Low Voltage Arcing and Fire Testing: Experiments to Compare Arc Flash and Fire Hazard Between Faults Inside LVAC Enclosures and LVDC Enclosures

by

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Abstract

Electrical fires are a significant hazard to the public in both low voltage AC networks and potential hybrid AC DC networks. New Zealand electricity customers are typically linked to an underground LV distribution network using a service fuse located inside an LV enclosure at the boundary between the road and the house. Each year, a small fraction (less than 0.1%) of the pillars on the network may catch fire due to internal component failure, known as a pillar fire. Pillar fires pose a considerable risk to individuals, property, and reputation because of the large number of assets in the fleet and their close proximity to residential and bustling metropolitan areas. Identifying how overheating of connections might result in a fire is essential for managing this risk.

The research commences by underlining the importance of fire testing in elevating safety standards and advocates for a stringent safety protocol to safeguard researchers, equipment, and the surrounding infrastructure. It then delves into the procedural steps crucial for executing fire testing experiments, encompassing the development of experimental objectives, methodology, and test plans. The thesis further addresses the setup and calibration of measurement instruments, emphasizing the creation of controlled test environments to ensure precise data collection. Additionally, the report underscores the significance of documentation and data collection, as well as post-experiment analysis and reporting.

This thesis's contribution lies in reporting experiments that elucidate the process from hot spots to pillar fires and arc flash events for both LVAC plastic pillars currently in use and the potential response of these pillars in LVDC-operated networks. The experimental setup, dedicated to studying LVAC/LVDC overheating and arc faults, examines the characteristics of AC and DC arc faults at LV levels. The potential data that can be collected aids in a better understanding of fire ignition involving materials associated with plastic LV pillars.

The results of these experiments enhance our comprehension of the process leading from overheating connections to pillar fires and arc flash events. Consequently, improvements in equipment specifications and requirements aim to reduce the occurrence of faults due to overheating, thereby mitigating associated risks.

Dedicated To My Loving Family

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Research Outputs

1. M. Gibson and N.-K. C. Nair, “DC Home For Integration To Low-Voltage AC Electricity Distribution Networks,” *in 2023 EEA – “Delivering A Net Zero Carbon Energy Future” Conference (EEA2023), 2023* (Paper Published)
2. M. Gibson, A. Cuppen and N.-K. C. Nair, “Experiment design to understand fire ignition and behaviour of components in LVAC and LVDC enclosures and plastic pillars,” *in 2024 CIGRE Paris Session C6 PS2 – “Power Electronic Based Solutions For Smart Distribution Systems” Conference (CIGRE Paris), 2024* (Manuscript submitted for publication)
3. A. Cuppen, K. Kueh and M. Gibson, “LV Cable Renewal Forecasting – How Near Is The Wall Of Wire,” *in 2023 EEA – “Delivering A Net Zero Carbon Energy Future Conference” Conference (EEA2023), 2023* (3rd Author of Paper Published)
4. A. Cuppen, K. Kueh and M. Gibson, “A Review Of Low Voltage Cable Diagnostics To Support Proactive Renewal Planning,” *in 2023 Cigre Cairns Session – “The End To End Electricity System: Transition, Development, Operation And Integration” Conference (CIGRE Australia), 2023* (3rd Author of Paper Published)
5. A. Cuppen, N.-K. C. Nair and M. Gibson, & B Greenwood. *Arc-flash and fire risk in the future hybrid ACDC network in low voltage enclosures from hot connections. *IEEE Transactions on Power Delivery 2025** (Journal Publication in Progress)

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Contents

List of Figures

List of Figures - Appendix

List of Tables

List of Tables - Appendix

Acronyms

AC	Alternating Current
ASTM	American Society for Testing and Materials
B1	Insulated Cables
CIGRE	International Council on Large Electric Systems/ Conseil International Des Grands Réseaux Electriques
DC	Direct Current
DER	Distributed Energy Resources
EV	Electric Vehicles
FAN	Future Architecture of The Network
GFCI	Ground Fault Circuit Interrupters
HV	High Voltage
IEEE	Institute of Electrical and Electronics Engineers
IEC	International Electrotechnical Commission
ISGT	Innovative Smart Grid Technologies
LV	Low Voltage
LVAC	Low Voltage Alternating Current
LVDC	Low Voltage Direct Current
MV	Medium Voltage
NFPA	National Fire Protection Association
OSHA	Occupational Safety and Health Administration
PES	Power & Energy Society
PLP	Preformed Line Products
PV	Photovoltaic Technology
UGC	Underground Cable
UOA	The University of Auckland

Chapter 1
Introduction

1.1 Background

AC architectures have been the standard for electricity distribution and have been the dominating features for grid structures across the world for the past century. With the increasing demand for renewable energy sources and advancements in technology, there is a growing interest in DC power distribution systems. DC power distribution systems offer advantages over traditional AC systems, such as higher power density and better efficiency [35]. They are also more flexible in terms of integrating renewable energy sources and energy storage systems. However, one major challenge in designing complex LVDC systems is the ability to handle faults and ensure proper protection [34]. To consider LVDC systems as a viable alternative, it is crucial to evaluate any imperfections in the current network structures.

The significant increase in the DC load within residential homes due to addition of PV and EVs and the lack of converter requirements have made low-voltage DC distribution systems an attractive prospect at home [38]. The benefits of efficiency that DC distribution systems have to offer, align heavily with New Zealand's commitments in the Paris Agreement to reduce its greenhouse emissions by 30% below its 2005 levels by 2030. [39].

It is in the best interests of Future Architecture of the Network (FAN) and its alignment with Matauranga Maori to properly address and rectify any imperfections in the defining architectures of

New Zealand. FAN's purpose is to create a sustainable and resilient distribution network that caters to the requirements of future generations while adhering to the principles of Matauranga Maori [32]. The themes of Taiao (Environment, sustainability), Hauora & Oranga (Health & wellbeing), and Mātauranga Māori (knowledge) all intertwine with the fundamental goal of establishing a sustainable and resilient distribution network [36].

The low-voltage distribution landscape in New Zealand features a significant number of LVAC distribution networks [37]. These networks have been designed and optimised for AC power distribution and have protection systems in place to detect and clear AC faults efficiently. Low-voltage pillars are a prominent feature in LVAC distribution networks, ensuring the safety of both the infrastructure and the people. These pillars are enclosed structures designed to house and distribute electrical equipment for low-voltage power distribution systems. The purpose of these pillars is to provide a centralised and organised location for electrical components, facilitating the distribution of power to nearby buildings or equipment. Customers are generally connected to an underground low-voltage reticulation network via a service fuse housed within these pillars located at the boundary between the road and the property. Annually, a small percentage (estimated to be less than 0.1% of the total number of pillars on the network [1]) of this asset type may experience pillar fires due to internal component failures. These pillar fires can present a significant risk to the surrounding infrastructure and pose a danger to nearby residents and pedestrians. The replacement of this infrastructure incurs significant economic losses to all stakeholders involved. It is important to analyse the causes of these pillar fires and develop effective protection mechanisms to mitigate the risk and ensure the safety and reliability of low-voltage distribution networks.

Research conducted by [1] on pillar enclosures from Powerco Ltd. indicates that most enclosures made of LDPE compositions are combustible under certain conditions. Once these pillars do ignite, they are likely to continue burning self-sustained due to the presence of combustible materials and lack of fire-resistant properties [1]. This emphasizes how important it is to understand these pillars' failure mechanisms because they present a serious fire risk.

1.2 Research Motivation

One of the main motivations for researching low-voltage arcing fire hazards is the need to enhance electrical safety in various settings, such as homes, and workplaces. This is particularly important because low-voltage arcing and pillar fire incidents can lead to devastating fires, injuries, and even fatalities. Understanding the causes and mitigation strategies for pillar fires is crucial for preventing such incidents and ensuring the safety of individuals and property.

Powerco Ltd. (NZ), is an electrical distribution company in New Zealand that owns and operates an electricity distribution network with over 300,000 network links, serving approximately 1.1 million people [1]. Alongside its distribution network, Powerco Ltd. also recognises the importance of addressing low-voltage arcing fire hazards to prevent accidents, improving asset management and promoting electrical safety within its network and the communities they serve. Therefore, they are committed to supporting research efforts in this area, both to enhance their understanding and to contribute to the development of best practices and safety standards. This commitment from Powerco Ltd. highlights the growing recognition of the significance of addressing low-voltage arcing fire hazards in ensuring electrical safety and minimising the potential risks associated with electrical incidents.

Alongside Powerco Ltd., an industry workshop called "CIGRE NZB1 Pillar Fires" consisting of electrical safety experts, researchers, and government agencies was held. The workshop aimed to share knowledge, discuss challenges, and identify potential solutions for mitigating pillar fires. The workshop provided a valuable platform for collaboration and knowledge exchange. Preformed Line Products New Zealand (PLP), a leading provider of products and solutions for the energy and communications industries in New Zealand, was one of the participants at the workshop and was willing to contribute their expertise and laboratory resources in aiding in research. Chapter 5 will focus on discussing the collaboration between Preformed Line Products New Zealand and The University of Auckland (UOA).

Safety is a crucial concern, and the financial implications of low-voltage arcing incidents cannot be overlooked. Looking from a more global perspective, based on the 2013 NFPA report, it was found that about 47,700 house structure fires reported to US fire departments in 2011 were caused by electrical failure or malfunction. The flames caused 418 fatalities among civilians, 1570 civilian injuries, and direct property loss amounting to US$1.4 billion. In 2011, there were approximately 16,400 electrical fires that occurred outside of homes. These incidents resulted in 13 civilian deaths, and 243 civilian injuries, and caused direct property damage amounting to US$501 million [30]. More recent statistics state that electrical fires caused an estimated average of 430 civilian deaths and 1,070 civilian injuries each year in 2015-2019, as well as an estimated US$1.3 billion in direct property damage a year. Wiring and related equipment were involved in just over two-thirds of home fires caused by the electrical distribution and lighting equipment [30].

According to data from the Fire Services Department of Hong Kong, the combined proportion of fire incidents in residential structures and housing estates rose to 43% between 2008 and 2010 [19], indicating a significant global issue with electric fires. According to the Taipei City Fire Department in 2010, an electrical failure is the most likely reason for fires [62]. Other statistics from South Korea documented 43,875 fires that led to a direct loss of $234 million in 2011. These incidents resulted in 263 deaths and 1,599 injuries based on data from the Korea Electrical Safety Corporation. Consequently, arc fault-related fires made up about 73% of the electrical fires. Despite these concerning figures indicating electrical fire hazards in Korea at this time Arc Fault Circuit Interrupters (AFCIs) have not been put into practice as a preventative measure against such incidents. These statistics demonstrate the significant financial and safety implications that low-voltage electrical fire incidents can have, further emphasising the importance of addressing this issue to minimise both human suffering and economic losses in various settings.

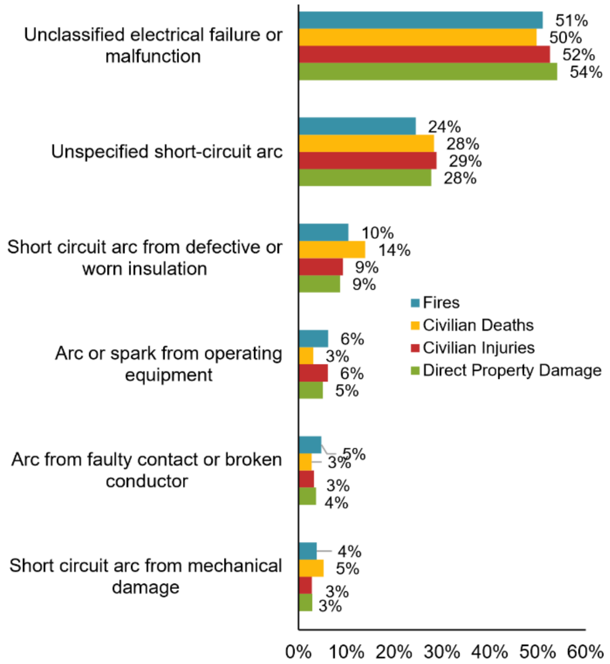


Figure 1 Home Fires Involving Electrical Failure or Malfunction by Factor Contributing to Ignition, 2012-2016 [18]

The primary factor contributing to these electrical fires is arcing, as indicated by the data set from the United States. Based on the data gathered from the 2018 NFPA Journal, Figure 1 demonstrates that residential fires resulting from electrical failure or malfunction primarily occur due to arcing. Arcing is the unintentional discharge of electrical current between two conductors. Arc faults, if allowed to persist and with a sufficiently high current, can generate enough heat to trigger a fire. Arc difficulties occur due to damaged conductors and connectors, which can include damaged wiring, worn-out appliance cords, loose connections, or faulty switches and junction boxes. Arc faults can occur in several areas inside a residential setting or nearly any electrical device or apparatus [18]. These figures highlight the significance of tackling arcing as a key contributor to low-voltage electric fires. It is essential to prioritise the mitigation of arcing as a leading cause of low-voltage electric fires to reduce the financial damages and safety hazards linked to these occurrences.

Collaborative efforts between researchers, industry stakeholders, and electrical service providers like Powerco Ltd. are crucial for advancing our knowledge in this field and implementing effective preventive measures. In summary, the research on low-voltage arcing fire hazards is motivated by the pressing need to improve electrical safety in various settings and prevent potential devastating fires that can result in property damage, injuries, and even loss of life. Figure 2 illustrates the rapid combustion of these pillars, highlighting their potential as a fire hazard.

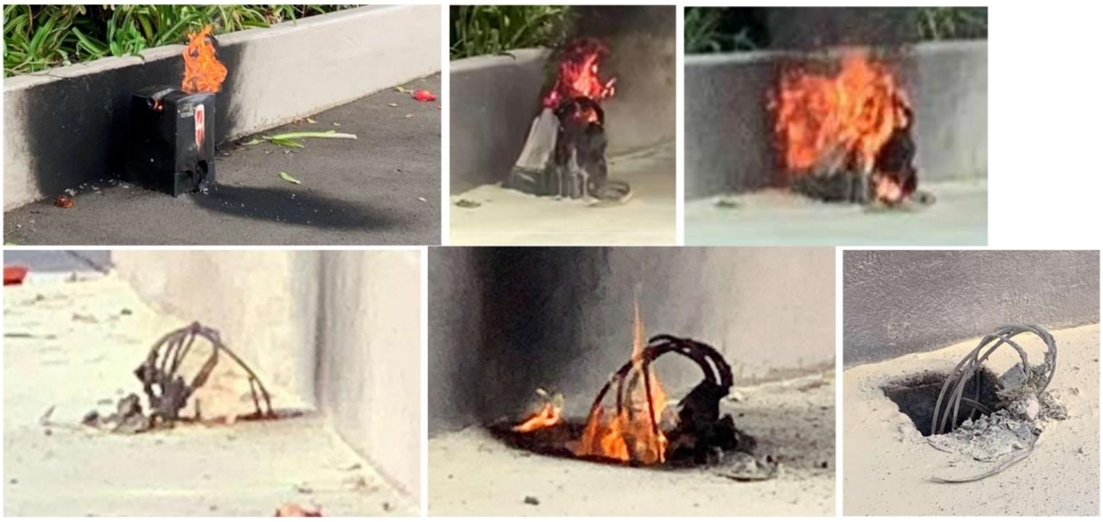


Figure 2 LV Pillar Fire Progression Over 90 Minutes [1]

1.3 Aims and Objectives

The objectives of this project were to evaluate the failure modes of the internal components in low-voltage pillars. The project aims to develop optimised proof-of-concept laboratory testing methods to simulate low-voltage arcing and assess its potential impact on pillar enclosures. Additionally, this project aims to identify potential protection and detection mechanisms to mitigate the risk of low-voltage arcing and pillar fires.

- Research to understand what the process is of a hotspot turning into a fire at an LV plastic pillar. Theorise the process and which measurements we could use to verify and understand the process. Then study how this process can be verified by experimental measurements.
- Understand the progression of a hotspot in an LV plastic pillar to a full-blown fire and

identify measurable parameters that can be used to validate and comprehend.

- Design experiment setup based on the measurements and processes that are expected from the literature review.
- Organise collaboration with network stakeholders and testing laboratories. Build the setup and decide how many experiments will show that the experimental setup works to verify our theory and improve the measurements and experiment.
- Process and analyse measurement data. Understand the ignition process and describe it in detail. Come up with recommendations of measurements that could be done in the field to detect deteriorating connections. Identify gaps in our theory based on the measurements.

1.4 Thesis Outline

In order to achieve these goals, taking into account the extent of this study, a blend of model theorisation and practical experimentation has been carried out. Thus, this thesis is structured into the subsequent chapters to outline the steps followed to accomplish the study objectives and also visually outlined in Figure 4.

Chapter 1 provides an introduction to the problem of low-voltage arcing in pillar enclosures and outlines the aims and objectives of the project.

Chapter 2 reviews the current literature on low-voltage arcing and its potential impact on pillar enclosures. It explores the existing knowledge on failure modes of internal components, fire progression, and protective measures.

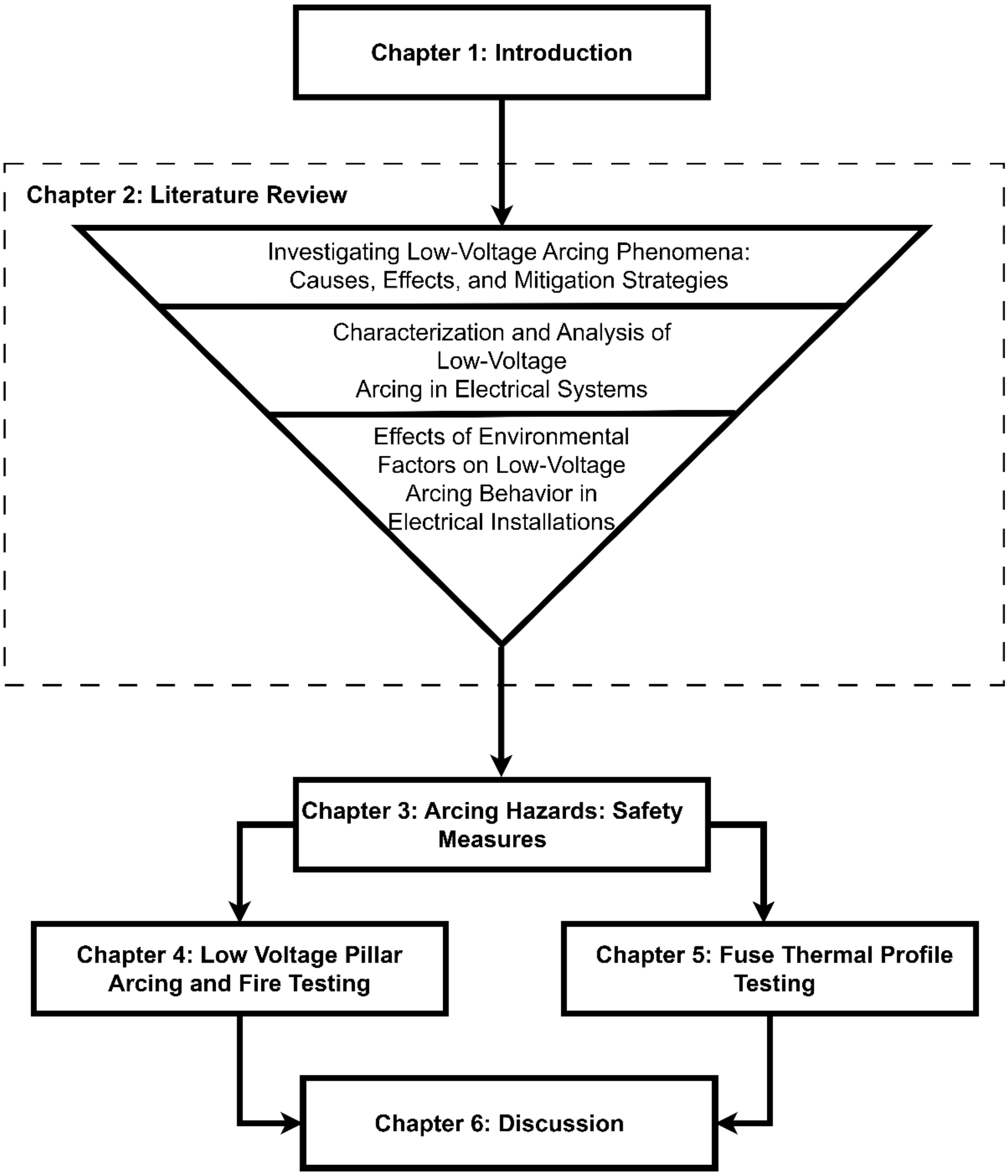
Chapter 3 looks into the safety standards and regulations relating to laboratory experimentation of low-voltage arcing and pillar fires to ensure compliance and ethical conduct.

Chapter 4 discusses the methodology used in this study, including the theoretical model development and the experimental setup design on generating a LV Hotspot. Further going over the theoretical framework for understanding the process of low-voltage arcing in pillar enclosures and outlines the measurements that can be used to verify and understand the process.

Chapter 5 presents the results and analysis of the experimental data from a case study with PLP on their take of how LV Hotspots are formed, highlighting the progression of a hotspot in an LV plastic pillar to a fire and identifying measurable parameters. This chapter goes into detail and focuses on the collaboration with network and laboratory partners to build the experimental setup and determine the number of experiments necessary to validate the theory and improve the measurements and experimental setup.

Chapter 6 concludes the thesis by summarising the key findings from the literature review, discussing the implications of the study's results, and providing recommendations for future research in the field of low-voltage arcing and pillar enclosures.

Figure 3 Overall Thesis Structure



Chapter 2
Literature Review

This chapter will examine the causes behind electric arc fires, including the elements that lead to their happening and the possible dangers they present. This chapter is segmented into seven sections to offer an in-depth examination of electric arc fires in power systems. It also reviews the current literature on low-voltage arcing and its potential impact on pillar enclosures. It explores the existing knowledge on failure modes of internal components, fire progression, and protective measures.

2.1 Understanding the Causes of Arcing
2.1.1 Requirements for Arcing

Arcing is the phenomenon that occurs when an electric current flows through an air gap or across a surface [42]. This can happen when there is a high voltage difference between two conductive objects or when there is a breakdown in the insulation material. Given the release of a large amount of energy, arcing can cause injuries to personnel in the immediate vicinity or damage equipment. This energy is released in the form of light, heat and electromagnetic radiation which can result in burns, fires, and even explosions [43]. Arc temperatures can range from 2,800 to 19,000 °C, exceeding the heat of the sun, and can cause arc explosions that generate pressure waves. To understand the occurrence and impact of arcing faults, it is important to examine the characteristics of these arcs and measure the relevant metrics.

