fire

MDPI

Review

Classification and Prevention of Electrical Fires: A Comprehensive Review

Guohui Li [1,2], Jiapu Guo [3,4], Yanhao Kang [3,4], Que Huang [3,4,5,6], Junchao Zhao [1,7,*] and Changcheng Liu [3,4]

1 Tianjin Key Laboratory of Fire Safety Technology, Tianjin 300381, China; liguohui@tfri.com.cn
2 Tianjin Fire Science and Technology Research Institute of MEM, Tianjin 300381, China
3 School of Environment and Safety Engineering, North University of China, Taiyuan 030051, China; s202314004@st.nuc.edu.cn (J.G.); sz202314016@st.nuc.edu.cn (Y.K.); que.huang@nuc.edu.cn (Q.H.); ccliu@nuc.edu.cn (C.L.)
4 Institute of Advanced Energy Materials and Systems, North University of China, Taiyuan 030051, China
5 Shanxi Key Laboratory of Efficient Hydrogen Storage & Production Technology and Application, Taiyuan 030051, China
6 School of Resources and Safety Engineering, Central South University, Changsha 410010, China
7 State Key Laboratory of Fire Science, University of Science and Technology of China, Hefei 230022, China
* Correspondence: zhaojc01@ustc.edu.cn

Abstract: With the development of society and the advancement of technology, the application of electricity in modern life has become increasingly widespread. However, the risk of electrical fires has also significantly increased. This paper thoroughly investigates the causes, classifications, and challenges of electrical fires in special environments, and summarizes advanced detection and extinguishing technologies. The study reveals that the causes of electrical fires are complex and diverse, including equipment aging, improper installation, short circuits, and overloading. In special environments such as submarines, surface vessels, and aircraft, the risk of electrical fires is higher due to limited space, dense equipment, and difficult rescue operations. This paper also provides a detailed analysis of various types of electrical fires, including cable fires, electrical cabinet fires, transformer fires, battery fires, data center fires, and residential fires, and discusses their characteristics and prevention and control technologies. In terms of detection technology, this paper summarizes the progress of technologies such as arc detection, video detection, and infrared thermography, and emphasizes the importance of selecting appropriate technologies based on specific environments. Regarding extinguishing technologies, this paper discusses various means of extinguishing, such as foam extinguishing agents, dry powder extinguishing agents, and fine water mist technology, and highlights their advantages, disadvantages, and applicable scenarios. Finally, this paper identifies the limitations in the current field of electrical fire prevention and control, emphasizes the importance of interdisciplinary research and the development of advanced risk assessment models, and outlines future research directions.

Keywords: electrical fire; electric safety; cable fire; fire protection technology; fire extinguishing system

check for updates

Academic Editor: Kaihua Lu

Received: 20 February 2025
Revised: 4 April 2025
Accepted: 7 April 2025
Published: 10 April 2025

Citation: Li, G.; Guo, J.; Kang, Y.; Huang, Q.; Zhao, J.; Liu, C. Classification and Prevention of Electrical Fires: A Comprehensive Review. *Fire* **2025**, *8*, 154. https://doi.org/10.3390/fire8040154

Copyright: © 2025 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (https://creativecommons.org/licenses/by/4.0/).

1. Introduction

As society progresses and science and technology rapidly advance, electricity has become increasingly vital in modern life. Its extensive application significantly enhances production efficiency, improves quality of life, and provides a new impetus for economic development. However, the proliferation and utilization of electrical equipment have

led to a marked increase in fire risks, posing a significant challenge to social safety management. In recent years, electrical fire accidents have become increasingly prevalent in China, with frequent occurrences of severe and large-scale accidents. According to the latest statistics, from January to August 2024, China experienced a total of 660,000 fire accidents, resulting in 1324 fatalities, 1760 injuries, and direct property losses amounting to CNY 4.92 billion. Among these, 208,000 fires were attributed to electrical causes, representing a 14.4% increase compared to the same period last year and accounting for 31.4% of the total number, making it the primary cause of fires [1]. Electrical fires are typically caused by the release of heat energy from electrical wiring, equipment, appliances, and power supply and distribution devices. Faulty releases include high temperatures, arcing, and electric sparks, while non-faulty releases include the blazing surfaces of electric heating appliances. When combustion conditions are present, these heat sources can ignite the body or other combustible materials, thereby causing a fire.

The uniqueness of electrical fires lies in the manner in which energy is converted into heat during the ignition process. For instance, (1) the temperature of an electric arc can exceed 6000 K. (2) The arc tracking mechanism uniquely integrates the behavior of the fuel with the ignition process by altering the inherent properties of the fuel itself. (3) Electrical ignition is one of the common causes of fire, and its mechanism may involve the ejection of molten metal particles. The causes of electrical fires are multifaceted, including equipment aging, improper installation, improper use, short circuits, overloading, lightning strikes, grounding faults, and poor connections and contacts. Among these factors, poor connections are typically characterized by inadequate contact between plugs and sockets or between wires and switch terminals. This can lead to an increased contact resistance, which in turn may cause localized overheating, sparking, or arcing, potentially leading to electrical fires. Moreover, due to excessive contact resistance, poor connections between wires or between wires and electrical equipment can generate high temperatures or arcs under the influence of electric current, which may also ignite the wire insulation and nearby combustible materials. These causes of electrical fires are often closely related to defects in the design, manufacturing, installation, and usage processes, such as loose connections, damaged insulation, or substandard construction quality. In addition, electrical fires exhibit distinct seasonality. High temperatures in summer and dry conditions in winter can increase the risk of fires, especially during thunderstorm seasons and holidays. If equipment is poorly managed or used improperly, the likelihood of a fire occurring further increases. With the continuous advancement of fire protection big data and Internet of Things (IoT) technologies, electrical fire risk assessment and early warning systems are being increasingly applied [2]. These technologies can proactively identify potential fire hazards through real-time monitoring and dynamic assessment, thereby significantly enhancing fire safety levels. Moreover, there is currently a lack of comprehensive research on the unique characteristics of electrical fires in different environments, especially in special environments such as submarines, surface vessels, and aircraft. These environments are more prone to fire risks due to their limited space, dense equipment, and difficulties in rescue operations.

The innovation and value of this study lie in its comprehensive investigation of electrical fires. It examines various aspects, including the causes of fires, their classification, challenges in special environments, and the most advanced detection and extinguishing technologies. By employing a multi-scale research approach, we conducted an extensive search on Web of Science, IEEE Xplore, and Google Scholar. The keywords used included “electrical fires”, “causes of electrical fires”, “cable fires”, “detection technologies for electrical fires”, and “suppression technologies for electrical fires”. Based on relevance and quality, we selected high-level academic papers, technical reports, and case studies. The paper

provides deep insights into cable ignition behavior, offering a holistic view of electrical fires from laboratory-scale experiments to comprehensive ignition tests.

A significant focus of this study is on electrical fires in special environments such as submarines, surface vessels, and aircraft. These environments are more prone to fire risks due to confined spaces, dense equipment, and difficulties in rescue operations. In addition to analyzing these special environments, this paper also summarizes advanced detection technologies such as arc detection, video detection, and infrared thermography, and explores their potential applications in the prevention and control of electrical fires.

The primary objective of this review is to conduct an in-depth investigation of electrical fire prevention and control technologies and to outline future research directions. The main contributions of this paper are as follows: first, the paper explores the unique characteristics of electrical fires in different environments and provides their classifications. Second, the paper reviews cable fires and electrical fires in specific environments, evaluates current detection and extinguishing technologies for electrical fires, and considers both laboratory research and field applications. Finally, this paper forecasts the future research directions for electrical fire prevention and control technologies.

This study, through its comprehensive overview and targeted analysis of electrical fires, identifies advanced detection and extinguishing methods for different environments and explores potential solutions.

The structure of the remainder of this paper is as follows: the second section provides an in-depth analysis of electrical wiring and equipment fires, as well as the challenges of electrical fires in special environments; the third section summarizes advanced detection and extinguishing technologies in both laboratory research and field applications, including the latest developments in arc detection, video detection, and infrared thermography technologies; the fourth section discusses the gaps and prospects in electrical fire prevention and control, and the final section concludes the paper.

2. Electrical Fire

2.1. Electrical Wiring Fire

2.1.1. Cable Fire

Electrical faults are a primary cause of fires. According to statistics from 2023, they account for 37% of all yearly fire incidents, resulting in approximately 2000 fatalities and over 7000 injuries. Among these, residential fires have the most severe casualties, accounting for 56% [3]. Wires and cables are prone to causing fires in various electrical products, resulting in significant casualties and property losses. In aircraft and spacecraft, the potential fire risk associated with wires and cables is extremely high, potentially leading to catastrophic consequences. For example, the Swissair Flight 111 accident in 1998 was caused by an arc in a wire bundle, which led to a fire and the subsequent crash of the aircraft [4]. In space exploration, numerous electronic devices and wires are used in spacecraft. Although at least five minor incidents involving electrical short circuits or component overheating have been reported in space shuttle missions, no fires have occurred as of yet.

Cables are widely used in various fields of human activities, including power systems, information transmission systems, and mechanical instrumentation systems, which increases the probability of cable fires, not only causing delays in power transmission and information delivery, but also resulting in casualties and disruptions to normal production and living activities. The fire hazards of cables in major facilities both domestically and internationally should not be underestimated. In China, cable fires in power plants have occurred frequently, with a total of 132 large-scale fires between 1960 and 1991, resulting in a power loss of approximately 11 billion kilowatt-hours. Between 18 October and

3 November 1991, three cable fires in North China caused the shutdown of seven 220 MW units, resulting in significant losses [5]. Electrical and control cable fires account for approximately 70% of the fire load in ITER, and statistics from Keski-Rahkonen et al. also confirm that cables are a major fire source in nuclear power plants, with thousands of kilometers of cables used for control and drive equipment in nuclear power plants, posing significant fire risks [6]. For example, in the 1975 Brown Ferry NPP accident, over 1600 cables were damaged by fire, causing short circuits in live conductors and leading to severe system failures [7].

Since the introduction of the cable, its research and development have never ceased, and the variety of cables available on the market has increased significantly, finding widespread application in various fields of production and life [5]. Concurrently, research into cable fire behavior has been continually deepening, with multi-scale research methods gradually taking shape. As early as 1966, the National Fire Protection Association (NFPA)'s Fire Hazard Study revealed 24 cases of fires propagating through cables, and clearly indicated that the single cable test method available at that time had serious deficiencies, as all early cable fire tests were small-scale and could not fully assess the fire performance of the cable [8]. Based on these findings, the European Union mandated in 2013 that cables must pass fire tests, including the EN50399 large-scale flame test [9]. However, such large-scale tests are not only time-consuming, but also costly. Consequently, researchers have proposed an alternative approach: to initially determine the fire performance of cables through laboratory-scale fire tests, and to proceed with further large-scale fire tests only if the results of these initial tests meet the expected requirements [10].

Reproducing fire scenarios under laboratory conditions is crucial for addressing the challenges and issues encountered in both fundamental and applied research [11]. For instance, Grigorieva et al. [12] developed physical and predictive mathematical models encompassing heat and mass transfer, phase transitions, and chemical reactions, with the objective of ascertaining the necessary and sufficient conditions for fires to occur in typical overloaded cable lines. In contrast, Sarazin et al. [13] utilized a combination of mass loss cone calorimetry and Fourier transform infrared (FTIR) to conduct simulations of fires in low-voltage cables, thereby investigating the profound impact of current on cable fires. It is worth noting that cone calorimetry has emerged as a common and essential tool for studying cable fires, playing a significant role in assessing the overall fire behavior of various products, including cables [14]. Zhang et al. [15] conducted 30 fire experiments utilizing cone calorimetry to examine the impact of insulating material aging on the fire performance of flame-retardant cables. Similarly, Magalie et al. [10], with the aid of a cone calorimeter, performed a comprehensive assessment of the fire performance of small telecommunication halogen-free cables by altering test conditions such as heat flow density, the number of cables, and cable spacing, as well as cable properties like sheath thickness and insulation quality. Furthermore, Martinka et al. [16] employed a cone calorimeter to thoroughly investigate the fire performance of three-core power cables and two-core electrical control cables in relation to fire risk. The cone calorimeter is capable of measuring the combustion characteristics of cable materials, such as ignition time, heat release rate, and mass loss rate. These measurements provide data for assessing the fire hazard of materials.

In addition to the cone calorimeter, which is an important tool, cable ignition test rigs are frequently employed to investigate the spontaneous and automatic ignition characteristics of cables (as depicted in Figure 1a). This aids in studying the ignition characteristics and fire propagation mechanisms of cables, offering a basis for the development of safer cable materials and designs. Meanwhile, "PITCAIRN" pyrolysis ovens are utilized to examine the mass loss and thermal decomposition of cables during fires (as illustrated

in Figure 1b), offering critical data for the development of fire suppressants. Moreover, the results indicate that positioning thermocouples near the cable sheath and between the cores of insulated cables can yield crucial information regarding the combustion process of the cable insulation layer, which is invaluable for studying flame propagation in cable fires [17].

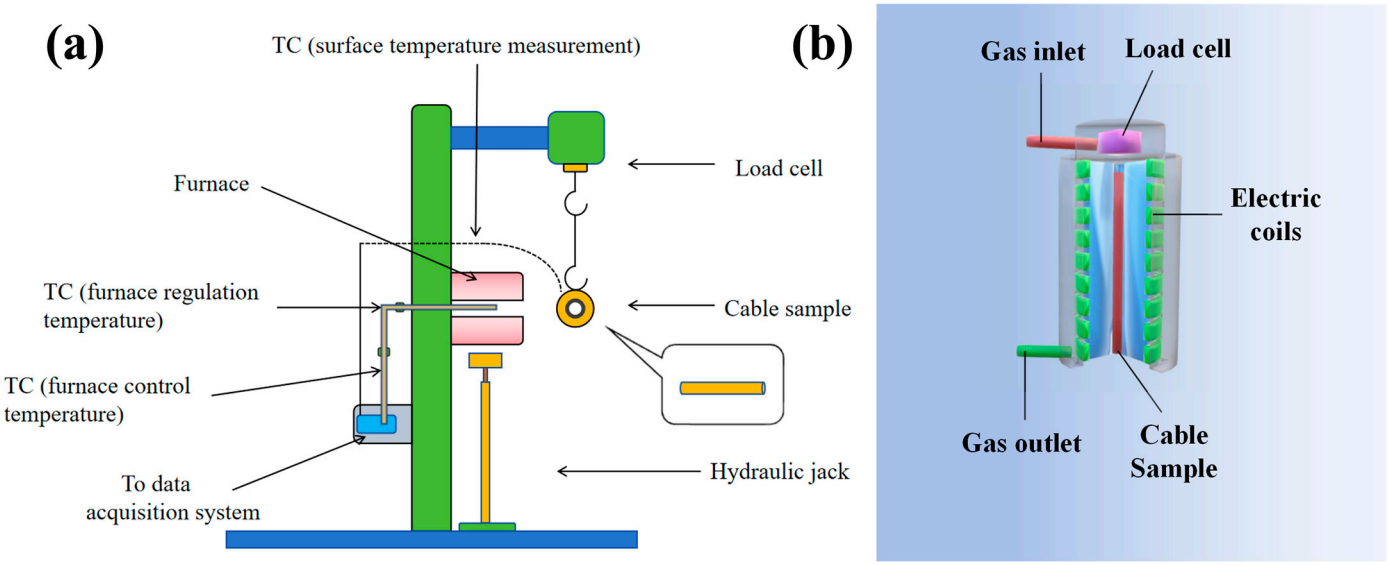


Figure 1. (**a**) Device scheme of cable ignition test bed; (**b**) PITCAIRN instrument scheme [18].

Over the past two decades, the pivotal role of cables in industrial fires has prompted in-depth investigations into associated fire incidents, with cable trays garnering significant attention as a crucial factor in fire propagation [18]. Research has indicated that the flame spread rate in vertical cable tray fires can reach up to 50 m per hour, which is nearly 15 times greater than that in horizontal cable tray fires [19,20], thereby underscoring the heightened risk associated with vertical cable tray fires. Typically, in horizontal cable tray fires, the fire tends to cease spreading upon the removal of the ignition source. This occurs because flame propagation must overcome gravity, and heat radiation and convection primarily act in an upward direction, exerting a relatively limited impact on the cables situated below or to the sides. However, there are exceptional scenarios, such as in multi-layer bridge experiments, where the fire can fully propagate to multiple horizontal cable trays even after the ignition source has been removed. Additionally, it is noteworthy that fires tend to spread more rapidly on upper cable trays compared to lower ones. The burning upper bridges radiate heat towards the lower cable trays, thereby initiating combustion in the lower bridges. Should this not occur, as depicted in Figure 2a, instances of fire spreading along a single horizontal cable tray are comparatively rare.

In contrast, in vertical cable tray fires, the fire spreads rapidly upward along the tray, readily resulting in complete combustion (as shown in Figure 2b). This phenomenon is primarily attributed to the natural upward spread of the flame due to gravity, while the upward movement of hot air driven by thermal buoyancy further accelerates fire development. The thermal buoyancy effect is particularly significant in vertical cable trays, where the hot air moves upward due to the temperature difference, thereby promoting the vertical spread of the fire within the tray. Consequently, fires in vertical cable trays are significantly more challenging to control and extinguish, and their destructive potential and danger are markedly increased [21].

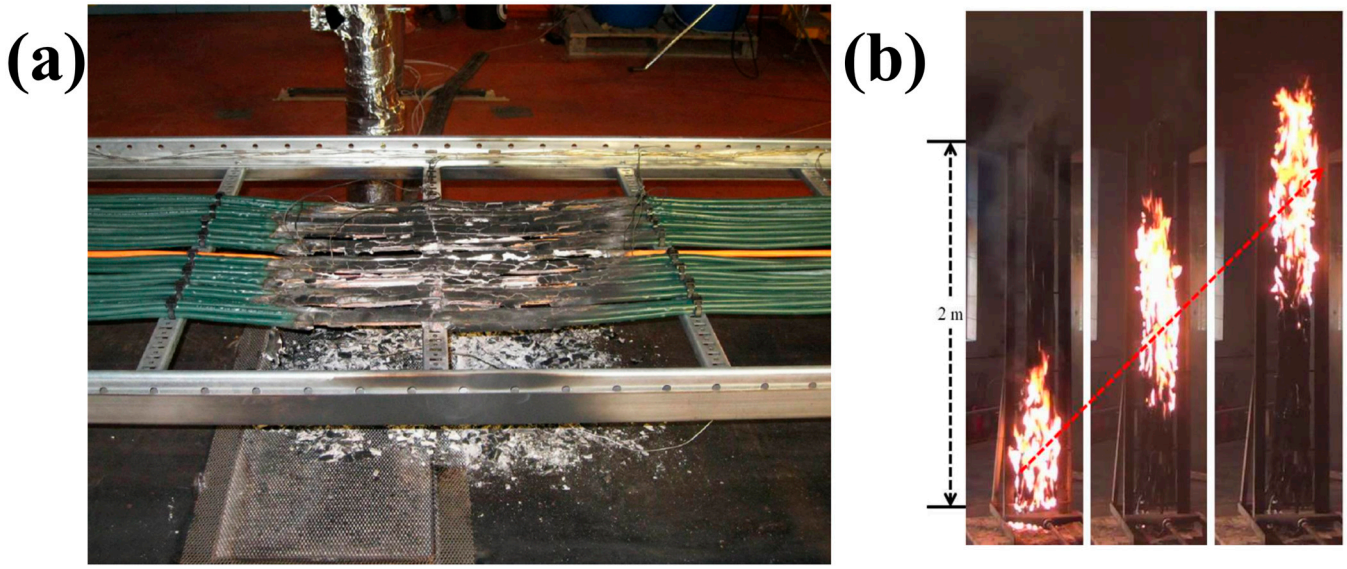


Figure 2. (**a**) Cable groove after horizontal fire test (FIREX cable) [22]; (**b**) time series photos of vertical cable trough fire [21].

The investigation of cable failure in fire scenarios has been a focal point within the cable fire research domain [23]. Despite the extensive conduct of numerous related tests, the failure criteria employed in these tests lack uniformity, and their applicability varies across diverse fire scenarios. Yang et al. synthesized prior research findings and categorized cable failure criteria into two primary classifications [24]:

The initial category relates to functional loss, with criteria focused on the degradation of cable insulation performance. This criterion is met when the cable cannot perform its intended function adequately due to insulation damage or degradation caused by heat, flame, or other fire-related factors. The insulation serves to protect the cable's conductors from short circuits and other malfunctions.

