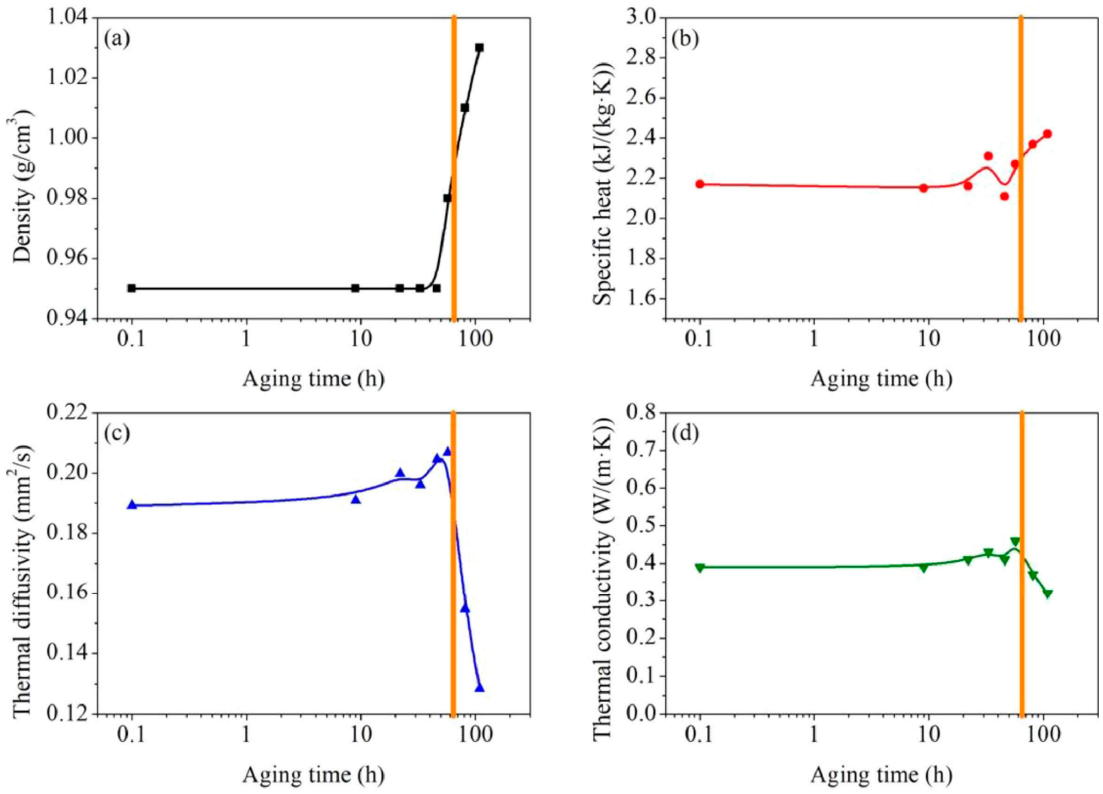


Figure 3. Evolution of density (**a**), specific heat (**b**), thermal diffusivity (**c**), and thermal conductivity (**d**) of XLPE insulation as a function of thermal aging time. Reproduced with permission from Elsevier from Liu et al. [60].

The reduction in thermal conductivity due to aging has a direct and quantifiable impact on the fire susceptibility of cable insulation, particularly by lowering the critical heat flux for ignition (CHF). As insulation materials degrade, oxidation, chain scission, and micro void formation diminish their ability to conduct heat away from the exposed surface. For a given external heat flux, this results in a steeper temperature gradient and more rapid surface heating, accelerating the time to ignition. Mathematically, the ignition resistance of a material can be characterized by the thermal response parameter (TRP), given by

$$TRP = \frac{k\rho c_p}{\left(T_{ign} - T_0\right)^2} \tag{7}$$

The CHF scales as $CHF \propto \sqrt{TRP}$, and even a relatively small drop in k can cause a significant decrease in the CHF. In an experimental study, Rantuch et al. [64] used cone calorimetry to measure the CHF of ethylene-based cable insulation. A 35% drop in the ignition threshold and a reduction in the CHF from 4.6 kW/m^2 to 3.0 kW/m^2 was reported following thermal aging. This behavior is particularly dangerous in confined environments, where convective cooling is hindered, such as in cable trays or tunnels, where aging cables exposed to modest radiant heat may ignite before external suppression mechanisms activate. Thus, the degradation of the thermal conductivity is not only a thermal management issue but a critical determinant of fire risk, and it must be explicitly considered in both predictive fire modeling and the safety assessment of aged electrical infrastructure.

