

Review

Recent Advances in Arc-Flash Protective Textiles: Materials, Mechanisms, and Performance

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Abstract

Arc-flash protective textiles are specialized technical fabrics designed to endure extreme thermal energy and inhibit ignition during electrical faults. It is an industry driven by the enhanced use of machine learning models, autonomous technologies, and advanced analytics. Key sectors, including healthcare, automotive, retail, financial services, and technology, are making considerable investments in high-quality training datasets to improve AI performance. Consequently, there is an escalating demand for scalable and accurate data annotation services. This review has as its main objective to demonstrate the recent advances on arc-flash protective textiles, including arc-flash environment, material failure mechanisms, structural design, performance characterization, and new materials breakthrough.

Keywords: arc-flash protective; electrical performance; personal protective equipment

1. Introduction

The Arc-flash Protective Clothing Market (AFPCM) is currently witnessing significant expansion, with projections indicating an increase from USD 2.1 billion to USD 4.5 billion. This growth is largely attributed to the rising integration of artificial intelligence across diverse industries. It is forecasted that the market will experience a substantial compound annual growth rate (CAGR) of 9% during the period from 2026 to 2033, driven by the enhanced use of machine learning models, autonomous technologies, and advanced analytics. Key sectors, including healthcare, automotive, retail, financial services, and technology, are making considerable investments in high-quality training datasets to improve AI performance. Consequently, there is an escalating demand for scalable and accurate data annotation services. Additionally, the increase in data volumes, rapid digital transformation, and the widespread adoption of generative AI applications are anticipated to further propel market growth in the coming years [1].

In the context of the industry, the market is characterized by a high degree of specialization, which emphasizes compliance-driven innovation and strict adherence to regional safety standards. Macro drivers, including the global transition to renewable energy infrastructure, the expansion of electric vehicle manufacturing, and the modernization of aging power grids, are increasing the demand for arc-flash protective clothing. These developments are further bolstered by rising investments in grid resilience, which enhance the importance of worker safety and the sophistication of protective gear. The primary focus



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of this market is fundamentally centered on risk mitigation, which includes safeguarding personnel from life-threatening electrical arcs, preventing costly downtime, and ensuring compliance with regulatory standards. As electrical systems become increasingly complex and voltage levels escalate, the necessity for advanced personal protective equipment (PPE) intensifies, transforming safety from a mere compliance obligation into a strategic operational imperative. This shift is further highlighted by the rising costs associated with arc-flash incidents, encompassing medical expenses, legal liabilities, and reputational damage, which compel organizations to adopt comprehensive protective solutions [2,3].

Arc-protective textiles incorporate specialized materials and multi-layered designs to safeguard workers against the intense thermal energy, radiant heat, and molten metal splashes associated with electric arc-flashes. The primary objective is to ensure that the fabric does not rupture, melt onto the skin, or transmit hazardous levels of heat. There are some key differences between standard and arc-protective textiles: while standard fabrics ignite and burn when combusted, arc-protective textiles automatically extinguish themselves, demonstrating an inherent flame retardancy due to the fibers used (meta- and para-aramids, and polybenzimidazole). Another important difference is that when exposed to extreme temperatures of an electric arc (above 10,000 °C), advanced outer layers present on the textiles rapidly expand and undergo endothermic reactions or carbonization (by creating a thickened and stable barrier that blocks convective and radiant heat transfer). Also, when exposed at high-hazard environments, arc-protective textiles utilize a composite layering that protects the user from the initial flash, sparks and molten materials, in addition to being breathable and providing thermal barrier protection [4]. Theories of protection related to arc-protective textiles emphasize the importance of preventing burn injuries by reducing the effects of intense thermal, radiant, and mechanical energy generated by an electric arc-flash. These textiles operate mainly through mechanisms of thermal insulation (act as a barrier against the extreme convective and radiant heat generated during arc-flash), flame resistance (unlike standard workwear that continues to burn), and break-open resistance (during an arc-flash event, rapid pressure blasts can cause physical damage to the fabric by tearing, ripping, or melting holes, thereby exposing the wearer to direct heat and flames), which collectively serve to minimize heat transfer to the wearer's skin. The mechanisms for the thermal insulation, flame resistance and break-open resistance are the fabric's inherent air permeability and low thermal conductivity restrict the transfer of heat to the skin, removal of the heat source, the textile should demonstrate self-extinguishing properties to mitigate the risk of the clothing serving as a fuel source, and maintenance of its structural integrity under extreme temperature conditions, respectively [5].

This review article aims to present the latest and innovative arc-flash protective textiles, encompassing the arc-flash environment, material failure mechanisms, structural design, performance characterization, and new-material breakthrough.

2. Arc-Flash Environment

An arc-flash environment constitutes a hazardous workplace involving electrical equipment, where an accidental short circuit generates intense thermal heat, blinding light, and projections of molten metal. In such high-risk areas, it is essential for workers to utilize specialized Arc-Rated (AR) and Flame-Resistant (FR) textiles. These environments, along with the protective textiles employed, exhibit several defining characteristics as (i) extreme heat: temperatures can escalate to 35,000 °F, which can instantaneously ignite oxygen and vaporize copper or aluminum components; (ii) thermal hazards: such incidents generate elevated levels of incident energy, typically quantified in calories per square centimeter (cal/cm^2), and (iii) physical projectiles: the explosive force can propel molten metal droplets, hot gases, and shrapnel into the surrounding area [5–7].

3. Physical and Chemical Phenomena of the Arc-Flash

An electric arc involves complex physical and chemical phenomena that occur when electricity propagates through the air due to an insulation failure. Arc-flash events constitute one of the most severe electrothermal phenomena associated with electrical power systems, characterized by the instantaneous release of thermal energy, electromagnetic radiation, mechanical pressure, and incandescent metallic particles. Temperatures exceeding 19,000 °C can be reached during the formation of the electric arc, exposing the worker to extreme risks of burns, fabric rupture, and structural failures of personal protective equipment (PPE). In this context, the development of high-performance technical textiles has become a strategic area of research in materials science, textile engineering, and occupational safety [8].

The first phenomenon involved in arc-flash is plasma formation. During the electrical discharge, the current ionizes the atmospheric air, creating a highly conductive channel composed of ionized particles and free electrons. This plasma exhibits high energy density and intense heat transfer. The relationship between these phenomena and the engineering of advanced protective textile materials is the subject of research; published studies demonstrate that fibers with high dielectric strength, especially meta-aromatic aramids such as Nomex[®], play a fundamental role in preventing secondary reionization near the skin surface. The electrical stability of these fibers reduces arc propagation and limits thermal conduction in the fabric [9].

Another critical mechanism is the thermal radiation emitted by the electric arc. Energy is transferred predominantly through infrared and ultraviolet radiation, which promotes extremely rapid heating of exposed surfaces. To minimize this effect, modern textiles incorporate aluminized coatings and refractory ceramic particles capable of reflecting a large portion of the incident radiation. Recent published research shows that nanostructured metallic coatings and surface modifications with ceramic nanoparticles and graphitic carbon significantly increase thermal reflectivity and reduce heat transfer by radiation, prolonging the worker's escape time in critical situations [10].

In addition to radiation, thermal convection represents an important mechanism of heat transfer during arc-flash. The expansion of superheated gases directs an intense flow of heat towards the garment. The thermal performance of fabrics depends heavily on their ability to retain air within their internal structure, since trapped air acts as a natural thermal insulator. High-density, multi-layered, three-dimensional structures and textured yarns favor the formation of microcavities that reduce the thermal diffusivity of the system [11].

According to studies [11,12], fabrics with complex volumetric architectures exhibit a higher ATPV (Arc Thermal Performance Value) index, demonstrating superior insulation capacity against extreme convective flows. In addition to thermal effects, the arc blast produces a mechanical pressure wave resulting from the rapid volumetric expansion of the plasma. This shock wave can cause structural rupture of the fabric, a phenomenon known as break-open, completely compromising the integrity of the fabric. To withstand this mechanical stress, high-performance fibers with high tensile strength and thermal stability are used, such as Kevlar[®] and other aromatic polyamides. Also, aramids exhibit an excellent balance between mechanical strength and thermal stability, maintaining structural integrity even after exposure to high temperatures and high strain rates.

Another relevant aspect is the ejection of molten metal during electrical faults, especially superheated copper and aluminum particles. These metallic particles can adhere to the fabric and cause perforation or localized degradation of the polymer matrix. Therefore, protective materials must exhibit low surface wettability and reduced chemical affinity with molten metals. Research in surface engineering indicates that hydrophobic finishes and ceramic coatings significantly reduce metallic adhesion, favoring the flow of particles

without penetration into the fabric. Nanostructural modifications on the textile surface increase resistance to metallic adhesion and enhance the functional durability of clothing.

Li et al. [12] demonstrated that exposure to arc-flash promotes molecular breakdown, followed by carbonization and controlled embrittlement of the fiber, forming a protective thermal barrier (char formation). The authors used FTIR, SEM, and thermal analyses to investigate structural changes. From a chemical and thermodynamic point of view, one of the most important mechanisms is the controlled pyrolysis of textile fibers. Under extreme temperatures, the polymer chains break down, leading to thermal degradation of the material. In advanced fibers, however, this process is directed towards the rapid formation of a carbonized layer (char formation), which acts as a physical and thermal barrier. This layer reduces oxygen diffusion, limits flame propagation, and decreases heat flow to the user. Aramid fibers and phosphorus-containing materials promote high formation of carbonaceous residue, substantially increasing the residual thermal resistance of the fabric.