The second category is loss of fire resistance, which focuses on a cable's capacity to withstand combustion. This refers to the cable's ability to maintain its structural integrity and resist ignition during a fire. Cables within this classification may either facilitate the spread of fire or fail to impede the fire's spread due to their own combustion. In critical systems, it is imperative that cables continue to function during a fire to ensure safety and prevent further disaster.

These classifications enable a more precise assessment of cable performance under different fire conditions, thereby providing a scientific basis for cable selection and fire protection design.

2.1.2. Electrical Cabinet Fire

Electrical cabinets are, indeed, widely utilized in industrial production for power distribution control and protection against power failures due to short circuits, overload, and leakage. The spatial distribution of materials within electrical cabinets can vary, as depicted in Figure 3, and this variation is acknowledged across different types of cabinets [25]. The classification of electrical cabinets can be approached in two primary ways. Functional classification includes power generation, power distribution, and control and instrumentation. Voltage classification categorizes cabinets as high-voltage (>480 V), medium-voltage (~480 V), and low-voltage (<480 V).

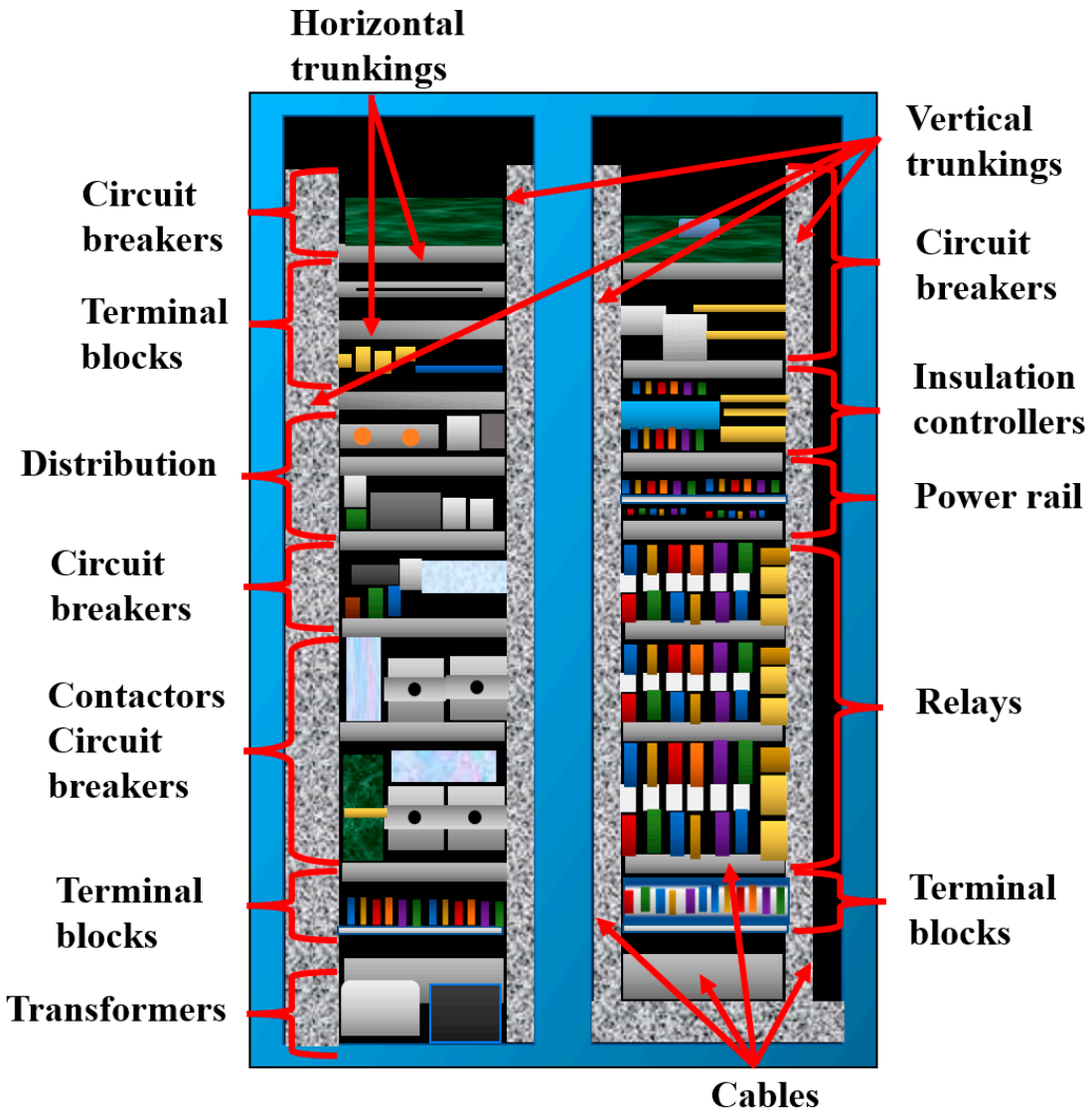


Figure 3. Electrical cabinet used as fire source [26].

To date, a relatively limited number of studies on electrical cabinet fires have been undertaken, primarily within the domain of nuclear power plants. From the 1980s through to the end of 2010, the Organization for Economic Co-operation and Development (OECD) fire database documented nearly 400 fire incidents in nuclear power plants [27], with electrical cabinets emerging as one of the principal sources of fire hazards in these facilities, constituting 12% of all prior fire events (i.e., 48 electrical cabinet fires). Nuclear power plants house a substantial number of electrical cabinets, which are tasked with reducing input power from 14 kV to 50 V and distributing power to hundreds of electrical components. The conjunction of fire loads and energized electrical components within electrical cabinets can precipitate fires and explosions [25], with such incidents potentially disrupting power supply, instrumentation, and plant control, thereby posing an extremely grave danger to nuclear power plants. Consequently, the investigation of electrical cabinet fires and their characteristics constitutes a vital component of electrical safety.

In the 1980s, Sandia National Laboratories (SNL) [28,29] in the United States pioneered electrical cabinet fire studies, employing diverse electrical cabinet geometries, ventilation openings, and ignition conditions. By the 1990s, the Finnish Technical Research Center (VTT) [30,31] utilized electrical and electronic components as fire loads within enclosed cabinets. Avidor et al. [25] at the University of Maryland reported on experimental simula-

tions (approximately 40 tests) of electrical cabinet fires, employing propane and heptane as fire loads. However, few experimental results accurately elucidate the mechanisms by which electrical cabinet fires ignite (whether doors are open or closed, in closed or open environments) and how heat release rates can be assessed to forecast the impacts of such fires in nuclear facilities.

The French Institute for Radiation Protection and Nuclear Safety (IRSN) devised an experimental program to investigate electrical cabinet fires, employing an analytical approach that examines the influence of combustible material content (poly(methyl methacrylate) (PMMA), polymer mixtures), door position (open or closed), and the size and location of openings (pertaining to closed doors only) on the fire's heat release rate. Subsequently, Plumecocq et al. [26,32] from IRSN carried out experiments on the combustion of closed electrical cabinets within calorimetric hoods and mechanically ventilated compartments, applying the findings to IRSN's experimental protocols. Bruynooghe contended [33] that ascertaining the heat release rate is imperative for comprehending the ramifications of fires in closed and ventilated compartments. However, given that chemical and mechanical methods are not invariably conducive to estimating the heat release rate, Coutin et al. [26] conducted the requisite thermal simulations to evaluate the heat release rate, grounded in the energy equilibrium among the fire compartment, the ventilation system, and the electrical cabinet itself, to investigate electrical cabinet fires in highly confined and mechanically ventilated compartments. They also examined the characteristic phases of electrical cabinet fire progression, primarily based on the temporal evolution of the fire's heat release rate, which served as the foundation for proposing a novel complex fire model (utilized in the study of fires in open electrical cabinets).

In many nuclear power plants (NPPs) and at the European Center for Nuclear Research (CERN), electrical cabinets are often arranged in adjacent configurations (AC). For example, at CERN, the electrical cabinets vary in geometry, content, and configuration (from individual cabinets to arrangements of 10 cabinets and racks in a row, and 20 enclosed cabinets in two rows, as shown in Figure 4a,b), as well as in location (above ground in control rooms or underground in tunnels 100 m below ground). Consequently, in addition to investigating the fire behavior of individual electrical cabinets, examining the fire behavior of electrical cabinet fires propagating to adjacent cabinets is another crucial aspect of electrical safety.

The research team led by Zavaleta systematically identified the key factors influencing fire spread between electrical cabinets in two studies. In a study on the natural ignition characteristics of air gaps and components [35], they designed a double steel shell experimental device to simulate adjacent electrical cabinets (Figure 4c). They found that when electrical components reach the critical ignition temperature and heat flux, spontaneous combustion is triggered. Additionally, expanding the air gap space significantly slows the temperature rise rate of the side wall, delaying component ignition by approximately 30%. In another fire propagation experiment involving ventilation mechanisms [36], the team conducted four comparative tests and found that in a mechanically ventilated environment, a fire in an open-door electrical cabinet spreading to the overhead cable tray and adjacent cabinets significantly shortens ignition time by accelerating oxygen convection. In contrast, natural ventilation delays the fire development process by only about 15% due to its lower air exchange efficiency.

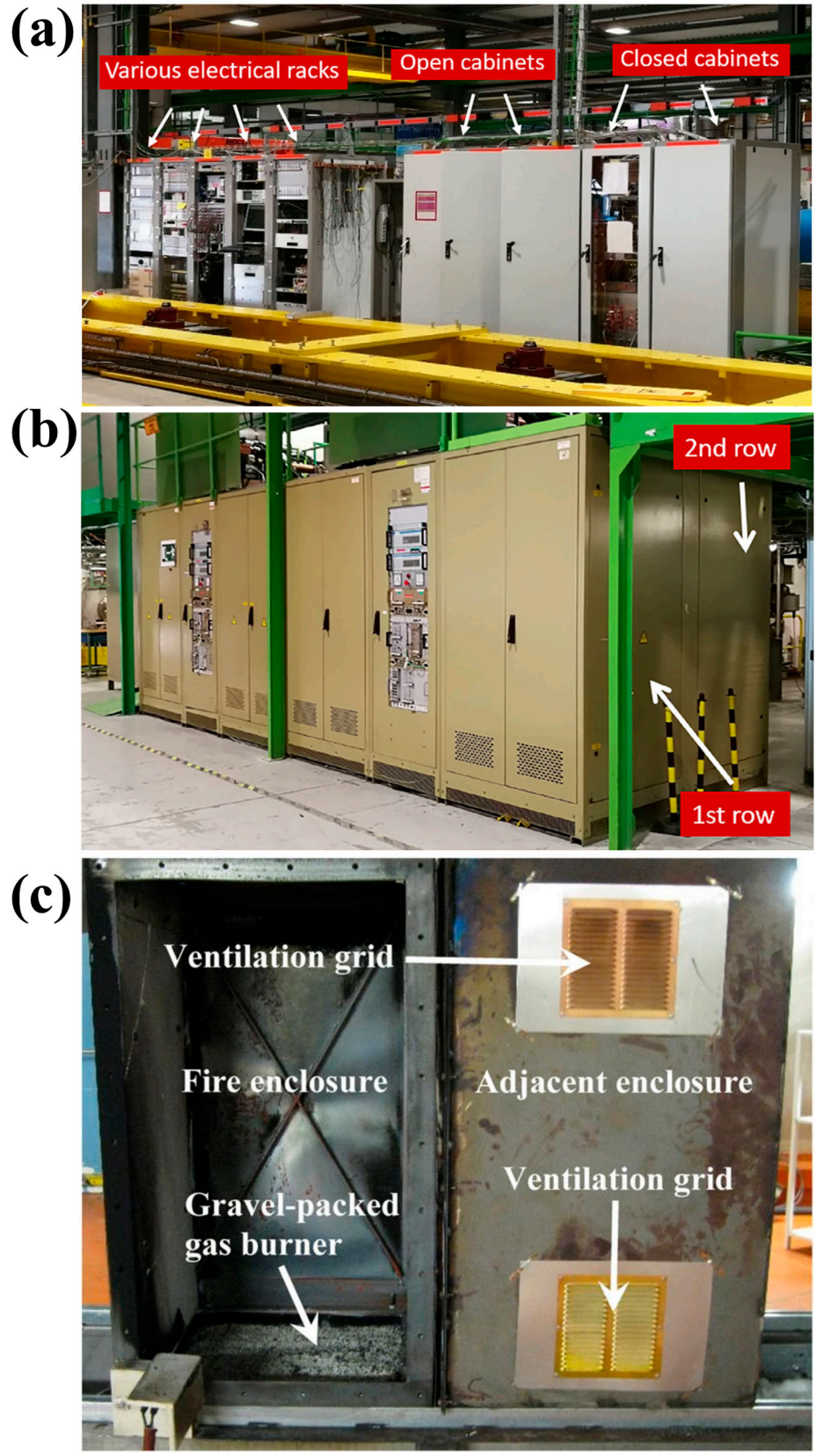


Figure 4. (**a**) Open/closed electrical cabinets and racks in the same row—photo taken at one of the CERN facilities; (**b**) 20 enclosed electrical cabinets divided into two rows—photo taken at one of the CERN facilities [34]; (**c**) ignition cabinet and adjacent cabinet [35].

Perovic et al. [34] developed an Excel-based design fire calculator for electrical cabinets that is capable of generating potential design fire curves for any quantity of electrical

cabinets or racks. This tool is of significant importance in mitigating fire risks, particularly in settings like nuclear power plants (NPPs) and CERN, where a substantial number of electrical cabinets are essential. Furthermore, Yang et al. [37] conducted an experimental study on the reverse identification technique for detecting overheated components within electrical cabinets using infrared thermography, by setting up a test bed for electrical cabinets. The study's results demonstrate that utilizing infrared thermography for surface temperature measurements to identify overheated components within electrical cabinets holds significant practical application value.

2.1.3. Transformer Fire

Presently, electricity generation in many countries continues to depend on the combustion of fossil fuels in thermal power plants [38]. These plants are typically situated on the outskirts of cities or at a considerable distance from urban areas, necessitating the transmission of power through high-voltage lines to substations, where the voltage is reduced to meet the requirements of cities and industries. Despite advancements in substation automation technology [39], there has been a notable rise in fire incidents attributed to the operation of substation power equipment, with transformers [40] and switchboards [41] being especially vulnerable. Transformers are a frequent source of substation fires. A case in point is the substation fire during the 2008 Wenchuan earthquake [42], which demonstrated that all three bushings of a 500 kV power transformer were damaged, the oil sleeper brackets were displaced, and the leakage of transformer oil ignited a fire within the substation.

Power transformers are essential components of substation equipment, utilized to regulate the rated voltage of the transmission and distribution system, and their reliable and stable operation is crucial for the generation and distribution of electricity [42,43]. Three types of transformers are extensively utilized: liquid-filled transformers, high-voltage liquid-filled transformers, and dry-type transformers. To ascertain the source of transformer failures in substation fires, Christina et al. [44] conducted multiple investigations and test analyses focusing on bushing failures, which are deemed the primary cause of transformer failures. Bushings are deemed vulnerable components of transformers, and studies have indicated that 44% of forced outages of large transformers are attributed to bushing issues [45]. This perspective is corroborated by a survey conducted by the International Conference on Large Electricity Grids (CIGRE), which revealed that 10% of transformer failures were due to casing damage, resulting in severe consequences [46].

Transformer fires and explosions are initiated by internal faults within the transformer oil compartment, which may be precipitated by overloads, atmospheric or switching over voltages, insulation degradation, short circuits within the main active components, or failures of transformer components such as the on-load tap changer, bushings, or oil cable box [47]. Should insulating oil leak from the transformer oil compartment, it may form a combustible material that can trigger sporadic transformer fires and explosions, potentially escalating into substation fires. Petroleum-derived mineral oils have been utilized as insulating fluids in transformers since 1887 [48]. The majority of modern power transformers employ mineral oils derived from petroleum for cooling and insulation purposes. These oils comprise a variety of hydrocarbon compounds, including naphthalene, paraffin, iso-paraffin, and aromatic hydrocarbons [49]. Should these oils leak and come into direct contact with high-voltage components [50,51], fires and explosions may ensue. El-Harbawi et al. [38] ascertained that under abnormal conditions, when the internal temperature of the transformer escalates to 150–300 °C, the mineral oils undergo chemical decomposition, producing hydrogen and methane gases, and at temperatures surpassing

300 °C, ethylene is generated, resulting in the production of substantial quantities of hydrogen and ethylene.

2.1.4. Battery Fires

Battery fires, particularly those involving lithium-ion batteries, have emerged as a significant concern in recent years due to the widespread adoption of electric vehicles (EVs), energy storage systems (ESS), and portable electronic devices. These fires differ markedly from traditional electrical fires because they involve complex chemical reactions, rapid energy release, and significant extinguishing challenges [52].

Battery fires are primarily caused by thermal runaway, which is a self-sustaining exothermic reaction triggered by internal short circuits, mechanical damage (such as squeezing or penetration), overcharging, or exposure to high temperatures. During the thermal runaway process, the decomposition of electrolytes (such as organic carbonates) and cathode materials (such as lithium cobalt oxide) generates flammable gases (such as CO, CH_4, H_2) and toxic compounds (such as HF), thereby intensifying the intensity and hazards of the fire. For example, in 2021, a fire occurred at an ESS facility in Arizona, USA, due to the release of explosive gases from lithium-ion battery failures [53]. This chain reaction of thermal runaway may not only lead to the rapid spread of the fire but also trigger an explosion, posing a serious threat to personnel and equipment.

Lithium-ion battery fires have unique hazardous characteristics. The large amount of electrochemical energy stored in these batteries can cause a fire when the flames are violently ejected, and the fire will spread rapidly. Thermal runaway can spread to adjacent batteries within seconds, forming a series of failures and greatly increasing the complexity and danger of the fire. This makes it difficult for traditional firefighting methods to effectively control the fire. In addition, the combustion of lithium-ion batteries releases highly corrosive and toxic hydrogen fluoride (HF), seriously threatening the health of firefighters and residents of the surrounding area [53]. This gas can also cause corrosive damage to firefighting equipment, complicating firefighting work and possibly leading to the spread of acid mist at the fire site, causing environmental pollution. The risk of reignition is also more prominent. Even after initial extinguishment, residual heat or damaged battery cells may still reignite, requiring long-term cooling. This means that we cannot solely rely on traditional fire extinguishing agents (such as water spraying) but also need to take more effective cooling and isolation measures to ensure complete fire extinguishment.

In recent years, the development of material innovation and early detection technologies has provided new ideas and methods for the prevention and control of battery fires. In terms of materials, significant progress has been made in the research and development of solid-state batteries and flame-retardant electrolytes (such as phosphorene derivatives). Solid-state batteries substantially reduce the risks of internal short circuits and thermal runaway by replacing traditional liquid electrolytes with solid-state electrolytes. Flame-retardant electrolytes like phosphorene derivatives can remain stable at high temperatures, reducing the production of flammable gases and thus effectively decreasing the fire risk [54]. Simultaneously, early detection technologies also play a crucial role. Advanced sensor systems can monitor real-time changes in temperature and gas concentration inside the battery by monitoring indicators such as abnormal voltage, peak temperature, and gas emissions (e.g., carbon dioxide, volatile organic compounds). Once an anomaly is detected, the system will immediately trigger an alarm and take appropriate firefighting measures. This early detection technology not only improves the efficiency of fire response, but also significantly reduces the losses caused by fires, providing strong support for the prevention and control of battery fires [55].

2.1.5. Data Center Fires

As a core facility of modern information technology, data centers are highly prone to electrical fires due to their densely packed high-power equipment and complex cooling systems. The main fire risks in data centers stem from electrical equipment overload, cooling system failures, and human operating errors. For example, in 2022, a large-scale data center in Seoul, South Korea, caught fire due to an overload in the uninterruptible power supply (UPS) system, resulting in significant data loss and infrastructure damage [56]. This incident highlights the urgent need for power load management and monitoring systems to prevent such overload events. Additionally, data centers rely heavily on air conditioning and liquid cooling systems to maintain the optimal operating temperature of the equipment. Failures in these systems, especially in densely packed server racks, can easily lead to local overheating. Existing research shows that for every 10 °C increase in the ambient temperature, the risk of thermal runaway in server components increases by 40%, which further emphasizes the importance of regular maintenance and redundant design of the cooling systems [57].