A more subtle yet important mechanism contributing to thermal instability in cables arises from temperature-dependent dielectric losses within the insulation itself. While most thermal models focus on Joule heating in the conductor as the dominant source of heat, Diban and Mazzanti [65] demonstrated that, under certain conditions, the poly-

meric insulation of HVDC cables—specifically XLPE—can become an active secondary heat source. It was shown that once the insulation temperature exceeds approximately 70–83 °C, leakage currents increase nonlinearly due to the temperature-dependent electrical conductivity of the dielectric material. This resulted in additional internal heat generation within the insulation that, in buried cable configurations, is often not adequately offset by external cooling mechanisms, leading to thermal imbalance. A formal distinction between intrinsic thermal runaway was introduced, which occurs due to internal material properties independent of external boundary conditions, and interactive thermal runaway, where the failure emerges from the coupling between internal heat generation and insufficient thermal dissipation. This finding highlights the need to revisit thermal design criteria for HVDC systems and incorporate dielectric loss behavior—especially in aging or high-load conditions—into models traditionally focused on metallic losses alone.

Although short-term increases in thermal conductivity have been observed in controlled aging experiments—particularly in polymer composites or early stages of crosslinked polymers (e.g., Omastová et al. [66] observed elevated k under sub-melting thermal treatment)—such effects are usually modest and transient. In the case of XLPE, thermophysical measurements by Liu et al. [60] show nonlinear trends in conductivity during aging, suggesting that minor plateaus or local upticks may occur before the onset of dominant degradation-driven decline. In polymer-filler systems, Torres-Regalado et al. [67] report that filler content can modulate the early-stage slope of $k(t)$, thereby reducing or delaying the net downward trend. In field service environments, however, these temporary increases are unlikely to dominate: real cables operate under multifactor stress (thermal, electrical, mechanical, oxidative), and the long-term oxidative degradation, void formation, and structural damage overwhelmingly drive a net decline in thermal conductivity (as seen in aging-behavior studies of insulation materials and composites), as shown in the work of Berardii et al. [68]. Thus, while temporary k increases observed under laboratory studies are mechanistically interesting and highlight complex aging pathways, they remain a secondary effect compared to the prevailing downward drift in k under realistic operating conditions.

3.4. Degradation of Dielectric Properties in Aged Electrical Insulation

The electrical insulation of power cables is primarily defined by its dielectric properties, particularly its dielectric strength, volume resistivity, dielectric constant (relative permittivity), and dissipation factor $\tan(\delta)$. These parameters collectively determine the insulation's ability to withstand electric field-induced breakdown, prevent leakage currents, and minimize dielectric losses. However, these properties are highly sensitive to aging mechanisms that operate under electrical, thermal, environmental, mechanical, and radiative stress factors. Over time, insulation materials such as XLPE, EPR, and PVC undergo physical, chemical, and morphological changes, resulting in a progressive deterioration of their dielectric performance. Degradation of dielectric properties occurs through several pathways, as discussed in the next few sections.

3.4.1. Dielectric Strength Reduction

Dielectric strength, defined as the maximum electric field a material can withstand without failure, decreases with aging due to the initiation and propagation of micro voids, cracks, and water trees. These defects act as localized field enhancers, lowering the breakdown threshold. The accumulation of space charge in aged insulation—particularly in semi-crystalline polymers like XLPE- can further distort the internal field distribution, accelerating electrical failure. Experimental studies have shown that water-tree-aged XLPE can experience dielectric strength reductions of over 50% compared to pure material, partic-

ularly under AC or impulse voltages (Boggs et al. [69]). To synthesize the key mechanisms responsible for the reduction in dielectric strength of electrical insulation materials, Table 5 summarizes representative experimental findings from recent literature. The studies span various insulation types, aging conditions, and diagnostic techniques, offering quantitative insights into the degradation process.

Table 5. Summary of representative experimental findings on dielectric strength degradation in aged cable insulation systems.

Aging Mechanism	Test Conditions and Results	Ref
Thermal aging of XLPE cables	220 kV XLPE cable slices aged at 135 °C for 70 days; tracked AC breakdown field vs. crystallinity and carbonyl index	Han et al. [70]
Thermal-oxidative aging of epoxy resin	DC bushings epoxy resin, 10 cycles at 250 °C → breakdown strength dropped by 9.9%; volume resistivity dropped by 53.8%	Liu et al. [71]
Thermo-oxidative aging of epoxy resin (HV aging)	Aging for 1440 h; breakdown strength dropped by 18.1%, conductivity increased by 59.6%	Kong et al. [72]
Defects in XLPE (scratches, moisture, particles)	Sheet simulations and lab tests show defect-induced breakdown voltage drop from ~129.6 kV → 59–70 kV (≈45–55% loss)	He et al. [73]
Partial discharges/electrical treeing	Electrical tree propagation creates weakened regions → reduced breakdown strength (~50%, depending on tree size)	Kim et al. [74]

Thermal-Oxidative Degradation

Thermal-oxidative degradation arises when oxygen diffuses into a polymer and reacts with the macromolecular chains at elevated temperatures (typically above 90–100 °C for most cable-grade materials). This process is autocatalytic and proceeds through free radical chain reactions, leading to chemical, morphological, and electrical changes that impair dielectric performance. Table 6 covers recent experimental studies conducted on various systems including epoxy resins, XLPE, EVA, and high-performance polymers. Each entry provides details on the aging protocol, observed dielectric strength deterioration, and relevant chemical or structural markers (e.g., carbonyl index).

