Electrical Safety Committee

IEEE Industry Applications Society

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ESW 2025

Advancing The Electrical Safety Culture

2025 IEEE IAS Electrical Safety Workshop

Jacksonville, FL March 3 – March 7 2024

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IEEE IAS Electrical Safety Committee (ESafeC) Subcommittees
"You Can Make a Difference"

The objective of the ESafeC is to advance the state of the art in methods and technologies that contribute toward prevention of occupational electrical incidents and injuries. The ESafeC has a number of subcommittees that support this objective, or support the annual Electrical Safety Workshop (ESW). You can make a difference in workplace electrical safety by volunteering to participate in the work of one or more of the subcommittees. Please contact the chair of any subcommittee that you have an interest in joining.

Academic Development Subcommittee
Chair: Afshin Majd afshin.majd@ieee.org
Engage students and instructors in all aspects of electrical safety and related standards. Implement initiatives designed to increase the value of the ESW for the subcommittee members. Seek out new and useful information and knowledge related to electrical safety standards, and guidelines which can be taught in academia. Find opportunities to use academia to spread information and knowledge related to electrical safety to students and others.

Standards Development Subcommittee
Chair: Arthur Smith arthur.smith@wsnelson.com
Manage codes and standards activities conducted at the current year workshop and lead the effort to initiate, develop and publish codes and standards sponsored by the ESafeC.

Construction Subcommittee
Chair: Eric Campbell ecampbell@brwncald.com
Engage individuals involved in construction activities from all disciplines and industries to get them involved in all aspects of electrical safety. This is done by communicating the advantages of proactive, positive, and engaged participation in the ESafeC, the Electrical Safety Workshop and other supported conferences.

Early Career Development Subcommittee
Chair: Jay Prigmore jrprigmore@gmail.com
Develop and implement methods to increase and maintain participation in ESafeC activities by individuals who are students or are early in their professional careers by providing guidance for improvements to their overall effort in electrical safety.

Government, Regulator, Inspectors and Laboratory Subcommittee
Chair: Lloyd Gordon lbgordon@lanl.gov
Engage with individuals, groups or organizations in governments, regulators, inspectors and laboratories for the purpose of increasing the involvement of this group in all aspects of electrical safety.

Historical and Records Subcommittee
Chair: Lanny Floyd h.l.floyd@ieee.org
Develop and maintain historical materials and information of the life and evolution of the ESafeC and the ESW and develop ways to make this information available. Encourage individuals and companies who have supported the committee or the ESW to submit memories

IEEE IAS Electrical Safety Committee (ESafeC) Subcommittees
"You Can Make a Difference"

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IEEE IAS Committee Relations Subcommittee
Chair: Matthew Hussey matthewrhussey@eaton.com
Engage individuals and leadership of other IAS committees and subcommittees for the purpose of increasing the reach and influence of the committee. To get individuals from other IAS committees involved in all aspects of electrical safety and to implement initiatives designed to increase the value of the ESW for these groups.

Industry Segment Development Subcommittee
Chair: Jeff Glenney jeff.glenney@bender-us.com
Engage individuals of all technical backgrounds in all segments of industry to become involved in electrical safety and implement initiatives designed to increase the value of the ESW for these organizations.

International Development Subcommittee
Chair: Marcelo E. Valdes marcelo.e.valdes@ieee.org
Engage individuals worldwide to be involved in all aspects of electrical safety. Seeking out and distributing new and useful information and knowledge related to electrical safety from all regions. Currently working with groups in Africa, Brazil, Costa Rica & India to fulfil the mission of the ESafeC.

Occupational Health and Safety Subcommittee
Chair: René Graves Rene.graves@yahoo.com
Engage occupational safety and health professionals from all disciplines and industries and develop mechanisms to broaden the electrical knowledge of those working in the occupational safety and health profession.

IEEE IAS Electrical Safety Committee (ESafeC) Subcommittees
"You Can Make a Difference"

Subcommittees that support the annual ESW

ESW Chair Subcommittee
Chair: Scott Seaver sseaver@ieee.org
The ESW Subcommittee plans, organizes and runs the annual ESW. Specific duties of the ESW Subcommittee and its members are outlined in the ESW Operating Manual..

Awards and Recognition Subcommittee
Chair: David Durocher davidbdurocher1@outlook.com
Manage the presentation of awards and recognition at the annual ESW and engage members of the ESafeC to nominate worthy individuals for the ESafeC awards.

Facilities and Finance Subcommittee
Chair: Stephen Wilson sfwilson7@yahoo.com
Oversee the logistics and financial matters related to hotels, meeting/eating/sleeping spaces, for the current year and future workshops.

Paper Review Subcommittee
Chair: Zarheer Jooma zarheer@e-hazard.com
Oversee the technical review of information presented at the ESW and other supported conferences, for the purpose of evaluating the accuracy and the value as reference or source material and recommend the selection of the various materials and information for publication and recognition.

Publicity and Media Subcommittee
Chair: Nehad El-Sherif nehad.e.el-sherif@ieee.org
Develop and maintain methods to promote and advertise the ESafeC and the ESW through various media outlets, including social media, websites and print media.

Technical Program Subcommittee
Chair: Mark Scott mascott@ieee.org
Oversee the solicitation, development, selection and presentation of technical information presented at ESWs globally by providing guidance for improvements of the overall technical effort for future years.

Organizing Committee
2025 IEEE IAS Electrical Safety Workshop

Position	Name	Company
ESW 2026 Chair	Michael Kovacic	ES Squared Safety
ESW 2025 Chair	Zarheer Jooma	e-Hazard
ESW 2024 Chair	Jay Prigmore	Google
Awards and Recognition Chair	Dave Durocher	Retired, Eaton
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Conference Support Materials VC	Bob Leroy	N/A
Conference Tech Support Chair	Michael Kovacic	ES Squared Safety
Conference Tech Support VC	Jennifer Martin	Pacific Northwest National Laboratory
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ESafeC VC	Paul Sullivan	DuPont
ESW Secretary	Michelle Smith	e-Hazard
ESW Secretary	Kathleen Cyrus	e-Hazard
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EventMobi App Chair	Paul Sullivan	DuPont
EventMobi App VC	Marcelo Valdes	ABB
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Local Participation Committee Chair	Karl Cunningham	ES Squared, Inc.
Media Analyst	Rebecca Krish-namurthy	RNA Associates, Inc

Organizing Committee
2025 IEEE IAS Electrical Safety Workshop

Position	Name	Company
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Product Expo Chair	Kevin Warren	Schewitzer Engineering Laboratories
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Registration Chair	Nelson Amy	Industrial Safety Training Council
Registration VC	Paul Sullivan	DuPont
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Website Support Chair	Nehad El-Sherif	MNKYBR Technologies Inc.
Website Support VC	Elisa Sellars	e-Hazard

The IEEE IAS Electrical Safety Workshop
Advancing the Electrical Safety Culture

Since its inception at the first meeting of the Safety Subcommittee of the IEEE IAS Petroleum and Chemical Industry Committee, held in Toronto in September 1991, the IEEE /IAS Electrical Safety Workshop has provided the forum to enable and accelerate change in the electrical safety culture limiting what we feel is possible in preventing workplace injuries from electrical hazards.

In 1991, US OSHA regulations for electrical safety in general industry had just been issued. NFPA70E was not widely known beyond a small group of people involved with the 70E technical committee. The IEEE Yellow Book, Guide for Maintenance, Operation and Safety of Industrial and Commercial Power Systems was still in draft. Arc flash was not in the safety vocabulary. For the people in that meeting in Toronto in 1991, there was a feeling that the future held much promise for reducing the number and severity of electrical injuries.

Today, In 2025, we are celebrating the 32nd anniversary of the Electrical Safety Workshop. Some things have changed. Electrical safety is a dynamic field. NFPA70E is widely known throughout electrical and safety communities. The IEEE Yellow Book was published and has evolved into IEEE 3007.1-3. Trade and professional magazines routinely feature articles on electrical safety. Arc flash mitigation created new markets for electrical equipment and personal protection. Occupational fatalities from electrical hazards in the US are down by more than 50%. The Workshop's impact extends beyond North America. One thing remains the same. The IEEE IAS Electrical Safety Workshop continues to enable and accelerate possibilities.

The mass market in electrical safety conferences is in the area of training and compliance with standards and regulations - helping people and organizations understand and apply current requirements. This is essential to preventing electrical incidents and injuries, but it is not the primary mission of the IEEE /IAS Electrical Safety Workshop. Our mission is more about path finding and creating the future in electrical safety by changing how we think about what is possible, or in other words, changing the electrical safety culture.

Our Mission is to: ·
- *Accelerate application of breakthrough improvements in human factors, technology, and managing systems that reduce risk of electrical injuries,*
- *Stimulate innovation in overcoming barriers,*
- *Change and advance the electrical safety culture to enable sustainable improvements in prevention of electrical accidents and injuries.*

Our Strategy includes:
- *Providing forums for people to meet and exchange ideas for preventing electrical accidents and injuries in the workplace*
- *Accelerating advancements in development and application of technology, work practices, standards, and regulations*
- *Linking professionals and centers of excellence in industry, engineering, government and medicine*

Past IEEE IAS Electrical Safety Workshops

Year	Location	Chair
2024	Tucson, AZ	Jay Prigmore, Google
2023	Reno, NV	Mark Scott, Lawrence Berkeley National Laboratory
2022	Jacksonville, FL	Thomas Domitrovich, Eaton
2021	Virtual	Kevin Lippert, Eaton
2020	Reno, NV	Scott Seaver, TE Connectivity
2019	Jacksonville, FL	Rene’ Graves, Texas Instruments
2018	Fort Worth, TX	Ken White, Olin (Retired)
2017	Reno, NV	Paul Sullivan, DuPont
2016	Jacksonville, FL	Dennis Hill, URS
2015	Louisville, KY	Hugh Hoagland, e-Hazard
2014	San Diego, CA	Marcelo Valdes, General Electric
2013	Dallas, TX	Dan Doan, DuPont
2012	Daytona, FL	Dennis Neitzel, AVO Training Institute Inc.
2011	Toronto, ON	Eva Clark, Lawrence Livermore National Laboratory
2010	Memphis, TN	Joe Rachford, Gallatin Steel
2009	St Louis, MO	Ben McClung, American Electric Power
2008	Dallas, TX	Jim White, Shermco Industries
2007	Calgary, AB	Mike Doherty, Ontario Power Generation
2006	Philadelphia, PA	Bob Huddleston, Eastman Chemical Co.
2005	Denver, CO	Stephen Wilson, Dofasco, Inc.
2004	Oakland, CA	D. Ray Crow, DRC Consulting
2003	Houston, TX	Lanny Floyd, DuPont
2002	Biloxi, MS	Charlie Hoy, R Stahl, Inc.
2001	Toronto, Ontario	John Gallagher, Bayer Corp.
2000	San Antonio, TX	Danny Liggett, DuPont
1999	San Diego, CA	David Pace, Olin Corp.
1998	Indianapolis, IN	Shahid Jamil, Exxon
1997	San Antonio, TX	Lynn Roach, Eastman Chemical Co.
1996	San Antonio, TX	Kim Eastwood, Thermon Manufacturing Co.
1995	San Antonio, TX	Clark Lockerd, Occidental Petroleum
1992	Dallas, TX	Co-chairs Don Vardaman, Oryx Energy and Lanny Floyd, DuPont

Past Regional Workshops Affiliated with the IEEE IAS Electrical Safety Workshop

Year	Location	Chair
2019	San Jose, Costa Rica	German Moya
2019	Salto/SP – Brazil	Edson Martinho
2017	Salto/SP - Brazil	Edson Martinho
2015	Rio de Janeiro/RJ -Brazil	Edson Martinho
2014	Pune, India	Satish Chaparala
2013	Recif - Brazil	Luiz K. Tomiyoshi
2012	Hyderabad, India	Satish Chaparala
2011	Sao Paulo, Brazil	Mario Ogava, Schindler Daniela Leal, DuPont
2009	Blumenau, Brazil	Fernando Bernardes, Areva Luiz Tomiyoshi, DuPont
2007	Rio de Jeniero, Brazil	Ricardo Mattos, Petrobras Luiz Tomiyoshi, DuPont
2005	Sao Paulo, Brazil	Estelitto Rangel, Jr., Petrobras Luiz Tomiyoshi, DuPont
2003	Guararema, Brazil	Estelitto Rangel, Jr., Petrobras Luiz Tomiyoshi, DuPont
2002	Bombay, India	Satish Chaparala
2000	New Delhi, India	Satish Chaparala Shahid Jamil, BP
1998	Madras, India	Satish Chaparala Shahid Jamil, BP

Useful Links to Non-Profit and Government Organizations Championing Prevention of Electrical Incidents and Injuries

ASSP, the American Society of Safety Professionals
www.assp.org

Founded in 1911, the American Society of Safety Professionals (ASSP) is the oldest and largest professional safety organization. Based in Des Plaines, Illinois, ASSP has 30,000 members who manage, supervise, research and consult on safety, health, transportation and environmental issues in all industries, government, labor and education. ASSP is a global organization that works to advance the technical, scientific, managerial and ethical knowledge and skills of occupational safety, health and environmental professionals, and is committed to protecting people, property and the environment.

CSA, the Canadian Standards Association
www.csa.ca

The Canadian Standards Association is a not-for-profit membership-based association serving business, industry, government and consumers in Canada and the global marketplace. CSA is developing the standard, seminars and supplemental materials for CSA Z462, Standard for Electrical safety in the Workplace.

ESFI, the Electrical Safety Foundation International
www.esfi.org

The Electrical Safety Foundation International was founded in 1994 in a joint effort by the National Electrical Manufacturers Association (NEMA), Underwriters Laboratories (UL) and the U.S. Consumer Product Safety Commission (CPSC). The Foundation was established to promote electrical safety in the home, school and workplace through public education about electrical hazards and the preventative measures we can take to avoid property damage, litigation, personal injury and death due to electrical accidents. The foundation's main annual activity is sponsorship and promotion of May as National Electrical Safety Month.

IAS, the IEEE Industry Applications Society
www.ewh.ieee.org/soc/ias/index.php

One of the 39 societies of the IEEE, the IAS has as its mission the advancement of the theory and practice of electrical and electronic engineering in the development, design, manufacture and application of electrical systems, apparatus, devices and controls to the processes and equipment of industry and commerce; the promotion of safe, reliable and economical installations; industry leadership in energy conservation and environmental health and safety issues; the creation of voluntary engineering standards and recommended practices; and the professional development of its membership. The IAS supports more than 20 annual technical conferences and more than 50 regional chapters around the world

Useful Links to Non-Profit and Government Organizations Championing Prevention of Electrical Incidents and Injuries

IEEE, the Institute of Electrical and Electronics Engineers, Inc.
www.ieee.org

The IEEE, a non-profit organization, is the world's leading professional association for the advancement of technology. With 365,000 members, IEEE promotes the engineering process of creating, developing, integrating, sharing, and applying knowledge about electro and information technologies and sciences for the benefit of humanity and the profession.

IEEE IAS Electrical Safety Committee
www.sites.ieee.org/ias-esafc/

Established in 2012, The Electrical Safety Committee is responsible for all matters within the scope of the IAS in which the emphasis or dominant factor specifically relates to occupational hazards of electrical energy. Topics include, but are not limited to: hazard phenomena, inherently safer design, work practices, hazard mitigation and electrical safety management.

IEEE IAS Electrical Safety Workshop
https://site.ieee.org/ias-esafc/

Sponsored by the Industry Applications Society of the Institute of Electrical and Electronics Engineers, Inc., the IEEE IAS Electrical Safety Workshop is a transnational technical forum organized by the IEEE IAS Electrical Safety Committee. It was founded in 1991 with the mission to accelerate application of breakthrough improvements in human factors, technology, and managing systems that reduce risk of electrical injuries; stimulate innovation in overcoming barriers; and change and advance the electrical safety culture to enable sustainable improvements in prevention of electrical accidents and injuries.

NETA, the International Electrical Testing Association
www.netaworld.org

The mission of the International Electrical Testing Association is to serve the electrical testing industry by establishing standards, publishing specifications, accrediting independent testing companies, certifying test technicians, and promoting the professional services of its members. The Association also collects and disseminates information and data of value to the electrical industry and educates the public and end user about the merits of electrical acceptance and maintenance testing.

NFPA, the National Fire Protection Association
www.nfpa.org

Established in 1896, NFPA serves as the world's leading advocate of fire prevention and is an authoritative source on public safety. NFPA's 300 codes and standards influence every building, process, service, design, and installation in the United States, as well as many of those used in other countries. NFPA offers books, training materials and seminars on NFPA Standard 70E, The Standard for Electrical safety in the Workplace.

Useful Links to Non-Profit and Government Organizations Championing Prevention of Electrical Incidents and Injuries

NIOSH, the National Institute for Occupational Safety and Health
www.cdc.gov/niosh

Part of the US Center for Disease Control, NIOSH ensures safety and health for all people in the workplace through research and prevention. Analysis of electrical injury trends, and electrical safety training and awareness tools and resources are available. In 2007, NIOSH launched the Prevention through Design initiative designed to bring greater emphasis to reducing hazard exposures through design processes.

NSC, the National Safety Council
www.nsc.org

The National Safety Council is a nonprofit organization whose mission is to save lives by preventing injuries and deaths at work, in homes and communities and on the road through leadership, research, education and advocacy. NSC advances this mission by partnering with businesses, government agencies, elected officials and the public to make an impact where the most preventable injuries and deaths occur, in areas such as distracted driving, teen driving, workplace safety and beyond the workplace, particularly in and near our homes.

OSHA, the Occupational Safety and Health Administration
www.osha.gov

OSHA's mission is to assure the safety and health of America's workers by setting and enforcing standards; providing training, outreach, and education; establishing partnerships; and encouraging continual improvement in workplace safety and health. Electrical safety training and awareness tools and resources are available.

Safe Electricity®
www.safeelectricity.org

Safe Electricity® is an award-winning, multi-media public awareness program of Energy Education Council. Since the program's creation in 2001, Safe Electricity® has been providing information to consumers and helping compliment the safety education activities of utilities and educators. The program provides life-saving information through many channels—including its comprehensive web site, radio and television public service announcements, videos, and more. Safe Electricity® has received national recognition for the quality and scope of its programs and services and is pleased to have the generous sponsorship support of Federated Rural Electric Insurance Exchange.

The IAS Electrical Safety Prevention through Design Student Engineering Education Initiative

Established in 2013, the IAS Electrical Safety Prevention through Design Student Engineering Education Initiative is geared toward graduate students in electrical engineering and safety engineering fields. The goals of this program are to award talented and promising students who have a passion for building electrical safety into their university curriculum by subsidizing travel, lodging and registration for participation in the IEEE IAS Electrical Safety Workshop. A limited number of students will be chosen for this honor.

Program Details

This program is three-fold:

A) an individual student submits a proposal essay for consideration;

B) chosen students are awarded attendance at the upcoming ESW, during which they present their proposal in the form of a poster;

C) students present to their fellow university classmates and professors what they have learned from their participation in technical program, tutorials, exposition and networking opportunities at the Electrical Safety Workshop. The specific details of Part C are to be determined by collaboration between the student and his/her professor and outlined in the application submission. One example could include hosting a department-wide presentation or brown bag series about the ESW.

Accepted Recipients for ESW 2025

- **Akabway Rurangwa**, Carnegie Mellon University Africa, RWANDA, *Electrical Safety Curriculum in Uganda*
- **Jhon Sebastián Montealegre Sterling**, Universidad Nacional de Colombia sede Manizales, COLOMBIA, *Low-Cost Software Tool for Arc Flash Protection Training Incorporating IEEE 1584.1 Standard*
- **Oliver Couillard**, Université du Québec à Rimouski, CANADA, *Arc Modeling for Transient Arc Flash Risk Assessment in DC Traction Systems*
- **Tate Dille**, University of South Dakota Mines, USA, *Development of an Automated DC Arc Generation and Data Acquisition System*
- **Vikram Decharwar**, University of Texas at Arlington, USA, *Electrical Safety in Industrial Environments*
- **Nazneen Ahmed**, The George Washington University, USA, *Prescribed Burning for Enhancing Electrical Safety and Resilience of Power Grids in Wildfire-Prone Areas*

Electrical Safety Workshop Papers

Competing Design Goals vs. Codes and Standards – Managing Electrical Hazards

Paper No. ESW2025-03

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Abstract – Industrial power system design engineers must balance design goals while meeting safety codes and standards, which may result in added expenses and complexities. This paper outlines the challenges faced by industrial power system design engineers in reconciling conflicting design objectives and explores principles for reaching a middle ground. Risk elements, risk evaluation, and management in relation to electrical hazards, as well as critical design objectives will be discussed. Finally, design examples are used to illustrate these concepts.

Index Terms — Design goals, Risk, Risk acceptance, Risk management, Hierarchy of risk control, CSA Z462, NFPA 70E.

I. INTRODUCTION

Industrial power system design engineers often face the challenge of reconciling conflicting design goals. Compliance with safety codes and standards can sometimes add yet another level of complexity. Additional codes and/or standards safety measures that are required offer one example of this additional complexity when trying to manage the cost of the installation. Another example involves selective coordination requirements or design goals that present a challenge around equipment protection and arc flash reduction. Selectively coordinated systems provide value to the installation around reliability and safety for electrical workers who must find and clear a fault, but these systems could be susceptible to higher incident energy levels resulting in extreme equipment damage and heavy PPE garments for electrical workers. Intentional delays implemented to achieve selective coordination present design challenges for the design professional who seeks to manage electrical safety risks. Moreover, redundancy makes the system more reliable but increases its overall cost by doubling the equipment required.

This paper aims to leverage power systems engineering fundamentals and establish a framework for industrial power system design engineers who must reconcile conflicting design goals while adhering to codes and standards requirements. Compromise is sometimes necessary, but the design engineer must manage electrical safety risk. The topic of risk is reviewed to establish a foundational understanding of its two primary components - likelihood and severity - in relation to competing design goals. Subsequently, a brief overview of risk assessment and risk management as they apply to electrical hazards is provided. Fundamentals of power systems engineering are reviewed considering essential design goals that pose challenges to design engineers striving to mitigate risk while designing a practical power system. Lastly, the paper will wrap up with a few design examples to illustrate the aforementioned concepts.

II. ELECTRICAL HAZARDS

Although electricity serves as the foundation of our modern lifestyle, it poses a significant risk of causing injuries due to its hazardous nature. The severity of these injuries is directly related to the voltage level, with higher voltages leading to more severe consequences. However, it is important to note that even low voltages have the likelihood of causing injuries, as demonstrated by the ability of lithium-ion batteries to ignite flammable materials. The NFPA 70E [1] and CSA Z462 [2] have established minimum thresholds for hazardous electrical energy, with the former setting it at 50 V for both ac and dc voltages, while the latter at 30 Vac and 60 Vdc for ac and dc voltages, respectively.

According to Annex K of [1] and [2], electrical injuries are classified into two general categories: electric shock and electric burns. Based on their cause, electrical burns can be further classified into: 1) arc burns that are caused by radiant energy, 2) thermal burns that are caused by exposure to ejected hot gases and materials, and 3) conduction burns that are caused by the flow of current through body parts. Additionally, the exposure to acoustic energy and toxic gases/pressure waves during an electrical arcing incident may lead to hearing impairment and traumatic injury, respectively.

An Electrical hazard, as defined in NFPA 70E and CSA Z462, is "*a dangerous condition such that contact or equipment failure can result in electric shock, arc flash burn, thermal burn, or arc blast injury.*" In light of this definition, electrical hazards are [2]:

1) *Electric Shock Hazard*: A source of possible injury or damage to health associated with current through the body caused by contact or approach to energized electrical conductors or circuit parts. The current passing through the body during an electric shock incident has two effects: thermal and neurological. The thermal effect on the body could cause skin burns that may require skin grafting and, if deep enough into subcutaneous tissue, may necessitate amputation of the affected body part. The neurological effect on the individual's nervous system, on the other hand, could include loss of voluntary muscle control, asphyxiation, ventricular fibrillation, and cardiac arrest. Research on the long-term effects of shock injuries, referred to as electric shock sequelae, is underway. These long-term effects include psychological, neurological, and physical symptoms, that may persist even in the absence of visible physical trauma

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2) *Arc Flash Hazard*: A source of possible injury or damage to health associated with the release of energy caused by an electric arc. This energy release is a result of the electrical breakdown of air producing an electrical discharge with associated temperatures that could reach extremely high temperatures. The four types of energies released during an arcing incident are:

a) Thermal energy: The thermal energy produced during an arcing incident is transmitted from the arc to the worker through radiation, convection, and conduction. Depending on the intensity of this thermal energy, direct exposure to the arc's thermal energy can cause skin burns, as well as ignition and burning of clothing, which can further transfer thermal energy to the skin. Inhaling hot gases from burning clothing can also result in internal burns in the upper respiratory system, including the mouth, throat, and nose. IEEE standard 1584 [3] is the industry resource primarily used to determine the amount of thermal energy released and exposed to the electrical worker

b) Blast pressure energy: In some cases, the rapid expansion of the surrounding air and metal can produce a significant blast pressure that causes destruction or damage of the surrounding environment in addition to the heat generated by the arcing incident. This expansion is associated with high pressure that can result in additional injuries. The vaporization of copper and other metals within the equipment that experiences an arc flash incident contributes to the life-threatening blast pressures. Copper undergoes a significant volume expansion when transitioning from a solid to a vapor state Once beyond the arc plasma, copper vapor temperature drops below the vaporization temperature and condenses into molten copper or forms a copper compound via chemical reaction. Studies have shown that the arc blast pressure is a function of the fault current, clearing time, voltage, frequency, size of the enclosure, and the failure of electrical components and equipment. Such failure unleashes pressure developed within the enclosure by the instantaneous heating, expansion, and confinement of the air surrounding the arc. Reported injuries suffered by workers include being hit by an ejected enclosure door, broken parts of equipment, and shattered insulators. Additionally, concussions and falls have also been documented. Research is currently being conducted by the US Nuclear Regulatory Commission (NRC) to understand the impact of blast pressure on safety related equipment located near other equipment when experiencing an arc flash incident [4]

c) Acoustic (sound) energy: Generally speaking, the louder the sound level (or noise) measured in Decibel (dB) is, the higher the likelihood of damaging the structures of the inner ear. A dB is a measurement that expresses the relative intensity of a sound pressure level (SPL) and is calculated relative to the threshold of human hearing, which is 0 dB [5]. According to the Centers for Disease Control and Prevention (CDC), a sound pressure level of 120 dB or higher can result in immediate hearing damage [6]. Examples of different sound levels in dB are in Fig. 1 [7], while their impact on hearing loss are in

d) TABLE *I* [5]. This sensorineural hearing loss is called noise-induced hearing loss (NIHL). The NIHL is also affected by the sound frequency because human ears are not evenly sensitive to all frequencies [8]. Thus, the sound perceived by human ears is different from the actual sound [8]. To compensate for this difference and to account for the effect of sound frequencies, the frequency-weightings for sound level measurements, including A-weighted decibel (dB(A) or dBA), C-weighted decibel (dB(C) or dBC), and Z-weighted decibel (dB(Z) or dBZ), were developed. For the purpose of this paper, only the dBA will be discussed. Readers who are interested in details on the difference between all frequency-weighted measurements and their applications are advised to review specialized referenced on the topic like [9].

The A-weighting is an adjustment applied to the measured sound level to express its relative loudness as perceived by the human ear. The human ear can perceive sound over a very large range of values, but our auditory system has limited sensitivity to low and high frequencies [8]. Accordingly, dB(A) assigns greater values to frequencies that fall within the central range of human hearing, and lower values to those frequencies at the peripheries, unlike the flat audio dB measurement that treats all frequencies equally. The average dB(A) ranges for some common sounds are shown in TABLE II [10]. It is worth noting that since a dB(A) measurement is an indication of what is heard by the human ear, two different sounds can have the same dB level, yet different dB(A) levels [8]. For example, the A-weighting levels of a 50 dB sound at a frequency of 1 kHz and a 50 dB sound at a 100 Hz are 50 dB(A) and 32 dB(A) respectively [8]. Thus, the 1 kHz sound is heard louder than the 100 Hz sound, because of the limitations of our ears in processing lower frequencies. An audible sample of these two sounds can be found in [8].

Exposure to sounds at or below 70 dB(A), even over a long period, is unlikely to cause hearing damage [10]. However, prolonged or repeated exposure to sounds at or above 85 dB(A) can result in hearing loss [10]. Thus, the Occupational Safety and Health Administration (OSHA) regulations require the employer to administrate a hearing conservation program whenever employee noise exposures equal to or exceed an 8-hour time-weighted average sound level (TWA) of 85 dB(A) or a dose of 50% [11]. Employee noise exposures (i.e., noise dose and TWA) are calculated using Appendix A of [11].

Sound level of an arc flash incident have been reported as being as high as or higher than 160 dB [1] or 130 dB [2]. That said, the authors were not able to locate any studies of recorded sound levels for arc flash incidents.

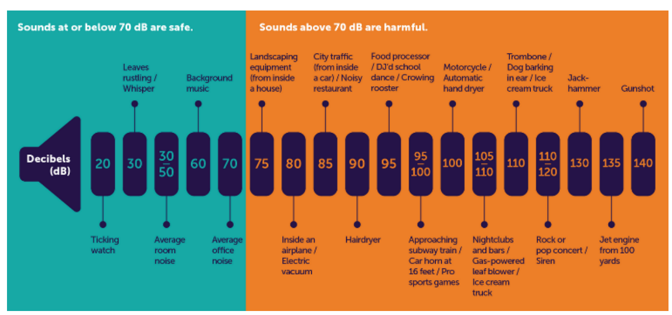

Fig. 1 Safe and unsafe dB sound levels [7]

TABLE I
IMPACT OF SOUND LEVELS ON HEARING LOSS

Hearing Loss	Threshold (dB)*	Description
None	0–25	Hearing within the normal range
Mild	25–40	Difficulty hearing distant or faint speech
Moderate	41–55	Difficulty hearing conversational speech
Moderately severe	56–70	Difficulty hearing most speech
Severe	71–90	Difficulty hearing loud speech and environmental sounds
Profound	>90	Difficulty hearing even very loud sounds

*The cutoff points for each threshold may vary slightly among practitioners and publications

TABLE II
A-WEIGHTED DECIBEL RANGE FOR COMMON SOUNDS

Sounds	dB(A) Range
Normal Conversation	60 – 70
Movie Theater	74 – 104
Motorcycles and dirt bikes	80 – 110
Music through headphones at max. volume, sports events, concerts	94 – 110
Sirens from emergency vehicles	110 – 129
Fireworks Show	140 – 160

e) Light energy: The term *arc flash* was coined to describe the bright light emitted during an electric arc. Research has shown that the brightness of the light generated during an arcing incident is influenced by various factors including voltage and current. Studies have also revealed that the light brightness observed by an individual facing the arcing incident (i.e., relative luminosity) is influenced by the distance from the arc, the orientation of the conductor (vertical or horizontal), and whether the arc is contained within an enclosure, and the dimensions of the enclosure (if present). Exposure to ultraviolet (UV) rays and radiant energy in the visible light bands produced by electric arcs and gas flames can cause eye injuries. The most frequent injury, UV Keratitis, commonly called welders flash, occurs when the unprotected eye is exposed to the intense light generated from an arc. The intense UV light literally sunburns the surface of the eye. Although this is painful and disabling, it is temporary in most instances. Chronic exposure, however, greatly increases the risk of cataracts. Nearby workers and workers passing through an area where welding is going on sometimes experience this injury if they happen to be watching when the welder strikes their arc. Radiation in the visible light band, if too intense, can also cause eyestrain, headache and retinal damage

3) *Thermal Burn Hazard*: A source of possible injury associated with touching an object or a surface that became hot due to the passage of electrical current. One example of these thermal burns is touching a light bulb while energized or immediately after turning it off. Another example is touching an enclosure or other conductive components that were heated by fault currents at voltages less than 50V. If the circuit voltage is lower than the electric shock threshold set by NFPA 70E and CSA Z462 for both ac and dc, then an electrical shock hazard does not exist and the only hazard present in this case is the thermal burn hazard. According to their severity, thermal burns are classified into [12] and [13]:

a) First-degree burns: The most common burns and are generally minor because they only affect the epidermis (i.e., the outer layer of skin) and usually do not cause scarring

b) Second-degree burns: Also known as partial-thickness burns, are more severe than first-degree burns because they affect both the epidermis and the dermis (i.e., the middle layer of skin). Second degree burns are painful and the injured area can swell and appear red with blisters. Second-degree burns have two subtypes: superficial and deep. Superficial second-degree burns heal quicker and typically do not scar, while deep second-degree burns take longer to heal, may require surgery depending on the size and location, and often have some degree of scarring

c) Third-degree burns: Also known as full-thickness burns, affect both skin layers as well as deeper tissues like sweat glands. Third-degree burns result in scarring and loss of fingernails and toenails if the burn is on the hand or the foot respectively. Skin grafting is often necessary because they burns do not heal by themselves

d) Higher-degree burns: Fourth-degree burns and beyond are deeper burns that destroy the skin, muscles, and bones. If the burn does not result in death, amputation will be required. In case amputation is not needed, skin grafting is required and permanent motor damage may occur

III. RISK AND RISK ACCEPTANCE

A. Risk

Given its hazardous nature, it is crucial to fully understand the risk associated with electrical energy. Understanding risk is the first step in taking all necessary precautions to mitigate electrical incidents by establishing an electrically safe work condition. Risk is defined in NFPA 70E and CSA Z462 as: "*A combination of the likelihood of occurrence of injury or damage to health and the severity of injury or damage to health that results from a hazard*." This definition states that the two components of risk are likelihood (or probability) and severity (or impact). The likelihood of occurrence is a weighted risk factor based on an analysis of the probability that a given threat is capable of exploiting a given vulnerability (or set of vulnerabilities) [14], while severity is the magnitude of harm expected to result from the hazard. The likelihood of occurrence of an incident is estimated based on:

1. Incident history statistics
2. Industry benchmarks
3. Personal experiences
4. Elements of human performance
5. Job site variabilities that result in changes in the working conditions

Both likelihood and severity play an important role in the decision-making process. Consider the following examples as a review of risk and its components of likelihood and severity:

1) *Climbing a Step Ladder*: Except those of us suffering from acrophobia, most people will climb a ladder with no hesitation because the likelihood of falling is perceived to be very low, although a fall could be severe resulting in a broken limb or death. The US Center for Disease Control and Prevention (CDC) had reported that during the holiday season (November 1st to January 31st), there were more than 5,800 fall injuries per season related to holiday decorating over three years [15]. Approximately 43% of these fall injuries were caused by falls from ladders with 47% of those resulting in hospitalization

2) *Air Travel*: The severity of a plane crash could be catastrophic but, it is a fact that commercial scheduled air travel is among the safest modes of transportation; the 2021 lifetime odds of dying as an aircraft passenger in the United States were too small to calculate. Hence, the likelihood of a plane crash is low enough for some to make the perceived risk acceptable but for others, the statistics may not be enough to overcome their fear of flying [16]

3) *Skydiving:* The activity of skydiving could have a high perceived risk leading those who are risk averse to not engage in this activity. In reality, reported statistics may demonstrate that the likelihood of a skydiving accident is very low. The US Parachute Association (USPA), the body that oversees skydiving activities in the US, reported a very low fatality rate (0.27 fatalities per 100,000 jumps) in 2023 [17]

B. Risk Acceptance

Risk acceptance varies considerably from one individual to another. We all accept a certain level of risk as part of our jobs and personal life. Even for the same individual, the risk acceptance level is not fixed and is dictated by many factors including age, experience, marital status, profession, and organization. To better understand this, let's consider the journey of one individual through the years:

1) *Childhood*: This individual may take on uncalculated risks due to inexperience
2) *Teenager*: With more experience the desire to take on more calculated risks increases, yet it may be curbed by the teen's legal guardians or financial dependency
3) *Single Young Professional*: Enjoying more financial freedom and no dependence, the risk acceptance level could increase substantially
4) *Married Middle*-aged: After getting married and having kids, the risk acceptance level may go down because of these new commitments
5) *Senior Year*: As the individual ages, the risk acceptance level significantly decreases for many reasons. Simple incidents can cause greater degrees of injury and take longer to heal

In addition to the changes above through the individual's personal life, risk acceptance levels may be influenced by an individual's occupation or employer. Some examples include firefighters, linemen, and professional athletes who are required to accept higher levels of risk than the average person. Within the same industry, every organization has a unique safety culture that dictates the acceptable level of risk an employee can take.

IV. RISK MANAGEMENT

There is no agreed upon definition for risk management that applies to all different fields of applications (e.g., business, quality control, environment, legal, security, strategy, or safety). Generally speaking, risk management is the process of identifying, evaluating, and ranking risks to strategically minimize, monitor, and control the likelihood of occurrence or severity of exposure, while maximizing favorable outcomes. The risk management process as defined in [18] is depicted in Fig. 2.