The unique challenge of data center fires lies in their high-density equipment layout, which can cause fires to spread rapidly. Meanwhile, burning plastics and electronic components release large quantities of toxic gases, such as carbon monoxide (CO), methane (CH_4), and hydrogen (H_2). These gases not only exacerbate the fire, but also pose a severe threat to the health of personnel. In addition, data centers are typically narrow, which further increases the difficulty of firefighting. Due to the high-density layout of the equipment, fires can spread rapidly to adjacent equipment in a short period, causing a cascade of failures and significantly increasing the complexity and danger of the fire. Therefore, traditional firefighting methods often struggle to effectively control such fires.

To address these challenges, advanced fire detection systems—such as video-based smoke detection [58] and infrared thermal imaging [59]—have been widely implemented. These systems enable real-time monitoring of fire indicators including smoke emission and temperature anomalies, triggering immediate alarms to facilitate prompt fire suppression actions. Additionally, the application of fire-resistant materials combined with automated suppression systems—such as the inert gas Novec 1230 [60] and water mist systems [61]—effectively mitigates fire damage while ensuring operational continuity. Inert gas systems suppress fires by reducing oxygen concentration, whereas water mist systems achieve fire control through dual mechanisms of cooling and oxygen displacement. The integration of these technologies offers a comprehensive solution for fire prevention and suppression in data centers, minimizing operational disruptions and asset losses during fire incidents.

2.1.6. Household Fires

Household appliance fires account for a significant proportion of residential electrical fires, primarily due to misuse or the aging of common electrical equipment. The insulation layers of older appliances, such as refrigerators, washing machines, and microwaves, degrade over time, significantly increasing the risk of short circuits. A 2023 study by the NFPA in the United States showed that appliances over 10 years old caused 35% of residential electrical fires [62]. Therefore, regular inspections and timely replacement of aging equipment are crucial for reducing fire risk.

Improper use is also an important factor in starting fires. For example, high-power appliances like electric blankets, space heaters, and hair dryers are prone to overheating if left on for a long time. In 2022, a fire broke out in an apartment in New York because an electric blanket had been on for more than 12 h, igniting the surrounding bedding. Hence, it is necessary to strictly follow the manufacturer's safety guidelines [63].

Household appliance fires usually lead to serious consequences, such as property damage and casualties. To reduce these risks, some preventive measures are essential, such as regular inspection and replacement of aging equipment, compliance with manufacturer's guidelines, and installation of arc fault circuit interrupters (AFCIs). Moreover, public awareness campaigns and education programs can also play a key role in promoting the safe use of electrical appliances and active fire prevention.

2.2. Scenario-Specific Electrical Fires

2.2.1. Submarine Electrical Fire

Electrical fires consistently pose a significant challenge to submarine safety. Unlike surface vessels, submarines have extremely limited options for fire suppression and rescue due to their confined space and dense electrical equipment. This makes electrical fires prone to sudden ignition and rapid spread within the submarine, while also generating large quantities of highly hazardous toxic smoke. Due to the limitations of the enclosed underwater environment, initial damage can escalate exponentially over time. For example, in 1989, the Soviet nuclear submarine Komsomolsk was on the way back to sea when a fire suddenly erupted in compartment seven and rapidly spread to compartment six. This led to an oil leak from the turbine engine's hydraulic unit. The high temperature and pressure compromised the compartment's seal, allowing seawater to ingress, and ultimately caused the submarine to sink five hours later [56]. This incident underscores the severe consequences of submarine fires.

According to statistics spanning the 30 years post-World War II [64], there were 16 major submarine accidents in the former Soviet Union, with fire accidents and associated fatalities comprising 62.5% and 62%, respectively. In the late 1970s, the U.S. Navy recognized that electrical fires were emerging as a significant issue on submarines, with roughly three fires per year affecting electrical equipment in the submarine fleet [65]. Over the past 25 years, the UK Ministry of Defense has documented 266 nuclear submarine fires, 20 of which necessitated substantial resources for containment [66]. During a five-year period from 2011 to 2015, there were four severe fires or incidents related to fire safety systems on Indian Navy conventional submarines, culminating in a total of 41 fatalities [66].

Comprehensive statistics of submarine accidents since 1946 indicate that fire remains one of the predominant types of submarine accidents. Figure 5 provides a summary of the breakdown of accident types, revealing that 10% of accidents are fires and 11% are explosions. The most recent publicly reported submarine accidents involving electrical fires from 2006 to 2015 are enumerated in Table 1.

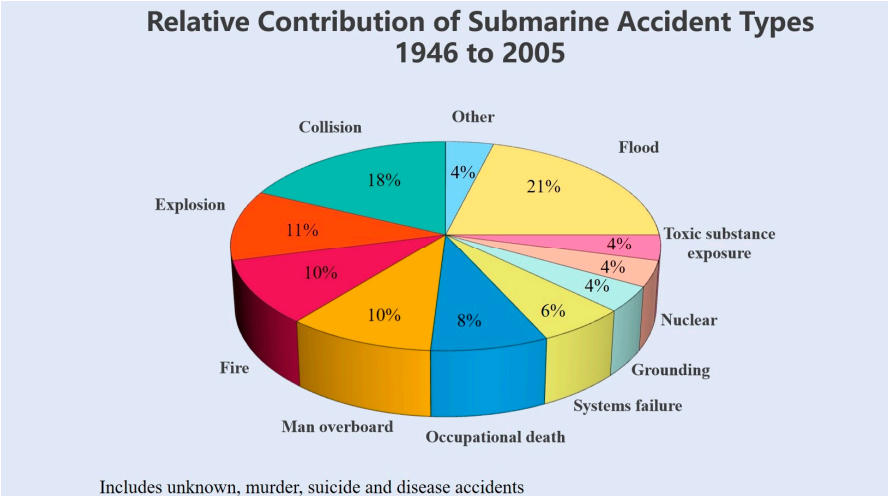


Figure 5. Relative causes of submarine accident types from 1946 to 2005 [67].

Table 1. Publicly reported electrical fire accidents from 2006 to 2015.

Submarine	Type	Year	Accident Types	Cause	Number of Deaths	Number of Injured	Reference
Daniil Moskovsky	Nuclear submarine	2006	Fire	Electrical line failure	2	0	[68]
INS Sindhu-ratna	Conventional submarine	2014	Fire	Electrical line failure	2	7	[69]

An examination of the causes of submarine fire accidents reveals that major submarine components, such as batteries, engines, and electrical equipment, have been responsible for the majority of submarine fatalities in recent years. For instance, the smallest generator on a submarine can send a current capable of burning a fist-sized hole in the side of a switchboard within three-quarters of a second. The causes of electrical fires on submarines are akin to those of most electrical accidents, with direct causes including short circuits, overloads, and arcing due to poor contact [70]. However, owing to the unique characteristics of the submarine environment, the factors that precipitate these direct causes warrant thorough investigation and research. For instance, electrical equipment, such as cables, relays, and switchboards, may directly cause fires due to factors like internal short circuits and overheating resulting from diminished insulation in humid environments.

On the Canadian submarine Chicoutimi, where approximately 2000 L of seawater infiltrated the hull, the seawater caused an electrical panel to short-circuit, thereby initiating a fire that led to the loss of all electrical power. Consequently, the submarine lost power and drifted, resulting in smoke inhalation for nine crew members and the subsequent death of one [71]. Arc faults on submarines also posed a significant problem. The main switchboards on board conduct thousands of amperes of current through bare copper busbars, while large circuit breakers regulate the flow of current to remote loads and smaller switchboards, where hundreds of amperes of arcing may occur. The arcing is not a complete short circuit but a resistive load that generates heat, thereby preventing the circuit breaker from opening. Errors resulting from corrosion, improper fastening, vibration, and other factors aboard submarines account for 60–80% of arcs [72], as do contamination and foreign objects. The severity of submarine arcing casualties varies, yet the 1975 incident aboard the submarine Patch (SSN 683) was particularly notable, in which one of the submarine's turbine generator switchboards was entirely destroyed, and the remaining generator switchboard sustained severe damage [66].

Lead–acid batteries supply backup and propulsion power for numerous submarines worldwide [73]. With the advent of nuclear-powered submarines, which primarily utilized steam for propulsion while still employing lead–acid batteries as backup power, the total electricity consumption of submarines increased significantly. However, a single misconnection or short-circuit in a lead–acid battery can result in over 4 MW of arcing, potentially causing significant damage and submarine fires [74].

2.2.2. Electrical Fire on Surface Ships

With the burgeoning shipping industry, the number of ships have surged, leading to an increase in ship accidents, which are primarily categorized into collisions, groundings, and fires [75,76]. Unlike land transportation, ships navigate in the ocean with minimal or no external assistance to address on-board fire accidents. Fire poses a significant threat to the safety of the ship, the lives of those on board, and the cargo [77–79]. An analysis of the available accident data reveals that fire and explosion accidents on ships constitute 14% of

major accidents on ships. Although fire and explosion accidents on ships are not the most frequent type of accident, they are among the most perilous accidents on ships.

Baalisampang et al. [80] analyzed the causes of fire and explosion accidents on ships and determined that electrical faults are a significant contributing factor to these accidents. Furthermore, Ugurlu [81] investigated reports of maritime accidents involving fire and explosion (F&E) incidents in tankers transporting hazardous liquid cargoes from 1999 to 2013 and found that electric arcs and static electricity are significant risk factors in the transportation of hazardous liquid cargoes in tankers. As ships evolve towards electrification, automation, and larger sizes, the diversity of electrical facilities on board has expanded, consequently increasing the risk of fires caused by these facilities [75].

The primary causes of electrical fires on ships are similar to those of most electrical fires, primarily involving short circuits, overloads, and arcing. However, due to the unique characteristics of the maritime environment, electrical installations on ships face additional risks compared to land-based electrical equipment and systems, including exposure to extreme temperatures, vibration, constant motion, high humidity, seawater, moisture, oil, and fuel [81].

The engine room, which powers the ship, is known as the "heart" of the vessel, providing power for propulsion and other onboard equipment [77]. Engine room fires are the most common type of ship fire and can jeopardize the safety of the entire vessel. According to statistics from the "Study of 165 Ship Fires 1992–1997" in the Det Norske Veritas (DNV) database [82], engine room fires accounted for nearly two-thirds of all ship fires, followed by cargo compartment fires and then passenger compartment fires.

The engine compartment houses power stations and various auxiliary systems, and the arrangement of these equipment and systems is highly complex on ships. Any failure of auxiliary systems, such as the cooling system, fuel system, pressure relief gauge, pumping system, etc., can easily lead to a fire. According to expert experience, short-circuiting, overcurrent heating, and transformer overheating of electrical equipment in the engine compartment may cause fires [83]. Additionally, electrical sparks or broken cable insulation may lead to fires, and the ignition of oil leakage around electrical equipment can cause fires in electrical equipment. Consequently, the engine compartment environment is highly susceptible to fires.

To investigate engine compartment fires in ships, Su et al. [84] used the Fire Dynamic Simulator (FDS) to construct a simulation model of the engine compartment, simulating the occurrence and development of such fires. Huang et al. [85] employed fuzzy comprehensive analysis to assess the influencing factors of fires in ship engine compartments.

Permanent magnet motors (PM motors), which boast the highest efficiency factor and the smallest mass and size, have the potential for widespread application in ships [86]. However, PM motors also possess a significant drawback that restricts their use in ships and ship systems. Mikhailov and Sen'kov [87] discovered that when a turn-to-turn fault occurs in PM motors, a substantial amount of heat is released in the turn-to-turn fault region, leading to the ignition of the stator windings' insulation and protection, thereby causing ship fires.

In addition to the engine compartment, the bridge is another critical area for electrical fires. The bridge serves as a vital on-site command center during ship navigation, and its safety directly impacts the safety of people, ships, and cargoes during transportation [88,89]. The electrical equipment on the bridge is essential for ship navigation and is designed to operate in a constant voltage, stable, and dry environment; however, this equipment has been operating in the harsh, wet, and vibrating conditions of the bridge for an extended period, increasing its fire hazard [90].

The ship's electrical network is also a risk factor for electrical fires. According to the study by Tarnapowicz [91], the risk of fire in electrical networks is influenced by the value of the leakage current, which depends on the component in the transverse impedance. The ship's cable system carries power, signaling, and communication, which is crucial for maintaining normal ship operations. However, cables can serve as a pathway for fire to spread from one compartment to another throughout the ship [92].

2.2.3. Aircraft Electrical Fire

In recent years, with the swift advancement of aviation technology, a significant number of military and civil aircraft have been deployed. As a highly sophisticated and technologically advanced mode of transportation with a complex system, the operating environment of an aircraft is intricate and unstable, and any minor errors during flight may result in severe accidents. For instance, in 1996, TWA Flight 800 crashed near Long Island, New York [93], and in 1998, Swissair Flight 111 crashed near Nova Scotia [94], resulting in no survivors. Both accidents were attributed to electrical wiring failures, and fires originating from aircraft electrical systems are among the primary causes of aircraft accidents. Arcing in electrical circuits [95–97], generator malfunctions in power generation systems [98–100], lightning strikes [101], and battery failures [102] are the principal causes of aircraft electrical fires. Electrical fire accidents in airplanes frequently result in significant losses, and as such, investigations into these accidents have been ongoing. Between 1978 and 1982, the U.S. Navy Safety Center (USNSC) conducted investigations into electrical accidents resulting in unidentified fires and wiring failures in fighter aircraft [103]. They documented a total of 791 incidents involving corroded, broken, or frayed wires and electrical circuits, as illustrated in Figure 6, some of which led to in-flight aircraft fires.

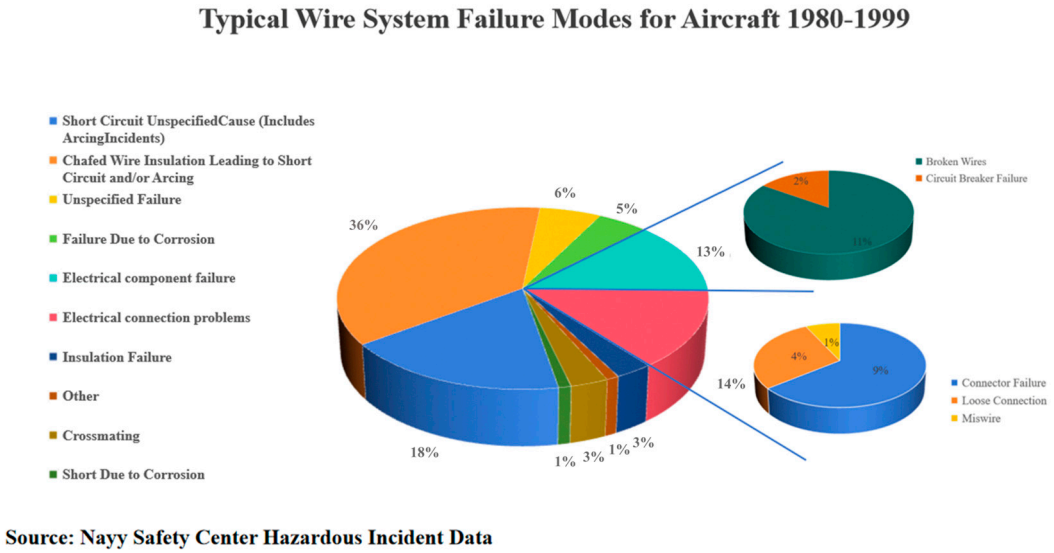


Figure 6. Typical wiring system failure patterns in aircraft (image courtesy of Naval Safety Center Hazardous Incident Data) [103].

The National Transportation Safety Board (NTSB) has reported that in-flight smoke and fire incidents are often attributed to wiring issues, electrical component malfunctions, lightning strikes, and pneumatic system failures [104]. The NTSB concluded its extensive investigation of TWA Flight 800, determining that a short circuit likely triggered the mid-wing fuel tank explosion. The investigation noted that the wiring condition was "not unusual for an airplane of this age [105]".

From the 1980s to 2010, Lebbin [106] analyzed 28 published investigation reports on aircraft fire and smoke incidents, authored by aviation safety agencies in Canada, the

United States, the United Kingdom, Germany, Sweden, Switzerland, and Saudi Arabia. Among these 28 reports, 17 addressed electrical system failures, which are detailed in Table 2.

Table 2. Aviation accidents involving electrical system failures [106].

Aviation Investigation Report Number	The Cause of the Accident
TSB 2009b	Arcing caused by damaged braiding can cause smoke in the cockpit windshield heater wiring terminals
TSB 1997b	Suspected broken copper braided wires causing arcing
TSB 2007a	Improperly routed wiring in the turbine engine and friction in the core caused high-voltage power to surge back into the flight deck electronics box, creating flames and smoke behind the electrical circuit breaker panel
TSB 1997a	Avionics relays-related failures
TSB 2003	Electric arcs from the wires ignited flammable insulation blankets, spreading the fire above the flight deck ceiling
TSB 2007b	The electric arc of the light switch failed and ignited dust that had accumulated nearby, causing the fire
TSB 2000a	An unconnected battery cable ran through the battery compartment, igniting flammable nylon lifebags in the adjacent baggage compartment
TSB 2009a	An electric arc was generated on one of the engines, which likely damaged a nearby fuel line, causing damage to the helicopter's hull
TSB 2010a	The fire was caused by an electric arc between the connector and the lighting source of the cabin panel
TSB 2002b	The internal switch regulator in one IFE controller generates excessive heat that causes the process board to ignite. Despite the loss of power, the system battery continued to power the IFE processor board, likely prolonging the duration of the fire
NTSB 2009a	A short circuit near the oxygen hose released oxygen and spread the fire
NTSB 2009b	The plane's weather radar system is suspected of causing the cabin fire
AAIB 2000	Arcing and associated heat damage in the case of improper installation of kitchen chillers
BFU 2009	An electrical short circuit caused by wear on the wire loom caused a fire in the insulating pad behind the cargo hold cladding
AAIB 2009	As the plane was preparing to taxi, an internal fault in the main circuit relay caused an electric arc and molten metal droplets fell, igniting the cabin insulation blanket

From the aforementioned accidents, it is evident that numerous air crashes and airplane malfunctions are directly or indirectly associated with arc faults in the aircraft's electrical system. During flight, when the connections of certain electrical equipment are loosened by vibration or short-circuited due to compromised wire insulation, the aircraft's electrical system may generate an arc, known as a failure arc [107]. In aircraft power systems, intermittent fault arcing can occur unpredictably when degraded wires are wet, vibrate against metal structures, or are subjected to mechanical stress [108]. Due to the high temperature and intense energy of the arcs, if left untreated, they can escalate into severe electrical faults, potentially leading to onboard fires, power interruptions, system damage, and catastrophic accidents. Energy transfer from faulted arcs and conductor ablation are two significant causes of fires and are closely related to the protection of faulted arcs [109–111]. Consequently, this issue has garnered considerable attention.

In both new and old military and civil aircraft, all critical electrical circuits are safeguarded against overheating through the use of a combination of thermal circuit breakers and magnetic circuit breakers, or solid-state power controllers (SSPCs) [103]. However, the operation of conventional thermal circuit breakers depends on the accumulation of Joule heat generated by the current, and faulty arcs can cause fires before the circuit breaker trips, as they do not detect and react to dangerous arcing faults [112]. It is worth noting that Kapton wire was once deemed an ideal insulated wire and was extensively used in military and commercial aircraft in the 1970s and early 1980s [105]. However, The Federal Aviation Administration (FAA) discovered that when Kapton wire is shorted or arced, a layer of conductive carbon insulation forms [103]. Moreover, although carbon is an excellent conductor, once a sufficient amount of carbon accumulates—depending on the type and thickness of the insulation, the power handling of the wire, and other factors—an explosive flashover can occur, with the exposed wire ejecting molten metal [113]. In 1988, the U.S. Navy prohibited the use of Kapton wires in repairs and in new aircraft.

The dense arrangement of electrical wiring in aircraft constitutes a primary contributing factor to electrical faults such as arcing. In modern commercial aircraft, the cumulative length of electrical wiring can exceed several dozen kilometers, significantly elevating the incidence of wiring-related failures including short circuits, equipment malfunctions, arc faults, and fire hazards [114]. Recent scholarly efforts have focused on characterizing fault arc behaviors across multiple domains, with particular attention to arc fault circuit breaker development [115–117]. Consequently, the comprehensive analysis of arc energy transfer mechanisms proves critical for aviation safety. Zhang et al. [107] employed a magneto-hydrodynamic arc model to quantify arc characteristics, energy transfer dynamics, and conductor ablation phenomena. Additionally, in-depth investigation of arc-induced molten droplet behavior under non-standard atmospheric conditions holds significant implications for fire risk assessment and mitigation strategy formulation in aerospace applications [118].