Partial discharges (PDs) and electrical treeing are among the most critical degradation phenomena affecting the dielectric integrity of polymeric insulation in high-voltage applications. These localized electrical discharges occur when the electric field within microscopic voids, cracks, or interfaces exceeds the dielectric strength of the surrounding material without causing immediate breakdown. Over time, PD activity induces cumulative damage through localized heating, chemical bond cleavage, and the formation of carbonized conductive channels. One of the most dangerous outcomes of sustained PD is the growth of electrical trees—branch-like microstructural defects that propagate through the insulation, often leading to catastrophic failure. The presence of these defects significantly lowers the breakdown voltage of the material by creating preferential paths for electrical conduction. Electrical treeing not only alters the physical structure of the dielectric but also increases its permittivity and dielectric loss, further escalating internal field distortions. Modern diagnostic methods, such as time-resolved PD detection and impedance-based monitoring, allow for the detailed tracking of tree initiation, propagation, and the associated changes in dielectric properties. Table 7 summarizes recent experimental investigations that quantify the impact of PD and electrical treeing on dielectric strength, along with the aging conditions and material-specific findings.

Table 6. Experimental studies on thermal-oxidative degradation of electrical insulation materials.

Material, Aging Protocol	Key Findings	Ref
Epoxy resin (DGEBA/anhydride), 10 cycles at 250 °C	DC breakdown dropped by 9.9%; volume resistivity dropped by 53.8%; carbonyl index (FTIR) increased	Liu et al. [71]
High-voltage epoxy, thermo-oxidative aging (1440 h)	Breakdown strength dropped by ~18.1%; conductivity increased by 59.6%	Kong et al. [72]
XLPE cable, thermal aging at 110–135 °C (2000 h)	Carbonyl index increased significantly; tensile/AC breakdown strength declined;	Smaida et al. [75]
XLPE/EVA sheets at 165 °C	FTIR shows diffusion-limited oxidation; carbonyl index rise matches dielectric constant and elongation loss	Ji et al. [76]
XLPE cables, multi-temperature aging, NIR and FTIR	Carbonyl index, tensile strength, elongation at break, and dielectric loss increased with aging	Li et al. [77]
Bio-PE (LDPE), long-term thermal oxidation	FTIR confirms carbonyl growth and chain scission; dielectric deterioration expected	Hedir et al. [78]
PEEK, PI, PTFE, aged at 250 °C in humid air	FTIR shows oxidative degradation, which implies a reduction in dielectric performance (breakdown not reported)	Barra et al. [79]

Table 7. Experimental studies on the effects of partial discharges and electrical treeing on dielectric strength.

Material and Conditions	Key Findings	Ref
35 kV and 110 kV XLPE slices, AC stress causing electrical tree growth	PD characteristics evolve with tree development; distinct time–frequency patterns at each growth stage; early detection possible	Gao et al. [80]
XLPE specimens underwent cyclic AC voltage	PD emissions recorded over 500 cycles; electrical tree growth monitored and correlated with PD evolution	Chandrasekar et al. [81]
Silicone rubber (SIR) under varied mechanical pressure	Electrical tree inception voltage increases under mechanical pressure; tree morphology and PD vary significantly	Su et al. [82]
XLPE cables aged thermally and PD-tracked	Dielectric breakdown accelerated by PD; treeing behavior dependent on thermal aging profile	Camalov et al. [83]
XLPE and EPR cables, PD progression under thermal cycling	Rate of PD increase strongly correlates with insulation degradation; PD progression metric proposed	Domingos et al. [84]
XLPE cable trunk impedance tracking (BIS)	Broadband impedance changes track tree growth; location errors < 3%; capacitance drop indicates degradation	Han et al. [85]

3.4.2. Aging-Induced Increase in Dielectric Loss and tan(δ)

Dielectric loss, quantified by the parameter tangent of the loss angle (tan δ), increases noticeably with insulation aging due to chemical changes and enhanced conduction pathways. This parameter is particularly sensitive to polar degradation products and moisture-induced conductivity. The problem of insulation dielectric properties degradation caused by aging was studied experimentally, generally in studies that focused on thermal aging. Wang et al. [86] experimentally investigated the aging state of cross-linked polyethylene (XLPE) in power cables under various thermal aging conditions, measuring the structural changes and very-low-frequency (VLF) nonlinear dielectric responses. The accelerated thermal aging experiments were conducted on XLPE insulation materials at 90 °C, 120 °C

and 150 °C following the provisions of the IEC 60216 standard [87]. The samples—10 kV commercial cable YJV62—were suspended vertically in the hot air-circulating ovens for different durations of 240 h, 480 h and 720 h, respectively. The choice of test parameters and conditions was grounded in the work of Li et al. [88] and Afia et al. [89]. It was reported that the dielectric constant of all the samples did not change considerably in the frequency range of 0.1 Hz–1 kHz, while in the lower frequency of 1 mHz–0.1 Hz, a significant increase was noticed: the dielectric constant increased from 5 (reference sample) to 23 (the sample aged at 150 °C for 720 h), as shown in Figure 4.