Researchers that have investigated electric arcs have determined that a specific threshold of voltage and current is required for an electric arc to occur. The values are contingent on the electrode material, with recorded values of 11.0 V and 0.45 A for copper electrodes [14]. Voltages below this threshold may result in discharges, typically referred to as sparks due to their short duration. This implies that the minimum power of an arc is equivalent to the multiplication of these minimum values of voltage and current, which equates to 4.95W. Research conducted by [63], using a 2000-5000 VAC power supply, demonstrated that 1W of power was typically sufficient to sustain an arc, while in certain cases as little as 0.2W was adequate depending on the circuit's resistance. Furthermore, due to the transient aspect of the conductance of hot air, the variations of conductance of air due to temperature also plays a role in the arcing phenomenon [64].

2.1.2 Implications of Poor Connections

Arcing can manifest in various ways. Unintentional series arcing, resulting from damaged line cords and loose connections, can provide a significant fire and safety risk under specific conditions [6]. This aligns with research instigated by [5], who identified that most series arcs are produced by a loose cable or a broken wire that introduces a small gap in the conductive path. This small gap can create an electrical arc as the voltage tries to bridge the interruption in the circuit [44]. The behaviour of these electric arcs can be reconstructed in laboratory experiments by decoupling two electrodes that were previously in contact. Section 2.7 delves deeper into generating arcing through laboratory experimentation.

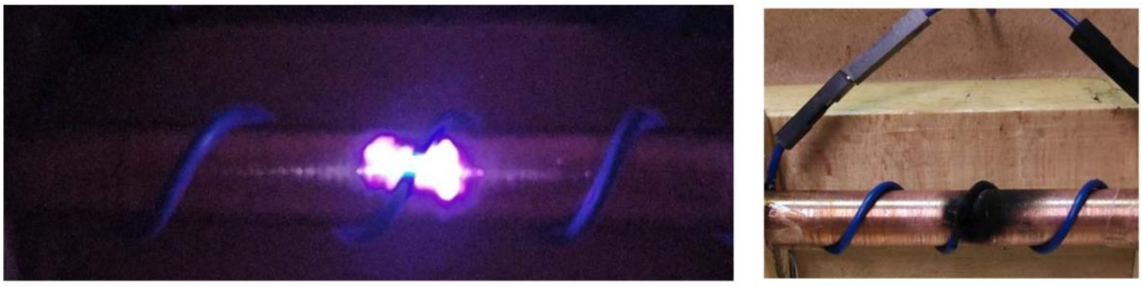
The National Fire Protection Association (NFPA) has highlighted poor connection as a leading cause of electrical fires. It occurs in the wiring between the power supply and end-use devices. Incorrect circuit switching caused by a weak connection can result in high temperatures and potential ignition, depending on the environment. Mechanical factors are important in series arcs because slack cables or broken wires can create gaps in the conductive circuit, which affects the properties of the arc [5].

Another study supports the idea that loose connections are an instrumental factor in causing arcing and also indicates that faulty wiring (line or neutral) can lead to series arcing [25]. Series arcing can occur from the make-and-break action of a damaged connection [6]. The study [6] shows that even with a series arc from 115V applications at 20A, the resulting plasma is hot enough to burn insulation in close proximity to the arc. The burnt or charred insulation can adhere to the wire, turning it into an effective thermionic emitter. This leads to another issue as short-duration arc tracking may happen due to the presence of carbonised paths that serve as semi-conductive layers or pathways, resulting in more arcing [17]. Short-circuit arcs between the defective polymeric insulated wire and another wire can cause partial thermal carbonisation of the insulation, leading to conductivity on the insulation's surface. Small leakage currents passing through the contaminated area deteriorate the base material, leading to arc discharge, charring, or burning adjacent flammable substances [15].

2.1.3 Implications of Surface Contamination and Arc Tracking

A burnt/ charred insulation is only one type of surface contamination that can cause arc tracking. This is particularly the case in polymeric materials where the insulated surface is contaminated with partially conductive moisture, conductive liquids, dust, or salts [15]. This concept of wet tracking can be a major concern for outdoor electrical installations in areas of high humidity and or rainfall [62]. The ASTM D3638-12 standard concerning wet tracking is associated with this issue. The ASTM D3638-12 uses a standardised practice that assesses the LV track resistance or comparative tracking index (CTI) of materials in the presence of aqueous contaminants. Dry tracking is a less frequent occurrence where a carbonised pathway forms in the absence of moisture. The typical test for this tendency involves creating an electrical arc on the insulator's surface to assess the ease with which a path can be constructed [17].

Arc tracking is prevalent due to the inherent benefits of polymeric materials. Polymeric materials are lightweight, flexible, cost-effective, and provide outstanding insulation and dielectric qualities. Nevertheless, this incurs a penalty because of their inherent chemical properties. Given the sufficient voltage applied, polymeric materials are susceptible to damage from arc tracking because they consist of organic carbon bonds, which get altered by arcing. Consequently, their resistance to electrical discharges is significantly lower compared to inorganic insulator materials such as glass or porcelain [15].



(a) (b)

Figure 4 Initial Corona Discharge at 10kPa under 600V-50Hz (b) Effect of Arc Tracking in a Conductor [15]

Electrical tracking is the evolution of surface partial discharge (PD) activity on organic materials, which poses a substantial threat to insulation integrity. The breakdown of polymers is caused by strong thermal shocks due to a high influx of electrons. These shocks cause the rupture of polymeric chains, leading to the formation of carbonised conducting pathways and triggering a shift from an insulating to a conducting state [15]. The tracking paths expand, diminishing the area of intact insulation, and the applied voltage creates more carbonised paths, resulting in flashovers or breakdowns, which present a fire risk. A self-sustained arcing phenomenon, known as arc tracking, can cause ignition in different systems, such as 12-volt automotive wiring. Figure 4 displays the initial corona discharge and the impact of arc tracking in a conductor [15].

Arc faults in low-voltage building circuits can occur due to intermittent contact between metal points caused by ageing or corroded wires. These faults are classified into series, parallel, and grounded forms [25]. Comprehending electrical tracking and arcing phenomena is essential for averting fire threats and guaranteeing electrical safety.

2.2 The Mechanisms of Ignition Caused by Arcing

2.2.1 Main Mechanisms from Previous Studies

Indications of overheating from a 'hot connection' include: melted and distorted plastic, evidence of pyrolysis (incomplete combustion) including blackening, soot, and cable insulation becoming brittle, and symptoms of high-temperature corrosion. These potential fire hazard conditions can be generated by currents as low as 0.9 Arms at 115 Vac with a 100W bulb load [6]. The phenomena of heated and glowing connections have been investigated through tests conducted by [6], [9], [17], [20], [27], [28] and [65].

Figure 5 The Fuse Holder Top is Stuck to the PE Pillar Lid and the Lid Shows Signs of Sooting and Melting. The Mounting Plate Shows that the Plastic Has Melted and Dripped Away Behind the Hot Connector.

Photographs of actual pillars in the network, as shown in the Figure 5, reveal the harm caused by hot connections to the fuse holder, cables, and pillar housing. In [66], the data gathered from inspections, defect reports, and undisclosed reports to utilities are consistent with the results of laboratory testing on PVC and PE concerning decomposition and fire behaviour.

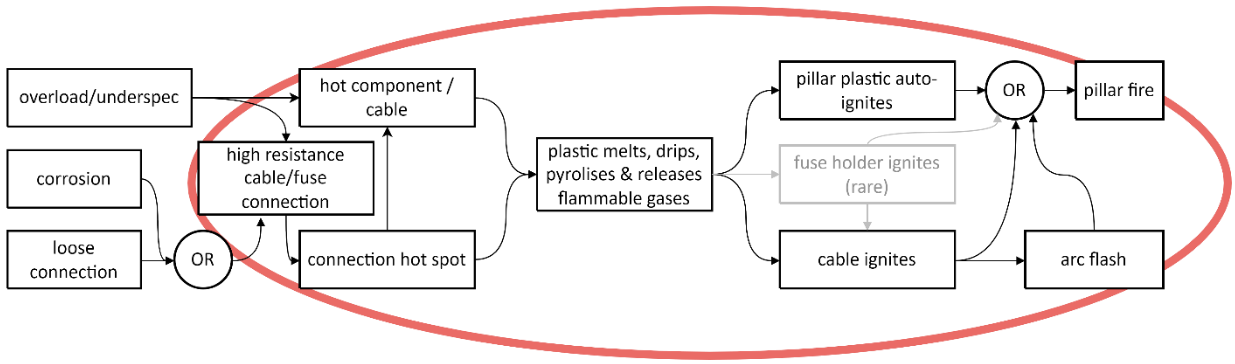


Figure 6 The Progression From Defective Component to Pillar Fire [1]

Cuppen's hypothesis is that the presence of a hot spot near the fuse holder is due to series arcing between the wire and the grub screw [1]. As a result, the wire heats up, leading to the ignition of the PVC insulation. This spark triggers a cable fire, which then causes the PE base, mounting plate, or lid to catch fire. Figure 6 depicts possible steps leading from the root cause to a pillar fire. The defective wires and fuses observed during inspection align with findings from laboratory investigations and experimental results related to PE pyrolysis by [24], PVC pyrolysis by [23], [17], and [25]. In addition, [29] demonstrated that the flame conduct of the housing material corresponds to the behaviour of PE.

The riser cable is commonly a 16 mm^2, 24 mm^2, or 32 mm^2 copper PVC insulated cable. The thermal degradation of a PVC-insulated wire is as demonstrated. [25]. An electrical discharge at the end of a copper PVC insulated wire can generate enough heat to ignite the PVC material. The time to ignition is determined by the AC fault current level, wire diameter, insulation thickness, and ambient temperature, as indicated by experimental results. They demonstrate that a minimum fault current is necessary to get the temperature to the igniting point [25]. According to [17], loose connections and arcing are the main causes of electrical fires in homes in the USA, as seen in Table 1.

Table 1 Physical Mechanisms causing electrical fires in residences in the USA [17]

Mechanism	Importance
poor connections	most
arcing across a carbonized path	↓
arcing in air	
excessive thermal insulation	
overload	
ejection of hot particles	
dielectric breakdown in solid or liquid insulators	
miscellaneous phenomena	least

2.2.2 Other Related Concepts

The ignition time and current have an exponential function correlation as seen in the Figure 7 below. An exponential decrease in the ignition time of PVC insulated wire occurs as the arc current increases, attributed to the elevated temperature of the arc [25]. A wire with a bigger cross-sectional area takes longer to be lit with the same current in an arc. Flame spreading on an inclined electrical wire can be influenced by gravity's impact on the molten insulator and buoyancy-induced flow, affecting the heat transfer balance between the flame and the wire [50].

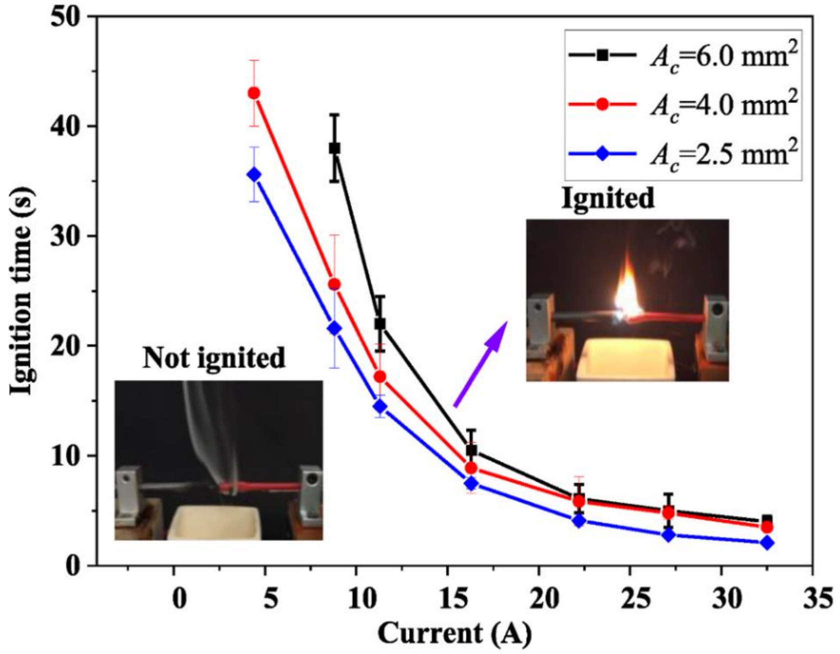


Figure 7 The Ignition Time of the at Different Currents [25]

Another important microconcept researched by [50] is that charged particles can affect the size and form of a spreading flame and, consequently, the Flame Spread Rate (FSR) through the Lorentz force. The conclusion was that applied electric fields affect the dynamic behaviour of molten insulators, leading to the spread of flame.

2.3 Characterisation and Analysis of Low-Voltage Arcing

2.3.1 Electrical Factors

The electrical characteristics that are important for characterising low voltage arcing include voltage levels, current levels, arc duration, and arc energy. These characteristics aid in comprehending arcing behavior and its effects on the electrical system. Voltage levels during low voltage arcing can vary depending on factors such as pressure. Other factors such as the type of insulation material, ambient temperature, and arc gap distance can also influence voltage levels. Additionally, the current levels during low-voltage arcing play a crucial role in determining the severity of the arc and its potential damage [45]. Table 2 & 3 in the Appendix summarise arcing factors.

Arc voltage is the voltage measured between the two electrodes across the gap. An initial arc voltage is necessary to start the arc, and this voltage rises until the arc is extinguished. The voltage can either remain steady, sustain an arc, or self-extinguish depending on the length of the gap [5]. DC circuits operate differently from AC circuits. AC circuits exhibit polarity reversal, while DC circuits have a constant current flow in one direction [46].

Arc current refers to the current that passes through the gap. The current of an arc exhibits an inverse relationship with arc voltage. It rapidly decreases at arc initiation and continues to decline as arc voltage increases until the arc is sustained, or it will drop to zero if the arc is extinguished [5]. The current density in an arc is high while the voltage drop is low. The current density at the cathode can reach up to one megaampere per square centimetre. The energy lost in the arc increases in direct proportion to the square of the current and the duration of the arc [41].

Series arcs exhibit resistive behavior with highly nonlinear arc resistance due to the volatile characteristics of the arc phenomena. Arc resistance can be determined by measuring the arc voltage and current at each instance and is typically averaged across the stable burning phase [5].

The influence of inductive elements on electrical systems is significant as they introduce resistance to changes in current, leading to slower variations. Higher levels of inductance also increase the time for electrodes to vaporise metal, contributing to the development and prolongation of series arc faults. In contrast, capacitive elements play a mitigating role by restricting the rate at which voltage changes occur, lowering the possibility of rapid fluctuations in gap voltage. This results in lower current density on the electrode, reducing its susceptibility to melting and forming a plasma channel across the gap. The addition of capacitance reduces the likelihood of arc generation. Tests have shown that lower capacitance values are associated with sustained arcs, while higher values result in more open circuits [13].

2.3.2 AC vs DC Differences

AC arcs typically self-extinguish because the current alternates and changes direction at the zero-crossing point. In DC circuits, polarity reversal does not happen, leading to a stable arc voltage during low-voltage arcing. DC arcs do not travel through zero voltage, hence, to extinguish the arc, the voltage must be increased exceeding what the circuit can tolerate by disconnecting the contacts. This difference is the reason that DC arcs have a longer burning duration than AC arcs, and the polarity of a DC arc remains steady, unlike the changing polarity of an AC arc. Prolonged DC arcs will lead to increased degradation of the contacts [65]. Therefore, circuits with equal power levels will necessitate more sophisticated contact materials and/or larger contacts to minimise the arc erosion that occurs in DC contacts. Due to the continuous polarity of the arc in DC contacts, one contact will experience higher wear than the other. This issue can be reduced by utilising asymmetric contact materials or varying contact sizes. The direction of the asymmetric wear is determined by the switch design, where short arc duration typically leads to greater anode erosion and long arc duration usually results in cathode erosion, providing the contact geometries and materials are similar [65].

2.3.3 Implications of these Characteristics in Research

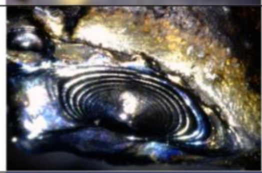
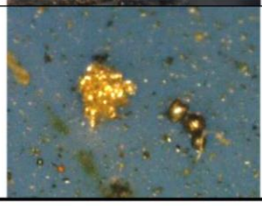
[24] conducted a study that highlights the various factors influencing the intensity of arc faults, such as current, electrode material and size, and the gap between electrodes. Through experiments on a 6 mm^2 wire at 22.2 A, they observed that higher heat generation under high currents led to faster ignition and heat transfer to the copper core of the wire. The cumulative ignition probability values for Heat-Resistant PVC Insulated Wires (HIV) wires at 220 V based on the UL 1699 standard indicate challenges in directly applying this to domestic electrical environments due to an ignition probability exceeding 50%.

The study [20] performed tests involving small series arcs at points of contact and found a voltage drop across poor connections, with 90% of it occurring in specific parts of the wire above and around the screw. The paper further discusses these findings by stating that connection voltage drops represent most measured voltage drops, leading to corresponding power dissipation calculations.

[10] examines the comparison of series arcing faults in residential wire at 240 Vrms and 120 Vrms. The study aimed to elucidate why there is a higher likelihood of ignition at 240 Vrms and to conduct initial tests to ascertain if ignition can occur within shorter durations than those suggested by the "fire curve." This investigation emphasises the significance of comprehending voltage fluctuations in residential environments for preventing arc faults effectively.

An overview of characteristic traits of damage from arcing can been seen in the Table 2 below. These characteristics describe how physical deformities can lead to arcing and subsequent damage.

Table 2 Overview of Characteristic Traits of Damage from Arcing [27]

Characteristic Trait	Additional Details	Example Photograph from Arcing Damage
Corresponding Damage on the Opposing Conductor	Damage located on another conductor proximate to the area of interest and in a location where arcing was possible.	
Localized Point of Contact with Sharp Line of Demarcation	N/A	
Round, Smooth Shape	Some or all of the damage is rounded without jagged or rough surfaces and edges.	
Resolidification Waves	Concentric rings emanating from the center of the arcing damage.	
Tooling Marks Visible Outside Damage Area	Stamped lettering, copper drawing lines, crisp edges of receptacle components remain outside of the arcing location.	
High Internal Porosity	Large percentage of voids internal to the arc damage.	
Spatter Deposits	Small spherical globules ejected during arcing; can be located on surfaces away from the arcing location.	

2.4 Effects of Environmental Factors on Low-Voltage Arcing Behavior

2.4.1 Typical Environmental Factors

In the examination of arc faults, it is vital to take into account the surrounding environmental conditions as they have a significant impact on the behavior of the arc. Environmental factors such as temperature, airflow, pressure, and humidity have been identified as key influencers. The use of environmental chambers allows for precise control over these factors during arc testing by maintaining specific and consistent test conditions including adjustable temperature and pressure [5].

Temperature is a fundamental factor that affects arc fault characteristics. Studies on photovoltaic systems indicate that with variations in temperature within a range from -20°C to 60°C, there is an increase in arc fault current. Temperature not only impacts arc fault current but also influences string current and voltage which can affect the operational point of a photovoltaic system. However, quantifying this influence proves challenging due to unique electrical characteristics [5].

Airflow across the arc gap also has a significant effect on arc characteristics until it is shielded by electrode gaps according to experimental findings. Additionally, standards like UL1699B incorporate polymer covers resembling typical DC cable connectors impacting plasma discharge sustainability.

Pressure changes in aircraft environments significantly influence various aspects of arcs such as sustaining series arcs becoming more challenging at higher altitudes or lower pressures leading to varied extinction times affecting electrode gap extension occurrences. Humidity holds potential for influencing air properties and contributing to arc formation; however not many studies explore its direct impact on series arcing particularly among aircraft environments where understanding controlling these environmental factors are crucial for accurate testing against faulty machinery. Copper and copper alloys are corrosion-resistant to dry gases at or below room temperature. Copper alloys are more susceptible to corrosion in liquid/vapor chlorine conditions and at high temperatures. [27].

2.4.2 Other External Influences

Tooling markings are a result of the production process of metal components used in receptacles and wiring. These processes can create a regular pattern on the surface or produce a distinct shape. Tooling marks consist of distinct edges and letters on stamped and bent brass and steel receptacle parts, as well as copper drawing lines on copper wires. When subjected to temperatures close to the conductor's melting point, these tooling marks may start to deteriorate. 80% of conductors with arcing damage showed tooling markings outside the damaged area [27]. This indicates that maintenance and installation humans' errors lead can lead to arcing and then associated pillar fires.

2.5 Glowing Connections

2.5.1 Concept

The existing studies on the behavior of glowing contacts, especially those created from loose or damaged copper conductors in electrical systems such as outlets, switches, and line conductors, are not extensive. This occurrence includes a situation where a loose or damaged wire connection experiences intermittent make/break conditions when under load. This leads to series arcing between the conductors and results in the creation of a semi-conductive film made of copper oxide at the interface.

It has been documented that researchers have the ability to produce glowing connections using minimal currents of 0.25 A [8]. Additionally, excessive surface arcing presents another fire risk as insulation may overheat and catch fire due to a glowing contact or breakdown occurring on charred insulation surfaces [8].

2.5.2 Glowing Bridge

The creation of this oxide can lead to an overheated resistive connection, which may result in the formation of an oxide bridge made of copper and copper oxide at temperatures higher than 1235°C [8]. This temperature is significantly above the melting point of CuO as well as the vaporization temperature of polymeric insulation commonly used in wiring [8]. The heat generated by the glowing connection can spread to overheat nearby insulation that is not directly connected to these hotspots.

Arcing can result in the formation of oxides that may impact the measured resistance, especially during switching duty currents, leading to an increase in resistance [7]. Research has shown that the resistivity of the CuO bridge changes with temperature. Furthermore, Japanese researchers have observed distinct effects on copper contacts due to arcing, such as the creation of a winding "worm" within the oxide bridge [8] as seen in Figure 8.