2.3. Summary

In this chapter, we have conducted an in-depth investigation of various types of electrical fires, each with distinct characteristics and causes. These fires can be classified based on their sources and causes of occurrence.

Among them, electrical wiring fires account for the majority, including cable fires, electrical cabinet fires, submarine electrical fires, surface vessel electrical fires, and aircraft electrical fires, which are caused by faults or abnormalities in the electrical wiring itself (such as short circuits, overloading, leakage, and poor connections). These fires typically have a degree of concealment and suddenness. Cable fires are usually caused by insulation degradation, short circuits, or mechanical damage, and can spread rapidly along the cable routes, posing significant risks. In particular, in electrical cabinet fires, submarine electrical fires, surface vessel electrical fires, and aircraft electrical fires, arc-induced fires due to confined spaces and dense electrical wiring account for the majority.

Transformer fires and battery fires are categorized as equipment-related fires. Transformer fires are typically caused by internal faults within the transformer, such as overloading, insulation degradation, or component failure. Battery fires, such as those involving lithium-ion batteries, are often caused by thermal runaway. These fires are characterized by complex chemical reactions and rapid energy release, resulting in intense and difficult-to-extinguish fires.

Data center fires and household appliance fires are categorized as facility-based electrical fires, both of which are primarily caused by the high-density use of electronic equipment and excessive aging of devices.

The causes of these fires, whether related to electrical wiring, equipment failure, special environments, or facility factors, share some commonalities, such as aging infrastructure, improper installation, misuse, short circuits, overloading, and environmental impacts. We will explore in subsequent chapters how to optimize and apply various detection and extinguishing technologies to address the specific challenges posed by different types of electrical fires.

3. Electric Fire Prevention and Control Technology

3.1. Electrical Fire Detection

Chapter 2 provides a detailed investigation of various types of fires. Each type of electrical fire corresponds to its unique scenarios. Therefore, in practical applications, it is necessary to select and configure appropriate electrical fire detection technologies based on specific electrical fire risks and environmental conditions to enhance the accuracy and effectiveness of fire prevention.

3.1.1. Sensor Detection Technology

Traditional Sensor Detection Technology

In the field of electrical fire detection, traditional sensor technologies establish a comprehensive early warning and real-time monitoring system by detecting changes in physical and chemical parameters during fires [119]. This system primarily consists of three core components, temperature sensors, smoke sensors, and carbon monoxide sensors, which complement each other to form a hierarchical monitoring network.

Temperature sensors, serving as the basic monitoring unit, mainly use thermistors or thermocouples to track environmental temperature changes in real time [120]. They are characterized by their simple structure and rapid response. When abnormal temperatures are detected in the monitored area, the system can immediately trigger an alarm mechanism. However, this technology has significant limitations: a single temperature parameter cannot identify the type of burning material, and it is susceptible to environmental temperature fluctuations in high-temperature environments, increasing the false alarm rate.

To detect earlier signs of fire, smoke sensors enhance detection sensitivity through a dual-mode detection mechanism [121]. Ionization sensors use radioactive substances to ionize air and form a stable ion current, detecting smoke particles through changes in current; photoelectric sensors are based on Mie scattering theory, measuring light intensity attenuation caused by smoke particles for detection. Although they can detect particulate matter at the microgram level, they still face non-fire interferences such as steam and dust in practical applications, and their detection sensitivity decreases in well-ventilated open spaces.

Notably, carbon monoxide sensors, as the core device for toxic gas monitoring, specifically identify colorless and odorless CO gas through electrochemical detection or semiconductor gas-sensitive principles [122]. However, limited by cross-sensitivity effects, their detection accuracy is easily affected by other reducing gases, and a regular calibration mechanism is required to maintain long-term reliability [123].

Video Detection Technology

Traditional point or line-based smoke, temperature, and light-sensing fire detectors generally offer early warnings by detecting characteristics like smoke-producing particles or flame temperature. However, these methods have limitations, such as the requirement for temperature and particles to be in close proximity to the sensor for activation, leading to delayed alarms [124,125]. The drawbacks of sensor-based fire detection techniques encompass susceptibility to interference, high false alarm rates, and an inability to detect

certain types of fires [126–132], as detailed in Table 3. In contrast, video-based fire detection technology excels at detecting fires promptly, as it can directly recognize the image features of smoke and fire sources within the monitored area. This technology offers advantages such as a long range, wide protection range, high sensitivity, and a rapid response time.

Table 3. Shortcomings of sensor-based fire detection technology [126–132].

Characteristics	Shortcomings
Space	More suitable for confined space fire detection, difficult to effectively apply to large spaces, such as shopping malls
Distance	Before particles or gases arrive at the sensor used to detect them, the alarm will not start, so the sensor must be close to the fire source. For example, smoke sensors require smoke from the fire source for the sensor's movement time, and gas concentration sensors require more CO release
Information	No details were given on the nature of the fire or its size
Detector	More protection of potential sources requires more sensors to be installed. In addition, the accuracy and speed of fire detection requires a combination of sensors, such as smoke sensors and temperature sensors
Accuracy	There are often false positives. For example, photosensitive sensors can be misled by sunlight and artificial lighting; smoke sensors can be affected by a variety of gases; and temperature sensors can be influenced by their own position, requiring minimal heat to trigger them;
Cost	Many sensors are expensive to use, and complex system configurations add to the budget
Power	The installed sensors require radio sources

The identification of fire characteristics serves as the core foundation of the development of fire detection systems. Its essence lies in efficiently distinguishing between fire and non-fire scenarios through the extraction of multi-dimensional dynamic and static features [133]. With the rapid development of computer performance and video processing algorithms, video-based fire detection techniques have emerged. To effectively detect flames in real time, most traditional flame recognition algorithms use manual features such as color [134], shape [135], texture [134,136], and motion features [137]. For example, Oghabi et al. [138] combined RGB and YCbCr color space analyses to screen candidate flame regions. By quantifying the irregularity of the dynamic boundary, they captured the chaotic characteristics of the early-stage fire, showing high accuracy in early warnings. However, its sensitivity to light changes and the high computational complexity of the Lyapunov exponent limit its universality in the real-time monitoring of complex environments.

With technological advancements, multi-feature fusion models have significantly enhanced detection robustness by integrating parameters such as color difference, similarity, and centroid movement. For instance, Teng Wang et al. [139] developed an expert system that replaced the motion difference method with the HIS color space and modeled flame flickering using high-frequency characteristics in the wavelet domain, thereby achieving a significant reduction in false alarm rates. Nevertheless, these methods remain limited by the assumption of a static background and high computational resource consumption.

Lv et al. [140] proposed a color-and-motion feature fusion model combined with deep learning. Leveraging the powerful feature extraction capabilities of convolutional neural networks, this model can more accurately generate candidate flame shapes. Zhu et al. [141] constructed an extreme learning machine model based on bag-of-words coding through the cross-modal fusion of SIFT features and the HSV color space. Its core contribution lies in embedding the sudden change characteristics of flame color into the feature descriptor

screening process, improving the feature matching accuracy of the traditional SIFT algorithm in flame detection scenarios. However, this method has limited ability to capture the dynamic flickering features of flames and is vulnerable to smoke interference in video stream detection.

The improved Gaussian mixture model developed by Chen et al. [142] enhanced the efficiency of real-time video detection (with a processing speed of up to 24 fps) through cascaded processing of moving foreground separation and color filtering. The LGATP model proposed by Wang et al. [143] combines Gabor multi-scale analysis with the local adaptive threshold ternary pattern (LTP), enabling the more comprehensive acquisition of local flame texture features. Using a weighted kernel sparse representation classification model, it effectively improves the accuracy of flame recognition. However, the proposed algorithm relies solely on feature extraction from original samples to construct a sparse representation dictionary, and its practical deployment requires large-scale cross-scenario sample training, thereby limiting its migration and application ability in industrial scenarios.

In recent years, deep learning technology has opened up new avenues through its end-to-end feature-learning capabilities. CNN models, characterized by their local perception and weight-sharing features, have demonstrated superior performance over traditional methods in tasks such as smoke recognition and flame area classification [144–146]. For instance, Zheng et al. [147] proposed an improved deep convolutional neural network model, namely MDCNN. The proposed MDCNN model achieved a false alarm rate as low as 0.563%, a false positive rate of 12.7%, a false negative rate of 5.3%, a recall rate of 95.4%, and an overall accuracy of 95.8%.

Notably, current technological trends show two major directions. On the one hand, hybrid models based on multi-modal feature fusion (such as the combination of Robust AdaBoost with static and dynamic features [148]) are breaking through the performance bottlenecks of single algorithms. On the other hand, the combination of lightweight deep-learning architectures and edge computing [149,150] is gradually resolving the contradiction between the lack of real-time performance of traditional algorithms and the high resource consumption of deep learning. Future development may focus on building intelligent systems with environmental adaptability and multi-sensor data fusion. In particular, key areas such as dynamic background interference suppression and robustness enhancement under extreme lighting conditions still require breakthroughs, and emerging technologies such as federated learning may provide new ideas for improving the generalization ability of cross-scenario models.

3.1.2. Infrared Thermal Imaging Detection Technology

Fire detection sensors and video detection systems play a crucial role in fire monitoring. However, they share a common limitation: they can only detect fires after they have already ignited. Nevertheless, potential fire hazards still exist. For example, electrical equipment may exhibit abnormally high temperatures before ignition, and rapid temperature changes can serve as a useful indicator of such a state [151].

In addition, infrared thermography (IRT) has emerged as an important and powerful innovation for diagnosing internal and external problems by observing the thermal state of electrical equipment [152]. Assessing and monitoring electrical components is essential for analyzing early thermal failures. Over the past three decades, IRT, as a condition inspection procedure, has achieved sustained development in general structures, electrical facilities, hardware and equipment, material defects under different stacking conditions, corrosion damage, and welding forms [153].

Thermography, as a physiological test, can detect subtle temperature changes in components, thereby indicating anomalies in various components. Generally, common

image processing methods for achieving infrared thermography can be divided into five steps: image pre-processing, segmentation, feature extraction, classification, and decision-making [154].

Joshi et al. [155] integrated infrared thermography, white light, and night vision imaging data and adopted a fusion strategy of ResNet50V2 and InceptionV3 models, achieving a 97% accuracy rate in early pile fire detection. Do et al. [155] proposed a multi-camera thermal infrared fusion strategy that reached a 95% mAP@0.5 in low-visibility human detection, but they did not evaluate the influence of the temperature drift effect on calibration parameters during the long-term operation of thermal infrared cameras. Sun et al. [156] combined a GIoU fusion algorithm of visible and thermal infrared modalities, increasing the F1 score of flame detection to 90.03%. However, the number of parameters and inference latency of the ConvNeXt + PAFPN architecture were not quantitatively disclosed, which may exceed the requirements of fire response timeliness. Moreover, the sample size of the constructed multi-modal flame dataset was limited, making it difficult to cover all fire scenarios in complex environments. Future research needs to focus on data augmentation for extreme environments, compensation algorithms for sensor attenuation, and optimization of edge computing.

3.1.3. Arc Detection Technique

In the context of aircraft electrical fires, analysis reveals that arcing is a primary cause of aircraft malfunctions and crashes. Figure 7 illustrates the progression of an electrical fire initiated by an arcing fault. The carbonization of the insulation layer on the damaged wire precedes intermittent arcing. Progressively, the carbonization path extends, leading to the formation of severe arcs. These arcs are capable of releasing immense energy, reaching temperatures of up to 13,000 K [157].

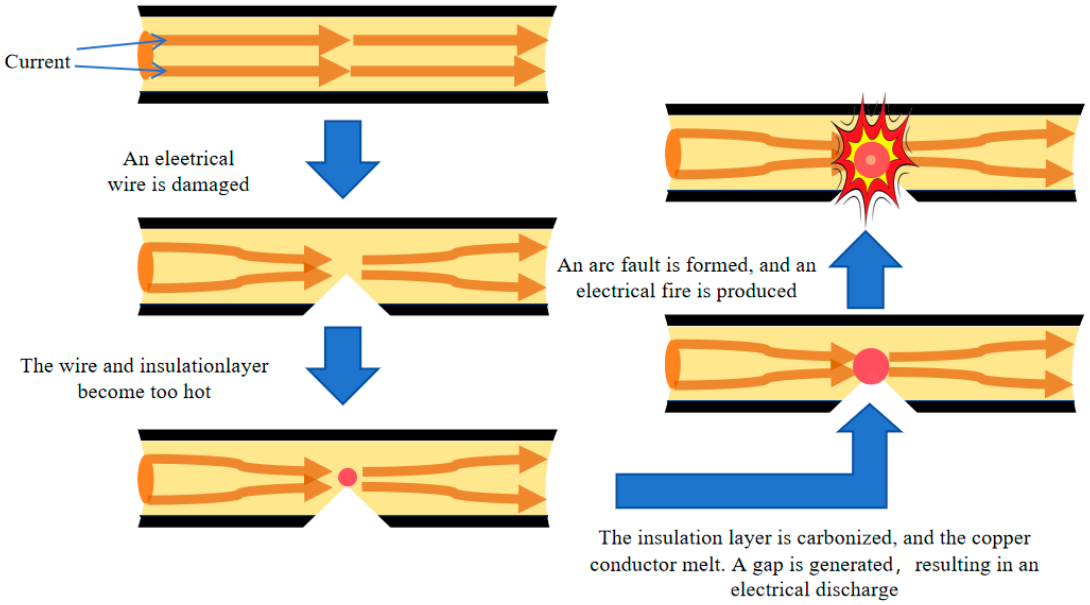


Figure 7. Electrical fire caused by arc fault [158].

Arc faults are a primary cause of electrical fires due to their inherent vulnerability, stochastic behavior, crosstalk, and the extremely high temperatures they generate. These factors significantly increase the likelihood of igniting combustible materials, posing severe fire hazards. Conventional overcurrent protection devices (e.g., circuit breakers, fuses) prove ineffective in detecting arcing faults due to their inability to capture the nonlinear current signatures, driving researchers to explore multidimensional physical signal analysis

(including acoustic emission and high-frequency magnetic field detection) combined with intelligent algorithm development [159,160].

For instance, acoustic emission technology identifies faults by detecting arc-generated ultrasonic waves (20–100 kHz frequency range) [161], yet its susceptibility to ambient noise necessitates complementary filter optimization. High-frequency magnetic detection employs Hall sensors to monitor H-field distortions caused by arcs, enabling discrimination between operational arcs and fault arcs [162], though this method demands high sensor precision (sensitivity threshold of 0.1 mT). Spectral analysis [163,164] utilizes photoelectric sensors to detect characteristic UV-IR spectral signatures (e.g., 206–310 nm UV peaks) from arcs, achieving millisecond-level response times. However, window contamination-induced false positives remain a critical challenge.

Current research focuses on hybrid time-frequency decomposition algorithms. The DWT-EMD-DTW model proposed by Liu et al. [165] exemplifies this approach: wavelet transforms extract arc [159,160] transient features (8–16 kHz high-frequency components), empirical mode decomposition (EMD) resolves intrinsic mode functions (IMFs), and dynamic time warping enables waveform matching, collectively reducing misjudgment rates to 2.3%. While machine learning algorithms demonstrate remarkable advantages in arc detection, several application bottlenecks persist: the 1DCNN model achieves 99.33% accuracy across nine unknown loads through high-frequency RLC feature extraction [166], yet requires extensive training data and suffers from feature drift caused by dynamic arc resistance. Comparatively, sparse representation algorithms attain 94.3% accuracy in identifying dual states (resistive, inductive, capacitive, switching) across various load types [167].

Notably, standardization and widespread adoption of arc detection technologies face dual challenges [168]: establishing unified arc signature databases and testing benchmarks to mitigate the "high laboratory accuracy vs. low field reliability" paradox, while balancing hardware costs and detection efficacy through strategies like embedding edge computing modules in existing power distribution equipment [169]. Furthermore, proactive prevention systems should integrate material science innovations (e.g., carbonization-resistant insulation) with IoT-enabled real-time monitoring and lifespan prediction, ultimately constructing a coordinated "material–equipment-system" fire prevention ecosystem.

3.1.4. Optical Fiber Detection Technology

Distributed temperature sensing (DTS) is a distributed temperature monitoring technology based on the Raman scattering effect and the principle of optical time-domain reflectometry [170]. When a light pulse propagates through the optical fiber, it interacts with the fiber molecules to produce Raman scattered light. The intensity ratio of Stokes light to anti-Stokes light is functionally related to the temperature surrounding the fiber. By measuring the time-of-flight of the returning Raman scattered light, the location of temperature events can be determined, enabling distributed temperature measurement along the fiber.

DTS technology is characterized by high precision and high resolution, capable of accurately measuring minute temperature differences with a spatial resolution as fine as centimeters. It can pinpoint temperature change locations and achieve continuous distributed temperature monitoring over distances of tens of kilometers. Additionally, the optical fiber material is electrically insulating, corrosion-resistant, and immune to electromagnetic interference, ensuring stable operation in harsh environments and hazardous areas such as flammable and explosive zones. DTS technology is suited for diverse complex environments and long-distance monitoring scenarios, such as power cables [171], oil wells [172], and transportation tunnels [173]. It effectively meets the demand for dis-

tributed temperature monitoring in these scenarios and enables timely detection of potential fire hazards.

Cables are typically installed in complex environments such as underground conduits, tunnels, and cable trays, where they are exposed to electromagnetic interference, humidity, and corrosive conditions. These factors place high demands on the stability and reliability of detection equipment. In the early stages of a cable fire, temperature changes may be subtle, but they can escalate rapidly. This requires detection systems to have high precision and rapid response capabilities. Given the long distances of cable routes, quickly and accurately locating the source of a fire is crucial for timely extinguishment and fire control. Traditional fire detectors, such as smoke detectors, struggle to respond promptly when smoke is not readily visible in the early stages of a fire. Heat-sensing cables have limited detection ranges, are susceptible to electromagnetic interference, and lack high positioning accuracy. Although fiber Bragg grating sensors offer high precision and resistance to interference, they are point-based measurement devices that can only provide temperature information at limited discrete points, and thus cannot achieve continuous distributed monitoring along the cable route.

The electromagnetic interference resistance and corrosion resistance of DTS systems enable stable operation in the harsh environments where cables are installed, free from environmental constraints. With its high precision and high resolution, DTS can sensitively detect subtle temperature changes in cables and track temperature trends in real time, providing strong support for early fire warning. Based on the principle of optical time-domain reflectometry, DTS can quickly pinpoint the exact locations of temperature anomalies, providing precise guidance for firefighting actions and effectively addressing the challenge of locating cable fires. Compared with traditional fire detectors and fiber Bragg grating sensors, DTS achieves long-distance, distributed, and high-precision temperature monitoring, with a broader coverage area and more comprehensive and accurate monitoring data. DTS systems can continuously and dynamically obtain temperature information along the cable route in real time and track the location and changes in the fire source, providing more timely and effective data support for fire prevention and control.

3.1.5. Exploration Technology Selection

By analyzing the above various fire detection techniques, Table 4 summarizes the above electrical fire detection techniques.

Based on the contents of Table 4 and the analysis of different electrical fires in Chapter 2, it is evident that the characteristics and environmental conditions of electrical fires vary significantly across different scenarios, necessitating the precise selection of detection technologies.

For cable fires, given the complex working environment, fiber optic detection technology stands out as the ideal choice. It offers long-distance, high-precision distributed monitoring, enabling precise fire location identification. In contrast, for electrical cabinet fires, submarine electrical fires, surface vessel electrical fires, and aircraft electrical fires, where spaces are cramped and wiring dense, arc detection technology proves more effective. It can swiftly detect potential issues with its timeliness and accuracy.

As for transformer fires, data center fires, and household fires, their diverse environments allow for flexible selection or the combination of multiple detection technologies. For instance, in data centers with complex internal structures, sensor detection technology and fiber optic detection technology can be used together for comprehensive fire hazard monitoring. For transformers, infrared thermal imaging detection technology can capture temperature anomalies in real time for effective monitoring.

Table 4. Fire detection technology comparison [119–173].