Ma et al. [13] compared polyimide and aramid fabrics used in arc-flash protective clothing. The authors analyzed thermal resistance, carbonization, structural degradation, and performance against the thermal plasma generated in the arc-flash. The work demonstrates that aromatic polymeric materials exhibit high thermal stability due to the formation of protective carbonized structures.

Furthermore, many textile systems incorporate endothermic mechanisms associated with the presence of flame retardants. Phosphorous, nitrogenous, and, to a lesser extent, halogenated compounds undergo endothermic chemical decomposition during exposure to heat, absorbing a significant portion of the incident thermal energy. This phenomenon reduces the surface temperature of the fabric and delays the ignition of the polymer matrix [14].

Also, organophosphate flame retardants have received attention due to their high thermal efficiency and lower environmental impact compared to traditional halogenated systems. Therefore, arc-flash protection mechanisms involve a complex combination of physical, chemical, and thermodynamic phenomena that act simultaneously to reduce heat transfer, dissipate energy, and preserve the structural integrity of the tissue [4].

Table 1 demonstrates the physical and chemical phenomena and their respective characteristics.

Table 1. Physical and chemical phenomena of the arc-flash and the respective characteristics.

Phenomena	Type	Characteristic
Ionization of air/plasma formation	Physical	The intense energy breaks down the dielectric properties of air, turning it into conductive plasma
Intense thermal radiation	Physical	The arc produces extreme radiant heat, including ultraviolet (UV) and infrared (IR) light, capable of causing fatal, third-degree burns from several feet away
Arc blast (pressure wave)	Physical	The rapid heating of surrounding air causes it to expand with supersonic speed, resulting in a blast wave that can exceed 100 kPa, or 2000 lbs per square foot, which can throw workers, damage structures, and create sound levels over 140 dB
Molten metal projectiles (shrapnel)	Physical	Vaporized and molten copper (or other conductor material) is blasted outward at high speed, exceeding 700 mph, often containing vaporized “plasma dust
Electromagnetic forces	Physical	High-current flow creates magnetic fields that can physically move the arc, often driving it away from the source towards the end of conductors
Rapid material expansion	Physical	Copper vaporizes and expands by a factor of up to 67,000 in volume, contributing directly to the explosive pressure wave
Vaporization of materials	Chemical	The extreme heat vaporizes metal conductors (copper, aluminum), insulation, and adjacent plastics/materials
Production of toxic gases	Chemical	The vaporized metals and burning insulating materials release toxic fumes (copper oxide, carbon monoxide, etc.), which pose severe inhalation risks
Metal oxidation	Chemical	Molten and vaporized metals react immediately with oxygen in the air (oxidation), creating metal oxides that contribute to the smoke and plasma dust
Ignition of flammable substances	Chemical	Nearby combustible materials, including clothing (if not fire-rated), can ignite due to the intense radiant heat

Current scientific research seeks to balance thermal protection, lightness, breathability, and sustainability. Although multilayer materials and high-performance fibers offer excellent protection, many systems still have limitations related to thermal comfort, high cost, and difficulty in recycling. Therefore, new approaches involving biomaterials, smart nanocomposites, and sustainable functional coatings represent promising trends for the next generation of protective textiles. Advances in research on smart materials, nanotechnology, and multilayer structures are enabling the development of increasingly efficient, lightweight, and safe garments, contributing significantly to the protection of workers exposed to arc-flash risks.

Material Failure Mechanisms

Arc-protective textiles are compromised when the incident heat and mechanical shock from an electrical arc exceed the fabric’s thermal and structural integrity. The failure occurs in two main stages: first, thermal breakdown, which may involve combustion or degradation, followed by mechanical failure, characterized by break-open or melting, ultimately exposing the skin to severe burns [7]. Table 2 presents the main material failure mechanisms and their characteristics.

Table 2. Material failure mechanisms for arc-protective textiles [5–8].

Stage	Mechanisms	Result
Thermal degradation and Pyrolysis	Intense incident radiant and convective heat (up to 20,000 °C) exceeds the polymer bonds of the fiber	The fabric undergoes pyrolysis, breaking down into flammable gases, volatile vapors, and solid combustible residues. The absorption coefficient of the fabric dictates how much heat gets transferred to the wearer
Oxidation and Combustion	If the fabric cannot self-extinguish when the electric arc ceases, continuous burning occurs	The material’s Limiting Oxygen Index (LOI) is overcome by atmospheric oxygen. Rapid consumption of the textile occurs, resulting in total loss of the protective barrier
Break-Open and Perforation	Electric arcs release a high-pressure blast wave (up to 0.3 MPa or 30 t/m ²) within 5–15 milliseconds. This immense mechanical force acts on the fabric after thermal carbonization and embrittlement	The threads snap and separate, creating holes larger than 5 mm. This energy break-open threshold (EBT) failure allows the arc and flames to directly contact the skin or melt underlayers
Melting and Adhesion (non-FR materials)	The use of standard, non-FR undergarments (e.g., polyester or nylon) layered under protective clothing is a common point of failure	Non-FR synthetics reach their glass transition and melting temperatures (120–260 °C) almost instantly. They melt, drip, and adhere to the skin, causing severe, deep-tissue contact burns

4. Fabrication Methods

The protective performance of arc-flash textiles depends not only on fiber composition but also on fabrication methods employed throughout the textile production chain. From fiber engineering and yarn formation to fabric construction, surface functionalization and multilayer assemblies, each processing step influences thermal insulation, structural integrity, and wearer comfort under arc-flash exposure [9,15,16]. Compliance with testing standards ensures that these materials meet required safety criteria [17]. Ultimately, optimization of fabrication methods requires a multidisciplinary approach integrating material science, textile engineering and ergonomic design.

4.1. Fiber Engineering

Fiber selection represents the first and most critical step in the fabrication of arc-flash protective textiles. Synthetic flame-retardant fibers generally comprise thermoset aromatic fibers, or thermoplastic fibers modified with flame-retardant fillers through extrusion or in situ polymerization. Inherently flame-resistant fibers such as aramids, PBI and modacrylics exhibit molecular structures capable of resisting thermal decomposition and sustaining

protective char formation under extreme heat exposure [12,18,19]. Recent work emphasizes the transition toward bio-based and eco-friendly flame retardants to reduce environmental impact while maintaining performance [18,19].

These fibers do not melt or drip when exposed to high temperatures; instead, they undergo carbonization, forming a protective char layer that acts as a thermal barrier. Alternatively, conventional fibers such as cotton can be chemically modified to impart flame retardancy through phosphorus- or nitrogen-based systems; however, durability to laundering remains a key limitation [20–23].

Blending different fiber types is a common strategy to balance protection and wearability. Blends of aramid fibers with flame-retardant viscose or cotton enhance moisture management and comfort while maintaining thermal protection. Recent advances include para-aramid/modacrylic core-spun blends coated with nitrile-based systems for arc-flash gloves [19]. Beyond chemistry, fiber morphology can be engineered to improve protection. Parameters such as fineness, cross-sectional geometry, crimp, and surface texture influence packing density and air retention, directly impacting thermal insulation [24].

4.2. Yarn Manufacturing Methods

Yarn manufacturing significantly affects fabric behavior under arc exposure, since yarn structure controls cohesion, porosity, strength and thermal transport.

4.2.1. Conventional Spinning Methods

Ring-spun yarns generally exhibit higher compactness and mechanical strength, contributing to improved resistance against fabric breakopen under arc exposure. In contrast, rotor-spun yarns offer cost efficiency but typically present lower structural integrity. Air-jet spinning produces smoother yarns with reduced hairiness, influencing ignition behavior [25]. Process variables such as twist level, spinning tension, and yarn linear density directly influence thermal performance and should be carefully controlled [24].

4.2.2. Advanced Yarn Architectures

Yarn architecture plays a decisive role in the thermal and mechanical response of protective fabrics. Engineered systems such as core-spun, wrap-spun and hybrid yarns combine high-performance filaments with staple fibers, improving tensile strength and resistance to rupture while preserving flexibility [25]. Commingled and textured yarns increase bulk and air entrapment, enhancing insulation efficiency without significantly increasing mass [17]. Recent studies highlight the importance of engineered yarn structures in optimizing arc rating performance through controlled porosity and cohesion [24].

4.3. Fabric Construction Methods

Despite the well-established role of fabric construction in determining protective performance, a critical trade-off exists between thermal protection and wearability. High-density woven fabrics typically provide superior resistance to heat transfer and breakopen; however, they may reduce breathability and increase physiological burden on the wearer. On the other hand, more rigid or flexible structures improve comfort, but may compromise arc-flash resistance performance. Therefore, optimizing fabric architecture requires balancing protection, mobility, and thermal comfort, particularly for prolonged industrial use [9]. Fabric construction governs the spatial organization of yarns and is a primary determinant of heat transfer and failure behavior under arc-flash conditions [26].

4.3.1. Woven Structures

Woven fabrics are extensively used due to their dimensional stability and mechanical strength. Performance depends on weave type, thread density, yarn count and cover factor.

Plain weaves provide compact structures with reduced permeability, while twill weaves offer improved flexibility. Satin weaves may present lower resistance to mechanical and thermal stress [19,27]. Recent developments include multilayer and 3D woven architectures designed to introduce built-in air gaps and enhance insulation [24].