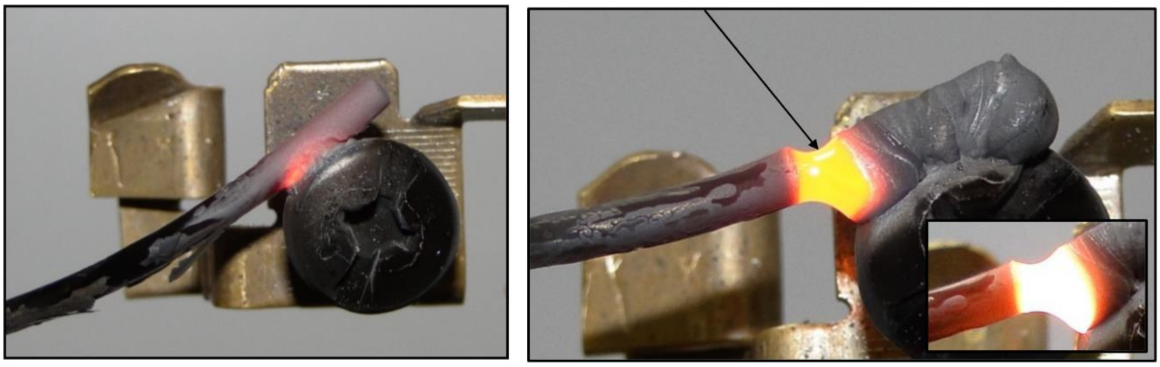


Figure 8 Glowing Contact Progressing into a Oxide Bridge [20]

The dynamic resistance surges with each occurrence of the voltage, current, and power reaching the zero-crossing point simultaneously. As proposed by Shea in 2006, this fluctuating resistance is attributed to temperature variations at 60Hz, particularly as the material undergoes cooling during the power zero crossing points. It is noteworthy that the Copper oxide bridge has the capacity to reach temperatures as high as 1800 degrees Celsius [73]. This temperature poses a severe fire hazard.

2.5.3 Insulation Testing

The study [6] highlights the significance of comprehending series arcing occurrences in polyvinyl chloride wiring, which is widely employed in consumer devices. The research indicates that under certain conditions, glowing contacts and arcing over the surface could cause PVC wire insulation to overheat, resulting in decomposition and the production of flammable gases that may be ignited by the series arc.

The experiments in [6] demonstrated that when PVC wiring is exposed to fire, it has a tendency to form a char layer and put out the flame at room temperature. However, at higher temperatures, especially close to or above its melting point, PVC does not self-extinguish but instead burns easily. The research indicates that the presence of ultra-fine calcium carbonate in the insulation might lead to decreased breakdown strength and increased moisture formation, which can further increase the risk of fire.

Moreover, elevated temperatures resulting from glowing contacts or arcing may cause gaseous compounds within the PVC wire to break down, producing highly flammable gases in the presence of oxygen. The combustible mixture formed from these gases occurs between their lower and upper explosive limits. These limits indicate the potential for dangerous fire incidents during overheating.

[8] conducted experiments using a gas chromatograph to analyse and measure the gases produced from pyrolyzing insulation. The study demonstrated the flammability of these gases when mixed in air and found that factors such as current level affected the number of make/break operations needed to create a glowing contact or charred insulation.

2.5.4 Influence of the Conductor Type

In another investigation, [20] discovered that copper and steel consistently formed overheating poor connections with a point contact and low force holding the metals together. This led to the formation of a semi-circular oxide mass growing inside the wire, known as "nugget," which ultimately separated from the wire during liquid burn-open observed in long-term trials of poor connections.

Additionally, [8] explored different material combinations and identified variations in behavior between copper- and steel-based materials. Specifically, the study noted distinct glowing voltage waveshapes, indicative of differences in oxide melting points. Copper-based materials exhibited filament-like molten glow, whereas iron-based materials displayed slower oxide growth within their glowing zone. These differences are illustrated in Figure 9.

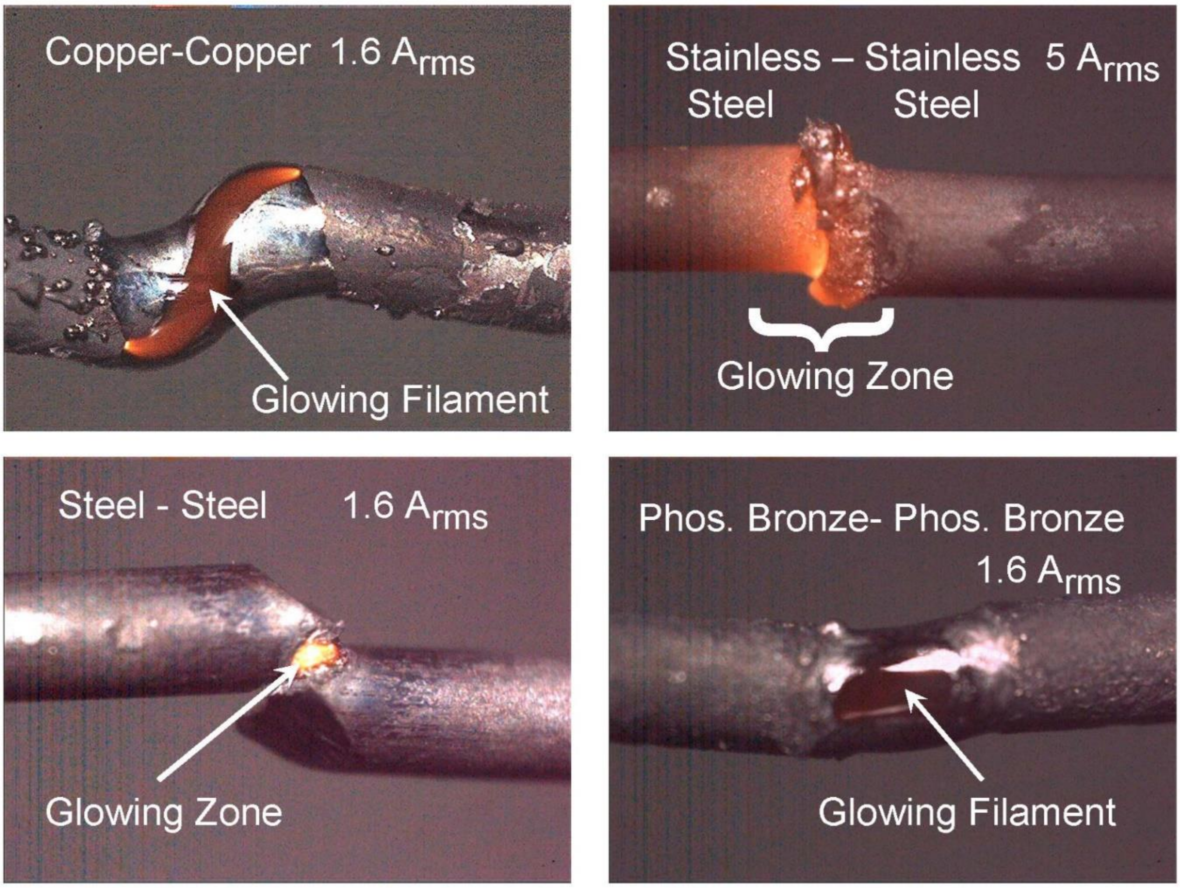


Figure 9 Different Contact Materials Glowing Contact Progressing into a Oxide Bridge [20]

[9] undertook research on the development of glowing connections in DC circuits and brought attention to the potential fire risk associated with low-voltage DC connections. The study observed glowing connections in both copper and steel conductors, with their behavior influenced by the material and polarity. This research emphasises that DC circuits could pose an electrical fire hazard similar to AC circuits, especially when exposed to low DC voltages

2.6 Material Impact on Arcing: Influential Factors and Considerations

2.6.1 Thermal Degradation

The thermal degradation process, known as pyrolysis, is crucial for understanding the combustion characteristics of different polymers in photovoltaic (PV) systems and evaluating their susceptibility to fire. Conclusions drawn in [31] recommend a trip time of less than 2 seconds for switchgear to prevent fire initiation during arc-fault events in PV systems. Understanding system faults and the burning properties of various polymers are essential for preventing fire incidents.

Pyrolysis entails the heat-driven decomposition of organic materials without oxygen, resulting in the production of products such as liquid and gaseous fuels, carbon, and substitutes for petrochemicals. This process occurs within temperatures ranging from 300 to 900°C and has applications in plastic waste conversion, biofuel generation, as well as substrate coating with pyrolytic carbon catalysts can enhance the effectiveness of pyrolysis by facilitating three main stages: Heating, Decomposition, and Ignition to initiate combustion [17].

Microscale combustion calorimetry, which investigates polymer and ternary mixtures, confirms that the flammability of columns is affected by formulation components like additives, plasticizers, and solvents. LV pillars typically utilise polyethylene with specific characteristics including an internal volume of 8 dm^3 and a melting point of 120°C [74]. Additionally, they have flash-ignition and self-ignition temperatures of 340°C and 350°C respectively.

2.6.2 Contact Materials

Examination results on contact materials indicate that contact surfaces with more than 73% silver content exhibit lower temperatures when no current is flowing [7]. However, as the number of arcing operations increases, the temperature rises due to strong field emission and rapid evaporation of silver. On the other hand, contacts made of tungsten or graphite with less than 65% silver concentration experience cathode surface emission and arc plasma column breakdown, which affects dielectric recovery after zero current [7]. Conversely, it was observed that contacts containing over 73% silver concentration have a significant impact on dielectric recovery due to arc plasma column breakdown.

Copper conductors bearing normal loads may develop arcs between them, which will stop at the next current zero in the AC waveform [6]. Contact resistance in circuit breakers is impacted by the amounts of arcing current, leading to silver depletion on contact surfaces and causing fluctuations in temperature rise, as stated by [7]. Most electrical wire insulation, often PVC-based, can provide safety risks because of char and ignitable smoke.

Research shows that copper and steel, when used as base metals, create weak connections with low-pressure contact points, leading to overheating and impacting electrical characteristics [20]. Defective wiring or insecure connections in 115V systems can lead to series arcing, resulting in charring and sustained arcing caused by carbon's thermionic emission characteristics.

2.6.3 Findings on the Low-voltage Pillars

The conclusions from [66] tests and observations on plastic pillars are: Plastic pillars burn self-sustained, confirming literature and laboratory test results. Materials used in different pillars are similar, showing little practical difference in response to fire exposure. The melting point of materials (LDPE or MDPE) ranges from 100 to 140°C. The burn rate is low, at less than 40 mm/min horizontally. There is no significant practical difference in fire performance between field-aged and newly purchased plastic pillars. Due to the energy and heat released from LV arcs, these LV pillars are very susceptible as a fire hazard due to their flammability and low melting points.

2.7 Exploring Diagnostic Techniques for Early Detection of Low-Voltage Arcing Faults

2.7.1 Arc Fault Diagnostic Methods

Arc fault diagnostic methods are essential for the detection and avoidance of electrical arc faults. Research from [5] stress the relevance of identifying the location of arcs when analysing DC arc faults in aircraft electrical systems. The research indicates that voltage and current features during arc faults vary depending on the location of the fault, underscoring the need to develop Arc Fault Detection Devices (AFDD) tailored to operate at specific network locations. The researchers highlight that employing a single AFDD at various points may result in its ineffective operation.

[70] explores different approaches to identify DC arc faults by examining their physical or electrical attributes. Specific sensors and data collection systems can be utilised to analyse physical indicators like sound, light, and electromagnetic radiation signals. For instance, acoustic sensors and infrared meters are employed for detecting arcs caused by switching actions, while antennas are used to capture electromagnetic-radiation signals in PV systems. In terms of electrical characteristics, the analysis involves studying arc current features within the time and frequency domains where variations in amplitude within the arc current spectra indicate potential arc faults.

The significance of arc fault protection is emphasised by both underwriter's laboratories and national electrical codes. In 2011, UL introduced standard UL 1699B for arc fault protection in PV systems, while the U.S. National Electrical Code required arc fault detection devices in PV systems with a rated voltage exceeding 80 V during the same year. Additionally, China enacted a national standard for arc protection in PV systems in 2021, which mandates the installation of arc protection devices that activate within 2.5 seconds when an arc fault occurs [70].

2.7.2 Challenges and Difficulties

[25] discusses the difficulties that manufacturers encounter when differentiating between unintentional series arcs and deliberate series arcing in distribution equipment and loads. The challenge is to accurately distinguish between the two within a current range of approximately 0.2 A (minimum glowing limit) up to 20 A (standard upper MCB rating). The authors emphasise that over-current protection devices can easily identify parallel arc faults and grounded arcs with high currents, but they face difficulty in detecting series arc faults, which do not cause a significant increase in current flow.

The paper [71] examines the time needed to create an overheated contact, highlighting the significance of monitoring overheated electrical joints. Their research presents results on the duration for forming overheated contacts at different levels of current and tightening torques. The study suggests that a direct temperature monitoring system may not be effective unless each joint is monitored individually.

[1] highlights smart meters as potential devices for identifying and monitoring arcs. Smart meters' ability to continuously monitor voltages and currents is valuable for detecting conditions such as voltage fluctuations, intermittent arcing, electrical faults, and high-resistance connections. The article explores different methods of arc detection including acoustics, magnetic fields, and electromagnetic radiation while stressing the significance of using smart meters for comprehensive monitoring of the LV distribution grid. There is a concern about the practical application of smart meters due to their low frequent measurement recordings. Arcing incidents may be temporary and transient, making it possible for them not to be captured in smart meter data if recordings are only taken hourly.

Current and voltage patterns may occur before such failures (Figure 10), resulting in fires, which are ideal for real-time detection [1], and can be well-suited for gaining a deeper insight into the failure-to-fire process. This research involves gathering data to evaluate the ignition patterns and failure features of electric fires in low-voltage pillars. By analysing the voltage and current waveforms, as well as monitoring internal and exterior temperature and gas development in low-voltage pillars, diagnostic procedures can be created to establish preventive measures to decrease the frequency of pillar fires. Diagnostic procedures may include the use of switchgear similar to that in Table 3.

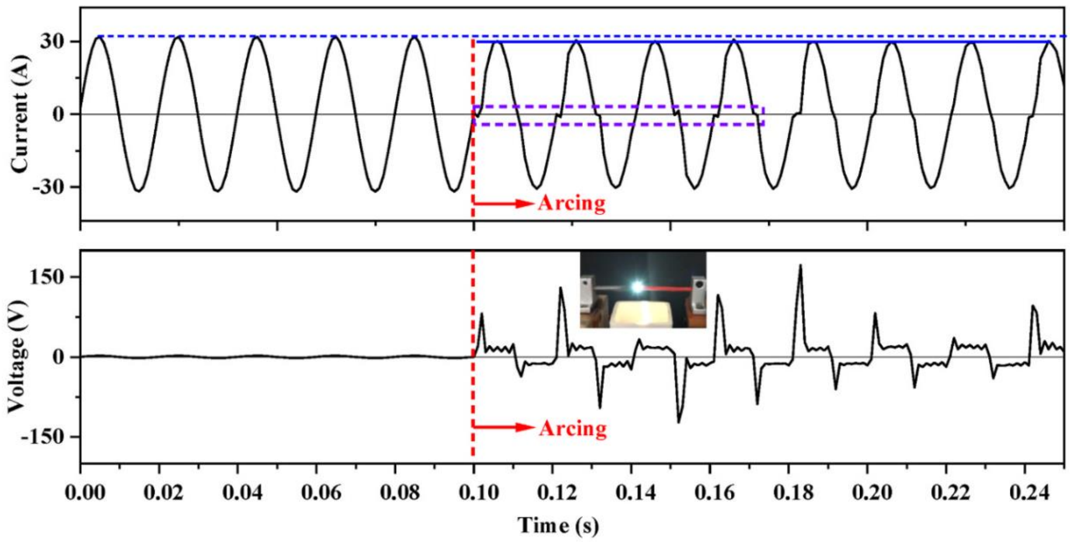


Figure 10 Example Waveforms of Current and Voltage for the Arc [71]

Table 3 Effect of Current and Torque on the Formation Process of Loose Connections [71]

Test Current (*A*)	Device Tested	Status of Loose Connection	Time led to detection	Temperature at electrical joint when detection occurred
5000	3000 *A* MV switchgear	Completely loose – 0 *in-lb*	~ 5 minutes	~ 36 *C* (temperature was still increasing at the time of detection)
3000	3000 *A* MV switchgear	Completely loose – 0 *in-lb*	~ 25 minutes	~ 56 *C* (7 *C* higher than fully tightened joints)
100	250 *A* rated panel board	6 *in-lb*	~ 3 weeks (power on 8 hrs per work day)	~ 60 *C* (18 *C* higher than fully tightened joints)

Chapter 3
Arcing Hazards: Safety Measures

This chapter presents an overview of the existing safety precautions and protocols related to arcing. The text emphasises the significance of dealing with arc hazards in power systems and underscores the possible dangers linked to arcing accidents. The ideas established in this chapter can be applied to shape the development of experimental designs that prioritise safety in Chapters 4 and 5.

3.1 Safety Protocols to Consider for Arcing Events
3.1.1 NFPA Approach Boundaries

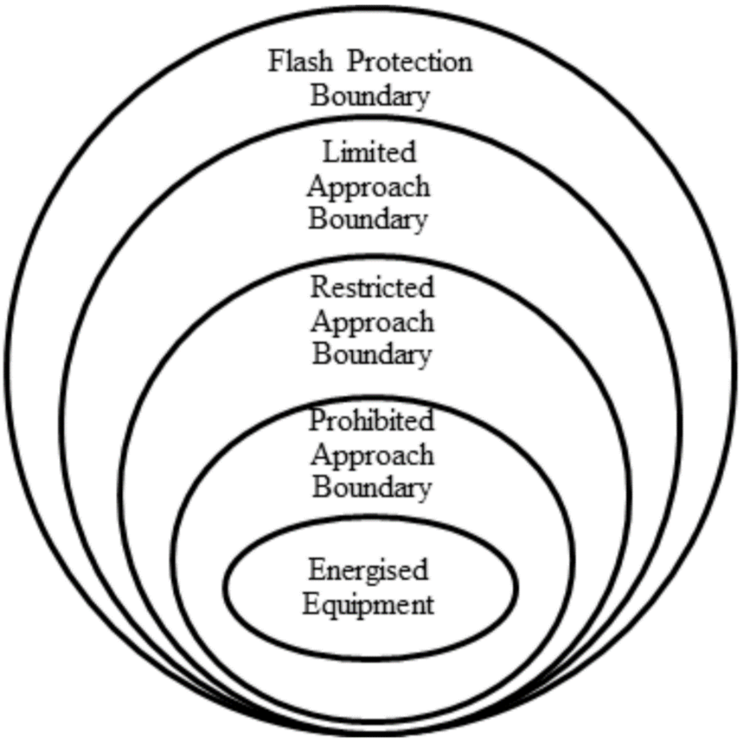


Figure 11 NFPA Approach Boundaries [47]

The National Fire Protection Association (NFPA) has developed a method with protocols to protect workers handling energised materials and equipment. The foundation of this method is outlined in Figure 11:

1. Protection against flash outer boundary: refers to the the farthest and farthest limit from the energy source. If an arc flash happens, employees in this area may sustain less severe second-degree burns that are treatable. The primary concern in this area is the excessive heat generated, leading to burns.

2. Restricted scope: this method is confined to a specific distance from the live section where the danger is present.

3. Restricted strategy: this strategy is confined to a specific distance from the site of an exposed live part where there is a heightened risk.

4. Prohibited approach: this refers to the distance from the exposed component that is typically considered to involve direct contact with the live section. The prohibited approach signifies the closest distance that workers should refrain from approaching to avoid direct contact with live components [47].

By establishing these well-defined boundaries and strategies, the NFPA aims to provide a structured framework for enhancing safety protocols and minimising the risks associated with arc flash incidents. These measures not only protect workers but also contribute to a safer working environment by clearly identifying and addressing potential hazards.

Testing devices may experience arc damage in the event of an arc flash occurring during testing or in real-world situations. Arc flash testing plays a critical role in evaluating and minimising the likelihood of arc flashes. This process allows for the precise identification of hazards and risks associated with electrical equipment within a particular setting. Additionally, it underscores the need to adhere to NFPA boundary protocols to ensure human safety, even if damage occurs during an experiment.

The Arc Damage Modeling Tool, developed by Lectromec, can predict the level of damage depending on circuit and material parameters. Based on over 3,000 arc damage assessment tests, the Arc Damage Modeling Tool (ADMT) is the state-of-the-art for wire failure damage assessment. The ADMT is capable of predicting the damage to both direct electrical arcing (direct contact) and indirect arcing (damage from the arc plume). The generated data can be utilised for national Emergency Warning and Intercommunication System (EWIS) certification, meeting requirements such as 25.1707 and 25.1709.

3.1.2 Environmental Influences

Awareness and control of environmental factors affecting laboratory testing is crucial for the effectiveness of an experiment. Issues with the precision of experimental safety can often arise from small particles present in the surrounding area. Dust or fine particles present substantial hazards to electrical equipment for various reasons. Initially, it can function as an insulator, causing overheating and the risk of arc flash dangers. Dust's capacity to draw in moisture can lead to leakages, increasing the likelihood of arc flash explosions [47]. Dust impurities can lead to poor contact in connectors, switches, and relays, and can also cause carbon tracking and arcing in high voltage equipment. Due to the ubiquitous nature of dust in our surroundings, it collects quickly and can penetrate even the most vital and hidden parts of electrical devices. Therefore, it is essential to take a proactive approach to dust management to ensure the safety and peak performance of electrical systems.

3.2 Risk Assessment and Prevention of Low-Voltage Arcing

3.2.1 Notable Standards

Various organisations, such as the National Fire Protection Association (NFPA) and the Institute of Electrical and Electronics Engineers (IEEE), have established comprehensive standards to ensure the safety of workers in environments where electrical hazards are present. NFPA 70E 2021, known as the “Standard for Electrical Safety in the Workplace”, outlines essential measures to protect workers, including proper grounding of electrical equipment, the use of ground fault circuit interrupters (GFCIs), and preventing circuit overloading. The IEEE 1584-2018 model, developed in collaboration with ASTM F18 and IEC TC78, utilises common calorimetry to test simulated equipment and fabrics, offering a valuable model for worker protection. Additionally, the Occupational Safety and Health Administration (OSHA) regulations, specifically outlined in 29 CFR parts 1910 and 1926, complement these standards, collectively contributing to the establishment of robust arc flash safety measures across various industries [2].

OSHA regulations primarily focus on arc flash accidents. OSHA regulations require all electrical equipment to have a visible warning sign that indicates the possibility of arc flash. Labeling should contain details like voltage, power rating, amperage, and other pertinent specifications. Furnishing this information in conjunction with adequate training can equip personnel to safeguard themselves against arc flash accidents [47]. OSHA requires employers to use barricades, attendants, safety tags, and signs to warn and protect workers from dangerous arc flash incidents.

OSHA's code description section 110.16 of the 2008 National Electrical Code requires that all electrical materials and equipment be labelled correctly to warn handlers and employees of possible arc flash dangers. Quantifying preventive actions is necessary for accurately assessing these threats. Incident energy is the standard measure for assessing arc flash incidents in an organisation. The arc is determined at a specified operating distance. The main objective of personal protection equipment is to decrease the occurrence and intensity of burns resulting from Arc flash accidents to a survivable level of second-degree or lower.