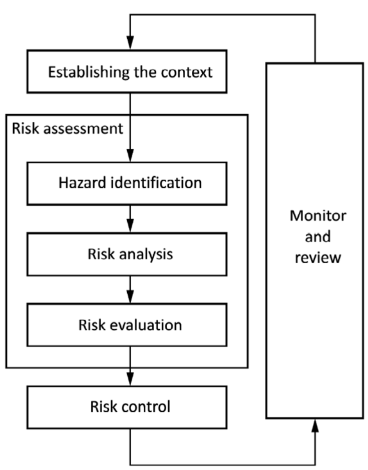

Fig. 2 Risk management process [18]

A. Risk Assessment

The process used to identify all potential hazards and the required protective actions is called risk assessment. The formal definition of risk assessment found in [1] and [2] is: "*An overall process that identifies hazards, estimates the likelihood of occurrence of injury or damage to health, estimates the potential severity of injury or damage to health, and determines if protective measures are required.*" Risk assessment is an essential part of risk management that entails the following steps per Annex F of [1] and [2]:

1. Hazards Identification (i.e., sources of harm or injury)
2. Risk level estimation
3. Risk evaluation to determine the required risk controls

When conducting a risk assessment, either a hazard-based or task-based risk assessment can be used. A task-based risk assessment is commonly used when performing a field level risk assessment as per Annex F of [1] and [2].

1) *Hazard-based*: Workplace hazards and the activities that might be affected by those hazards are identified. The likelihood and severity of risks associated with each activity are evaluated
2) *Task-based*: Each job is broken down into specific tasks to identify the hazards associated with each task (this is often referred to as task-hazard pairs). The risk associated with each hazard is evaluated for its likelihood and severity

In the context of workplace electrical safety, the two risk assessments conducted are electrical shock and arc flash risk assessment. For more details on electric shock and arc flash risk assessment, the reader is advised to review Sections 130.4 and 130.5 of [1] or Clauses 4.3.4 and 4.3.5 of [2] respectively. Finally, it is worth noting that there are different techniques for performing risk assessment. Brainstorming, checklist, and risk assessment matrix are a few examples. The choice of the risk assessment method is based on the application, desired outcome, and skillfulness of the individuals performing the risk assessment. In the following section, the risk assessment matrix will be discussed. Details on different risk assessment techniques can be found in [18].

B. Risk Assessment Matrix

One of the tools that could be used for estimating the risk level is the risk assessment matrix (also known as risk rating or risk control matrix). A risk assessment matrix generates a risk score based on the likelihood and severity of the hazard under consideration. A risk matrix is a grid structure with different likelihood levels displayed on the vertical axis and severity levels on the horizontal axis.

Likelihood of occurrence is a weighted risk factor based on an analysis of the probability that a given threat is capable of exploiting a given vulnerability, or set of vulnerabilities [14]. Accordingly, the likelihood level is determined based on: 1) History of incidents, 2) Industry benchmarks, and 3) Personal experience. On the contrary, quantifying an incident severity is not that straightforward, because severity is highly subjective and varies drastically for the same incident. For example, an injury resulting from falling off a ladder could vary from a few bruises, broken bones, spiral cord injury, or a head injury (e.g., concussion, skull fracture, and traumatic brain injury) and influenced by the employee's age and health. Thus, assigning the severity level is a judgement call at best, depending on the assessor's knowledge and the hazard under consideration.

The risk level/score is obtained by multiplying the likelihood and severity levels. For example, if the likelihood level is 3 and severity level is 2, then the risk score is 6. The risk assessment matrix comes in different sizes, for example 5 x 5, 4 x 4, 3 x 3 and 2 x 2. A smaller matrix size yields less granularity, thus the risk matrix size used will depend on the level of detail needed. An example of a color-coded 5 x 5 risk assessment matrix is shown in TABLE III. This matrix is comprised of 5-columns and 5-rows, creating 25-indivudual cells. The quantitative risk score in each cell is the product of likelihood and severity levels, while the qualitative values are determined based on valid risk scores shown in TABLE IV. It is worth noting that the assignment of qualitative risk values to risk scores in TABLE III is situation dependent. These tables can be customized per company or tasks. Thus, reassignment of these scores is possible. For example, a risk score of 3 (shown as *minimal risk* in TABLE III) could be reassigned as *low risk*, a risk score of 6 (labeled *low risk* in TABLE III) could be reassigned as *medium risk*, and a risk score of 10 (identified as *medium risk* in TABLE III) could be reassigned as *high risk*.

TABLE III
A COLOR-CODED 5 x 5 RISK ASSESSMENT MATRIX

		Severity				
		1 Insignificant	2 Minor	3 Significant	4 Major	5 Catastrophic
Likelihood	5 Frequent	5 Low	10 Medium	15 high	20 Extreme	25 Extreme
	4 Possible	4 Low	8 Medium	12 High	16 high	20 Extreme
	3 Occasional	3 Minimal	6 Low	9 Medium	12 High	15 high
	2 Remote	2 Minimal	4 Low	6 Low	8 Medium	10 Medium
	1 Improbable	1 Minimal	2 Minimal	3 Minimal	4 Low	5 Low

TABLE IV
QUALITATIVE RISK VALUES AND RISK SCORES

Qualitative Values	Risk Scores*
Minimal	1, 2, 3
Low	4, 5, 6
Medium	8, 9,10
High	12,15,16
Extreme	20, 25

*Risk scores 7, 11, 13, 14, 17, 18, 19, 21, 22, 23, and 24 are invalid

To illustrate the practical application of the above risk matrix, let's use it to obtain a risk score for air travel. The first step is to determine the likelihood of a plane crash. Based on published statistic [16], a plane crash is improbable but its severity is catastrophic. Using TABLE III, air travel risk score, which is the product of likelihood and severity is 5 (1 x 5), i.e., l*ow risk* activity.

The process of leveraging the risk matrix and exploring the likelihood and severity is in itself a healthy process to understanding risk. The risk score calculated is not what matters most, it is the process and the journey to understand the factors that impact likelihood and severity.

C. *Hierarchy of Risk Control*

The hierarchy of risk control is a systematic approach for identifying and ranking 6 risk controls (i.e., protective measures) to safeguard workers from potential hazards. These risk controls are prioritized in order of their effectiveness (i.e., from the most effective to the least effective protection method), as depicted in

Fig. 3. Hierarchy of risk control methods and examples of how they are implemented in the context of electrical safety are listed in TABLE V. A brief overview of the hierarchy of risk control methods is given below. More details are in [19] and [20].

1) *Elimination*: Removing hazards from the workplace to ensure that they do not exist. This is the preferred risk control method as it is most effective and should be used whenever possible. In the process of hazard elimination, it is important to understand that a job site has many different hazards involved (i.e., hazards could include trip and fall, cut and abrasion, electrical, chemical and more). Hazard elimination is often focused on a hazard-by-hazard basis and may not result in removing all of the hazards involved. Examples of hazard elimination include:

- Eliminating hearing loss hazard through specifying / using equipment with sound levels less than 70 dB(A)
- Eliminated fall hazard by implementing solutions that can be serviced without the use of ladders or similar equipment
- Eliminating chemical burn hazard through prohibiting the use of hazardous chemicals

2) *Substitution*: Replacing a higher risk hazard (if cannot be eliminated) with a lower risk hazard. Since risk is comprised of likelihood and severity, substitution would have to impact one or both components. Examples of hazard substitution include:

- Substituting solvent-based paint with water-based
- Substituting refined sugar with a sugar substitute
- Substituting lead-based materials with lead-free ones
- Substituting chemical pesticides with natural ones
- Substituting diesel engines exhaust emissions with electric motors

3) *Engineering Controls*: Reducing exposure of personnel to the hazard. In this case, the hazard exists and is not eliminated or substituted, but rather exposure to the hazard is controlled and/or eliminated through design decisions and implementation. In other words, personnel are isolated from the hazard. Examples of engineering controls include:

- Adding guardrails to a balcony adds a barrier to personnel standing on the balcony, thus reducing the likelihood of a fall. Though, the hazard of fall from a high location is still there
- A cage around a fan prevents intrusion of fingers keeping them away from hazardous moving blades. Though, the hazard of moving fan blades is still there

- Implementing a fall harness for personnel working at heights prevents a fall. Though, the hazard of the fall from a high location is still there

4) *Awareness*: Increasing the ability of personnel to recognize hazards that exist. Awareness of hazards and the ability to recognize them does not remove nor reduce the hazards that are present. Hence, the reason awareness is ranked low on the hierarchy of risk controls. Examples of awareness controls include:

- Educating new drivers on roads signs and how to appropriately respond to them when driving, but does not prevent drivers from ignoring the signs. The hazards exist regardless of the signs
- No swimming signs can make personnel aware that waters are dangerous and swimming is prohibited but does not stop them from getting in the water. The hazards associated with the water body still exist
- Product manuals for appliances educate individuals on how to properly use them to avoid harm. This does not prevent a person from ignoring the provided information. The hazards associated with the appliance still exist

5) *Administrative Controls*: Developing work policies and procedures to ensure work is performed in a manner that minimizes risk. Administrative controls influence the way people work to manage risk by reducing its likelihood and severity. Like awareness, this control is ranked low because it does not remove the hazard but acts to influence personnel behavior. Examples of awareness controls include:

- Scheduling shorter work hours in contaminated areas can limit the worker's exposure to hazards but does not eliminate the hazard. This does not prevent a person from ignoring the scheduling and working extra hours
- Performing preventative maintenance on a vehicle at scheduled intervals can decrease the likelihood of failure of breakers and other parts, but there is no guarantee that the owner of the vehicle will perform the maintenance as specified
- Providing procedures to be followed when work is performed is meant to control the process to reduce risk, but the hazards still exist. Procedures may be ignored as there is no guarantee they will be followed

6) *Personal Protective Equipment (PPE)*: Wearing clothing and other accessories to protect personnel from hazards. PPE can only provide adequate protection against hazards, if worn and used correctly. Thus, Personnel must be vigilant in following proper procedures and undergoing regular training to ensure the effectiveness of their PPE. Examples of PPE include:

- Respirators, gloves, and hardhats
- Eye protection (e.g., face shields and safety glasses)
- Hearing protection (e.g., ear plugs and ear muffs)
- Skin protection (e.g., coveralls and full body suits)
- Foot protection (e.g., steel-toed boots and slip resistant soles)
- Fall protection (e.g., guardrail systems, safety net systems, and personal fall arrest systems)

When selecting a risk control method, it should be noted that the three most effective risk controls (elimination, substitution, and engineering controls) rely less on human behavior and reduce the likelihood of human errors. Also, risk control methods are not mutually exclusive and a combination of controls is usually the most effective in controlling a single hazard. For example, controls for addressing the risk of driving to work during extreme winter conditions may include: 1) avoiding to drive (elimination), 2) taking public transit to work (substitution), 3) installing winter tires (engineering), and 4) training for driving in winter conditions (awareness).

TABLE V
THE HIERARCHY OF RISK CONTROL METHODS

Method	Examples
Elimination	Conductors and circuit parts in an electrically safe working condition, industrial control circuits designed below thresholds for hazardous electrical energy (50 Vac and 50 Vdc in the US and 30 Vac and 60 Vdc in Canada)
Substitution	Use of battery-operated tools instead of cord-plug connected tools, using equipment with maintenance schedule advantages (e.g., LED lighting with long-life), Removing the need for ladders to conduct work, arc resistance switchgear
Engineering Controls	Zone selective interlocking, maintenance switch, arc flash relays, absence of voltage testers, insulation barriers, GFCIs, remote racking, arc quenching
Awareness	Warning signs, job and hazard awareness training
Administrative Controls	Lockout/tagout, procedures and job planning tools
PPE	Arc flash suits, rubber gloves, hearing protection

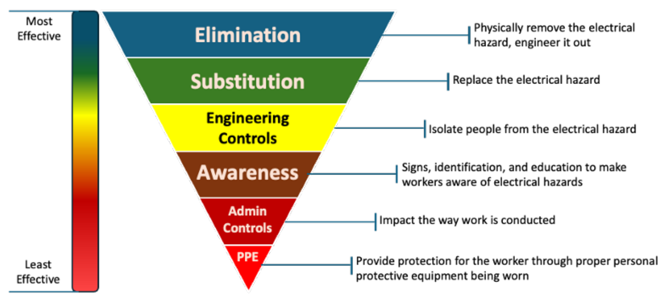

Fig. 3 The Hierarchy of risk control

V. DESIGN GOALS

When designing an industrial power system, design engineers are often faced with the challenge of meeting various competing design goals. Balancing these competing goals requires careful consideration of trade-offs and compromises at various stages of the design process. Moreover, identifying and ranking these goals is based on their relative significance or impact on the overall project or system. Prioritization of design goals helps guide the decision-making and resource allocation to ensure that the most important objectives are addressed effectively. Thus, high priority goals are the most critical goals that deserve the greatest attention and resources, while low priority goals receive less emphasis and are subject to trade-offs. It is worth noting that goal prioritization is industry-driven and goal ranking could vary drastically based on the situation. For example, reliability is the number one priority for nuclear power plants but it is not for residential dwelling units or commercial buildings. In this paper, the following design goals are taken into consideration:

1) *Reliability*: Ensuring that the electrical system operates consistently and predictably over time without failure by: i) selecting reliable components, ii) implementing redundancy as necessary, and iii) designing for durability

2) *Efficiency*: Maximizing the efficiency of electrical systems to minimize energy losses, space, and operating costs by i) optimizing the design of components, ii) minimizing power consumption during standby or idle states, and iii) minimizing electrical system footprint

3) *Safety*: Designing electrical systems that are safe for both users and equipment minimizing electrical safety risks by: i) protecting against all electrical hazards and ii) complying with relevant safety standards and regulations

4) *Cost*: Lowest cost electrical installation solution to meet budgets and financial constraints by selecting components and design solutions that stay within budget constraints

5) *Scalability*: Designing systems that can easily scale up or down to accommodate changing requirements by: i) identifying and addressing applications where future expansion is anticipated, ii) Implementing modular design principles and flexible architecture, and iii) sizing of the electrical system to meet future demand

6) *Environmental Impact*: Minimizing the environmental impact of electrical systems by: i) reducing energy consumption, ii) using environmentally friendly materials, and iii) considering end-of-life disposal and recycling options

7) *Ease of Maintenance*: Designing systems that are easy to maintain and repair to minimize downtime and reduce long-term operating costs. This involves considerations like: i) accessibility of components, ii) diagnostic capabilities, and iii) documentation

8) *Security*: Power system security describes the controls and safeguards that an organization takes to ensure its networks and resources are safe from downtime, interference or malicious intrusion. This includes the protection of data from bad actors and reliability of the electrical system to perform its function (cyber-attacks, physical attacks, and similar on the power distribution system and its components)

VI. DESIGN EXAMPLES

This section is dedicated for discussing a few design examples, to demonstrate the aforementioned concepts.

A. Transformer Suppling a Panelboard vs. Incident Energy

The first panelboard on the secondary of a transformer shown in Fig. 4 presents greater hazard to electrical workers through increased severity of arc flash. The incident energy is likely to be high at this secondary equipment due to the protecting overcurrent protective device (OCPD) being on the primary of the transformer that is increased in size to accommodating transformer inrush current. The selection of OCPD 1 in Fig. 4 is such that its role is to provide short-circuit protection of the transformer, not the panelboard on the secondary, and enable the transformer to energize without tripping on the inrush current of the transformer. Section 450.3 of the National Electrical Code (NEC) [21] and Rules 26-250, 26-252, and 26-254 of the Canadian Electrical Code (CE Code) [22] provide the maximum size of OCPDs on primary and secondary of the transformer for proper transformer protection. To understand the hazard of the first panel on the secondary of a transformer to electrical workers, a complete analysis of the system shown in Fig. 4 is given in the Appendix.

The analysis in the Appendix demonstrates that by placing OCPD 2 in its own enclosure, the incident energy is moved from the panelboard that has a higher likelihood of justified energized work to the OCPD 2 enclosure which has a much lower likelihood of justified energized work. Accordingly, the severity was reduced in the equipment likely to be worked on while energized. Though, the severity was not reduced in the OCPD 2 enclosure, but since it is a single OCPD in an enclosure, the likelihood of justified energized work in that enclosure is very low. The overall risk for the secondary panelboard has been reduced. This could come at the cost of system efficiency by increasing its footprint due to the addition of a sperate enclosure with an OCPD. Installation cost may be higher due to mounting additional equipment. Using a transformer with a secondary integrated OCPD may remove the footprint concerns, but may still be an increase in cost.

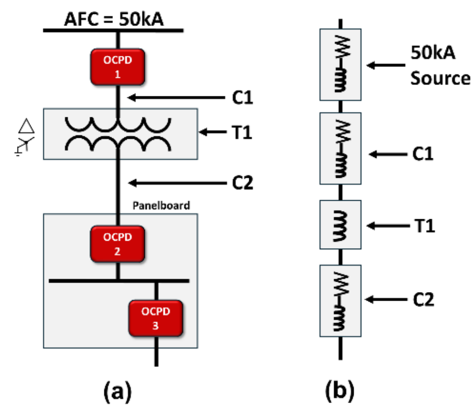

Fig. 4 A delta-wye-grounded transformer supplying a secondary panel: (a) single-line, (b) impedance diagram

B. Selective Coordination vs. Incident Energy

Selective coordination is not only a design goal but also a code requirement for some applications. Selective coordination is fundamental to power system reliability by ensuring that the OCPD closest to the fault clears first without any upstream OCPD opening. The power systems engineer who seeks to achieve selective coordination must first ensure an accurate single-line diagram, then calculate the maximum available fault current at each distribution equipment in the power system, and then ensure that the OCPDs are selected such that there is a localization of any overcurrent condition restricting outages to only the circuit or equipment affected. Ensuring selectivity for all currents from overload to available fault current will likely generate higher incident energy values throughout the selectively coordinated system. Technologies are available to help the design engineer achieve a selectively coordinated system and address possible high incident energy concerns.

Selectively coordinating a power system for all overcurrents up to and including the three-phase bolted fault current introduces intentional delays that could result in long clearing times for arcing currents. Addressing risk for these applications comes in the form of reducing the severity of the event by reducing the amount of time the arcing current is permitted to flow without jeopardizing selective coordination during normal operations. Each solution will come with some level of risk and cost. Risk management is achieved by understanding the technologies to be implemented and their zones of protection. The following are design options for addressing higher incident energy generated when a power system is selectively coordinated:

1. Zone selective interlocking (ZSI).

The technology of ZSI has been around for a very long time and has historically been used to provide protection of equipment When installed, ZSI provides a zone of protection that includes everything between the load side lugs of the upstream circuit breaker and the line-side lugs of the downstream circuit breaker. When implementing ZSI, the upstream device ignores its trip curve and trips without an intentional delay for a fault within the zone of protection. Faults outside of the zone of protection are not afforded the reduced clearing times. Therefore, ZSI reduces incident energy but it does not achieve selective coordination.

2. Differential relaying

Differential relaying is very similar to ZSI in that the technology provides a zone of protection. It is different in that the sensors used to provide the zone of protection are external to the circuit breakers. This technology can be applied on fusible systems as well. The zone of protection is expanded beyond that of ZSI because the sensors are placed on the conductors and engulf the line and load side terminals of both upstream and downstream OCPDs. This is an expensive solution but provides complete protection. The relay could also be employed such that it opens an upstream OCPD and not the main OCPD in the equipment. This technology detects faults in the zone of protection and acts to reduce the clearing time of the OCPD.

3. Arc energy reduction switch

The arc energy reduction switch is a technology that can reduce incident energy to downstream equipment when activated. This technology modifies the trip curve of the OCPD while activated reducing the clearing time for downstream arcing faults thus resulting in less damage and less incident energy for the electrical worker. An additional level of complexity is introduced with the requirement that the technology be turned on before justified energized work is performed and off after work has been completed. Protection is not provided during normal operation.

4. Current limiting fuses

Fuse technology by design when implemented in a selectively coordinated system may provide inherent incident energy reduction when fault currents are high. Selecting fuses with a 2:1 ratio (i.e., a downstream fuse will selectively coordinate with an upstream fuse with double its rating or higher up to their interrupting rating) for selectivity enables reducing the size of the upstream OCPD regardless of the available fault current of the system. For high fault currents, the arcing currents may be in the fast-clearing time of the upstream fuse providing incident energy reduction and equipment protection.

5. Active arc-flash mitigation system

Active arc-flash mitigation systems leverage current sensing and the sensing of light within the equipment to determine when an internal arc fault occurs. The response time of this technology is exceptionally fast and reduces incident energy and equipment damage to a point where replacement is not necessary. The disadvantage is the cost and availability for equipment other than switchgear and switch boards. Panel boards and other types of equipment that cannot be equipped with an active arc-flash mitigation system must use a different technology for incident energy reduction. Active arc-flash mitigation system has a zone of protection within which the light sensors are installed, providing no protection upstream or downstream of the equipment.

6. Arc-resistant equipment

Employing arc-resistant equipment is not a method of reducing equipment damage for the faulted equipment. Employing this technology simply contains and redirect the energy. It will provide protection for equipment outside of the equipment located in the room next to the equipment. This technology will not provide protection when any of the doors are opened which is when faults are more likely to occur. It will provide protection from internal faults during normal operation.

C. Series Ratings vs. Cost and Scalability

Series ratings for circuit breakers and fuses refers to the practice of combining two or more OCPDs, such as a main upstream OCPD (circuit breaker or fuse) and a downstream circuit breaker, in a system to achieve a higher interrupting capacity than the downstream circuit breaker alone can handle. This arrangement relies on both devices working together, the upstream OCPD (circuit breaker or fuse) and downstream circuit breaker, to clear faults that exceed the downstream device's interrupting rating, ensuring the system operates safely during high-current fault conditions. Series ratings are cost-effective but must be carefully evaluated to ensure proper coordination and compliance with Article 240.86 of the NEC [21] and Rule 14-014 of the CE Code [22], which governs their application and requires testing and labeling to confirm compatibility.

The challenge to the engineer that leverages series ratings to address cost goals comes in the form of scalability. A series rated system limits the ability to add motors connected between the higher-rated OCPD and lower-rated OCPD of a series rated combination. Section 240.86 of the NEC [21] and Rule 14-014 of the CE Code [22] prohibit the combined full-load amperes of motors connected at this location from exceeding 1% of the interrupting rating of the lower-rated circuit breaker. In the case of a pair of circuit breakers with the upstream device having a 65kA interrupting rating and the downstream device having a 10kA interrupting rating, the combined full-load current of the motors connected between the 65kA circuit and 10kA circuit breaker cannot exceed 100A. This challenges some of the design goals including: scalability, ease of maintenance, and reliability. Only specific circuit breakers can be used in these applications as they must be listed for use in a series rated system and the likelihood of multiple devices opening increases the outage due to a fault.

A design decision to leverage a fully rated system, ensures future scalability but may challenge goals related to cost. The types of circuit breakers and fuses that can be used are expanded giving the engineer the ability to select cost effective overcurrent devices.

VII. CONCLUSIONS

Industrial power system design engineers often face the challenge of balancing conflicting design goals. Compliance with safety codes and standards can sometimes add yet another level of complexity. Additional safety measures that are required by codes and/or standards offer one example of this additional complexity when trying to manage the cost of the installation. Other examples include selective coordination requirements and design goals that pose a challenge around equipment protection and arc flash reduction. Selectively coordinated systems provide value to the installation around reliability and safety for electrical workers who must find and clear a fault, but these systems could be susceptible to higher incident energy levels resulting in extreme equipment damage and heavy PPE dress for electrical workers. Intentional delays implemented to achieve selective coordination present design challenges for design professional who seeks to manage electrical safety risks.

This paper aims to leverage power systems engineering fundamentals and establish a framework for industrial power system design engineers who must reconcile conflicting design goals while adhering to codes and standards requirements. Compromise is sometimes necessary, but the design engineer must manage electrical safety risk. The topic of risk is reviewed to establish a foundational understanding of its two components (likelihood and severity) in relation to competing design goals. Subsequently, a brief overview of risk assessment and risk management as they apply to electrical hazards is provided. Fundamentals of power systems engineering are reviewed considering essential design goals that present challenges to design engineers striving to mitigate risk while designing a practical power system. Lastly, the paper wraps up with a few design examples to illustrate the aforementioned concepts.

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IX. VITAE

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X. APPENDIX

In what follows, a 75 kVA delta-wye-grounded transformer supplying a secondary panel shown in Fig. A1 is analyzed to demonstrate the effect of moving OCPD 2 out of the panel on the incident energy. The data of the system shown in Fig. A1 are:

Source	I_{AFC} = 50 kA (Available Fault Current), X/R = 6
OCPD 1	125 A molded case circuit breaker
Conductor C1	1 AWG, CU, 1-conductor/phase, 25 ft., metal raceway
Transformer T1	75 kVA, 480 V/208 V, Z = 2%
Conductor C2	4/0 AWG, CU, 1-conductor/phase, 10 ft., metal raceway
OCPD 2	225 A molded case circuit breaker

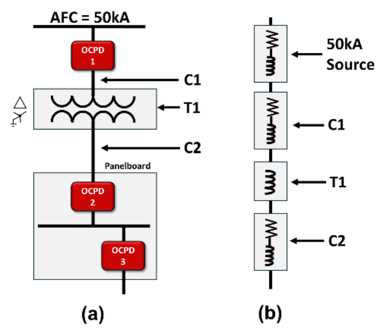

Fig. A1 A delta-wye-grounded transformer supplying a secondary panel: (a) single-line, (b) impedance diagram

A.1 OCPD 2 Installed in the Secondary Panelboard

The parameters of the per unit impedance diagram shown in Fig. A2 are calculated using the system data as follows:

The base values for the 480 V system are:

$$I_{base} = \frac{75000}{\sqrt{3}*480} = 90.21\ A \ \ \&\ \ Z_{base} = \frac{480}{\sqrt{3}*90.21} = 3.07\ \Omega$$

The base values for the 208 V systems are:

$$I_{base} = \frac{75000}{\sqrt{3}*208} = 208.18\ A \ \ \&\ \ Z_{base} = \frac{208}{\sqrt{3}*208.18} = 0.58\ \Omega$$

<u>Source Impedance:</u>

$$Zpu = \frac{Z_{\Omega}}{Z_{base}} = \frac{V/I_{AFC}}{V_{base}/I_{base}} = \frac{I_{base}}{I_{AFC}} = \frac{90.21}{50{,}000} = 0.0018$$

Thus,

$$Rpu = Zpu * \cos(\tan^{-1} X/R) = 2.97e^{-4}$$
$$Xpu = Zpu * \sin(\tan^{-1} X/R) = 1.78e^{-4}$$

<u>Conductor C1 Impedance :</u>

According to Table 9 of the NEC [21], The impedance of C1 per 1000 ft is: $C1 = 0.016 + j0.057$. Therefore, impedance or a 25 ft of length, the impedance of C1 in ohms is: $C1 = (0.016 +$

$j0.057) * \left(\frac{25}{1000}\right) = 0.0004 + j0.001425\ \Omega$. Thus, the per unit impedance of C1 using the base of the 480 V system is:

$$C1pu = \frac{(0.0004+j0.001425)}{3.07} = 0.0001302 + j0.0004639$$

Transformer T1 Impedance:

The transformer impedance is assumed to be all reactive and at the high end of the +/- 10% value. The transformer impedance is given to be 2% and hence the per unit impedance at a higher 10% value is: $ZT1pu = (0 + j0.02) \times 1.1 = j0.02$

Conductor C2 Impedance:

According to Table 9 of the NEC [21], The impedance of C2 per 1000 ft is: $C1 = 0.067 + j0.051$. Therefore, for a 10 ft of length, the impedance of C2 in ohms is: $C2 = (0.067 + j0.051) \times \left(\frac{10}{1000}\right) = 0.00067 + j0.00051\ \Omega$. Thus, the per unit impedance of C2 using the base of the 208 V system is:

$$C2pu = \frac{(0.00067+j0.00051)}{0.58} = 0.00116148 + j0.000884112$$

Total System Impedance:

The per unit system impedance is obtained by adding the per unit impedance of all system components (Source, C1, T1, & C2):

$$Zpu = 0.001588 + j0.025128$$

The available fault current (AFC) at the panelboard on the secondary of Transformer T1 is:

$$Ipu = \frac{Vpu}{Zpu} = \frac{1}{0.001588 + j0.025128} = 2.51 + j\,39.6$$

Accordingly, the AFC in Amperes is:

$$I = Ipu \times I_{base} = |(2.51 + j\,39.6) * 208.18| = 8{,}265\ A$$

Thus, the AFC at the panelboard is estimated to be 8,265 A. This AFC is used to calculate the minimum and maximum arcing currents based on the equations of IEEE standard 1584 [3]. The following assumptions for the panelboard on the secondary of Transformer T1 are:

Voltage	208 V
Available fault current	8,265 A
Electrode gap	25 mm
Electrode configuration	VCCB

Based on these assumptions, the min and max arcing currents are 3.5 kA and 4.09 kA respectively. Since the min arcing current is the worst-case scenario, it will be used to determine OCPD 1 clearing time. Therefore, the min arcing current is transposed to the primary of transformer T1 to determine what value of arcing current OCPD 1 sees for an arcing fault in the panelboard. That value of arcing current is then compared to the time current curve (TCC) of OCPD 1 to determine its clearing time.

$$Iprimary\ arcing = 3.5 \times \frac{208}{480} = 1.52\ kA$$

The TCC for OCPD 1 molded case circuit breaker is shown in Fig. A2. Based on an arcing current of 1.52 kA, the clearing time is estimated to be 2 s. According to IEEE standard 1584 [3], if the total protective device clearing time is longer than 2 s, that time is a reasonable assumption for the arc duration to determine the incident energy. The estimated clearing time is depicted in Fig. A2 as a dashed line demonstrating that OCPD 1 is estimated to take upwards of 20 s to clear this arcing current resulting in a much higher level of incident energy. The incident energy can be estimated to be approximately 16.9 Cal/cm^2.

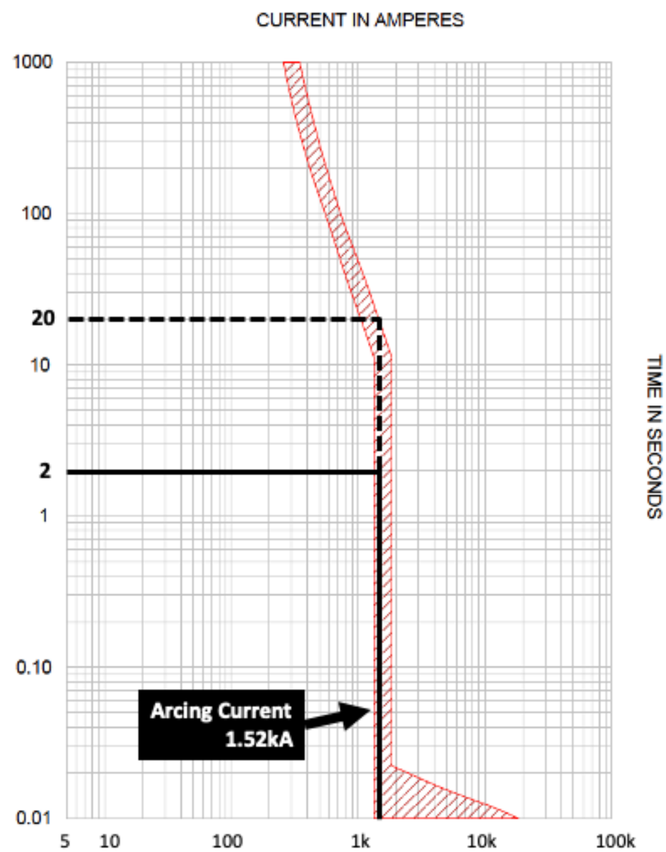

Fig. A2 TCC curve for OCPD 1 at reference voltage of 480 V

A.2 OCPD 2 Installed in its Own Enclosure

To use the safety by design approach, the single-line diagram of the previous example is modified to move OCPD 2 out of the panelboard and place it in its own enclosure on the secondary of the transformer as shown in Fig. A3.

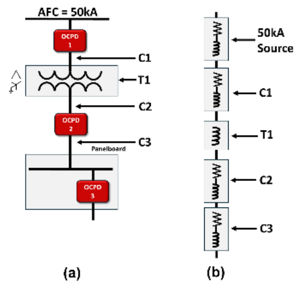

Fig. A3 The modified system design to reduce incident energy in the panelboard: (a) single-line, (b) impedance diagram

In the system depicted in Fig. A3, Conductors C2 and C3 are identical in length, size and all other details. The OCPD 2 is now located separate from the panelboard which is now a main lug only panel. Accordingly, OCPD 2 is now the OCPD protecting the panelboard. The fault current, arcing currents, and estimated incident energy are as follows:

Conductor 3 is added to the overall impedance diagram changing the total impedance of the circuit. The per unit system impedance is obtained by adding the per unit impedance of all system components (Source, C1, T1, C2, & C3):

$$Zpu = 0.0027497 + j0.0260118$$

The AFC at the panelboard on the secondary of Transformer T1 is:

$$Ipu = \frac{Vpu}{Zpu} = \frac{1}{0.0027497 + j0.0260118} = 4.02 + j\,38.0$$

Accordingly, the AFC in Amperes is:

$$I = Ipu \times I_{base} = |(4.02 + j\,38.0) * 208.18| = 7{,}952\ A$$

Thus, the AFC at the panelboard is estimated to be 7,952 A. Based on this updated AFC amount and the assumptions used in the previous calculation, the min and max arcing currents are 3.35 kA and 3.92 kA respectively.

The TCC for OCPD 2 molded case circuit breaker is shown in Fig. A4. Based on a min arcing current of 3.35kA, the clearing time is estimated to be 0.018 seconds. The incident energy can be estimated to be approximately 0.14 Cal/cm2.

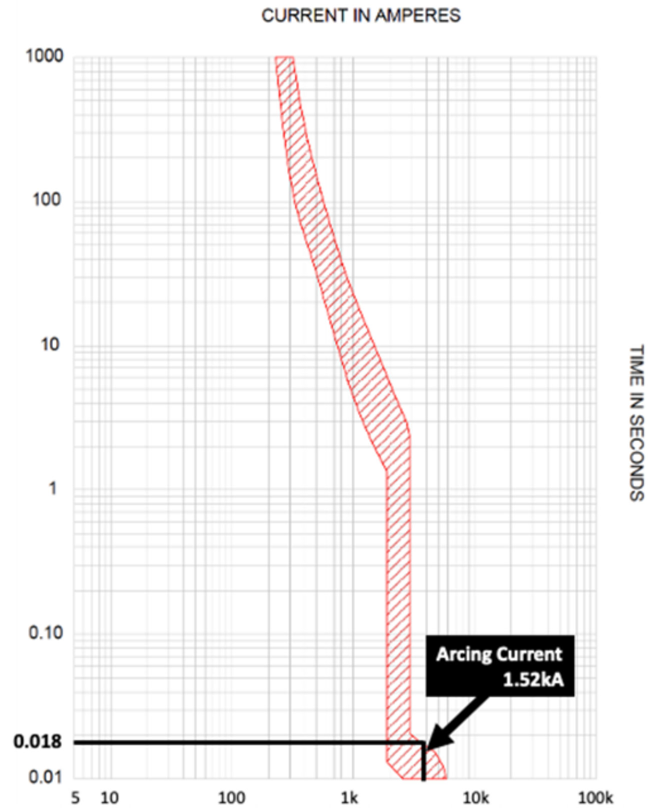

Fig. A4 TCC curve for OCPD 2 at reference voltage of 208 V

Use of Personal Voltage Detectors to Protect Electrical Contractors: A Case Study

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Abstract – Most electrical contractors have well-developed Electrical Safety Programs consistent with NFPA 70E in place, but human error can still come into play leading to near-misses and contact injuries. Examples of these errors include team verification of lockout with an overlooked energy source, inaccurate technical documentation, miscommunication in facility isolation, faulty grounding, and look-alike gear.

This paper examines the application of wearable personal voltage detectors (PVDs) to protect workers as an additional line of defense in situations where employees may make false assumptions or errors when working around energized parts and gear. We explore the evaluation of options, use case applicability, deployment, and results, drawing from a case study at a medium-sized electrical contracting company.

Index Terms — electrical safety, voltage detectors, human factors, Internet of things, leading indicators, engineering controls, electrical contractors

I. INTRODUCTION

Electrical work is inherently dangerous. Electricians and industrial workers face a constant risk of serious injuries and fatalities due to the nature of their work. Here's why electrical safety is critical concern in industry:

High Fatality Rates: According to the Electrical Safety Foundation International (ESFI), electrical hazards are the 4th leading cause of workplace fatalities in the U.S. The Bureau of Labor Statistics (BLS) reports that in 2021, there were 158 electrical fatalities in the construction industry alone.

Severe Injury Potential: Electrical accidents often result in severe burns, nerve damage, heart irregularities, and even amputations. These injuries can have long-lasting physical and psychological effects on workers. Beyond immediate injuries, electrical incidents can trigger falls from heights or cause fires, leading to further harm.

Variety of Hazards: Electricians encounter various hazards, including: electric shock (Direct contact with energized conductors or equipment), electrocution (Fatal electric shock), arc flash (sudden release of electrical energy that can cause intense heat and pressure) and falls (Working at heights or in confined spaces increases the risk of falls, which can be exacerbated or caused by electrical shock).

Electrical accidents carry significant financial and reputational consequences for companies. Beyond the obvious costs of medical expenses, lost productivity, and equipment damage, a poor safety record can hinder a company's ability to attract and retain skilled workers, secure new business from safety-conscious clients, and even access capital markets where a strong safety record influences creditworthiness.

Even with comprehensive safety programs, rigorous training and strict adherence to standards like NFPA 70E, human error remains a significant contributing factor in electrical accidents. This is because human behavior is inherently variable and influenced by numerous factors, making it difficult to eliminate mistakes entirely.