4.3.2. Knitted Structures

Knitted fabrics provide high elasticity and comfort but generally exhibit higher heat transfer due to their open structure. They are therefore often used as inner layers rather than primary barriers. Spacer fabrics create controlled three-dimensional air layers that significantly enhance thermal insulation [24].

4.3.3. Nonwoven Manufacturing

Nonwoven fabrics, produced by processes such as needle punching, spunbonding, meltblowing and electrospinning, are widely used as thermal barriers due to their high porosity and air entrapment capacity. Advanced systems incorporating silica aerogels have shown enhanced insulation performance. For example, aerogel-loaded nonwoven fabrics demonstrated improved thermal resistance while maintaining flexibility [28,29].

4.4. Surface Modification and Finishing

Surface modification is essential for enhancing flame resistance and multifunctionality. Conventional pad-dry-cure processes remain widely used for applying flame-retardant chemistries [23]. Recent advances focus on improving durability and environmental compatibility through crosslinked and nanostructured systems. Advanced techniques such as sol-gel processing, plasma treatment, magnetron sputtering and layer-by-layer deposition enable thin multifunctional coatings with minimal impact on flexibility. Metal oxide coatings and conductive polymers have shown promising results in enhancing both thermal resistance and antistatic behavior. Nanocomposite and bio-based coatings are emerging as key trends, offering improved performance with reduced environmental impact [19–21].

4.5. Multilayer Assembly Strategies

Although multilayer assemblies are widely recognized as the most effective approach to improving arc-flash protection, they also introduce significant limitations. Increased thickness and mass can negatively impact wearer mobility, heat stress, and overall ergonomics, particularly in hot working environments. Furthermore, improper layer integration or excessive compression of air gaps during use may reduce the expected insulation performance. These limitations highlight the need for optimized multilayer designs that maintain protective efficiency while minimizing physiological strain [24]. Multilayer assemblies enable synergistic interactions between functional layers and are highly effective for arc-flash protection. A typical system includes an outer shell, thermal barrier and inner comfort layer. Air gaps between layers play a critical role by reducing conductive and convective heat transfer. Their optimization significantly influences arc rating values. Spacer fabrics and engineered separations are increasingly used to control air-gap distribution [30]. Garment assembly techniques also affect performance. Seams and bonding methods can act as weak under thermal stress, requiring the use of heat-resistant threads, reinforced seam structures and advanced bonding techniques [31–35].

4.6. Emerging Fabrication Technologies

Nanotechnology-based approaches incorporating graphene, nanoclays and ceramic nanoparticles have demonstrated improved thermal stability and barrier performance [36–38]. Smart textiles with integrated sensors enable real-time monitoring of temperature and heat flux [39]. Recent research also explores advanced materials such as metal-organic

frameworks (MOFs) and intelligent fire-warning coatings, which combine protection with sensing capabilities [39]. Additive manufacturing and 3D textile engineering are emerging as promising routes for customized protective structures with optimized thermal and mechanical behavior [40].

4.7. Processing–Structure–Performance Relationship

While the processing–structure–performance framework provides a robust basis for designing protective textiles, several challenges remain. Variability in manufacturing processes can lead to inconsistencies in fabric density, porosity and finishing distribution, ultimately affecting arc rating performance. In addition, durability issues associated with flame-retardant treatments, particularly under repeated laundering and mechanical wear, remain a critical concern. Environmental and health considerations related to certain flame-retardant chemistries also represent ongoing challenges for the industry [41]. Addressing these limitations requires the development of more stable, sustainable and reproducible fabrication strategies.

The relationship between processing conditions, resulting structure and performance is central to textile design. Fiber processing determines intrinsic thermal stability, yarn manufacturing governs cohesion and porosity, fabric construction defines heat transfer pathways, and finishing modifies surface interactions [19,24]. Recent studies demonstrate that fabric structure and grammage significantly influence arc-flash performance, highlighting the importance of processing parameters in determining ATPV values [24]. Multilayer systems further enhance protection through controlled air entrapment. Therefore, the optimization of fabrication methods requires a holistic approach integrating materials science, textile engineering and advanced manufacturing technologies, while addressing emerging challenges such as durability, environmental impact and multifunctionality [39].

4.8. Structural Design

Arc-protective textiles are structurally designed as multi-layered composite systems engineered to withstand intense thermal energy, resist ignition, and dissipate radiant heat generated during an arc-flash. These systems combine high-performance fiber blends with specialized weave architectures to provide effective thermal protection while maintaining wearer comfort, flexibility, and ergonomic mobility. Fiber composition plays a fundamental role in the structural design of arc-protective textiles, as the inherent flame resistance of the constituent fibers largely determines the thermal stability and protective performance of the fabric. Aramids, modacrylics, polybenzimidazole (PBI), and conductive fibers are among the most commonly used materials for this purpose. Since no single fiber can simultaneously satisfy all performance requirements, manufacturers typically employ intimate fiber blends and engineered weave architectures to optimize protection, durability, and comfort.

Fabric construction also significantly influences thermal performance by determining the fabric's ability to trap insulating air and reduce direct heat transfer during an arc-flash. Plain and twill weaves are the most common constructions, with twill fabrics generally providing greater density, improved abrasion resistance, and enhanced durability, making them the preferred choice for outer-shell protective garments. Ripstop fabrics incorporate a grid of reinforced yarns that limits tear propagation and reduces the spread of burn holes under severe thermal exposure. More recently, three-dimensional textile structures have attracted increasing attention. Advanced 3D weaving technologies enable the manufacture of spacer fabrics and double-layer structures containing internal air pockets, thereby improving thermal insulation while preserving breathability, flexibility, and wearer comfort.

Multi-layered garment systems are particularly important for environments with elevated arc-flash hazards. These systems typically consist of an outer shell, a thermal

liner, and a flame-resistant base layer. The outer shell generally comprises a durable flame-resistant composite, commonly based on blends of Nomex® and Kevlar®, and is designed to withstand intense thermal exposure while preserving the integrity of the underlying layers. The thermal liner, frequently manufactured from quilted aramid batting, functions as an insulating barrier by trapping stagnant air and minimizing heat transfer to the wearer’s skin. Finally, the base layer, which remains in direct contact with the skin, should also be manufactured from flame-resistant (FR) materials to prevent melting or ignition during arc exposure. Conventional, non-flame-resistant cotton garments should not be worn beneath arc-protective clothing, as they may ignite and significantly increase the risk of burn injuries [40,41].

4.9. Performance Characterization

The performance characterization of arc-protective textiles depends on the assessment of a fabric’s thermal insulation, mechanical integrity, and flame retardancy under high-heat electrical incidents. The main objective is to prevent material rupture and restrict heat transfer to levels that avoid the occurrence of second-degree burns [3,11,42]. Table 3 presents the performance characteristics of arc-protective textiles.

Table 3. Performance characterization for arc-protective textiles.

Key Performance Metrics	Standardized Testing Methods	Influencing Factors & Material Characteristics
A. Arc Rating—The maximum incident energy that a fabric can with-stand before there is a 50% probability of causing a second-degree burn, expressed in calories per square centi-meter (cal/cm²).	ASTM F1959 [17] is the primary international standard in which fabric specimens are exposed to an electrical arc while calorimeters measure the transmitted thermal energy to determine the arc rating.	Fiber Composition: Premium arc-protective textiles are constructed from inherently flame-resistant (FR) materials, such as aramids (e.g., Nomex, Kevlar),polybenzimidazole, or blends that include PBI and modacrylics.
B. A1. ATPV (Arc Thermal Performance Value): The amount of energy required to cause a second-degree burn, typically used for fabrics that do not break open easily.		Fabric Weight & Weave: Higher fabric weight (g/m²) and denser weave structures contribute to superior thermal protection; however, advancements in engineered blends now facilitate the creation of lighter and softer materials.
A2. EBT (Energy Breakopen Threshold): The energy level at which the fabric cracks, splits, or melts, allowing excessive heat transfer to the wearer.	IEC 61482-1-1 [43] is the international counterpart to ASTM F1959, employing open-arc test methodologies to determine the Arc Thermal Performance Value (ATPV) or Energy Breakopen Threshold (EBT) ratings.	Layering: The application of multiple fabric layers substantially enhances the arc rating and creates an air gap, which significantly slows heat transfer.
C. HAF (Heat Attenuation Factor): The percentage of total incident thermal energy blocked or absorbed by the fabric structure.	IEC 61482-1-2 [44] emphasizes the “box test” methodology, which evaluates the ability of a garment or material to withstand a specified confined electrical arc without ignition or failure.	Environmental & Use Factors: Contaminants, including sweat, oil, and dust, can impair fabric performance, while moisture, such as internal sweat, may accelerate the rate of heat transfer during an arc-flash.
D. Break-Open Threshold: The maximum incident energy a fabric can absorb before breaking open or failing		

5. Industrial and Lab Applications

Arc-flash protective textiles are essential materials for industrial and laboratory environments where workers are exposed to electrical discharge hazards and high thermal energy. Protective clothing acts as the final barrier between the worker and the arc event, aiming to reduce heat transfer and provide sufficient escape time during accidents [12].