Technical Type	Technical Characteristics	Advantages	Limitations
Traditional Sensor Detection Technology	Multi-dimensional perception of physical and chemical parameter changes during a fire	Early warning and real-time monitoring	Obvious limitations, such as the single temperature parameter's inability to identify the type of burning material
Video Detection Technology	Direct identification of smoke and fire source image features within the monitored area	Long detection range, wide protection area, high sensitivity, and fast response speed	Need to consider adaptability to complex environments, such as light changes and smoke obscuration
Infrared Thermal Imaging Detection Technology	Observes the thermal state of electrical equipment and detects subtle temperature changes in components	Early fire warning, suitable for various complex environments and long-distance monitoring	Image processing methods need optimization
Arc Detection Technology	Multi-dimensional physical signal analysis and intelligent algorithm identification of arc faults	Identifies arc faults	Need to balance computational complexity and hardware costs
Optical Fiber Detection Technology	Based on the Raman scattering effect and optical time-domain reflectometry principle for distributed measurement	High precision and resolution, suitable for long distances and complex environments	Unable to achieve continuous distributed monitoring

In residential fire monitoring, compared with fires in industrial environments or other large-scale settings, the domestic environment offers distinct advantages. Residential fires typically occur in relatively calm and confined spaces, with fewer external interferences affecting sensors. These environmental characteristics enable smoke sensors to swiftly detect smoke particles in the early stages of a fire, thereby triggering alarms in a timely manner. Consequently, smoke sensors exhibit high reliability and effectiveness in residential fire monitoring.

In battery fire monitoring, temperature sensors, smoke sensors, and carbon monoxide (CO) sensors have a certain applicability. Temperature sensors can promptly capture the temperature increase during battery thermal runaway, but single-temperature monitoring is limited in distinguishing the causes of temperature changes. Smoke sensors can trigger alarms by detecting smoke concentration, but the unique chemical components produced by battery fires may affect their sensitivity and accuracy. Moreover, in well-ventilated environments, smoke dispersion can reduce detection effectiveness. CO sensors can detect flammable gases produced during battery thermal runaway, but their detection accuracy is susceptible to interference from other reducing gases, and they require regular calibration to maintain reliability. To enhance the accuracy and reliability of battery fire monitoring, a multi-sensor collaborative monitoring approach is typically required. This involves integrating data from various sensors, including temperature, smoke, and CO sensors, and conducting comprehensive analysis using data fusion algorithms to enable early warning and achieve the precise location of battery fires.

This context-sensitive and flexible approach to detection technology selection maximizes the strengths of each technology, ensuring early fire detection and prompt response.

3.2. Electrical Fire Extinguishing

Electrical fires are defined as fires involving energized electrical equipment. Currently, electrical fires are classified as Class C fires according to the NFPA standard in the United States [174], and as Class E fires in China [175].

3.2.1. Electrical Fire Extinguishing Agent

Foam fire suppression agents extinguish fires by forming a foam layer that isolates air and cools combustibles: aqueous film-forming foam (AFFF) forms a film of water on the surface of combustible materials to block oxygen. By adding inorganic particles, surfactants, it is possible to effectively regulate its electrical conductivity, making it suitable for electrical fires [176]. The development of AFFF represents a significant advancement in foam extinguishing technology, expanding its applicability to electrical fires. In addition, high-expansion foam technology is used in specialized scenarios. For example, in ship cabin fires, high-expansion foam rapidly fills the space and reduces the oxygen concentration, effectively suppressing the fire [177]. Nevertheless, post-fire cleanup and equipment recovery challenges must be considered when selecting foam agents, requiring a balance between suppression efficacy and equipment protection. Practical applications should tailor foam agent selection based on fire scenarios and equipment characteristics.

Dry powder fire suppression technology is widely used in electrical fires due to its high efficiency and rapid response. The primary components of dry powder agents, such as sodium bicarbonate and ammonium phosphate, chemically inhibit combustion reactions to achieve rapid extinguishment [178]. The suppression mechanism combines chemical inhibition, oxygen isolation through flame coverage, and temperature reduction via endothermic reactions. These synergistic effects enable dry powder agents to control and extinguish fires swiftly. Another notable advantage of dry powder agents is their excellent insulation properties, making them particularly suitable for electrical fires without secondary damage from electrical conductivity. Furthermore, their broad applicability covers not only electrical fires (Class E), but also solid, liquid, and gas fires, establishing them as versatile suppression materials. However, dry powder agents have limitations. For instance, residual powder may physically contaminate precision electrical equipment, complicating post-fire recovery. Additionally, large-scale fire suppression may require substantial quantities of powder, increasing costs and environmental burdens [179]. Recent advancements focus on optimizing formulations and application techniques to minimize contamination and environmental impact [180]. For example, eco-friendly dry powder agents are under development to enhance suppression efficiency while reducing ecological footprints. These improvements enhance both performance and safety in electrical fire applications. In Table 5, we have summarized the experimental conditions, fire extinguishing effects, and the advantages and disadvantages of each of the abovementioned extinguishing agents.

Dry powder fire suppression technology is widely used in electrical fires due to its high efficiency and rapid response. The primary components of dry powder agents, such as sodium bicarbonate and ammonium phosphate, chemically inhibit combustion reactions to achieve rapid extinguishment [178]. The suppression mechanism combines chemical inhibition, oxygen isolation through flame coverage, and temperature reduction via endothermic reactions. These synergistic effects enable dry powder agents to control and extinguish fires swiftly. Another notable advantage of dry powder agents is their excellent insulation properties, making them particularly suitable for electrical fires without secondary damage from electrical conductivity. Furthermore, their broad applicability covers not only electrical fires (Class E), but also solid, liquid, and gas fires, establishing them as versatile suppression materials. However, dry powder agents have limitations. For instance, residual powder may physically contaminate precision electrical

equipment, complicating post-fire recovery. Additionally, large-scale fire suppression may require substantial quantities of powder, increasing costs and environmental burdens [179]. Recent advancements focus on optimizing formulations and application techniques to minimize contamination and environmental impact [178]. For example, eco-friendly dry powder agents are under development to enhance suppression efficiency while reducing ecological footprints.

Despite the advantages of dry powder agents, the unique challenges posed by lithium-ion battery fires necessitate the exploration of novel technologies. Microencapsulated fire suppression is an emerging technology that shows promise, particularly for battery fires such as those involving lithium-ion batteries. Accelerating rate calorimetry (ARC) analysis of lithium-ion battery packs revealed that the substantial exothermic heat generated by the decomposition of electrolytes and active materials intensifies thermal runaway [181–183], leading to violent combustion reactions. Yim et al. [184] proposed an innovative strategy by incorporating temperature-responsive microcapsules filled with fire suppressants into lithium-ion batteries. This approach prevents temperature escalation, mitigates undesired thermal runaway, and significantly enhances safety. Integrating fire extinguishing materials with battery structures achieves a proactive preventive effect. Future research could focus on optimizing microcapsule performance, such as improving temperature response accuracy and suppressant release efficiency, to better address lithium battery fires.

With the expanding range of battery-based electric energy applications, electrical fire accidents related to lithium-ion batteries continue to occur, despite extensive research on the principles and safety applications of batteries, particularly lithium-ion batteries [185–188]. Consequently, the quest for ideal extinguishing agents for lithium-ion battery fires has emerged as an effective approach to mitigate the spread of electrical fires. The National Technical Information Service (NTIS) assessed the flammability of lithium-ion batteries [189] and performed fire extinguishing tests to examine the suppression of battery flames using various halon products, such as Halon 1301 and 1211.

Water-based extinguishing agents are extensively utilized for fire suppression, yet their efficacy in electrical fires remains a subject of debate. The FAA [190] examined the extinguishing efficiency of various extinguishing agents on fires in 18,650 LIBs under heat release conditions, and the findings indicated that water-based extinguishing agents, such as water, AF-21, AF-31, and Aqueous A-B-D, were more effective in cooling than non-water-based agents and hindered the spread of flames. The NFPA [191] issued a technical report on the use of water-based extinguishing agents for electric vehicle battery fires, indicating that continuous extinguishing required at least 6 min. It has been demonstrated [192] that pouring water on a lithium-ion battery fire can extinguish the flames. However, since the reduction of lithium ions in water releases hydrogen gas, this may revive the fire and make it more difficult to extinguish. Research from the National Renewable Energy Laboratory has shown [190] that the only effective means of extinguishing lithium-ion battery fires are Class D fire extinguishers, dry sand, or dry table salt.

Xu et al. [193] examined the suppression effects of three extinguishing agents—CO_2, sevoflurane, and water mist—on lithium-ion battery fires. As shown in Figure 8, fine water mist exhibited superior cooling effects compared to CO_2 and sevoflurane. Wang et al. [194,195] designed and established an experimental system to conduct fire suppression tests, investigating the suppression effects of dodecafluoro-2-methylpentan-3-one (C6F-ketone) and sevoflurane extinguishing agents on lithium battery fires. The results demonstrated that C6F-ketone was the most effective, being capable of extinguishing lithium-ion battery fires within thirty seconds.

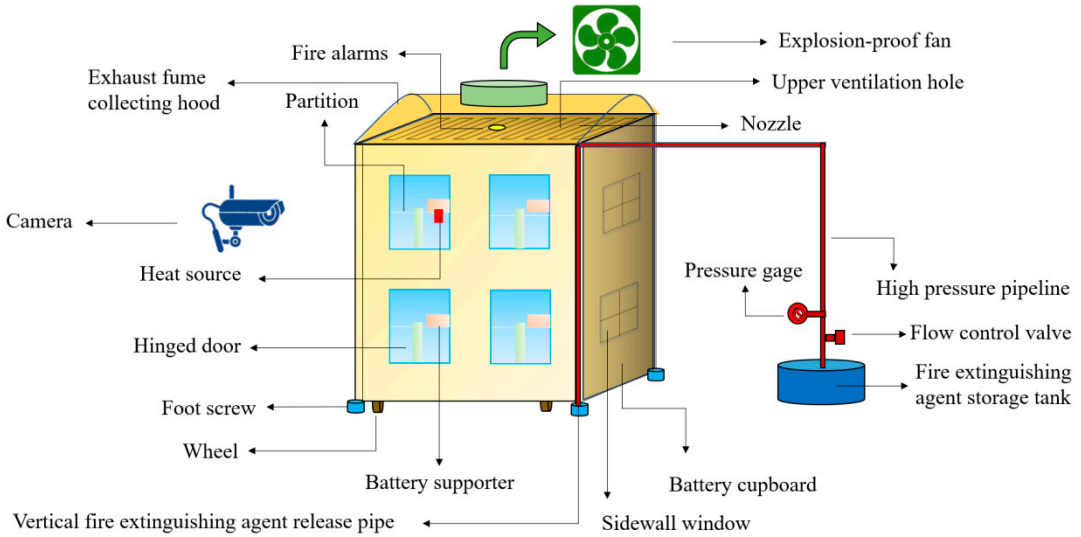


Figure 8. Experimental apparatus for fire extinguishing test [194].

C6F-ketone is regarded as a next-generation alternative to Halon extinguishing agents. It boasts excellent suppression properties and an exemplary environmental profile. C6F-ketone has zero ozone depletion potential (ODP), zero global warming potential (GWP), an atmospheric lifetime of 5 days, and is highly safe for occupied spaces. The cf-ketone extinguishing agent is based on a single substance which is considered to be an ideal extinguishing agent for lithium-ion battery fires, and is capable of extinguishing fires within 30 s. Its properties are detailed in Table 5.

With its boiling point of 49.2 C and vaporization heat of 88.0 kJ/kg, it can quickly vaporize and absorb a large amount of heat to achieve efficient fire extinguishing. The liquid specific heat capacity is 0.891 kJ/kg K and the gaseous specific heat capacity is 1.103 kJ/kg K, which make the temperature change less when absorbing heat and enhance the fire extinguishing effect. The critical temperature is 168.7 C and the critical pressure 18.65 bar, indicating that it is stable at room temperature. C6F-ketone fire extinguishing agent is suitable for various fire types. It is equipped with an intelligent control system which can automatically detect fire and start fire extinguishing in time and improve the fire extinguishing efficiency. Therefore, the C6F-ketone fire extinguishing agent is an ideal choice for high efficiency, environmental protection, and safe and wide applications.

Table 5. Properties of C6F-ketone [196].

Properties	C_6F-ketone
Chemical formula	$CF_3CF_2C(O)CF(CF_3)_2$
Molecular weight	316.04
Boiling point at 1 atm (°C)	49.2
Freezing point (°C)	−108.0
Critical temperature (°C)	168.7
Critical pressure (bar)	18.65
Critical volume (cc/mole)	494.5
Critical density (kg/m^3)	639.1
Density, sat. liquid (g/mL)	1.60
Density, gas at 1 atm (g/mL)	0.0136
Specific volume, gas at 1 atm (g/mL)	0.0733
Specific heat, vapor at 1 atm (kJ/kg·K)	1.103
Specific heat, liquid (kJ/kg·K)	0.891
Heat of vaporization at boiling point (kJ/kg)	88.0
Relative dielectric strength, 1 atm (N_2 = 1.0)	2.3

We systematically summarize the experimental conditions, fire extinguishing effects, and their advantages and disadvantages of the abovementioned extinguishing agents in Table 6, to allow readers to select suitable extinguishing agents more scientifically.

Table 6. Comparison of fire suppression agents [176–196].

Fire Suppression Agent	Experimental Conditions	Extinguishing Effects	Advantages/Disadvantages	Service Restrictions
Water Mist	Spray time: 5–10 min; Droplet size: <1000 μm	Effective cooling, but may not fully suppress lithium-ion battery reignition	Pros: Widely available, low cost; Cons: High conductivity, potential damage to electrical equipment	Suitable for non-conductive environments, not suitable for high-density electrical equipment locations, may cause equipment damage
CO_2	Spray time: 1–2 min; Concentration: 30–40%	Rapid extinguishing, but limited cooling effect; may not prevent reignition	Pros: Non-conductive, suitable for electrical equipment; Cons: High environmental impact, potential health hazards	Suitable for use in high-density electrical equipment locations, not suitable for use in enclosed or poorly ventilated environments as this may result in health hazards
C_6F-ketone	Spray time: 30 s; Concentration: 5–7%; Ambient	Rapid extinguishing, effective suppression of reignition, significant cooling effect	Pros: Non-conductive, environmentally friendly (ODP = 0, GWP = 1); Cons: High cost	Suitable for lithium battery fires, but the cost is high
Dry Powder	Spray time: 1–3 min; Concentration: 10–15%	Significant extinguishing effect, but limited cooling; may not prevent reignition	Pros: Suitable for multiple fire types; Cons: Potential damage to electrical equipment, difficult to clean up	Suitable for a wide range of electrical fires, not suitable for use in places with delicate electrical equipment as this may result in damage to the equipment
Aqueous Film-Forming Foam (AFFF)	Spray time: 2–5 min; Concentration: 5–10%	Effective cooling and isolation of oxygen, mainly used to extinguish liquid fires	Pros: Highly efficient fire suppression; good burnback resistance; Cons: May leave residue, requires cleanup	Suitable for use in non-conductive environments, not suitable for use in high-density electrical equipment locations where residues may be left behind

3.2.2. Electrical Fire Extinguishing Technology

In the prevention and protection of electrical fires, water mist fire extinguishing technology is regarded as an effective firefighting measure. The NFPA 750 standard stipulates that the diameter of water droplets in water mist does not exceed 1000 μm [197].

Research has shown that the fire extinguishing efficiency of water mist is significantly higher than that of traditional water spraying systems [198–202]. Due to the small diameter and large specific surface area of water droplets, water mist can absorb heat and evaporate more quickly, thereby reducing the temperature and oxygen concentration at the fire scene more effectively. In addition, the water vapor formed during its evaporation can also isolate air and dilute combustible gases, which is the key to its high fire extinguishing efficiency.

Water mist systems have been widely applied in electrical rooms, indoor spaces [203,204], and outdoor locations, including preventing wildfires near transmission lines. The full-scale experiments by Hills [205] and Mawhinney [206] showed that electrical equipment treated with water mist could operate normally, verifying the safety of water mist in electrical fires. This fully demonstrates the applicability and reliability of water mist fire-extinguishing technology in different scenarios. However, these studies mainly evaluated the feasibility of extinguishing low-voltage electrical fires. Subsequently, Liu et al. [207] quantified the leakage current of water mist under 50 kV. However, due to the insufficient test voltage, they did not investigate the breakdown performance of water mist. Additives can improve the fire extinguishing efficiency of water mist. Their main components include alkali metal salts [208–210], surfactants [211–213], and multi-component formulations [188,214]. Different additives improve the fire extinguishing effect by changing the physical and chemical properties of water mist [215–223]. Alkali metal salts may participate in the combustion reaction and inhibit the transmission of the combustion chain, while surfactants can reduce surface tension and enable water mist to adhere better to the surface of the combustible. Lu et al. [224] evaluated the fire extinguishing performance of water mist with and without additives for high-voltage transformer fires. The test results are shown in Figure 9. The results indicate that water mist with an appropriate safety margin can protect high-voltage electrical equipment. Both natural water mist and mist with non-ionic water mist additive (WMA) are viable options for such protection. This provides a practical solution for the fire protection of high-voltage electrical equipment and further expands the application scope of water mist fire extinguishing technology.

3.2.3. Selection of Fire Fighting Technology

In addressing electrical fires, the precise selection of fire extinguishing agents and techniques is of critical importance. The types of fires, environmental characteristics, and equipment sensitivity vary across different scenarios, necessitating comprehensive consideration and rational allocation of firefighting plans.

Carbon dioxide extinguishing agents are suitable for environments with high-density electrical equipment, such as electrical cabinets, data centers, submarines, surface vessels, and aircraft. They protect electronic devices from damage and effectively safeguard precision instruments. However, they are not suitable for enclosed or poorly ventilated environments due to potential risks to human health. When the fire is intense, they can be combined with foam or dry chemical extinguishing agents to enhance firefighting effectiveness.

In the context of battery fires, traditional water mist extinguishing agents have proven to be ineffective. In contrast, C6F-ketone extinguishing agents and microencapsulation firefighting technologies have demonstrated significant effectiveness in extinguishing such fires.

For transformer fires, residential fires, and cable fires, the environments are complex and require firefighting plans tailored to specific scenarios. Transformer fires, typically caused by internal faults, can be effectively mitigated by dry chemical and foam extinguishing agents that rapidly interrupt the combustion process; residential fires can be controlled by installing fine water mist firefighting systems and selecting appropriate extinguishing

agents to prevent fire spread; cable fires require a comprehensive assessment of factors such as the fire scene, cable type, and surrounding environment. Fine water mist firefighting technology, foam extinguishing agents, and dry chemical extinguishing agents can be used individually or in combination to achieve optimal firefighting effectiveness.



(a) Before spraying

(b) Spraying for 45s

Figure 9. Water mist is discharged onto a 220 kV HV transformer with a size of 10.12 × 7.9 × 7.8 m. The transformer is protected by 60 nozzles with a flow rate of 15 L/min per nozzle [224].

In summary, by considering factors such as fire type, environmental characteristics, and equipment sensitivity, and weighing costs against effectiveness, the rational allocation of firefighting technologies can build an efficient and reliable protection system to minimize fire risks and losses.

4. Research Gaps and Prospects for Electrical Fire Prevention and Control

In the realm of electrical fire prevention and control, despite the advancements made in recent years, numerous limitations and challenges persist. Current research often focuses on specific types of electrical fires and lacks a comprehensive understanding of various fire scenarios. Moreover, most studies depend on laboratory settings, which may not accurately reflect the complex conditions of the real world. Concurrently, there are notable deficiencies in data collection, particularly the absence of longitudinal data, which is essential for tracking long-term trends in electrical fire incidents and devising effective predictive models and mitigation strategies. With the swift advancement of technology and

the introduction of new materials and systems, research on their fire safety characteristics has lagged behind, leading to significant knowledge gaps in the field.

To address these research gaps, future research should focus on developing environmentally friendly and efficient fire extinguishing agents that can meet the demands of high efficiency, safety, and environmental protection in various scenarios, particularly for lithium battery fires; integrating the Internet of Things, big data, and artificial intelligence to enhance the intelligence and accuracy of fire detection systems; improving fire detection technologies to enhance their precision and response speed; and refining fire databases by collecting and analyzing more fire case data to optimize fire risk assessment models and integrate more data sources and factors to improve the accuracy of assessments.

5. Conclusions

In this review, we explored the multifaceted nature of electrical fires, examining their classifications, causes, and high-risk scenarios encountered in specific environments. These scenarios include cable fires, electrical cabinet fires, substation fires, battery fires, data center fires, residential fires, and fires in special environments such as submarines, surface ships, and aircraft. Each scenario presents unique challenges, demanding specialized knowledge to devise effective risk mitigation and incident response strategies.