1. Types of Human Error in Electrical Work:

- Failure to follow procedures: Rushing, complacency, or taking shortcuts can lead to workers deviating from established safety protocols, such as neglecting to properly lockout/tagout equipment or failing to wear appropriate PPE.
- Miscommunication: Breakdown in communication between workers, supervisors, or control room operators can result in misunderstandings about energized equipment or isolation procedures.
- Assumptions and complacency: Workers may make incorrect assumptions about the state of electrical equipment or become complacent over time, leading to a lapse in vigilance.
- Distractions and fatigue: External distractions or mental and physical fatigue can impair a worker's focus and increase the likelihood of errors.
- Lack of experience or training: Inadequate training or insufficient experience can lead to poor decision-making and unsafe actions.

OSHA notes failure of process in many of these events, with LOTO violations the fourth most common citation (covering all scenarios, not just electrical incidents).

2. What are PVDs?:

PVDs are wearable devices designed to enhance electrical safety by alerting workers to the presence of voltage. Unlike traditional voltage testers that require deliberate action, PVDs provide a passive, continuous monitoring system. They are

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typically worn on the wrist, clipped to a hard hat, or attached to the body in some other way, ideally close to the likely point of contact with an energized source. This allows for immediate detection and real-time awareness for a faster response to potential electrical hazards.

PVDs function as wearable capacitive sensors, constantly measuring the strength of the electric field around a worker. Any nearby energized AC conductor alters the electric field, creating a change in capacitance that the PVD detects and signals with an alarm. This gives the worker an immediate warning about the presence of voltage. It's important to emphasize that PVDs primarily work with AC power sources and have limitations. They cannot detect DC voltage, and conductive materials can block the electric field, hindering detection. Environmental conditions like extreme temperatures or humidity can also impact performance, and occasional false alarms may occur due to static electricity or distant high-voltage lines. Training and procedures help workers to both set PVDs to the appropriate settings for their environment, and to identify sources of notifications and assess if they do, in fact, present a risk.

This paper examines the application of wearable PVDs to protect workers as an additional line of defence in situations where employees may make false assumptions or errors when working around energized parts and gear. We explore the evaluation of options, use case applicability, deployment, and results, drawing from a case study at a medium-sized electrical contracting company.

II. LITERATURE REVIEW

While research on PVDs specifically is limited, existing literature on wearable safety technology in industrial settings provides valuable context. A 2021 survey in Sensors [1] highlighted the potential of wearables to improve safety through:

Early hazard detection: This aligns with the core function of PVDs in alerting workers to electrical fields. The paper highlights how wearables excel at real-time monitoring of both environmental hazards (e.g., gas leaks, noise levels) and worker physiological states (e.g., fatigue, heat stress). This allows for proactive intervention, preventing incidents before they escalate. PVDs can compliment these other sensors and may have ratings like IS or ATEX for explosive environments

Enhanced situational awareness: PVDs contribute to this by providing real-time information about potential electrical hazards.

Improved communication and response times: Though not a primary function of current PVDs, future integration with communication systems could enhance this aspect.

A 2016 paper [2] emphasized the role of wearables in ensuring PPE compliance. While PVDs are not traditional PPE, they represent a similar commitment to worker safety through technology.

Studies on electrical safety in construction, like the 2021 analysis in IEEE Industry Applications Magazine [3], consistently identify human error as a significant contributing factor in incidents. This underscores the need for additional safeguards like PVDs to mitigate these risks.

Research on biometrics and the IIoT, while relevant to broader workplace safety, is less directly applicable to PVDs.[4]

III. CASE STUDY METHODOLOGY

This established electrical contractor has been operating for over a century, building a strong reputation in the industry. With a large workforce of over 2,000 employees, including more than 1,500 electricians, they provide a comprehensive range of electrical services across diverse sectors and geographic regions.

Their expertise spans various areas, including industrial and commercial electrical construction, renewable energy systems, power system testing and maintenance, and engineering and integration services. They also offer a variety of specialized services, such as low voltage cabling, security and surveillance systems, audio-visual installations, telecommunications, residential electrical work, IT solutions, drone services, millwright and ironworks, fire protection systems, and automated solutions.

A key characteristic of this company is its strong emphasis on safety. They maintain a dedicated team of in-house safety professionals and have achieved incident rates significantly below the national average for the industry. Their commitment to safety has been recognized through multiple awards and their position as a leader in safety practices within the electrical contracting sector. They prioritize exceeding regulatory compliance standards in all their operations.

1. Evaluation

This company sought a "last line of defence" to enhance worker safety in environments with potential electrical hazards. The goal was to supplement existing PPE, processes, and procedures, not replace them, adding an extra layer of protection against inadvertent contact with energized electrical components.

Various Personal Voltage Detectors (PVDs) were evaluated, including those attached to hard hats and clothing. Ultimately, the company selected a wrist-worn PVD. This choice was driven by the device's proximity to the wrist, considered the most likely point of contact with an energized source.

The decision-making process also considered the value of data analytics provided by the chosen PVD. The ability to gather insights into wearer exposure to electrical hazards was seen as a valuable tool for identifying risk trends and developing targeted mitigation efforts.

A key factor in the decision was a thorough internal review examining cost versus savings. While objective savings were analyzed by comparing PVD implementation costs to potential injury claim costs, the company prioritized worker safety, company values, and the potential severity of electrical contact incidents.

The company recognized the significant financial impact of a severe electrical injury, including direct costs exceeding \$150,000 and potential future rate increases. Their analysis indicated that preventing a single injury could result in a \$210,000 impact. Furthermore, they acknowledged the substantial indirect costs associated with such incidents, including damage to company culture and morale, reputational harm, OSHA implications, and potential effects on future work opportunities.

While the ROI of implementing PVDs is considered subjective, the company measures success and value in terms of worker safety. The decision to adopt this technology underscores their commitment to providing a safe working environment and prioritizing employee well-being.

2. Implementation

This company took a systematic approach to implementing PVDs, prioritizing high-risk areas and ensuring employee understanding and acceptance:

A. Risk Assessment and Targeted Deployment:

A comprehensive risk assessment was conducted to identify areas and tasks with the highest potential for electrical hazards. This involved analyzing various factors, such as work environments, types of electrical systems, and historical incident data.

Based on the assessment, a phased deployment strategy was implemented, prioritizing divisions and projects with the highest risk levels. This ensured that those facing the greatest potential hazards were equipped with PVDs first.

B. Clear Policy and Communication:

A dedicated policy was created to outline the parameters of PVD use, including when and how the devices should be worn, maintenance requirements, and reporting procedures. This provided clear guidelines for employees and ensured consistent application across the organization.

The company actively communicated the benefits and value of PVDs to employees, emphasizing their role in enhancing safety and reducing risk. This proactive communication fostered understanding and buy-in, crucial for successful adoption.

C. Comprehensive Training

Formal training was provided to each worker before they were issued a PVD. This training covered the device's functionality, how to interpret alerts, proper response to warnings, and the device's limitations.

The training also reinforced existing safety protocols, emphasizing that PVDs are an additional layer of protection and not a replacement for established procedures for identifying and verifying the absence of voltage.

D. Integration with Existing Safety Practices

The company integrated PVDs into their existing safety program, ensuring they complemented and reinforced established practices. This included maintaining rigorous protocols for identifying and verifying the absence of voltage before work commences, with the PVDs serving as an added safeguard in case other measures fail. By combining risk-based deployment, clear policy development, comprehensive training, and integration with existing safety practices, this company ensured that PVDs were effectively implemented as an additional layer of protection for their workers, demonstrating a strong commitment to safety and a proactive approach to mitigating electrical hazards.

This company developed a comprehensive data collection plan to assess the impact of PVD implementation on worker safety, both before and after deployment. Pre-Implementation data collection included the following:

- Incident Reports: Detailed incident reports were collected for any unintentional contact with energized sources, regardless of injury. These reports included investigations with root cause analysis, contributing factors, corrective actions, and lessons learned. This data was analyzed to understand the frequency, severity, and trends of electrical incidents.
- Near Miss Reports: Near miss events involving potential contact with energized sources were also documented and analyzed. This provided insights into potential hazards and areas where preventative measures could be improved.
- Data Segmentation: Both incident and near-miss data were categorized by company division and project industry, allowing for targeted analysis and identification of specific risk areas within different work environments.
- PEER Data Analysis: Industry-wide data from the Partnership for Electrical Efficiency and Reliability (PEER) was analyzed to understand high-level trends and events related to electrical contact incidents, providing valuable context and benchmarking information.

Post-Implementation Data Collection included:

- Continued Incident and Near Miss Reporting: The company continued to collect and analyze incident and near miss reports after PVD implementation. This allowed for direct comparison with pre-implementation data to assess the effectiveness of the PVDs in reducing incidents.
- Worker Self-Reported PVD Prevention Data: A crucial addition to post-implementation data collection was the inclusion of worker self-reported data on instances where the PVDs prevented potential contact with energized sources. This provided valuable real-world evidence of the PVDs' effectiveness in preventing incidents.
- By diligently collecting and analyzing this data both before and after PVD implementation, the company aimed to gain a comprehensive understanding of the impact of this technology on worker safety. This data-driven approach enabled them to measure the effectiveness of the PVDs, identify areas for improvement, and continually refine their safety protocols to minimize electrical hazards.

IV. RESULTS

While the sample size is relatively small, the data on safety incidents and near misses reveals a promising trend following the implementation of PVDs in March 2024. However, this means that no statistical inference can be made from these results, the study can form a basis for a more comprehensive analysis in the future.

1. Pre-Implementation (2012 - March 2024):

Contact with Energized Sources: 6 incidents total, 4 resulted in injuries, 2 were non-injury events.

Near Misses: 4 incidents where the presence of voltage was identified before an event occurred.

Incident Rate Trend: While the absolute number of incidents is small, it's important to consider the company's significant growth (>500%) during this period. This suggests a potential decrease in the incident rate per employee over time, even before PVD implementation.

Oct 2012	Contact, no Injury
July 2014	Contact, no Injury
Dec 2015	Injury
May 2017	Near-Miss
June 2018	Near-Miss
Nov 2020	Contact, no Injury
Sept 2021	Near-Miss
Nay 2022	Near-Miss
Aug 2022	Injury
Mar 2023	Injury
Dec 2023	Injury
May 2024*	Contact, no Injury
July 2024*	Near-Miss

Fig. 1. Raw Data by date and outcome
* Post PVD Implementation

2. Post-Implementation (March 2024 - Present):

The following chart shows the work days used with PVDs per month and the number of alerts received by the workers in that same month. The data shows a very high correlation between usage and alerts, which is not unexpected.

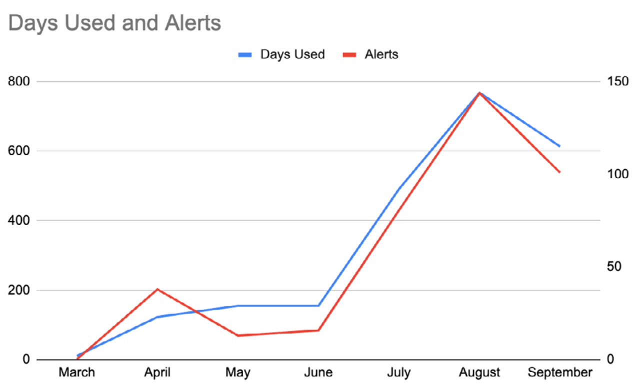

Fig. 2. PVD Days Used and Alerts

0 incidents were reported among employees using PVDs. 1 incident occurred within the group of workers who were not yet assigned PVDs. This highlights the importance of expanding PVD usage to all electricians. 1 near-miss incident was reported where a PVD alerted a worker to a potential hazard, preventing contact and potential injury. This demonstrates the effectiveness of PVDs as a last line of defence.

Qualitative feedback from both workers and management regarding the implementation of PVDs has been overwhelmingly positive, with a few key themes emerging:

Positive Reception and Appreciation: Workers expressed appreciation for the company's commitment to their safety and the investment in PVDs as an additional safety resource. This demonstrates a positive impact on morale and reinforces the value placed on employee well-being.

Value and Risk Mitigation: The majority of workers recognize the potential severity of electrical contact incidents and see the value of PVDs as a "last line of defense." This understanding fosters acceptance and promotes proper use of the devices.

Increased Confidence and Peace of Mind: Workers report feeling a greater sense of confidence and peace of mind during the energy isolation process when wearing PVDs. This highlights the psychological benefit of the technology, reducing anxiety and promoting a safer work environment.

Vision for the Future: Many workers envision PVDs becoming a standard piece of PPE for electricians, similar to hard hats and safety glasses. This forward-thinking perspective indicates a willingness to embrace new safety technologies and a belief in the long-term value of PVDs.

Challenges and Areas for Improvement: Some workers expressed initial resistance to wearing the devices, viewing them as a burden. This highlights the importance of ongoing communication and education to reinforce the benefits and address any concerns.

Minor usability issues were reported, such as the need for frequent sensitivity adjustments in certain work environments like substations. Addressing these challenges through training and potential device modifications will further improve user experience and acceptance.

Overall, the qualitative findings indicate that the implementation of PVDs has been successful in enhancing worker safety and fostering a positive safety culture. By addressing minor challenges and continuing to gather feedback, the company can further optimize the use of PVDs and ensure their long-term effectiveness in protecting workers from electrical hazards.

V. DISCUSSION

To effectively interpret the results of this company's PVD implementation, we need to link the findings back to the initial research questions and the broader context provided by the literature review. High level questions include:

- Do PVDs reduce the frequency and severity of electrical contact incidents among electricians?
- How do PVDs impact workers' perceptions of safety and their confidence in performing tasks involving electrical hazards?
- What are the challenges and facilitators to successful PVD implementation in an electrical contracting company?

1. Interpretation in Relation to Research Questions:

Incident Reduction: The quantitative findings suggest a positive impact of PVDs on safety outcomes. The absence of contact incidents among PVD users post-implementation, despite a previous history of incidents and the company's growth, supports the hypothesis that PVDs can reduce the frequency of these events. The single incident occurring in the non-PVD group further strengthens this argument.

Worker Perception and Confidence: Qualitative feedback indicates that PVDs enhance workers' sense of safety and confidence when working around electrical hazards. This aligns with literature suggesting that providing workers with additional protective measures can improve their psychological well-being and reduce anxiety related to workplace risks.

Implementation Challenges and Facilitators: The findings highlight both challenges and facilitators to successful PVD implementation. Worker resistance to change, the need for ongoing training and support, and addressing usability issues in specific work environments are key challenges identified. However, strong management commitment to safety, clear communication, and a phased rollout strategy appear to have facilitated successful adoption.

2. Connecting to the Literature Review:

Alignment with Existing Research: The positive impact of PVDs observed in this case study likely aligns with findings from the broader literature on safety technology and injury prevention. Research has consistently shown that providing workers with additional layers of protection, especially those that offer real-time feedback and warnings, can significantly reduce workplace accidents.

Contribution to the Field: This case study contributes to the growing body of evidence supporting the use of PVDs in electrical work. It provides real-world data and qualitative insights into the effectiveness of this technology, adding to the understanding of its potential benefits and implementation considerations.

Future Research Directions: This study also highlights areas for future research, such as the long-term impact of PVDs on safety culture, the development of best practices for training and implementation, and the exploration of how PVD data can be used to proactively identify and mitigate electrical hazards.

By connecting the findings to the research questions and the existing literature, this case study provides valuable insights into the effectiveness of PVDs in enhancing electrician safety. It demonstrates the potential of this technology to reduce incidents, improve worker perception of safety, and contribute to a safer work environment.

The introduction of PVDs has had a multifaceted impact on worker behavior, safety awareness, and the overall safety culture within this company:

Positive Safety Culture Shift: The provision of PVDs has been well-received by workers, who appreciate the investment in their safety and the added layer of protection. This has fostered a positive safety culture where employees feel valued and protected.

The initiative has reinforced the company's commitment to safety, demonstrating a proactive approach to hazard mitigation and a willingness to embrace new technologies.

Sustained Safety Awareness: While no significant change in overall safety awareness was observed, the company actively emphasized the importance of maintaining vigilance and preventing complacency.

The training and communication surrounding PVD implementation reinforced the message that PVDs are a supplement to, not a replacement for, existing safety protocols like "test before touch" and energy isolation verification.

Knowledge and Buy-In: Education on the functionality and value of PVDs has been crucial in driving acceptance and proper use. Workers who understand the potential severity of electrical hazards and how PVDs mitigate those risks are more likely to embrace the technology.This highlights the importance of clear communication and comprehensive training in ensuring the success of any new safety initiative.

Heightened Awareness Among Those with Near-Miss Experience: Workers who have personally experienced or witnessed near misses or incidents exhibit a heightened awareness of the importance of safety advancements like PVDs. This suggests that personal experiences can be powerful drivers of safety consciousness and a willingness to adopt new protective measures.

Overall Impact: While PVDs haven't drastically altered overall safety awareness, they have contributed positively to the safety culture by demonstrating a commitment to worker well-being and providing an additional layer of protection. The emphasis on preventing complacency and the targeted education efforts have been crucial in ensuring the effective integration of PVDs into the company's safety program.

Moving forward, the company can further enhance the impact of PVDs by:

- Continuously reinforcing the importance of existing safety protocols: Regular reminders and refresher training can prevent complacency and ensure that PVDs are used as intended - as a last line of defence.
- Gathering and sharing data on PVD activations and near-miss preventions: Communicating these successes can further reinforce the value of PVDs and encourage consistent use.
- Encouraging worker feedback and suggestions: Actively soliciting input from workers on their experiences with PVDs can lead to improvements in usability, training, and overall program effectiveness.

The successful implementation of PVDs in this company can be attributed to several key factors:

Data-Driven Justification and Worker Buy-in: The company utilized real-life incident data to highlight the need for additional protective measures. This data-driven approach demonstrated the potential consequences of electrical contact incidents, making the value of PVDs clear to workers and fostering their acceptance of the technology.

Pilot Program and Worker Empowerment: Conducting a pilot program before full-scale implementation allowed for valuable feedback from workers and empowered them to have a say in their own safety. This participatory approach fostered a sense of ownership and increased the likelihood of successful adoption.

Phased Rollout and Flexibility: The staged deployment of PVDs prevented overwhelming both management and workers, allowing for focused attention and support during each phase. The flexible approach to policy implementation, incorporating worker feedback and allowing for adjustments, ensured a sensible and reasonable final policy.

Comprehensive Training and Support: The "train-the-trainer" approach equipped management with the knowledge and confidence to answer worker questions and provide ongoing support. This ensured consistent messaging and reinforced the importance of PVDs.

Thorough Education and Open Communication: Dedicating time for thorough education and discussion about PVDs helped workers understand the rationale behind the implementation, fostering buy-in, compliance, and a positive safety culture. This open communication channel addressed concerns and ensured that workers felt heard and valued.

Overall, the success of this PVD implementation stemmed from a combination of data-driven decision-making, worker involvement, a phased and flexible approach, comprehensive training, strong leadership commitment, and open communication. By prioritizing worker safety and actively engaging employees throughout the process, the company created a supportive environment for the adoption of this new safety technology.

While the PVD case study presents compelling evidence for the effectiveness of this technology in enhancing electrical safety, it's essential to acknowledge its limitations to ensure a balanced perspective:

Small Sample Size: The company's relatively small size and the limited number of incidents, even pre-implementation, limit the generalizability of the findings. Larger-scale studies with more diverse participants would strengthen the evidence base for PVD effectiveness.

Short Post-Implementation Period: The evaluation focuses on a relatively short period after PVD implementation. Longer-term data collection is needed to assess the sustained impact of PVDs on incident rates and safety culture.

Lack of a Control Group: The study design lacks a true control group, making it difficult to definitively attribute the observed improvement in safety outcomes solely to PVDs. A comparative study with a control group of electricians not using PVDs would provide stronger evidence.

Potential for Reporting Bias: There's a possibility of underreporting of incidents or near misses, especially post-implementation, due to workers' fear of repercussions or a desire to present the PVDs in a positive light. Anonymous reporting mechanisms and a culture of open communication can help mitigate this bias.

Focus on a Single Technology: The study focuses solely on PVDs as a safety intervention. It doesn't consider other factors that might contribute to electrical safety, such as improved training programs, enhanced work practices, or organizational safety climate.

Limited Generalizability to Other Industries: The study focuses on an electrical contracting company. The findings may not be directly applicable to other industries with different electrical hazards or work environments.

Lack of Cost-Benefit Analysis: While the company considered cost vs. savings, a detailed cost-benefit analysis was not presented. A comprehensive analysis considering both direct and indirect costs and benefits would provide a more complete picture of the economic impact of PVD implementation.

Despite these limitations, the case study offers valuable insights into the potential of PVDs to enhance electrical safety. By acknowledging these limitations and conducting further research, a more comprehensive understanding of the effectiveness and broader implications of this technology can be achieved.

VI. CONCLUSION

This case study examined the implementation of personal voltage detectors (PVDs) in a medium-sized electrical contracting company. The findings demonstrate the potential of PVDs to enhance worker safety by providing an additional layer of protection against inadvertent contact with energized electrical equipment.

1. Key findings include:

Reduced incidents: The company experienced zero contact incidents among PVD users post-implementation, suggesting a positive impact on safety outcomes.

Enhanced worker perception: PVDs increased workers' sense of safety and confidence when performing tasks involving electrical hazards.

Successful implementation factors: Data-driven justification, worker involvement, phased rollout, comprehensive training, strong leadership commitment, and open communication were crucial for successful PVD adoption.

Positive safety culture: PVDs contributed to a positive safety culture by demonstrating the company's commitment to worker well-being and providing an additional safeguard.

These findings have significant implications for the electrical contracting industry, where electrical hazards pose a constant risk. PVDs offer a promising solution to mitigate these risks, particularly those associated with human error.

2. Recommendations for further research and practice:

Larger-scale studies: Conduct studies with larger sample sizes and control groups to further validate the effectiveness of PVDs and assess their long-term impact on safety outcomes.

Industry-specific research: Investigate the applicability and effectiveness of PVDs in various electrical industry segments, considering different work environments and hazard profiles.

Data analysis and utilization: Explore how PVD data can be used to proactively identify and mitigate electrical hazards, improve safety training programs, and enhance risk assessment procedures.

Integration with other safety technologies: Investigate the potential benefits of integrating PVDs with other safety technologies, such as augmented reality systems or wearable sensors that monitor physiological factors.

Standardization and best practices: Develop industry standards and best practices for PVD selection, implementation, training, and data management.

In conclusion, this case study provides compelling evidence for the potential of PVDs to significantly enhance worker safety in the electrical contracting industry. By serving as a "last line of defence" against human error, PVDs can help prevent electrical contact incidents and foster a culture of safety consciousness. As technology continues to advance and PVDs become more sophisticated, their role in mitigating electrical hazards is likely to become even more critical. Investing in PVDs and implementing them effectively can help create a safer and more secure work environment for electricians, reducing the risk of injuries and fatalities associated with this inherently dangerous profession.

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VIII.VITA

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Special Treatment – Temporary Power in Construction

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Abstract – Temporary power and the associated equipment are problematic in the construction industry. The equipment is often recycled from one project to the next and in a state far from normal operating condition, as defined by NFPA 70E. Installations do not meet NEC standards of permanently installed equipment. Engineered design is overlooked and results in undersized conductors and underrated equipment. Incident energy analyses are not performed, which limits the ability to properly select adequate PPE. Urgency and time constraints emphasize the need to have temporary power available, leading to rushed installations and poor craftsmanship. Combining all of these issues results in unsafe equipment, unsafe operations, and an increased risk of electric shock and arc flash hazards with inadequate levels of PPE. This paper will show why temporary installations should be treated the same as permanent installations. It will detail why the same effort should be made to install temporary equipment to NEC standards, have the same quality control measures, implement the same commissioning processes, and assess potential incident energy exposures. Ultimately, the same respect should be given to all temporary installations as permanently installed equipment to make it safer for all.

Index Terms — Construction, Temporary Power, Abnormal Operating Condition, Electrical Hazard Assessment, Equipment Condition, Arc Flash Analysis.

I. INTRODUCTION

In new construction and renovations, temporary power is a typical component required for the completion of the project. To meet the power and lighting demands for all trades, the electrical contractor typically is obligated to provide sufficient power either by temporary generators or temporary transformers and switchgear. Installations of temporary power equipment are often rushed to meet time constraints of the project. Feeder cables and branch circuit conductors are often acquired from previous projects to save time and money. Construction industry experience has shown that arc flash hazard studies are rarely performed. Without knowing the available fault current of the system, overcurrent protective devices cannot be properly selected to adequately withstand or interrupt the available fault current as NFPA 70E Article 210.6 requires [4]. The result is a system that has unacceptable risk levels when employees have to interact with, modify, maintain, or service the equipment.

Construction industry experience has also shown that temporary power equipment more often than not does not meet NFPA 70E's definition of "normal operating condition" [4]. Temporary power equipment is often approaching the end of useful life, not installed per electrical code of permanent power equipment, has a higher-than-normal risk of being damaged or compromised due to the construction environment, and wire sizes potentially undersized with little to no upstream fault protection. The enhanced content of NFPA 70 (NEC) Article 590.2(A) states "electrical accidents do not discriminate and can occur in any installation, permanent or temporary, if the requirements of the NEC are not followed. Due to the nature of work occurring at construction sites and the higher probability of wiring systems being damaged and compromised, following the requirements of Article 590 is essential to electrical safety" [5].

Rarely is there a focus on performing an arc flash hazard assessment for temporary power systems. NFPA 70E permits the use of Tables 130.7(C)(15)(a) and (b) when the equipment meets the specified parameters (available fault current, fault clearing time, and working distance) [4]. However, not all equipment currently in use meets the parameters for the table method specified in NFPA 70E. So, the ultimate question arises, how do you interact with this equipment safely? How does the employer protect the employees? As Floyd suggests, "OSHA regulations are specific with regard to employers' responsibility to assess the workplace for hazards and enable employees to recognize and avoid these hazards, and to implement controls to protect employees from these hazards" [1].

II. DANGERS OF GIVING TEMPORARY POWER SPECIAL TREATMENT

A. *Personal Protective Equipment Selection*

While examining the hierarchy of risk control (NFPA 70E Table F.3), personal protective equipment (PPE) is the least effective measure to reduce risk [4]. However, to implement proper PPE controls, risk assessments must be performed for the specific task. This is the primary obstacle when assessing temporary power systems in construction. More often than not, an arc flash study on the system has not been performed, and oftentimes the equipment does not meet the specific criteria outlined in NFPA 70E Tables 130.7(C)(15)(a) and (b) [4]. NFPA 70E provides clear guidelines for selecting appropriate arc flash personal protective equipment in Article 130.5(F). There are two options offered (as illustrated by Fig. 1), as NFPA 70E 130.5(F) states "One of the following methods shall be used for the selection of arc flash PPE: (1) The incident energy analysis method in accordance with 130.5(G), or (2) The arc flash PPE category method in accordance with 130.7(C)(15)" [4]. Northcott claims that "the reality is that the problem of determining the precise hazard employees face, and what it

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takes to properly protect them from that hazard is not solved by using NFPA 70E tables" [3]. Northcott also proclaims that "one must keep in mind that the tables are not an exact science" [3]. In the absence of an arc flash study and without the ability to use the tables, proper PPE selection is unattainable.

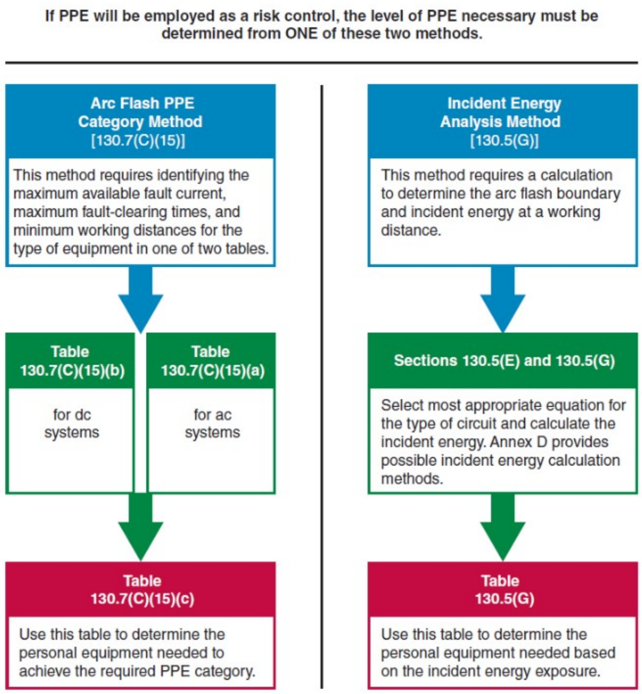

Fig. 1 NFPA 70E Art. 130.5(F) Enhanced Content Illustration used with consent of the NFPA.

Additionally, there is a gap between what the NEC requires for arc-flash hazard warning on equipment and what NFPA 70E requires to determine proper PPE levels. NEC Article 110.16(A) only requires a warning label of the arc flash hazard on most equipment [5]. NEC Article 110.16(B) only requires an arc flash label (with available fault current, protection boundaries, system voltage, and date applied) for service equipment and feeder supplied equipment rated for 1000 amperes or greater [5]. Since there is no requirement to utilize equipment that meets the specific criteria of the table method in NFPA 70E, and no requirement to utilize arc flash labeling on service equipment and feeder supplied equipment rated less than 1000 amperes, situations arise where technicians cannot determine proper levels of PPE. Northcott agrees that "most employees may not use [the NFPA 70E tables] properly anyway" [3].

B. Quality Control Needs

Moving up the hierarchy of risk control, the next level above PPE is Administrative Controls (ex. Procedures and job planning tools). Quality control and quality assurance programs are written and implemented with the intent to verify equipment is safe to energize. Quality programs are typically only designed to encompass permanent power systems, with temporary power overlooked. The truth is that temporary power equipment has a higher need for a robust quality process than permanent installed equipment. Temporary power equipment installations seldom meet NEC requirements. The NEC makes several requirement exemptions for temporary installations with the understanding that at some point it will be demolished and removed. For example, Article 590.2(G) has exceptions for splices such as "on construction sites, a box, conduit body, or other enclosure shall not be required for either of the following conditions: (1) the circuit conductors being spliced are all from nonmetallic multiconductor cord or cable assemblies, provided that the equipment grounding continuity is maintained with or without the box" [5].

However, even the NEC recognizes the hazards that exist with temporary installations. NEC Article 590.8(A) states "Overcurrent protective devices that have been previously used and are installed in a temporary installation shall be examined to ensure they have been properly installed and properly maintained, and there is no evidence of impending failure" [5]. Herein lies the challenge and the need to service and maintain temporary equipment prior to placing the equipment back into service on another project. Maintenance of equipment is one of several criteria to determine if equipment is in Normal Operating Condition as defined by NFPA 70E Article 110.2(B), Exception No. 1. The Informational Note No. 2 of NFPA 70E Table 130.5(C) states that "improper or inadequate maintenance can result in increased fault clearing time of the overcurrent protective device, thus increasing the incident energy" [4].

C. Safety By Design

Continuing to climb the hierarchy of risk control, engineering controls and substitution are areas where electrical safety by design can drastically reduce hazard exposure levels. Performing an arc flash analysis of the temporary system is crucial in this design process. Without knowing where the high hazards exist, steps cannot be taken to reduce the incident energy levels to a lower hazard level. The study is already needed to determine PPE levels. "An arc flash analysis determines the most severe incident energy that can be produced at each location of the distribution system so that there is no doubt what level of arc flash PPE is required to protect workers from being burned during an arc flash event" [Northcutt, 3]. Once high hazard areas of the system are identified, then safety by design can potentially lower incident energy to acceptable levels.

1) *Case Study I: Arc Flash of Temporary Power Skid:*

In August of 2019, an arc flash event occurred while relocating a temporary power skid while energized. The skid was moveable on caster wheels with enough length in the feeder cables to relocate the skid several feet. The feeder cables were installed in seal-tight conduit. After only moving the skid a few inches, the seal-tight conduit pulled free from the panelboard and the insulation of B and C phase conductors was compromised. This resulted in the conductors contacting the panelboard can through the knockout opening. This resulted in a multiple phase to ground arc (Fig. 2) that tripped the feeder breaker and deenergized the temporary skid.

Upon investigation, after creating an electrically safe work condition, it was identified that a PVC female adapter (Fig. 3) was used on the inside of the panel to secure the seal-tight connector to the panelboard vice the standard lock ring. The PVC female adapter threads were stripped out, compromising the integrity of the connection. It was believed to be a result of moving the skid around multiple times throughout the construction process, to gain access for various work tasks. There were no barriers in place to prevent access to the skid from unqualified persons.

Fig. 2 Photograph of arc flash event
Used with consent of the Photograph Owner.

Fig. 3 Photograph of improper installation
Used with consent of the Photograph Owner.

It was determined that the arc flash event was a result of several factors: improper installation, the lack of a quality process for temporary installations, and the continuous movement of the skid throughout construction. No injuries were sustained during this event, however there were employees in close proximity when it occurred. The feeder cables were replaced. The repairs and installation were inspected by the quality control team. The skid was returned to service with no issues. This event resulted in a process change that required quality inspections of all temporary installations prior to initial energizations.

2) *Case Study II: Back-feed of Permanent Feeders:*

In October of 2022, a Lockout-Tagout was requested to deenergize a temporary feed to a lighting panel for a cut-over to the panel's permanent feeders. When the Lockout-Tagout Coordinator removed the dead front of the panel to perform zero energy confirmation, it was noted that the permanent feeder conductors were landed on the main lugs with the temporary feeder conductors (Fig. 4). The lack of a quality inspection process on equipment fed from temporary power allowed for energization of a panel that resulted in a back-feed situation from the temporary source to the permanent source. This event was categorized as a near miss due to the permanent source work completion, as no personnel were exposed to the back-feed, nor were any injuries or equipment damage sustained.

Fig. 4 Photograph of improper installation
Used with consent of the Photograph Owner.

III. THE SOLUTION

The problem statement is simply that temporary power equipment is very likely to have unacceptable risk levels when employees have to interact with, modify, maintain, or service the equipment. The solution is just as simple, hold temporary electrical systems to the same expectations as permanent electrical systems. First, inspect all installations to the same standards and extent as if it was a permanent system prior to energization. Second, either utilize equipment that meets the criteria to have the ability to use the NFPA 70E table method or perform an arc flash hazard analysis of the entire system. Third, close the gaps between what the NEC requires for installations of electrical equipment and what NFPA 70E requires for working safely on electrical equipment. Fourth, incorporate temporary equipment into the Equipment Maintenance Plan. Lastly, treat all electrical equipment the same from a standards point of view, regardless of whether or not it is temporary or permanent.

IV. ACKNOWLEDGEMENTS

Stephen Sanchez with Allison-Smith Company, LLC contributed to the idea of this paper and is the author’s mentor. Jerome Clark with Inglett & Stubbs provided clarity of the NEC standards and was also consulted as a quality control subject matter expert.

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VI. VITA

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Implementation of an Electrical Safety Authority at a Global Testing, Inspection and Certification (TIC) Organization

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Abstract – The authors describe their experience implementing an electrical safety authority (ESA) at a global testing, inspection and certification (TIC) organization (herein referred to as “the enterprise”) where part of its operations conducts potentially hazardous electrical testing. In addition to internal training, on-the-job training, safety compliance, and Occupational Safety and Health Administration (OSHA) reporting, the enterprise has implemented a cross-functional team approach to identify, research and implement electrical workplace safety protocols, procedures and practices for the employees who conduct electrical testing in the enterprise’s numerous and diverse locations. This paper addresses the journey from identifying the need for an ESA as defined by NFPA 70E, the Standard for Electrical Safety in the Workplace [1], the current successes of such a program, struggles the ESA met/worked through, and future goals to continue supporting employees’ safety through the work of the ESA. The application of NFPA 70E to the electrical testing performed is also explored, along with how an ESA functions within the workplace and the employee’s role as the ESA. A case study is also presented where the ESA helped address a potentially hazardous electric shock situation.

The goal of the ESA is to implement approaches to electrical and workplace safety to eliminate electrical incidents. The authors believe that this type of approach to workplace safety can be implemented in a variety of workplace safety situations.

Index terms — Certification, testing, laboratory, safety, electrical safety authority, authority having jurisdiction, incident investigation, electric shock, job safety analysis, workplace safety

I. INTRODUCTION

This paper describes the experience of implementing an electrical safety authority (ESA) at a global testing, inspection, and certification (TIC) organization (herein referred to as “the enterprise”) where part of its operations conducts potentially hazardous electrical testing. Laboratory employees are engaged in testing a variety of electrical components and end products for a wide range of consumer, commercial, and industrial applications. Product testing and other laboratory operations often require equipment and/or sources of energy that may be potentially hazardous.

As required by government regulations in the areas in which the enterprise conducts business, the enterprise maintains a comprehensive global environmental, health and safety (EHS) management system program to oversee workplace safety. The EHS department is tasked with identifying, assessing, controlling, and communicating the various workplace safety regulations to the testing laboratory. The testing laboratory is required to comply with the safety regulations and implement any appropriate control measures, job safety analyses (JSAs), training, signage, personal protective equipment (PPE) and procedures. Compliance with local regulations may include inspections by the regulatory authority, maintenance of training records and other forms of evidence of compliance. While regulations have contributed significantly to overall workplace safety globally, these regulations only establish the minimum requirements for a workplace and may not address the specific needs of an enterprise involved in the activities of a TIC organization among other business activities.

Previously, when an electrical safety incident occurred within the enterprise, the findings and root causes were documented properly, though the information about the event was primarily shared and distributed locally. This resulted in the enterprise not effectively nor efficiently learning from the incident, which may have mitigated additional incidents when staff faced similar electrical hazards. In 2022, the enterprise decided to update its approach to increase the global awareness of potential electrical safety hazards and control measures with the goals of standardizing systems and reducing or eliminating the frequency and severity of electrical incidents. When an incident occurs, the enterprise now conducts a thorough investigation and publishes the results internally to more effectively share lessons learned.