These textiles are widely used in electrical power systems, industrial maintenance, petrochemical facilities, railway systems, welding operations, high-voltage laboratories, and electrical testing environments, where accidental arc generation may occur [9]. The

protective fabrics must withstand extreme thermal exposure while maintaining dimensional stability and mechanical integrity. In practical applications, the materials should avoid ignition, excessive shrinkage, fabric break-open, melting, and continuous combustion after exposure to the electric arc. Additionally, the textiles must minimize heat transmission to the skin and resist damage caused by plasma flow and molten metal droplets [45].

The literature demonstrates that aramid-based textiles, especially para-aramid and meta-aramid fibers, are among the most suitable materials for arc-flash protection because of their excellent thermal stability and resistance to degradation. Para-aramid fibers do not melt during exposure and maintain high dimensional stability even under severe thermal conditions. Experimental analyses showed that, during arc exposure, para-aramid fabrics undergo progressive carbonization and embrittlement instead of melting, forming a protective carbonized layer that helps reduce thermal transfer to the user [12].

Several fabric parameters directly influence arc protective performance, including areal density, weave structure, air permeability, thermal protective performance (TPP), and mechanical resistance. Heavier and denser fabrics generally exhibit superior arc protection because their compact structure reduces pore size and limits heat penetration through the material. Studies also demonstrated that fabrics with higher aramid content presented improved Arc Thermal Performance Value (ATPV), indicating greater resistance to thermal exposure [9].

Laboratory evaluations of arc-protective textiles are commonly performed according to ASTM F1959 [17] and IEC 61482 [43,44] standards, which determine parameters such as ATPV and Energy Breakopen Threshold (EBT) [9]. These tests simulate arc-flash events and measure the thermal energy transferred through the fabric to predict the level of protection offered to workers.

In addition to the scientific literature, several commercial suppliers and manufacturers of protective clothing were analyzed in order to identify the most commonly available textile systems currently used in the market. Through the evaluation of commercial catalogs, it was possible to extract and compare the principal fabric compositions, multilayer structures, technical fibers, and protective textile constructions adopted in industrial arc-flash PPE. The market analysis revealed a predominance of aramid-based blends, FR cotton systems, modacrylic fabrics, antistatic fibers, FR viscose blends, and multilayer textile architectures designed to balance thermal protection, durability, comfort, breathability, and compliance with international safety standards [45–50].

The Arc Thermal Performance Value (ATPV) and the Energy Breakopen Threshold (EBT) are the two principal metrics used in accordance with ASTM standards to assess the performance of arc-rated (AR) textiles, both expressed in cal/cm^2 . Both metrics indicate a 50% probability of a specific failure; however, ATPV emphasizes heat transfer, specifically the onset of second-degree burns, whereas EBT focuses on the structural integrity of the material, particularly its tendency to tear or break open. The Arc Thermal Performance Value (ATPV) quantifies the maximum incident energy that a fabric can withstand before there is a 50% probability that sufficient heat will be transferred through the material to cause a second-degree burn, as determined by the Stoll Curve. At this point, the material remains physically intact, although heat begins to penetrate the fabric. Conversely, the Energy Breakopen Threshold (EBT) represents the incident energy at which the fabric undergoes physical cracking, melting, or tearing, resulting in an opening larger than 1.6 cm^2 . This failure occurs when the fabric loses its structural integrity before the heat transfer reaches the threshold required to produce a second-degree burn.

According to ASTM F1506 [51], both ATPV and EBT values may be determined during testing; however, only the lower of the two values is certified and officially reported as the garment's Arc Rating (AR). In general, ATPV is more commonly associated with durable

woven fabrics, whereas EBT is more frequently observed in inherently flame-resistant but structurally softer knitted fabrics. It is important to note that neither rating is inherently superior to the other, as both represent equivalent measures of arc protection based on different failure mechanisms. Within the European standard IEC 61482-2 [52], the more recent Incident Energy Limit (ELIM) parameter is also adopted. Unlike ATPV and EBT, which correspond to a 50% probability of burn injury or fabric break-open, ELIM represents the maximum incident energy at which there is no predicted probability of a second-degree burn under the specified test conditions.

Major textile manufacturers occupy a prominent position in the commercial AR/FR (flame-resistant) market by developing proprietary fiber blends designed to achieve specific ATPV or EBT ratings across different hazard categories (CAT 1 to CAT 4). Examples include Nomex[®] (DuPont, Wilmington, DE, USA), a meta-aramid fiber recognized for its excellent inherent thermal insulation and mechanical strength, typically achieving ATPV ratings suitable for CAT 2 garments (approximately 8–12 cal/cm²); Tecasafe[®] One and Tecasafe[®] Plus (Milliken) (Union City, GA, USA), inherent blends commonly based on modacrylic and cellulosic fibers that provide excellent comfort and breathability while frequently exhibiting EBT ratings because of their knitted constructions and offering CAT 2 and CAT 3 protection; Protera[®] (DuPont), an inherent flame-resistant blend optimized for everyday industrial wear that combines breathability with high ATPV performance, typically achieving CAT 2 ratings between 9 and 12 cal/cm²; UltraSoft[®] and Indura[®] UltraSoft[®] (Westex by Milliken) (Union City, GA, USA), treated cotton-nylon blends that provide high mechanical strength and cost-effective arc protection, generally with ATPV ratings suitable for low- to moderate-risk electrical maintenance; and Kevlar[®] blends, which are frequently incorporated with other flame-resistant fibers to enhance structural integrity and improve ATPV and EBT performance in CAT 3 and CAT 4 heavy-duty arc-flash suits [9,45–47].

5.1. Textiles Used in Arc-Flash Protective Clothing and Their Properties

Arc-flash protective garments are manufactured using technical textiles specifically engineered to provide thermal insulation, flame resistance, electrical arc protection, mechanical durability, and ergonomic comfort. Commercial catalogs frequently report the use of blended textile systems combining natural and synthetic fibers to optimize protective performance [12,46–50]. The most commonly identified textile compositions are contained in Table 4.

Among the materials most frequently reported in commercial catalogs and technical specifications are cotton [53–56], modacrylic [57–61], para-aramid fibers [62–65], and polyamide (nylon) [66–69]. Cotton is widely used due to its comfort, breathability, and ability to form a protective char layer during thermal exposure, although untreated cotton remains combustible. Polyamide contributes to abrasion resistance, tensile strength, and garment durability; however, conventional polyamide fibers may soften or melt when exposed to high temperatures. Modacrylic fibers are inherently flame-resistant synthetic materials that exhibit self-extinguishing behavior and reduced flame propagation, making them suitable for protective clothing applications. Para-aramid fibers, such as Kevlar[®], are recognized for their exceptional thermal stability, high tensile strength, and resistance to ignition, decomposition, and mechanical damage. Studies on flame-resistant textile systems have demonstrated that blends containing para-aramid, flame-resistant cellulosic fibers, and polyamide can provide an effective balance between fire protection, durability, and comfort, promoting self-extinguishing behavior, dimensional stability, and reduced fabric degradation during flame exposure [70–73].

Table 4. The most common textiles contained in diverse commercial catalogs [46–50].

Textile/Composition	Standardized Textile Type
100% Cotton FR/Flame-Retardant Cotton	FR Cotton Textile
44% Modacrylic, 30% Cotton, 20% Polyamide FR, 5% Aramid, 1% Antistatic	Modacrylic-Aramid FR Blend
44% Modacrylic, 30% Cotton, 5% Para-Aramid, 1% Antistatic	Modacrylic Para-Aramid Blend
48% Modacrylic, 37% Cotton, 15% Para-Aramid	Modacrylic-Aramid Cotton Blend
40% Viscose FR, 26% Modacrylic, 8% Polyamide, 6% Para-Aramid	FR Viscose Technical Blend
54% FR Viscose, 20% Wool, 20% Polyamide, 5% Aramid, 1% Antistatic	FR Wool-Aramid Blend
50% FR Viscose, 50% Merino Wool	FR Merino Wool Blend
88% Cotton, 12% Polyamide/Nylon	Cotton-Polyamide FR Textile
88% Cotton, 12% Polyamide—Safety Jeans Fabric	Reinforced FR Denim Textile
60% Cotton, 40% Polyester	Cotton-Polyester Technical Blend
98% Polyester, 2% Antistatic	Antistatic Polyester Blend
Outer Layer: 98% FR Polyester, 2% Antistatic	FR Polyester Antistatic Textile
Inner Layer: 60% Protex-Type FR Fiber, 40% Cotton	FR Cotton Blend
Modacrylic/Cotton/Antistatic Blend	Antistatic Modacrylic Blend
8% Modacrylic, 37% Cotton, 3% Elastane, 2% Antistatic	Stretch FR Modacrylic Blend
Cotton & Spandex	Stretch Cotton Blend
Spandex/Elastane FR Blend	Elastomeric FR Textile
Nylon & Antistatic	Antistatic Nylon Blend
Polyamide FR Reinforced Fabric	FR Polyamide Textile
Para-Aramid	Para-Aramid Textile
Para-Aramid + Polyamide	Aramid-Polyamide Textile
Meta-Aramid	Meta-Aramid Textile
Aramid + FR Viscose Blend	Aramid FR Viscose Textile
Rip-Stop Reinforced Aramid Fabric	Reinforced Rip-Stop Aramid Textile
Multilayer Aramid Fabric	Multilayer Aramid Textile
Double-Layer Aramid Fabric	Double-Layer Aramid Textile
Modacrylic Fabric	Modacrylic FR Textile
FR Knit Cotton Fabric	FR Knit Cotton Textile
FR Knit Jersey Fabric	FR Jersey Knit Textile
Interlock/Pique Knit	Technical Knit Textile
FR Fleece Fabric	FR Fleece Textile
High-Visibility FR Fabric	High-Visibility FR Textile
Impermeable FR Fabric	Waterproof FR Textile
PU/PVC Coated Fabric	Coated Protective Textile
FR Cotton Quilting + Polyfil Padding	Quilted FR Insulated Textile
Polyfil	Synthetic Insulation Textile
Matelassé Inner Lining	Quilted Thermal Lining
100% Cotton Lining/FR Cotton Inner Layer	FR Cotton Lining Textile
Wool/Merino Wool FR Blend	Technical Wool FR Textile
FR Modacrylic Knit Fabric	FR Modacrylic Knit Textile