This paper reviewed established methods and recent advances in electrical fire prevention and control research, emphasizing the critical importance of addressing electrical fires in an increasingly electricity-reliant society. Electrical fires typically originate from circuit faults, infrastructure aging, operational errors, or environmental factors, which can lead to rapid fire spread, massive release of toxic smoke and gases, and explosions. Despite ongoing improvements in fire safety measures for electrical systems and equipment, completely eradicating electrical fires remains a significant challenge.

The paper explored multi-scale approaches for cable fire research, including laboratory-scale and full-scale fire tests, as well as cable fire behavior simulations. It analyzed various classifications and standards for evaluating cable fire faults, with a particular focus on the high-risk nature of electrical fires in specialized environments such as submarines, ships, and aircraft, where limited space and rescue capabilities complicate fire control.

The study highlighted the pivotal role of research and application of electrical fire prevention and control technologies in safeguarding human lives and property. It stressed the need for ongoing technological advancements to address these challenges effectively.

Author Contributions: Conceptualization, G.L.; methodology, J.G.; software, Y.K.; validation, Q.H.; formal analysis, G.L.; investigation, C.L.; resources, J.Z.; data curation, G.L.; writing—original draft preparation, J.G.; writing—review and editing, Q.H.; visualization, Y.K.; supervision, C.L.; project administration, C.L.; funding acquisition, J.Z. All authors have read and agreed to the published version of the manuscript.

Funding: This study has been sponsored by the Open Project of Tianjin Key Laboratory of Fire Safety Technology (No. 2023TKLFST02), the National Natural Science Foundation of China (52304264, 12202410 and 12472370), Fundamental Research Funds for the Central Universities (No. WK2320000064). The project was funded by China Postdoctoral Science Foundation (2022M723016, 2023T160734 and 2023M733935), the Natural Science Foundation of Hunan Province (2023JJ40726), the Changsha Municipal Natural Science Foundation (kq2208277), Research Project Supported by Shanxi Scholarship Council of China (2022-139), and was supported by Fundamental Research Program of Shanxi Province (202303021211145), the Opening Foundation of Key Laboratory in North University of China (DXMBJJ2023-03 and DXMBJJ2024-08), and the Graduate Innovation Project of Shanxi Province (2024KY622).

Acknowledgments: The authors thank Wei Yue from Shiyanjia Lab (https://www.shiyanjia.com) for the DSC analysis.

Conflicts of Interest: The authors declare no conflicts of interest.

Abbreviations

ITER	International Thermonuclear Experimental Reactor
NPP	Nuclear power plant
CERN	European Organization for Nuclear Research
PM	Permanent magnet
SSPCs	Solid-state power controllers
USNSC	U.S. Navy Safety Center
TWA	Trans World Airlines
NTSB	National Transportation Safety Board
AAIB	Air Accidents Investigation Branch
BFU	Bundesamt für Flugunfalluntersuchung
CIGRE	International Conference on Large Electricity Grids
IEEE	Institute of Electrical and Electronics Engineers
NFPA	National Fire Protection Association
AFFF	Aqueous film-forming foam
IT	Insulation transformer
NREL	National Renewable Energy Laboratory
FAA	Federal Aviation Administration
DO-160	Environmental Conditions and Test Procedures for Airborne Equipment
WMA	Water mist additive
DTS	Distributed temperature sensing
Raman	Raman scattering
OTDR	Optical time-domain reflectometry
ARC	Accelerating rate calorimetry
CO_2	Carbon dioxide
C_6F-ketone	Dodecafluoro-2-methylpentan-3-one
WMA	Water mist additives
CO	Carbon monoxide
CH_4	Methane
H_2	Hydrogen
HF	Hydrogen fluoride
Novec 1230	Dodecafluoro-2-methylpentan-3-one
DTS	Distributed temperature sensing
EPA	Environmental Protection Agency
MIL-STD	Military standard
ARINC	Aeronautical radio, incorporated
RTCA	Radio Technical Commission for Aeronautics
ARL	Aerospace research laboratory

References

1. National Fire and Rescue Administration. National Fire and Rescue Administration Held a Press Conference on the National Fire Safety Situation from January to August This Year [EB/OL]. Available online: http://www.china.com.cn/app/template/amucsite/web/webLive.html#3697 (accessed on 4 December 2024).
2. Zhang, Y. Design and Implementation of Fire Safety Assessment and Early Warning System for High Rise Buildings. In *Smart Infrastructures in the IoT Era*; Al-Turjman, F., Ed.; Springer Nature: Cham, Switzerland, 2025; pp. 245–257. [CrossRef]
3. Shelby Hall. Fire Loss in the United States [EB/OL]. Available online: https://www.nfpa.org/education-and-research/research/nfpa-research/fire-statistical-reports/fire-loss-in-the-united-states?os=httpswww.google.com&ref=app (accessed on 4 December 2024).
4. Jia, F.; Patel, M.K.; Galea, E.R.; Grandison, A.; Ewer, J. CFD fire simulation of the Swissair flight 111 in-flight fire—Part 1: Prediction of the pre-fire air flow within the cockpit and surrounding areas. *Aeronaut. J.* **2006**, *110*, 41–52. [CrossRef]

5. Huang, W.; Zhou, C.; Wang, X.Q. Fire Statistic and Prevention Measures for Cables in Power Plant. *Adv. Mater. Res.* **2013**, *614–615*, 1949–1952. [CrossRef]
6. Keski-Rahkonen, O.; Mangs, J. Electrical ignition sources in nuclear power plants: Statistical, modelling and experimental studies. *Nucl. Eng. Des.* **2002**, *213*, 209–221. [CrossRef]
7. Mcgrattan, K.B.; Dreisbach, J. (Eds.) *Cable Response to Live Fire (CAROLFIRE) Volume 3: Thermally-Induced Electrical Failure (THIEF) Model*; Office of Nuclear Regulatory Research: Rockville, MD, USA, 2008. [CrossRef]
8. Hirschler, M.M. Survey of fire testing of electrical cables. *Fire Mater.* **1992**, *16*, 107–118. [CrossRef]
9. *BS EN 50399:2022*; Common Test Methods for Cables Under Fire Conditions. British Standards Institution: London, UK, 2022.
10. Magalie, C.; Anne-Sophie, C.; Rodolphe, S.; Laurent, F.; Emmanuelle, G.; Christian, L. Fire behaviour of electrical cables in cone calorimeter: Influence of cables structure and layout. *Fire Saf. J.* **2018**, *99*, 12–21. [CrossRef]
11. Huang, X.; Nakamura, Y. A Review of Fundamental Combustion Phenomena in Wire Fires. *Fire Technol.* **2020**, *56*, 315–360. [CrossRef]
12. Grigorieva, M.M.; Ivanova, E.V.; Strizhak, P.A. Forecasting investigation of mode fire hazard of electrical overload of cable lines. *EPJ Web Conf.* **2015**, *82*, 1031. [CrossRef]
13. Sarazin, J.; Bachelet, P.; Bourbigot, S. Fire behavior of simulated low voltage intumescent cables with and without electric current. *J. Fire Sci.* **2017**, *35*, 179–194. Available online: https://journals.sagepub.com/doi/abs/10.1177/0734904117698843 (accessed on 4 December 2024). [CrossRef]
14. Hirschler, M.M. Flame retardants and heat release: Review of traditional studies on products and on groups of polymers. *Fire Mater.* **2015**, *39*, 207–231. [CrossRef]
15. Zhang, B.-S.; Zhang, J.-Q.; Li, Q.; Wang, L.-F.; Xie, H.; Fan, M.-H. Effects of Insulating Material Ageing on Ignition Time and Heat Release Rate of the Flame Retardant Cables. *Procedia Eng.* **2018**, *211*, 972–978. [CrossRef]
16. Martinka, J.; Rantuch, P.; Sulová, J.; Martinka, F. Assessing the fire risk of electrical cables using a cone calorimeter. *J. Therm. Anal. Calorim.* **2019**, *135*, 3069–3083. [CrossRef]
17. Polanský, R.; Polanská, M. Testing of the fire-proof functionality of cable insulation under fire conditions via insulation resistance measurements. *Eng. Fail. Anal.* **2015**, *57*, 334–349. [CrossRef]
18. Courty, L.; Garo, J. External heating of electrical cables and auto-ignition investigation. *J. Hazard. Mater.* **2017**, *321*, 528–536. [CrossRef]
19. McGrattan, K.B.; Lock, A.J.; Marsh, N.D.; Nyden, M.R. (Eds.) *Cable Heat Release, Ignition, and Spread in Tray Installations During Fire (CHRISTIFIRE): Phase 1—Horizontal Trays*; Contractor Report; NUREG/CR-7010; Office of Nuclear Regulatory Research: Rockville, MD, USA, 2012.
20. Mcgrattan, K.; Bareham, S. (Eds.) *Cable Heat Release, Ignition, and Spread in Tray Installations During Fire (CHRISTIFIRE) Phase 2: Vertical Shafts and Corridors*; NUREG/CR-7010; Office of Nuclear Regulatory Research: Rockville, MD, USA, 2013; Volume 2.
21. Huang, X.; Wang, Y.; Ren, Z.; Li, Z.; Cheng, C.; Chow, W. Experimental investigation on maximum ceiling jet temperature generated by a vertically spreading cable fire. *Fire Saf. J.* **2021**, *120*, 103125. [CrossRef]
22. Passalacqua, R.; Cortes, P.; Taylor, N.; Beltran, D.; Zavaleta, P.; Charbaut, S. Experimental characterisation of ITER electric cables in postulated fire scenarios. *Fusion Eng. Des.* **2013**, *88*, 2650–2654. [CrossRef]
23. Huang, X.; Ren, Z.; Zhu, H.; Peng, L.; Cheng, C.; Chow, W. A modified zone model on vertical cable tray fire in a confined compartment in the nuclear power plant. *J. Fire Sci.* **2018**, *36*, 472–493. [CrossRef]
24. Yang, Y.-C.; Li, Q.; Zhang, J.-Q.; Fan, M.-H. The Study of the Cable Failure Criteria Used in Fire PSA. *Procedia Eng.* **2016**, *135*, 510–514. [CrossRef]
25. Avidor, E.; Joglar-Billoch, F.J.; Mowrer, F.W.; Modarres, M. Hazard Assessment of Fire in Electrical Cabinets. *Nucl. Technol.* **2003**, *144*, 337–357. [CrossRef]
26. Coutin, M.; Plumecocq, W.; Zavaleta, P.; Audouin, L. Characterisation of open-door electrical cabinet fires in compartments. *Nucl. Eng. Des.* **2015**, *286*, 104–115. [CrossRef]
27. Woodward, R. (Ed.) *The Organisation for Economic Co-Operation and Development (OECD)*, 1st ed.; Taylor & Francis: London, UK, 2009. [CrossRef]
28. Chavez, J.M. *An Experimental Investigation of Internally Ignited Fires in Nuclear Power Plant Control Cabinets: Part 1: Cabinet Effects Tests*; No. NUREG/CR-4527-1; SAND-86-0336; Sandia National Labs.: Albuquerque, NM, USA; Nuclear Regulatory Commission: Washington, DC, USA, 1987.
29. Chavez, J.M.; Nowlen, S.P. *An Experimental Investigation of Internally Ignited Fires in Nuclear Power Plant Control Cabinets: Part 2, Room Effects Tests*; No. NUREG/CR-4527-Vol. 2; SAND-86-0336-Vol. 2; Sandia National Labs.: Albuquerque, NM, USA; Nuclear Regulatory Commission: Washington, DC, USA, 1988.
30. Mangs, J.; Keski-Rahkonen, O. *Full Scale Fire Experiments on Electronic Cabinets*; Technical Research Centre of Finland: Espoo, Finland, 1996.

31. Mangs, J.; Paananen, J.; Keski-Rahkonen, O. Calorimetric fire experiments on electronic cabinets. *Fire Saf. J.* **2003**, *38*, 165–186. [CrossRef]
32. Plumecocq, W.; Coutin, M.; Melis, S.; Rigollet, L. Characterization of closed-doors electrical cabinet fires in compartments. *Fire Saf. J.* **2011**, *46*, 243–253. [CrossRef]
33. Bruynooghe, C.; Noël, M. European clearinghouse: Contributing factors to incidents related to reactivity management. *Prog. Nucl. Energy* **2010**, *52*, 523–526. [CrossRef]
34. Perović, D.; Van Hees, P.; Madsen, D.; Malmborg, V.; Gren, L.; Pagels, J.; Rios, O.; La Mendola, S. Identification and characterization of design fires and particle emissions to be used in performance-based fire design of nuclear facilities. *Fire Mater.* **2021**, *45*, 1008–1024. [CrossRef]
35. Zavaleta, P.; Bouygues, O.; Lapuerta, C. Electrical component ignition in a closed enclosure adjacent to a controlled fire. *Fire Mater.* **2021**, *45*, 331–344. [CrossRef]
36. Zavaleta, P.; Suard, S.; Audouin, L. Fire spread from an open-doors electrical cabinet to neighboring targets in a confined and mechanically ventilated facility. *Fire Mater.* **2019**, *43*, 466–485. [CrossRef]
37. Yang, L.; Wang, Y.; Liu, H.; Yan, G.; Kou, W. Infrared identification of internal overheating components inside an electric control cabinet by inverse heat transfer problem. *Proc. SPIE-Int. Soc. Opt. Eng.* **2014**, *9300*, 293–298. [CrossRef]
38. El-Harbawi, M.; Al-Mubaddel, F. Risk of Fire and Explosion in Electrical Substations Due to the Formation of Flammable Mixtures. *Sci. Rep.* **2020**, *10*, 6295. [CrossRef]
39. Morandi, A.; Trevisani, L.; Ribani, P.L.; Fabbri, M.; Martini, L.; Bocchi, M. Superconducting transformers: Key design aspects for power applications. *J. Phys. Conf. Ser.* **2008**, *97*, 12318. [CrossRef]
40. Hao, Y.; Zhang, Y.; Wang, Z.; Liu, X.; Chen, M.; Yang, L. Analysis and design of an intelligent fire alarm system for UHV Substation. *IOP Conf. Ser. Mater. Sci. Eng.* **2019**, *677*, 42023. [CrossRef]
41. Land, H.B. Determination of the Cause of Arcing Faults in Low-Voltage Switchboards. *IEEE Trans. Ind. Appl.* **2008**, *44*, 430–436. [CrossRef]
42. Ma, G.-L.; Xie, Q. Seismic Analysis of a 500-kV Power Transformer of the Type Damaged in the 2008 Wenchuan Earthquake. *J. Perform. Constr. Facil.* **2018**, *32*, 4018007. [CrossRef]
43. Ziomek, W. Transformer Electrical Insulation [Editorial]. *IEEE Trans. Dielectr. Electr. Insul.* **2012**, *19*, 1841–1842. [CrossRef]
44. Christin, A.J.; Salam, M.A.; Rahman, Q.M.; Wen, F.; Ang, S.P.; Voon, W. Causes of transformer failures and diagnostic methods—A review. *Renew. Sustain. Energy Rev.* **2018**, *82*, 1442–1456. [CrossRef]
45. Metwally, I.A. Failures, Monitoring and New Trends of Power Transformers. *IEEE Potentials* **2011**, *30*, 36–43. [CrossRef]
46. Bossi, A.; Dind, J.E.; Frisson, J.M.; Khoudiakov, U.; Light, H.F.; Narke, D.V.; Tournier, Y.; Verdon, J. An international survey of failures in large power transformers in service. *Cigré Electra* **1983**, *88*, 21–48.
47. Valenta, L.; Černý, I.; Maternik-Demontoux, A. Power Transformers and Environmental Protection. *IFAC-Pap.* **2016**, *49*, 18–22. [CrossRef]
48. Oommen, T. Vegetable oils for liquid-filled transformers. *IEEE Electr. Insul. Mag.* **2002**, *18*, 6–11. [CrossRef]
49. Pawel Rozga, P.; Beroual, A.; Przybylek, P.; Jaroszewski, M.; Strzelecki, K. A Review on Synthetic Ester Liquids for Transformer Applications. *Energies* **2020**, *13*, 6429. [CrossRef]
50. Muller, S.; Brady, R.; De Bressy, G.; Magnier, P.; Pe'rigaud, G. Prevention of Transformer Tank Explosion: Part 1—Experimental Tests on Large Transformers. In Proceedings of the ASME 2008 Pressure Vessels and Piping Conference, Chicago, IL, USA, 27–31 July 2008. [CrossRef]
51. Muller, S.; Boiarciuc, M.P.; Perigaud, G. Protection of oil-filled transformer against explosion: Numerical simulations on a 200 MVA transformer. In Proceedings of the 2009 IEEE Bucharest PowerTech, Bucharest, Romania, 28 June–2 July 2009. [CrossRef]
52. Claassen, M.; Bingham, B.; Chow, J.C.; Watson, J.G.; Chu, P.; Wang, Y.; Wang, X. Characterization of Lithium-Ion Battery Fire Emissions—Part 2: Particle Size Distributions and Emission Factors. *Batteries* **2024**, *10*, 366. [CrossRef]
53. Clark, K. Battery Storage Fire in Arizona Is Under Investigation [EB/OL]. Available online: https://www.power-eng.com/energy-storage/batteries/cause-of-battery-storage-fire-in-arizona-under-investigation/ (accessed on 4 December 2024).
54. Li, M.; Xu, L.; Wang, X.; Mo, D.; Hu, Y.; Wang, N.; Yang, K.; Deng, K. Multifunctional diluent regulated flame-retardant localized high concentration electrolyte boosting Li||NCM811 batteries. *Chem. Eng. J.* **2025**, *504*, 158923. [CrossRef]
55. Guo, X.; Guo, S.; Wu, C.; Li, J.; Liu, C.; Chen, W. Intelligent Monitoring for Safety-Enhanced Lithium-Ion/Sodium-Ion Batteries. *Adv. Energy Mater.* **2023**, *13*, 2203903. [CrossRef]
56. Han-joo, K. (LEAD) Kakao, Naver Suffer Service Disruption due to Fire at Data Center [EB/OL]. Available online: https://en.yna.co.kr/view/AEN20221015002451315 (accessed on 4 December 2024).
57. Shi, P.; Zhu, H.; Dong, X.; Hai, B. Research Progress on Thermal Runaway Warning Methods and Fire Extinguishing Technologies for Lithium-Ion Batteries. *World Electr. Veh. J.* **2025**, *16*, 81. [CrossRef]
58. Gragnaniello, D.; Greco, A.; Sansone, C.; Vento, B. Fire and smoke detection from videos: A literature review under a novel taxonomy. *Expert Syst. Appl.* **2024**, *255*, 124783. [CrossRef]