An ESA as defined by National Fire Protection Association (NFPA) 70E [1] is a qualified individual or committee who is knowledgeable about NFPA 70E and who functions within an organization as the authority having jurisdiction (AHJ) for the safety of electrical workers. This paper follows the journey the enterprise began in 2023 to focus on protecting the safety of electrical workers by implementing an ESA. This paper will address the purpose, structure, and benefits of the ESA. The critical role of employee involvement, the challenges in implementation, how the ESA has positively impacted workplace safety for laboratory and facilities operations, and the continued work of the ESA will also be addressed. The

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authors' intent is that the information provided herein will assist other companies that also wish to adopt the ESA concept and advance the level of workplace safety at their organization.

II. THE CASE FOR ESTABLISHING AN ESA

The enterprise employs more than 15,000 employees in hundreds of global locations. Enterprise experts conduct testing on several thousand types of electrical components, end products, and systems. The electrical environment at the enterprise is usually in an indoor setting and historically has been primarily low voltage (less than 600 V) 50/60 Hz AC. In recent years, DC sources (up to 2,000 VDC), complex waveforms — i.e., from switched power supplies, ballasts, and other sources — and battery, charging, and electric vehicle testing are becoming increasingly common. Also, of increasing prevalence is laboratory and field testing of medium-voltage equipment (operating in the tens of kilovolts) and field testing of high-voltage infrastructure (involving voltages in the hundreds of kilovolts or more).

This diversification of electrical hazards suggests the need for a more comprehensive approach to electrical safety at the enterprise, as the tasks of training, verifying, and maintaining electrical competency and implementing safe work practices have become increasingly complex. The enterprise conducts JSAs or risk assessments for operations, using the National Institute of Occupational Safety and Health (NIOSH) Hierarchy of Controls [2] to reduce the hazards.

The NIOSH Hierarchy of Controls is a system of ranking the efficiency of methods to reduce hazards in a job. The most effective method is eliminating the hazard, followed by substituting, applying engineering controls, applying administrative controls and having the employees wear PPE to reduce their exposure to hazards. Due to the unique nature of each test set-up, the use of temporary physical barriers, guarding, and indicator lights, along with PPE specific to the hazards of the job (such as voltage rated rubber insulating gloves) are used to protect others from hazards. Specific electrical safety training is required for all employees who will potentially be exposed to electrical hazards.

In the last few years, an updated tool was implemented by the enterprise to capture safety observations, near misses, and incidents. The tool provides the ability to complete and document specific actions on the reports received. Continuous improvement has resulted in comprehensive reporting that includes an analysis of lost workdays, hazard categories ranked by percentage of occurrences, specific location information, and the status of the investigation into the event. This information is available to management and select safety experts to enable improvement in safety through analysis of repeated events, locations, and root causes.

Understanding the complexity of the testing operations, implementing a global reporting tool, acting on the reporting, along with following the NIOSH Hierarchy of Controls, and the continued commitment to and emphasis on employee safety are all positive actions. However, it was found that incidents needed to be addressed in a more proactive manner. The goal of the ESA is to eliminate electrical incidents. Establishing an Authority which includes the global laboratory organization, the Facilities department, and EHS to drive awareness and compliance with the safety requirements in NFPA 70E was determined to be the next level in electrical safety for the enterprise.

III. IMPLEMENTATION OF THE ESA AND ITS PRIMARY FUNCTIONS

NFPA 70E is the Standard for Electrical Safety in the Workplace [3]. Section 350.4 [1] states the following:

Each laboratory or R&D system application shall be permitted to assign an ESA to ensure the use of appropriate electrical safety-related work practices and controls. The ESA shall be permitted to be an electrical safety committee, engineer, or equivalent qualified individual. The ESA shall be permitted to delegate authority to an individual or organization within their control.

1) *Responsibility: The ESA shall act in a manner similar to an authority having jurisdiction for R&D electrical systems and electrical safe work practices.*

2) *Qualifications: The ESA shall be competent in the following:*

    - *The requirements of this standard*
    - *Electrical system requirements applicable to R&D laboratories*

The term "authority having jurisdiction" is critical to understanding the roles and responsibilities of the ESA. NFPA 70E defines the AHJ as the following:

An organization, office, or individual responsible for enforcing requirements of a code or standard or for approving equipment, materials, an installation, or a procedure [4]

Using the guidance provided in NFPA 70E 2024, Section 350.4 [3], and upon review of the diversity in testing, equipment and locations, the enterprise implemented a committee approach to act as the ESA and established the following parameters under which the committee will operate:

1. The enterprise's ESA "identifies the use of appropriate electrical safety-related work practices and controls" in accordance with NFPA 70E, the Standard for Electrical Safety in the Workplace [3].
2. The responsibility of the ESA is to act as the electrical authority for the laboratory and facility operations and:

    - Be qualified and competent in the requirements of NFPA 70E and the electrical system requirements applicable to the electrical testing laboratories.
    - This is accomplished through:

        a. Adherence to safety publications such as NFPA 70E, applicable Occupational Safety and Health Administration (OSHA) requirements and qualifications for competent and qualified electrical workers.
        b. Determining, developing and implementing the basic, advanced and refresher electrical

   training that is necessary for employees to safely perform their jobs.
   c. Assisting in electrical safety incident investigations where root cause and corrective actions are identified.
   d. Sharing findings from safety incidents, observations, near misses and success stories.
   e. Communication and active engagement and involvement with employees in safety initiatives while sharing progress and success.
3. Because the success of the ESA hinges on the diversity of function, experience, and roles, leaders and laboratory and facility operations employees' partner with the EHS department to fulfill the ESA responsibilities.
4. The ESA meets at least once per month, prepares an agenda, and provides meeting minutes and action items.
5. Any projects handled by the ESA are documented and tracked.

Some ways that the organization meets the above ESA responsibility of identifying the use of appropriate electrical safety-related work practices and controls are:

- Establishing training requirements for new and existing employees and setting the frequency of the training.
- Sharing findings and trending of incidents and near misses and capturing the discussions in the meeting minutes.
- Overseeing the implementation and management of the voltage rated rubber insulating glove program, Lockout/Tagout, training on use of Rescue Hooks are direct outcomes of incident and near miss reviews.

IV. CHALLENGES AND LEARNINGS FROM IMPLEMENTING THE ESA

The global reach of the enterprise, variety of testing capabilities, and number of employees conducting testing and facilities electrical work allow the enterprise to meet the needs of many different companies that require testing, inspection, and certification. This specialization and diversity also resulted in a significant challenge as the ESA was implemented.

To adequately represent the enterprise's needs for electrical safety, employees were initially selected from several sites representing a cross section of the electrical testing conducted. The ESA initially held regularly scheduled meetings every other week. Each meeting began by discussing a specific safety topic and addressing topics such as training needs, lock out/tag out implementation, use and implementation of electrical PPE (such as voltage rated rubber insulating gloves), rescue equipment (such as electrical rescue hooks), and development of JSAs for testing and equipment support activities.

For the first several months, meetings were held with regular attendance by a majority of the ESA members. After a few months, the participation level and interest began to decline. Laboratory, facilities, and EHS leaders met to discuss the reasons for the lack of participation, and two primary concerns in how the ESA was initially implemented were identified:

1. Several meetings were spent discussing the role of the ESA as the AHJ, and yet it was found that the group was hesitant, unable, and/or felt ill-prepared to make decisions that impacted the larger part of the enterprise. Individuals were only knowledgeable and interested in their specific areas of influence.
2. The existence and outcomes of the ESA were not known by the audience it was intended to serve: the employees working in the laboratories and facilities who were conducting electrical work.

Further discussions about the inability and lack of preparation to act as the AHJ revealed that:

1. The individuals selected had, for the most part, worked in one area of laboratory testing or facility operations for much of their career and were not familiar with the testing or activities performed for other products and at other locations.
2. Because of the physical distances between testing locations, many of the employees on the ESA did not know each other. The ESA also included too high a proportion of leadership, some of whom were several levels above the employees performing the work. Not enough technicians who worked day to day in the laboratory and facility were part of the ESA. Due to this imbalance, technicians tended to be reluctant to speak up and make decisions within the ESA; therefore, safety concerns were not adequately shared.
3. The most significant revelation was that the enterprise had never given employees at the technician level the rights, role, authority and responsibility to make the types of decisions necessary for the ESA.

The ESA membership was asked for positive and negative feedback on the current state of the ESA. As a result, the laboratory and EHS leadership team implemented the following changes:

1. To help facilitate better communication with and representation of the laboratory testing sites:

   - All locations conducting electrical testing and work must have at least one representative on the ESA.
   - Agendas are to be sent before each meeting and meeting minutes distributed after each meeting.
   - Members are encouraged to share outcomes with their local laboratories.
   - The ESA reports its accomplishments each month in a newsletter to all employees.

2. To reduce the imbalance between the number of leaders and technicians and to encourage the technicians to exercise control of the ESA, changes were made to include the following:

- Leadership of the ESA now belongs to two “frontline” technicians to develop the agenda, facilitate the meeting, document action items and provide minutes.
- Many of the enterprise leaders now function as an advisory team, not primary members of the ESA.

3. The challenge of the ESA having the rights, role, and responsibility to make decisions as the authority are and will continue to be addressed as follows:

   - Frequent reminders throughout the meetings that the decisions made are those of the Authority, and all members have an equal voice.
   - The leadership advisory team commit to supporting and promoting the decisions of the ESA to all affected employees and address any barriers that may inhibit the implementation of actions resulting from decisions.

These changes resulted in an ESA that better represents the electrical workplace, is being led well and is achieving results. The next section will provide a case study on how the properly functioning ESA worked to address an electrical issue.

V. CASE STUDY: THE ESA AND INCIDENTS INVOLVING CAPACITOR DISCHARGE EXPOSURE

The enterprise implemented an observation, near miss, and incident reporting system that enables the enterprise to track and address global safety, security and environmental incidents, and was discussed previously by Brazis, Peterson, and Jiang [5]. One of the mandates to the ESA is to assist in electrical safety incident investigations where root cause and corrective actions are identified. According to an incident report, a technician received an electric shock when unplugging an AC/DC programmable power supply. The attachment plug was already out of the receptacle (no contact with the outlet) as the prongs rolled between the employee’s thumb and first two fingers of their right hand (Fig. 1). The employee felt a sharp pain that passed very quickly (after about 0.5 seconds), and at that point, the employee realized they had received a shock from the unplugged prongs of the power supply.

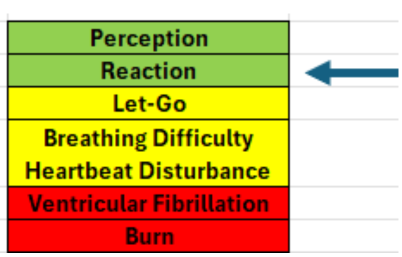

Fig. 1: Electrical shock path of travel	Fig 2: Electrical shock severity indicator

The employee received a reaction shock (Fig. 2) and was able to let go easily. No evident injuries such as burns or exit wounds were observed. To understand the potential that may have been present at the time of the incident, the employee and their manager also performed testing afterward to measure potential voltage versus time to assist.

The ESA was leveraged to investigate this incident. Through the investigation process, the source of the residual electrical energy was determined to be from incompletely discharged capacitors within the power supply circuit internal to the equipment.

The ESA met to discuss the issue and sent a notice to all global laboratories using power supplies. As a user of the equipment, the enterprise was only concerned about the presence of voltage external to the test equipment and not hazards internal to the unit. End-product standards for requirements on voltage remaining on the electrical connection means for the equipment was researched: it was determined that UL 62368, the Standard for Audio/Video, Information and Communication Technology Equipment, Ed. 3 was the most appropriate for verifying absence of voltage at the mains. The intent was to leverage existing, standardized methods for evaluating the hazard and was not intended to otherwise evaluate the unit for compliance to UL 62368.

A notice was sent instructing the laboratories to ascertain whether a capacitor is in the circuit for the mains and, if so, to measure the voltage remaining accessible at the power input prongs after disconnection from the mains or powered receptacle.

Section 5.5.2.2, of UL 62368, Capacitor Discharge After Disconnection of a Connector [5], was used as the basis for measurement of the voltage at the connector to the mains, which states:

> *Where a capacitor voltage becomes ACCESSIBLE upon disconnection of a connector (for example, the MAINS connector) the ACCESSIBLE voltage measured 2 s[econds] after disconnect of the connector shall comply with: [the limits stated in Table 5* [6] *(not included) of UL 62368].*

A simple test setup was developed to measure the residual voltage of the DC power supply and the time to discharge so laboratory employees could compare this time to Table 5 of UL 62368 [6] (Fig.2).

Fig. 3: A DC power supply and the test setup for measuring voltage

Each DC power supply was analyzed, the voltage after two seconds recorded and a voltage for comparison to Table 5 of UL 62368 for each was made using the condition ES1, which establishes a voltage limit based on capacitance for an ordinary person (for capacitance greater than 300 µF, the voltage limit is 60 V).

If the voltage did not drop to an acceptable level within two seconds, a warning marking (an example is shown in Fig.4) was placed on the equipment to alert the user of a shock hazard along with, where necessary, instructions for reducing the output to a safe voltage before disconnecting the equipment from the power source. If the discharge occurred in under two seconds, no further action was required.

Fig.4: Example of equipment warning label

Lessons learned from this shock incident include the following:

1. There remains a need to continue to improve the electrical shock risk identification and assessment process.
2. Improved training on capacitor discharge steps is needed.
3. Improve the understanding of the relationship between capacitors and the output for power supplies.

As a result, the following was implemented:

1. Identify and label equipment to warn of the presence of a capacitor that may result in a hazard from stored energy.
2. Create a procedure for de-energizing stored energy (voltage) in capacitors.

Moving forward, the ESA will continue to enhance the investigation process through:

1. Using the observation, near miss and incident reporting tool to recognize recurring issues resulting in electric shock hazards.
2. Identifying the source of the shock hazard.
3. Notification of all locations to check for the presence of the shock hazard.
4. Providing a remedy to reduce or prevent further shock incidents.
5. Establishing a feedback loop to collect responses to determine the extent of the problem.

VI. CONCLUSIONS

When the enterprise provides a safe working environment for its employees, the reputational gains are significant in the areas of external reputation, employee retention, clear direction across the organization, reduced downtime, and increased profit margins. When worker safety is not made a priority, harm to the employee, loss of physical assets, harmful environment events, and loss of intellectual property may occur, which lead to increased costs, fines, lawsuits, adverse regulatory actions, and loss of competitive advantage.

One of the successes in forming the ESA at the enterprise is empowering the team members to be decision makers and for leadership to act as enablers in the process. Through the ESA, employees are now developing safety practices and protocols that have a direct impact on them and their work, resulting in more thorough and meaningful safety management systems. Effective safety leadership enables the employee-led ESA by providing relevant safety training, supporting safe workplace practices and implementing a means to report observations, near misses and incidents.

This paper describes the experience of a single company in the TIC industry implementing a safety authority for electrical safety. The authors believe that the concept of a safety authority can be implemented across electrical and nonelectrical disciplines within various industrial, commercial and manufacturing facilities.

It is expected that the ESA in its current employee-led structure will continue to have an increasingly positive impact on employee safety and will benefit the enterprises' growth and reputation.

VII. REFERENCES

[1] NFPA 70E 2024; Article 350, Section 350.4

[2] Hierarchy of Controls, The National Institute for Occupational Safety and Health (NIOSH), Centers for Disease Control,

[3] NFPA 70E 2024, Standard for Electrical Safety in the Workplace, Quincy, MA: NFPA.

[4] NFPA 70E 2024; Article 100

[5] P. Brazis, L. Peterson and H. Jiang, "Electric Shock Incident Investigation Utilizing In-Depth Electrical Exposure Reconstruction Techniques," 2023 IEEE Symposium on Product Compliance Engineering (ISPCE) May 2023.

[6] UL62368, Audio/Video, Information and Communication Technology Equipment - Part 1: Safety Requirements, 3rd Edition, Section 5.5.2.2

[7] UL62368, Audio/Video, Information and Communication Technology Equipment - Part 1: Safety Requirements, Table 5.

VIII. VITAE

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‘Avoid Contact’ – The Shock Boundary Without a Distance

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Abstract – When using air as the dielectric insulation for worker protection against electric shock, OSHA, NESC and NFPA 70E primarily use a physical distance from the exposed energized part which is incumbent upon the nominal system voltage. While the three employ differing terms to denote this safety demarcation, their purpose is essentially identical by providing a physical space to prevent unintentional contact or unsafe encroachment to exposed energized part(s). OSHA and the NESC uses the term Minimum Approach Distance (MAD) while 70E refers to it as the Restricted Approach Boundary (RAB).

For most voltages, the MAD and RAB establishes a defined distance in feet/inches or meters. However, at lower albeit hazardous voltages, these standards move away from an actual linear measurement in units of length with the statement ‘AVOID CONTACT’ as the MAD and RAB.

This paper will provide supportive evidence that ‘AVOID CONTACT’ requires proactive actions on the part of the worker that actually Avoids Contact.

Index Terms — OSHA, NFPA 70E, National Electrical Safety Code, NESC, IEEE C2, Minimum Approach Distance, MAD, Restricted Approach Boundary, RAB, Avoid Contact, Do Not Touch, Inadvertent Movement Factor, Ergonomic Component, Electrical Component, Air Insulation.

I. INTRODUCTION

At face value ‘AVOID CONTACT’ appears to be an easy concept, and when asked what it means, most electrical workers will reply “Don’t Touch It.” However, as one digs into the conditional actions required to cross the MAD/RAB, we find its true meaning hidden in the technical details. With no definition or a lack of clear guidance, ‘AVOID CONTACT’ is subjective which leads to misunderstandings that unnecessarily increases risk of shock.

Using atmospheric air as the dielectric insulation to protect workers from electric shock has been a well-known and scientifically proven safe work practice for decades which is incontrovertible. Air is an effective insulator and offers excellent resistance against the passage of electric current. This can be seen by the modern-day design of overhead electric transmission and distribution (T&D) infrastructure consisting of bare aluminum, copper, aluminum conductors with steel reinforcement (ACSR) wires, or rigid bus segments. Insulators made of solid highly resistive materials such as porcelain, glass or polymer are used to insulate the energized bare metallic conductors or bus, AKA ‘phases’, from the grounded metal or wooden poles and towers to prevent ‘phase-to-ground’ faults. But atmospheric air is the dielectric medium employed between the wires or bus segments to prevent ‘phase-to-phase’ short circuits of the exposed parts that can be energized at thousands, tens of thousands and even hundreds of thousands of volts. The greater the nominal system voltage, the greater the air gap needed to compensate for the voltage stresses imposed.

At the higher voltage ranges, the physical distances listed in OSHA’s and the NESC’s MAD tables for >300 volts, and NFPA 70E’s RAB for >150 volts, all contain an electrical component of air coupled with an ergonomic component.

II. ELECTRICAL COMPONENT OF AIR

The electrical component is also known as the ‘*Minimum Air Insulation Distance’ (MAID)*, is designed to prevent an “arc over/sparkover/flashover” incident where the electrical potential stress is greater than the dielectric strength offered by a certain amount of air, also known as the ‘*voltage breakdown of air*’ or ‘*dielectric strength of air*’ [1]. Scientific studies have shown ambient air at standard atmospheric conditions has a dielectric breakdown resistance of approximately 3kV per millimeter [1].

The electrical component of air is based on five key factors [2]:

1. The maximum system voltage
2. The wave shape of the voltage
3. The configuration of the ‘electrodes’ forming the end points of the gap
4. The insulating medium in the gap, and
5. The atmospheric effect

Factor number 5 “atmospheric effect”, takes into consideration the altitude, barometric pressure, relative humidity (air density) and other parameters. Thinner less dense air at higher altitudes and climates with hot dry air, can reduce the insulation capacity of the ambient air, thus requiring greater distances to achieve the same level of protection from flash/arc over. Paschen’s curve law and Townsend discharge theory is foundational in determining the dielectric value of various gases at certain distances and pressure.

Voltage breakdown of air at medium voltages (>1kV to ≤100kV), high voltages (>100kV to ≤230kV), extra high voltages (>230kV to ≤1MV) and ultra-high voltages (≥1MV) [3] systems can also be affected by fluctuations of the nominal system voltage, often called ‘*voltage transients, spike or swells*’, requiring countermeasures to be factored in. OSHA 29CFR1910.269 subpart R and 1926 subpart V, ‘*Appendix B – Working on Exposed Energized Parts’*, requires additional correction factors that must be accounted for with voltages greater than 72.5kV for the maximum anticipated per-unit transient overvoltage, phase-to-ground exposure. This means

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the employer must consider the effects of any voltage transients that can be unexpectedly imposed upon the lines or equipment originating from internal and external conditions such as switching activities, faults, heavy inductive loads and during storms. Such momentary voltage spikes will require greater air distances to compensate for the additional transient stresses. Tables 3 from OSHA's 1910 subpart R and 1926 subpart V, and their Appendix B contains equations for calculating transient overvoltage factors.

III. ERGONOMIC COMPONENT

The ergonomic component is primarily a safety buffer for human errors made by the workers and is often described as the "inadvertent movement factor" or "adder". Its primary purpose is to include safety margin to compensate for any mistakes on the part of the worker, such as his ability to correctly judge the physical distance of the exposed energized part to himself, thus ensuring the worker does not inadvertently breach this space. For example, when the worker is adjusting his hardhat and other PPE, reaching for tools or materials, after a slip or stumble, swatting insects, and to account for any movements of the body when performing the work activity.

OSHA's Appendix B contains a pictorial image depicting a worker in relation to the MAD from an exposed energized part coupled with the inadvertent movement factor to aid the reader's understanding as shown by Fig. 1.

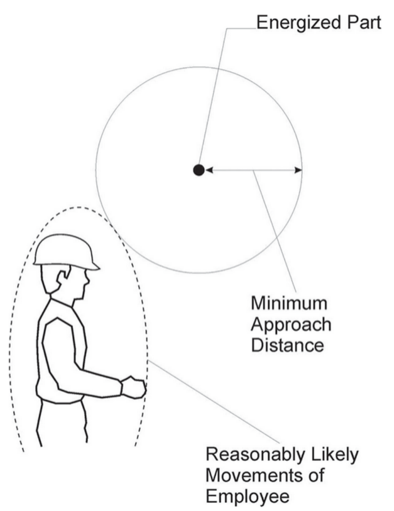

Fig. 1 – MAD Relationship to Exposed Energized Parts

IV. OCCUPATIONAL SAFETY AND HEALTH ADMINISTRATION (OSHA) – MAD

OSHA regulations addressing electrical safety for electric utilities and those for utilization equipment under the General Industry and Construction standards all incorporate the MAD. However, it should be noted, OSHA does not distinguish a difference between alternating current (ac) or direct current (dc) for the MAD.

A. 29CFR1910 subpart R and 1926 subpart V

Subparts R and V, mainly apply to electric utilities during the generation, transmission, and distribution of electricity, but can cross over to equivalent installations of industrial establishments. For the ergonomic component, OSHA states '*…the ergonomic movement factor must be sufficient for the employee to be able to recognize a hazardous approach to an energized line and withdraw to a safe position so that he or she does not breach the air gap required for the electrical component of the MAD*.' A "response time-distance analysis" is also factored into the ergonomic component, which estimates the response time by workers to avert a hazard after the danger is perceived by converting the time to distance traveled [2].

From 751 volts to 72.5 kV, the electrical component of the MAD is one foot (12 inches/0.31m) which is smaller than the ergonomic component, however once the voltage exceeds 72.6kV, the reverse is noted where the electrical component is greater than the ergonomic component.

OSHA 1910.269 defines the *Minimum Approach Distance* (MAD) as '*The closest distance an employee may approach an energized or a grounded object.'* The reason the MAD includes an approach to a "grounded object" is for live-line-barehand work (LLBHW), where the worker's body is energized at the same electrical potential as the conductive line or part he is in contact with. This makes an approach to anything at a different voltage, including ground, extremely hazardous by increasing the risk of electric shock and is controlled by 1910.269(q).

If the employee must cross into the MAD, 1910.269(l)(3)(iii) establishes two mandatory conditions before this is allowed with the conditional directive '*The employer shall ensure that no employee approaches or takes any conductive object closer to exposed energized parts than the employer's established minimum approach distance, unless:*

(A) *<u>The employee is insulated from the energized part</u> (rubber insulating gloves or rubber insulating gloves and sleeves worn in accordance with paragraph (l)(4) of this section constitutes insulation of the employee from the energized part upon which the employee is working provided that the employee has control of the part in a manner sufficient to prevent exposure to uninsulated portions of the employee's body), or*

(B) *<u>The energized part is insulated from the employee</u> and from any other conductive object at a different potential.'*

Table R-3 '*AC Live-Line Work Minimum Approach Distance'* can be used to calculate the MAD using mathematical formulas. Whereas two additional Tables, R-6 and R-7, titled '*Alternative Minimum Approach Distance'* can be used in lieu of equations. Table R-6 is limited to voltages from 50 volts to 72.5 kV and Table R-7 for voltages of greater than 72.5 kV up to 800kV. Both tables contain one column for '*Phase-to-ground-exposure*' and a second column for '*Phase-to-phase-exposure*'. The use of Tables R-6 and R-7 is further limited to locations with an elevation of 3000 feet (900 meters) above sea level or less.

B. OSHA 1910.333, Subpart S and 1926 Subpart K

Subparts S and K, primarily apply to industries that utilize electricity, such as industrial and commercial locations. Neither subpart S of 1910 nor subpart K of 1926 contains a definition of the MAD. However, both standards incorporate terms that imply the MAD such as '*Likelihood of <u>approach</u> to a point of contact or danger*', '*Admitting close <u>approach</u>*' and '*Capable of being inadvertently touched or <u>approached</u> nearer than <u>a safe distance</u> by a person*', emphasis added, are used within the definitions of the words "Exposed", "Accessible" and "Guarded".

1910 subpart S contains Table S-5 titled '*Approach Distances for Qualified Employees - Alternating Current'* that houses a column titled '*Minimum Approach Distance*' listing physical distances, in relationship to exposed overhead lines. The voltage ranges used in Table S-5 from 50 volts to 750 are identical to subpart R but differ starting at 751 volts or more. Additionally, Table S-5 has a maximum voltage of 140kV with no mention of an elevation or transient overvoltage criteria and applies to only ac with no distinction between a "phase-to-phase" or phase-to-ground" exposure as found in the corresponding tables of subparts R and V.

Furthermore, no such table with defined minimum approach distances is found in 1926 subpart K for construction, therefore Table S-5 from 1910 subpart S should be considered for use during construction activities.

V. NATIONAL ELECTRICAL SAFETY CODE (NESC) – MAD

The NESC Section 2 defines the '*Minimum Approach Distance'* as '*The closest distance a qualified employee is permitted to approach either an energized or grounded object, as applicable for the work method being used*.'

NESC contains two MAD tables, one for ac and the other for dc with established physical distances from energized ac and dc parts. Table 441-1 addresses '*AC Live Work Minimum Approach Distance'* while Table 441-5 is specific to '*DC Live Work Minimum Distance'*.

Table 441-1 is separated into two columns for ac exposure from 51 Vac to 72.5kVac titled:

- *'Phase-to-ground*'
- '*Phase-to-phase'*

For voltages greater than 72.5kVac up to 800kVac, Table 441-1 separates into three columns with the titles:

- *'Without live-line tools – Phase-to-ground*'
- '*With live-line tools – Phase-to-ground'*
- '*Without live-line tools – Phase-to-phase*'

Table 441-5 has only one column for dc exposure from 51 Vdc to 72.5kVdc titled:

- *'Pole-to-ground*'

For voltages greater than 72.5kVdc up to 750kVdc, Table 441-5 separates into two columns with the titles:

- *'Without live-line tools – Pole-to-ground*'
- *'With live-line tools – Pole-to-ground*'.

Section 44, Rule 441 also contains correction factors for altitude elevations greater than 3,000 feet (900m), and Transient Overvoltage (TOV) for voltages above 72.6kVac and 72.6kVdc.

The NESC requires one of three conditions to exist before workers are permitted to enter the MAD according to Section 44, Rule 441.A which states:

1. *'Employees shall not approach or bring any conductive objective within the MAD listed in Table 441-1 or 441-5 to exposed energized lines or parts unless one of the following is met:*
   a. *The line or part is de-energized and grounded per Rule 444D*
   b. *<u>The employee is insulated from the energized line or part</u>. Electrical protective equipment insulated for the voltage involved, such as tools, rubber gloves, rubber gloves with sleeves, shall be considered effective insulation for the employee from the energized line or part being worked on.*
   c. *<u>The energized line or part is insulated from the employee</u> and from any other line or part at a different voltage.'*

VI. NFPA 70E – RAB

NFPA 70E on the other hand has developed two demarcation points designating the minimum physical distances necessary to maintain safe work approach from exposed energized parts. They are designated as the '*Limited Approach Boundary (LAB)*' and the '*Restricted Approach Boundary (RAB)*'. The LAB is the greater distance of the two boundaries and is further sub-divided into '*Exposed Moveable Conductor'* and '*Exposed Fixed Circuit Part*'. Neither OSHA nor the NESC has an equivalency for the LAB.

The LAB is defined as '*An approach limit at a distance from an exposed energized electrical conductor or circuit part within which an electrical shock hazard exists*.' The RAB on the other hand, is defined as '*An approach limit at a distance from an exposed energized electrical conductor or circuit part within which there is an increased likelihood of electric shock, due to electrical arc-over* [i.e. the electrical component] *combined with inadvertent movement.'* [.e. the ergonomic component], clarification added.

The RAB is very similar to the MAD as used by OSHA and NESC but differs for the voltage ranges. The RAB only applies to exposed energized parts, with no mention of grounded objects as used by OSHA and the NESC. NFPA 70E like the NESC, also separates ac from dc voltages into two distance tables specifically for each type of exposure.

Table 130.4(E)(a) is for ac voltages from 50 Vac to 800kVac is titled:

- *'Nominal System Voltage Range – Phase to Phase*'

Table 130.4(E)(b) is for dc voltages from 50 Vdc to 800kVdc is titled:

- *'Nominal Potential Difference*'

The fourth columns of Tables 130.4(E)(a) and (b) are titled '*Restricted Approach Boundary – Includes Inadvertent Movement Adde*r' which incorporates the ergonomic component into the RAB distances previously mentioned in its definition. According to Table 120.4(E)(a), Note "d", the RAB for ac voltage is limited to a maximum elevation of 3000 feet (900m) and '*For higher elevations, adjustments of the RAB shall be considered*.', however no assistance is offered to aid the reader in calculating the necessary adjustments. The RAB for dc voltages does not contain any information nor the need for an elevation adjustment.

NFPA 70E 130.4(G) like OSHA and the NESC, mandates one of two conditions to be in place before the RAB can be entered with the statement:

'No qualified person shall approach or take any conductive object closer to exposed energized electrical conductors or circuit parts than the RAB set forth in Table 130.4(E)(a) and Table 130.4(E)(b), unless one of the following conditions applies:

(1) The qualified person is insulated or guarded from energized electrical conductors or circuit parts operating at 50 volts or more. Insulating gloves and sleeves are considered insulation only with regard to the energized parts upon which work is performed.

(2) *The energized electrical conductor or circuit parts are insulated from the qualified person and from any other conductive object at a different potential*.'

Additionally, section 130.7(D)(2) further supports this position by the mandatory use of voltage rated barriers (as defined) whenever exposed energized parts at 50 volts or more are present within the RAB to "*prevent unintentional contact*".

Lastly, NFPA 70E *Informational 'Annex C – Limits of Approach'*, states for a qualified person to cross the RAB and enter the restricted space they need to '*Minimize the likelihood of bodily contact with exposed energized conductors and circuit parts from inadvertent movement by keeping as much of the body out of the restricted space as possible by using only protected body parts in the space as necessary to accomplish the work*.', emphasis added.

VII. "AVOID CONTACT" – THE MAD/RAB WITHOUT A DISTANCE

The obvious goal of the MAD and RAB is to provide an adequate safety gap through a physical air distance to ensure workers do not encroach or move themselves or a conductive object being held, too closely to an exposed energized part. As previously mentioned, its objective is to Avoid Inadvertent or Unintentional Contact. This is accomplished by built-in safety margins, consisting of clearly established physical gaps incorporating both the electrical and ergonomic factors found with higher voltages to minimize the negative impacts of human errors. But at lower, albeit hazardous voltages, such safety buffers are not offered nor explained. OSHA 1910.269, Appendix B informs the MAD for voltage between 50 to 300 volts is "Avoid Contact" followed by the statement: '*The minimum approach distance for this voltage range contains neither an electrical component nor an ergonomic component*.', emphasis added. No such explanatory information is provided by NFPA 70E.

Therefore, Avoid Contact is a safety directive without a defined physical distance but without contextualization against the purpose and restrictions of the MAD/RAB, confusion and misunderstanding invariably arise. This coupled with the subjectiveness of "Avoid Contact" can easily leads to misinterpretation by workers to mean "Don't Touch It" or "I Won't Touch It." This misunderstanding is because no technical definition of Avoid Contact is offered in any of the existing safety regulations, standards or codes. Without a definition, the worker is left to his normal understanding of the conjunction of two simple words based on the common vernacular.

According to the Merriam-Websters online Dictionary [4] the verb 'Avoid' is defined as '*to keep away from*' and the word 'Contact' when used as a noun, can mean a *'union or junction of surfaces*' or *'the junction of two electrical conductors through which current passes*." And when used as an intransitive adverb, it means '*the point at which two surfaces contact one another*.' Therefore, when the word "Avoid" is coupled with "Contact", this without exception, leads to incorrect and dangerous misinterpretation by workers. Consequently "Avoid Contact" is understood to mean nothing more than "Be Careful."

The worker's success of not accidentally contacting exposed energized parts at hazardous electrical potentials such as 120 volts (NFPA 70E) or 208, 240 and even 277 volts (OSHA and NESC) is based on human factors such as the skill of the worker, his training, attention to detail and situational awareness. But such human performance tools are inherently flawed as they rely on imperfect human beings to maintain them. Because even the most skilled and technically astute individuals are plagued by our common weakness; that all humans make mistakes, so errors are inevitable [5]. But when errors are made with exposed energized parts and contact occurs, this can and has resulted in irreversible consequences.

The dilemma of Avoid Contact is often encountered when employees are conducting trouble-shooting activities or taking voltage or current readings of low voltage (i.e. ≤ 1kV) equipment inside of enclosures or compartments containing a multitude of exposed energized parts, such as terminal strips, relays, fuse blocks, etc. If the technician's employer has a robust electrical safety program, then it is likely he will be required to wear rubber insulating gloves with protectors while handling the test probes. Most test probes from quality manufacturer's carry an IEC 61010 rating of CAT II or III of 1kV and CAT IV of 600 volts [6], which is substantially greater than the system voltage exposure. However, other individuals with a lower tolerance of the risks, may disregard the use of insulating gloves and opt to rely on the probes' rating alone, handling them with bare hands. This latter practice is a poor safety choice because it significantly increases the hazards the worker faces and is strongly discouraged. Donning class 0 or 00 rubber insulating gloves with protectors, does not unduly restrict dexterity of the hands, especially when using test instruments and probes, but offers another layer of defense if the hands should unexpectantly slip or move.

For the sake of argument, let's say the worker has decided to don his rubber insulating gloves during a troubleshooting task but is this adequate to fully protect him from electric shock? The answer is YES and NO, depending on the type and configuration of the equipment being worked. For this reason, OSHA, 1910.333(c)(3)(ii)(A), 1910.269(l)(3)(iii)(A), NESC 441.A.1.b and NFPA 130.4(G)(1) all state the insulating gloves are considered insulation for only the energized part(s) being worked, therefore the hands and lower arms are protected. But what about the other energized parts or lines close to the worker's body that isn't being worked on, such as the upper portions of the arms, elbows, back, etc.?

To answer this question, the following example is given for the task of taking voltage reads of the 480-volt contactor mounted to the backplane located towards the center of enclosure circled in **blue** as shown in Fig. 2. The worker's hands would be sufficiently protected from shock by the part being worked on [the contactor] by wearing ASTM D120 class 0 or 00 rubber insulating gloves when combined with ASTM F696 protectors [7]. However, the electric shock hazards presented by the hardware mounted on the inside of the hinged door circled in **red** obviously would not be abated by using rubber insulating gloves.

If the exposed energized parts on the inside of the door is energized at 120 volts, then both the MAD and RAB would be "Avoid Contact". And if the voltage is greater than 150 volts, then the RAB according to NFPA 70E would be established at 12 inches which would initiate proactive actions. However, the MAD according to OSHA and the NESC would remain unchanged from Avoid Contact for up to 300 volts with no physical distance or required changes in worker safety practices.

Let us assume the door parts are energized at a 120 vac which directs the worker to Avoid Contact for either the RAB or MAD. He now has two options to accomplish this. First, if his understanding means "Don't touch it", he might position his body in such a way as to keep his back and backside from touching the energized parts through situational awareness and "being careful". But can the worker lose focus, become distracted, or forget the hazard directly behind him then step back into the exposed parts or could a breeze push the hinged door closed on him? The obvious answer is YES. This leads to the rhetorical question "So did the worker really avoid contact?" which can only be answered NO but only after contact is made and an injury sustained. His undeniable intention was to Avoid Contact but through a series of factors, contact was still made. However, if the worker understood the proper context and requirements for preventing inadvertent contact, he would use voltage rated sheeting according to ASTM F1742 or F2320 [8] as an insulating barrier to cover the exposed parts as shown by the **green** box in Fig. 3. This simple, but effective action by placing insulation between the exposed energized parts and himself would effectively avert unintentional contact by the dielectric sheeting placed between the exposed energized parts and himself. The presence of the barrier will protect the worker if he moves towards it or it moves towards him, thus avoiding injury.