Cotton

Cotton remains one of the most widely used fibers in flame-resistant and arc-flash protective clothing due to its comfort, breathability, moisture absorption, softness, and widespread availability. Unlike many synthetic fibers, cotton does not melt or drip when exposed to heat, reducing the risk of severe skin injuries during thermal incidents. In addition, its cellulosic structure facilitates chemical modifications and the incorporation of flame-retardant treatments, allowing the development of fabrics that combine thermal protection with wearer comfort. For this reason, cotton is frequently used either as the main component of flame-resistant fabrics or blended with high-performance fibers such as modacrylics and aramids to balance protection, durability, and ergonomic performance [53–56].

Zhu et al. (2022) [53] developed a phosphorus–nitrogen–boron flame-retardant treatment for cotton fabrics, achieving an LOI of 36.1% and maintaining flame-retardant performance after 50 laundering cycles. The treatment promoted char formation, reduced heat release and smoke production, and improved thermal stability while preserving the fabric's mechanical properties.

Liao et al. (2021) [54] proposed a formaldehyde-free phosphorus–nitrogen system chemically grafted onto cotton fibers. The treated fabrics reached an LOI of 50.6%, retained significant flame resistance after 50 washing cycles, and exhibited substantial reductions in heat release, demonstrating excellent durability and thermal protection.

Beduini et al. (2023) [55] investigated a phosphonate-containing polyamidoamine coating that enhanced char formation and significantly reduced smoke and CO₂ emissions during combustion. Although the treatment improved thermal stability and self-extinguishing behavior in horizontal tests, it showed limited performance in vertical flame testing.

Jiang et al. (2023) [56] developed a phosphorus–nitrogen coating based on tea polyphenol, melamine, and phenylphosphonic acid. The treated cotton achieved an LOI of 28.7%, met ASTM D6413 [74] requirements, reduced the peak heat release rate by 88.5%, and maintained good mechanical properties, air permeability, and fabric comfort.

Overall, these studies demonstrate that significant advances have been achieved in the development of flame-retardant cotton fabrics through the incorporation of phosphorus-, nitrogen-, boron-, and sulfur-containing systems. Such modifications enhance thermal stability, promote the formation of protective char layers, reduce heat release and smoke generation, and improve durability against repeated laundering. Consequently, these technological improvements have expanded the applicability of cotton in arc-flash protective clothing, allowing the material to combine its inherent comfort, breathability, and moisture management properties with the high levels of flame resistance and thermal protection required for hazardous industrial environments.

Polyamide

Polyamide fibers are widely used in protective textiles due to their excellent mechanical strength, abrasion resistance, flexibility, and durability. Among the most common commercial polyamides are polyamide 6 (PA6), polyamide 66 (PA66), and bio-based polyamides such as PA56 and PA1010. Although conventional polyamides are combustible materials, recent advances in polymer engineering have enabled the development of intrinsically flame-retardant polyamides through the incorporation of phosphorus-, silicon-, and metal-containing structures into the polymer backbone or through reactive flame-retardant systems. These modifications significantly improve flame resistance, thermal stability, char formation, and heat-release suppression while maintaining the mechanical properties required for protective clothing. Consequently, flame-retardant polyamides have emerged as promising materials for advanced flame-resistant and arc-flash protective textile applications, where durability, flexibility, and thermal protection are simultaneously required [66–69].

Zhang et al. (2021) [66] developed an intrinsically flame-retardant polyamide 66 (PA66) by incorporating a phosphorus-containing monomer (CPPOA) into the polymer structure. The modification significantly improved the flame-retardant performance of PA66, increasing the limiting oxygen index (LOI) to 27.2% and achieving a UL-94 V-0 rating with only 6 wt% flame retardant. Thermal and combustion analyses revealed enhanced char formation, reduced heat release, and improved thermal stability due to the formation of phosphorus-rich protective layers during combustion. Importantly, the modified PA66 maintained good mechanical properties, reaching a tensile strength of 70 MPa and an impact strength of 5.6 kJ m^{−2}. These results demonstrate that intrinsically flame-retardant polyamides can effectively combine fire resistance and mechanical durability, making them promising materials for protective textile applications.

Zhao et al. (2023) [67] developed an intrinsically flame-retardant bio-based polyamide 56 (FRPA56) through the copolymerization of a phosphorus-containing reactive flame retardant (DOPDA). The modified polymer exhibited excellent flame-retardant performance, achieving an LOI of 28.4% and a UL-94 V-0 rating with only 6 wt.% flame retardant.

Thermal analyses revealed enhanced char formation and reduced heat release during combustion, while mechanical properties were largely preserved, maintaining a tensile strength of 72 MPa and a melting temperature of 248 °C. In addition, the material showed improved moisture absorption, which is advantageous for textile applications requiring comfort and moisture management. The authors concluded that FRPA56 combines flame resistance, thermal stability, mechanical durability, and sustainability, making it a promising candidate for protective textile applications.

Ye et al. (2023) [68] developed a flame-retardant bio-based polyamide 1010 (PA1010) by incorporating 10 wt.% of an iron-containing polyhedral oligomeric silsesquioxane (Fe-Ph-POSS). The additive significantly improved the flame resistance of the polymer, increasing the limiting oxygen index (LOI) from 22.6% to 28.4% while reducing heat release, smoke production, and toxic gas emissions during combustion. Thermal analyses demonstrated enhanced thermal stability and higher char residue formation due to the synergistic action of iron and silicon species. Importantly, the modification preserved the mechanical performance of the material, maintaining high elongation at break (473.8%), tensile strength (46.87 MPa), and impact resistance. The authors attributed the improved fire performance to the formation of dense, thermally stable protective char layers composed of iron silicates and carbonates, which effectively hinder heat and mass transfer during combustion.

Liang et al. (2024) [69] synthesized a polymer-type flame retardant (PFR) based on a DOPO derivative and incorporated it into polyamide 6 (PA6) through melt blending. The flame-retardant system significantly improved the fire performance of PA6, achieving a UL-94 V-0 classification with only 3000 ppm phosphorus content and increasing the limiting oxygen index (LOI) from 21.7% for neat PA6 to 28.8% for the formulation containing 5000 ppm phosphorus. Cone calorimetry results revealed substantial reductions in fire hazards, with peak heat release rate (p-HRR), total heat release (THR), and effective heat of combustion reduced by 35.4%, 21.9%, and 26.5%, respectively. Mechanistic analyses indicated that flame retardancy was mainly associated with phosphorus-containing radical quenching in the gas phase, while a dense char layer provided a secondary protective effect.

Collectively, these studies demonstrate that modern flame-retardant polyamides can successfully combine mechanical durability with enhanced thermal and fire resistance. Through the incorporation of advanced phosphorus-based and hybrid flame-retardant systems, polyamides have become promising materials for arc-flash protective textiles, offering improved safety while preserving the performance characteristics required for industrial applications.

Modacrylic

These synthetic fibers are produced from copolymers containing 35–85% acrylonitrile combined with halogen-containing monomers, such as vinyl chloride or vinylidene chloride, which provide their intrinsic flame-retardant behavior. As a result, modacrylic fibers exhibit self-extinguishing properties and do not sustain combustion once the ignition source is removed. During thermal exposure, they tend to form a protective char layer rather than supporting flame propagation, contributing to thermal insulation and reduced heat transfer. In addition, modacrylic fibers can be readily blended with cotton, aramids, FR-viscose, and other technical fibers to improve moisture management, softness, and wearer comfort while maintaining protective performance. These characteristics have made modacrylic fibers key components in firefighter garments, industrial workwear, military uniforms, and arc-flash protective clothing [62–65].

Rijavec et al. (2023) [57] investigated affordable flame-resistant textile blends composed of modacrylic, polyacrylate, and lyocell fibers intended for protective underwear applications. The authors highlighted that modacrylic is an inherently flame-resistant synthetic fiber produced from acrylonitrile and vinyl chloride copolymers, exhibiting self-

extinguishing behavior and forming a protective char layer instead of melting during thermal exposure. Commercial modacrylic fibers such as Protex present limiting oxygen index (LOI) values between 26 and 33%, making them suitable for protective clothing systems. The developed knitted fabrics showed excellent moisture transport and absorption properties while maintaining afterflame and afterglow times below 2 s, satisfying non-flammability requirements. The study concluded that modacrylic-based blends can provide a balance between flame resistance, thermal comfort, durability, and cost-effectiveness, supporting their use in firefighter, military, industrial, and other flame-resistant protective garment applications.