59. Sousa, M.J.; Moutinho, A.; Almeida, M. Thermal Infrared Sensing for Near Real-Time Data-Driven Fire Detection and Monitoring Systems. *Sensors* **2020**, *20*, 6803. [CrossRef]
60. Lee, S.-Y.; Park, I.-C.; Park, J.-H.; Jung, H.-S. Evaluation of Initial Fire Extinguishing System for Marine ESS. *J. Mar. Sci. Eng.* **2024**, *12*, 877. [CrossRef]
61. Farrell, K.; Hassan, K.; Hossain, D.; Ahmed, B.; Rahnamayiezekavat, P.; Douglas, G.; Saha, S. Water Mist Fire Suppression Systems for Building and Industrial Applications: Issues and Challenges. *Fire* **2023**, *6*, 40. [CrossRef]
62. Military Wiki. Soviet Submarine K-278 Komsomolets [EB/OL]. Available online: https://military-history.fandom.com/wiki/Soviet_submarine_K-278_Komsomolets (accessed on 4 December 2024).
63. Intelligencer Staff. What We Know About the Deadly Bronx Apartment-Building Fire 17 People Were Killed, Including Eight Children. [EB/OL]. Available online: https://nymag.com/intelligencer/2022/01/bronx-apartment-building-fire-kills-at-least-19-updates.html (accessed on 4 December 2024).
64. Takano, M.; Romanova, V.; Yamazawa, H.; Sivintsev, Y.; Compton, K.; Novikov, V.; Parker, F. Reactivity Accident of Nuclear Submarine near Vladivostok. *J. Nucl. Sci. Technol.* **2001**, *38*, 143–157. [CrossRef]
65. Land, H.B. Sensing Switchboard Arc Faults. *IEEE Power Eng. Rev.* **2002**, *22*, 18–27. [CrossRef]
66. Depetro, A.; Gamble, G.; Moinuddin, K. Fire Safety Risk Analysis of Conventional Submarines. *Appl. Sci.* **2021**, *11*, 2631. [CrossRef]
67. Tingle, C. Submarine Accidents A 60-year Statistical Assessment. *Prof. Saf.* **2009**, *54*, 31–39. Available online: https://www.jstor.org/stable/48687573 (accessed on 4 December 2024).
68. Military Wiki. List of Submarine and Submersible Incidents Since 2000 [EB/OL]. Available online: https://military-history.fandom.com/wiki/List_of_submarine_and_submersible_incidents_since_2000 (accessed on 4 December 2024).
69. Tripathi, A. WHY AN INDIAN SUBMARINE 'INS Sindhuratna' STUCK IN RUSSIA? [EB/OL]. Available online: https://world-defence.com/why-an-indian-submarine-ins-sindhuratna-stuck-in-russia/ (accessed on 4 December 2024).
70. Fang, T.; Pan, L.; Guofeng, C.; Jianghui, X. An Estimation Method of Fire Extinguishing Time in Closed Ship Cabin. *E3S Web Conf.* **2020**, *165*, 6007. [CrossRef]
71. Griffin, L.; Bollan, H. Review and Rationalisation of Post-Fire Monitoring for Atmosphere Control in Submarines. In Proceedings of the 44th International Conference on Environmental Systems, Tucson, AZ, USA, 13–17 July 2014.
72. Land, H.B.; Eddins, C.L.; Klimek, J.M. Evolution of Arc Fault Protection Technology at APL. *Johns Hopkins APL Tech. Dig.* **2004**, *25*, 140–153.
73. Szymborski, J. Lead-acid batteries for use in submarine applications. In Proceedings of the 2002 Workshop on Autonomous Underwater Vehicles, San Antonio, TX, USA, 21 June 2002. [CrossRef]
74. Skjong, E.; Rodskar, E.; Molinas, M.; Johansen, T.A.; Cunningham, J. The Marine Vessel's Electrical Power System: From its Birth to Present Day. *Proc. IEEE* **2015**, *103*, 2410–2424. [CrossRef]
75. Wu, S.B.; Chen, X.Q.; Chen, H.X.; Lu, J.Q. Intelligent fire early warning and monitoring system for ship bridge based on WSN. *Int. J. Sci.* **2020**, *7*, 248–255.
76. Zong, L.; Wang, Y.; Wu, B. Risk assessment framework for fire accidents in the ship engine room. In Proceedings of the 2017 4th International Conference on Transportation Information and Safety (ICTIS), Banff, AB, Canada, 8–10 August 2017; pp. 1093–1098.
77. Dutta, B.B.; Kar, A.R. Simulation Techniques for Ship Onboard Fire Safety. In Proceedings of the ASME 2009 28th International Conference on Ocean, Offshore and Arctic Engineering, Volume 2: Structures, Safety and Reliability, Honolulu, HI, USA, 31 May–5 June 2009; pp. 641–649. [CrossRef]
78. Garri, G. Fire on board ship. In *The Management of Mass Burn Casualties and Fire Disasters: Proceedings of the First International Conference on Burns and Fire Disasters*; Masellis, M., Gunn, S., Eds.; Springer: Dordrecht, The Netherlands, 1992; pp. 93–105. [CrossRef]
79. Ben, D.-F.; Ma, B.; Chen, X.-L.; Zhu, S.-H.; Tang, H.-T.; Lu, W.; Xia, Z.-F. Burn injuries caused by ship fire: A 12-year study in Shanghai. *Burns* **2010**, *36*, 576–580. [CrossRef] [PubMed]
80. Baalisampang, T.; Abbassi, R.; Garaniya, V.; Khan, F.; Dadashzadeh, M. Review and analysis of fire and explosion accidents in maritime transportation. *Ocean Eng.* **2018**, *158*, 350–366. [CrossRef]
81. Uğurlu, Ö. Analysis of fire and explosion accidents occurring in tankers transporting hazardous cargoes. *Int. J. Ind. Ergon.* **2016**, *55*, 1–11. [CrossRef]
82. Casals-Torrens, P.; Castells, M. Upotreba niskodimnih bezhalogenih kabela u dizajnu protupožarne zaštite na brodu. *Nase More* **2018**, *65*, 12–17. [CrossRef]
83. Tao, J.; Liu, G.; Lam, K. Design Optimization of Marine Engine-Mount System. *J. Sound Vib.* **2000**, *235*, 477–494. [CrossRef]
84. Su, S.; Wang, L. Three dimensional reconstruction of the fire in a ship engine room with multilayer structures. *Ocean Eng.* **2013**, *70*, 201–207. [CrossRef]

85. Huang, Q.; Wang, S.; He, J.; Xu, D.; Abdou, S.N.; Ibrahim, M.M.; Sun, S.; Chen, Y.; Li, H.; Xu, B.B.; et al. Experimental design of paraffin/methylated melamine-formaldehyde microencapsulated composite phase change material and the application in battery thermal management system. *J. Mater. Sci. Technol.* **2023**, *169*, 124–136. [CrossRef]
86. Constable, S. Marine electromagnetic methods—A new tool for offshore exploration. *Lead. Edge* **2006**, *25*, 438–444. [CrossRef]
87. Mikhailov, V.M.; Sen'kov, A.P. The Use of Permanent-Magnet Machines in Ship Electrical Systems. *Russ. Electr. Eng.* **2017**, *88*, 814–817. [CrossRef]
88. Shichuan, S.; Liang, W.; Yuhong, N.; Xiang, G. Numerical computation and characteristic analysis on the center shift of fire whirls in a ship engine room fire. *Saf. Sci.* **2012**, *50*, 12–18. [CrossRef]
89. Lehr, W.; Simecek-Beatty, D. Comparison of hypothetical LNG and fuel oil fires on water. *J. Hazard. Mater.* **2004**, *107*, 3–9. [CrossRef]
90. International Conference on Applications of Statistics and Probability in Soil and Structural Engineering ICASP-4: Florence, Italy, 1983. *J. Appl. Probab.* **1981**, *18*, 791. [CrossRef]
91. Tarnapowicz, D. Reduction of the fire risk in the aspect of ground currents in ship electrical grid LV type IT. In Proceedings of the 2016 International Conference on Information and Digital Technologies (IDT), Rzeszow, Poland, 5–7 July 2016. [CrossRef]
92. Ward, T.A.; Ykema, J.I. Fire Protective Coating System for Shipboard Electrical Cables. *Nav. Eng. J.* **1990**, *102*, 154–161. [CrossRef]
93. Reed, J.W. TWA Flight 800, explosion airblast unexplained. *J. Acoust. Soc. Am.* **2003**, *114*, 2442. [CrossRef]
94. Jia, F.; Patel, M.K.; Galea, E.R.; Grandison, A.; Ewer, J. CFD fire simulation of the Swissair flight 111 in-flight fire—Part II: Fire spread analysis. *Aeronaut. J.* **2006**, *110*, 303–314. [CrossRef]
95. Foo, S. A machine vision approach to detect and categorize hydrocarbon fires in aircraft dry bays and engine compartments. *IEEE Trans. Ind. Appl.* **2000**, *36*, 459–466. [CrossRef]
96. Parise, G.; Hesla, E.; Mardegan, C.S.; Parise, L.; Capaccini, E.B. Measures to Minimize Series Faults in Electrical Cords and Extension Cords. *IEEE Trans. Ind. Appl.* **2019**, *55*, 4551–4556. [CrossRef]
97. Cunningham, J.C.; Davidson, W.M. A-C and D-C Short-Circuit Tests on Aircraft Cable. *Trans. Am. Inst. Electr. Eng.* **1944**, *63*, 961–969. [CrossRef]
98. Goraj, R. Novel coupled model for power loss prediction in a record-breaking electric aircraft motor. *Aircr. Eng. Aerosp. Technol.* **2018**, *92*, 345–354. [CrossRef]
99. Lewis, J.; Lloyd, E. The airworthiness and reliability of aircraft electrical systems. *Proc. IEEE Part A Power Eng.* **1956**, *103*, 34–49. [CrossRef]
100. Walkinshaw, D.S.; Preston, K.F. Controlling Cabin and Envelope Air Flows and Pressure Differentials to Prevent Envelope Condensation, Enable Cabin Humidification, Improve Fire Safety, and Decrease Fuel Use. *SAE Int. J. Aerosp.* **2011**, *4*, 1243–1253. [CrossRef]
101. Bryant, J.M.; Newman, M.M.; Robb, J.D. Aircraft protection from thunderstorm discharges to antennas. *Trans. Am. Inst. Electr. Eng. Part II Appl. Ind.* **1953**, *72*, 248–254. [CrossRef]
102. Song, T.; Li, Y.; Song, J.; Zhang, Z. Airworthiness Considerations of Supply Chain Management from Boeing 787 Dreamliner Battery Issue. *Procedia Eng.* **2014**, *80*, 628–637. [CrossRef]
103. Brusso, B.C. History of Aircraft Wiring Arc-Fault Protection [History]. *IEEE Ind. Appl. Mag.* **2017**, *23*, 6–11. [CrossRef]
104. Werfelman, L. Battery Rules. *AeroSafety World* **2010**, *5*, 44–46.
105. Furse, C.; Haupt, R. Down to the wire [aircraft wiring]. *IEEE Spectr.* **2001**, *38*, 34–39. [CrossRef]
106. Lebbin, P. Review of Canadian Flight Deck and Cabin Smoke and Fire Incidents: 2001–2010. *SAE Int. J. Aerosp.* **2013**, *6*, 286–298. [CrossRef]
107. Zhang, J.; Lu, C.; Guan, Y.; Liu, W. Thermodynamic properties and transport coefficients of air thermal plasmas mixed with ablated vapors of Cu and polytetrafluoroethylene. *Phys. Plasmas* **2015**, *22*, 103518. [CrossRef]
108. Yaramasu, A.; Cao, Y.; Liu, G.; Wu, B. Aircraft electric system intermittent arc fault detection and location. *IEEE Trans. Aerosp. Electron. Syst.* **2015**, *51*, 40–51. [CrossRef]
109. Elkalashy, N.I.; Lehtonen, M.; Darwish, H.A.; Izzularab, M.A.; Taalab, A.-M.I. Modeling and experimental verification of high impedance arcing fault in medium voltage networks. *IEEE Trans. Dielectr. Electr. Insul.* **2007**, *14*, 375–383. [CrossRef]
110. Carvou, E.; Le Garrec, J.L.; Pérez, J.; Praquin, J.; Djeddi, M.; Mitchell, J.B.A. Small angle x-ray scattering and electron microscopy of nanoparticles formed in an electrical arc. *AIP Adv.* **2013**, *3*, 32139. [CrossRef]
111. Naidu, M.; Schoepf, T.; Gopalakrishnan, S. Arc fault detection scheme for 42-V automotive DC networks using current shunt. *IEEE Trans. Power Electron.* **2006**, *21*, 633–639. [CrossRef]
112. McDougall, J.L.; Klepacki, D.G.; Stevenson, M.E.; Kenner, M.T. Post-fire Structural Integrity Evaluation of an Aircraft Utilizing ASTM E 1004-02. *J. Fail. Anal. Prev.* **2015**, *15*, 3–6. [CrossRef]
113. Stavnes, M.; Hammoud, A. Assessment of safety in space power wiring systems. *IEEE Aerosp. Electron. Syst. Mag.* **1994**, *9*, 21–27. [CrossRef]

114. Wileman, A.; Aslam, S.; Perinpanayagam, S. A road map for reliable power electronics for more electric aircraft. *Prog. Aerosp. Sci.* **2021**, *127*, 100739. [CrossRef]
115. Gregory, G.; Wong, K.; Dvorak, R. More About Arc-Fault Circuit Interrupters. *IEEE Trans. Ind. Appl.* **2004**, *40*, 1006–1011. [CrossRef]
116. Momoh, J.; Button, R. Design and analysis of aerospace DC arcing faults using fast fourier transformation and artificial neural network. In Proceedings of the 2003 IEEE Power Engineering Society General Meeting (IEEE Cat No03CH37491), Toronto, ON, Canada, 13–17 July 2003. [CrossRef]
117. Wu, Y.; Li, M.; Rong, M.; Yang, F.; Murphy, A.B.; Wu, Y.; Yuan, D. Experimental and theoretical study of internal fault arc in a closed container. *J. Phys. D Appl. Phys.* **2014**, *47*, 505204. [CrossRef]
118. Zhang, Y.; Fang, J.; Wang, J.; Zhang, Y.; Song, L. Lower pressure dripping limits of inclined polyethylene-insulated wires during flame spreading under different oxygen concentrations. *Fire Saf. J.* **2021**, *120*, 103108. [CrossRef]
119. Fonollosa, J.; Solórzano, A.; Marco, S. Chemical Sensor Systems and Associated Algorithms for Fire Detection: A Review. *Sensors* **2018**, *18*, 553. [CrossRef] [PubMed]
120. De Tommasi, F.; Massaroni, C.; Presti, D.L.; Grasso, R.F.; Carassiti, M.; Fong, Y.; Schena, E. Temperature monitoring during thermal treatment by thermocouples and thermistors: Current status and perspectives. In *The Application of Heat in Oncology: Principles and Practice*; Wiley: Hoboken, NJ, USA, 2023; pp. 107–119. [CrossRef]
121. Sulthana, S.F.; Wise, C.T.A.; Ravikumar, C.V.; Anbazhagan, R.; Idayachandran, G.; Pau, G. Review Study on Recent Developments in Fire Sensing Methods. *IEEE Access* **2023**, *11*, 90269–90282. [CrossRef]
122. Nikolic, M.V.; Milovanovic, V.; Vasiljevic, Z.Z.; Stamenkovic, Z. Semiconductor Gas Sensors: Materials, Technology, Design, and Application. *Sensors* **2020**, *20*, 6694. [CrossRef] [PubMed]
123. Hangauer, A.; Chen, J.; Strzoda, R.; Fleischer, M.; Amann, M.C. Performance of a fire detector based on a compact laser spectroscopic carbon monoxide sensor. *Opt. Express* **2014**, *22*, 13680–13690. [CrossRef] [PubMed]
124. Kong, S.G.; Jin, D.; Li, S.; Kim, H. Fast fire flame detection in surveillance video using logistic regression and temporal smoothing. *Fire Saf. J.* **2016**, *79*, 37–43. [CrossRef]
125. Töreyin, B.U.; Dedeoğlu, Y.; Güdükbay, U.; Çetin, A.E. Computer vision based method for real-time fire and flame detection. *Pattern Recognit. Lett.* **2006**, *27*, 49–58. [CrossRef]
126. Hackner, A.; Oberpriller, H.; Ohnesorge, A.; Hechtenberg, V.; Müller, G. Heterogeneous sensor arrays: Merging cameras and gas sensors into innovative fire detection systems. *Sens. Actuators B Chem.* **2016**, *231*, 497–505. [CrossRef]
127. Kanwal, K.; Liaquat, A.; Mughal, M.; Abbasi, A.R.; Aamir, M. Towards Development of a Low Cost Early Fire Detection System Using Wireless Sensor Network and Machine Vision. *Wirel. Pers. Commun.* **2017**, *95*, 475–489. [CrossRef]
128. Krüger, S.; Despinasse, M.-C.; Raspe, T.; Nörthemann, K.; Moritz, W. Early fire detection: Are hydrogen sensors able to detect pyrolysis of house hold materials? *Fire Saf. J.* **2017**, *91*, 1059–1067. [CrossRef]
129. Jelicic, V.; Magno, M.; Brunelli, D.; Paci, G.; Benini, L. Context-Adaptive Multimodal Wireless Sensor Network for Energy-Efficient Gas Monitoring. *IEEE Sens. J.* **2013**, *13*, 328–338. [CrossRef]
130. Vidas, S.; Moghadam, P. HeatWave: A handheld 3D thermography system for energy auditing. *Energy Build.* **2013**, *66*, 445–460. [CrossRef]
131. Mahdipour, E.; Dadkhah, C. Automatic fire detection based on soft computing techniques: Review from 2000 to 2010. *Artif. Intell. Rev.* **2014**, *42*, 895–934. [CrossRef]
132. Çetin, A.E.; Dimitropoulos, K.; Gouverneur, B.; Grammalidis, N.; Günay, O.; Habiboğlu, Y.H.; Töreyin, B.U.; Verstockt, S. Video fire detection—Review. *Digit. Signal Process.* **2013**, *23*, 1827–1843. [CrossRef]
133. Kang, M.; Tung, T.X.; Kim, J.-M. Efficient video-equipped fire detection approach for automatic fire alarm systems. *Opt. Eng.* **2013**, *52*, 17002. [CrossRef]
134. Gunay, O.; Toreyin, B.U.; Kose, K.; Cetin, A.E. Entropy-Functional-Based Online Adaptive Decision Fusion Framework with Application to Wildfire Detection in Video. *IEEE Trans. Image Process.* **2012**, *21*, 2853–2865. [CrossRef] [PubMed]
135. Jenifer, P. Notice of Violation of IEEE Publication Principles: Effective visual fire detection in video sequences using probabilistic approach. In Proceedings of the 2011 International Conference on Emerging Trends in Electrical and Computer Technology, Nagercoil, India, 23–24 March 2011. [CrossRef]
136. Chen, L.-H.; Huang, W.-C. Fire Detection Using Spatial-temporal Analysis. In Proceedings of the World Congress on Engineering 2013 Vol III (WCE 2013), London, UK, 3–5 July 2013.
137. Kuo, J.-Y.; Lai, T.-Y.; Fanjiang, Y.-Y.; Huang, F.-C.; Liao, Y.-H. A behavior-based flame detection method for a real-time video surveillance system. *J. Chin. Inst. Eng.* **2015**, *38*, 947–958. [CrossRef]
138. Oghabi, E.; Moghaddam, R.K.; Kobravi, H. A new strategy for fire detection based on analyzing the irregularity pattern of image contour. *Signal Image Video Process.* **2024**, *18*, 6143–6155. [CrossRef]
139. Wang, T.; Bu, L.; Yang, Z.; Yuan, P.; Ouyang, J.; Shi, L. A new fire detection method using a multi-expert system based on color dispersion, similarity and centroid motion in indoor environment. *IEEE/CAA J. Autom. Sin.* **2020**, *7*, 263–275. [CrossRef]