Fig. 2 – Unprotected Exposed Energized Parts

Fig. 3 – Protected Exposed Energized Parts

This leads to the inevitable question "Does the MAD/RAB of Avoid Contact truly prevent accidental contact if the understanding is "Don't Touch It"?" The clear answer is NO because when we review the three standards carefully, OSHA 1910.269(l)(3)(iii)(A) & (B), NESC 441-5 and NFPA 70E 130.4(G)(1), we find the common directive within all of them with the same two minimum conditional actions that must be employed by the worker before he is permitted to breach the MAD or RAB, consisting of:

1. The worker is insulated from the exposed energized parts or
2. The exposed energized parts are insulated from the worker

The conscientious mitigation act shown in Fig. 3 fulfills the conditional requirements to breach the RAB or MAD, because the act of crossing the MAD or RAB is treated the same as intentionally touching the energized part, yet the purpose of the MAD and RAB is to prevent unintentional contact through safety buffers and adders. Consequently, this begs another question, how does the worker maintain the MAD or RAB of Avoid Contact, which has no physical distance, before inadvertent contact is made and the MAD/RAB is violated? This apparent dichotomy, clearly means Avoid Contact requires the worker to employ some kind of proactive countermeasures to ensure unintentional contact is effectively avoided.

This position is further supported by OSHA's official final rules with the directive '*The hazards posed by installations energized at 50 to 300 volts are the same as those found in many other workplaces. <u>The employee must avoid contact with the exposed parts, and the protective equipment used (such as rubber insulating gloves) must provide insulation for the voltages involved.</u>*', emphasis added [2].

OSHA is not alone in this position because the NESC Rule 441 contains a very interesting caveat within 441.A.2 specifically targeting the voltage range of 51 to 300 volts (ac or dc) titled '***Precautions for approach – Voltages 51 V to 300 V***'. It mandates '*Employees shall not contact exposed energized parts* *operating at 51V to 300V, <u>unless the provisions of Rule 441.A.1 are met</u>*.', emphasis added. What does Rule 441.A.1 require before contacting exposed energized parts?

441.A.1.(b) *<u>The employee is insulated from the energized line or part</u>.*

441.A.1.(c) *<u>The energized line or part is insulated from the employee</u>…'*

Therefore, the use of some type of insulating material, rated for the voltage exposure, must be installed over the exposed energized parts to avoid unintentional contact.

The practice of "rubber up/cover up" is a common practice by electric utility linemen and electricians working on overhead electric distribution lines and parts at higher "primary voltages" as shown by Fig. 4 which affords barriers to inadvertent contact but is often disregarded or downplayed when working on lower "secondary voltages".

Fig. 4 – Linemen Covering Up Exposed Energized Parts

VIII. DEADLY RESULTS OF CONTACT WITH "ONLY" 120 VOLTS

Within OSHA's Final rules, we find data regarding 26 fatalities of electric utility workers who lost their lives from inadvertent contact with 120 volts between 1984 to 1996, which validates such low voltage circuits are deadly, even for seasoned and experienced electric utility workers [2][9]. This OSHA information validates the deadliness of contact with low voltage systems.

When inquiries are made of qualified electrical workers who are asked the question "What does Avoid Contact mean to you?", the overwhelming majority of respondents will reply something to the effect of **"Don't touch it"** or **"I won't touch it"**. The thought process is to use good judgement, their skills, and an awareness of the work area to prevent inadvertent contact with the energized part(s). This misunderstanding coupled with complacency and overconfidence when working on or near lower voltage circuits, exacerbates the risks to workers' safety. How many reading this paper have ever heard someone say or even made the statement yourself **"It's Only 120 volts."** which indicates a lack of respect for this voltage? This further supports the misbelief and underestimation of the safety implications associated with low, albeit hazardous voltages.

According to more recent data provided by Electrical Safety Foundation International (ESFI) of OSHA workplace fatality data from 2011 to 2022 reveals 30 workers lost their lives from voltages ranging between 110 to 120 volts, 23 deaths from 208 to 240 volts and 62 fatalities from 270 to 300 volts. While some of these system voltages listed by ESFI were greater than 120 volts, the actual voltage that caused many of the fatalities were likely a phase-to-ground exposure rather than phase-to-phase. For most poly-phase systems energized at less than 300 vac, the single phase-to-ground potential would be in the range of 120 volts. The ESFI data also revealed an additional 807 deaths occurred where the voltage was not listed within the accident reports researched [10]. This missing information could very likely account for higher fatality numbers of the voltages within the ranges of 50 to 150 volts and 50 to 300 volts. Finally, the occupations of the victims were not researched, the point being made here is lower voltages are extremely hazardous to humans, regardless of job title or qualifications.

Expecting the sole use of human performance tools such as situational awareness, self-checking, etc. reinforced with training, "skill of the craft" and technical acumen, as adequate barriers to prevent unintentional contact with energized parts is ineffective and places the safety of workers at great risk. The data of workplace deaths and serious injuries from contact with lower voltages of less than 300 volts (primarily 120 vac) validates this position of the hazardous nature of "low voltage" systems.

IX. PREVENTION THROUGH DESIGN RECOMMENDATIONS

Over the subsequent decades since electricity was first harnessed, improvements in equipment design have slowly evolved to minimize contact with energized parts. Take for example the common household male plug used on countless electrical appliances and tools. Originally, it was designed with only two blades with a "waffle dead front cover" as shown in upper image of Fig. 5 (dead front cover removed) which evolved to three blades and later as a one piece molded assembly as depicted by the lower image of Fig. 5. This simple change, fundamentally impacted the ergonomic positioning by moving the user's finger and thumb further back from the exposed blades when inserting and removing the male plug from an energized outlet as seen in Fig. 6.

Fig. 5 – Comparison of Vintage vs Modern Male Plug [11]

Fig. 6 – Finger and Thumb Positioning [11]

Another example of safety by design to minimize the chances of inadvertent contact is the evolution of the standard open style fuse holders compared to the Ingress Protection (IP20) [12]as shown in Fig. 7. To remove the fuses from the traditional open style shown on the left requires the use of a non-conductive fuse pulling tool and rubber insulating gloves while the design of IP20 fuse holder on the right, disconnects the fuse from the energized parts as soon as the cradle is opened, alleviating the need for special tools and PPE.

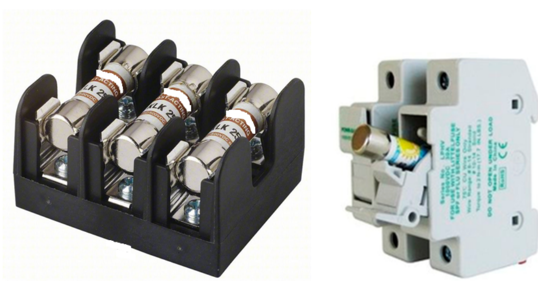

Fig. 7 – Traditional Open Style Fuse Block vs IP20 'Finger Safe' Fuse Holder

A final illustration of improvements in safety design of common electrical equipment can be seen in the configuration of a standard safety disconnect switch. The original vintage design was not housed in an enclosure with all energized parts fully exposed. The non-conductive handle was connected directly to the movable energized blades, as seen in Fig. 8. As safety improvements continued, the exposed energized parts were enclosed inside a grounded metal compartment with a hinged door that could be closed and secured. The handle, which also had the capability for a Lockout/Tagout, was moved to the external side of the box which allowed the operator to manipulate it without unnecessary exposure to energized parts which are now guarded by grounded sheet metal. But the door could still be opened with the switch in either the ON or OFF position. Understanding this weakness, mechanical interlocks were later added to prevent opening the hinged door when the switch handle is in the ON position. However, even with the handle in the OFF position, the line side remained energized and fully exposed when the interlock was defeated as shown in Fig. 9. Revised safety improvements by several manufacturers have further reduced any exposure to energized parts by "finger-safe" designs" from the line side terminals when the door is opened as visible in Fig. 10.

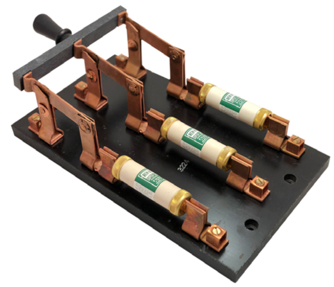

Fig. 8 – Vintage Safety Disconnect, all Energized Parts Fully Exposed

Fig. 9 – Modern Safety Disconnect with Handle Moved Outside the Box but with Exposed Parts on Line Side

Fig. 9 – Reengineered Safety Disconnect with "Finger Safe" Design of the Line Side Terminals

X. CONCLUSION

Therefore, the purpose of the MAD and RAB in all the cited standards and regulations is to prevent Inadvertent Contact with exposed energized parts. The preemptive actions needed to cross the MAD/RAB are the same as intentionally contacting the exposed energized parts and require the identical two minimum conditional actions that must be employed by the worker before breaching the MAD or RAB, consisting of:

1. The worker is insulated from the exposed energized parts or
2. The exposed energized parts are insulated from the worker

With existing installations of older designs, the only practical way to minimize the risk of inadvertent contact by electrical workers is by PPE, temporary insulation, updating training and robust administrative controls in work rules and safety procedures. Engineering controls by modifying existing equipment and retrofitting shields, guarding and barriers is also an option. However, for future installations and during equipment upgrades, employers, workers, designers, equipment manufacturers and standards developers must collaborate to further reduce 'accepted risk' of inadvertent contact by pursuing better safety by design features.

A. *Employers*

Employers need to recognize there are many common tasks that place workers within reach of lethal energy of 120V. Control measures to prevent contact may be heavily dependent on human performance, but a simple error, mistake or unanticipated event can result in a serious or fatal injury.

B. *Workers*

As the ultimate stakeholder, workers are the ones at direct risk of making inadvertent contact. They must understand that any contact with voltages at greater than 50 volts is considered hazardous to their safety and health and may result in serious injury or death. Based on this fact, some international standards such as the National Standard of Canada CSA Z462 reduces the threshold of hazardous voltage to 30 vac. Workers must understand the most skilled, competent and empierced veteran in the electrical trade can make a mistake and unanticipated events can happen even during the most routine and common tasks.

C. *Designers*

Facility and project designers need to recognized there are engineering design choices that can significantly reduce the likelihood of a worker making inadvertent contact with hazardous voltages. Assuming the skills of qualified and competent workers is sufficient preventions is flawed and short sighted.

D. *Equipment Manufacturers*

Manufacturers of electrical equipment need to assess their current designs to identify opportunities to incorporate solutions that further reduce the likelihood of electrical workers making inadvertent contact with exposed 120V parts.

E. *Standards Developers*

Lastly, the developers of standards need to recognize past practices of accepted risks may not and should not be acceptable for the future by considering the advancements in technology, global best practices, understanding of human vulnerabilities and performance and by risk assessments. Raising the bar on minimum requirements to reduce the likelihood of inadvertent contact must be correctly prioritized.

The common misunderstanding and confusion by qualified electrical workers that Avoid Contact means "Don't Touch It" is telling of gaps and weaknesses in our current electrical safety regulations, standards, codes, and training programs, which is indicative of what risks employers and employees consider acceptable. This unintentional oversight unnecessarily increases risk to workers from electric shock through a dangerous misinterpretation of two common words "Avoid" and "Contact", simply because no official definition or clarification is provided. But this knowledge gap and subsequent safety challenge can be effectively bridged and the confusion eliminated, if the regulations, codes, and standards are revised to identify a physical distance for the RAB and MAD, such as 2 or 3 inches in place of Avoid Contact. This would remove the subjectivity altogether. However, an alternative for the deletion of the term Avoid Contact is to develop a clear definition of Avoid Contact that explains it requires the implementation of intentional actions by applying additional control measures, including PPE and the use of insulating sheeting, that will prevent inadvertent contact during assigned tasks. This new definition should be coupled with practical examples demonstrating how to achieve a safe condition that makes certain inadvertent contact will be avoided. Once a definition is developed within the regulations, standards, and codes, the electrical safety training programs must be promptly updated to transfer this critical safety knowledge to the workers to help them fully comprehend what Avoid Contact is but more importantly what it is not.

If "rubber up/cover up" is effective in preventing accidental contact with higher voltages with existing exposed designs as shown in Fig. 4 then it will be effective as the same abatement action with lower voltages as shown in Fig. 3. Pursuing safety by design for future installations and system upgrades will also drive the numbers of serious injuries and fatalities caused by lower voltages in the desired direction.

As an interim mitigation action, employers should develop their own definitions and practices of Avoid Contact using the same parameters required whenever crossing into the RAB or MAD for the higher voltage, that is to:

- insulate the employee from the exposed energized part(s) or
- insulate the energized part(s) from the employee.

An example of a definition for Avoid Contact could be:

'Avoid Contact – Means taking the necessary actions, such as using PPE and placing insulating materials over exposed energized parts, to reduce the risk and likelihood of making inadvertent contact.'

Long term stake holders in electrical safety and those who wish to further reduce fatalities and injuries must change our modus operandi regarding the hazards posed by lower voltage systems and equipment by taking appropriate proactive steps and actions necessary to Avoid Contact. These measures must be followed by incorporation into our electrical safety programs and training curriculum until the regulations, standards, and codes are finally revised and updated.

XI. ACKNOWLEDGEMENTS

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[11] Images provided by Lanny Floyd used by permission

[12] IEC 60529, Ingress Protection (IP Code) Testing – IP20: Finger Sized Object Protection

XIII. VITA

George Cole is a native of Phoenix, AZ and is employed with the Arizona Public Service (APS) Company and currently works at the Palo Verde Nuclear Generating Station as the electrical safety consultant and formally as a journeyman maintenance electrician. During his career with APS, George has also worked in the T&D and electronic communications sectors.

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Transient DC Arc-Flash Incident Energy Calculations for DC Distribution Systems

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Abstract – The pressing need to reduce our carbon footprint has led to a significant increase in the integration of direct current (dc) distribution systems into our existing alternating current (ac) power network infrastructure. The various dc power sources and loads that are coming online are commonly integrated into the ac systems using active front end (AFE) power converters. An AFE is a device which makes the connection between the ac and dc networks. These dc power sources along with large dc capacitor banks introduce new challenges for the calculation of the dc arc-flash thermal incident energy (IE). This paper presents a case study on the analysis of an actual dc distribution power system and focuses on the simulation methods that can be used to evaluate its dc arc-flash hazards. The paper discusses the fast transient dc fault currents which can be developed by this technology along with considerations on how to use these fault currents to perform the IE calculations. The presentation includes an overview of AFE systems and how they are applied to dc distribution systems and provides insights into how this equipment is serviced and the types of hazards an electrical worker is exposed to when working around this type of equipment to help qualified workers assess the risks and select the proper risk control methods and PPE to be used when working in this type of installation.

Index Terms — AFE, dc arc flash, dc arc, arc resistance, dc arc-flash methods, dc capacitor, heat flux, arc-flash incident energy

I. INTRODUCTION

This work focuses on the topic of dc arc-flash incident energy calculations for dc power distribution networks utilizing active front-end power converters, which is technology that is often not well understood. This paper presents an overview of this technology and provides methods to estimate their short-circuit current and arc-flash incident energy. The main motivation for this paper is to continue the effort started in [1] for photovoltaic systems and continued in [2] for battery energy storage systems. This work expands into the modeling of converters under short-circuit conditions with the intent of establishing an accurate bolted dc short-circuit current to perform dc arc-flash incident energy calculations. The authors examined the application of IEC 61660, which was developed to offer a computational approach for transient dc short-circuit currents in auxiliary dc systems within power plants and substations. There is no IEEE standard for the calculation of transient short-circuit currents in dc systems but there are some other standards which provide some guidelines such as IEEE standards 141, 242, 399, 666, 946,1375 and IEEE standard C37.14. The only standard which has comprehensive details for transient dc short-circuit currents is IEC 61660. The authors' experience on this subject is that the short-circuit behavior of dc power sources is often misunderstood, which has led to overly high incident energy predictions as was the case in [3],[4] and others. It is true that there is no formally reviewed industry consensus standard such as [5] available for dc arc-flash incident energy calculations, yet the authors have found and reported in [1],[2] and [6] that utilizing the current methods mentioned in Annex D.5 of [7], (also known as the rigorous calculation methods), based on arc resistance and the actual gap between conductors provide far more accurate results. The accuracy of the incident energy predictions is enhanced when the dc source short-circuit current is modeled with more accuracy. This paper expands on the various previous works but focuses on AFE's in dc power distribution networks.

II. DC POWER DISTRIBUTION SYSTEMS

DC Power distribution systems connect different types of sources (e.g., Utility/Grid, PV, Battery) to the loads through a common dc bus as shown in Fig. 1.

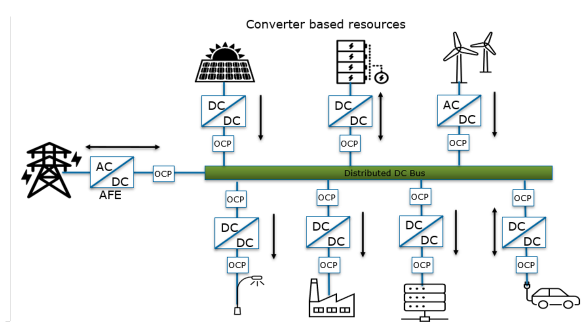

Fig.1 - Grid-tied dc microgrid with converter/inverter based resources and loads and overcurrent protective devices

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Each equipment is connected to this bus through an inverter or converter. This type of architecture simplified the power flow between each element by adjusting the voltage level to the main dc bus voltage level (droop control). The short-circuit fault current in these systems is limited by fast acting fault current protection because the power electronics embedded in all active converter cannot sustain a fault current for a long period of time. The peak fault current might be high, but the duration will be very short (as shown in the next chapters). Hence the total energy is low. In case the batteries are directly connected to the bus, the fault current and the total energy could be higher.

III. OVERVIEW OF AFE POWER CONVERTERS

DC power distribution systems are commonly connected to the grid via an active front end converter. This type of converter allows the current to flow in both directions, hence enable sharing energy.

There are different types of topologies which include isolated, non-isolated, boost, and buck. The common part of these converters is the dc link capacitance at the dc output. This capacitance provides filtering effect to the power signal (linked to frequency switching of the power electronic) and provides buffer to the system to absorb load change. When a short-circuit occurs, the capacitance will discharge into the system, creating a high and fast current transient waveform. Then, depending on the topology of the converter, once the capacitance has discharge, there could a follow through current, limited or not by the converter [8], as shown in Fig. 2 and 3.

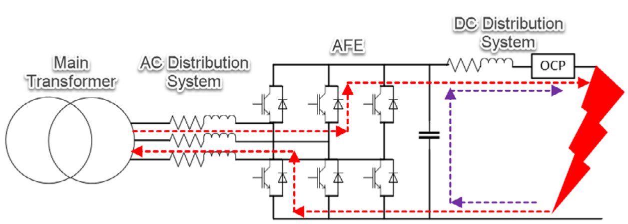

Fig.2. Prospective fault current path an Interlink ac/dc converter.

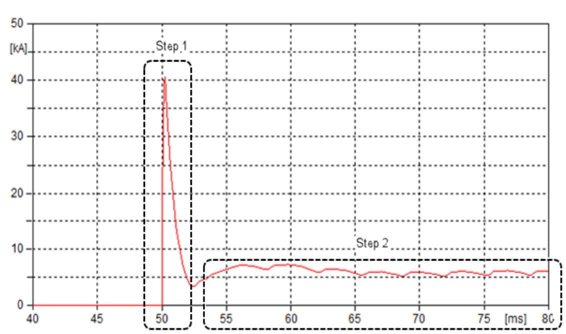

Fig. 3 - Simulated prospective fault current waveform with an Interlink ac/dc converter.

Other capacitance in the system, like those at the input terminal of the other converters, will also participate in the fault current. However, the main contributor to the fault current is usually the AFE. In this paper, the Authors studied a dc power distribution system composed of a 1.7 MW AFE connection to the grid and feeding 7 x 570 Vdc DC loads through 100 kW DC/DC Converters. Fig. 4 shows the location of the capacitors which contribute to the fault current and the location of the protective devices which limit or clear the fault current.

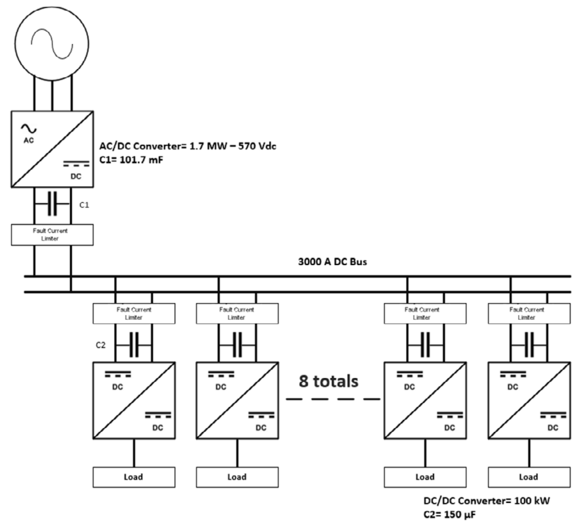

Fig. 4 - Simplified diagram of the proposed dc distribution system studied in this paper.

IV. CONVERTER TRANSIENT MODEL

According to [9], the converter short-circuit current is shown in Fig. 5. Similar to how [10] explains, the converter short-circuit current reaches a maximum eight to ten milliseconds after the fault (half cycle based on the system frequency). As explained in [10], this maximum or peak current is caused by a physical behavior similar to the dc offset in the ac power system. The R/X or X/R determines the magnitude of this peak current. The ac system source reactance, the rectifier transformer impedance, and the resistance and reactance of the dc system impedance between the converter output and the location of the fault play a factor on the dc short-circuit current.

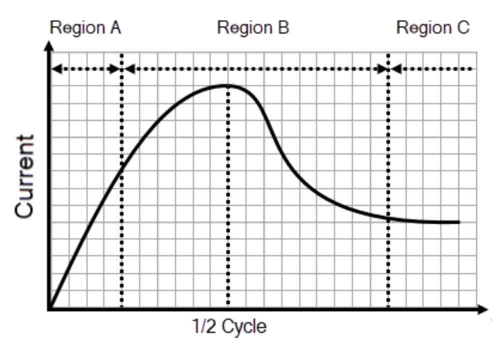

Fig. 5 – Generalized rectifier SC current [9]

There are three expected regions which cover the rise, expected peak, and the final value of the short-circuit current. If a smoothing reactor is present in the output of the converter, then it tends to suppress the peak current significantly as shown in Fig. 6.

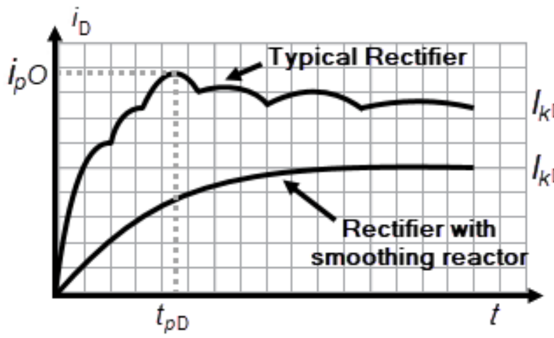

Fig. 6 – Effect of smoothing reactor [9]

Fig. 7 shows the main components of the rectifier branch including the ac network source impedance, connecting ac lines or cables, rectifier transformer and the rectifier / converter circuit components.

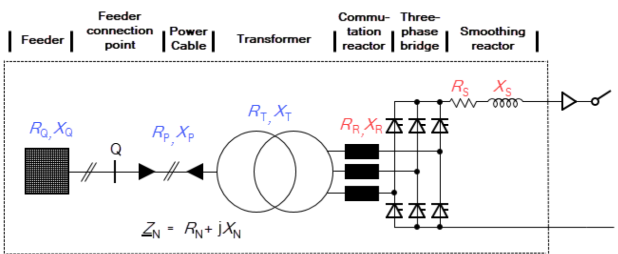

Fig. 7 – Generalized rectifier branch (Fig. 3 of [9])

The equivalent short-circuit diagram of the rectifier or converter system shown in Fig. 7 is shown in Fig. 8. All resistances and inductances are reflected towards the output of the rectifier/converter.

Now that the components involved have been identified and the rectifier/converter equivalent short-circuit diagram has been established, the intermediate values needed to derive the transient short-circuit current can be elaborated as follows.

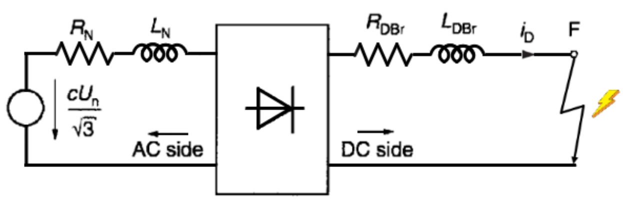

Fig. 8 – Equivalent SC circuit of the rectifier/converter

The maximum short-circuit current is given by minimum impedance Z_{Qmin} (1), which is obtained from the maximum short-circuit I''_{kQmax} of the ac system at the point of interconnection (POI).

$$Z_{Qmin} = \frac{CU_n}{\sqrt{3}I''_{kQmax}} \quad (1)$$

The minimum dc current is given by Z_{Qmax} (2) from the minimum short-circuit current I''_{kQmin}.

$$Z_{Qmax} = \frac{CU_n}{\sqrt{3}I''_{kQmin}} \quad (2)$$

where:

C	Factor C according to IEC 60909 (Ω)
U_n	Nominal System Voltage (kV)

It is necessary to determine the resistance and reactance of the ac power system side referred to the secondary of the rectifier transformer according to (3) for R_N and (4) for X_N (once again note that all individual component resistance and reactance are referred to the secondary side).

$$R_N = R_Q + R_P + R_T + R_R \quad (3)$$

$$X_N = X_Q + X_P + X_T + X_R \quad (4)$$

where:

R_N	Equivalent resistance of the ac side (Ω)
X_N	Equivalent reactance of the ac side (Ω)
R_Q	Resistance of the ac source (Ω)
X_Q	Reactance of the ac source (Ω)
R_P	Resistance of the power supply cable (Ω)
X_P	Reactance of the power supply cable (Ω)
R_T	Resistance of rectifier transformer (Ω)
X_T	Reactance of the rectifier transformer (Ω)
R_R	Commutating reactor resistance (Ω)
X_R	Commutating reactor reactance (Ω)

Similarly, it is necessary to obtain R_{DBr} and L_{DBr} using (5) and (6).

$$R_{DBr} = R_S + R_{DL} + R_Y \quad (5)$$

$$L_{DBr} = L_S + L_{DL} + L_Y \quad (6)$$

where:

R_S	Saturated dc reactor resistance (Ω)
R_{DL}	Rectifier conductor resistance (Ω)
R_Y	Common branch resistance (Ω)
L_S	Saturated dc reactor inductance (H)
L_{DL}	Rectifier conductor inductance (H)
L_Y	Common branch inductance (H)

The quasi steady-state i_{kD} short-circuit current is given by (7) as follows. According to [9] is possible to use an alternative equation to obtain λ_D but that is omitted for brevity.

$$I_{kD} = \lambda_D \frac{3\sqrt{2}}{\pi} \frac{cU_n}{\sqrt{3}Z_N} \frac{U_{rTLV}}{U_{rTHV}} \quad (7)$$

where:

Z_N	ac side 3-ph network impedance (Ω)
λ_D	Factor obtained from Fig. 7 of [6]
U_n	Phase to phase network voltage (kV)
U_{rTLV}	Transformer secondary voltage (kV)
U_{nrTHV}	Transformer primary voltage (kV)

The peak short-circuit current can be obtained using (8).

$$I_{pD} = \kappa_D I_{kD} \quad (8)$$

Where the factor κ_D is dependent on (9) and (10) as follows.

$$\frac{R_N}{X_N}\left[1+\frac{2R_{DBr}}{3R_N}\right] \quad (9)$$

$$\frac{L_{DBr}}{L_N} \quad (10)$$

The time to peak t_{pD} when $\kappa_D \geq 1.05$ is given by (11) and (12):

$$t_{pD} = (3k_D+6)\ (ms) \text{ when } \frac{L_{DBr}}{L_N} \leq 1 \quad (11)$$

$$t_{pD} = \left[(3k_D+6)+4\left(\frac{L_{DBr}}{L_N}-1\right)\right]\ (ms) \text{ when } \frac{L_{DBr}}{L_N} > 1 \quad (12)$$

The situation when $\kappa_D < 1.05$ represents a condition where the maximum current compared to the quasi-steady-state current is neglected and thus $t_{pD} = T_k$. The rise time constant is provided in [9] for 50 Hz systems; however, in North America the system frequency is 60 Hz. The authors searched for additional information on 60 Hz rise time constant; however, no specific equations were found for such frequency. It was assumed that the rise time constants for 50 Hz would yield accurate enough results. The MFR of the specific converter should be consulted for more details. The rise time constants are therefore derived using (13) and (14) as follows:

$$\tau_{1D} = \left[2+\ (k_D-0.9)(2.5+9\frac{L_{DBr}}{L_N})\right]\ (ms)$$

when $k_D > 1.05$ (13)

$$\tau_{1D} = \left[0.7+\left[7-\frac{R_N}{X_N}\left(1+\frac{2}{3}\frac{L_{DBr}}{L_N}\right)\right](0.1+0.2\frac{L_{DBr}}{L_N})\right]\ (ms)$$

when $k_D < 1.05$ (14)

For simplification it is possible to use (15) to calculate the rise time constant.

$$\tau_{1D} = \frac{1}{3}t_{pD} \quad (15)$$

The decay time constant τ_{2D} for 60 Hz systems was once again assumed based on the 50 Hz equation provided in [9] using (16).

$$\tau_{2D} = \frac{2}{\frac{R_N}{X_N}\left(0.6+0.9\frac{R_{DBr}}{R_N}\right)}\ (ms) \quad (16)$$

Note that due to brevity requirements a few of the steps or alternative equations were omitted from this section. The reader is encouraged to review [9] and [10] for more detailed information.

V. DC CAPACITOR MODEL

The resistance and inductance of a capacitor according to [9] can be determined using (17) and (18).

$$R_{CBr} = R_C + R_{CL} + R_Y \quad (17)$$

$$L_{CBr} = L_{CL} + L_Y \quad (18)$$

where:

R_C	Equivalent dc resist. of the capacitor (Ω)
R_{CL}	Capacitor line Resistance (Ω)
L_{CL}	Capacitor line inductance (H)
R_Y	Mutual circuit resistance (Ω)
L_Y	Mutual circuit inductance (H)

Fig. 9 and Fig. 10 show the individual parameters for (17) and (18) along with E_C which is the capacitor voltage at t = 0- (before the arc).

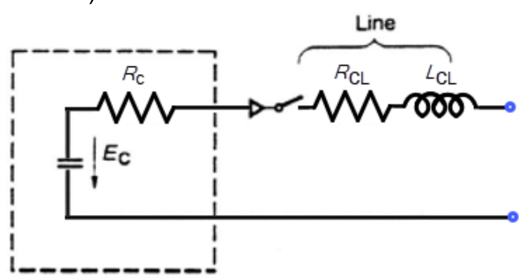

Fig. 9 – Partial current dc capacitor circuit

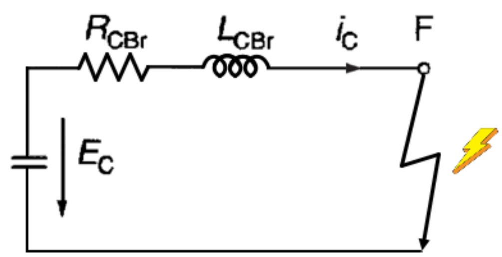

Fig. 10 – DC Cap. equiv. circuit for partial current

Now that the individual components and equivalent capacitor short-circuit representation have been established, the partial capacitor short-circuit current can be defined. In order to determine the peak current i_{pC} it is necessary to determine the factor κ_C using (19) from [9].

$$i_{pC} = \kappa_C \frac{E_C}{R_{CBr}} \quad (19)$$

To determine the factor κ_C we can use (20) and (21). According to [6], If $L_{CBr} = 1$, then automatically $\kappa_C = 1$.

$$\frac{1}{\delta} = \frac{2*L_{CBr}}{R_{CBr}} \quad (20)$$

$$\omega_0 = \frac{1}{\sqrt{L_{CBr} * C}} \qquad (21)$$

where:

C	Capacitance (F)
$\frac{1}{\delta}$	Factor obtained from Fig. 12 of [9]

The factor κ_C can be obtained from Fig. 12 of [9]. The time to peak t_{pC} is also dependent on δ and can be obtained using (20) and (21) and Fig. 13 of [8]. If L_{CBr} = 0, then automatically t_{pC} = 0. The rise time τ_{1C} constant is given by (22).

$$\tau_{1C} = k_{1C} * t_{pC} \qquad (22)$$

where:

t_{pC}	Time to peak (sec)
k_{1C}	Rise time constant factor (Fig.14 of [9])

The rise time constant factor k_{1C} is also dependent on δ and ω_0 and can be obtained from Fig. 14 of [9]. The decay time constant τ_{2C} can be obtained using (23).

$$\tau_{2C} = k_{2C} * R_{CBr} * C \qquad (23)$$

where:

k_{2C}	Decay time constant factor (Fig.15 of [9])

The rise time constant factor k_{2C} is also dependent on δ and ω_0 and can be obtained from Fig. 15 of [9]. If L_{CBr} = 0 , then automatically κ_{2C} = 1. Fig. V.3 shows the dc capacitor short-circuit current profile derived using the methods of [9].

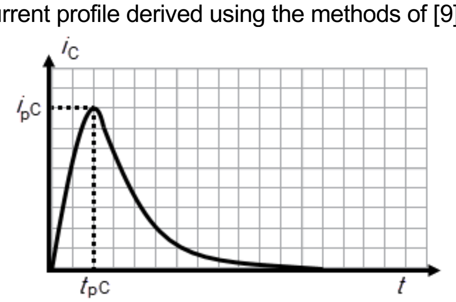

Fig. 11 – DC capacitor short-circuit current profile

Note that due to brevity requirements a few of the steps or alternative equations were omitted from this section. The reader is encouraged to review [9] and [10] for more detailed information including annex A of [9].

VI. DC AF TRANSIENT MODEL

The preferred method by the authors to represent the dc arc resistance and voltage is the A.D. Stokes and W.T. Oppenlander method which is based on an exhaustive study of free-burning vertical and horizontal arcs between series electrodes in open air [11]. The work of [1],[2],[6] and [12] document a few of the laboratory tests and simulations performed using the models of [11] to predict the dc arc current and incident energy. Each of these works includes model validation comparative analysis sections to help the reader visualize the correlation between test measurements and simulations produced using the equations of [11]. It must be mentioned that additional physical model adjustments are added to enhance the performance of the equations provided in [11]. The dc power distribution system under discussion in this paper exhibited similar electrode configurations as those shown in Figs. 8 and 9 of section III of [2] and can be omitted.

For brevity, the arc resistance and voltage are determined mainly based on equations (24) and (25) for currents above the transition current which is given by (26). Each of these parameters becomes time dependent based on the transient short-circuit current solution described in sections IV and V.

$$R_{arc(t)} = \frac{20 + 0.534 \times Z_g(t)}{I_{\mathrm{arc(t)}}^{0.88}} \qquad (24)$$

$$V_{arc(t)} = \left(20 + 0.534 \times Z_g(t)\right) \times I_{\mathrm{arc(t)}}^{0.12} \qquad (25)$$

$$I_T = 10 + 0.2 \times Z_g \qquad (26)$$

where:

$R_{\mathrm{arc}}(t)$	Arc resistance vs. time (Ω)
$V_{\mathrm{arc}}(t)$	Arc voltage magnitude (V dc)
$I_{\mathrm{arc}}(t)$	Arc current vs time (A dc)
$Z_{\mathrm{g}}(t)$	Gap between conductors vs time (mm)
I_{T}	Transition current at current time (A dc)

The time dependency on (24) and (25) is established based on the principles of arc elongation and conductor erosion as described in [1] and [2] and of course based on the changing transient bolted fault current determined using the methods described in [9] and [10]. DC arc behavior is influenced as well by magnetic field forces during the arc lifetime [13]. Once the arc current settles to a quasi-steady-state operating point, the influence of magnetic field is expected to reduce. Arc ignition and extinction are accompanied by magnetic field forces which depending on the conductor orientation can either work towards making the arc more sustainable or the opposite.

VII. CASE STUDIES

A. DC Short-Circuit Analysis: Case 1

The methodology under consideration is implemented on two distribution systems, one being a simplified configuration comprising a single load as illustrated in Fig. 12 while the other system is a more complex distribution system as shown in Fig. 16. The dc short-circuit currents are computed in accordance with the methodology from [9] as outlined in Section IV and Section V.

The ac medium voltage (MV) 13.8kV network has been modeled using an ideal voltage source and impedance. The transformer is modeled by an impedance. The dc network is connected to the ac system by an AFE power converter. The system parameters for this case are shown in Table 1. The objective of the calculation is to calculate the dc short-circuit current at the “Converter Output Bus”.