According to the National Fire Protection Association (NFPA) guidelines, it is imperative for all companies to ensure that their electrical equipment undergoes regular and thorough inspection. The benefits of routine equipment inspections are multifaceted, including the ability to detect signs of overloading, identification of potential fire hazards and arc flash explosion risks, resolution of wiring issues, detection of electrical faults, and spotting damaged fuses. Adherence to legal requirements regarding the use and maintenance of electrical equipment is outlined in the Electricity of Work Regulations 1989 [72], emphasising the significance of compliance with safety standards to mitigate potential risks and enhance overall workplace safety.

3.2.2 Risk Management

Before commencing any experimentation, it is imperative to conduct a comprehensive risk assessment that evaluates all potential hazards associated with the process. This involves assigning values to various factors, such as arc flash energy, as illustrated in the provided Table 4. Similarly, all identified potential hazards should undergo a systematic evaluation against this risk assessment matrix which considers likelihoods and consequences of the hazards.

Table 4 Arc Flash Category Levels [47]

Incident Energy (cal/cm^2)	Hazard Category
0 to 1.2	0
1.2 to 4	1
4 to 8	2
8 to 25	3
25 o 40	4

The risk assessment is an essential instrument for evaluating the degree of risk connected with each hazard, enabling informed decision-making and the application of efficient risk reduction methods. Through assigning values and using a ranking matrix, businesses can prioritise hazards according to their seriousness and probability of occurrence. As an example, Doan indicates that the intensity of an arc flash on workers depends on three things: the number of faults in the system, the time it takes to clear the fault, and the distance between the worker and the fault arc flash. He then rates the risk of the arc flash according to these variables [61].

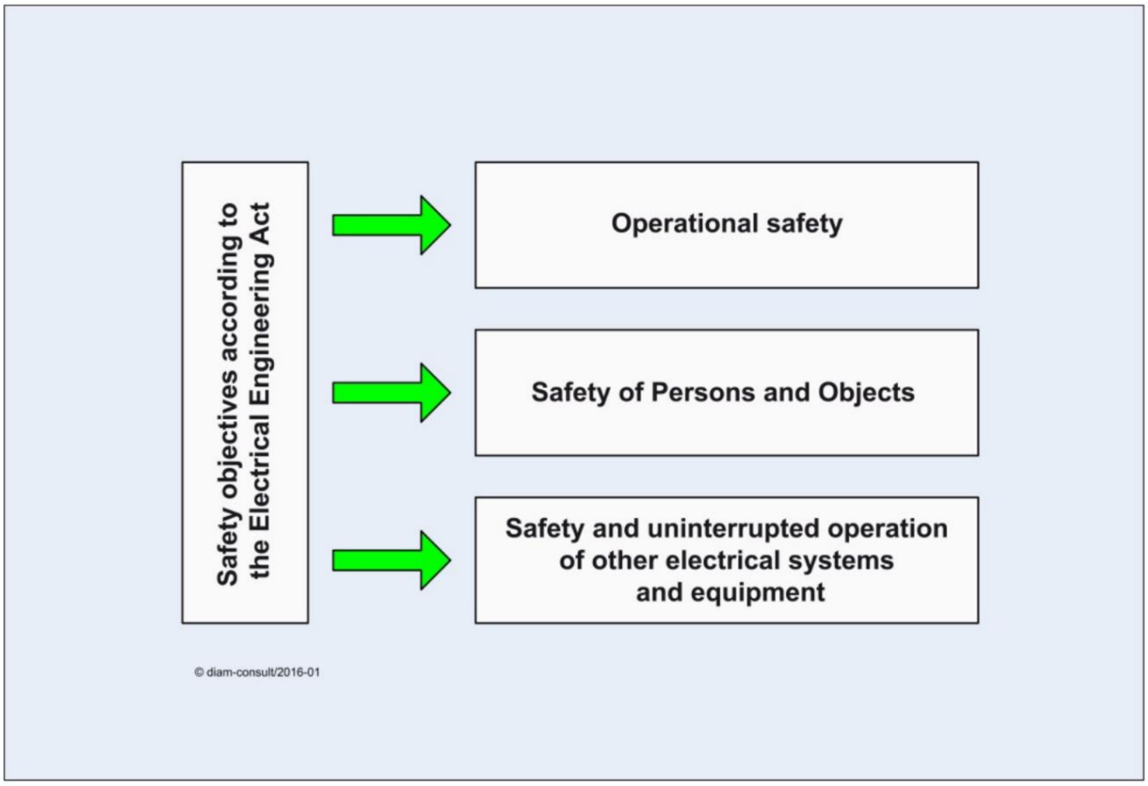


Figure 12 Safety Objectives According to the Austrian Electrical Engineering Act [75]

This method guarantees a systematic and impartial examination of possible risks, considering the unique circumstances of the experiment. A risk assessment should include all factors that contribute to operational safety, personal and equipment safety and account for accidents as seen in the Figure 14. It allows researchers and stakeholders to recognise, comprehend, and resolve potential hazards in an organised fashion, ultimately leading to a safer and more regulated experimental setting. Figure 15 shows the important risk management factors the researcher [47] has considered when exposed to arc flash.

Figure 13 Risk Management Factors [47]

3.3 Protective Measures and Incident Prevention

3.3.1 Personal Protective Equipment for Arc Flash

Typically, selecting the appropriate personal protective equipment (PPE) for certain tasks is done using one of two techniques. The first technique involves consulting a table that classifies sorts of hazards. The Table 5 categorises different electrical requirements based on varying voltages and suggests the appropriate PPE to wear when working with electrical equipment [47]. Another approach involves selecting PPE based on an arc flash calculation to determine the amount of arc energy present. Upon completion of the computation, the results will provide guidance on the proper assembly of the necessary PPE for adequate protection. To mitigate arc flash risk, it is essential to set priorities such as making an arc flash assessment and implementing technological solutions like high resistance grounding [49], which has proven to be successful in decreasing both severity and frequency of such incidents.

Table 5 Showing Arc Flash Requirements for all Industries [47]

Arc Flash Risk Level	Typical FR (Fire Resistance) gear at this level	Min. ATPV
0	Non-melting clothing, face shield, safety glasses, leather rubber arc flash gloves	<2 cal
1	FR pants and shirt, safety glasses and face shield, leather boots	4 cal/cm2
2	2 or 3 layers of pants and shirts, face shields, safety glasses, cotton undergarments, leather work boots	8 cal/cm2
3	3 or 4 layers of clothing, leather work boots, arc flash gloves, leather over rubber gloves	25 cal/cm2
4	FR pants and shirts, several layers of arc flash coveralls, face shield, safety glasses, leather over rubber gloves, leather boots	40 cal/cm2

ASTM F2675 standard test method for determining arc ratings of hand protective products developed and used for electrical arc flash protection and ASTM F3258 standard specification for protectors for rubber insulating gloves meeting specific performance requirements both address the need for impact protection with arc ignition withstand in testing [3].

There is no standard for establishing an arc rating for respirators, but the city of Seattle (Washington) study indicated that firefighter-certified breathing apparatuses meeting NFPA 1981 showed no ignition when tested using ASTM F2621 at 40 cal/cm² and 80 cal/cm² [3].

For Arc flash protective equipment, extended heat exposure may not harm the fabric's integrity in some cases, but a short exposure to a small quantity of heat can cause the fabric to melt or ignite. Many firms have created personal protective devices to protect humans from arc flashes due to increased knowledge of the hazards. These goods are tested for their arc ratings, which indicate the maximum energy they can endure before splitting open or causing 50% second-degree burns [69].

3.3.2 Inspection Before and After Laboratory Testing

The frequency of testing and inspection of electrical equipment depends on the company's specific characteristics and the related hazards [60]. After each inspection, a detailed record must be kept and periodically updated during future inspections [59]. Any recognised worn or torn equipment must be promptly replaced. The documented information should include the electrician's name who performed the inspection, the date of inspection, the inspection results, and the next scheduled inspection date.

Inspection and analysis of arc flash hazards are essential components of electrical safety measures, particularly in industrial and commercial environments. Inspection entails a comprehensive assessment of electrical systems, parts, and machinery to detect possible problems, deterioration, or non-compliance with safety regulations. This procedure encompasses visual inspections, testing, and the recording of information about the electrical framework. A summary given by OSHA outlines the different parameters that should be observed by electrical workers to adhere to an experiment related to arc flash (Table 6).

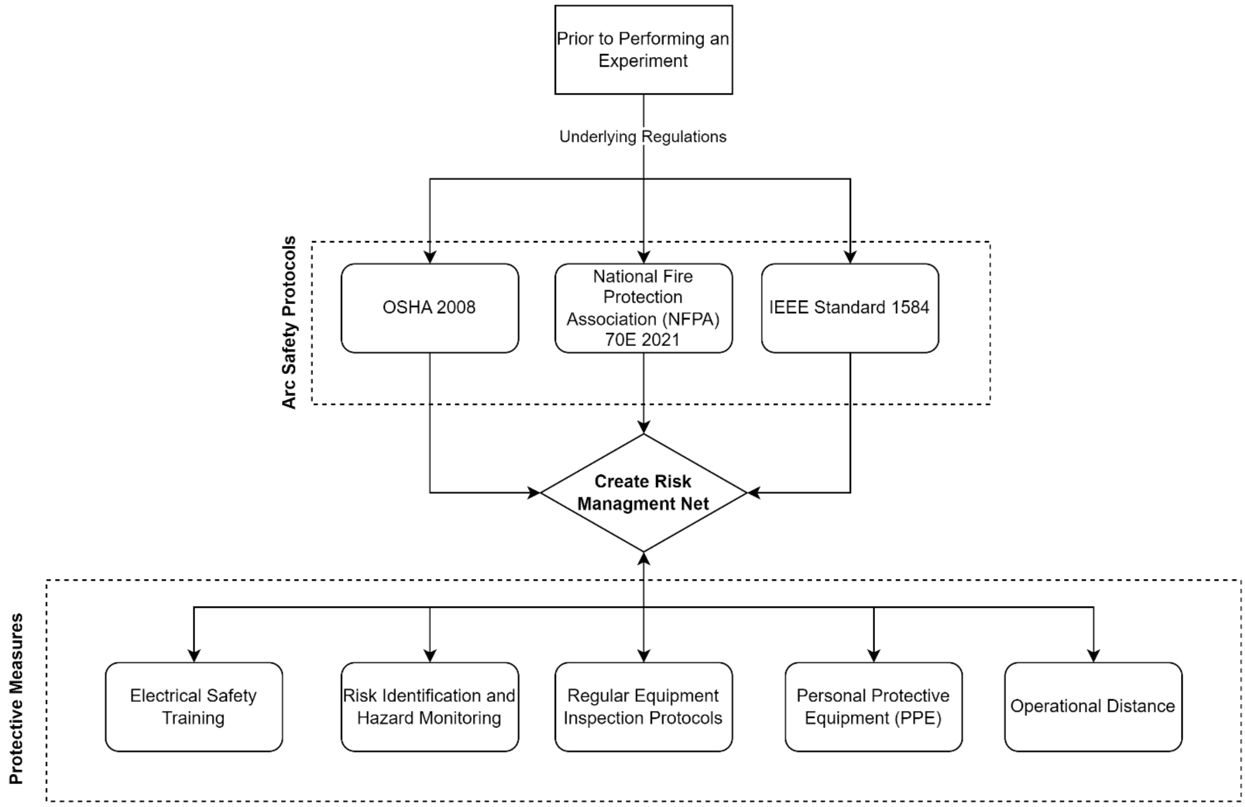
Table 6 Summary of Arc Flash Hazard Analysis [47]

Specification	Parameter
Incident Energy	11.7 cal
Arc Flash Boundary	3 inches
Arc Flash Hazard PPE	Category 3
Shock Hazard Voltage	480 v
Shock Hazard PPE	Class 00
Limited Approach Boundary	42 inches
Restricted Approach Boundary	12 inches
Prohibited Approach Boundary	1 inch

3.4 Arcing Hazard Risk Management Net

The preceding three subsections in this chapter delineate the guidelines, safety protocols, and precautionary measures essential for conducting experiments involving the severe consequences of arc flash. The depicted Figure 14 encapsulates these three subsections, serving as a reference for past experiments and anticipating future utilisation in further research endeavors.

Figure 14 Safety Measures Summarised



Chapter 4
Low Voltage Pillar Arcing And Fire Testing

This chapter presents details regarding conceptual experiments created to investigate the progression of a hotspot to pillar fire and arcing events in LVAC plastic pillars that are being utilised by industry. It encompasses the procedures and setups of the tests, which include selecting suitable materials and test conditions based on previous and comparable studies. This chapter serves as the cornerstone of the approved paper presented at the 2024 CIGRE Paris Session.

4.1 Contextual Framework
4.1.1 Electrode Orientation Selection

The studies conducted by [14], [25], [6], and [24] involved investigating ignition properties and collecting data on voltage, current, temperature, and gas development. These previous experiments served as examples and laid the groundwork for the proposed research. This experiment aims to investigate the boundary conditions of deterioration in the presence of fire and high resistance without fire. Additionally, it is important to document prevalent voltage fluctuations linked to deteriorated fuse connections. As the DC distribution network is expanding globally, conducting tests in both AC and DC is necessary.

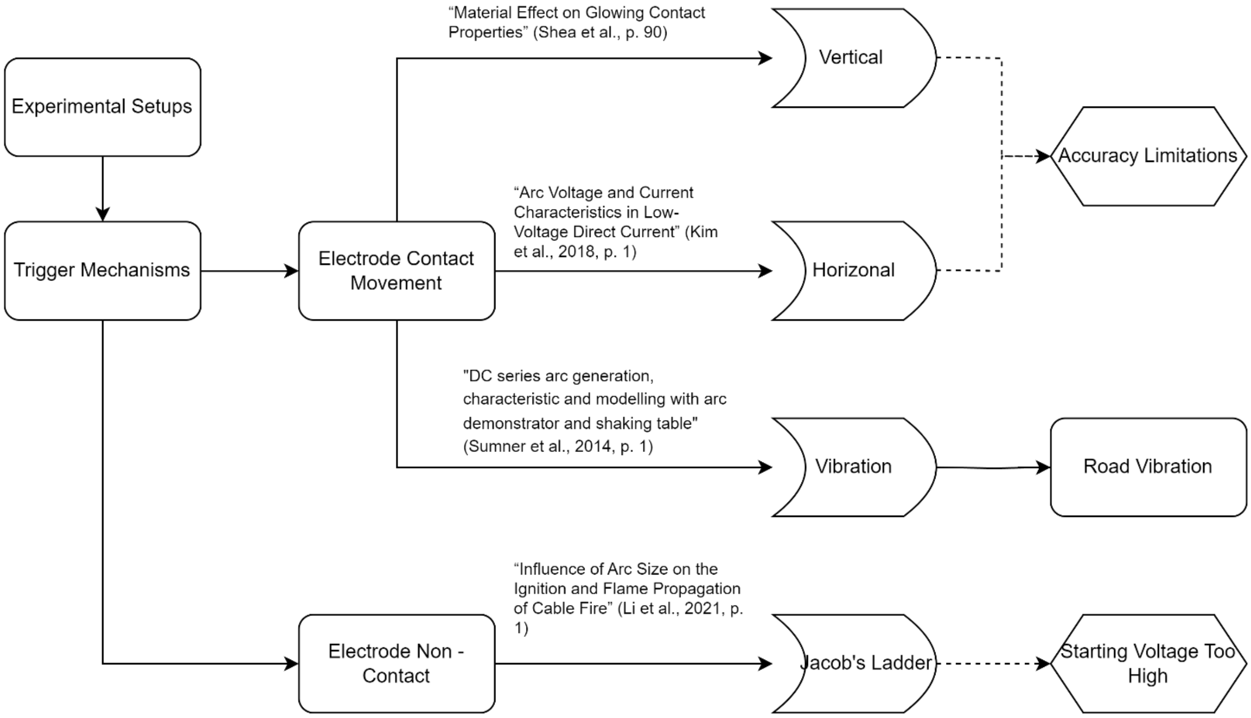


Figure 15 Typical Methods to Create an Arc in Laboratory Settings

The precision and dependability of arc creation rely on choosing the appropriate mechanical movement between electrodes. Three common types of arc generators use mechanically moving electrodes. 1) [68] utilised vertical movement, 2) [12] focused on horizontal movement, and 3) [21] researched vibration seen in this Figure 15. Vibration most accurately replicates the impact of traffic and seismic activity on LV pillars. One can replicate traffic-induced vibrations using a shaker table, as seen in Figure 16.

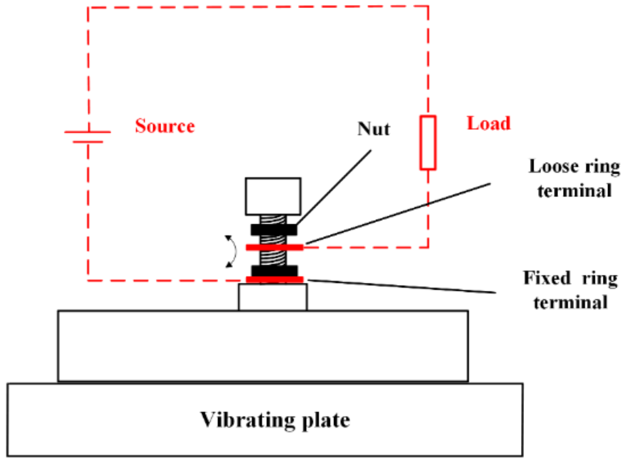


Figure 16 Shaker Table-Based Arc Generator [5]

The Figure 14 also indicates that arcs can also be formed using the Jacobs Ladder approach, however this is not the main focus of the studies. This is due to the minimum conditions of these tests. Jacob's Ladder refers to a high voltage travelling arc. This is a type of electrical discharge that occurs when the voltage difference between two electrodes exceeds the breakdown voltage and the maximum gap distance between these two electrodes is known as the Jacob's Ladder [50]. Jacobs Ladder setups usually require voltage in the range of several kVAC [50], to generate sufficient energy for an arc to form. These arcs may occur at lower voltage levels; however, their stability and reliability are significantly diminished.

4.1.2 Arcing Generation Choice

The oscillations produced by vehicular movement and seismic activity can exert a substantial influence on the immediate surroundings. Studies have demonstrated that low-intensity para-seismic occurrences, such as mining tremors, can elicit comparable impacts on both individuals and buildings, akin to vibrations caused by road traffic [56]. Seismic noise refers to a continuous and long-lasting ground vibration, which has been extensively researched in the disciplines of geophysics, geology, and civil engineering [54]. Although statistical data do not explicitly mention the specific effects of road vibrations caused by earthquakes, it may be deduced that both types of vibrations can have an impact on the human environment and structures. To have a thorough grasp of this subject, additional research focusing on the effects of road vibrations during earthquakes is necessary. New Zealand, situated on the boundary where the Pacific and Australian tectonic plates converge and collide, encounters a substantial frequency of earthquakes daily. Each year, there are between 14-15,000 earthquakes in and around the country, with approximately 150 to 200 of them being of sufficient magnitude to be perceptible [55].

The influence of earthquakes on road vibrations is a complex problem. Although the mentioned data do not explicitly discuss the impact of earthquakes on road and footpath vibrations, it can be deduced that earthquakes can cause substantial ground vibrations in New Zealand. These vibrations can subsequently influence the condition of roads and the transmission of waves in the nearby soil where these low-voltage pillars are located. Earthquakes generate seismic waves encompassing a spectrum of frequencies, including high-frequency oscillations capable of inflicting structural damage. Moreover, ground rupture observed in extreme seismic events has the potential to compromise the stability of the road foundation and cause significant damage to its infrastructure.

The magnitude of road vibrations induced by vehicles can fluctuate based on various parameters, such as road surface irregularities, vehicle attributes, and velocity. The car body's vibration amplitude can vary between 0.069 m/s^2 and 0.18 m/s^2 depending on the road surface [56]. Surface defects in road pavements can generate vibrations that propagate through the foundation ground and subsequently affect nearby structures. The vibrations generated by vehicle travel typically fall within the frequency range of 5 to 25 Hz, with soil velocity varying from 0.05 to 25 mm/s [56]. To gain a thorough grasp of the problem and the extent of vibrations in low-voltage pillars, additional studies explicitly targeting the impact of earthquakes on road vibrations are required. Vibration has been chosen as the method for moving electrodes due to the close proximity of low voltage pillars to highways and the potential impact of earthquakes.

4.2 Essential Criteria and Requirements for Pillar Fire Formation

4.2.1 Temperature and Time Considerations

Pillar fires are primarily caused by a high-temperature connections between the incoming or outgoing cables and the fuse holder. The uncertainty stems from identifying the exact place where the fire started, whether it was caused by the PVC insulation of the cables, the PE housing, or the fuse holder.

The fuse holder is excluded as a potential source since it passes fire resistance testing using methods such as the direct method [UL 94] or indirect method [IEC-60695.2.11:2000], where the sample is subjected to flame or a glow wire element. The heat source is withdrawn after a specific time, and for the test to be successful, the sample must not ignite, or the flame must go out within a specified time frame [29].

Various investigations show that fuse holders sustain significant damage without igniting if the pillar does not catch fire [66]. Furthermore, the PVC insulation and/or PE housing in some cases also display notable deterioration. Component damage indicates that prolonged high-temperature connections can cause cable insulation to char. Furthermore, glow wire tests on the PE housing material show that it usually does not catch fire during the brief glow wire test as outlined in [IEC-60695.2.11:2000] and [29]. Therefore, it is essential to extend the period of trials in order to evaluate the time to ignition for all the components involved.

4.2.2 Gas Emission During Pillar Decomposition

The gas in close proximity to an LV pillar also plays a significant role, as it can ignite without the need for a fire or electric spark due to its temperature properties. Investigating the propensity of gas mixtures to ignite involves considering two key parameters: the autoignition temperature and the MIE (minimum ignition energy). The MIE is typically determined using ASTM E582 standards. If the fuel-to-air ratio deviates from the required level for worst-case scenarios, more energy may be needed for ignition compared to the MIE [14].

The gases produced during the decomposition of plastics are involved in the ignition process and serve as an indication of the ongoing activities. Monitoring the gas composition will aid in comprehending the breakdown process and, consequently, the ignition process. Regulating the gas atmosphere and monitoring pressure enables a more precise replication of actual arc settings, facilitating the examination of arc generating behaviour and potential risks. The objective is to determine the gas composition and its variations during the experiments.

[68] used an arc chamber that was created to mimic the arc chamber found in a tiny industrial circuit breaker. The design described in [68] allowed for accurate control of several parameters including

contact materials, polarity contact opening speed, opening time, contact force, arc location, pressure, and wall material. The arc chamber's crucial feature was the regulation of its internal gas through ventilation holes, enabling gas to escape from one end of the chamber. The chamber includes a piezoelectric pressure transducer to measure the chamber pressure variations during the test.