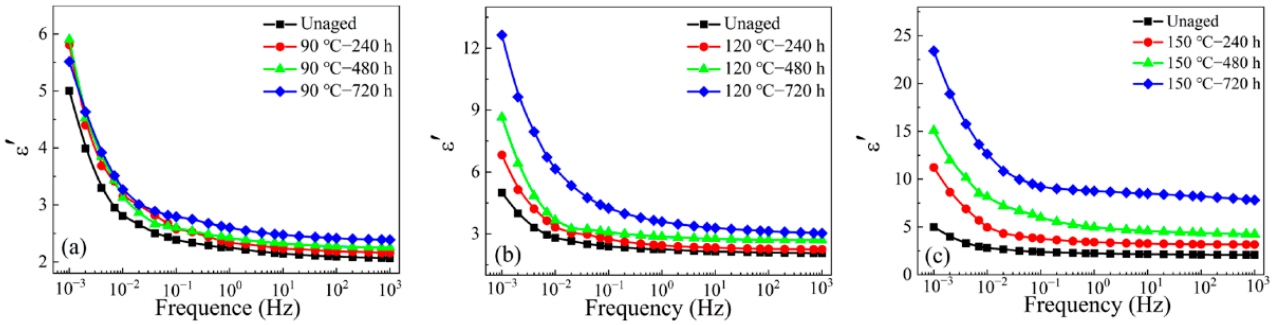


Figure 4. VLF dielectric constant of XLPE sample under thermal aging at (**a**) 90 °C, (**b**) 120 °C and (**c**) 150 °C. Reproduced from [86].

The dielectric loss follows the same variation profile, with a steady plateau at high frequencies and a steep increase starting at 0.1 Hz, as shown in Figure 5.

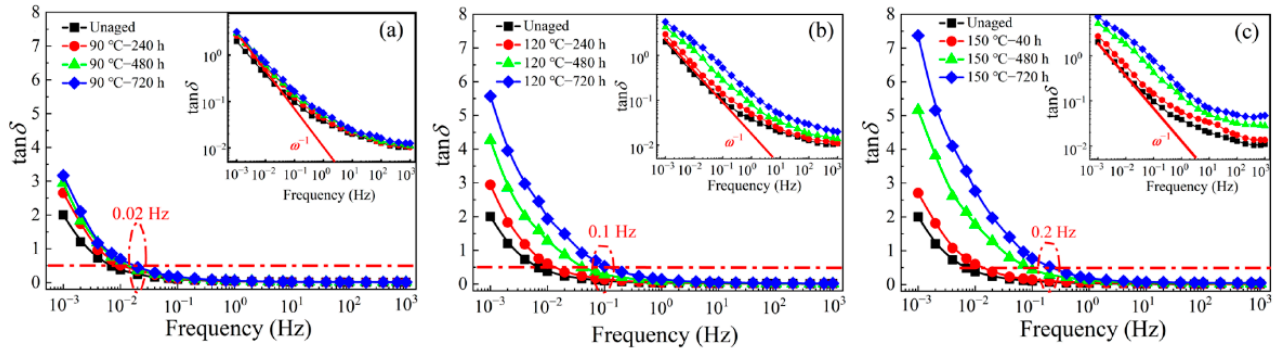


Figure 5. VLF dielectric loss— tan δ of XLPE samples under thermal aging at (**a**) 90 °C, (**b**) 120 °C and (**c**) 150 °C. Reproduced from [86].

Both Figures 4 and 5 confirm that thermal aging duration and temperature play critical roles in accelerating the degradation of dielectric properties in cable insulation. A noteworthy outcome is the emergence of nonlinear voltage–current behavior in the aged insulation, likely due to increased conduction mechanisms, space charge effects, and interfacial polarization. These nonlinearities can result in the generation of high-order harmonics, which may cause interference, disrupt electrical regime stability, and affect intercomponent compatibility in high-voltage systems.

In a recent study, Han et al. [70] proposed a device based on a high-voltage amplifier and high-precision dielectric loss measurement algorithm to measure the dielectric loss values of cables at different aging stages. XLPE slice samples were prepared and the carbonyl index, crystallinity, AC breakdown field strength, and elongation at break (used to assess the aging degree) were measured. The tan(δ) was measured for frequency values ranging from 0.01 to 0.1 Hz, confirming the same ascending trend at very low frequencies

as the aging degree increased. The mechanical test also demonstrated that tan(δ) correlates to the elongation at break.