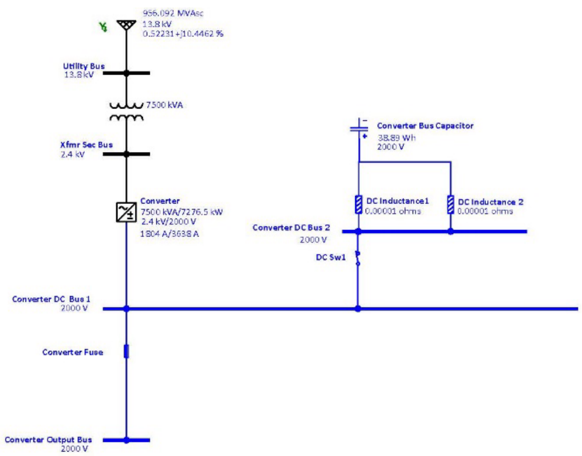

Fig. 12 – Simplified system for analysis tool validation

Table 1
Parameters for Simplified System

Component	Parameters
Ac Grid	Rated Voltage Ur= 13.8 kV X/R = 20 MVAsc = 956 MVA Transformer kVA = 7500 kVA Transformer rated voltage = 13.8/2.4 kV Transformer X/R = 8 Transformer Z = 5.5%
Converter	Rated Power = 7500 kVA Rated voltage 2.4 kV(ac)/2000V (dc) DC side smoothing reactor = 80 μH DC side resistance = 0.003 Ω.
Capacitors	Rated voltage = 2000 Capacitance = 70 mF Capacitor Resistance = 80 mΩ Capacitor inductance = 4.5 μH

1) *Short-Circuit Current from Converter:* Based on the ac side data, the source impedance in series with the transformer impedance referred to the secondary side of the rectifier transformer is:

$$R_Q + jX_Q = 0.0003 + j0.006\ \Omega \tag{27}$$

$$R_T + jX_T = 0.00524 + j0.0419\ \Omega \tag{28}$$

Therefore, the total ac resistance (R_N) and inductance (X_N) at 2400V are:

$$R_{N2400} + jX_{N2400} = 0.0055 + j0.0479\ \Omega \tag{29}$$

In order to account for the 2000 V dc converter output voltage, a “phantom” transformer must be added into the circuit. The primary voltage of this transformer is 2.4 kV. The secondary voltage U_1 is calculated as follows:

$$U_1 = 2000\ V \times \frac{\pi}{3\sqrt{2}} = 1481\ V \tag{30}$$

The impedance reflected to the 1481 V side of the “phantom” transformer is therefore:

$$\begin{aligned} R_N + jX_N &= (R_{N2400} + jX_{N2400})\left(\frac{1481V}{2400V}\right)^2 \\ &= 0.0021 + j0.018\ \Omega \end{aligned} \tag{31}$$

On the dc side, by inspection the following values may be stated:

$$R_{DBR} = 0.003\ \Omega \tag{32}$$

$$L_{DBr} = 80\ \mu H \tag{33}$$

From [8] the short-circuit factor λ_D may be calculated:

$$\lambda_D = \sqrt{\frac{1 + \left({R_N}/{X_N}\right)^2}{\left(1 + \left({R_N}/{X_N}\right)^2\left(1 + 0.667\left({R_{DBr}}/{R_N}\right)\right)\right)^2}}$$

$$= 0.982 \tag{34}$$

The quasi-steady-state current may be calculated from (7):

$$I_{kD} = 64.79\ \text{kA} \tag{35}$$

The peak short circuit current is given by (8). The factor κ_D in (8) was calculated as follows, from [9]:

$$\varphi_D = arctan\left(\frac{1}{\left(\frac{R_N}{X_N}\right)\left(1+\frac{2R_{DBr}}{3R_N}\right)}\right) = 1.349\ rad \tag{36}$$

$$\begin{aligned} \kappa_D &= 1 + \left(\frac{2}{\pi}\right)e^{-\left(\frac{\pi}{3}+\varphi_D\right)cot(\varphi_D)}sin\left(\frac{\pi}{2} - arctan\left(\frac{L_{DBr}}{L_N}\right)\right) \\ &= 1.20 \end{aligned} \tag{37}$$

Therefore, from (8) the peak current is :

$$i_{PD} = 77.6\ \text{kA} \tag{38}$$

The peak time t_{PD}, rise time constant τ_{1D} ,and decay time constant τ_{2D} may be calculated per (11), (13), and (16) respectively :

$$t_{PD} = 12.2\ \text{ms} \tag{39}$$

$$\tau_{1D} = 7.16\ \text{ms} \tag{40}$$

$$\tau_{2D} = 9.20\ \text{ms} \tag{41}$$

The final short circuit current from converter based on the above calculated values is as follows [9], with *i*(t) in kA and *t* in ms:

$$i_{1D}(t) = i_{pd}\left(\frac{1-e^{-\frac{t}{\tau_{1D}}}}{1-e^{-\frac{t_{pD}}{\tau_{1D}}}}\right) = 94.8\left(1 - e^{-t/7.16}\right) \tag{42}$$

$$i_{2D}(t) = i_{pd}\left[\left(1 - \frac{1}{\kappa_D}\right)e^{-\frac{t-t_{pD}}{\tau_{2D}}} + \frac{1}{\kappa_D}\right]$$

$$= 77.6\left(0.835 - 0.165e^{-(t-12.2)/_{9.20}}\right) \quad (43)$$

$$i_D(t) = \begin{cases} i_{1D}(t) & 0\ t \le t \le t_{pD} \\ i_{2D}(t) & t > t_{pD} \end{cases} \quad (44)$$

Simulation plots of the rectifier current per (42) and via commercially available power system simulation software [14] (referred to as "simulation software" for brevity going forward) are shown in Fig. 13.

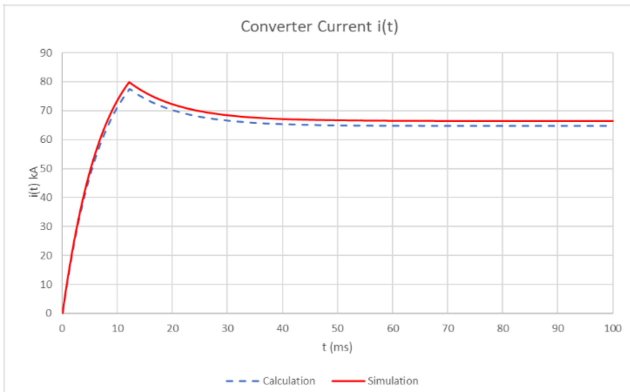

Fig. 13 – Case 1 Converter Short-Circuit Current

The results show that the hand-calculated values and the results of the simulation software have good correlation.

2) *Short-Circuit Current from Capacitor:* The capacitor parameters per table VII.1 are:

$$R_{CBr} = 0.08\ \Omega \quad (45)$$

$$L_{CBr} = 4.5\ \mu\text{H} \quad (46)$$

The decay coefficient δ and natural frequency ω_0 may be calculated by (20) and (21). The capacitor time-to-peak current t_{pC} and related quantities may be calculated per [8]:

$$\delta = 8,889\ \text{Hz} \quad (47)$$

$$\omega_0 = 1,782\ \text{Hz} \quad (48)$$

$$\omega_d = \sqrt{\delta_0^2 - {\omega_0}^2} = 8,708\ \text{Hz} \quad (49)$$

$$t_{pC} = \frac{1}{2\omega_d} ln\left(\frac{\delta+\omega_d}{\delta-\omega_d}\right) = 0.263\ \text{ms} \quad (50)$$

$$\kappa_C = \frac{2\delta}{\omega_d} e^{-\delta t_{pC}} sinh(\omega_d t_{pC}) = 0.9634 \quad (51)$$

The steady-state short circuit current of the capacitor is zero. The peak current is given (19), which yields:

$$i_{pC} = 24.1\ \text{kA} \quad (52)$$

The rise time constant τ_{1c} and decay time constant τ_{2c} of the capacitor short-circuit current may be calculated from (22) and (23) respectively. The constants κ_{1c} and κ_{2c} used in (22) and (23) may be estimated from [9]:

$$k_{1C} \simeq 0.2 \quad (53)$$

$$\tau_{1C} = 0.052\ \text{ms} \quad (54)$$

$$k_{2C} \simeq 1 \quad (55)$$

$$\tau_{2C} = 5.6\ \text{ms} \quad (56)$$

The final short circuit current from the capacitor, based on the above-calculated values, is as follows [9], with *i*(t) in kA and *t* in ms:

$$i_{1C}(t) = i_{pc}\left(\frac{1-e^{-\frac{t}{\tau_{1C}}}}{1-e^{-\frac{t_{pC}}{\tau_{1C}}}}\right) = 24\left(1 - e^{-t/_{0.0526}}\right) \quad (57)$$

$$i_{2C}(t) = i_{pc}\left[\left(1 - \frac{1}{\kappa_C}\right)e^{-\frac{t-t_{pC}}{\tau_{2C}}} + \frac{1}{\kappa_C}\right]$$
$$= 24e^{-(t-0.263)/_{5.6}} \quad (58)$$

$$i_C(t) = \begin{cases} i_{1C}(t) & 0\ t \le t \le t_{pC} \\ i_{2C}(t) & t > t_{pC} \end{cases} \quad (59)$$

In order to obtain the simulated capacitor current, the short-circuit current from the converter was subtracted from the total short-circuit current of the converter and capacitors. The result is shown in Fig. 14 along with the calculated short circuit current per (59). Once again, the simulation software results aligned with the hand calculations.

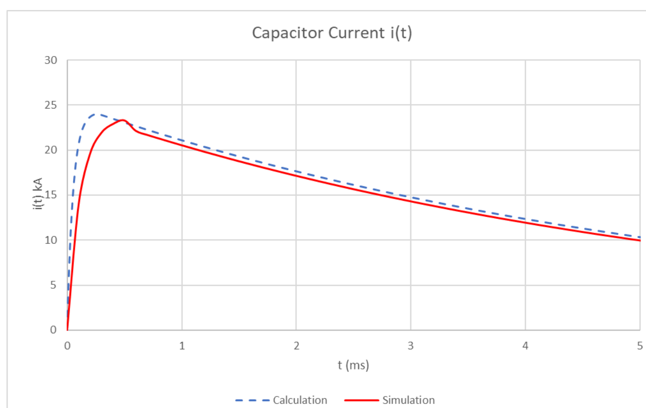

Fig. 14 – Case 1 Capacitor Short-Circuit Current

3) Total Short-Circuit Current: The total short-circuit current may be calculated as:

$$i_{SC}(t) = i_D(t) + i_C(t) \quad (60)$$

As can be seen from Fig. 15, the hand calculations and the Simulation Software output have a good correlation. The following observations were made from the simulations and hand calculated results:

i.) The short circuit current is a function of time, with a peak value well above the steady-state value and subsequent decay.

ii.) The peak current occurs well within the first 20 ms of the event.

iii.) The capacitor current increases much more quickly than the converter current, reaching its peak value within the first 1 ms of the event and contributing the majority of the current within this timeframe.

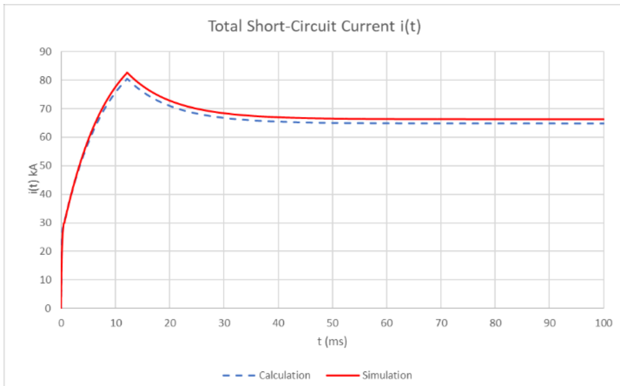

Fig. 15 – Case 1 Total Short-Circuit current

B. Short-Circuit Analysis, Case 2

Case 1 was used to validate the implementation of the methodology of [9] in the simulation software to establish a confidence level in the subsequent system simulations. Case 2 considers the more complex MV distribution system entered into the simulation software as shown in Fig. 16. It consists of a converter with an input voltage of 345 V ac and an output voltage of 570 V dc, a dc fuse, a busway forming the main 570 V dc bus, and conventional electromechanical circuit breakers used as tap-off units feeding the dc/dc converters for process loads. It is assumed for purposes of this simulation that there are no dc power sources below the level of the load converters.

"Bus Tap 2" in Fig. 16 is the location of interest for this simulation. The resulting short-circuit current contribution from the AFE converter for a fault at this this bus is shown in Fig. 17.

The fault contribution from the AFE Bus capacitor is shown in Fig. 18, and the fault contribution from the load converter bus capacitors is shown from Fig. 19. These individual source contributions were obtained by applying the same subtraction methodology as in Case 1. It is worth noting that the individual load converter capacitor contributions would be very time-consuming to calculate by hand, given the number of impedances and the location of the bus under consideration.

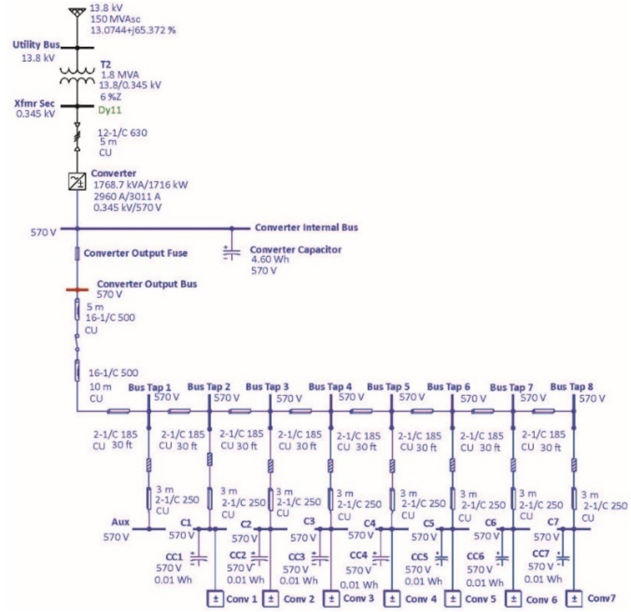

Fig. 16 – More complex system for simulation

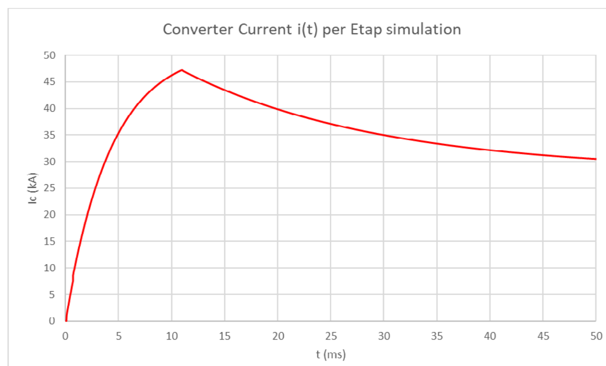

Fig. 17 – Case 2 Simulated Converter Current

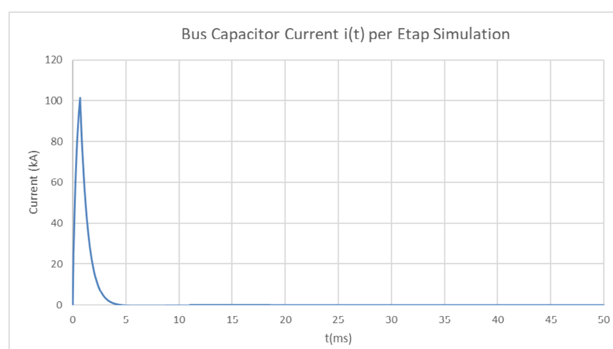

Fig. 18 – Case 2 Simulated Converter Bus Capacitor Current

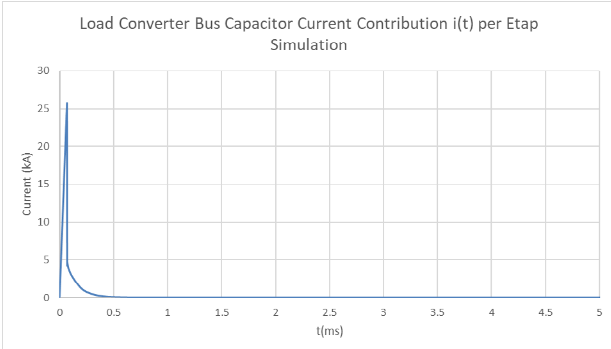

Fig. 19 – Case 2 Simulated Composite Current Contribution from Load Converter Capacitors

The same observations given VII.A.3. are also applicable here.

C. DC Arc-Flash Analysis, Case 1

The dc arc-flash hazard was calculated for the system of Fig. 16 at the "Converter Output Bus", in accordance with the methodology outlined in Section VI. This takes as an input the total dc short-circuit current per (60). Because the method requires an iterative approach, manual calculations were not performed. Instead, the calculations were made using the simulation software [14].

The simulation software methodology used to calculate the arcing current has been described in Section VI. Once the arcing current is known, the arc clearing time or arc duration t_c is determined based upon the clearing time of the overcurrent protective device (PD). In this case, the clearing device is the "DC Output Fuse". The arc duration t_c can be determined by plotting the arcing current as a function of time superimposed upon the Converter fuse time/current characteristic (TCC) as shown in Fig. 20. In this case, t_c was determined to be 6.66ms, rounded up to 7 ms.

The simulation software predicts the arcing power $P_{arc}(t_1)$ using (61).

$$P_{arc}(t_1) = V_{arc}(t_1) \times I_{arc}(t_1) \tag{61}$$

The arc energy E_{arc} is then calculated as the integral over the arcing period defined t_c using (62).

$$E_{arc} = \int_0^{t_c} P_{arc}(t)dt \tag{62}$$

The incident energy E is then calculated from the working distance d (in cm) using (63) for open air conditions.

$$E = 0.239 \times \frac{E_{arc}}{4\pi d^2} \tag{63}$$

A plot of the prospective incident energy, based upon a 20 mm bus gap and a working distance of 457 mm (18 in), is shown in Fig. 21 as a function of time. At the clearing time t_c = 7 ms, the accumulated incident energy is 0.514 cal/cm^2. This is the value of E based upon the 7 ms arc duration.

The value of this approach may be demonstrated by performing the same calculation in the simulation software using the Stokes and Oppenlander method, with the same 7ms fault clearing time but using the peak arcing current for the entire duration. This yields an arc-flash incident energy E = 0.889 cal/cm^2 – a value that is 72% higher. If the fault clearing time is defined by the DC Output Fuse and peak arcing current, the Stokes and Oppenlander method using peak arcing current yields 0.293 cal/cm^2 – a value which is 43% less than the value calculated using the transient arcing current. This is due to the fact that the peak arcing current is assumed to flow starting at time 0, yielding an overly optimistic clearing time for the fuse. Both of these situations are undesirable; the use of the transient arcing current allows for increased accuracy of the result.

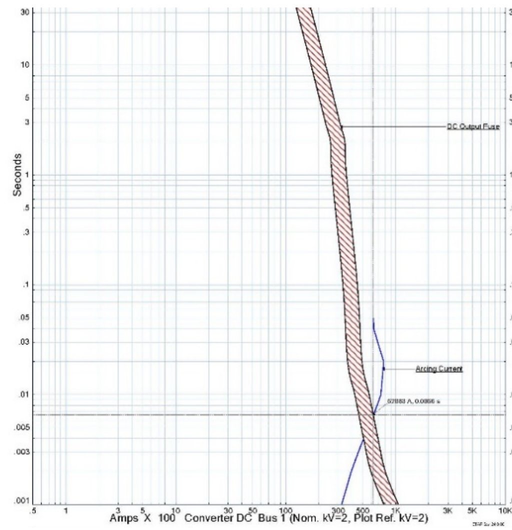

Fig. 20 – Clearing PD TCC and Arcing Current Plots

The simulated Arc-Flash Boundary (AFB) was determined as 28.9 cm (11.4 in). However, the capacitor presents additional hazards in the form of arc blast, as discussed in [7] Annex R. The thermal burn hazard calculated in cal/cm^2 does not include arc-blast hazards.

The simulation software was also used to establish the Hearing Protection Boundary (HPB) as 251 cm (99 in) and Lung Protection Boundary (LPB) as 7 cm (2.75 in). Due to the size of the capacitor and the converter output voltage, the hearing protection boundary significantly exceeds the AFB. This can be visualized in the form of a plot as shown in Fig. 22.

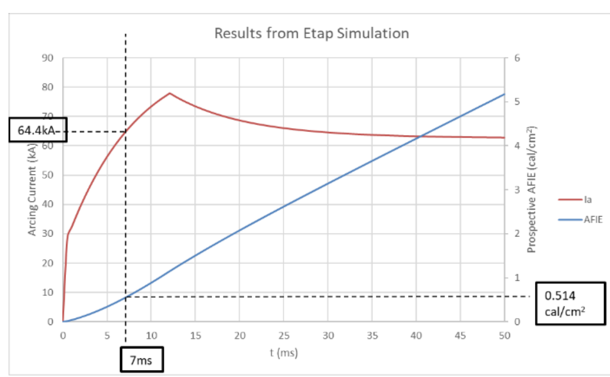

Fig. 21 – Simulated prospective incident energy and arcing current

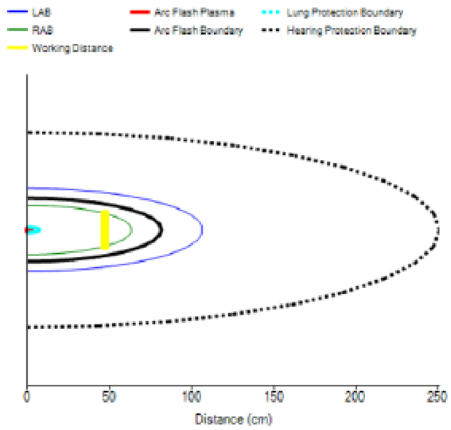

Fig. 22 – Visualization of HPB due to capacitor along with other hazard boundaries

This leads to the observation that, due to the capacitor size, evaluation of the thermal burn hazard, as in a typical arc-flash study, is insufficient to fully quantify the arc-flash hazards due to dc bus capacitors.

D. DC Arc-Flash Analysis, Case 2

The dc arc thermal hazard was calculated using the simulation software for the "AFE Output Bus" in Fig. 16. Due to the timeframe involved, the clearing time was established as 3.79 ms (rounded up to 4 ms) using the fuse total clearing I^2t; a plot showing the method is shown in Fig. 23. This yielded an arc-flash incident energy of 0.165 cal/cm^2, with an AFB of 14 cm (5.5 in).

The same calculations were repeated in the simulation software for "Bus Tap 2" in Fig. 16. The result was an arc-flash incident energy of 0.584 cal/cm^2 and an AFB of 31.1 cm (12.2 in). Repeating these two analyses in the simulation software using the Stokes and Oppenlander method with the same clearing times but using peak arcing current instead of the transient arcing current analysis, yielded the results shown in Table 2. The results from above with the transient arcing current analysis are also shown in the table for comparison.

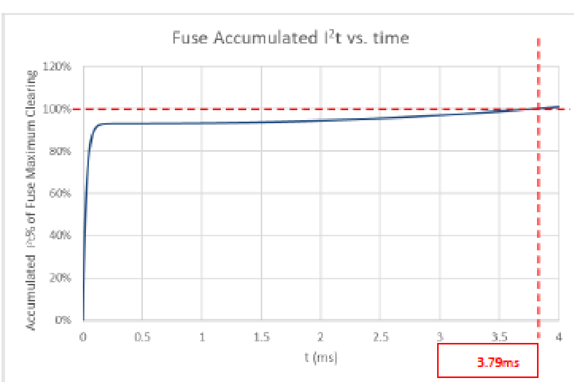

Fig. 23 – Accumulated I^2t plot for determination of fuse clearing time

Table 2
Summary of Arc-Flash Thermal Burn Hazard Results

Bus	AFIE using transient arcing current analysis (cal/cm^2)	AFIE without transient arcing current analysis (cal/cm^2)
AFE Output	0.165	6.943
Bus Tap 2	0.584	7.721

The efficacy of the transient arcing current calculation can be readily seen from this table. The increased accuracy of the calculation results in significantly lower calculated arc-flash thermal burn hazards at each bus.

The HPB at the AFE Bus Capacitor was calculated using the simulation software. The result HPB is a 121 cm and negligible LPB. These boundaries are plotted in Fig. 24.

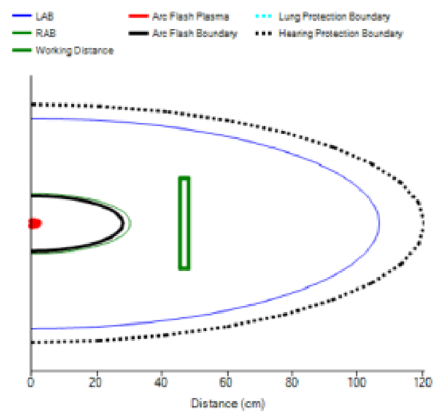

Fig. 24 – AFE bus capacitor HPB and LPB

VIII. ADDITIONAL SAFETY CONSIDERATIONS

This paper does not present a method to select personal protective equipment (PPE) or make recommendations on how it should be used. The purpose of arc-rated PPE is to reduce the severity of burn injuries by providing a thermal barrier that limits the exposure to a worker's skin to an incident energy of 1.2 cal/cm² or lower. However, it is beneficial to look at what other electrical hazards may be relevant for the types of AFE systems described in section II. As shown in Fig. 25, there are numerous hazards to consider, but this paper focuses on the arc flash and arc blast hazards.

A. AFE DC Short Circuit Wave Forms

As documented in sections II, III and IV, an AFE source has a unique fault current profile. AFE sources do not behave like an ac transformer where high short-circuit faults can be created and sustained for several seconds. Nor does the AFE source behave like a battery source where high short-circuit fault currents can be sustained for seconds to minutes. As shown in Fig. 3 the source has a two-step characteristic that makes up the fault current profile. The first step characteristic is a high fault current due to large capacitance in the system, which may primarily be due to the large capacitors used in the AFE. The second AFE characteristic step is the sustained power conversion from ac to dc.

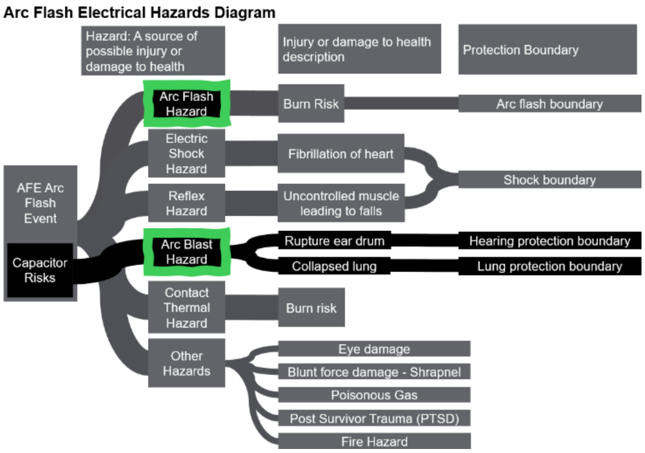

Fig. 25 – Arc-Flash electrical hazards diagram

B. Arc-Flash Hazard

The unique AFE dc short circuit wave form can result in a low amount of arc-flash incident energy. In many cases, these AFE systems can be designed so that incident energy is below 1.2 cal/cm^2 at the working distance. If the incident energy is below 1.2 cal/cm^2 lower PPE levels may be required according to NFPA 70E.

C. Arc Blast Hazard

AFE solutions can have large capacitors. Per NFPA 70E Article 360.3, any system with voltage greater than 100V and 1.0 joules of stored energy, or greater than 400V and 0.25 joules of stored energy, appropriate controls should be applied [7]. In the examples presented in section VII, these thresholds are exceeded and therefore the arc blast hazard needs to be accounted for.

Per Article 360 of NPFA 70E the hearing protection boundary for capacitors occurs when the "worker distance at which a 1 percent probability of ear damage exists from a 20 kPa (3.0 psi) shock wave" [7]. NFPA 70E simplifies this analysis by stating when the stored energy of a capacitor is greater than 100 joules, hearing protection is required.

The risk for collapsed lung is recognized in Article 360 of NFPA 70E to occur at 122 kJ and greater. There is no PPE recognized in NPFA 70E as providing protection for a collapsed lung. The lung protection boundary must be determined, and the worker must not cross this boundary. If Case 2 calculated a collapsed lung risk, it would be necessary that before a worker approaches the system, energy from the capacitors must be reduced to a safe level.

There are ongoing proposals to evolve Article 360 which may narrow the focus to specific voltages and types of capacitors. A recent paper on this topic identifies "three parameters [that] are important for the creation of a supersonic acoustic wave [include]: (a) voltage, (b) current, and (c) risetime)" and therefore result in an acoustic hazard [15]. The paper identifies several capacitor types that can exceed the Lung Protection Boundary and the Hearing Protection Boundary thresholds, but do not meet the proper combinations of voltage, current and risetime to result in an acoustic hazard.

IX. CONCLUSIONS

This work introduces a detailed method to represent converters and capacitors for dc short-circuit and dc arc-flash incident energy calculations. It elaborates on the methods presented in [1] and [2], but this time presenting insights into AFE considerations. Here are some of the key take aways:

- The integration of dc sources and loads is reshaping the electrical infrastructure of facilities, and this work helps by presenting new more comprehensive methods and new/better tools to evaluate their inherited hazards.
- This paper qualifies the dc arc-flash incident energy hazards using hand calculations and software-based simulations with improved accuracy. The results of these simulations revealed relatively low arc-flash incident energy levels.
- The more accurate transient short-circuit current integration methods for the capacitor stored energy show that NFPA 70E annex R methods produce conservative estimations.
- DC power distribution networks powered by AFEs include larger capacitors which present other non-thermal electrical hazards related to arc blast which are not commonly considered in arc-flash studies or commonly seen in arc-flash labels.

The accuracy of the dc arc-flash thermal energy calculations is highly dependent on the modeling of the bolted short-circuit current. There is certainly a need for a dc arc-flash calculation standard(s) similar to the one described in [16] for ac; however, the intent of this work is not to promote/establish a universal calculation method, but instead to take one more step forward by improving the precision of the thermal energy estimation with the use of advanced transient bolted short-circuit currents along with the best available dc AF thermal energy estimation methods as described in this paper.

X. ACKNOWLEDGEMENTS

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Lithium-Ion Propulsion Battery Occupational Safety

Paper No. ESW2025-10

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Abstract – The global automotive industry is rapidly moving towards electricity for propulsion of personal and commercial mobility. Designing and assembling batteries in-house is a priority for many automakers which brings a new level of complexity and workplace safety challenges to the industry. Lithium-Ion batteries powering todays electric vehicles (EVs) are posing new electrical, thermal, and chemical hazards to the workforce. As Dr. Gordon stated in many presentations made over the past few years, most safety standards and regulations are focused on consumer and end-user safety rather than occupational safety for workers assembling and servicing these high-voltage systems [1]. This paper intends to identify some of those hazards posed by these large batteries. There are no lockout/tagout methods available to disable the high voltage inside these batteries. The modular design of some batteries allows for segmentation to reduce the level of hazard [15], but the trend of cell-to-pack design is making battery segmentation improbable. Product design controls are the highest form of mitigation in the hierarchy of controls and this paper will discuss some aspects of design that can address these hazards and lays the foundation for industry best practices and potential future safety requirements in this emerging technology area of battery production and service. This paper will also discuss administrative controls where design solutions are not feasible.

Index Terms — dc electric shock, dc arc flash, thermal burns, battery safety, high voltage (≥50vdc), low voltage (<50vdc), design for occupational safety, zero voltage exposure terminals.

I. INTRODUCTION

In 1972, when M. Stanley Whittingham, an Exxon scientist, created the first iteration of the lithium-ion battery [2], he could not have envisioned the indispensable role these batteries would play years later. The global demand for lithium-ion battery cells is forecasted to reach 4,700-GWh by 2030 with automotive propulsion batteries being one of the largest consumers of these energy storage devices [3][4]. The propulsion lithium-ion batteries used in electric vehicles are a large assembly component with many mechanical, thermal, electrical, and chemical subsystems functioning inside the enclosure. Compared to typical smaller lithium-ion batteries used in consumer appliance applications, these large batteries are comprised of hundreds of cells connected in series and parallel configuration surrounded by thermal management systems and mechanical protection structures. The design and configuration of battery cells are increasingly seen as a competitive advantage, driving the push to develop and manufacture automotive propulsion batteries in-house or through specialized battery system suppliers, independent of global lithium-ion cell manufacturers. This strategic shift combined with geo-political policies is shifting the battery assembly centers from Asia to North America, Europe, and other continents closer to the automotive manufacturing locations.

The process of battery assembly can range from a completely manual operation for a low volume niche product, to a highly automated one for a high-volume plant supporting a range of mass-produced final products. The design of the battery plays a significant part in the ability to automate the assembly processes or perform manual assembly operations safely and efficiently to meet the desired cycle time within the allocated budgets to be financially sustainable. Historically, battery design safety has focused on preventing thermal runaway and protecting the vehicle and occupants from the potential hazards associated with thermal, electrical, or mechanical abuse.

Most product engineering testing and documentation lists maximum and nominal operating voltages for the battery pack which are significantly higher than what a manufacturing site would ever see. When conducting process design and task-based risk assessments, especially in the context of batteries, it is crucial to consider a more realistic state of charge (SOC) scenario, such as 30% SOC, rather than relying solely on maximum or nominal voltage values.

All battery designs should incorporate safety strategies involving fuses and contactors that control the flow of energy into and outside the battery based on isolation and thermal monitoring systems. However, inside the battery, there are areas that are “always live” and do not have such controls available. The interconnect between cell groups and internal high voltage bus circuits are some examples of such areas. While the battery is being manufactured or serviced, these areas are accessible when the cover is off of the battery case.

In battery assembly operations, production workers are performing assembly tasks which could expose them to lethal voltages during the bussing operations as well as work within the approach boundaries on non-electrical assembly tasks. Most of these production workers are not trained as electricians and are typically mechanically inclined. They are familiar with and trained on mechanical workplace hazards like lacerations, slips, trips, falls, and ergonomic stressors but not well versed in shock and arc flash hazards around high voltage dc energy sources. The onus of protecting the operators currently resides on process design teams who must identify the electrical, chemical, thermal, and mechanical hazards posed during the various tasks in the assembly process. The process design teams are also mechanically inclined manufacturing engineers who understand mechanical hazards much better than electrical ones. While they focus on the voltage presence at the immediate assembly task on a busbar connection, they may fail to recognize the arc flash hazard posed during a structural metal bracket assembly near “always energized” conductors within the pack.

Similarly, the quality inspectors in manufacturing sites are posed with electrical, chemical, and thermal hazards that they

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are not accustomed to in typical manufacturing environments. A quality defect may now expose them to parts that may have isolation loss resulting in a shock hazard on a group of connected cells or a thermal burn hazard on a single cell with an internal short circuit resulting in surface temperature rise. The material handling of energized components in manufacturing and warehousing environments poses the potential for a thermal event if the components are damaged during the transportation process. A fork truck driver on a dock unloading trailers cannot distinguish the hazards posed by a pallet of cells compared to metallic structural inert components.

A single 100Ah lithium-ion cell at 3.5vdc, short circuited, can reach temperatures exceeding 200°F (93°C) within 2-seconds. Handling of individual good, suspect, and scrap cells is a risk factor in the whole lifecycle. Improperly handled, transported, or disposed cells, modules, or packs can result in injuries and fires as seen in the multiple media reported events in the past few years.

In the following sections, we will discuss the various hazards, mitigation strategies, and design suggestions to build occupational safety elements into the future battery designs with the intention to reduce the potential for injury by utilizing the upper levels of hierarchy of controls [4] to provide cost-effective, intelligent, robust solutions to some of these hazards. These suggested approaches will reduce the need to implement arc flash PPE for production operators and repair personnel in manufacturing environments, which is the lowest form of safety control protecting personnel but does not prevent incidents from happening.

II. LITHIUM-ION BATTERY BASICS

Lithium ion is a broad category of cells with various chemistries and formats. Most of us are familiar with the button or coin cells used in wrist watches since early 1980s [2]. The three most used formats in large lithium-ion batteries are [5]:

i. Cylindrical
ii. Prismatic (can)
iii. Pouch

The illustration below shows these formats with a cross section of the internal components. Coated dis-similar metal foils form the electrodes, separated by an electrically insulating yet permeable membrane called the separator, inside the shell, filled with gel like fluid, called the electrolyte.

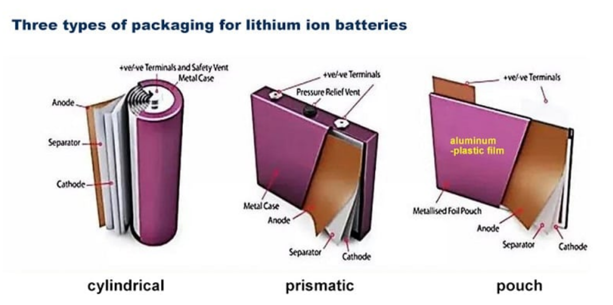

Figure 1 Cell Formats [6]

Cylindrical and prismatic cells have other components such as pressure relief valves and thermal fuses integrated inside the shell between the electrode current collectors and the terminals on the top of the cell. This allows controlled release of gas in case of a thermal runaway event which can be directionally routed. Pouch cells typically do not have these features and can vent on any of the sealed interfaces near the tabs or folded edge. The pressure of gas release is higher on the cylindrical and prismatic cells compared to the pouch cells which can make them become a projectile in free state during storage, handling, and transportation before assembly.