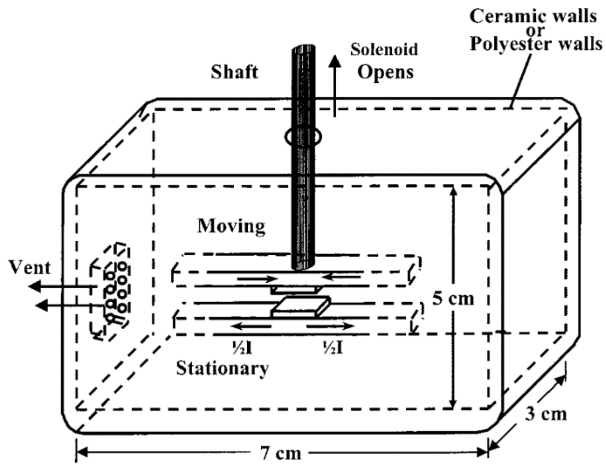


Figure 17 Arc Chamber [68]

PVC compounds are considered to be relatively resistant to fire compared to other common organic polymers. When PVC undergoes thermal decomposition, it primarily produces hydrogen chloride, benzene and unsaturated hydrocarbons. In the presence of oxygen during combustion, carbon monoxide, carbon dioxide and water are commonly formed. The primary toxic substances released from PVC fires are hydrogen chloride (which irritates both sensory organs and lungs) and carbon monoxide (a chemical that can cause asphyxiation) [23]. Having a gas sensor will enable the monitoring of gas emissions and aid in comprehending the progression of a pillar fire. [68] developed a confined arc chamber model using a circuit breaker to precisely monitor pressure and gas levels through the ventilation system as seen in the Figure 17. Regulating the gas atmosphere and monitoring the pressure enables a more precise replication of actual arc conditions, facilitating the research of arc generation behaviour and potential risks. Similarly, the experimental setup by [28] utlises planar conductivity and breakdown sensors to measure air conductivity and air breakdown as seen in the Figure 1 in the Appendix.

4.2.3 Arc Dynamics: Characteristics of Electrical Arcs

Arc voltage refers to the voltage measured across the arc terminals and is directly related to the arc length. The stability of an arc is influenced by the length of the arc, with arcs having lower voltages and currents needing a smaller separation gap for stability [65]. When the arc voltage is significantly higher than the source voltage, typically seen in low voltage faults, the arc current will exhibit deformed, distorted, and unstable characteristics. Moreover, an LV fault can exhibit intermittent behaviour characterised by short intervals of arcing alternating with periods of varying durations without arcing [13]. Arc duration periods serve as indicators of the characteristics, behaviour, and severity of the arcing defect.

4.3 Conceptual Laboratory Setup

Figure 18 shows the experimental setup conceptually, and Table 7 details the equipment and components to be used. Both AC and DC power sources will be used in these studies to analyse the effects in voltage. The DC voltage will be an equivalent value for comparison with 230V AC. Tests on regularly utilised fuse holder varieties and brands, equipped with the standard 63A fuse will be conducted. Test both terminals of the fuse holders individually as the live connection, for example, the bottom and top terminals. Table 1 in the Appendix and Putorti's work in general should be reviewed while constructing this conceptual laboratory setup due to the similarities in the projects.

The main difficulty in the experimental arrangement is generating corrosion and/or unstable connections that can be reliably replicated, with tangible instances to safeguard equipment as outlined in [26]. [67] details practical techniques for inspecting and conducting autopsies to analyse the features and actions of electrical fires.

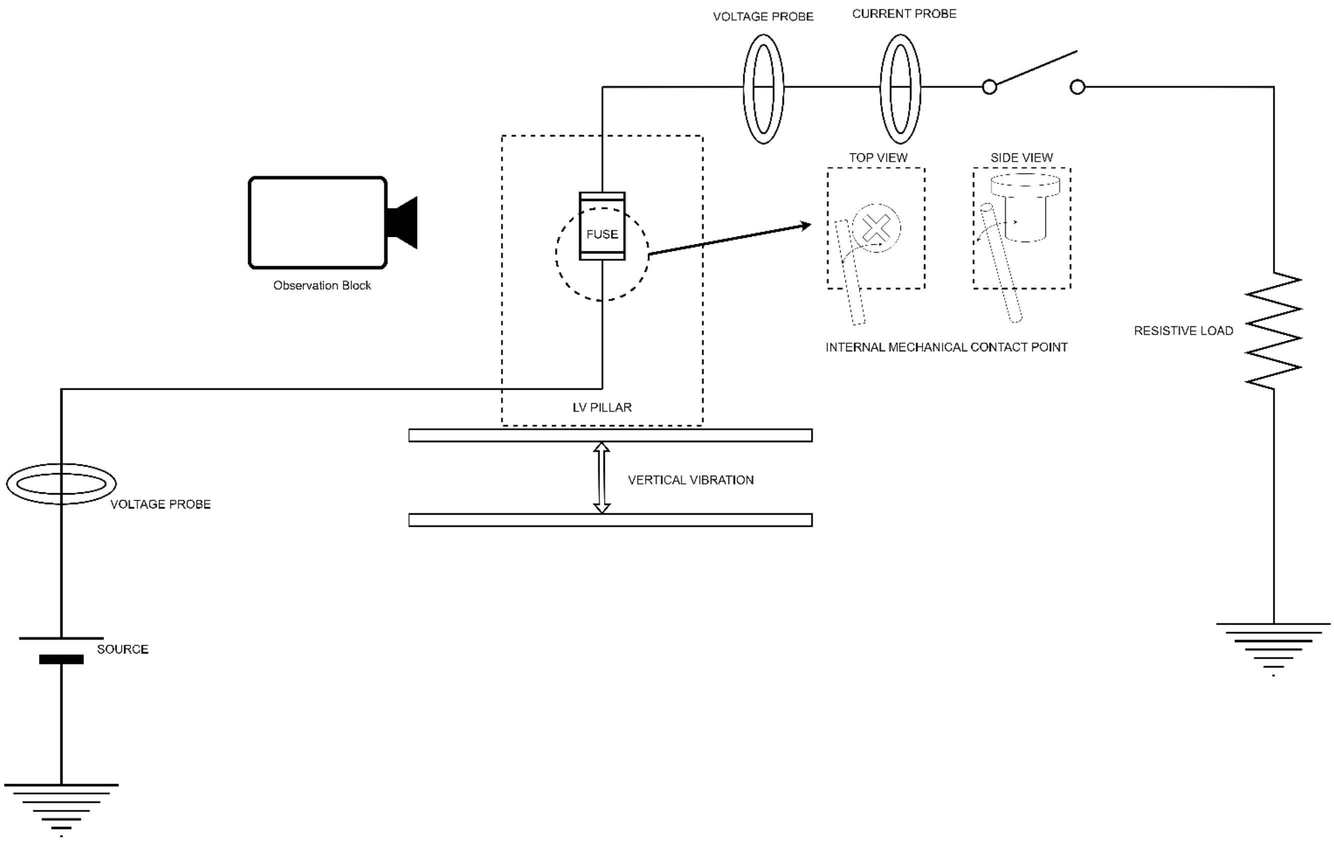


Figure 18 Conceptual Setup of Experiments

Table 7 Equipment and Components to be Employed in the Experiment Setup

Usage or Comment	Equipment Type	Example
230V +/- 6% at 50Hz [AS/NZS 3112] and [IEC 60038].	AC power source	
325V DC Equivalent Voltage	DC power source	
Oscilloscope	Voltage and current probes	[28]
The shaker arc generating unit is positioned on the sample holder of the shaker head	Arc generation	[5, Figure 13].
Measures temperature, humidity and air pressure	Environmental sensors	[7]
Record the heating and ignition processes.	Monitoring Instruments: High-speed cameras, gas detectors, infrared cameras and thermal sensors	[28]
Various lengths of cable are employed as an inductive load and a waveguide for high-frequency signal propagation and time delay.	Variable inductive load	
Simulate customer load conditions and control arc current	Resistive load	
Data Acquisition: Captures instantaneous voltage, current, and power. are employed to capture instantaneous, maximum, and minimum values	Digital multi-channel oscilloscope	[28]

Chapter 5
Fuse Thermal Profile Testing

This chapter examines the thermal characteristics of market fuses and their propensity to cause fires, along with the reasons that lead to hotspot failures in these devices. Furthermore, the chapter delves into several significant outcomes that form the basis of these discussions.

Some resources mentioned in this chapter are confidential and not publicly accessible due to company privacy policies. Brand names of certain resources have been removed to maintain anonymity. Only a portion of the data has been provided to support the arguments and conclusions of this research. Additional data can be obtained by contacting the author of this thesis. Nevertheless, this material has been omitted from the thesis because of privacy and confidentiality issues.

5.1 Foundation for Research Initiative

5.1.1 Industry Engagement

Collaboration between industry and academia is essential for creating a mutually advantageous partnership that can benefit both sectors. Research collaboration facilitates combined research endeavors, leading to new solutions and providing practical insights into real-world issues and this project was assigned due to its relevance to the industry. Academia can assist in tackling certain issues encountered by companies like the network companies that are affect by pillar fires on their network. By engaging in collaborative initiatives, researchers can address industrial issues, creating solutions that are both backed by research evidence and practically relevant.

A CIGRE NZB1 Pillar Fires Workshop was held to discuss the issue of LV Pillar fires and explore potential solutions at the end of August 2023. During the workshop, it was identified that one of the key areas of concern is understanding the thermal profile of fuses in LV plastic pillars. This concern was raised by Preformed Line Products (PLP), a company specialising in electrical infrastructure solutions for utilities. A suggestion from their side was to conduct a case study to investigate how likely fuses may become a fire hazard in LV plastic pillars. In response to this suggestion, a case study was conducted in collaboration with PLP at their laboratory facility with make up this chapter (Chapter 5) of the thesis.

A range of tests were done to collect data and analyse the thermal profile of fuses in LV plastic pillars and how they may contribute to the formation and progression of LV hotspots. The thermal profile testing of the fuse was conducted to analyse its performance under different temperature conditions.

The value of this chapter is that originally this experimental investigation was going to be solely on findings from research papers, but now because of the input of this chapter it includes the practical experimentation based on investigations from findings from industry. That is important because this problem of pillar fires is an industry related problem and taking advice from a variety of sources, including research papers and industry experts, allows for a more comprehensive understanding and potential solutions to the problem as seen in the Figure 19 below.

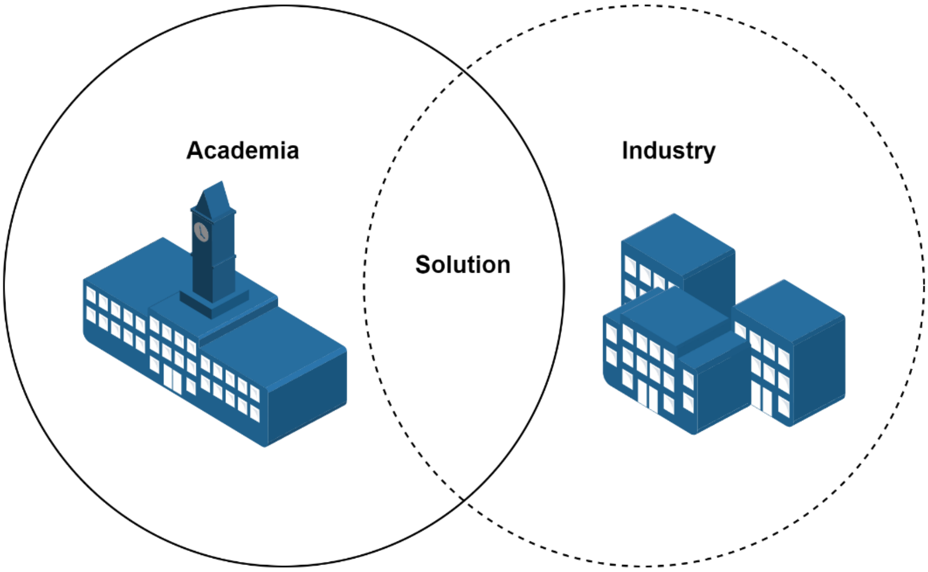


Figure 19 Importance of Collaboration Between Academia and Industry

5.1.2 Scope

The objectives of these tests are to optimise the production of heat inside the experimental arrangement. By analysing the heat profile of these experiments, we can evaluate the probability of a fire resulting from a particular cause.

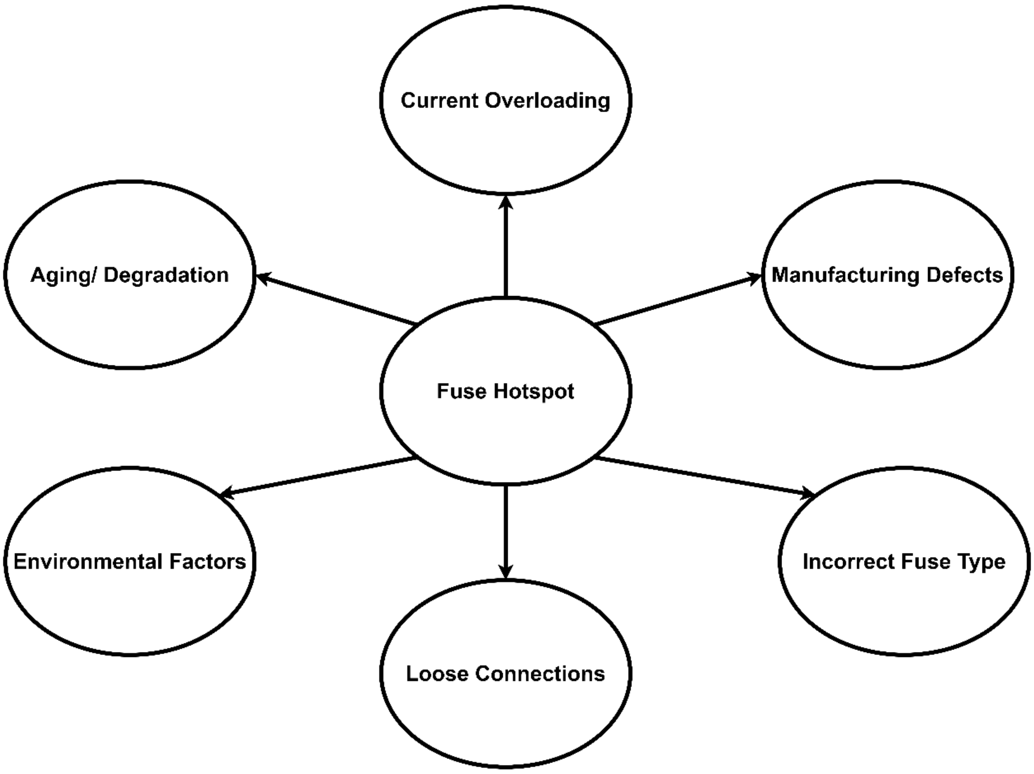


Figure 20 Causes of Fuse Hotspots

Figure 20 displays potential failure mechanisms that could lead to excessive heating of fuses, which might result in fire hazards. Two common failure scenarios, which are frequently encountered in practice, can be directly examined in an experimental setup and provide the most reliable indications of how pillar fires may originate from overcurrent fuses.

These two causes of fuse hotspots are:

1. **Loose Connection**
2. **Current Overloading**

5.1.3 Research Assumption

Given the importance these LV pillars have for the distribution network and the economic and social activities it supports and due to the heavy importance of these fuses to ensure protection, it is assumed that the pillars do not have fuses that have either manufacturing defects or the incorrect fuse type.

5.2 Fuse Thermal Profile Testing

The purpose of this testing was to simulate the worst-case scenario for low-voltage arcing incidents and assess the potential impact and consequences. The testing involved creating a scenario where a single strand of copper from the cable was used to generate high resistance and heat. This testing aimed to replicate the conditions that could lead to low-voltage arcing incidents and assess their potential impact and consequences.

Worst scenario testing was done to evaluate the potential impact and consequences of low-voltage arcing incidents. This featured using only strand of copper from the cable to create an area of high resistance to generate as much as heat as possible.

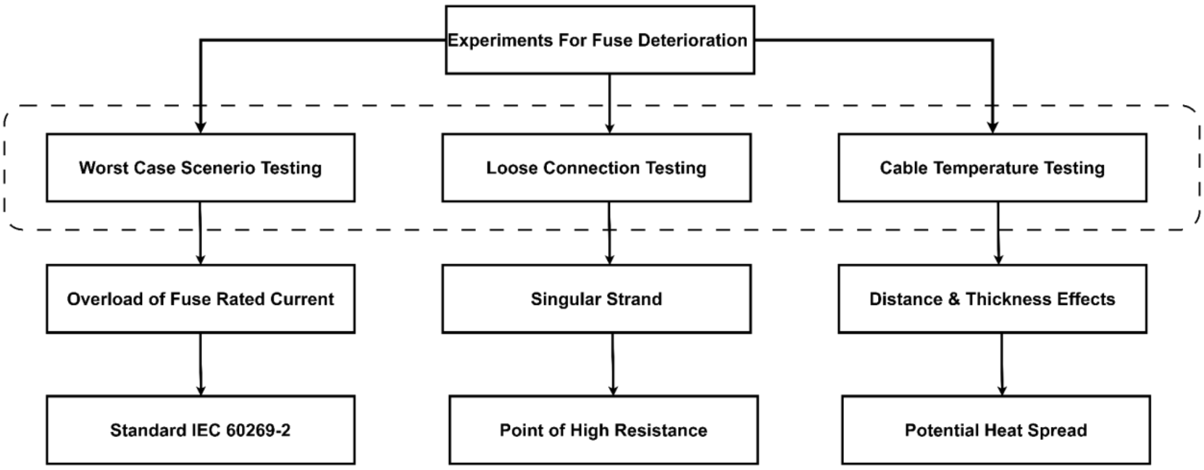


Figure 21 Testing Flowchart

Figure 21 displays the flowchart for the experiments, and the three configurations for testing, namely worst-case scenario, loose connection and cable temperature, are detailed below.

5.2.1 Worst Case Scenario Testing

Experimentation can assist us in analysing potential failures of fuses in three specific areas. We can simulate the worst-case scenario by deliberately exceeding the rated capacity of the fuse at various levels. Every fuse is designed according to the IEC 60269-2 standard. For testing purposes, we are investigating whether the current standard used for fuses in low voltage pillars effectively prevents heat-related damage. In this situation, analysing the thermal profiles of the fuses over time and comparing them to the melting temperatures of the material would provide us with valuable information regarding the safety of these fuses during a fault (current overload).

5.2.2 Loose Connection Replication Testing

The primary cause of ignition for these pillars is typically a loose connection. In the case of pillars, a loose connection refers to a situation where either a few strands or none of the internal copper wire in the cable are in contact with the inside of the fuse holder. This results in the formation of a point of elevated resistance inside the circuit, as a reduction in the cross-sectional area will produce an augmentation in resistance. From a hypothetical perspective, this rise in resistance is expected to result in a substantial elevation in temperature. Similarly to worst-case scenario testing, we can evaluate the safety of these pillars by comparing their thermal profiles to the melting points of the material.

5.2.3 Cable Temperature Testing

Another noteworthy aspect is to observe the extent to which heat propagates through the wires within these pillars. The cables have copper as their interior material, which possesses conductivity. The conductive nature of the wire allows the transmission of heat, which, depending on the temperature, can cause the insulation to deteriorate. This can lead to arcing between connections, which is a substantial discharge of energy that greatly increases the likelihood of fire ignition.

5.2.4 Relationship Between Melting Point and Pillar Breakdown

Table.8 Physical Properties of Different Materials [2]

Material / Grade	Melting Point (General)	Conductivity	Impact strength Relative	Flexibility
LDPE	115	Non- Conductive	Med	High
HDPE	130	Non- Conductive	High	High
Polypropylene	140	Non-Conductive	Low	Low to Med
Flame Retardant HDPE	130	Non- Conductive	Low	High
Fibreglass	~80-100 *Poly Resin	Non- Conductive	Low to Med	Low to Med
Metal (1.5mm stainless)	N/A	high - needs to be earthed	High	Low to Med
Concrete	N/A	Low	Very High	Very Low

Table 8 above shows the research done by Andre Cuppen from Powerco Ltd about the melting points of LV pillar materials found in the New Zealand distribution network. From this research we can conclude that pillars will start to melt between temperatures of 80 - 130 degrees Celsius [2]. Similarly, the melting point of the cable insulation for the cables found in LV pillars are between 100 - 260 degrees Celsius [3].

Understanding the relationship between melting points and fire hazards is crucial in assessing the safety of electrical infrastructure. When the melting points of materials used in electrical infrastructure are reached or exceeded, there is a high risk of structural failure and potential fire outbreak as mentioned in the literature review.

5.3 Experimental Setups

Testing the melting points of material and fire hazard potential of AC fuses and equivalent DC fuses is necessary to ensure the safety and reliability of both current and future electrical systems. This is to align with FAN's research objectives of the potential of having both a hybrid and resilient distribution network. These research setups aim to determine the correlation between the melting points of materials used in electrical infrastructure and their fire hazard potential. Two experimental setups were utilised to gather information for this purpose.

Source and Measurements:

The source is a low frequency current transformer heat unit that operates as a current source. The source had outlets to measure the current and sent that data to a data acquisition system for real time tracking of the experiment. Calibrated external instrumentation and measuring systems used for data logging and electronic control of heat units are carried out using National Instruments' Labview systems. Real time data of the voltage, current and temperature characteristics were able to be recorded via this system.

These experiments are categorised as heat cycle tests and adhered to the specified standardised criteria. The following lab equipment were adapted to accommodate the BS3288:1andAS1154.1 standards.

The current source (Heat Unit) had a varying technical capacity as follows:

- 25kVA Max Output
- Continuous: 2500A@10V
- Short- term: 3000A@10V

The following accreditation was met for these experiments:

- IANZ Accreditation for IEC61238 (power cables upto 30kV) and IEC61284 (overhead lines).
- IANZ is an ILAC Mutual Recognition Authorized Signatory. EPLP can co-accredit IANZ Reports with other ILAC Accreditations such as: NATA(Au)/ CGCRE(Br)/ NAS(Ch)/ NABL(Id)/ KAN(In)/ SM(Ma)/ PAO(Ph)/ SANAS(SA)/ NSC(Th) / UKAS(UK).

Controlled Variables:

The materials for all experiments are LDPE pillar housing, 63A fuses and 16mm^2 PVC insulated copper cable due to their typical use in the New Zealand distribution Network [1]. Wiring method for the fuse holder is a screwed terminal between the holder and the cable. These fastening screws have been tightened to overly exposed areas of copper at a hand tight tension.

Temperature Measuring Devices:

Thermocouples need to be connected to each fuse holder to measure the temperatures inside the fuse and at the terminals during testing. Utilise a thermal camera to measure the heat fluctuations and heat spectrum of the experimental setup wherever feasible. Furthermore, it is important to document as much photographic evidence as possible to demonstrate the physical transformation of the samples throughout time.