Jamshaid et al. (2023) [58] evaluated knitted fabrics produced from inherently flame-resistant fibers, including modacrylic (Protex), Nomex, FR-viscose, FR-polyester, and carbon fibers, for firefighter station-wear applications. The authors described Protex as an inherently flame-resistant modacrylic fiber that does not melt or drip during combustion, instead forming a protective char barrier that promotes self-extinguishing behavior. The fiber can be easily blended with cotton, polyester, and other technical fibers, improving the flame-retardant performance of the textile system while maintaining a soft handle and good comfort properties. Thermal analyses showed that modacrylic fibers exhibit low moisture regain (0.3–0.4%) and maintain stability up to approximately 200 °C before significant thermal degradation occurs. The study also demonstrated that blends containing Protex provided good tactile comfort, while fabrics composed entirely of Protex ranked among the best combinations when flame resistance and wearer comfort were simultaneously considered for protective clothing applications.

Hursa Šajatović et al. (2022) [59] investigated the flammability performance of a firefighter protective clothing system composed of a 55% modacrylic/45% cotton outer fabric and a 70% wool/30% modacrylic underwear layer. The authors evaluated the protective performance using a fire manikin exposed to direct flame for 4 s, followed by microscopic, thermogravimetric, and combustion analyses. The results showed that the clothing system provided effective thermal protection, with only minor fabric damage and no life-threatening burns predicted for the wearer. Microscopic analyses revealed that the modacrylic-containing fabric did not melt during exposure but instead underwent charring and stiffening, preserving the structural integrity of the textile. Furthermore, thermogravimetric analyses demonstrated relatively high thermal stability and confirmed that the principal decomposition products were H₂O, CO₂, and CO. The authors concluded that modacrylic-based textile systems provide an effective balance between flame resistance, thermal protection, and comfort, making them suitable for firefighter and other heat- and flame-protective clothing applications.

Kim et al. (2018) [60] investigated the flame-retardant, antistatic, and comfort properties of woven fabrics composed of modacrylic fibers blended with flame-retardant rayon (FR-rayon), cotton, and antistatic PET fibers. The study compared modacrylic/FR-rayon/antistatic PET fabrics with modacrylic/cotton/antistatic PET fabrics using flammability, moisture management, thermal conductivity, water vapor permeability, and wearer comfort tests. The results demonstrated that the modacrylic/FR-rayon blends exhibited superior flame-retardant performance, presenting carbonized areas up to 42.2% smaller than the cotton-blended fabrics, as well as improved antistatic behavior. Furthermore, the FR-rayon-containing fabrics showed faster moisture absorption and drying, lower thermal conductivity, higher water vapor permeability, and reduced microclimate humidity during wear trials. The authors concluded that modacrylic-based blends incorporating FR-rayon provide an effective combination of flame resistance, antistatic protection, thermal insulation, and wearer comfort, making them suitable for protective clothing applications.

The literature indicates that continuous improvements in modacrylic-based textile systems have focused on optimizing flame resistance, thermal protection, moisture transport, and comfort through the incorporation of complementary fibers and functional components. As a result, modacrylic fabrics have evolved into multifunctional protective materials capable of meeting the demanding safety and performance requirements of modern flame-resistant and arc-flash protective garments.

Para-aramid

Para-aramid fibers are high-performance aromatic polyamides widely used in protective textiles because of their inherent flame resistance, exceptional mechanical strength, and thermal stability. Their highly crystalline molecular structure provides high tensile strength, low shrinkage, and excellent resistance to thermal degradation, while preventing melting and dripping during fire exposure. These characteristics have established para-aramids as key materials in firefighter garments, military protective equipment, and arc-flash protective clothing [62–65].

Wu et al. (2020) [62] investigated the flame-retardant efficiency of modified para-aramid fibers synergistically combined with ammonium polyphosphate (APP). The authors highlighted that para-aramid fibers are inherently flame-resistant materials with limiting oxygen index (LOI) values above 28%, excellent thermal stability, high mechanical strength, and permanent flame-retardant properties that do not deteriorate with washing or prolonged use. To further enhance their performance, the fibers were modified with phosphoric acid and silane groups, introducing phosphorus and silicon functionalities that promoted char formation and improved compatibility with the polymer matrix. The modified para-aramid fibers exhibited a strong synergistic effect with APP, enabling the composite to achieve a UL-94 V-0 rating and an LOI of 28–29. In addition, the system reduced total heat release by 23.6% and total smoke release by 47%, while simultaneously improving tensile and tear strength by 33.3% and 35.9%, respectively. The study demonstrated that para-aramid fibers can act not only as reinforcing agents but also as effective char-forming components, contributing to enhanced flame resistance, thermal stability, smoke suppression, and mechanical durability.

Chen et al. (2017) [63] investigated the influence of para-aramid fibers on the fire safety performance of thermoplastic polyurethane (TPU) composites. The authors emphasized that para-aramid fibers are high-performance materials characterized by high strength, high modulus, thermal resistance, chemical resistance, low density, and excellent flame-retardant behavior. Their aromatic and highly crystalline molecular structure promotes char formation during combustion, while the limiting oxygen index (LOI) exceeds 28%, allowing the fiber to self-extinguish once the ignition source is removed. Furthermore, the flame-retardant performance is permanent because it is an inherent property of the polymer structure and is not affected by washing or prolonged service life. Experimental results showed that the incorporation of only 1 wt.% para-aramid fiber reduced the peak heat release rate by 52%, decreased the peak smoke production rate by 40.5%, and increased residual char formation compared to neat TPU. The improved performance was attributed to enhanced thermal stability and the formation of a compact protective carbonaceous layer during combustion, which effectively limited heat and mass transfer. These findings demonstrate the potential of para-aramid fibers as reinforcing and flame-resistant components for advanced protective textiles and thermal hazard applications.

Rathour et al. (2022) [64] investigated the effect of repeated radiative heat exposure on firefighter protective fabrics manufactured with Nomex[®] IIIA (meta-aramid) and Nomex[®]/Kevlar[®] (para-aramid) blends. The authors highlighted that aramid fibers are inherently flame-resistant, thermally stable, lightweight, and mechanically robust materials widely used in thermal protective clothing. The results demonstrated that fabrics

containing Kevlar[®] exhibited higher radiative protective performance (RPP), lower thermal shrinkage, and better dimensional stability than fabrics composed solely of Nomex[®]. The Nomex[®]/Kevlar[®] blends retained approximately 95% of their original surface area after repeated thermal exposures and achieved RPP values up to 13 cal/cm², confirming the beneficial contribution of para-aramid fibers to thermal protection and durability in firefighter protective clothing.

Li et al. (2024) [65] investigated the thermal decomposition and charring behavior of composite papers produced from para-aramid fibers and polyphenylene sulfide (PPS). The authors highlighted that para-aramid fibers are high-performance materials characterized by low density, high thermal durability, excellent dielectric properties, and high strength and modulus. The incorporation of PPS promoted the formation of a dense and highly graphitized carbon layer during combustion, which acted as an effective barrier against heat transfer, oxygen diffusion, and flame propagation. The composite paper exhibited thermal degradation temperatures above 500 °C, reduced char length during vertical flame testing, and enhanced structural integrity after combustion. Furthermore, the resulting char layer was sufficiently robust to support mechanical loads and effectively protected the underlying material from further degradation. The authors concluded that para-aramid/PPS systems provide excellent flame retardancy, fire resistance, thermal insulation, and electrical insulation properties, demonstrating strong potential for applications in firefighting clothing interlayers and high-voltage electrical insulation materials.

Recent studies have demonstrated that para-aramid fibers remain among the most important materials for high-performance protective textiles due to their intrinsic flame resistance, exceptional mechanical strength, thermal stability, and dimensional integrity under extreme conditions. Current developments have focused on surface modifications, synergistic flame-retardant systems, and hybrid composites incorporating phosphorus-, silicon-, and PPS-based structures to enhance char formation, heat shielding, smoke suppression, and fire resistance. These advancements have expanded the functionality of para-aramid materials beyond traditional reinforcement applications, reinforcing their role in firefighter garments, electrical insulation systems, and arc-flash protective clothing where reliable thermal protection and long-term durability are essential.

Arc-flash textiles are classified into two main categories: inherently flame-resistant (IFR) fabrics and chemically treated materials. The selection of an appropriate material requires careful consideration of the hazard level (CAT 1: 4 cal/cm², CAT 2: 8 cal/cm², CAT 3: 25 cal/cm², and CAT 4: 40 cal/cm²), worker comfort, and fabric durability to ensure optimal thermal and mechanical protection. A comparison of the main arc-flash textile materials is summarized in Table 5.

Table 5. Comparison of the main arc-flash textile materials [5,6,75,76].

Textile	Fabric Type	Arc Rating (ATPV)	Thermal Performance	Key Strengths	Main Limitations
Aramid and Polybenzimidazole (PBI) Fibers	Inherently flame-resistant (IFR) fibers	Excellent (8–40 cal/cm ²)	Very high. Carbonize rather than melt, offering superb heat blocking	Exceptional durability and abrasion resistance. Ideal for high-heat environments and are highly resistant to repeated industrial launderings.	Can feel stiff and have historically lacked breathability compared to blends. They can also produce toxic gases when exposed to extreme combustion temperatures
Modacrylic blends (Westex DH, Indura Ultra Soft)	Inherently flame-resistant r engineered blends	Moderate to high (CAT 2, 8–12 cal/cm ² in single layers)	Carbonizes when exposed to a flame; not melt or drip.	Fast-growing in industrial PPE due to supreme comfort, softness, and natural moisture-wicking properties. They are excellent for daily wear	Slightly lower mechanical tear strength compared to 100% aramid fabrics

Table 5. Cont.