The most common material and chemistry combination of lithium-ion cells include [7]:

- Lithium Nickel Manganese Cobalt Oxide (NMC)
- Lithium Nickel Cobalt Aluminum Oxide (NCA)
- Lithium Iron Phosphate (LFP)

Regardless of chemistry, most lithium-ion cells generally operate within the 2.5 - 4.2 Vdc range. According to OSHA (Occupational Safety and Health Administration) and NFPA 70E (National Fire Protection Association's Standard for Electrical Safety in the Workplace), voltages over 50V DC (direct current) are typically considered high voltage in most Original Equipment Manufacturer (OEM) settings. Typical EV propulsion batteries operate at 300-800 Vdc ranges.

The state of charge (SOC) refers to the amount of charge available in the cell at the given state. It is analogous to the fuel gauge for vehicles. The open circuit voltage (OCV) is used to determine the SOC of a cell. A cell at 0% SOC is not the same as 0vdc. The industry practice based on international shipping regulations is to transport cells at 30% SOC to the battery assembly sites [8]. This number was established based on a 2016 International Civil Aviation Organization study applied to standalone lithium-ion batteries for air shipments [9]. Over the years this rule was adapted as a best practice across other shipping modes.

The inference that lithium-ion batteries at 30% SOC are safer than higher SOC ones is not practical in occupational safety realm. An off-gassing lithium-ion cell produces large quantity of toxic gases even at 30% SOC. The potential for ignition during a thermal runaway event is reduced at 30% SOC compared to a high state of charge cell.

The charge and discharge rate of cells is noted in terms of "C" rate [19]. A 1C discharge rate for a 100Ah cell would provide 100A for one hour to completely discharge the cell. A 2C discharge rate for the same cell would provide 200A for thirty minutes (assuming no efficiency loss). A charge rate of 1/2C would feed 50A for one hour to recharge the above-mentioned cell.

Cells are grouped together in series and parallel configurations to form cell groups and smaller battery segments called sections or modules. The cylindrical and prismatic cells are often glued together to form the cell groupings. Pouch cells are stacked, compressed, and enclosed in external structural components to form a module. Thermal barriers may be applied between cells and cell groups to mitigate the thermal runaway propagation within the module. Cell thermal management components like cooling plates, cooling fins, and temperature sensors can be integrated in the module as well. Cell terminals in a module are connected via an interconnect board (ICB) to the module positive and negative terminals. Cell terminals are welded to ICB for reliability of connection and terminal resistance is verified via voltage drop measurement and optical temperature rise monitoring systems at these interfaces. The 30% SOC OCV of the module can range from tens to hundreds of volts based on the number of cells connected in series in each module.

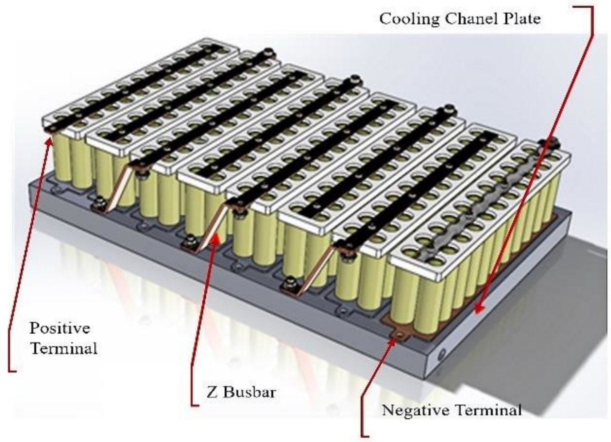

Figure 2 Cylindrical Cell Module [10]

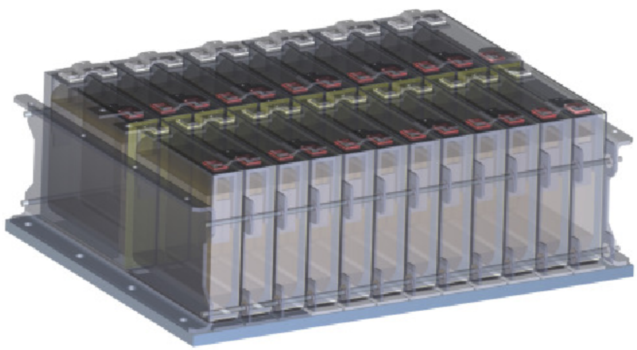

Figure 3 Prismatic Cell Module [11]

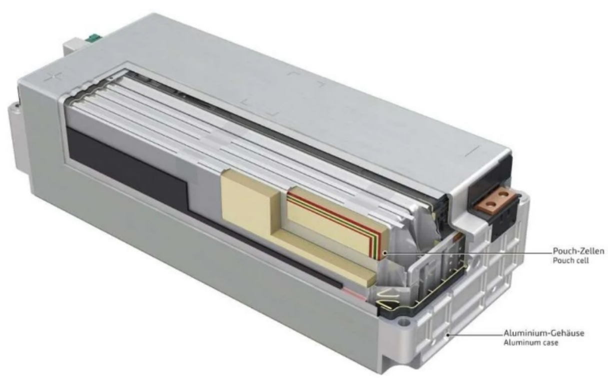

Figure 4 Pouch Cell Module [12]

Modules are then mounted to a structural tray and connected in series and parallel configurations via busbars or cables (round or flat) via fastened terminals or connector systems to form the high voltage bus within the battery.

The high voltage circuit formed by connecting modules terminates into a critical safety component called the battery disconnect unit (BDU). This is the gate keeper of the energy and typically comprises of contactors, fuses, current sensor, and other components. The BDU controls the flow of energy out of the pack to the vehicle in discharging mode and back into the battery during charging mode. It typically connects to the vehicle interfaces for drive unit inverter(s), auxiliary power module (APM) to support low voltage dc systems, high voltage devices like air-conditioning compressors, and on-board charging module (OBCM). The BDU is also a critical part of the high voltage interlock system (HVIL) to control the energy flow in case of open circuits, disassembled components in the loop, etc. Another safety critical function within the BDU is to maintain the high voltage isolation from chassis ground.

Unlike the chassis grounded low voltage dc circuits in a vehicle, the high voltage bus is not grounded to the chassis. For safety reasons it is either a floating system or referenced to chassis via a large resistor network. This is a key safety feature in electric vehicles to ensure that a single point isolation loss does not lead to shock, arc flash, or thermal runaway.

There are other components inside the battery such as:

- low voltage dc cables used to connect battery management system (BMS) components such as cell monitoring units (CMU), to higher level controllers in the vehicle,
- battery thermal management components such as cooling hoses, valves, drain plugs,
- thermal runaway mitigation related insulating materials, vent gas exhaust tubes and pressure relief valves, etc.

The design of the battery is intended to control the energy flow and protect the vehicle, its occupants, and the service technicians as a subcomponent in the vehicle. Most of these safety functions apply to the battery once it is completely assembled in the vehicle.

The high voltage circuit within the pack is always live and cannot be turned off. Most designs do not have fuse protection at module level which poses uncontrollable safety hazards inside the pack during assembly, root cause, repair, and disassembly. Finally, there is no visual indicator on the battery itself to determine the state of the charge of the battery.

A welded contactor(s) could make it impossible to disable the voltage presence at the connectors outside the pack without disassembly.

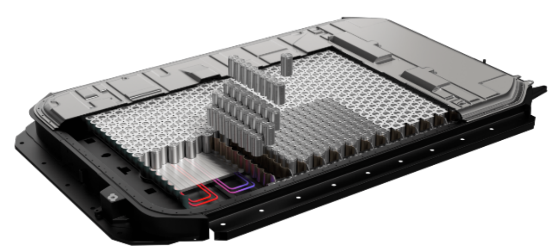

Figure 5 Cylindrical Cell Pack [17]

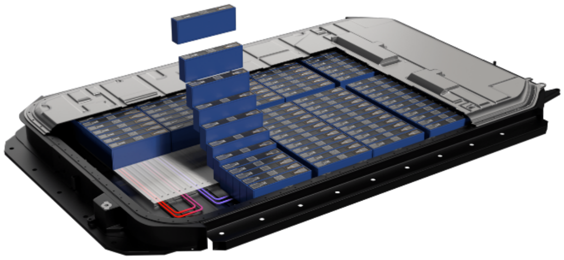

Figure 6 Prismatic Cell Pack [17]

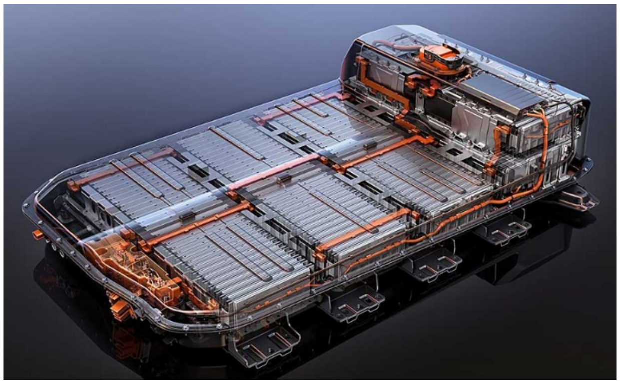

Figure 7 Pouch Cell Pack [18]

Since battery packs are typically located below the vehicle cabin floor in EVs, there is a height and space restriction on allowable space after accounting for crush zones in the event of a crash. Typically, the battery packs do not have enough clearance for larger insulated tools, fixtures or even shock protection personnel protective equipment (PPE) (class 00 / 0) gloves inside the pack.

There is a trend emerging for “cell to pack” design integrated into the vehicle structure [20] rather than a component marrying to a vehicle body. This will driving significant changes in the battery design and assembly processes in near future.

III. HAZARD OVERVIEW

The manufacturing of lithium-ion battery poses mechanical, thermal, chemical, and electrical hazards to the work force. The cell tabs on pouch cells are sharp and pose laceration hazards. The prismatic cans are heavier than pouch or cylindrical cells, can easily slip when handling, and be dropped. Cylindrical cells are smaller, have a circular shape, which makes them more prone to rolling away if left unsecured. Pouch cells are more fragile and can be easily damaged in handling. Typically, prismatic and pouch cells have higher energy content per cell compared to cylindrical cells.

Puncturing of cells, modules, or batteries can expose personnel to electrolyte which is a mixture of solvents and lithium hexafluorophosphate. Leaking electrolyte can form hydrofluoric (HF) acid upon contact with moisture, which can cause severe chemical burns which are painful and slow to heal. HF exposure effects can be felt up to 24-hours later if not treated.

Due to the high energy density a short-circuited single lithium-ion cell at 3.5vdc can heat up to temperatures exceeding 200F within a few seconds. Prolonged shorting of the cell(s) can lead to thermal runaway resulting in off-gassing, fire, and explosion regardless of SOC.

Sparks generated during accidental shorting of cell tabs have resulted in burns to fingers through typical non-thermal rated, cut resistant work gloves.

Due to the large size of EV modules and batteries, dropped components can cause injuries along with property damage and thermal events at storage, manufacturing, transportation, and recycling stages.

If a thermal event occurs, lithium-ion batteries produce all three elements of the fire triangle: heat, fuel (hydrogen), and oxygen. Lithium-ion battery fires require large quantities of water to cool the battery and contain the fire.

An interesting phenomenon noted in many battery assembly plants during low humidity conditions is related to electro-static discharge (ESD). Personnel working in a cell or battery assembly plant cannot distinguish between an ESD and a dc shock. There are processes in lithium-cell manufacturing that generate significant charge build up on cell bodies which needs to be mitigated to prevent these events. Capacitive charge build up is also possible during the module and pack assembly processes. Appropriate charge dissipation methods and PPE should be used to address these seemingly insignificant but psychologically traumatizing hazards. Specialized training is required for all personnel working in battery assembly plants to raise awareness of the various types of hazards posed in these facilities.

Often the risk from electrical and thermal battery hazards are overlooked in large automated high volume manufacturing sites as typical occupational safety is focused on traditional ergonomic and equipment related hazards only.

A cultural mind shift is needed in the battery assembly sites to treat quality failures and scrap parts with more caution than good production parts. The suspect and scrap parts pose higher risk to the personnel handling them compared to good parts used to assemble the battery packs.

IV. SAFE ASSEMBLY OF BATTERY PACKS

The assembly process for batteries requires a thorough analysis of all the hazards present at each stage of the process starting with a cell coming to the line to the end where a battery pack exits the process and transported to a vehicle assembly plant. In addition to the typical ergonomic hazard assessments, special attention needs applied to thermal, chemical, and electrical hazards. The storage and handling of cells within a site requires facility assessment for adequate fire suppression systems, emergency response planning, and allowance for quick removal of energized components showing signs of distress which are the early stages of thermal runaway. Most battery assembly sites should have non-contact temperature monitoring equipment (thermal camera) available as part of the emergency response and monitoring procedures. External shelters for housing suspect and damaged energized components away from the facility structure are good practices in site design and risk mitigation.

Each task should be assessed for voltage exposure to determine shock hazard as well as arc flash potential based on increasing voltages as the cells are connected to form larger sections and ultimately the battery pack. A voltage map of the assembly at a designated SOC is a good starting point to clarify the understanding of the voltage hazard present at various stages of the assembly process as cells combine to form sections, and sections combine to form a battery pack.

Risk mitigation strategy in manufacturing process drives the need to keep the high voltage bus open to segment the battery and allow non-electrical assembly operations to occur without the high voltage presence and elimination of arc flash hazard. Insulated and isolated tools are critical to ensure safety in operations. Exposed terminals should be guarded regardless of voltage to prevent accidental contact as well as to keep the critical electrical contact surfaces free of debris and contamination. Designs with IPxx (finger safe) terminal systems are preferred means of protecting the operators at all stages of energized components and battery assembly.

Requiring workers to wear electrical safety work practice (ESWP) PPE is the last resort in a manufacturing site and often not feasible due to dexterity limitations and tight spaces inside the battery packs in addition to fatigue and thermal stress for workers. Insulating guards to cover energized sections of the battery during non-energized sub-component assembly are recommended engineering controls as part of a good process design to reduce exposure.

When working on energized sections of the battery assembly, only one operator or robot should be allowed to perform the high voltage connection tasks as a safety best practice. There have been incidents related to robots short-circuiting battery packs during assembly operations via grounding paths causing property damage and site evacuation due to off gassing.

The requirements of insulated and isolated assembly tools are critical for safety in a battery assembly operation to prevent these types of incidents. Limiting conductive tools, metallic debris, and fluids in battery assembly sites is part of the basic occupational safety system. Suction cups and other material handling devices should prevent energized parts from falling in case of lockout/tagout being activated. A dropped cell can result in off gassing and thermal runaway which would cause operational disruption for hours. A good process design should also incorporate safety features to prevent equipment and tooling fasteners to loosen over time and fall inside the battery which could result in arc flash incidents downstream.

DC arc flash incident energy calculation for exposure inside battery packs is an area currently in development, and many methods and software modeling tools are coming to market to improve the estimation of the incident energies for lithium-ion battery arc flash events. At this time, most industry accepted methods yield conservative results which in many cases are magnitudes higher than actual values seen in physical tests. An arc flash event involving lithium-ion battery is an electro-chemical thermal event with multiple factors. Ion shuttle velocity between cell electrodes, thermal impact on the chemistry and materials, limitations of maximum discharge current (C-rate) over time are various aspects that need modeled in addition to copper electrode erosion at the short circuit location resulting in increasing gap, along with electrode geometry and orientation [13].

Most cell manufacturers are not required or willing to share the maximum C-rate of their lithium-ion cells to help establish the maximum fault current over time to determine the arc flash incident energies. However, testing data for various lithium-ion cell manufacturers has shown that short circuit events can produce 20-30C discharge current instantaneously for a very short duration (<1second), and 8-10C sustained discharge current.

Most battery manufacturing sites are erroring on the side of caution and over specifying PPE requirements for battery assembly, repair, and service operations. Based on battery SOC and OCV, 8 to 12 calorie/cm^2 arc flash PPE are often recommended for high voltage tasks. Arc flash is a risk factor when working on the high voltage bus inside the battery pack which is not protected by fuse and contactors and cannot be de-energized.

Each task inside the battery requires an engineering analysis to determine the voltage presence at or near the components being worked on in addition to arc flash potential in case of inadvertent short circuit to chassis or between two terminals. Most high voltage busbars and cables inside the pack are orange in color but many of them are switched connections which makes it difficult to distinguish them from always energized conductors.

There is also a need for safety verification of safety critical components before assembly at the battery assembly site in addition to supplier end of line tests. A component quality defect from a supplier can result in a safety incident at a battery assembly plant. There has been arc flash and thermal runaway incidents on packs assembled with defective components at OEMs.

Federal Motor Vehicle Safety Specification (FMVSS) 305 requires a minimum of 500-ohms/volt AC and 100-ohms/volt DC isolation between chassis ground and high voltage conductors for customer and service personnel safety on vehicles [14]. Since EVs operate in the AC domain in the drive units and inverters, most EVs use the 500-ohms/volt as a requirement for all vehicle components including the propulsion battery. This equates to a minimum isolation of 200-kohms on a 400-vdc system. Most EV batteries have tens-to-hundreds of megaohms isolation between high voltage positive and negative bus to chassis ground to prevent arc flash and thermal runaway in case of a single short circuit event.

Battery assembly requires verification of the designed isolation resistance at various stages of the build to ensure personnel, product, and process safety. The high resistance isolation circuit also limits the current flow in case of accidental contact with energized connection and chassis ground for the personnel. Hence an exposure to over 50vdc could still yield fault currents that are in the imperceptible range for the personnel involved. Process safety measures are still designed based on voltage exposure regardless of the current limiting design based on the unpredictable variables such as human contact resistance.

The high impedance isolation resistance circuit poses a challenge when it comes to measuring voltage within the pack using a digital multimeter. There have been documented cases where a category I or II generic multimeter was displaying incorrect voltage values due to the multimeter impedance being lower than the isolation resistance circuit connected in series via chassis ground. It is important to understand this impact and prescribe the appropriate category III multimeter with a high impedance voltage measurement circuit design. It is likely that the move to 800-volt architecture for EVs will result in isolation circuit resistance to exceed the capability of commercially available multimeters resulting in the need for specialized portable test equipment to accurately determine the voltage of such systems.

Over the past decade, most hybrid and EVs have eliminated a key safety feature that allowed battery pack high voltage bus to be disabled, from outside the battery pack, by opening the circuit using a plug in connector with a lever often referred to as a manual service disconnect (MSD). Some MSDs had a thermal fuse integrated in the design versus shunt type disconnect option. Software driven high voltage interlock loops (HVIL) and pyrotechnical safety switch system are now being used to control the high voltage circuit control in the vehicle applications.

However, once the battery is removed from the vehicle, these functions may not be available to the service personnel at the battery level. Batteries with welded contactors, loss of isolation, etc. must be handled with high voltage bus active due to this missing key feature. The MSD posed some design challenges with location for accessibility, pack sealing issues with fluid intrusion via MSD interface, nuisance faults due to connection component failures, etc. which were some of the drivers to the decision to eliminate this feature.

From a service and recycling perspective, it added significant risk to the later stages of the battery life cycle. In addition to not being able to determine the pack SOC in case of contactor(s) failed open and loss of communication with BSM, service and recycling personnel do not have tools to discharge these large batteries quickly and safely.

There is a need to standardize the service disconnect safety requirements for propulsion batteries across the industry. There is also an emerging market need to develop solutions to safely remove energy from these packs without adding the risk of thermal runaway. Some countries in the world are trying to submerge large lithium-ion batteries (and vehicles) in large saltwater tanks to quickly discharge them.

Battery Pack Assembly Challenges:

1. Cell level thermal hazards created by electrical shorting between terminals can generate sparks and heat due to high current, low voltage, events which can burn through work gloves. Hence it is recommended to wear appropriate ASTM cut resistant, arc thermal performance value rated, work gloves while handling energized components under 50vdc.

2. Cell damage from electrical shorting or mechanical abuse can result in off-gassing. Large format battery lithium-ion cells have the potential to release a high volume of gases when damaged resulting in a potentially toxic atmosphere and inhalation hazard. Some cell short circuits end up in thermal runaway resulting in flame generation and fire hazard based on surrounding factors. Hence storage and handling of energized components requires adequate risk assessment and planning for facility design {ventilation, fire mitigation, gas sensing}.

3. Metal objects such as extra fasteners and non-insulated/non-isolated tools dropped or left in the battery pack during the assembly process have the potential to create shock and arc flash hazards downstream. When a conductive object creates a short circuit across the battery terminals, the high current that flows can generate significant forces due to electromagnetic effects. This force can expel the object from the terminal with substantial velocity, posing a risk of injury to personnel or damage to surrounding equipment. In some cases, the short circuit caused by the conductive object may be so severe that it welds the object to the battery terminals [21]. This occurs when the heat generated by the high current is sufficient to cause the metals to melt and fuse together.

   A good design practice for battery components is to use component-trapped fasteners and non-metallic fastening components to reduce the hazard of dropped or extra parts inside the battery assembly which are hard to detect. Zero voltage exposure terminals on all energized components can help mitigate these hazards.

   A good process design ensures tooling contact points with energized components are insulated and isolated to prevent equipment damage and/or short circuit events. IPXX terminals do not protect against shock and arc flash hazards while using tools that can penetrate the opening during operations such as fastening.

4. Fluid intrusion (coolant, moisture, salt water) from improperly installed connectors or leaking external interfaces can create a loss of isolation and arc flash condition within the battery.

5. Measuring voltage presence inside the pack HV circuit with high impedance isolation protection circuits between HV + and – to chassis ground can result in incorrect hazard assessment and insufficient risk mitigation efforts.

6. Lack of a service disconnect (MSD) increases the complexity to reduce potential voltage exposure for workers via battery segmentation when working inside the battery pack during assembly or before removing the cover for service and recycling operations [15]. The importance of following establish de-bussing sequence is critical in these cases.

   There is a need to establish a standard to visually identify and distinguish the busbar designated as the "Last In, First Out" (LIFO) inside the packs. This relatively simple step can eliminate significant amount of safety incidents downstream in the life cycle of the battery where disassemblers, after-market battery salvage and rebuild operators, and recyclers may not have access to the company-design specific disassembly sequence documentation. There is a need for safety regulation to standardize this safety device standard and application across the industry.

7. The use of live battery cells for automated assembly equipment (high volume) setup, debug, runoff, and troubleshooting activities poses operational risks. High risk tasks performed during these activities need to be identified and require the use of non-live (dummy) cells or modules. Programming robot paths, alignment of part present sensors on conveyors, etc. can result in punctured cells, dropped modules and lead to a hazardous exposure event.

8. Battery manual build (low volume) processes require standardized sequence of operations along with appropriately rated insulated, isolated hand tools and PPE to reduce the risk during high voltage bussing activities. Non-electrical tasks should be performed in de-bussed state to limit the voltage exposures and mitigate accidental arc flash hazards. Sequencing non-HV tasks earlier in the assembly process before bussing operation is a preferred approach for occupational safety. Automating the high-risk assembly processes like HV bussing are preferred over manual assembly with operator in arc flash/voltage PPE, using insulated and isolated tools.

9. Energized components present a challenge in industrial process lockout/tagout programs. Most process equipment lockout points in automation do not control the energized component present inside the cell. Lockout/tagout placard standards must be updated to reflect the new category of energized component present which is not mitigated by the lockout of the process equipment. An electrician addressing a process fault in automation may need to wear arc flash PPE and consider the additional hazards posed by the energized component in the fixture or robot end-of-arm tooling. Ideally automated assembly cells should be cycled to remove the energized part before entering the cell to perform routine maintenance tasks and troubleshooting.

10. The appropriate level of training must be identified for workers performing electrical and non-electrical tasks on a battery. This differs from the traditional definition of a “qualified worker” for construction or operation of equipment. Operators working in battery assembly must be trained on electrical, thermal, and chemical hazards present in the operation and the importance of following standardized work for occupational safety. Performing non-electrical tasks inside the battery pack during assembly operations within the limited approach and arc flash boundaries requires electrical safety qualification training.

11. All personnel entering a battery assembly site must be provided a safety orientation training which covers key safety topics such as not having exposed metallic objects (jewelry, metal watches, keys, lanyards, glasses with metallic frames, etc.), identifying areas that are considered high voltage exposure risk while the battery cover is not installed, and emergency response procedures in case of a thermal event. There could also be areas that need access controls to reduce the traffic and potential for accidental exposure while the battery is being assembled and for work in process inventory.

V. CONCLUSION

DC batteries are posing new challenges in the large-scale automated EV battery manufacturing environments. Production operators, skilled trades, material handling, and service personnel are now faced with chemical, thermal, and electrical hazards. The process-based engineering and administrative controls are expensive and limited in their ability to prevent incidents from happening.

Designing in occupational safety elements in the battery packs are more effective approaches to engineering control of identified hazards upstream resulting in a safer life cycle for these rechargeable energy storage systems. Product design has its challenges and complexities based on limited space, the need to package large quantities of cells in tight spaces, with thermal runaway mitigations while allowing thermal regulation of cell temperatures inside the pack.

Due to the cost of cells, there are constant pressures to remove cost from other components inside the battery pack which makes it difficult to justify adding expensive connection systems and other proposed mitigations. However, the enterprise cost of mitigation downstream and disruption to operations from safety incidents should be considered as part of the business case for design decisions.

Finally, the serviceability of large propulsion batteries is a critical topic of research and development. Due to thermal propagation mitigation and thermal management adhesive materials used to assemble the various format batteries, replacing individual cells or modules is not a feasible strategy on most high-volume production designs [22].

VI. ACKNOWLEDGEMENTS

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Finally, we want to thank our families for constantly supporting us in our endeavor to grow our skillsets and to spend time on documenting these concepts and sharing these learnings via this paper and workshop.

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VIII. VITA

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Lubaczewski began his career in 1995 at GM's Saginaw Malleable Iron/Local 455 as a production worker, where after 8 months on the line he accepted an UAW-GM electrical apprenticeship. In 2000 Lubaczewski transferred to GM's Saginaw Grey Iron (Saginaw Metal Casting Operations) as an UAW Journeyman Electrician where he became a Skilled Trades Team Leader. In 2012 he was appointed to Local 668's Apprentice Committee eventually becoming Apprentice Chairman. While at SMCO he held various roles in leadership: T3 Health & Safety Trainer, Safety Rep, Skilled Trades Rep, Skilled Trades Technical Training, ESWP Chair/SME/CAC, Fire Brigade/ERT, etc. In 2014 Lubaczewski was asked to join the UAW-GM NJC ESWP Committee where after the joint team updated the ESWP Red Book in 2019 he has been doing all the ESWP T3 training. In his current role Scott is an electrical safety specialist and is the program manager/owner/trainer for the following UAW-GM performance standards: Lockout, Electrical Safety, Contractor Safety, Design-In Safety, Test Vehicle Safety, Laboratory Safety, Electric Vehicle Safety, and Element 4.6 Safety Equipment Inspections and Preventive Maintenance, Robotic Safety, g-Comply, g-Risk, Laser Safety. Scott also audits all UAW-GM sites on their Workplace Safety System maturity level and is solely responsible for all the Non-Manufacturing and Ultium Cell plants. He holds a UAW Journeyman Electrician card, State of Michigan Master Electrician license, Michigan Electrical Contractor license, and an NFPA CESCP

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MANAGEMENT OF ELECTRICAL INSTALLATIONS AFTER FLOODS: IMPROVEMENTS AND SAFETY PRACTICES

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Abstract – Floods affect more than 20 million people worldwide annually, resulting in an annual cost of $96 billion. In May 2024, in the state of Rio Grande do Sul, Brazil, more than 400 cities were affected by floods, leaving thousands of families homeless. There are potential dangers in re-energizing equipment and installations affected by floods without proper inspection and restoration. Currently, there is a lack of comprehensive guidelines on how to handle and restore electrical components after floods. The objective of this research is to establish a set of best practices for dealing with flood-damaged electrical installations to ensure safety and functionality. The methodology involves two stages: i) first, a literature review of existing guidelines, and ii) lessons learned from the case of Rio Grande do Sul in Brazil in 2024. An analysis was conducted on various electrical components, such as transformers, motors, and cables, and the impact of floodwater on the integrity and performance of these components. The results indicate that most electronic components and devices exposed to floodwater should be replaced due to irreversible damage, while certain mechanical parts can be reconditioned if handled by professionals. The conclusions emphasize the importance of following these guidelines to prevent accidents and ensure the reliable operation of electrical systems in post-flood scenarios. Additionally, the need for specialized training and appropriate equipment to manage these tasks is highlighted, along with the role of manufacturers in providing support and recommendations for reconditioning or replacing affected components.

Index Terms — Flood-damaged electrical installations, Post-flood safety, Electrical component restoration, Best practices, Reconditioning and replacement.

I. INTRODUCTION

Flooding is intensifying globally due to various. Rapid population growth and unplanned urbanization—often lacking adequate infrastructure—significantly increase the vulnerability of affected regions [1]. Urban areas in developing countries, especially those with low-income populations, are particularly susceptible to the devastating impacts of these floods, which disrupt lives, livelihoods, and essential services [2].

Between April and June 2024, more than 400 municipalities in the state of Rio Grande do Sul (affecting 90% of the population—over 2 million people) faced an unprecedented crisis due to severe flooding. This extreme event, caused by a combination of climatic factors and intensified by anthropogenic climate change, posed significant public health risks, particularly regarding outbreaks of infectious diseases [3]. The floods contaminated water and food sources, leading to the spread of diseases such as hepatitis A, typhoid fever, and leptospirosis, while also creating favorable conditions for mosquito proliferation, which heightened the transmission of diseases like dengue and malaria. The impact was most severe among vulnerable populations, including low-income groups and the elderly, underscoring the urgent need to strengthen disaster management strategies and epidemiological surveillance to mitigate the future effects of such extreme weather events [4], [5].

The floods in Rio Grande do Sul in 2024 resulted in estimated financial losses of R$ 12.2 billion, affecting 478 municipalities. According to data from the Civil Defense and the National Confederation of Municipalities (CNM), the housing sector was the most affected, with 110.9 thousand units damaged or destroyed, totaling R$ 4.7 billion in losses. The public sector suffered losses of R$ 2.5 billion, primarily in infrastructure projects, while the private sector accounted for R$ 5 billion in damages, particularly in agriculture, which registered R$ 4.1 billion in losses.

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The floods in Rio Grande do Sul in 2024 also caused significant damage to the electrical infrastructure, with losses estimated at R$ 1 billion. More than 500 kilometers of cables and 300 transformers were damaged, requiring extensive repairs. The event affected 93% of the state's municipalities, impacting approximately 2.3 million people. These damages to the electrical grid compromised both energy distribution and the continuity of essential services, exacerbating the public calamity and necessitating substantial investments for the recovery of the electrical infrastructure.

II. FLOODING AND LOW-VOLTAGE ELECTRICAL INSTALLATIONS

During floods, electrical installations can suffer significant damage, becoming extremely unsafe due to mud and debris, which can conduct electricity. Additionally, floodwater can cause corrosion in electrical connections, increasing the risk of failures and fires. To safely restore the power supply, conducting a thorough inspection and carrying out necessary repairs before reconnection is essential. Below are behavioral recommendations for before, during, and after floods, considering the Brazilian context:

A. Recommendations for preparation before a flood:

- *a) Whenever possible, elevate electrical appliances above the expected flood level.*
- *b) If prior flood warnings are issued, contact your energy provider to request disconnection before your home is affected.*
- *c) If the energy company has not disconnected the supply, turn off all circuit breakers and the main panel before the flood, using non-conductive tools to avoid electric shock.*

B. Recommendations for preparation during the flood:

- *a) Do not stay inside flooded buildings while the electrical power is still connected.*
- *b) Avoid using electrical appliances that have been wet or damaged.*
- *c) When operating portable generators, strictly follow the manufacturer's instructions and maintain a safe distance from submerged electrical cables and equipment.*
- *d) Pay special attention to buildings with rooftop photovoltaic systems. Even if the utility company has disconnected power and parts of the installation are "islanded," other parts of the photovoltaic system may still be energized by sunlight.*

C. After the flood:

- *a) If the energy company has disconnected the installation due to flooding, hire a qualified electrician to inspect and test the installations before reconnection.*
- *b) Only reconnect or use any device exposed to floodwater after being checked by a trained professional.*
- *c) Before turning the power back on, contact the energy company to ensure the installation is safe for reactivation.*
- *d) Never touch down power lines, as they may still be energized, posing a severe risk of electric shock. Always maintain a safe distance and report them immediately to the utility company or local authorities.*

The contact between floodwater and electrical equipment can severely compromise its functionality and pose a direct risk to the safety of both occupants and professionals involved in re-energizing efforts. Following a series of procedures is necessary before attempting to re-energize any installation affected by floods.

D. Final Verification of Electrical Installations After Floods

The final verification of electrical installations after floods is a fundamental process to ensure the safety and functionality of the system before any attempt at re-energization. According to item 7 of NBR 5410 [6], the complete procedure involves a series of steps, each designed to identify potential faults that could compromise the installation.

1) *Visual Inspection (7.2): The first step involves a detailed visual inspection of all electrical components exposed to the flood. The goal is to check for visible signs of damage, such as corrosion, oxidation, lose or burned cables, damage to conductors and terminals, and the presence of debris or mud in equipment and distribution boxes. This analysis is crucial, as many damages may not be immediately visible, but the visual inspection can reveal structural problems that compromise system safety. Additionally, protective devices such as circuit breakers and fuses should be checked for deformation.*
2) *Electrical Testing (7.3): After the visual inspection, a series of electrical tests must be performed to verify the integrity of the systems. These tests include:*
   - *a) Continuity Test of Protective Conductors (7.3.1): This test ensures that all protective conductors (ground) are continuous and were not interrupted or damaged during the flood. Lack of continuity in these conductors can result in electrical shock hazards.*
   - *b) Insulation Resistance Test (7.3.2): This test measures the insulation resistance between live conductors and protective conductors and between live conductors and the ground. Low insulation resistance may indicate the presence of moisture in the cables or internal damage, which can lead to short circuits or system failures.*
   - *c) Polarity Test (7.3.3): The polarity of the circuits must be checked to ensure that phase, neutral, and ground are correctly connected. Polarity errors can cause equipment malfunction and shock hazards.*
   - *d) Ground Resistance Test (7.3.4): The verification of ground resistance ensures that the grounding system is functioning correctly. Inadequate grounding can result in overload risks and failures in protecting against lightning strikes or short circuits.*
3) *Functional Testing (7.4): In addition to electrical tests, functional tests verify the performance of protection and*

control devices. It is necessary to test circuit breakers, fuses, residual current devices, and other components to ensure they function correctly. The correct operation of these devices is essential to guarantee the safety of the installation in case of overload or short circuit. Emergency lighting systems, if present, should also be tested.

4) *Documentation and Final Report (7.5): After all tests are completed, it is essential to document the results in a detailed report. This report should include observations from visual inspection, the results of the electrical and functional tests, and any recommendations for maintenance or replacement of damaged components. This documentation is essential to ensure the installation complies with regulatory requirements and is ready to be safely re-energized.*
5) *Additional Procedures for Photovoltaic Installations: In the case of buildings with photovoltaic systems, special attention must be given to inspecting the solar panels and inverters. Even if the central system has been disconnected, parts of the system may still be energized by sunlight, representing a shock hazard. Ensuring that the entire system is adequately isolated and inspected before any repair or maintenance is essential.*

III. GUIDELINES FOR RECONDITIONING AND REPLACEMENT

Not all electrical equipment affected by flooding can be recovered. Depending on the extent of the damage and the type of equipment, reconditioning may be possible, though complete replacement is generally recommended in many cases. The following table provides an overview of which equipment can be reconsidered and which should be replaced after exposure to floodwaters:

TABLE I
RECONDITIONING VS. REPLACEMENT OF ELECTRICAL EQUIPMENT AFTER FLOOD EXPOSURE

Equipment / Component	Replace	Recondition
Low-voltage molded-case and mini circuit breakers	X	
Low-voltage open circuit breakers (without electronic components)		X
Medium- and high-voltage circuit breakers (without electronic components)		X
Electromechanical relays and meters (without electronics)		X
Equipment with electronic components (RCD, AFDD, etc.)	X	
Low-, medium-, and high-voltage fuses	X	
Disconnect switches, transfer switches, etc.	X	
Protection and switching assemblies (panels, boards, etc.)	X	
RCD, SPD, AFDD	X	
Switches, outlets, dimmers	X	
Junction boxes and pass-through boxes	X	(evaluate)
Conduits and accessories	X	

TABLE I (*continuing*)

Equipment / Component	Replace	Recondition
Low-, medium-voltage, and control cables	X	(evaluate)
Cable trays, ladders, and raceways		X
Luminaires, ballasts, LED drivers	X	
Electric motors		X
UPS (uninterruptible power supplies) and batteries	X	
Dry-type, encapsulated, or oil-filled transformers	X	(evaluate)

This table serves as a practical guide for determining the appropriate procedures after equipment has been exposed to floodwater. Safety should always be the priority, and all reconditioning or replacement procedures must be performed by qualified professionals, strictly following the manufacturer's recommendations and applicable safety standards.

IV. FLOODS AND HOUSEHOLD APPLIANCES

Electrical equipment exposed to floods can suffer severe damage, compromising its safety and functionality. After floods, it is essential to evaluate the condition of these systems to determine whether components should be reconditioned or replaced. Based on the extent of damage, many electronic devices and circuits, such as low-voltage molded-case circuit breakers, relays, and devices containing electronic components, should generally be replaced due to irreversible damage caused by moisture and contaminants. On the other hand, some mechanical components, such as open low-voltage and medium-voltage circuit breakers without electronic parts, may be reconditioned if properly handled by qualified professionals. The inspection process must follow strict safety guidelines, considering the risk of corrosion, contamination, and electrical failures that can persist even after superficial drying or cleaning. By adhering to these recommendations, accidents can be prevented, and the proper operation of electrical systems restored, ensuring safety for users and technicians.