Experimental Setup

The Assembly Setups are shown below on Figure 22 and Figure 23:


Figure 22 Assembly Single Fuse Holder & Figure 23 Assembly Three Fuse Holders

5.3.1 Single Fuse Holder Setup

The experimental configuration should be set up with a single 63A fuse in the circuit insulation as seen the Figure 24 below. These pillars are made of LDPE and the cables are made internally of copper with PVC.

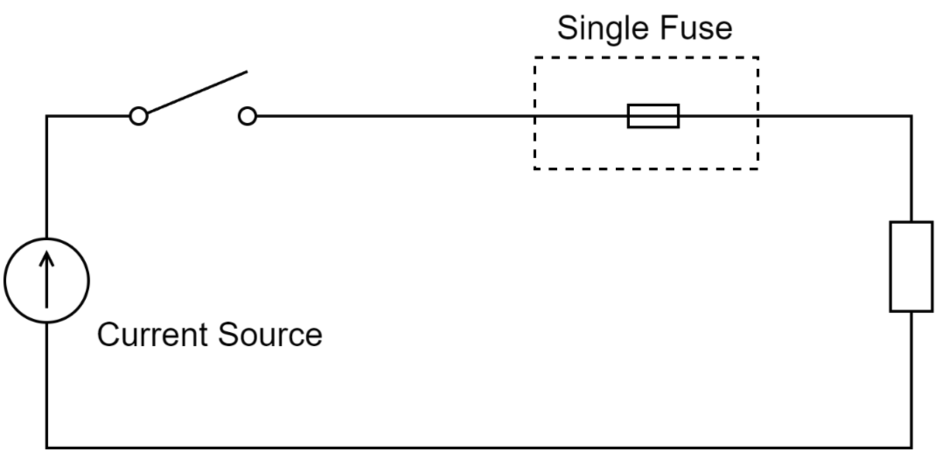


Figure 24 Simplified Single Fuse Circuit Model

This setup was utilised for Loose Cable Testing, presented Table 9.

Table 9 Loose Cable Testing

Test Case	Loose Cable Testing Testing
Details	Place a single fuse in series and run the test at 100% rated current. Connect only a single copper strand from the cable to the fuse holder.
Lid On	Use a thermocouple to measure the fuses temperature and terminal temperature.

Single Strand of Copper in the Fuse Holder:

- Length of Cable = 4m
- Single Strand Diameter: = $1.65 * 10^{-6}\ m$
- Resistivity of Copper = $1.77 * 10^{-8} \Omega m$

$$R = \frac{\rho * \mathrm{L}}{\mathrm{A}}$$

$$Where\ A = \pi r^2$$

$$A = \pi * \left(\frac{1.65 * 10^{-6}}{2}\right)^2$$

$$A = 2.1383 * 10^{-12}\ m^2 (4dp)$$

$$R = \frac{(1.77 * 10^{-8}) * 4}{(2.1383 * 10^{-12}\ )}$$

$$Resistance\ at\ the\ Fuse\ Holder\ Terminal\ = 33111.2433\ \Omega \text{ (4dp)}$$

Comparison to cable with all strands secured in the fuse holder:

- Length of Cable = 4m
- Cable Diameter (all strands): = $4.95 * 10^{-6}\ m$
- Resistivity of Copper = $1.77 * 10^{-8} \Omega m$

$$R = \frac{\rho * \mathrm{L}}{\mathrm{A}}$$

$$Where\ A = \pi r^2$$

$$A = \pi * \left(\frac{4.95 * 10^{-6}}{2}\right)^2$$

$$A = 1.9244 * 10^{-11}\ m^2 (4dp)$$

$$R = \frac{(1.77 * 10^{-8}) * 4}{(1.9244 * 10^{-11}\ )}$$

$$Resistance\ at\ the\ Fuse\ Holder\ Terminal\ = 3679.0270\ \Omega\ \text{(4dp)}$$

$$Magnitude\ of\ Difference\ = \frac{33111.2433}{3679.0270} = 9$$

The difference in resistance at the fuse holder terminal is nines time by only using a single strand. This point oh high resistance will increase the heat dissipation of the fuse due to ohmic heating.

$$Ohmic\ Heating\ of\ Single\ Strand: P = R * I^2$$

$$P = 33111.2433 * 63^2 = 131418.5247\ MW\ (4dp)$$

5.3.2 Three Fuse Holders Setup

The experimental configuration should be set up with a three 63A fuses in the circuit. The fuses should be connected in series to enable heating of all fuses at the same current level as seen in the Figure 25 below. These pillars are made of LDPE and the cables are made internally of copper with PVC insulation.

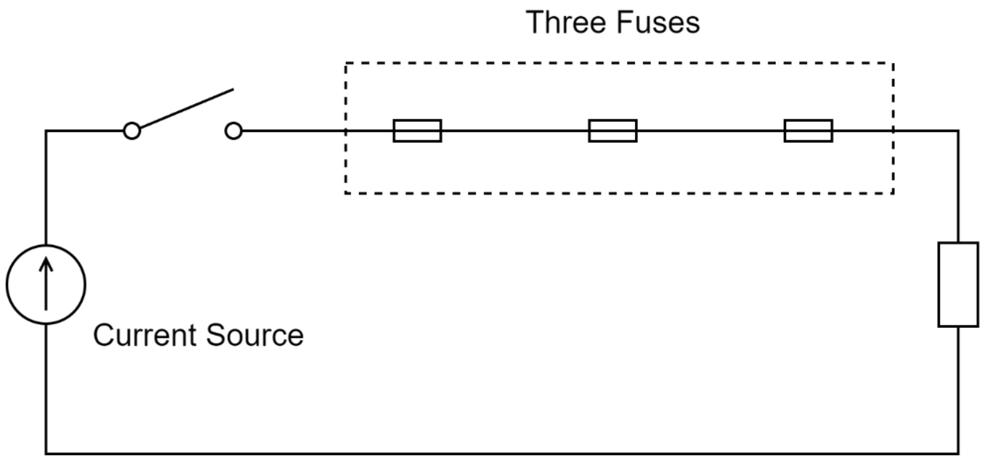


Figure 25 Simplified Three Fuse Circuit Model

This setup was utilised for Worst Case Scenario Testing (Table 10).

Table 10 Worst-Case Scenario Testing

Test Case	Worst Case Scenario Testing
Details	Place 3 fuses in series connection and equidistant placement then heating of the fuses at 100%, 140% & 150% rated current to simulate the worst case. Connect only a single copper strand from the cable to each of the fuse holders.
Lid On	Use a thermocouple to measure the fuses temperature and terminal temperature.
Lid Off	Utilising a thermal camera enables the observation of finer temperature details, providing insights into the gradual accumulation of heat and the surrounding temperature dynamics.

5.4 Results Interpretation

5.4.1 Loose Cable Scenario Results

Figures 5 & 6 in the appendix shows that the wire strands were split, and only one strand was placed into the fuse holder. Table 11 shows the maximum temperature recorded over a two-hour period. The fuse took less than eight minutes to heat up to 151.18 °C.

Table 11 Maximum Temperature for Terminal and Fuse

Test Case	Maximum Temperature
Fuse Holder Terminal	95.50 °C
Fuse (Fuse Holder Internal)	151.18 °C

The temperature findings did not show a significant enough effect to cause any material melting, and no noticeable alterations in the material composition were observed. Despite the fuse inside the holder reaching high temperatures, it remained well-insulated from the surroundings. See Figures 5 & 6 in the Appendix for data. The terminal of the fuse holder approached nearly 100 °C, prompting consideration for further investigation through worst-case scenario testing to better understand how heat propagates along the cable. Although excessive heating was observed in this test, there was no obvious physical damage in the given timeframe.

5.4.2 Worst Case Scenario Results

By observing the Figure 7 in the Appendix, at the 100% Rated Current test, significant findings from the study are as follows: when the lid was placed on, indicating minimal natural ventilation for the fuses, there was a slight increase in temperature. The temperatures recorded with the lid both on and off exceeded the melting points of cable insulation and pillar self. These temperatures were comparable to those observed during testing in scenarios involving loose cables.

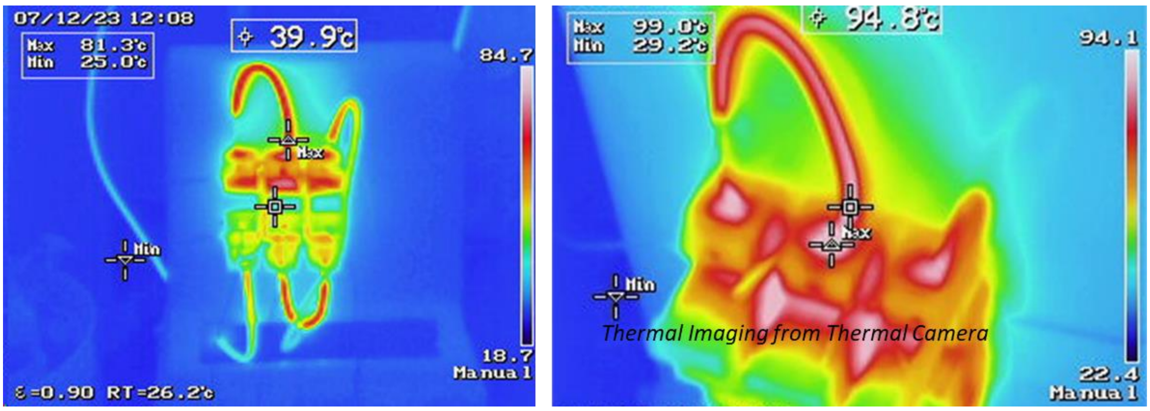


Figure 26 Distribution of Heat Via Thermal Camera

A thermal imaging camera was used to analyse the transmission of heat along the cable. The infrared findings depicted in the Figure 26 indicate that heat originates from the fuse terminal and spreads outward along the cable at a temperature comparable to that of the fuse heating up, as shown in the figure above. This suggests that the heat generated by the fuse can potentially cause thermal damage to the surrounding materials, such as cable insulation and pillars. The experiment involved exposing the cable to fully ventilated air, but it did not experience a significant decrease in temperature. When the lid was off at 1:10pm and 1:55pm in Figure 7 in the Appendix, the temperature only decreased by a few degrees. This suggests that the heat produced by the fuse is not effectively dissipated in this configuration. In practical situations, such inadequate dissipation could result in thermal damage to cables placed in underground ducts, potentially leading to series arcing between adjacent cables if insulation breaks down and exposes copper conductors.

Significant alterations in the material were noted when the current was increased to 140% of its rated capacity and left for two hours. The exposed copper at the terminals displayed evident evidence of carbonisation and discoloration, suggesting a transformation of the material caused by high temperatures (Figure 9 in the Appendix). The fuse reached a temperature of 200 degrees celsius, leading to oxidation of the copper, this is an essential observation as it raises the risk of a low voltage AC arc that could potentially ignite a fire. Additionally, there was noticeable colour change in the insulation, signaling degradation due to heat. The experiment showed that when the current exceeded the rated capacity by 140%, there were significant changes in the material.

The Figure 7 in the Appendix, shows that the fuse blew after 15 minutes when exposed to 150% of the specified current, causing a disruption in the circuit. At this point, the fuse became stuck inside its holder and started producing smoke (Figure 8 in the Appendix). Furthermore, upon inspecting the condition of the fuse, it was found that the fuse holder had become jammed due to melting. The difficulty in opening other holders was attributed to fuses melting inside them. It is worth noting that a design flaw exists where fuses blow from overcurrent rather than from heat.

5.4.3 Implications of Time Current Characteristics and Collected Data

If the fuse holders were equipped with additional spring or screw functionality, it could potentially decrease the likelihood of a loose connection. Regular inspections by maintenance and installation teams to assess the condition of the fuse holders would help in detecting and addressing potential issues before they develop into safety hazards. Maintenance checks should include examining for insulation breakdown or copper oxidation if they do not already. The necessity of incorporating a heat fuse to prevent overheating inside the LV pillar should also be reevaluated as part of its design. Furthermore, there is a potential need for reassessment of standard IEC 60269 to ensure that it effectively addresses potential hazards related to high temperatures in fuse holders. Preliminary tests have revealed that the time-current characteristics of these fuses might contribute to them becoming hotspots and leading to fire hazards. It has become apparent from test results and observations that there are significant concerns regarding current LV pillar protection designs based on their specifications and capacity to withstand high temperatures.

An important aspect to consider is the rise in residential electricity consumption over the past ten years, driven by market expansion and the widespread use of electric-powered household appliances, electronic devices, and electric vehicles. This increase has been significant and is expected to continue growing rapidly [38]. In this particular case study, despite the surge in electricity usage, rated fuse currents have remained unchanged for many years. Therefore, it's imperative to reassess protection measures based on evolving demands and load requirements to guarantee optimal safety and performance.

$$Ideal\ Fuse\ Rating = \frac{Nominal\ Operating\ Current}{Temperature\ Rerating\ Factor\ \times\ 0.75}\ [58]$$

The equation for the ideal fuse rating above also specifies the importance of accounting for the increasing load demand in the selection fuses. Climate change is also a factor to consider in this equation as well due to the increasing ambient temperature of New Zealand [57]. This implies that there should be an ongoing asset management plan to account for these evolving factors.

The findings of this chapter and theory from the literature review has been summarised in Figure 27.

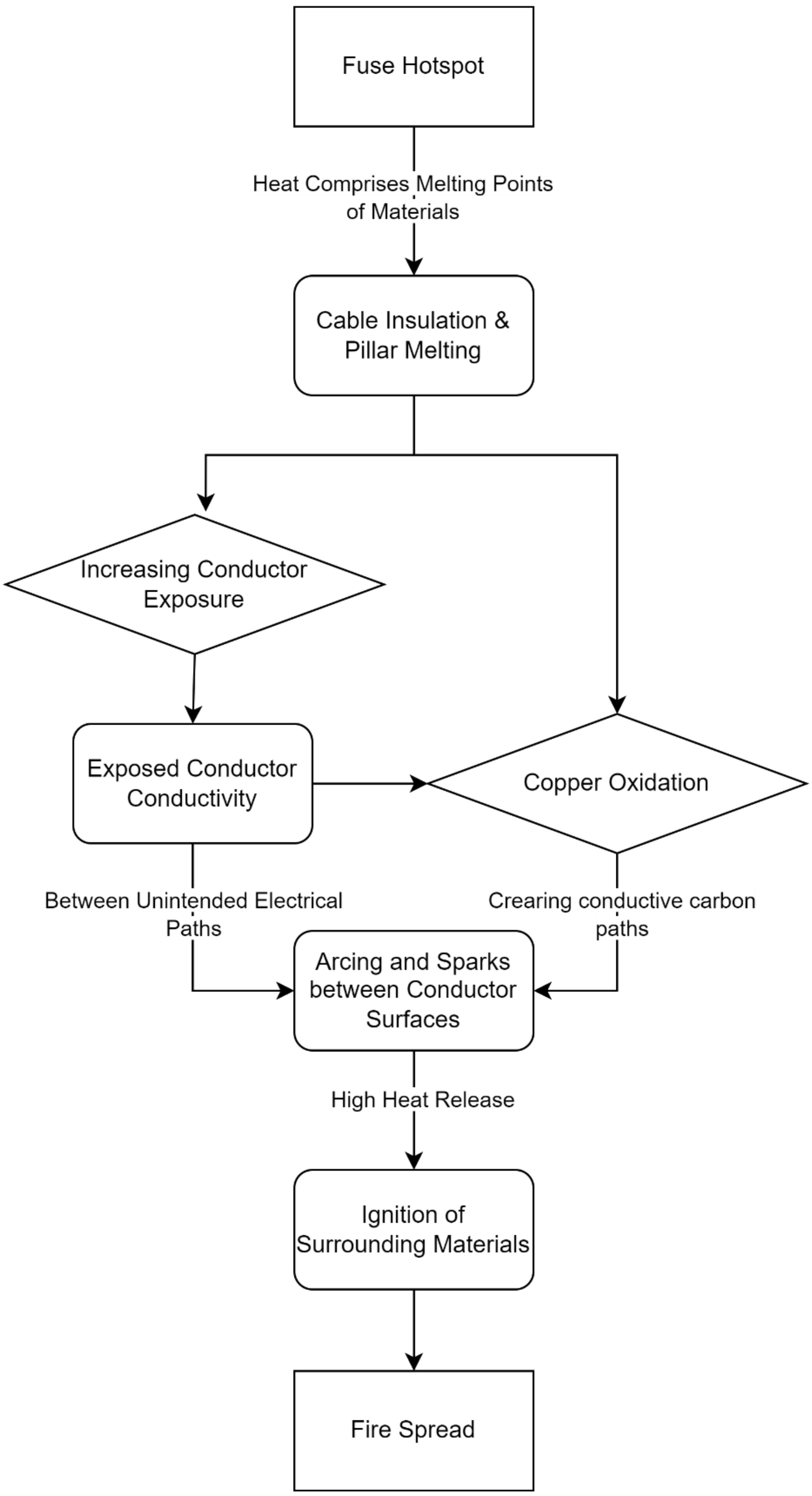


Figure 27 The Relationship Between Fuse Hotspot and Pillar Fire

5.4.4 Limitations and Constraints

The experiment employed a constant voltage of around 5V, which remained fixed and unmodifiable due to the equipment available. The likelihood of electrical arcing would have been significant due to the oxidation of the copper, which creates additional conduction paths. An escalation in voltage would have heightened the likelihood of encountering arcing. In the event of arcing, there would have been a substantial increase in the probability of a pillar fire.

Given more time, a more comprehensive study could be carried out to test a broader selection of fuses, cable insulation materials, and scenarios in order to fully assess the effects of high temperatures on cables and pillars. Furthermore, it would be advantageous to investigate the implications of testing DC equivalent fuses as well.

Chapter 6
Discussion

6.1 Conclusions

Pillar fires present a significant and perilous threat that demands careful consideration and proactive measures. These fires, often fueled by combustible materials in structural pillars, pose severe risks due to their potential for rapid and uncontrollable escalation. The heat generated in pillar fires can compromise the structural integrity of buildings, leading to catastrophic consequences. It is imperative that effective suppression techniques and fire safety measures be implemented to mitigate the potential impact of pillar fires. The development of relevant arcing experiments and equipment testing would further contribute to understanding the behaviour and dynamics of pillar fires, enabling the development of more targeted and effective pillar fire mitigation strategies.

6.1.1 Conclusions of Arc Experiments

In conclusion, the comprehensive exploration of enhancing power system reliability involved a systematic journey from conceptualising an experimental setup. The experimental setup will serve as a crucial foundation for simulating failure mode scenarios, allowing for rigorous experiments and data collection in a controlled environment.

Although the production of a standardised test is yet to be realised, the groundwork laid in this study sets the stage for its future development. A collaboration between industry partners to encompass a combination of fuses, fuse holders, cable type (PVC/ wire size), arrangement, etc. The documented methodology, parameters, and expected outcomes will serve as a foundational blueprint, promising a tangible and applicable tool to foster a standardised approach to fault detection in power systems.

In summary, this research effort not only advances theoretical understanding but also offers practical insights and solutions for enhancing fault detection in power systems. As the study progresses into empirical testing in both AC and DC scenarios, it aims to improve our understanding of processes leading to defects and pillar fires. The anticipated results, including data on currents and voltages, will enable proactive repairs and the prevention of fires, contributing to the resilience, efficiency, and adaptability of power systems. The proposition of LV pillars being type-tested as complete units further emphasises the commitment to fire reduction in these critical components.

6.1.2 Conclusions of Fuse Testing

The design and specifications of the fuse raise legitimate concerns regarding a potential fire hazard, particularly evident during overload testing. As observed, when the fuse fails under an overload, heat propagates down the cable from the terminals, inducing alterations in the material composition. This thermal descent of heat triggers changes in the cable material composition, contributing to an increased potential for fuse failure and, consequently, elevating the risk of a fire event. It becomes imperative to reevaluate the prevailing standards and safety regulations associated with low voltage pillars in light of these findings. The outcomes strongly indicate an augmented likelihood of arcing phenomena occurring under suitable voltage conditions.

Limitations of the experiment include the utilisation of a fixed voltage, approximately 5V, which remained unalterable. A noteworthy consideration is that an increase in voltage could have substantially elevated the probability of experiencing arcing. In the event of arcing, the risk of a pillar fire would have been considerably heightened. It underscores the importance of acknowledging this constraint and prompts further exploration with varying voltage levels to comprehensively understand the potential implications on arcing and fire risks in low voltage pillars.

6.2 Future Research

6.2.1 Transitioning from Conceptual Arc Experimental Setup to Physical Setup

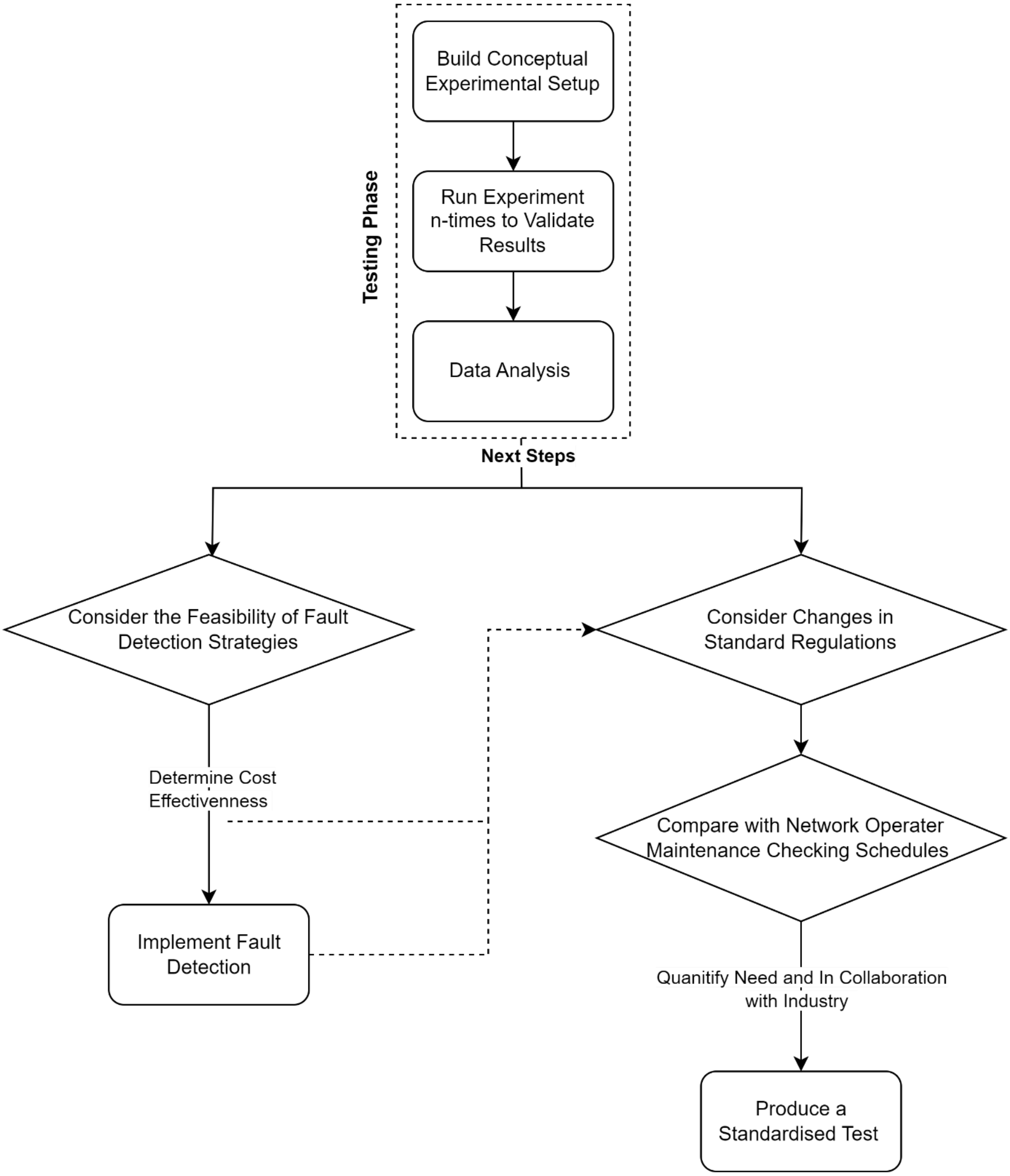


Figure 28 Next Steps for the Arcing Experiments

A proactive step that these conceptual experiments will involve considering changes in standard regulations to align fault detection strategies with evolving industry norms. The assessment of adherence to existing standards and recommendations for potential regulatory adjustments emphasised staying up to date of industry developments and ensuring adaptable fault detection methodologies.