Afia et al. [90] performed accelerated aging tests on low-voltage, unshielded single-core power cable samples using a combination of thermal and mechanical stresses applied simultaneously. The thermal stress protocol involved placing the cables—coiled on a 15 cm diameter cylinder—inside a forced-air circulation oven at 120 °C, in accordance with the IEEE-383 standard [91]. The aging durations were 176, 162, 169, and 272 h. To assess the dielectric properties, capacitance and tan(δ) were measured across a frequency range of 0.1 Hz to 1 kHz using a dielectric response analyzer. The results indicated that 10 Hz acts as a central frequency: below this threshold, tan(δ) decreased with aging, whereas above it, tan(δ) increased. This frequency-dependent trend was observed both before and after thermal–mechanical aging. In the case of semi-crystalline polymers, the dissipation factor is strongly influenced by morphological changes. The pronounced increase in tan(d) within the 10–100 Hz range is attributed to the enhanced mobility of charge carriers and the presence of free radicals generated during the aging process.

In summary, the reviewed studies clearly demonstrate that dielectric loss, particularly at very low frequencies, is a sensitive and reliable indicator of insulation aging. Both thermal and thermo-mechanical stress contribute to the formation of conductive pathways and polar degradation products, which enhance dipolar and conductive losses. The frequency-dependent behavior of tan(δ), with pronounced increases below 0.1 Hz and in the 10–100 Hz range, reflects the complex interplay between morphological changes, charge carrier dynamics, and aging-induced defects. These insights highlight the diagnostic potential of dielectric spectroscopy for evaluating the health of cable insulation systems under various aging scenarios.

3.4.3. Aging Mechanisms: Natural Versus Artificial Aging

In experimental studies, artificial aging protocols—such as thermal, electrical, mechanical, or environmental stress applied in controlled laboratory conditions—are widely employed to replicate the degradation processes that occur during natural aging over extended service periods. These accelerated tests enable studying the material behavior, failure mechanisms, and diagnostic indicators within practical timeframes. However, it is important to recognize that artificial aging does not always perfectly replicate the complexity and stochastic nature of natural aging, as noted by Frigione and Rodríguez-Prieto [92]. In real-world conditions, insulation materials are subjected to a combination of variable and interacting stressors, including seasonal thermal cycling, fluctuating electrical loads, mechanical vibration, moisture ingress, and contamination. To reproduce the effects of long-term natural exposure within short experimental timeframes, acceleration factors in artificial aging tests are often significantly intensified. However, this approach may lead to unrealistic degradation scenarios that do not accurately reflect real-world conditions, as discovered by Colom et al. [93]. Moreover, polymers—being a highly diverse class of materials—do not respond uniformly to the same environmental stress factors. In parallel, environmental conditions vary significantly across geographic regions, further complicating the extrapolation of aging results. As a result, it may be necessary to develop material-specific and climate-specific aging standards to ensure that accelerated tests more accurately predict field performance.

Given the limitations of accelerated aging and the variability of environmental effects on different polymeric materials, it becomes clear that aging behavior must be evaluated in relation to the specific stress factor and context. In this regard, Qiao et al. [94] conducted a comprehensive review of studies addressing different aging mechanisms, emphasizing that the results, degradation rates, and associated effects are strongly dependent on the type of

aging process involved. Several distinct environmental aging conditions were identified, as summarized in Table 8.

Table 8. Aging experiments in various environments.

Environment	Material/Test Conditions	Main Findings	Reference
Salt-fog environment	Silicone rubber; Salt-fog environment, simulated by generating ultrasonic water–salt mist into the test chamber at 2.5 kg/h with salt particles 1–10 mm; The spray device was first activated, and then a predetermined voltage was applied to the sample to initiate pressure aging for 2, 4, 6, and 8 h in the salt-fog environment with different water conductivity rates (γ_{20}) of 100, 1000, 3000, and 5000 μS/cm	ε and tan(δ) increased; Change in surface morphology (SEM images) from compact to rough and porous; FTIR spectra showed a hydroxylation and decomposition of alumina trihydrate	Zhang et al. [26]
Tropical environment	33 kV insulators, silicone rubber, on-site test Koggala (KG site), on the west coast of Sri Lanka, and the other one was an inland site situated in Peradeniya (PG site)	Leakage current varied from 0.5 mA to 2 mA with a 16 mA peak	Fernando and Gubanski [27]
Radiation environment	Silicone rubber under gamma radiation, dose rates 0.14 and 0.47 kGy/h; Inclined plane test procedure IEC—60587	Variation in gamma dose did not affect the performance of insulation when AC voltage was applied	Rajini and Udayakumar [28]
High-intensity electric fields	Polymeric insulator;Cable samples placed under a DC electric field, ±2.4 kV. 10,000 h, aging was performed according to IEC1109/IEC61109-modified standard (equivalent to 15 years of normal operation)	FTIR shows that unfilled SR suffers loss in main peaks at wavenumber 1008 cm^{-1}; of depolymerization.	Ullah et al. [95]
Low temperature/icing environment	Silicone rubber 500 kV insulator; Test performed according to IEEE 1783-2009 Standard.	The icing surface density causes a significant drop in the flashover voltage. The study does not examine the degradation effect of icing on the material	Qiao et al. [96]
Underground mining environment	PVC sheathing in MYJV-type mining cables TG-FTIR analysis	Thermal decomposition of PVC sheathing occurs in four stages Primary chain scission reaction, occurring in the second stage of PVC decomposition, released a large amount of combustible and toxic gases	Wang et al. [97]

As demonstrated throughout this review, insulation degradation mechanisms—including thermal, electrical, mechanical, and environmental stress—have profound and often compounding effects on the fire behavior of electrical cables. To synthesize these interactions, Table 9 provides a cross-mapping between dominant degradation mechanisms, their material-level consequences, and the resulting changes in fire-relevant parameters.