Textile	Fabric Type	Arc Rating (ATPV)	Thermal Performance	Key Strengths	Main Limitations
Treated Cotton and Cotton-Nylon Blends (88/12 Cotton-Nylon)	Chemically treated base fabric (e.g., 88% cotton, 12% high-tenacity nylon)	Good (usually 8–12 cal/cm ² , making it a popular choice for CAT 2 compliance).	When flashed, the cotton chars and self-extinguishes rather than melting.	Highly comfortable, breathable, and cost-effective. The added nylon improves the garment’s overall durability	The flame retardant can degrade or wear off if laundering guidelines are not followed, though modern treatments last significantly longer
FR Viscose Blends	Repurposed or engineered plant-based FR fibers blended with aramids.	Moderate (often 8–15 cal/cm ²).	Chars without melting.	Designed explicitly for worker comfort, softness, and breathability, allowing for lighter, single-layer daily wear.	Generally less abrasion and tear-resistant than pure aramid fabrics

5.2. Standards for Arc-Flash Protective Textiles

Standards and testing methods play a fundamental role in the development, certification, and selection of arc-flash protective textiles, ensuring that garments provide reliable protection against the thermal hazards generated during electrical arc events. Arc-flashes can expose workers to intense thermal radiation, molten metal particles, pressure waves, and temperatures exceeding several thousand degrees Celsius, making the evaluation of textile performance essential for occupational safety. To address these risks, international standards establish requirements for material testing, garment design, labeling, and performance classification. These standards assess critical properties such as arc thermal protection, flame resistance, heat transfer, afterflame behavior, fabric break-open resistance, and overall garment integrity following arc exposure. However, the effectiveness of arc-flash protective clothing depends not only on the properties of the textile materials but also on garment design, fit, layer configuration, and the understanding of the protection mechanisms behind each performance requirement. Features such as adequate coverage, air gaps between fabric layers, closure systems, and resistance to fabric opening during arc exposure can significantly influence the thermal protection provided to the wearer. Therefore, understanding the rationale behind standardized requirements is essential for designing protective clothing systems that effectively minimize burn injuries and improve worker safety in electrical hazard environments.

Table 6 summarizes the standards most frequently referenced in commercial catalogs [46–50] of arc-flash protective clothing, highlighting the category of protection and the country/region of each standard.

Table 6. Most frequent standards referenced in commercial catalogs [46–50].

Category	Standard	Full Name	Country/Region
Arc-flash Protection	IEC 61482-1-1 [43]	Open Arc Test Method for Arc Rated Clothing	International (IEC)
	IEC 61482-1-2 [44]	Box Test Method for Arc Protective Clothing	International (IEC)
	IEC 61482-2 [52]	Protective Clothing Against Thermal Hazards of an Electric Arc	International (IEC)
	ASTM F2178 [77]	Face Protective Products Against Electric Arc Exposure	United States
	NFPA 70E [78]	Electrical Safety in the Workplace	United States
	ASTM F1959 [17]	Arc Thermal Performance Value (ATPV) Test Method	United States
Heat and Flame Protection	ASTM F2621 [79]	Heat Transfer Performance of Arc Rated Face Protective Products	United States
	ISO 11612 [80]	Clothing to Protect Against Heat and Flame	European Union/ISO
	ISO 11612 [80]	Protective Clothing Against Heat and Flame	Brazil/ISO
	ISO 14116 [81]	Protective Clothing with Limited Flame Spread Properties	European Union/ISO
	NFPA 2112 [82]	Flame-Resistant Clothing for Industrial Personnel Against Flash Fire	United States
Welding Protection	ISO 11611 [83]	Protective Clothing for Welding and Allied Processes	European Union/ISO
Electrostatic Protection	EN 1149-5 [84]	Protective Clothing—Electrostatic Properties	European Union
High Visibility	EN ISO 20471 [85]	High Visibility Protective Clothing	European Union/ISO
General Protective Clothing	EN ISO 13688 [86]	General Requirements for Protective Clothing	European Union/ISO

Table 6. *Cont.*

Category	Standard	Full Name	Country/Region
Chemical Protection	EN 13034 [87]	Protective Clothing Against Liquid Chemicals	European Union
Eye and Face Protection	ANSI Z87.1 [88]	Occupational and Educational Personal Eye and Face Protection Devices	United States
Glove Protection	EN 166 [89]	Personal Eye Protection	European Union
	EN 388 [90]	Protective Gloves Against Mechanical Risks	European Union
	EN 407 [91]	Protective Gloves Against Thermal Risks	European Union
Knee Protection	EN 14404 [92]	Knee Protection for Work in Kneeling Position	European Union
Electrical Safety Regulation	NR-10 [93]	Safety in Electrical Installations and Services	Brazil
PPE Certification	CA (Certificado de [94] Aprovação)	Brazilian PPE Approval Certificate	Brazil
	CE [95]	European Conformity Marking	European Union

5.3. Garment Confection Requirements According to Technical Standards

In addition to the intrinsic performance of flame-resistant fabrics, the protective effectiveness of arc-flash garments is strongly influenced by garment construction and design requirements established by international standards. Technical standards such as ASTM F1506 [51], IEC 61482-2 [52], ISO 11612 [80], ISO 11611 [83], EN ISO 20471 [85], and NFPA 70E [78] specify not only material performance criteria but also construction features intended to maximize body coverage and minimize the risk of burn injuries during thermal incidents. Elements such as high protective collars, covered closure systems, reinforced stress areas, ergonomic garment fit, adequate sleeve and leg lengths, and the proper placement of reflective trims contribute significantly to maintaining garment integrity and reducing skin exposure during arc-flash events. Therefore, understanding garment confection requirements is essential for translating the protective properties of technical textiles into effective real-world protection.

Figure 1 illustrates key garment design features commonly required by technical standards and frequently incorporated into commercial arc-flash protective clothing systems. Figure 1 highlights key garment construction features commonly incorporated into arc-flash protective clothing in accordance with international standards. The protective trousers incorporate reinforced knee panels designed to improve durability and mobility during physically demanding tasks. Utility cargo pockets with covered flaps enhance functionality while reducing the risk of snagging or exposure to thermal hazards. Flame-resistant reflective tapes, compliant with EN ISO 20471 [85] and compatible with flame-resistant clothing requirements, improve worker visibility without compromising thermal protection. Reinforced seams and ergonomic fitting are consistent with the durability and performance requirements specified in ASTM F1506 [51] and IEC 61482-2 [52].

The protective jacket includes a high protective collar that extends coverage to the neck region, reducing the risk of thermal exposure to vulnerable body areas. This design feature aligns with the body coverage principles established in IEC 61482-2 [52] and NFPA 70E [78], which emphasize minimizing exposed skin during arc-flash events. Adjustable cuffs help prevent the entry of heat, sparks, and molten particles, while reinforced elbow sections improve durability under repetitive movements and mechanical stress. The covered front closure system also follows recommendations found in ASTM F1506 [51] and ISO 11612 [80], which require garment constructions capable of maintaining integrity during thermal exposure.

The protective hood is designed to provide extended coverage of the head, neck, and shoulder regions, which are particularly susceptible to burn injuries during arc-flash incidents. The ergonomic face opening minimizes exposed skin while preserving visibility and compatibility with other personal protective equipment. These design principles are consistent with NFPA 70E [78] and IEC 61482-2 [52], both of which emphasize complete coverage of exposed body regions when arc-flash hazards are present.