Comparing the network operator maintenance checking schedules with the current industry regulations can provide insights into the current effectiveness within existing industry practices. Integrating fault detection into these maintenance schedules may showcase the potential for synergy, optimizing system reliability and minimising downtime.

As demonstrated in the Figure 28 above, conducting thorough fault mitigation feasibility studies and reevaluating installation and maintenance operations along with a completed experimental setup will establish the groundwork for a standardised test. This standardised test can be utilised by network operators to guarantee resilient LV pillar infrastructure against electrical fires.

6.2.2 Fuse Thermal Profile Next Steps

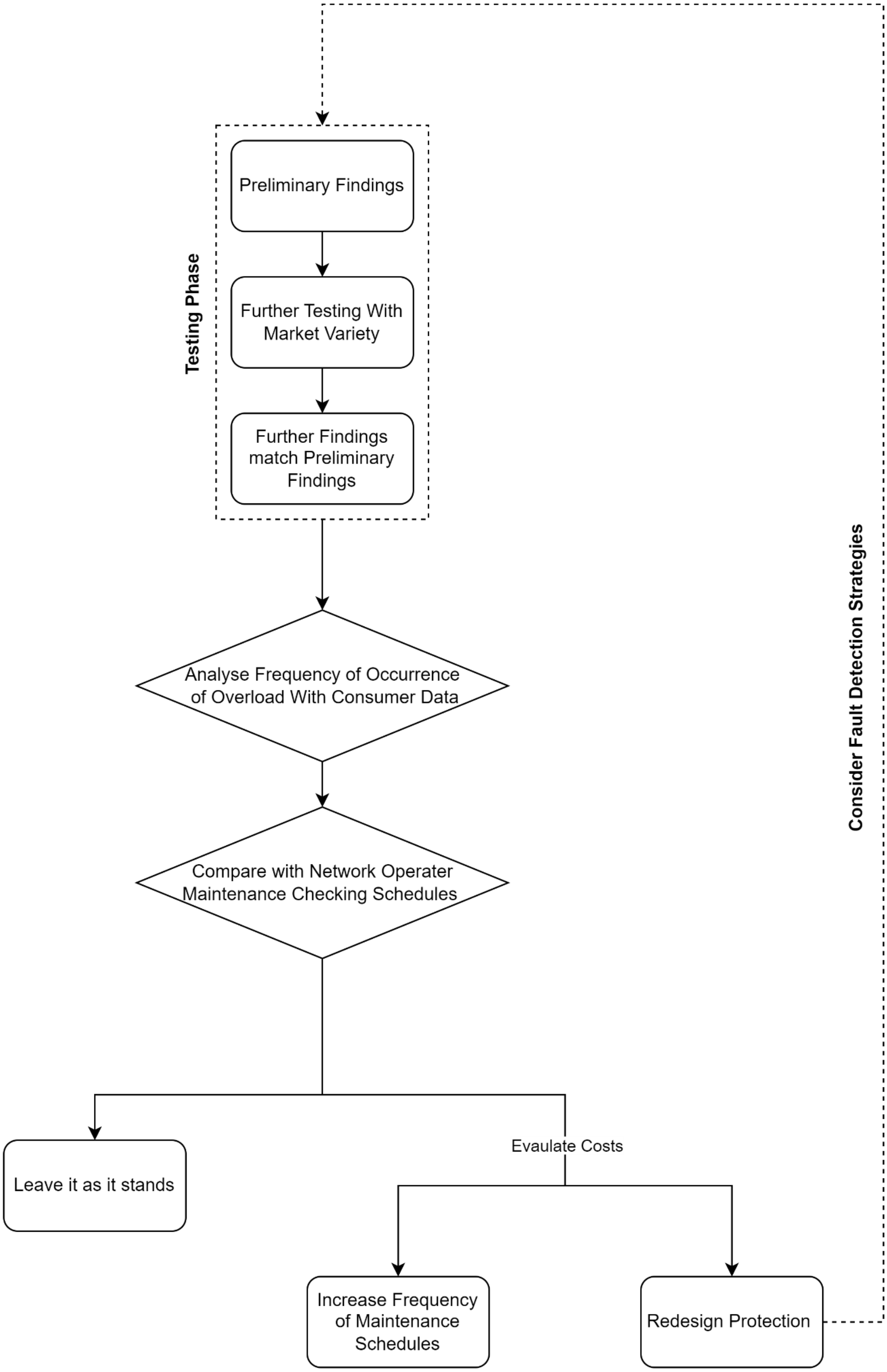


Figure 29 Next Steps for the Fuse Testing Experiments

For future investigations, it is imperative to conduct a comprehensive analysis of diverse voltage scenarios. This entails examining the influence of varying voltages on cable materials, fuse types, fuse holder types and fuse performance to foster a more robust comprehension of potential risks and implement preventive measures. Additionally, exploring material and design modifications may be imperative to augment the overall safety and reliability of low voltage pillars. The experimental setup not only provided valuable insights but also offers direct applicability to further testing, including the examination of DC fuses, a facet yet to be explored. This is demonstrated in the Figure 29 above.

Subsequent testing endeavors should scrutinise the ramifications of coupling the two primary failure modes addressed in this project, namely loose connection and current overload, with other failure modes such as aging and environmental factors. This holistic approach will contribute to a more nuanced understanding of the interplay between various failure mechanisms and inform strategies for comprehensive risk mitigation.

6.3 Insights Gained

6.3.1 Limitations

Conducting the research on low-voltage arcing was constrained by limitations in both time and costs. Despite the constraints of time and expenses, it is imperative to perform research on low-voltage arcing to create efficient preventive measures and enhance the safety of low-voltage electrical systems. Presently, The University of Auckland is in the process of building the facilities for high-risk electrical testing. However, due to this transition period, the university does not currently have the resources to carry out an all-encompassing investigation on low-voltage arcing. Nevertheless, this experiment highlights the pressing want for additional investigation and funding in comprehending low voltage arcing and creating efficient preventative strategies. This study emphasises the imperative requirement for cooperation among industry experts, researchers, and policymakers to tackle the problem of low-voltage arcing and guarantee the safety of low-voltage electrical systems.

Importance of collaboration with PLP, Powerco and other industry experts to further explore, analyse, and address the critical issues related to low voltage hotspots in LV enclosures. This collaborative approach will lead to comprehensiveness in finding effective solutions for this pressing concern. This research project necessitates substantial investment from external laboratories and industry stakeholders to conduct comprehensive testing, making it a significant endeavour. This thesis features an extensive literature review on crucial aspects of pillar fires, has effectively pinpointed their failure modes, and offers recommendations for future testing and research. It is hoped that this thesis serves as an initial stride towards further exploration of pillar fires with the ultimate goal of minimising them to zero occurrence on the distribution network.

6.3.2 Learning Outcomes

Being part of this research project has provided me with the opportunity to collaborate closely with industry, which is not commonly experienced in traditional academic research at the master's level. Additionally, due to the limited laboratory facilities at the University of Auckland, it was necessary to learn how to effectively engage industry professionals and organise workshops to secure funding for the project. As this type of research is novel at the University of Auckland, being involved in launching this initiative brings both excitement and challenges. Managing isolation has been a significant aspect of my learning process. Engaging in this research has also granted me access to various conferences and hands-on laboratory training that I would not have had access to otherwise. Hopefully, this project will underscore the necessity for an on-campus laboratory facility to advance our research efforts.

Overall, this experience exceeded my initial expectations by a significant margin. It proved to be transformative and the most valuable learning opportunity I have encountered thus far. The chance to work alongside professionals in the industry, as well as attend various international conferences, is something that I will cherish deeply. Once again, I am grateful for this opportunity which has greatly expanded my professional development prospects and future career opportunities.

Appendix

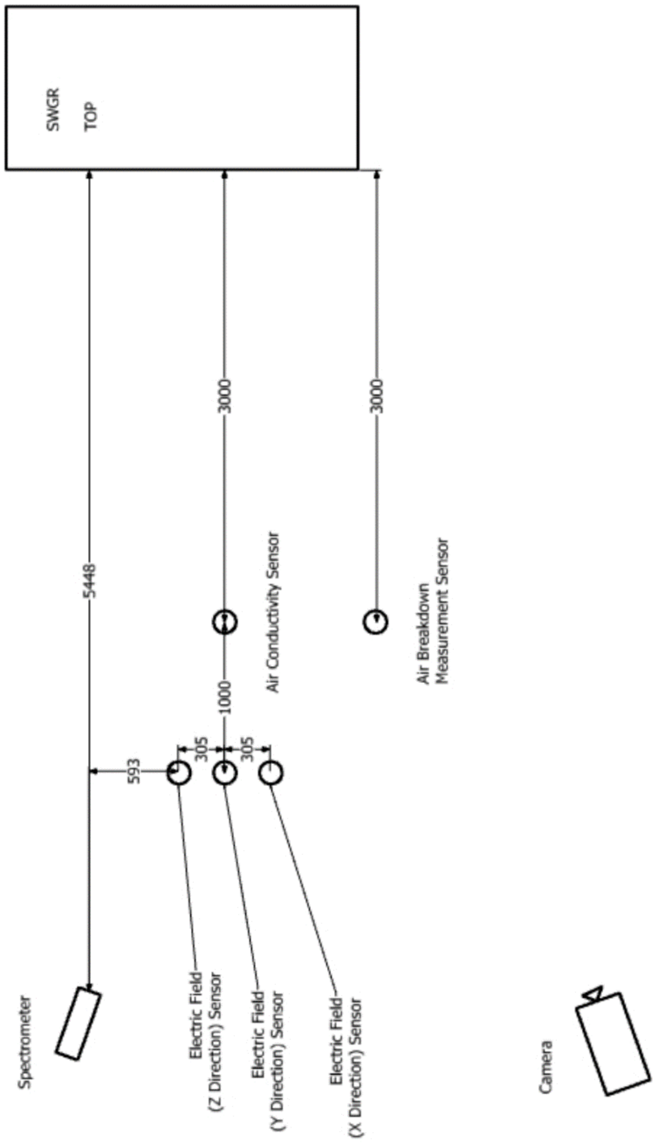


Figure 1 Setup for Electric Field and Air Sensors[28]

Figure 2 Single Fuse Holder Setup

Figure 3 Three Fuse Holders Setup

Figure 4 Strand Separation of Copper Cable

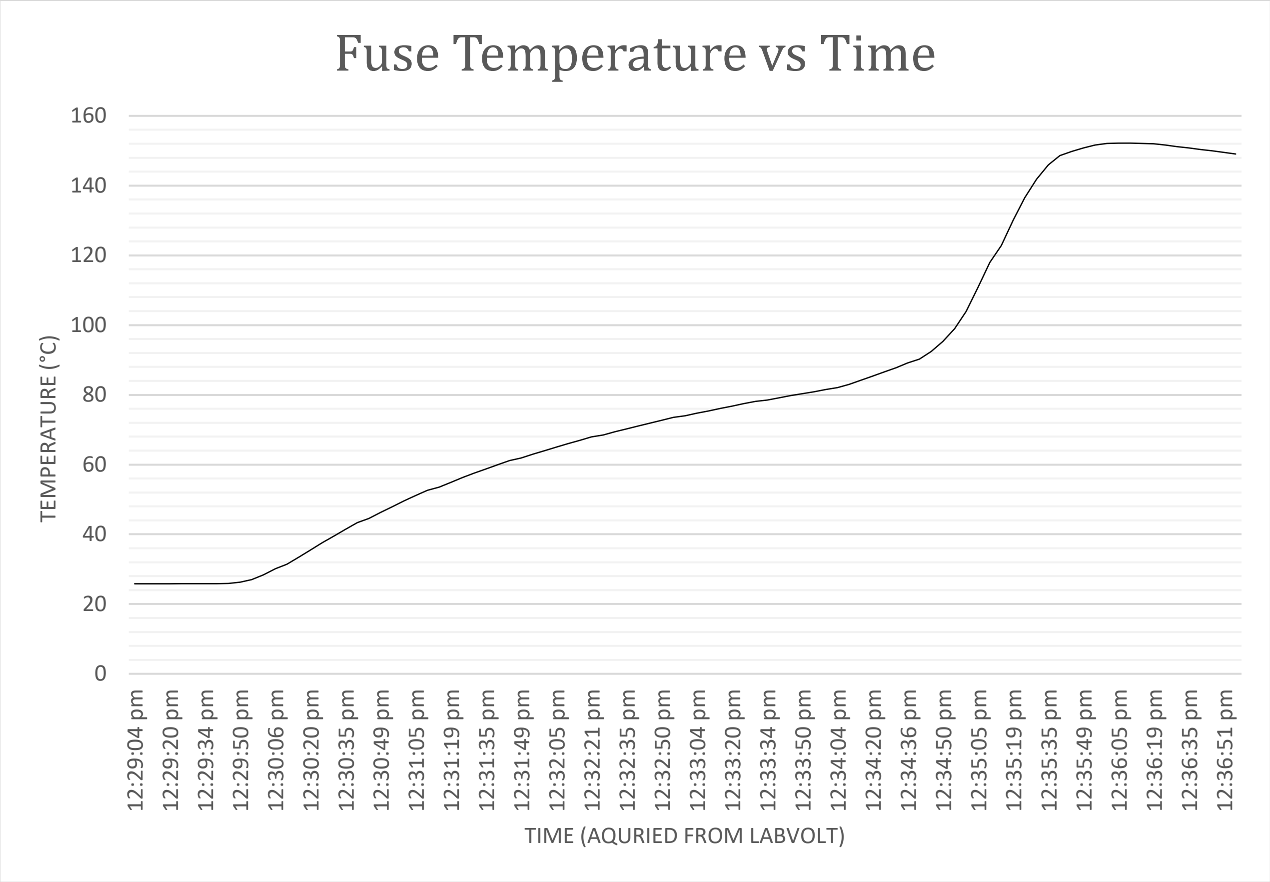


Figure 5 Loose Connection Scenario Results (Fuse)

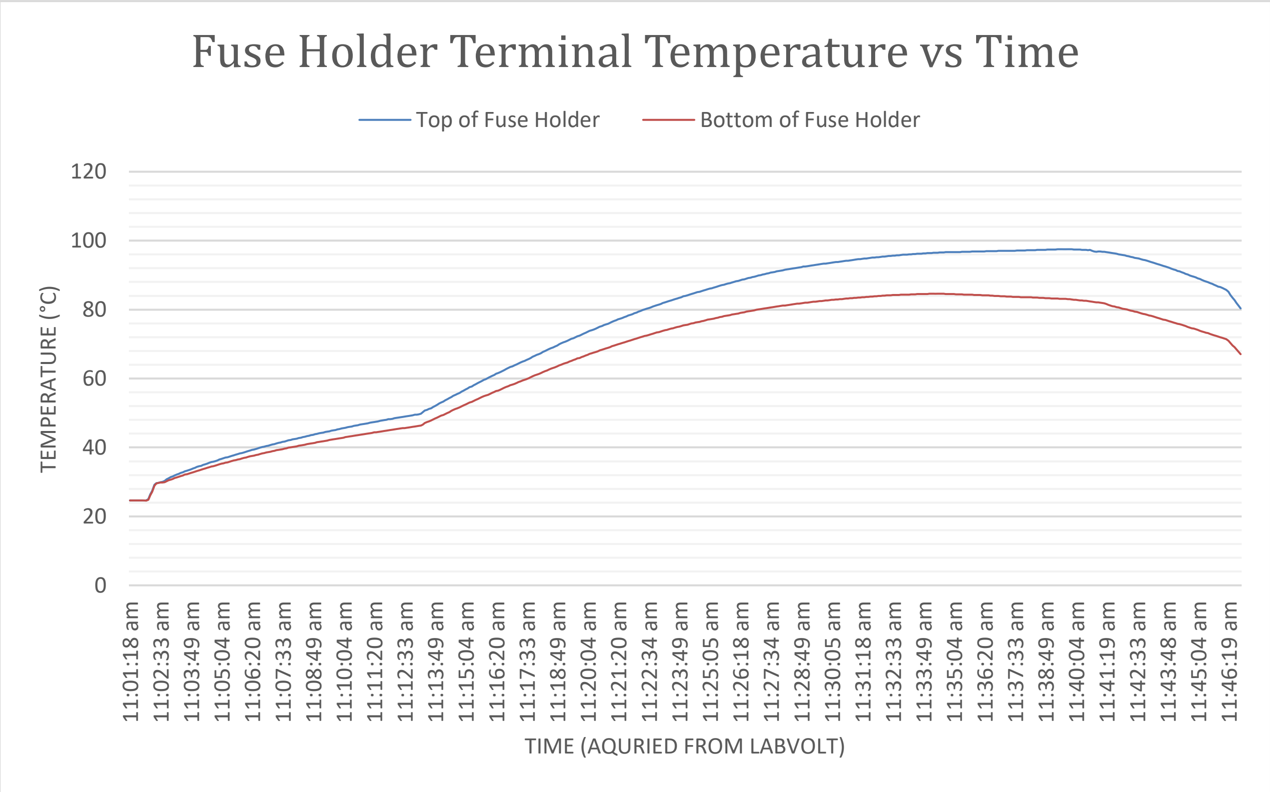


Figure 6 Loose Connection Scenario Results (Fuse Terminals)

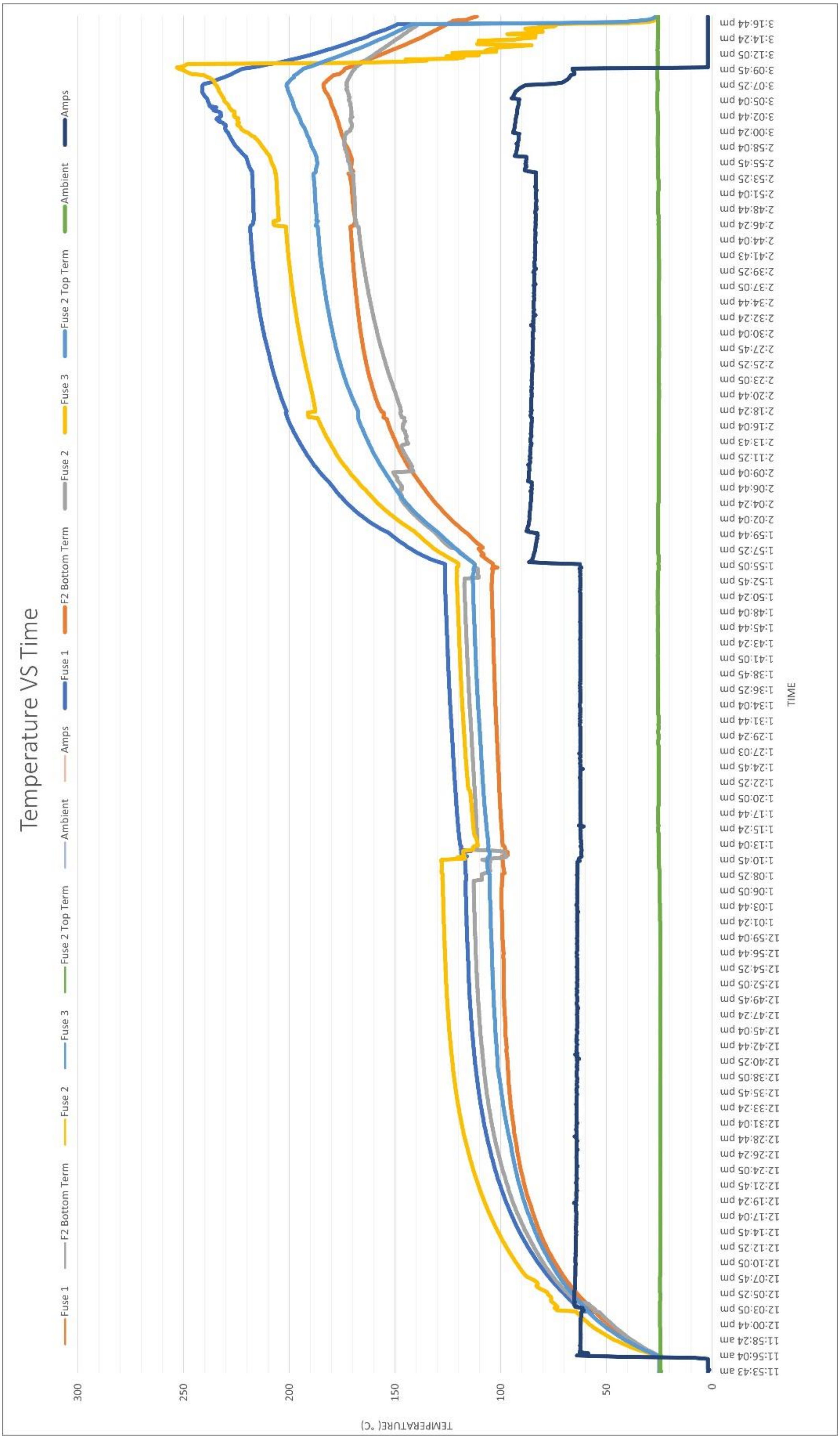


Figure 7 Worst Case Scenario Results

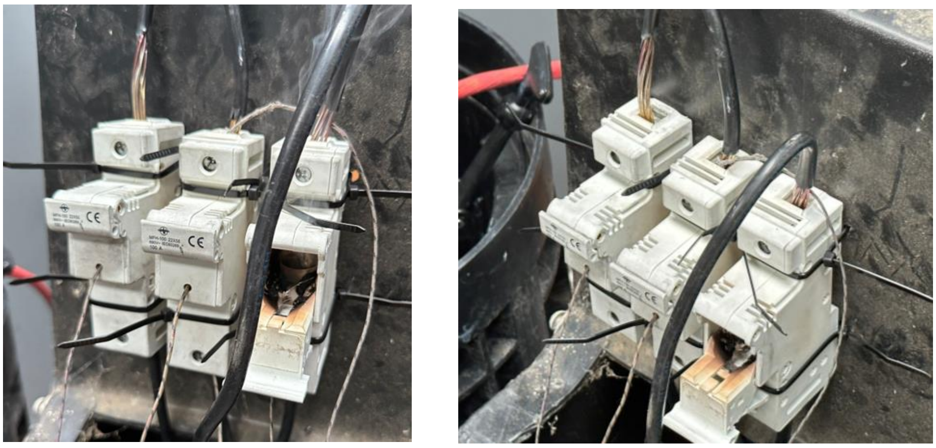


Figure 8 Melted Fuse in Fuse Holder

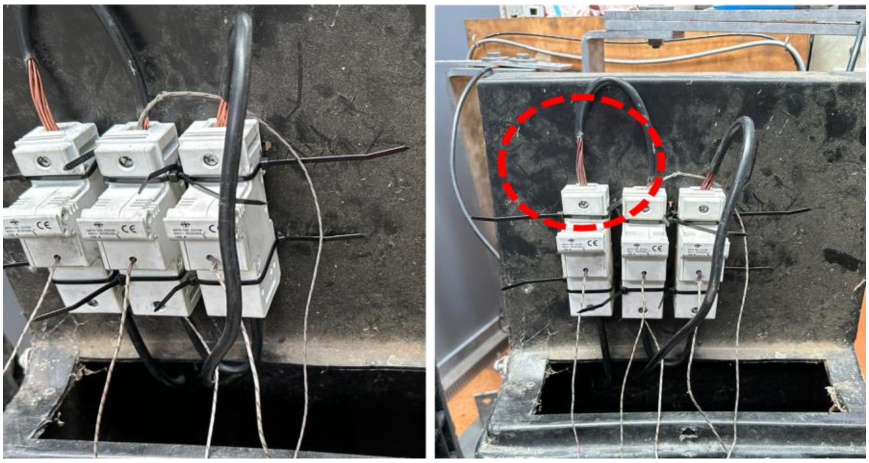


Figure 9 Copper Oxidation Due to High Temperatures

Table 1 Experimental Measurement Instrumentation and Techniques [28]