This structured overview highlights the importance of incorporating material aging into fire risk assessments, predictive modeling, and insulation design standards.

Table 9. The influence of various degradation mechanisms on fire parameters.

Degradation Mechanism	Key Material Effects	Fire-Relevant Consequences	Fire Parameters Affected	Reference
Thermal aging/Oxidation	- Chain scission - Carbonyl formation - Reduced crystallinity	- Lower ignition temperature - Increased flammable volatiles - Faster decomposition	Reduced ignition time Increased HRR Increased smoke production	Kim et al. [45] Jiang et al. [98]
Electrical degradation (PD, treeing)	- Carbonized paths - Local heating - Surface cracking	- Local hot spots - Arc-induced ignition - Accelerated failure modes	Higher arc frequency Reduced dielectric strength Higher flame probability	Zhang et al. [99] Fard et al. [100] Han et al. [86]
Surface tracking	- Conductive carbon trails - Surface erosion	- Flashover risk - Ignition via arcing - Thermal runaway	Higher surface temp Higher ignition risk Higher flame spread rate	Xing et al. [101] Tariq Nazir et al. [102] Li et al. [103] Riba et al. [104]
UV/Radiation degradation	- Crosslink scission - Surface embrittlement	- Reduced flame retardancy - Greater crack formation - More volatiles	Lower char yield Higher HRR Higher smoke density	Hedir et al. [78] Liu et al. [25] Maraveas et al. [105]
Moisture ingress	- Increased conductivity - Hydrolysis	- Higher leakage currents - Tracking/PD susceptibility - Easier ignition under arc conditions	Higher dielectric loss Lower flashover voltage	Liu et al. [106] Frišković et al. [107] Ahmad et al. [108]
Thermal conductivity degradation	- Reduced k - Local heat concentration Impaired dissipation	- Faster ignition - Hot spots - Enhanced flame propagation	Lower critical heat flux Higher temperature gradients Higher flame spread rate	Liu et al. [71] Kim et al. [109] Gunnarshaug et al. [110]

Table 9 illustrates how different degradation mechanisms map onto fire-relevant parameters. A key comparative insight is that while thermal aging universally reduces ignition resistance, electrical degradation introduces additional ignition pathways via arc faults—mechanisms which are largely absent in purely thermal studies. Similarly, UV/radiation degradation exacerbates smoke density, a factor that is not emphasized in thermal or electrical studies. Such contrasts emphasize that multi stress-factor experimental designs are essential for capturing realistic degradation–fire interactions.

4. Flame Retardants for Polymeric Materials and Aging

Despite significant advances in the formulation of fire-retardant polymeric insulation materials, the long-term degradation of flame-retardant additives under service conditions remains incompletely understood. Fire retardants incorporated into cable sheaths, such as halogenated compounds, aluminum hydroxide, or phosphorus-based systems, are known to undergo chemical and physical changes when exposed to combined thermal, electrical, and environmental stress factors. These degradative processes can lead to the loss of flame-retardant efficiency, increased smoke/toxicity during combustion, and even alterations in the dielectric properties of the insulation. While the behavior of base polymers such as PVC, XLPE, or polyurethane under aging has been widely investigated, systematic studies focusing on the stability and degradation pathways of the fire-retardant systems themselves are still scarce. Recent research indicates that fire-retardant degradation can interact synergistically with polymer matrix aging, producing unexpected fire behavior in aged cables. Moreover, there are a lack of predictive models linking retardant depletion or structural modification to long-term fire hazard assessment, representing a clear gap in the literature.

A comprehensive review of the effects of aging on the fire-retardant performance of polymeric compounds (not limited to cable insulation materials) was presented by Troitzsch [111]. The analysis demonstrates that the impact of aging is highly dependent on both the polymer matrix and the type of flame retardant employed:

- Mineral fillers such as aluminum trihydrate (ATH) generate a protective residual layer on the polymer surface during combustion, which not only shields the underlying material from fire exposure but also limits moisture ingress into the degraded matrix. As a result, ATH-containing systems can retain or even enhance their flame-retardant performance after prolonged aging.
- Organically modified montmorillonite (OMMT) nanocomposites exhibit limited thermal stability and contain metal ions that deactivate stabilizers, leading to a reduction in the flame-retardant efficiency of APP-based intumescent polypropylene composites following aging. By contrast, in glass fiber-reinforced polyamide systems combined with brominated epoxy/antimony trioxide, OMMT, were found to slow degradation by promoting crosslinking of the polymer matrix.
- Red phosphorus maintains flame retardancy under thermo-oxidative aging by migrating to the material surface, where it decomposes and forms a charred, intertwined network of P–O and P–C complexes that reinforce the protective barrier.
- Phosphinate salts, such as diethyl aluminum phosphinate, show high resistance to aging and hydrolysis, combined with elevated thermal stability. Consequently, they effectively preserve the fire performance of polyamides over extended aging.
- Brominated flame retardants, although capable of initiating adverse interactions with the host polymer and stabilizers, benefit from high thermal and hydrolytic stability, allowing them to maintain flame-retardant functionality after aging.