Arc Flash Protection Clothes

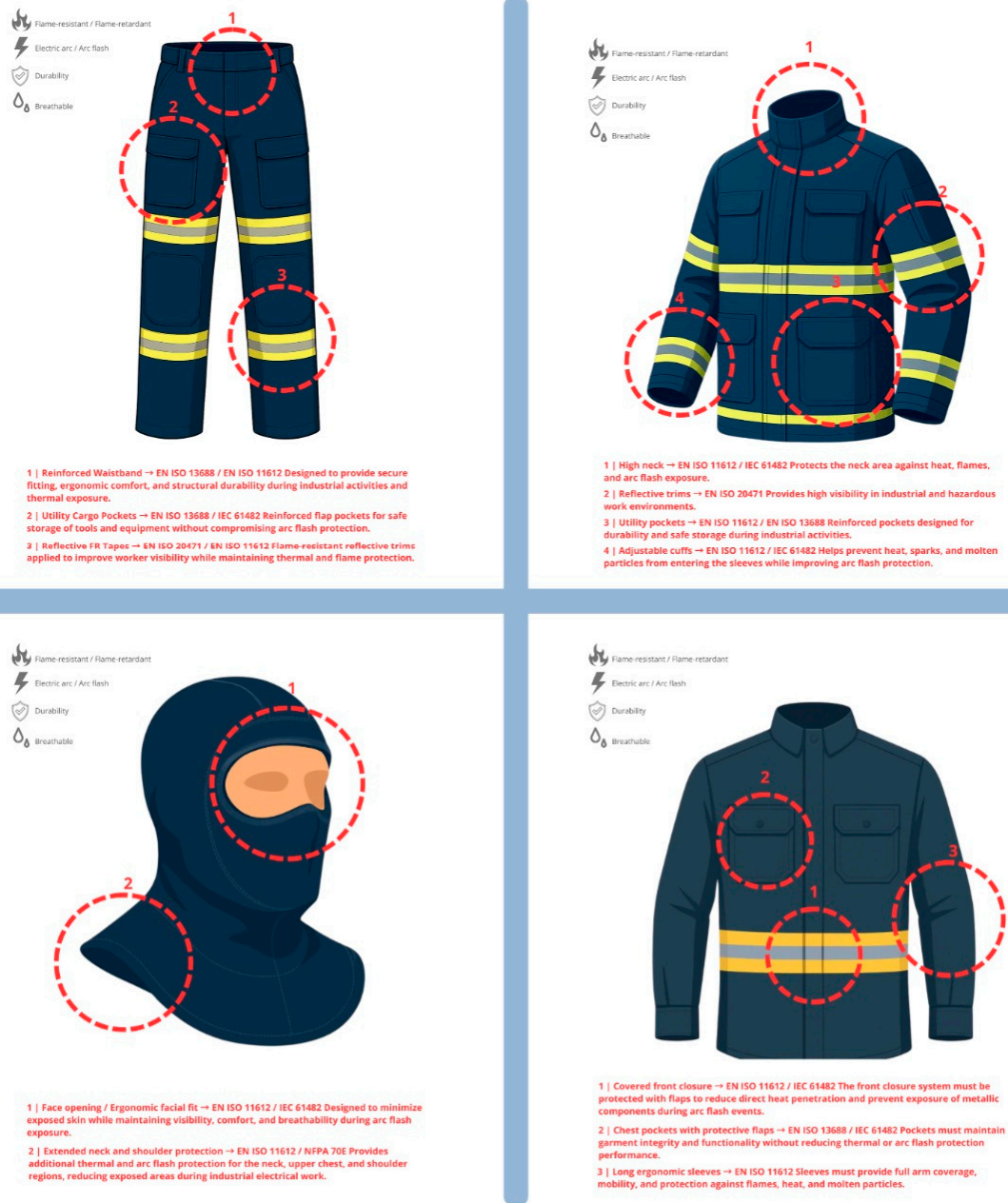


Figure 1. Key garment construction features commonly incorporated into arc-flash protective clothing in accordance with international standards [17,43,44,52,78,80,85].

The protective shirt incorporates a covered front closure system, chest pockets with protected flaps, and strategically positioned flame-resistant reflective tapes. These features improve visibility, functionality, and comfort while preserving thermal protection and garment integrity. Such requirements are consistent with ISO 11612 [80], ISO 11611 [83], ASTM F1506 [51], and IEC 61482-2 [52], which establish criteria for flame resistance, structural integrity, and protective performance. Together, these design elements demonstrate that effective arc-flash protection depends not only on flame-resistant materials but also on garment construction details that maximize coverage, durability, mobility, and safety during exposure to thermal and electrical hazards.

6. Current Trends and Challenges

The main current trends are described below [1–3]:

Smart and Integrated Systems: The adoption of Internet of Things (IoT) sensors for real-time monitoring and predictive maintenance is on the rise.

Advanced Protective Devices: There is an increasing utilization of arc-rated (AR) clothing that is both lighter and more breathable, alongside the implementation of active arc-quenching systems (AQS) that are capable of detecting light and pressure to extinguish arcs more swiftly than traditional circuit breakers.

Predictive Risk Assessment: The application of machine learning and data analytics to model arc-flash risks is enhancing traditional IEEE 1584 calculations.

Digital Relays: The market is transitioning towards multifunctional digital relays that integrate protection with advanced communication and diagnostic capabilities.

The main challenges and barriers are described below [1–3]:

High Implementation Costs: The introduction of new equipment necessitates a considerable financial investment, which poses challenges particularly for small and medium-sized enterprises.

Aging Infrastructure: The process of retrofitting modern, fast-acting protective devices into older legacy systems is often fraught with technical complexities and high costs.

Human Factor and Compliance: Despite technological advancements, over 90% of incidents arise from personnel mistakenly assuming that equipment is de-energized or failing to properly utilize personal protective equipment (PPE), such as leaving jackets unzipped.

Balancing Sensitivity: Protection systems need to respond immediately to prevent injuries while simultaneously minimizing nuisance trips that could lead to costly and unnecessary facility downtime.

Skilled Personnel Shortage: There exists a deficit of specialized personnel capable of designing, commissioning, and maintaining sophisticated modern arc-flash protection systems.

7. Future Outlook

The segmentation of the emerging application market for arc-flash protective clothing underscores significant innovation and substantial growth potential within consumer-focused, healthcare, and next-generation applications. These segments are positioned to challenge traditional markets by providing new revenue opportunities, which are propelled by technological advancements and regulatory requirements.

Consumer Applications: The rising awareness of personal safety and safety standards in do-it-yourself (DIY) and small-scale electrical work is driving demand. The potential for scalability is substantial, as innovations in product design are making protective clothing more accessible and affordable, thereby expanding markets beyond conventional industrial sectors. This segment presents considerable growth opportunities for brands that effectively balance safety, comfort, and cost-effectiveness.

Healthcare and Life Sciences: The incorporation of arc-flash protective clothing within healthcare environments, particularly in biomedical research and pharmaceutical manufacturing, represents an emerging trend. The substantial growth potential in this area is propelled by rigorous safety standards and the necessity for contamination-free settings. Advancements in lightweight, breathable fabrics facilitate this adoption, thereby generating transformative opportunities for personal protective equipment manufacturers.

Recent Developments in Arc-Protective Materials: Arc-protective textiles are evolving from the use of heavy and rigid aramid materials. Current innovations emphasize the development of lightweight, multilayer laminates, inherently flame-retardant (FR) fibers, and advanced materials such as shear-thickening liquids. These novel materials offer outstanding protection against arc-flash and thermal hazards, while significantly enhancing

breathability, moisture-wicking capabilities, and overall comfort for the wearer throughout the day. Some top materials and trends are presented below: (i) GORE®PYRAD® technology (Newark, DE, USA): high arc fault protection, APC class 2, ATPV 39 cal·m⁻², extremely light weight (310 g·m⁻²), very good breathability (RET value: 8.3 m²·Pa·W⁻¹), good washability, no color loss [51,96]; (ii) PyroTex fiber: These fibers possess the ability to self-extinguish permanently and exhibit superior moisture-wicking properties, thereby ensuring safety for individuals with sensitive skin [95,97]; (iii) shear-thickening liquid armor: advanced safety equipment incorporates silica nanoparticle fluids. The fabric retains flexibility and comfort during regular movement, yet it hardens immediately upon impact or exposure to extreme force, effectively dispersing kinetic energy and intense thermal radiation [98]; (iv) dual and multi-standard materials: Contemporary textiles are designed to simultaneously address a variety of workplace hazards. Manufacturers such as Marina Textil provide fabrics that offer protection against electric arcs, while also incorporating antistatic, acid-resistant, and high-visibility characteristics [99]. Recent advancements in arc-protective textiles focus on substituting cumbersome, multi-layered garments with innovative single-layer aramid blends and inherently flame-resistant (IFR) fibers. Notable innovations, such as Modacrylics and specialized treatments like PFC-free chemistries, achieve high Arc Thermal Performance Value (ATPV) ratings of up to ≥ 40 cal/cm², while simultaneously reducing bulk and weight by as much as 20%. This transition from rigid, multi-layered switchgear suits to highly breathable, high-performance daily wear necessitates specific material enhancements: (i) IFR and Aramid Blends: The integration of flame-resistant viscose derived from wood pulp with aramid fibers enhances softness and natural comfort, all while ensuring optimal heat and flame resistance, (ii) Fluorine-Free Finishes: State-of-the-art coatings provide exceptional acid splash resistance and water repellency without relying on traditional perfluorochemicals (PFAS), (iii) Nanotechnology: Enhancements at the molecular level incorporate nanoparticles directly into the fibers, thereby increasing thermal stability and imparting moisture-wicking capabilities without sacrificing breathability [95–102].

Next-generation and disruptive use cases, including wearable technology, Internet of Things (IoT)-enabled protective gear, and smart personal protective equipment (PPE), are redefining the Arc-flash Protective Clothing Market by application. These innovations are anticipated to facilitate rapid growth, significant scalability, and the potential to transform safety standards across various industries. The market's potential for disruption is fueled by the convergence of safety, digitalization, and advanced material science, thereby positioning it for exponential expansion in the forthcoming years.

The prospects for the Arc-flash Protective Clothing Market appear highly favorable. This positive outlook can be attributed to significant advancements in technology and the growing integration of innovative digital tools across various sectors. Technologies such as artificial intelligence (AI), automation, cloud computing, and data analytics are improving operational efficiency, thereby accelerating market growth in the upcoming years. Furthermore, a multitude of companies is increasing their investments in research and development to create superior and more advanced products. Emerging trends, including smart automation and data-driven decision-making, are likely to further drive market expansion. Collaborative efforts among corporations, technology experts, and research institutions are crucial for promoting the development of innovative solutions. As enterprises continue to utilize modern digital technologies to sustain their competitive advantage, the Arc-flash Protective Clothing Market is anticipated to maintain its growth trajectory. This expansion is likely to create new opportunities for both established corporations and emerging businesses in the near future [1–3].

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