Measurements	Instrument / Technique
Temperature	Infrared (IR) Imaging, Plate Thermometer (PT)
Heat flux (time-varying)	Plate Thermometer (PT)
Heat flux (average)	Plate Thermometer (PT), Thermal Capacitance Slug (T_{cap} slug)
Incident Energy	ASTM F1959 Slug calorimeter (slug), Thermal Capacitance Slug (T_{cap} slug)
Pressure	Piezoelectric pressure transducer
Arc plasma / fire dimensions	Videography, IR Imaging
Surface deposit analysis	Sample collection (carbon tape / aerogels), post-experiment laboratory analysis (energy dispersive spectroscopy)
Qualitative damage	Cable samples

Table 2 Range or List of Parameters Considered for Each Arc Influencing Factor [5]

Category	Factor	Range/list
Mechanical	Electrode motion	constant speed, constant gap, constant acceleration
	Electrode opening speed	[0.1-700] mm/s
	Direction of motion	horizontal, vertical, vibratory
	Electrode shape	rounded, conical, flat
	Electrode material	Cu, Al, Ag, Pt, Ni, Au, Brass
	Electrode diameter	[3-19] mm
Electrical	System voltage	[30-680] V
	Current	[3-350] A
	Load/grid components	resistive, inductive, capacitive, CPL
Environmental	Temperature	-20^{o}C to 60^{o}C
	Pressure	[10-100] kPa
	Humidity	N/A

Table 3 List of Parameters vs Arcing Factors [5]

Factor	Arc Voltage	Arc Current	Extinction Time	Arc Sustainability
Electrode motion	✓	✓	✓	✓
Direction of motion	×	×	×	✓
Electrode shape	×	✓	×	✓
Electrode material	✓	×	✓	×
Loading conditions	✓	×	✓	×
Load/grid components	×	×	✓	✓
Arc location	×	✓	×	×
Temperature	×	×	×	×
Air flow	×	×	×	✓
Pressure	✓	×	✓	✓
Humidity	×	×	×	×

References

[1] [Cuppen, 2022] A. N. Cuppen, B. Greenwood, W. Heffernan, and D. Bredda, "Developments towards a Risk Based Maintenance program to reduce fires at LV cable terminations and plastic enclosures," Aug. 2022.
[2] [Hoagland, 2020] Hoagland, H., Maurice, C., Eblen, M., & Phillips, J. (2020, March). Matching ARC Rated PPE to the Hazard: Why Does it Work? In 2020 IEEE IAS Electrical Safety Workshop (ESW), Reno, NV, USA: IEEE, pp. 1–8. doi: 10.1109/ESW42757.2020.9188328.
[3] [Hoagland, 2022] Hoagland, H., Shiels, B., & Klausing, S. (2022, March). Challenge Accepted: Specialty PPE for Shock and Arc Flash Protection. In 2022 IEEE IAS Electrical Safety Workshop (ESW), Jacksonville, FL, USA: IEEE, pp. 1–7. doi: 10.1109/ESW49146.2022.9925041.
[4] [Cuppen, 2023] Cuppen, A., Kueh, K., & Gibson, M. (2023). A review of low voltage cable diagnostics to support proactive renewal planning. Powerco Ltd., Unison Networks Ltd., EPECentre New Zealand.
[5] [Psaras, 2022] Psaras, V., & Seferi, Y. (2022). Review of DC Series Arc Fault Testing Methods and Capability Assessment of Test Platforms for More-Electric Aircraft. IEEE Transactions on Transportation Electrification, 8(4).
[6] [Shea, 2007] Shea, J. J. (2007). Conditions for Series Arcing Phenomena in PVC Wiring. IEEE Transactions on Components and Packaging Technologies, 30(3).
[7] [Shea, 1999] Shea, J. J. (1999). Effect of polymeric gassing walls during arcing on AgW/AgC contact resistance. Electrical Contacts - 1999. Proceedings of the Forty-Fifth IEEE Holm Conference on Electrical Contacts (Cat. No.99CB36343).
[8] [Shea, 2007] Shea, J. J. (2007). Material Effect on Glowing Contact Properties. Electrical Contacts, Proceedings of the Annual Holm Conference on Electrical Contacts, 32(4), 90-97. DOI: 10.1109/HOLM.2007.4318200.
[9] [Shea, 2017] Shea, J. J. (2017, September). Glowing connections in DC circuits. Paper presented at the 2017 IEEE Holm Conference on Electrical Contacts. https://doi.org/10.1109/HOLM.2017.8088098.
[10][Shea, 2008] Shea, J. (2008). Comparing 240 Vrms to 120 Vrms Series Arcing Faults in Residential Wire. Proceedings of the 54th IEEE Holm Conference on Electrical Contacts, 8 December 2008. DOI: 10.1109/HOLM.2008.ECP.47.
[11][NFPA, 2022] National Fire Protection Association. (2022, January 1). Home Electrical Fires. https://www.nfpa.org/News-and-Research/Data-research-and-tools/Electrical/Electrical.
[12][Kim, 2018] Kim, W., Kim, Y. J., & Kim, H. (2018). Arc Voltage and Current Characteristics in Low-Voltage Direct Current. Energies, 11(10), 2511. https://doi.org/10.3390/en11102511.
[13][Koch, 2008] Gaudreau, A., & Koch, B. (2008, February). Evaluation of LV and MV arc parameters. IEEE Transactions on Power Delivery, 23(1), 487-492. https://doi.org/10.1109/TPWRD.2007.905566.
[14][Babrauskas, 2022] Babrauskas, V. (2022). Minimum Values of Voltage, Current, or Power for the Ignition of Fire. Fire, 5(6), 201. https://doi.org/10.3390/fire5060201.
[15][Riba, 2020] Riba, J. R., Gómez-Pau, Á., Moreno-Eguilaz, M., & Bogarra, S. (2020). Arc Tracking Control in Insulation Systems for Aeronautic Applications: Challenges, Opportunities, and Research Needs. Sensors, 20(6), 1654. https://doi.org/10.3390/s20061654.
[16][Lentini, 2013] Lentini, J. (2013). Evidence Collection at Fire Scenes. In Encyclopedia of Forensic Sciences (pp. 387-391). https://doi.org/10.1016/B978-0-12-382165-2.00211-7.
[17][Babrauskas, 2008] Babrauskas, V. (2008). Research on Electrical Fires: The State of the Art. Fire Safety Science, 9, 3-18. https://doi.org/10.3801/IAFSS.FSS.9-3.
[18][Campell, 2022] Campbell, R. (2022, February 01). Home Electrical Fires. NFPA Research: Electrical.
[19][Chow, 2016] Chow, H. M., Chow, W. K., & Hung, H. Y. (2016, March 2-3). A Study on Residential Fires due to Electrical Faults in Hong Kong. Paper presented at the 3rd Residential

Building Design & Construction Conference, Penn State, University Park. Retrieved from PHRC.psu.edu.
[20][Koreinek, 2016] Koreinek, C. W. (2013). Pre and post-flashover characteristics of an electrically overheated poor connection between copper and steel. In Proceedings of the 13th International Interflam Conference 2013.
[21][Sumner, 2014] Sumner, M., Thomas, D. W. P., Cao, Y., & Christopher, E. (2014, January). DC series arc generation, characteristic and modelling with arc demonstrator and shaking table. Paper presented at the 12th IET International Conference on Developments in Power
[22][System Protection, 2014] System Protection (DPSP 2014). DOI: 10.1049/cp.2014.0129.
[23][Huggett, 1987] Huggett, C., & Levin, B. C. (1987, September). Toxicity of the pyrolysis and combustion products of poly(vinyl chlorides): A literature assessment. Fire and Materials, 11(3). DOI: https://doi.org/10.1002/fam.810110303.
[24][ZhishengLi, 2023] Li, Zhisheng., Kim, J., Kang, M., Zhang, Y., Park, J., & Chung, S. H. (2023). Effects of applied AC electric fields on flame spread over inclined polyethylene-insulated electrical wire with Cu-core. Fire Safety Journal, 141, 103995. https://doi.org/10.1016/j.firesaf.2023.103995.
[25][FanliangGe, 2023] Ge, F., Qiu, T., Zhang, M., & Ji, J. (2023). Experimental research on the thermal characteristic of low-voltage alternating current (AC) arc faults. Fire Safety Journal, 136, 103732.
[26][Plesca, 2019] Plesca, A. (2019). Thermal Analysis of Busbars from a High Current Power Supply System. Energies, 12, 2288. https://doi.org/10.3390/en12122288.
[27][Benfer, 2014] Benfer, M., & Gottuk, D. (2014). Electrical Receptacles - Overheating, Arcing, and Melting. In Fire Safety Science-Proceedings of the Eleventh International Symposium (pp. 1010-1023). Copyright © 2014 International Association for Fire Safety Science. DOI: 10.3801/IAFSS.FSS.11-1010.
[28][Putorti, 2021] Taylor, G., Putorti Jr., A. D., Salley, M. H. (2021). Report on High Energy Arcing Fault Experiments: Experimental Results from Low-Voltage Switchgear Enclosures (NIST Technical Note 2197). National Institute of Standards and Technology.
[29][Nursultanov, 2020] Nursultanov et al. (2020). Investigations into LV distribution pillars - presentation.
[30][Home Electrical Fires, 2022] Home Electrical Fires. (2022, January 1). https://www.nfpa.org/News-and-Research/Data-research-and-tools/Electrical/Electrical.
[31][Armijo, 2014] Armijo, K M., Johnson, J., Hibbs, M., & Fresquez, A. (2014, June 1). Characterizing fire danger from low-power photovoltaic arc-faults. https://doi.org/10.1109/pvsc.2014.6925658.
[32][FAN] Future Architecture of the Network. (n.d). https://www.fan.ac.nz/.
[33][Han, 2015] Han, J., Oh, Y., Gwon, G., Kim, D., Noh, C., Jung, T., Lee, S., & Kim, C. (2015, September 11). Modeling and Analysis of a Low-Voltage DC Distribution System. https://doi.org/10.3390/resources4030713.
[34][Javed, 2018] Javed, W., & Chen, D. (2018, September 1). Low Voltage DC Microgrid Protection System - A Review. https://doi.org/10.1109/upec.2018.8541944.
[35][Kouchakipour, 2021] Kouchakipour, N. (2021, May 24). A DC-side fault-tolerant bidirectional AC/DC converter for power system in integration of low-voltage DC distribution systems. https://scite.ai/reports/10.32920/ryerson.14664750.
[36][MacConnell, 2021] MacConnell, F., Duggal, R., Rayudu, R., & Nair, N C. (2021, December 7). Mātauranga Māori in Power Engineering - Achieving sustainability and zero carbon futures with countries' indigenous knowledge in design. https://doi.org/10.1109/tencon54134.2021.9707384.
[37][Nair, 2009] Nair, N C., & Li-xi, Z. (2009, September 1). SmartGrid: Future networks for New Zealand power systems incorporating distributed generation. Energy Policy. https://doi.org/10.1016/j.enpol.2009.03.025.
[38][Normark, 2017] Normark, B., Shivakumar, A., & Welsch, M. (2017, January 1). DC Power Production and Consumption in Households. Elsevier eBooks, 237-248. https://doi.org/10.1016/b978-0-12-809806-6.00028-6.

[39][Paris Agreement, 2015] Paris Agreement under the United Nations Framework Convention on Climate Change (Paris Agreement) - The Faculty of Law. (2015, December 12). https://www.jus.uio.no/english/services/library/treaties/06/6-03/un_paris-agreement.xml.

[40][Shabani, 2016] Shabani, A., & Mazlumi, K. (2018, January 16). Studying grounding arrangements of the LVDC system through simulation. https://scite.ai/reports/10.1177/0037549717752069.

[41][Wang, 2017] Wang, D., Emhemed, A., & Burt, G. (2017, June 1). A novel protection scheme for an LVDC distribution network with reduced fault levels. https://scite.ai/reports/10.1109/icdcm.2017.8001024.

[42][Sweeting, 2011] Sweeting, D. (2011, January 5). Arcing Faults in Electrical Equipment. https://ieeexplore.ieee.org/document/5625907/.

[43][Tureski, 2011] Tureski, B., & Cromey, S. (2011, May 17). Arc-Flash Study. https://ieeexplore.ieee.org/document/5768055/.

[44][Zhang, 2007] Zhang, X., Zhang, J., & Pietsch, G J. (2007, June 1). Estimation of the Arc Power During a Three-Phase Arc Fault in MV Electrical Installations. https://doi.org/10.1109/tps.2007.897666.

[45][Alabani, 2023] Alabani, A., Ranjan, P., Jiang, J., Chen, L., Cotton, I., & Peesapati, V. (2023, September 1). Electrical Characterization and Modeling of High Frequency Arcs for Higher Voltage Aerospace Systems. https://doi.org/10.1109/tte.2023.3244776.

[46][Ammerman, 2010] Ammerman, R., Gammon, T., Sen, P., & Nelson, J P. (2010, September 1). DC-Arc Models and Incident-Energy Calculations. https://doi.org/10.1109/tia.2010.2057497.

[47][Khered, 2016] Khered, M. O. (2016). Arc Flash Safety in Company XYZ (Unpublished master's thesis). University of Wisconsin-Stout, Graduate School.

[48][Tensility, 2024] Tensility International. (n.d.). High-Temperature Cables and Connectors. Retrieved February 15, 2024, from https://tensility.com/product-news/high-temp-cables-connectors.

[49][Friday, 2022] Amakiri, O. F., Aghaukwu, C. N., & Simon, I. O. (2022). Electrical Arc Flash Safety Detection in Power Distribution Network. Journal of Engineering Studies and Research, 28(4), 61.

[50][Li et al., 2023] Li, C., Chen, J., Zhang, W., Hu, L., Cao, J., Liu, J., Zhu, Z., & Wu, S. (2021). Influence of Arc Size on the Ignition and Flame Propagation of Cable Fire. Energies, 14(18), 5675. https://doi.org/10.3390/en14185675

[51][Beben, 2022] Beben, D., Maleska, T., Bobra, P., Duda, J., Anigacz, W., Yepes, V., & Kripka, M. (2022). Influence of Traffic-Induced Vibrations on Humans and Residential Building—A Case Study. *International Journal of Environmental Research and Public Health, 19*(9), 5441. https://doi.org/10.3390/ijerph19095441

[52][Bonnefoy-Claudet, 2006] Bonnefoy-Claudet, S.; Cotton, F.; Bard, P.-Y. (2006). "The nature of noise wavefield and its applications for site effects studies. A literature review". *Earth-Science Reviews*. 79 (3–4): 205–227.

[53][Stacey, 2020] Stacey, K. (2020, March 3). Earthquakes at Brown University. Brown University. https://www.brown.edu/news/2020-03-03/earthquakes

[54]U.S. Department of Commerce, National Oceanic and Atmospheric Administration, National Geophysical Data Center. (n.d.). EARTHQUAKE DAMAGE TO TRANSPORTATION SYSTEMS. Boulder, Colorado 80303, USA. Retrieved from https://pubs.usgs.gov/unnumbered/70114624/report.pdf

[55]Earthquakes in New Zealand, URL: https://www.learnz.org.nz/geohazards163/bg-standard-f/earthquakes-in-new-zealand

[56][Hunaidi, 2000] Hunaidi, O. (2000, January). Traffic Vibrations in Buildings.

[57][NIWA, 2021] NIWA. nd. ‘Seven-station’ series temperature data. URL: https://www.niwa.co.nz/our-science/climate/information-and-resources/nz-temp-record/seven-station-series-temperature-data (accessed 20 April 2021).

[58]Littelfuse. Fuseology Selection Guide. Retrieved from https://m.littelfuse.com/~/media/electronics/product_catalogs/littelfuse_fuseology_selection_guide.pdf.pd
[59][Goodman, 2007] Goodman, M. (2007). Methods of inspection to determine the presence of potential arc flash incidents. NETA WORLD, 67
[60][Grondzik, 2014] Grondzik, W. T. (2014). Mechanical and electrical equipment for buildings. Boston: John Wiley & Sons.
[61][Doan, 2010] Doan, D. R. (2010). Arc flash calculations for exposures to DC systems. Industry Applications, 46(6), 2345.
[62][Lee, 2016] Lee, H. M., Chow, W. K., & Hung, H. Y. (2016). A Study on Residential Fires due to Electrical Faults in Hong Kong. In Proceedings of the 3rd Residential Building Design & Construction Conference, March 2-3, 2016, Penn State, University Park. Retrieved from PHRC.psu.edu
[63][Pugh, 2006] Pugh, S. N. (2006). *Forensic Evidence of Electric Arcs* (Doctoral dissertation, University of California, Davis)
[64][Matsumera, 2002] K. Nakayama, Y. Yokomizu, T. Matsumura et al, “Mechanism of voltage rise of high-current arc at atmospheric pressure due to deion plates,” IEEJ Transactions on Power & Energy 122, 1016 (2002)
[65][Land, 2008] Land, H. B. (2008). The Behavior of Arcing Faults in Low-Voltage Switchboards. *IEEE Transactions on Industry Applications, 44*(2), 437-444. doi: 10.1109/TIA.2008.916611.
[66][Cuppen, 2022] Cuppen, A., Greenwood, B., & Heffernan, W. (2022, September 19-21). Evaluation of performance and fire response of LV plastic pillar material. Paper presented at EEA2022 Conference, Hamilton Stream: Asset Enhancement.
[67][Utt, 2010] Utt, D. P. (2010). Electrical evidence at fire scenes. In 2010 IEEE Symposium on Product Compliance Engineering Proceedings (pp. 1-5). Boston, MA, USA: IEEE. doi: 10.1109/PSES.2010.5637801.
[68][Shea, 2000] Shea, J. J. (2000). The influence of arc chamber wall material on arc gap dielectric recovery voltage. In IEEE Transactions on Components and Packaging Technologies, 24(3), 342-348. doi: 10.1109/6144.946477.
[69][Young, 2007] Young, C. (2007). Electrical arc flash safety. Irvine, CA: Wumbus Corp.
[70][Miao, 2023] W. Miao, Z. Wang, F. Wang, K. H. Lam, and P. W. T. Pong. (2023). Multicharacteristics Arc Model and Autocorrelation-Algorithm Based Arc Fault Detector for DC Microgrid. In IEEE Transactions on Industrial Electronics, 70(5), 4875-4886. doi: 10.1109/TIE.2022.3186351.
[71][Zhou, 2011] X. Zhou and T. Schoepf. (2011). Characteristics of Overheated Electrical Joints Due to Loose Connection. In 2011 IEEE 57th Holm Conference on Electrical Contacts (Holm), Minneapolis, MN, USA (pp. 1-7). doi: 10.1109/HOLM.2011.6034795.
[72][Ridley, 2008] Ridley, J. C. (2008). Safety at work. New York: Routledge.
[73][Shea, 2009] Shea, J. J., & Zhou, X. (2009). Material Effect on Glowing Contact Properties. IEEE Transactions on Components and Packaging Technologies, 32(4), 734-740. https://doi.org/10.1109/TCAPT.2009.2034328.
[74][Xu, 2021] Xu, Q., Mensah, R. A. M., Jin, C., & Jiang, L. (2021). A critical review of the methods and applications of microscale combustion calorimetry for material flammability assessment. *Journal of Thermal Analysis and Calorimetry*, 147(10), 1-13. https://doi.org/10.1007/s10973-021-10963-4.
[75]Morx, A. (2016). Electrically Ignited Fires in Low Voltage Installations. Eaton. Retrieved from: https://www.eaton.com/content/dam/eaton/products/electrical-circuit-protection/circuit-breakers/arc-fault-detection-device/documentation/en/eaton-afdd-electrically-ignited-fires-in-low-voltage-installations-whitepaper-br003011-en-us.pdf