The mechanisms governing the aging of flame-retardant insulation materials are inherently complex and multifaceted, involving simultaneous changes in both the polymer matrix and the flame-retardant additives. As an illustrative example is provided in the study conducted by Yang et al. [112], consisting of exposing flame-retardant cross-linked polyethylene (FR-XLPE) to prolonged thermal aging at 100–155 °C for 800–2000 h. The degradation mechanism was found to follow a three-stage scheme:

(1) Additional cross-linking within the polymer reduces conduction current and lowers the imaginary part of the complex permittivity.
(2) Oxidative degradation dominates, producing an increase in conduction current together with higher real and imaginary permittivity values.
(3) The conduction current stabilizes while the complex permittivity continues to rise, reflecting sustained structural and chemical transformations.

While this sequence demonstrates one possible pathway of degradation under thermal stress, it must be recognized that flame-retardant aging is highly system-dependent, and the interplay between polymer oxidation, additive migration, decomposition, or synergistic reactions can yield diverse outcomes. This example therefore highlights the need for a more comprehensive, mechanism-oriented framework to understand and predict the long-term performance of flame-retardant cable insulation under realistic service conditions. Most studies aiming to assess the effect of aging on the FR effectiveness consider long glass fiber-reinforced polypropylene with various FRs, as summarized in Table 10.

Table 10. Aging effects on FRs for polymeric materials.

Material/FR	Aging Procedure	Flammability Test/Results	Ref
Long glass fiber-reinforced (LGF) polypropylene/ red phosphorus	Thermo-oxidative exposure at 140 °C	UL94, LOI, and cone calorimeter demonstrated no significant effect on	Zhou et al. [113]
Long glass fiber-reinforced polypropylene/organic intumescent montmorillonite	Different exposure times at 140 °C	UL94, LOI, cone calorimeter, TGA. Aging reduces the effectiveness of the FR Aging causes ground particles and microscale cracks on the surface	Zhou et al. [114]
Long glass fiber reinforced polypropylene/ decabromodiphenyl ethane	Thermal-oxidative exposure time (0–50 days) at 140 °C	LOI values varied within statistically insignificant limits with increasing the aging time, UL-94 level maintains a constant V-0 rating	Guo et al. [115]
Long glass fiber-reinforced polyamide 6 composites/tris (tribromophenyl) cyanurate	Thermal-oxidative exposure time (0–50 days) at 140 °C	LOI, UL94, cone calorimeter The surface migration effect improved the flame retardancy of the composites with better LOI values, a more protective char layer structure, and excellent UL 94 ratings	Zuo et al. [116]
Long glass fiber-reinforced polyamide 6 composite/ organo-modified montmorillonite/brominated epoxy resins/antimony trioxide	Thermal oxidative exposure for 50 days.	LOI increased from 25% to 38% UL94 maintained class V0 Contrary to its negative effect in polypropylene composites, OMMT promotes crosslinking at the surface of the polyamide composite and improves its flame retardancy.	Zuo et al. [117]

A standardized framework for assessing the durability of flame-retardant systems in cable insulation is the Relative Thermal Index (RTI), Troitzsch [111]. RTI provides a canonical measure of a polymer's ability to retain functional properties when subjected to elevated temperatures over long periods, typically defined as the temperature below which at least 50% of the original property value is maintained for a service life of 60,000–100,000 h. The evaluation relies on accelerated thermal-aging experiments in hot-air ovens, with parallel monitoring of mechanical, electrical, and flammability characteristics (including vertical burning according to UL 94) before, during, and after exposure. Conventional RTI determinations mainly address the base polymer (PVC, XLPE, polyamides), with reported values usually ranging between 65 and 150 °C depending on material class. However, the stability of flame-retardant additives themselves is rarely incorporated into RTI methodologies, despite their critical role in sustaining fire performance. Integrating flame-retardant degradation behavior into RTI testing would therefore represent a valuable step toward more realistic lifetime prediction and safety assessment of insulated cables under thermal and environmental stress.