140. Lv, C.; Zhou, H.; Chen, Y.; Fan, D.; Di, F. A lightweight fire detection algorithm for small targets based on YOLOv5s. *Sci. Rep.* **2024**, *14*, 14104. [CrossRef]
141. Zhu, D.; Ahmad, K.A.; Chen, A. Research on flame recognition technology based on local complex features. *J. Phys. Conf. Ser.* **2022**, *2246*, 12074. [CrossRef]
142. Chen, J.; He, Y.; Wang, J. Multi-feature fusion based fast video flame detection. *Build. Environ.* **2010**, *45*, 1113–1122. [CrossRef]
143. Wang, Y.; Wu, H.; Wang, Y.; Wang, W.; Duan, Y.; Liu, J. Video flame recognition based on LGATP texture feature and sparse representation. *Signal Image Video Process.* **2024**, *18*, 8911–8923. [CrossRef]
144. Shahid, M.; Virtusio, J.J.; Wu, Y.-H.; Chen, Y.-Y.; Tanveer, M.; Muhammad, K.; Hua, K.-L. Spatio-Temporal Self-Attention Network for Fire Detection and Segmentation in Video Surveillance. *IEEE Access* **2021**, *10*, 1259–1275. [CrossRef]
145. Zhao, E.; Liu, Y.; Zhang, J.; Tian, Y. Forest Fire Smoke Recognition Based on Anchor Box Adaptive Generation Method. *Electronics* **2021**, *10*, 566. [CrossRef]
146. Lu, P.; Zhao, Y.; Xu, Y. A Two-Stream CNN Model with Adaptive Adjustment of Receptive Field Dedicated to Flame Region Detection. *Symmetry* **2021**, *13*, 397. [CrossRef]
147. Zheng, S.; Zou, X.; Gao, P.; Zhang, Q.; Hu, F.; Zhou, Y.; Wu, Z.; Wang, W.; Chen, S. A Forest Fire Recognition Method Based on Modified Deep CNN Model. *Forests* **2024**, *15*, 111. [CrossRef]
148. Rosadi, D.; Andriyani, W.; Arisanty, D.; Agustina, D. Prediction of Forest Fire using Hybrid SOM-AdaBoost Method. *J. Phys. Conf. Ser.* **2021**, *2123*, 12030. [CrossRef]
149. Ma, S.; Li, W.; Wan, L.; Zhang, G. A Lightweight Fire Detection Algorithm Based on the Improved YOLOv8 Model. *Appl. Sci.* **2024**, *14*, 6878. [CrossRef]
150. Dong, Y.; Yang, H.; Yin, M.; Li, M.; Qu, Y.; Jia, X. Research on Lightweight Method of Segment Beam Point Cloud Based on Edge Detection Optimization. *Buildings* **2024**, *14*, 1221. [CrossRef]
151. Gade, R.; Moeslund, T.B. Thermal cameras and applications: A survey. *Mach. Vis. Appl.* **2013**, *25*, 245–262. [CrossRef]
152. Huda, A.; Taib, S. Suitable features selection for monitoring thermal condition of electrical equipment using infrared thermography. *Infrared Phys. Technol.* **2013**, *61*, 184–191. [CrossRef]
153. Pareek, S.; Sharma, R.; Maheshwari, R. Application of artificial neural networks to monitor thermal condition of electrical equipment. In Proceedings of the 2017 3rd International Conference on Condition Assessment Techniques in Electrical Systems (CATCON), Rupnagar, India, 16–18 November 2017. [CrossRef]
154. Almeida, C.A.L.; Braga, A.P.; Nascimento, S.; Paiva, V.; Martins, H.J.A.; Torres, R.; Caminhas, W.M. Intelligent Thermographic Diagnostic Applied to Surge Arresters: A New Approach. *IEEE Trans. Power Deliv.* **2009**, *24*, 751–757. [CrossRef]
155. Joshi, D.D.; Kumar, S.; Patil, S.; Kamat, P.; Kolhar, S.; Kotecha, K. Deep learning with ensemble approach for early pile fire detection using aerial images. *Front. Environ. Sci.* **2024**, *12*, 1440396. [CrossRef]
156. Sun, W.; Liu, Y.; Wang, F.; Hua, L.; Fu, J.; Hu, S. A Study on Flame Detection Method Combining Visible Light and Thermal Infrared Multimodal Images. *Fire Technol.* **2024**, 1–22. [CrossRef]
157. Lee, R.H. The Other Electrical Hazard: Electric Arc Blast Burns. *IEEE Trans. Ind. Appl.* **1982**, *IA-18*, 246–251. [CrossRef]
158. Yang, K.; Zhang, R.; Yang, J.; Liu, C.; Chen, S.; Zhang, F. A Novel Arc Fault Detector for Early Detection of Electrical Fires. *Sensors* **2016**, *16*, 500. [CrossRef]
159. Gregory, G.; Scott, G. The arc-fault circuit interrupter, an emerging product; In Proceedings of the 1998 IEEE Industrial and Commercial Power Systems Technical Conference. Conference Record. Papers Presented at the 1998 Annual Meeting (Cat. No.98CH36202), Edmonton, AB, Canada, 3–8 May 1998. [CrossRef]
160. Maroni, C.-S.; Cittadini, R.; Cadoux, Y.; Serpinet, M. Series arc detection in low voltage distribution switchboard using spectral analysis. In Proceedings of the Sixth International Symposium on Signal Processing and Its Applications (CatNo01EX467), Kuala Lumpur, Malaysia, 13–16 August 2001. [CrossRef]
161. Pulkkinen, J.P. Commercial arc fault detection devices in military electromagnetic environment. *IEEE Electromagn. Compat. Mag.* **2018**, *7*, 49–52. [CrossRef]
162. Phipps, K.; Cooke, T.; Dorr, D.; Keebler, P. Frequency phenomenon and algorithms for arc detection. In Proceedings of the 2010 IEEE International Symposium on Electromagnetic Compatibility, Fort Lauderdale, FL, USA, 25–30 July 2010. [CrossRef]
163. Sidhu, T.; Sagoo, G.; Sachdev, M. On-line detection and location of low-level arcing in dry-type transformers. *IEEE Trans. Power Deliv.* **2002**, *17*, 135–141. [CrossRef]
164. Sidhu, T.; Sagoo, G.; Sachdev, M. Multisensor secondary device for detection of low-level arcing faults in metal-clad MCC switchgear panel. *IEEE Trans. Power Deliv.* **2002**, *17*, 129–134. [CrossRef]
165. Liu, Y.-J.; Chen, C.-I.; Fu, W.-C.; Lee, Y.-D.; Cheng, C.-C.; Chen, Y.-F. A Hybrid Approach for Low-Voltage AC Series Arc Fault Detection. *Energies* **2023**, *16*, 1256. [CrossRef]
166. Jiang, R.; Wang, Y.; Gao, X.; Bao, G.; Hong, Q.; Booth, C.D. AC Series Arc Fault Detection Based on *RLC* Arc Model and Convolutional Neural Network. *IEEE Sens. J.* **2023**, *23*, 14618–14627. [CrossRef]

167. Wang, Y.; Zhang, F.; Zhang, S. A New Methodology for Identifying Arc Fault by Sparse Representation and Neural Network. *IEEE Trans. Instrum. Meas.* **2018**, *67*, 2526–2537. [CrossRef]
168. Qin, Y.-W.; Zhang, P.-H.; Song, R.-N.; Zhu, M.-N. Arc fault diagnosis technology and trend of development in novel power system. *Electr. Meas. Instrum.* **2024**, *61*, 1–9. [CrossRef]
169. Tumialis, P.; Skierkowski, M.; Przychodny, J.; Obszarski, P. The Impact of 8- and 4-Bit Quantization on the Accuracy and Silicon Area Footprint of Tiny Neural Networks. *Electronics* **2025**, *14*, 14. [CrossRef]
170. Shatarah, I.S.; Olbrycht, R. Distributed temperature sensing in optical fibers based on Raman scattering: Theory and applications. *Meas. Autom. Monit.* **2017**, *63*, 41–44.
171. Yaodong, Z.; Yi, K.; Xiaopo, M.; Xueming, Z.; Zhiqiang, F.; Zeqi, H.; Xiang, R.; Tianru, S.; Jianjin, F.; Junjie, H. Analysis of Current Carrying Capacity of Power Cable Based on DTS. *J. Phys. Conf. Ser.* **2020**, *1639*, 12029. [CrossRef]
172. Bian, H.; Zhu, Z.; Zang, X.; Luo, X.; Jiang, M. A CNN Based Anomaly Detection Network for Utility Tunnel Fire Protection. *Fire* **2022**, *5*, 212. [CrossRef]
173. Blöcher, G.; Regenspurg, S.; Kranz, S.; Lipus, M.; Pei, L.; Norden, B.; Reinsch, T.; Henninges, J.; Siemon, R.; Orenczuk, D.; et al. Best practices for characterization of High Temperature-Aquifer Thermal Energy Storage (HT-ATES) potential using well tests in Berlin (Germany) as an example. *Geothermics* **2024**, *116*, 102830. [CrossRef]
174. National Fire Protection Association. *NFPA 10: Standard for Portable Fire Extinguishers*; NFPA: Quincy, MA, USA, 2022.
175. *GB/T 4968-2008*; General Administration of Quality Supervision, Inspection and Quarantine of the People's Republic of China, & Standardization Administration of China. Classification of Fires. Standards Press of China: Beijing, China, 2008.
176. Sheng, Y.; Zhang, S.; Ma, W.; Peng, Y.; Ma, L.; Wang, Q.; Hu, D. Tuning stability, rheology, and fire-extinguishing performance of advanced firefighting foam material by inorganic nanoparticle flame retardants. *J. Colloid Interface Sci.* **2024**, *677*, 378–389. [CrossRef]
177. Zhang, J.; Shang, F.; Zhang, S.; Wang, L.; Ke, Y.; Huang, J.; Su, W.; Liu, R.; Sheng, Y. Research on Key Parameters and Fire Extinguishing Effectiveness of Compressed Air Foam System Used for UHV Substation. In *Fire Technology*; Springer: Berlin/Heidelberg, Germany, 2024; pp. 1–22. [CrossRef]
178. Liu, Y.; Chen, R.; Zhixuan, W.; Zhang, R.; Jing, H.; Yu, D.; Pan, R. Effects of thermal aging on the performance of ordinary and novel superhydrophobic and oleophobic ultra-fine dry powder extinguishing agent. *Sci. Rep.* **2025**, *15*, 3668. [CrossRef] [PubMed]
179. Wang, L.; Du, S.; Zhou, Z.; Guo, Y.; Yang, Q.; Yao, S.; Zhang, H. Enhanced Fire-Extinguishing Performance and Synergy Mechanism of HM/DAP Composite Dry Powder. *Materials* **2025**, *18*, 533. [CrossRef] [PubMed]
180. Cao, F.-C.; Ma, X.-Y.; Zhou, H.-L.; Tang, Y.; Dong, X.-L.; Huang, A.-C. Enhanced suppression of metal combustion processes using a compound expansible graphite extinguishing agent: Experimental study and mechanistic insights. *J. Loss Prev. Process Ind.* **2023**, *85*, 105154. [CrossRef]
181. Lee, C.W.; Venkatachalapathy, R.; Prakash, J. A Novel Flame-Retardant Additive for Lithium Batteries. *Electrochem. Solid-State Lett.* **2000**, *3*, 63–65. [CrossRef]
182. E Hyung, Y.; Vissers, D.R.; Amine, K. Flame-retardant additives for lithium-ion batteries. *J. Power Sources* **2003**, *119*, 383–387. [CrossRef]
183. Aurbach, D.; Talyosef, Y.; Markovsky, B.; Markevich, E.; Zinigrad, E.; Asraf, L.; Gnanaraj, J.S.; Kim, H.-J. Design of electrolyte solutions for Li and Li-ion batteries: A review. *Electrochim. Acta* **2004**, *50*, 247–254. [CrossRef]
184. Yim, T.; Park, M.-S.; Woo, S.-G.; Kwon, H.-K.; Yoo, J.-K.; Jung, Y.S.; Kim, K.J.; Yu, J.-S.; Kim, Y.-J. Self-Extinguishing Lithium Ion Batteries Based on Internally Embedded Fire-Extinguishing Microcapsules with Temperature-Responsiveness. *Nano Lett.* **2015**, *15*, 5059–5067. [CrossRef]
185. Kim, G.-H.; Smith, K.; Ireland, J.; Pesaran, A. Fail-safe design for large capacity lithium-ion battery systems. *J. Power Sources* **2012**, *210*, 243–253. [CrossRef]
186. Sahraei, E.; Meier, J.; Wierzbicki, T. Characterizing and modeling mechanical properties and onset of short circuit for three types of lithium-ion pouch cells. *J. Power Sources* **2014**, *247*, 503–516. [CrossRef]
187. Nakayama, M.; Iizuka, K.; Shiiba, H.; Baba, S.; Nogami, M. Asymmetry in anodic and cathodic polarization profile for $LiFePO_4$ positive electrode in rechargeable Li ion battery. *J. Ceram. Soc. Jpn.* **2011**, *119*, 692–696. [CrossRef]
188. Capasso, C.; Veneri, O. Experimental analysis on the performance of lithium based batteries for road full electric and hybrid vehicles. *Appl. Energy* **2014**, *136*, 921–930. [CrossRef]
189. Summer, S. *Flammability Assessment of Lithium-Ion and Lithium-Ion Polymer Battery Cells Designed for Aircraft Power Usage*; US Department of Transportation, Federal Aviation Administration: Washington, DC, USA, 2010.
190. Doughty, D.H. Vehicle Battery Safety Roadmap Guidance [EB/OL]. Available online: https://www.osti.gov/biblio/1055366/ (accessed on 4 December 2024).
191. Park, O. *Best Practices for Emergency Response to Incidents Involving Electric Vehicles Battery Hazards: A Report on Full-Scale Testing Results*; (1205174.000): F0F; The Fire Protection Research Foundation: Quincy, MA, USA, 2013.

192. Zhang, L.; Jin, K.; Sun, J.; Wang, Q. A Review of Fire-Extinguishing Agents and Fire Suppression Strategies for Lithium-Ion Batteries Fire. *Fire Technol.* **2024**, *60*, 817–858. [CrossRef]
193. Xu, J.; Guo, P.; Duan, Q.; Yu, X.; Zhang, L.; Liu, Y.; Wang, Q. Experimental study of the effectiveness of three kinds of extinguishing agents on suppressing lithium-ion battery fires. *Appl. Therm. Eng.* **2020**, *171*, 115076. [CrossRef]
194. Wang, Q.; Li, K.; Wang, Y.; Chen, H.; Duan, Q.; Sun, J. The Efficiency of Dodecafluoro-2-Methylpentan-3-One on Suppressing the Lithium Ion Battery Fire. *J. Electrochem. Energy Convers. Storage* **2018**, *15*, 41001. [CrossRef]
195. Wang, Q.; Shao, G.; Duan, Q.; Chen, M.; Li, Y.; Wu, K.; Liu, B.; Peng, P.; Sun, J. The Efficiency of Heptafluoropropane Fire Extinguishing Agent on Suppressing the Lithium Titanate Battery Fire. *Fire Technol.* **2016**, *52*, 387–396. [CrossRef]
196. Kim, A.; Crampton, G.P. *Performance of Novec1230 in Electronic Facility Fire Protection*; NRCC-53526; National Research Council Canada: Ottawa, ON, Canada, 2022.
197. Mawhinney, J.R.; Back, G.G. Water Mist Fire Suppression Systems. In *SFPE Handbook of Fire Protection Engineering*; Hurley, M.J., Gottuk, D., Hall, J.R., Harada, K., Kuligowski, E., Torero, J., Watts, J.M., Wieczorek, C., Eds.; Springer: New York, NY, USA, 2016; pp. 1587–1645. [CrossRef]
198. Xiaomeng, Z.; Guangxuan, L.; Bo, C. Improvement of water mist's fire-extinguishing efficiency with MC additive. *Fire Saf. J.* **2006**, *41*, 39–45. [CrossRef]
199. Liu, Z.; Kim, A.K. A review of water mist fire suppression systems—Fundamental studies. *J. Fire Prot. Eng.* **1999**, *10*, 32–50.
200. Shi, X.; Li, Y.; Ren, X.; Zhang, X.; Zhang, Y.; Zhang, Y.; Jiao, F.; Zhang, Y.; Yu, Y.; Cao, W. Smoldering characteristic and energy utilization for regulating coal dust with moisture and non-combustible substances. *Int. Commun. Heat Mass Transf.* **2025**, *162*, 108570. [CrossRef]
201. Li, S.; Chen, R.; Zhang, Y.; Cheng, S.; Li, X.; Zhang, T.; Zhang, X.; Zhou, W.; Shi, X.; Cao, W. The effect of NH3 concentration on explosion venting characteristics and combustion mechanism. *Int. J. Hydrogen Energy* **2025**, *101*, 1172–1182. [CrossRef]
202. Zhao, Y.; Xiao, X.; Zhang, X.; Wang, B.; Wu, C.; Chu, Z.; Shi, X.; Yu, Y.; Zhao, H.; Jiao, F.; et al. Experiment study on the explosion suppressing characteristics and mechanism of melamine cyanurate and ammonium dihydrogen phosphate for lignite dust. *Powder Technol.* **2024**, *448*, 120246. [CrossRef]
203. Liu, Z.; Kim, A.K.; Carpenter, D.; Kanabus-Kaminska, J.M.; Yen, P.-L. Extinguishment of Cooking Oil Fires by Water Mist Fire Suppression Systems. *Fire Technol.* **2004**, *40*, 309–333. [CrossRef]
204. Hansen, R.L.; Back, G.G. Water Spray Protection of Machinery Spaces. *Fire Technol.* **2001**, *37*, 317–326. [CrossRef]
205. Hills, A.T.; Simpson, T.; Smith, D.P. Water mist fire protection systems for telecommunication switch gear and other electronic facilities. In Proceedings of the Water Mist Fire Suppression Workshop, Gaithersburg, MD, USA, 1–2 March 1993; pp. 123–142.
206. Mawhinney, J.R.; Taber, B. Findings of experiments using water mist for fire suppression in an electronic equipment room. In Proceedings of the Halon Alternatives Technical Working Conference, Albuquerque, NM, USA, 7–9 May 1996; p. 15.
207. Liu, Z.; Kim, A.K.; Carpenter, D. A study of portable water mist fire extinguishers used for extinguishment of multiple fire types. *Fire Saf. J.* **2007**, *42*, 25–42. [CrossRef]
208. Joseph, P.; Nichols, E.; Novozhilov, V. A comparative study of the effects of chemical additives on the suppression efficiency of water mist. *Fire Saf. J.* **2013**, *58*, 221–225. [CrossRef]
209. Yang, L.; Zhao, J. Fire extinct experiments with water mist by adding additives. *J. Therm. Sci.* **2011**, *20*, 563–569. [CrossRef]
210. Cao, X.; Ren, J.; Zhou, Y.; Wang, Q.; Gao, X.; Bi, M. Suppression of methane/air explosion by ultrafine water mist containing sodium chloride additive. *J. Hazard. Mater.* **2015**, *285*, 311–318. [CrossRef]
211. Hiltz, J. *Additives for Water Mist Fire Suppression Systems*; DRDC Atlantic TM 2012-236 2012; Defence R&D Canada-Atlantic: Halifax, NS, Canada, 2012. [CrossRef]
212. Man, C.; Shunbing, Z.; Litao, J.; Xiaoli, W. Surfactant-containing Water Mist Suppression Pool Fire Experimental Analysis. *Procedia Eng.* **2014**, *84*, 558–564. [CrossRef]
213. LeFort, G.; Marshall, A.W.; Pabon, M. Evaluation of Surfactant Enhanced Water Mist Performance. *Fire Technol.* **2009**, *45*, 341–354. [CrossRef]
214. Lu, J.; Chen, B.-H.; Wu, C.; Liu, X.; Zhou, T.; Tan, Y. A multi-additive suppressant agent–based low-flow and long-distance firefighting approach for suppressing wildfires near electrical transmission lines. *J. Fire Sci.* **2016**, *34*, 398–415. [CrossRef]
215. Yang, Z.; Liu, H.; Li, M.; Wang, X.; Das, O.; Han, Z.X.; Jiang, L. Al-Mg@PVDF and Al-Si@PVDF composites with enhanced combustion and energy release characteristics. *Def. Technol.* 2024; *in press*. [CrossRef]
216. Zhao, S.; Li, M.; Jiang, L. Exploring the influence of metal oxides on the pyrolytic behavior and decomposition mechanism of the green gas generating agent 5-Aminotetrazole. *J. Loss Prev. Process. Ind.* **2024**, *92*, 105481. [CrossRef]
217. Cheng, X.-N.; Xu, G.-Z.; Liu, H.; Han, Z.-X.; Li, M.; Jiang, L. Thermal safety characteristics of nanoscale nitrocellulose/stabilizer composite materials. *Cellulose* **2024**, *31*, 9623–9643. [CrossRef]
218. Yang, X.; Jiang, L.; Li, M. Experimental and simulated study on continuous laser ablation of glass fiber epoxy resin plate. *Int. Commun. Heat Mass Transf.* **2023**, *148*, 107088. [CrossRef]

219. Li, M.; Zhang, D.; Han, Z.-X.; Jiang, L. Thermal oxidation characteristics of polystyrene with different particle sizes based on the traditional kinetic approaches and distributed activation energy model. *J. Therm. Anal. Calorim.* **2024**, *149*, 993–1001. [CrossRef]
220. Liu, H.; Li, M.; Zhao, S.; Jiang, L.; Xu, Q.; Majlingová, A. Applications of distributed activation energy model on the pyrolysis of green renewable wood. *Fuel* **2024**, *359*, 130457. [CrossRef]
221. Zhao, S.-N.; Li, M.; Liu, H.; Han, Z.-X.; Chen, J.; Jiang, L. Insights into oxidant matching with green gas generator 5-aminotetrazole from aspects of thermal decomposition behavior, kinetics and combustion mechanism. *Renew. Energy* **2024**, *224*, 120156. [CrossRef]
222. Xu, G.; Li, M.; Mensah, R.A.; Jiang, L.; Das, O. A strategic approach to thermal stability enhancement of nitrocellulose. *J. Therm. Anal. Calorim.* **2024**, 1–17. [CrossRef]
223. Yao, Y.; Tan, L.; Chen, F.; Pan, A.; Ma, Q.; Zhao, J.; Kang, R. Hydrogen energy industry in China: The current status, safety problems, and pathways for future safe and healthy development. *Saf. Sci.* **2025**, *186*, 106808. [CrossRef]
224. Lu, J.; Chen, B.-H.; Liang, P.; Sun, Y.; Fang, Z.; Huang, S. Experimental Evaluation of Protecting High-Voltage Electrical Transformers Using Water Mist with and without Additives. *Fire Technol.* **2019**, *55*, 1671–1690. [CrossRef]

Disclaimer/Publisher's Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.