5. The Service Lifetime of Cable Insulation

The expected service lifetime of non-flame-retardant crosslinked polyethylene (XLPE) cables is typically reported in the range of 40–60 years at the rated operating temperature of 90 °C. However, recent experimental findings indicate that elevated operating conditions substantially shorten this lifespan. Alghamdi et al. [118], for instance, reported an estimated lifetime between 7 and 30 years when XLPE cables were operated at 95–105 °C (end-of-life criteria included the percentage reduction in elongation at break, which is considered in [116] to be 50%). The most stringent performance durability requirements are imposed on nuclear power plant cables, where safety-critical applications require extended lifetimes under combined thermal and radiation stress. Comprehensive assessments of cable aging in nuclear environments show that service conditions may involve gamma radiation levels

up to 100 Gy/h and temperatures approaching 120 °C, yet cables are still expected to maintain a lifetime beyond 40 years [119].

Although such performance data emphasize the robustness of cable insulation systems, they also highlight a critical research gap: the durability of the flame-retardant systems themselves is seldom assessed independently. Most lifetime predictions focus on the polymer matrix, while the long-term stability, migration, or depletion of aluminum trihydrate and other flame retardants under thermal and radiation aging remain largely unquantified. Bridging this gap requires integrating flame-retardant degradation analysis into lifetime assessment methodologies (e.g., RTI testing), thereby ensuring that the projected service lives of safety-critical cables rest on a complete evaluation of all functional components.

6. Conclusions

This review has systematically demonstrated that the degradation of polymeric cable insulation represents a critical determinant of fire hazard in electrical systems. Thermal, electrical, mechanical, and environmental stressors interact in complex, often nonlinear ways, progressively altering the dielectric, mechanical, and thermophysical properties of insulation materials. These aging-induced transformations lower dielectric strength, facilitate the onset of partial discharges, treeing, and surface tracking, and reduce the ignition resistance of cable systems. Collectively, such mechanisms act as both precursors to catastrophic electrical failure and as direct initiators of fire ignition.

Taken together, the comparative analysis across Tables 1–10 demonstrates that cable fire performance is controlled by an interplay of geometry, material composition, and degradation history. Consistencies (e.g., faster ignition after aging, higher flame spread in vertical trays) provide robust design guidance, whereas discrepancies between studies often trace back to divergent test protocols. A more critical integration of these datasets therefore highlights the need for standardized, multi-factorial test frameworks that combine aging, material chemistry, and installation geometry.

Experimental evidence consistently confirms that aged insulation exhibits reduced ignition times, increased peak heat release rates, and elevated smoke production compared to unaged materials. Of particular concern is the degradation of thermal conductivity, which impairs heat dissipation, amplifies local temperature gradients, and reduces the critical heat flux for ignition, thereby creating conditions for thermal runaway. These results underline the necessity of explicitly incorporating aging-dependent property variations into fire risk models, rather than relying on static material characterizations.

The bibliometric analysis further reveals that while the literature is strongly clustered around material degradation and flame retardancy, important research gaps remain. In particular, ignition mechanisms, diagnostic monitoring strategies, and system-level fire propagation models are underrepresented despite their practical relevance to real-world fire scenarios. Bridging these gaps requires integrative approaches that couple materials science, high-voltage engineering, and fire dynamics, and that explicitly link degradation pathways to ignition thresholds and propagation behaviors.

From an applied perspective, our findings emphasize that insulation aging must be recognized as a dynamic, time-dependent variable in both predictive fire-safety modeling and reliability assessments. Future work should prioritize the following:

(i) The development of more realistic artificial aging protocols that better replicate field conditions;
(ii) Advanced diagnostic and monitoring techniques capable of detecting degradation-induced precursors to ignition;
(iii) Multi-scale fire modeling frameworks that incorporate evolving material properties.

A notable gap that has been identified in the literature is the absence of data-driven or artificial intelligence (AI)-based approaches for linking insulation degradation to fire hazard prediction. While significant progress has been made in characterizing material aging and in developing experimental fire tests, no reported attempt has systematically applied machine learning or advanced data analytics to capture the complex, nonlinear interactions between degradation pathways and ignition phenomena. The integration of AI methodologies—particularly explainable machine learning techniques, or physics-informed machine learning (PIML)—could enable the development of predictive models that bridge material-level aging processes with system-level fire risk. Such approaches hold potential to transform diagnostic monitoring, accelerate the identification of early warning indicators, and provide adaptive, real-time risk assessment tools for electrical infrastructure.

While the reviewed studies provide valuable insights, most are conducted under controlled laboratory conditions, which may not fully replicate the complexity of real service environments. Sample sizes are often limited, and reproducibility across laboratories remains insufficiently addressed. In particular, accelerated aging protocols, though indispensable for practical timeframes, may yield degradation pathways that differ from natural long-term exposure. This limitation underscores the need for multi-site interlaboratory validation and long-term field monitoring to confirm the transferability of laboratory findings to real-world cable installations. Bridging this gap requires coordinated interlaboratory studies, long-term field monitoring, and standardized methodologies that combine material aging diagnostics with realistic fire performance testing.

In conclusion, cable fire safety cannot be dissociated from insulation aging. Addressing this nexus requires a paradigm shift from static evaluations toward predictive, degradation-informed risk assessments. Such an approach will provide a more robust basis for design standards, maintenance strategies, and system-level fire safety in modern electrical infrastructures.

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