Fig. 1 Risks and Precautions for Electrical Equipment After Floods.

V. FLOODS AND ELECTRIC POWER DISTRIBUTION

Floods can have a severe impact on the distribution of electrical energy, especially in regions where critical infrastructure, such as power lines and substations, is affected. During the 2024 floods in Rio Grande do Sul, for example, over 500 kilometers of power cables and 300 transformers were damaged, leading to widespread power outages across 93% of the state's municipalities. These damages not only disrupt the supply of electricity to homes and businesses but also affect essential services like hospitals, water treatment plants, and communication systems. Restoring the electrical grid after such events requires substantial investments in repair and replacement, as well as careful inspection to ensure that all damaged components are either replaced or adequately reconditioned to prevent future failures. Ensuring a reliable and safe electricity supply is essential for recovering from such disasters and preventing further public safety risks.

Fig. 2 Impact of Floods on Electrical Infrastructure and Housing.

Fig. 3 Recovery of Electrical Infrastructure After Floods.

VI. FLOODS AND SUBSTATIONS

Electrical substations play a crucial role in critical infrastructure and, as such, must be designed to withstand adverse environmental conditions, including flooding. Rising sea levels and floodwaters pose significant challenges to the operation of substations, particularly those located in coastal areas or flood-prone regions.

Substation failures caused by flooding can compromise critical systems, such as protection and control equipment, leading to the de-energization of the substation and potentially catastrophic damage, such as fires. To mitigate these risks, it is recommended that substations be designed above the 100-year flood elevation, with an additional one-foot safety margin to minimize the impact of severe flooding [7]. Furthermore, constructing substations and Motor Control Centers (MCCs) above ground level, such as on the second floor, is advised to enhance their protection against floodwaters.

Additionally, innovative solutions, such as elevated and encapsulated substations, can protect equipment from external influences, including floods, severe weather conditions, and atmospheric contaminants.

Fig. 4 Flooded Substation: Critical Infrastructure at Risk.

VII. FLOODS AND PHOTOVOLTAIC SYSTEMS

Flooding presents a significant risk to the safe operation of solar photovoltaic plants, especially during extreme weather events. The Brazilian Distributed Generation Association (ABGD) and inverter manufacturers have issued specific guidelines aimed at the protection and maintenance of these systems in such circumstances. Although solar modules are designed to be water-resistant, it is essential to verify their integrity after floods. Recommissioning the modules before re-energization is necessary to ensure the proper functioning of the system.

Solar inverters, critical components in photovoltaic plants, require thorough inspection before being switched back on. Physical damage, such as the presence of water, dirt, or signs of short circuits and corrosion, must be addressed. If exposed to water, it is crucial to ensure they are completely dry, using natural ventilation or low-temperature heaters. After this process, the functionality of the inverters should be tested, verifying the integrity of the connections and circuitry.

Given the complexity of power electronics systems, it is recommended that inspection and recommissioning be performed by qualified professionals. Safety is paramount, and it is essential to avoid contact with any part of the system during floods due to the high risk of electric shock. In the event of visible damage, the system should be immediately shut down, and specialized technical assistance should be sought.

Additionally, continuous monitoring of weather conditions and water levels is essential to take preventive measures. Ensuring adequate protection of the equipment and the people involved is vital to maintaining the efficient and safe performance of photovoltaic plants. Inspection, drying, and reconnection procedures must be carried out in compliance with safety standards, always under conditions with no solar irradiance. If damage is identified, replacement or repair of the compromised components must be completed before re-energization, ensuring the safety of operators and users.

Fig. 5 Flooded Photovoltaic Systems: Risks and Recovery Measures.

Ketjoy et al. (2022) [8] conducted a comprehensive study on the impact of floods on thin-film photovoltaic modules. The study first observed that the insulation resistance of the modules significantly decreased after prolonged exposure to moisture, with a high failure rate in insulation resistance tests, compromising the functionality of the systems. In addition, variations in the voltage observed across several modules increased the risk of inverter failures and raised serious safety concerns, requiring heightened attention when monitoring such systems in adverse conditions. After floods, the insulation resistance test can be a cost-effective and efficient alternative for evaluating voltage withstand capability in the field, although tests under humid conditions remain more accurate following flooding events. The study highlighted that tropical weather conditions, with high humidity levels, are an aggravating factor in module degradation, especially compared to drier climates, emphasizing the need for mitigation strategies tailored to local climatic realities. Finally, the study underscored the importance of preventive measures, such as the installation of efficient drainage systems and regular maintenance of photovoltaic plants, to minimize moisture ingress into modules, thereby reducing energy production losses and safety risks.

The dry electrical insulation test on photovoltaic modules is designed to verify the electrical insulation between the electrical terminals (positive and negative) of the module and its metallic frame, as specified in item 10.3 of the IEC 61215 standard. This test is relatively easy to perform in the field and ensures that there is no dielectric breakdown or surface tracking, following the guidelines of IEC 61215 - Clause 10.3.4 - item C. For modules with an area greater than 0.1 m², the measured insulation resistance must not be less than 400 MΩ. Additionally, the Insulation Resistance test under humidity conditions checks the insulation of the module when exposed to moisture, ensuring that rain, dew, or melting snow does not penetrate into energized parts of the circuit. This test, conducted according to item 10.15 of the IEC 61215 standard, is critical to preventing issues such as corrosion, ground faults, or safety hazards. These tests are essential for maintaining the safety and functionality of photovoltaic systems, particularly in environments exposed to varying weather conditions.

VIII. CONCLUSIONS

The findings from this study highlight the critical importance of proper inspection, maintenance, and safety protocols when handling electrical installations affected by floods. Floodwater contamination, corrosion, and debris can cause significant damage to electrical systems, leading to potential hazards such as electric shock, short circuits, and even fires if systems are re-energized prematurely. The results of the study emphasize that most electronic components, such as breakers and protective devices, should be replaced due to irreversible damage, while certain mechanical components may be reconditioned under professional supervision. Additionally, the complexity of photovoltaic systems and the need for meticulous testing before reactivation were underscored, with recommendations to improve resilience through preventive maintenance and innovative solutions, like elevated and encapsulated substations. Ultimately, the study advocates for the development of comprehensive guidelines, specialized training, and strong manufacturer support to ensure the safe and reliable operation of electrical systems post-flood.

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X. VITA

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Best Practice for Contractor Evaluation: Failure to Plan Is a Plan to Fail….

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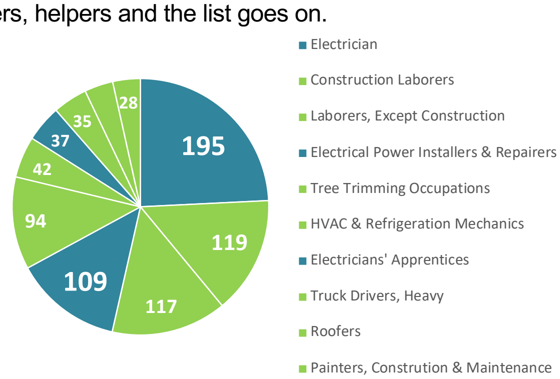
Abstract – Having the right electrical contractor for the next electrical job or project can be the difference between a safe, reliable installation, value added, schedule accommodation, as well as peace of mind. When it comes to determining your best fit in regard to electrical contractors for the success of a project, it all starts with the electrical contractor selection process. This paper will focus on the following areas for important considerations: 1) selecting the right electrical contractor for your project or site; 2) evaluating electrical contractor proposals; 3) risky pitfalls for the lack of an effective evaluation process, and; 4) consequences attributed to not being proactive. Without considering best practices and other successful electrical contractor evaluation processes, the likelihood of experiencing potentially dangerous consequences for using poor or unprepared electrical contractors is increased. Hiring an electrical contractor for your job that is not the best fit could greatly increase the risk of significant consequences causing project delays, financial losses, safety hazards, and/or ultimately the loss of life.

Index Terms — Contractor, evaluate, managing contractors, evaluating performance, proactive, contractor selection, contractor selection process.

I. INTRODUCTION

Unfortunately, individuals are injured or killed due to contact with electricity every day. These individuals are fathers, mothers, uncles, aunts, brothers, sisters, friends. Seventy percent of workplace electrical fatalities occurred in non-electrical occupations [1]. These occupations include: construction labor, tree trimming, HVAC and Refrigeration Mechanics, truck drivers or heavy equipment operators, roofers, painters, telecommunication workers, carpenters, welders, helpers and the list goes on.



Fi. 1 Source: ESFI 2011-2022 Workplace Fatalities & Injuries

Both Occupational Safety and Health Administration (OSHA) & the National Fire Protection Association (NFPA) 70E Standard for Electrical Safety in the Workplace Article 110.5 outline electrical contractor responsibilities providing these basic minimum requirements. In accordance with NFPA 70E 2024 Article 110.5 Host and Contract Employer Responsibilities [2]. The Host and the Contract Employer have specific duties they must follow to ensure each party has met the NFPA 70E requirements. These duties include the host communicating the known hazards associated with the location, work activities, and how the host employer will communicate any contractor related violation of NFPA 70E. The Contract Employer shall ensure each of their sub-contractors are aware of the hazards present at the host site, ensure that the contract employer follows all Environmental Safety and Health (ESH) appropriate codes and standards as well as the host employer's specific requirements and ensure the host employer understands the hazards the contracted employees may be introducing into the worksite. To meet this NFPA 70E Article 110.5 requirement selecting the right electrical contractor for your project will help you maintain your safe work environment. As you begin your project, choosing the right electrical contractor can mean the difference between completing a project safely, on-time, and within budget or having significant project delays, unexpected losses, or events that impact the overall cost to you and your company. The next several pages will discuss considerations you should make to assist you in selecting the best electrical contractor for your project. First a global illustration of the contractor selection process.

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Fig. 2
Contractor Selection Process

II. PREQUALIFICATION PROCESS

The first consideration you should make when selecting an electrical contractor for your next project is: will the electrical contractor impact my current business operation or reputation. You might ask yourself what does this mean? Hiring an electrical contractor to perform work they are not accustomed to, can place the electrical contractor, as well as others working in the area, at risk. For example, they may not be accustomed to working in an environment that is unfamiliar to them, or they may be inexperienced with complex equipment or working with industrial or commercial electrical equipment, performing work on the equipment you have specified, etc., can place your employees, the electrical contractor as well as others working in the area at risk. Therefore, performing a prequalification assessment to evaluate prospective electrical contractors can save time and money in the long run. The evaluation should start with basics including: insurance, licensing, experience. Knowing what requirements your company requires for any electrical contractor to perform work at your location is the start. For example, typically anyone who performs work must be insured for that type of work. The dollar value may differ based on the work activity but two million dollars or higher is not uncommon. The amount assigned is to assist your company in the event your company experiences an unplanned shutdown or harm to one or more of your employees, there is a way to recuperate loss.

In a majority of states within the intercontinental United States, the state or local government will require companies wishing to operate in their jurisdiction or state to be registered as a business. The licensing is important as it is an indication that the company being considered has been registered to perform as a business and plans on staying in the state. A local license is also an indication that the company is a legitimate company and recognized as such. Another license a contract company may be required is specific to performing electrical work. Not all states or local authorities require a company or electrical contractor to have a license, however, it is important for you to understand the requirements within your local jurisdiction to ensure the minimum regulatory requirements are met. Once you have met the insurance and licensing requirements the next component of your prequalification evaluation will be safe work practices. Are they safe?

Identifying components of safe work practices include asking questions such as: 1) has the electrical contractor been fined by OSHA or been a part of an OSHA investigation; 2) has the electrical contractor experienced any fatalities; 3) what is the electrical contractor's Days Away Restricted Time (DART), and; 4) their Total Recordable Case Rate (TRCR). These rates should be based on a formula identified in 29 Code of Federal Register (CFR) 1904 Recording and Reporting Occupational Injury and Illnesses [3]. Basically, a DART rate is a formula that is used to standardize an accident rate for companies that have more than 10 employees during the last calendar year. The formula to calculate a DART rate equation (1) is as follows:

$$\frac{(Number\ of\ lost\ workdays * 200{,}000)}{Number\ of\ Manhours\ worked} \quad (1)$$

The number 200,000 is derived from 100 full time employees working 2000 hours each year. (Each employee works 40 hours a week times 50 weeks = 200,000 hours). Basically, the correlation will be the lower the DART rate, the fewer lost or restricted days occurrences. Evaluation should call for prospective electrical contractors you are evaluating to have their DART history available for review. Requesting the electrical contractor to provide the past 5 years history of their DART is an acceptable request. If the electrical contractor will be using contract labor, then you should understand the reason for the contract labor and determine how this could impact your project. Hiring an electrical contractor to perform a task that they in turn hire others to perform the task could lead to unexpected consequences, unscheduled shutdown, or injury to a worker.

Another important indicator, albeit lagging, is the Experience Modification Rate (EMR). An EMR of 1 is considered average. It is the belief that a company's EMR can be an indication of future worker compensation losses [4]. Lower EMR rate would be an indication that the worker compensation rates are lower while a higher EMR would indicate higher worker compensation premiums. Another question to ask about the electrical contractor's EMR is: does the contract company pay extra money to lower their EMR. This extra money spent on lowering the EMR rate can be an indication that the worker compensation premiums are being bought down to hide or cover the fact that the electrical contractor's performance and injuries to their employees is higher than the EMR number indicates.

III. COMPREHENSIVE ESH PLANS

Safety and Health programs and compliance with these programs are a must when it comes to electrical contractor selection at your facility. These requirements are based on the OSHA standards as well as NFPA 70E. Under the OSHA requirements a company of greater than 10 employees should have a safety and health manual containing certain programs. These programs include but are not limited to: Personal Protective Equipment (PPE); Electrical Safety, Control of

Hazardous Energy (also known as Lockout/Tagout (LOTO)), and; Hazardous Communication to name a few. When talking with an electrical contractor, one should ask for a copy of the electrical contractor's safety and health program(s) and provide the electrical contractor with a copy or access to your company's safety and health programs. When you receive the electrical contractor’s program(s) you should review the information contained to ensure the latest requirements as identified by OSHA and NFPA 70E are present. This would be a great time to contact your local safety and health team to assist you in the evaluation of the contractor’s program(s). For example, NFPA 70E (Articles 130.4 and 130.5) discusses the requirements to perform risk assessments; How does the contractor's electrical safety program (ESP) address shock and arc flash risk assessments? Article 130.7(C) discusses personal protective equipment; How does the electrical contractors ESP address PPE. Does the contractor's ESP identify a different PPE category rating than what is identified in NFPA 70E Table 130.7(C)(15)(c) Personal Protective Equipment. Does the electrical contractor's program align with your company's program for electrical safety. There is no requirement for the two electrical programs to align, however it is important to understand the differences and ensure that both companies understand each other’s Safety and Health program(s).

As you evaluate the electrical contractor’s program(s) one should look for how the contractor’s program(s) are implemented and how their programs align with your work schedule and needs. For example, if the job that the electrical contractor is bidding on requires exposed energized work, how does the electrical contractor's ESP define energized work, identify when energized work is justified and considerations to be taken while performing energized work. Does the ESP have an energized work permit for this type of work activity? Does the ESP identify who can perform energized work? Does your own internal ESP permit allow for exposed energized electrical work? What are the limitations of each program? OSHA 29 CFR 1910.333(a)(1) allows energized work only if one can demonstrate de-energizing introduces additional or increased hazards or is infeasible due to equipment design or operational limitations. When preparing a job scope, considerations for the implementation of safety by design in the electrical system can drastically reduce exposure when performing work deenergized and under LOTO. This is not always possible due to the nature of the work activity and limitations of the equipment design. When you meet with the electrical contractor, a discussion establishing set expectations should be included. If it is determined that exposed energized work is required, consider having the electrical contractor provide you, in writing, with who will be performing exposed energized work, and what are their qualifications. You want to ensure you have the most qualified and experienced person available to perform this task.

Another consideration for the electrical contractor review should be their emergency response plan. How does the ESP identify emergency response? Does the plan include minimum training requirements? For example, NFPA 70E Article 110.4(C) identifies the requirements for emergency response training. This training should include contact release. Does the electrical contractor's ESP program identify a method for contract release? How does the ESP identify response for first aid, emergency response and resuscitation? How does the electrical contractor's ESP align with your site's emergency response plan? Request the electrical contractor to identify how they maintain employee training in their Safety and Health program(s). For example, how are training records being verified to ensure a contractor is maintaining first aid, cardiopulmonary resuscitation (CPR), and automated external defibrillator (AED) training. The best approach may be to request the contractor provide certificates of completion.

IV. EFFECTIVE COMMUNICATION

Communication protocols are vitally important because each player has limits to their sphere of influence. Any solicitation should include additional recommendations for coordination. A host employer holds the contract with a subcontractor but not with their sub tier contractors, therefore most companies cannot direct the work of the sub tier subcontractors. If a company representative observes issues with project documentation, implementation, or execution of scope, they need to know who to speak with and how to intervene effectively. If a representative of the company observes issues with any contractors, they will need to know who the correct representative is to inform. A company must develop an effective communication process and flow down requirements that set clear expectations to establish methods for interacting and communicating with the contractor and their sub tier contractors. The means and methods of interfacing and the flow down of those requirements need to be aligned before work begins and before contracts are signed. Communication protocols are vitally important because each player has limits to their sphere of influence.

V. DEDICATED OVERSIGHT

As you plan your project and identify the need for electrical contractor's to assist you with achieving your goal as a Project Manager one should determine how the electrical contract personnel will receive direction. There are two basic types of contract personnel. The first type of contract personnel would be those persons who receive daily direction from you or a company representative. The second type of electrical contract personnel would be those persons who receive daily direction from their company representative. This might also be known as a turn-key contract. Using an electrical contractor to perform a specific task for a project will provide you with a method to hold the electrical contractor accountable for their work. Contract work could occur in the form of construction, maintenance or service. The project will dictate the type of contract needed. Having the right supervision to manage and oversee the daily activities can make or break a project. Ensuring that you and your electrical contractor supervisor(s) are on the same page, heading down the same path and will make your partnership and project much easier.

VI. TRAINING, DEVELOPMENT & ASSESSMENT

As a host employer of an electrical contractor, as noted above, must review ESH training or equivalent and any other training as required by applicable laws and regulations. Does the requisition include site specific training? Has the proposed contractor included adequate cost and time to accomplish the training within a reasonable time frame that does not impact the schedule? Is the training web-based or in person? Are sessions available to accommodate on-going work activities? So many factors that can directly impact the desired project schedule coupled with limited resources can be a showstopper. Training, training, training, if you are not measuring your training through assessments how does one know the effectiveness of the material being taught. A field assessment at a predetermined frequency should be established to determine if the individuals are comprehending and implementing the training being provided.

VII. TECHNICAL ACCURACY & INSTALLATION QUALITY

Proposal evaluation must provide documentation of the offeror’s ability to perform the identified contract scope successfully. [5] Your company needs to evaluate each proposal and assess their technical offer on the factors and subfactors specified in the requisition. Evaluation of the proposed documents should be approached using any scoring technique or combination of techniques. Any defined strengths, inaccuracies, deficiencies, significant weaknesses, or risks supporting the basis for selection should be captured in the offeror's potential contract file. Important factors that are a must to consider in the evaluation should include price evaluation, past performance history, and the technical accuracy required to ensure the offeror is clear on the expectations within the requisition and have the overall ability to achieve them. On many occasions the proposed means and methods of installation differ enough to impact quality or delivery of your project and are nested within the cost of the overall proposal. Take for example using electrical metallic tubing EMT vs. metal clad (MC) cable, per the NEC [5] it states to install in a skilled and professional manner. While both EMT and MC Cable have various properties that allow for similar permitted installations, the experience of a contractor who is not proficient in the installation of EMT may deliver a poor quality and performance, having an overall negative effect on your reputation.

VIII. BUDGET & CLOSING YOUR PROJECT

How does the budget affect electrical contractor evaluation? Construction projects should include electrical safety with prevention through design as a core design principle [6]. This is sometimes not considered or is overlooked. Evaluating your electrical contractors ahead of time and knowing when to bring the electrical contractor into your construction project could be the very factor your company needs to save money and prevent injuries or loss of life [7]. Components to consider as a part of your budget and plan include: how does/did the electrical contractor perform based on a deadline (do they finish projects following the design, on-time and within budget); has the electrical contractor been utilized in the past and do they meet expectations for performance; do they ask clarifying questions during the project walk-throughs when the scope of work (SOW) is reviewed; are the contractors bid estimates accurate, and includes the components defined in the SOW; has the electrical contractor performed other projects that include over-runs of the budget, these questions and others will assist you in performing your electrical contractor evaluation. Measuring apples to apples and considering what is important to your company should be your top priority.

Once a project has concluded and bills are paid, one might consider creating a summary and conducting a post project evaluation of each electrical contractor used. In conducting this evaluation, a team evaluation approach might be appropriate. If a team worked on the project, team members may have had different interactions and/or observations with the electrical contractor. This evaluation will allow you and your team/company to determine if the electrical contractor meets expectations and would you consider using them again on future projects. Additional self-reflections you might not have considered previously: did the SOW provide adequate detail to achieve the desired goal and/or outcome; did the SOW provide or identify the allowable components or equipment that you prefer or require the electrical contractor to use. Using a safety management style approach (Plan – Do – Check – Act): create a plan; work the plan; see how the plan worked, and; make improvements based on lessons learned; to create a continuous improvement process will only make oneself and team better.

IX. CONCLUSIONS

This paper addressed the importance of finding your best fit in regard to electrical contractors for the success of a project, it all starts with the electrical contractor selection process. This paper focused on the following areas for important considerations: 1) selecting the right electrical contractor for your project or site; 2) evaluating electrical contractor proposals; 3) identifying risky pitfalls for the lack of an effective evaluation process, and; 4) pinpointing consequences attributed to not being proactive.

Global Illustration of Contract Selection (Figure 2) highlighted the major topics of this paper including: Performing a prequalification assessment to evaluate prospective electrical contractors can save time and money in the long run. Ensuring your electrical contractor is in compliance with required Safety and Health programs are a must when it comes to electrical contractor selection at your facility. This includes meeting the OSHA and NFPA requirements and following those requirements. Evaluation of the electrical contractors will involve looking for how the contractor’s program(s) are implemented, and how their programs align with your work programs and schedule. Be sure and include a survey of the electrical contractor’s training records. Communication of programs and protocols are vitally important because each player has limits to their sphere of influence.

The means and methods of interfacing and the flow down of those requirements need to be aligned before work begins and before contracts are signed. As you plan your project and identify the need for electrical contractor's to assist you with achieving your goal as a Project Manager one should determine how the electrical contract personnel will receive direction. Having the right supervision to manage and oversee the daily activities can make or break a project. Ensuring that you and your electrical contractor supervisor(s) are on the same page and are heading down the same path will make your partnership and job much easier.

Overall, using a safety management style approach (Plan – Do – Check – Act): create a plan; work the plan; see how the plan worked, and; make improvements based on lessons learned; to create a continuous improvement process will only make oneself and the team better. A successful project isn't just measured by "on-time, on-budget" but 100% safety from beginning to end. All is achievable when a comprehensive plan is created, implemented, executed, evaluated and evolves.

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XI. VITA

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Is the Relay Programmed?

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Abstract – Electrical protective devices are often installed or modified during capital projects, facility changes, retrofits, or due to changes related to arc flash incident energy reduction opportunities identified during completion of arc flash hazard incident energy analysis studies. During field implementation of Electrical Safety Programs and while performing external electrical safety audits it was discovered that Qualified Persons (e.g. Qualified Electrical Workers Low Voltage or High Voltage) did not know if the electrical protective devices had been commissioned and programmed and are functioning as intended, with a documented testing reported issued. When reviewing installed arc flash and shock equipment labels while completing an Energized Electrical Job Safety Planning form the Qualified person assumes the indicated incident energy and arc flash boundary are valid and the electrical protective devices are set to provide those incident energy and arc flash boundary results.

This is a serious problem with respect to incident energy values and the arc flash boundary distance. Residual risk to the Qualified person would be "high" risk as they may be wearing arc flash PPE with an arc thermal performance value (ATPV) lower than the actual expected incident energy. When performing an energized electrical works task the potential for injury or damage to health would not be acceptable.

Index Terms — arc flash boundary, arc flash hazard, arc flash incident energy, arc flash risk assessment, arc thermal performance value, arc rating, arcing fault, circuit breaker, commissioning, current-limiting, fuse, electrical protective device, fault current, harm, hazard, hazardous, incident energy, incident energy analysis, inherent risk, injury, inspection, likelihood, probability, programmed, qualified person, residual risk, risk, risk assessment, testing.

I. INTRODUCTION

In the last two decades electrical equipment manufacturers have brought innovation to industry globally with electrical equipment "substitution" and engineering "safety by design/Prevention through Design (PtD)"" related hierarchy of risk control methods related to abnormal arcing fault and arc flash. PtD tools have been applied to power distribution electrical equipment with new electrical protective devices or electrical protection philosophies to reduce arc flash incident energy passively or actively.

Has the Qualified Person received any training or adequate training on the "safety by design/Prevention through Design (PdT)" elements that can reduce incident energy provided with new electrical equipment or retrofitted on existing electrical equipment? Has the Qualified Person personally verified that the engineered incident energy reduction method has been programmed, commissioned and is functioning? Has the Qualified Person been complacent in assuming that the PtD was programmed, commissioned and is functioning?

There is a significant residual risk (e.g., the arc flash PPE worn may not adequately protect the Qualified Person when exposed to an arc flash) to the Qualified Person if the electrical protective device has not been programmed, commissioned and is functioning as intended.

II. RISK ASSESSMENT, POTENTIAL INJURY OR DAMAGE TO HEALTH & LIKELIHOOD OF OCCURENCE

NFPA 70E [1] and CSA Z462 [2] since their 2015 Editions have included detailed requirements and supporting information related to risk assessment. With respect to electric shock and arc flash hazards two parameters are evaluated: potential severity of injury or damage to health and likelihood of occurrence.

With respect to likelihood of occurrence NFPA 70E Article 110.3(H) Risk Assessment Procedure, Article 110.3(H)(2) Human Error and CSA Z462 Clause 4.1.7.8 Risk assessment procedure, Clause 4.1.7.8.3 Human error places focus on ensuring evaluation of human error is appropriately addressed and managed with respect to the risk assessment procedure completed. [1,2]

"The risk assessment procedure shall address the potential for human error and its negative consequences on people, processes, the work environment, and equipment relative to the electrical hazards in the workplace. Note: The potential for human error varies with factors such as the work task performed and the work environment. For more information regarding human error see, NFPA 70E, Annex Q or CSA Z462, Annex U." [1,2]

In NFPA 70E Annex F Risk Assessment and Risk Control and CSA Z462 Annex F Risk assessment and risk control, the following Risk Management Process flow chart as depicted in Figure 1 is provided. After the risk assessment procedure is completed it is critical that in the field the validation of expected risk control methods is confirmed by the employer and more importantly the employee. This is extremely important related to any incident energy reduction method deployed.

Potential severity of injury or damage to health can be negatively influenced if the expected arc flash personal protective equipment (PPE) worn with an Arc Thermal

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Performance Value (ATPV) is not equal to or greater than the theoretically calculating incident energy and the arc flash boundary listed on an installed detailed arc flash and shock equipment label. [1,2]

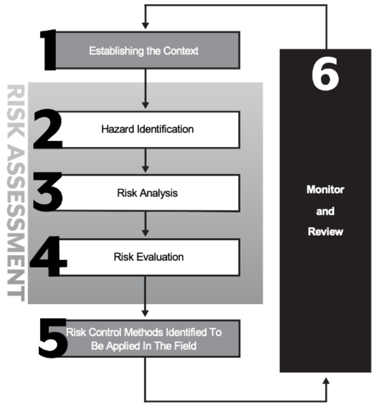

Figure 1 Risk Management Process

With respect to the content of NFPA 70E Annex Q Human Performance and Workplace Electrical Safety or CSA Z462 Annex U Human performance and workplace electrical safety, Table Q.5/Table U.1 Error Precursor Identification and Human Performance Tool Selection several error precursors can impact human error related to completing a work task's arc flash risk assessment. [1,2]

Human Error Precursor Identification Examples
Interpretation Requirements
Assumptions
Lack of Knowledge
New Technique Not Used Before
Lack of Proficiency or Experience

Table 1 Summary of Human Error Precursor Identification [1,2]

Wrongly assuming that electrical protective devices have been programmed based on engineered settings without personal validation can lead to a high residual risk.

"Prevention through Design" can be qualified as substitution, minimizing, simplifying, passive controls or active controls as depicted in Figure 2. When electrical protective devices are engineered to reduce incident energy they can be classified as passive such as a maintenance mode switch or they can be classified as active such as an arc flash relay. The Qualified Person has to manually initiate passive controls and should validate the active controls are functioning in real time to ensure that if an abnormal arcing fault occurs it will be detected and result in the expected incident energy reduction and arc flash boundary distance been decreased.

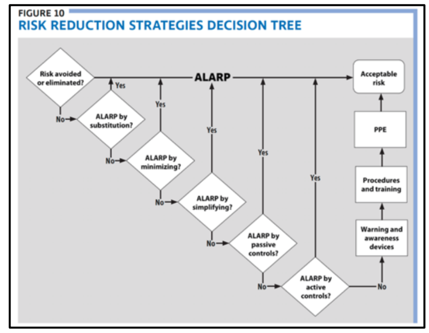

Figure 2 – Risk Reduction Strategies Decision Tree [12]

III. FIELD BASED WORK CASE HISTORIES

In two separate instances it was discovered that Qualified Persons did not have appropriate knowledge and assumed that when they manually turned maintenance mode switches that the incident energy and arc flash boundary indicated on detailed arc flash and shock equipment labels was correct. Low and high voltage switchgear also included integral arc flash relays on a multi-function relay and separately a stand-alone arc flash relay and the Qualified Persons also assumed it had been programmed and was active.

CASE HISTORY #1 Large Liquid Pipeline Pumping Station.

At the pumping station there were similar low and high voltage electrical rooms and identified power distribution equipment with maintenance mode switches installed on power circuit breaker relays and multi-function relays included an arc flash module. In one electrical room the multi-function relay had an auxiliary LED labelled that the arc flash relay was ON and in the second electrical room the same multi-function relay did not have the auxiliary LED labelled and programmed.

Both electrical rooms had maintenance mode switches installed on the switchgear's power circuit breakers.

When the Qualified Persons were asked if they knew if the maintenance mode switches and integral arc flash relays had been programmed they said "No."

When the Qualified Persons were asked if they had access to a copy of the commissioning report for the electrical equipment they answered "No" and they were not aware of who may have it.

In this case the Qualified Persons had access to the programming software for the multi-function electrical protective relay and power circuit breaker but had not personally validated the settings and downloaded them for record purposes and due diligence.

CASE HISTORY #2 Large Metropolitan City Hospital

At a large city hospital a campus expansion resulted in new 12.47kV metal clad arc resistant electrical equipment to be procured and installed. The 12.47kV switchgear included circuit breakers that sourced power to step down transformers, 12.47kV/600V sourcing power to low voltage switchgear that included an arc flash relay and maintenance mode switches on digital relays for the Main Circuit Breaker and Sub-Feed Circuit Breakers.

All of this electrical equipment was new to the Qualified Persons and the capital projects team did to provide formal training to the electrical maintenance department Qualified Persons. When one of the Qualified Persons was asked if they knew that the 12.47kV metal clad switchgear was of an arc resistant design they were unsure and when asked what Standard it was constructed to they did not know to check for ANSI/IEEE C37.20.7 & CSA C22.2 No. 0.22 on the nameplate of the electrical equipment and the specific, type and protection it provided. There was no plenum installed and they did not know about the ventilation ports on the top of the switchgear.

With respect to the low voltage switchgear the Qualified Persons were not aware if the electrical protective relays on the low voltage power circuit breakers had been programed to change settings when the maintenance mode switches were turned on and that the stand-alone arc flash relay had been programmed and was active. They were not even aware what the arc flash relay was. Installed arc flash and shock equipment labels had not been referred to and they had not been completing a formal work task-based arc flash risk assessment and documenting it on a formal Energized Electrical Job Safety Planning form until the training that was provided was been implemented.

No technical skills training had been provided for the new low voltage switchgear and the Qualified Persons did not have access to the commissioning report to confirm if relays had been programmed.

When the Qualified Persons were asked if they knew if the maintenance mode switches and integral arc flash relays had been programmed they said "No."

Even though a Qualified Person was assigned to perform work on the new high and low voltage switchgear without appropriate training, knowledge and skills they would be considered an Unqualified Person to work on this electrical equipment.

When the Qualified Persons were asked if they had access to a copy of the commissioning report for the electrical equipment they answered "No" and they were not aware of who may have it.

The white box is the arc flash relay on the low voltage switchgear, but it was not labeled with any identification as shown in Picture 1 and Picture 3. The Energy Reduction Maintenance Setting (ERMS) switch is shown in Picture 2.

Picture 1 – Hospital Low Voltage Switchgear

Picture 2 - The ERMS is the maintenance mode switch.

Picture 3 – Example Stand Alone Arc Flash Relay Installed

IV. IMPLICATIONS IF THE INCIDENT ENERGY IS NOT REDUCED BY PASSIVE OR ACTIVE REDUCTION METHOD

The examples below are provided to clarify the implications if incident energy reduction methods have not been programmed, commissioned and are active. Several other examples are also provided on how incident energy could be reduced or that indicate how the incident energy may be lower or higher depending on decisions made by the P.Eng. or PE Electrical Engineer.

As defined in NFPA 70E, Table 130.5(C) [1] and in CSA Z462 Table 2 [2] two arc-rated levels for arc flash PPE are recommended when incident energy analysis has been completed (e.g., you cannot call arc flash PPE by an HRC#, CAT #, or Level "letter" when incident energy analysis has been completed), everyday task wear with an ATPV of 1.2 to 12.0 cal/cm^2 or and arc flash suit with an >12.0 cal/cm^2 ATPV. Reference Figure 3 below.

As shown in Figure 3 below if the relays have not been programmed the incident energy may increase such that the Qualified Person is only wearing Level 1 arc-rated arc flash PPE when they actually required Level 2 arc-rated arc flash PPE and thus the residual burn injury received if they were exposed to an abnormal arcing fault and arc flash could be 3rd degree or worse.

Arc-Rating Level #	Arc Flash PPE Minimum Requirements
Level 1 **8.0-12.0 cal/cm²** **ATPV or E_{BT}** 	**Body:** Everyday/task wear long sleeved shirt/pant or coverall (with storage bag). 100% natural fibre clothing to be worn underneath. **Emergency Rescue:** "Escape Strap" vest available for use. **Head & Face:** CSA approved eyewear, clear lens. Arc-rated balaclava and arc-rated face shield (with storage bag) with true colour grey lens, CSA approved Class E hard hat and LED lamp. **Hearing:** CSA approved minimum ear canal insert ear plugs. **Hands:** Appropriate Class # of rubber insulating gloves with protectors (with storage bag sized to the Class #). **Footwear:** CSA approved Ohm rated leather/rubber footwear. Note: Rubber insulating gloves with protectors provide arc flash protection for the hands. Where there is no electric shock hazard exposure heavy duty leather work gloves or specifically tested arc-rated gloves provide arc flash protection for the hands.
Level 2 **Minimum 75, 100 or 140 cal/cm²** **ATPV** 	**Body:** Arc flash suit: bib overalls, and jacket with "Escape Strap." 100% natural fibre clothing to be worn underneath. Manufacturer's storage bag. **Emergency Rescue:** "Escape strap" can be used. **Head & Face:** CSA approved eyewear, clear lens. Arc flash suit hood with true colour grey lens, CSA approved Class E hard hat, arc flash suit hood ventilation system and LED lamp. **Hearing:** CSA approved minimum ear canal insert ear plugs. **Hands:** Appropriate Class # of rubber insulating gloves with protectors (with storage bag sized to Class #). **Footwear:** CSA approved Ohm rated leather/rubber footwear. Note: Rubber insulating gloves with protectors provide arc flash protection for the hands. Where there is no electric shock hazard exposure heavy duty leather work gloves or specifically tested arc-rated gloves provide arc flash protection for the hands. Arc flash suits are available with an ATPV of up to 140.0 cal/cm² and can be procured for use.

Figure 3 – Two Arc-Rated Arc Flash PPE Levels

A. High Voltage Working Distance

If the working distance related to exposure to an abnormal arcing fault and arc flash is reduced by the Qualified Person incident energy can increase significantly due to an inverse squared relationship it has in impacting calculated incident energy. Review Table 2 below that illustrates the change in incident energy in relationship to the change in working distance for the high voltage electrical equipment example. Review Table 3 for the change in incident energy in relationship to the change in working distance for low voltage electrical equipment.

It is important that the Qualified Person is trained that they must maintain the minimum working distance listed on the detailed arc flash and shock equipment label to their face and torso or incident energy will increase, and they may not be adequately protected.

Bus Name	Protective Device Name	Bus kV	Bus Bolted Fault (kA)	Bus Arcing Fault (kA)	Prot Dev Bolted Fault (kA)	Prot Dev Arcing Fault (kA)	Trip/ Delay Time (sec.)	Breaker Opening Time/Tol (sec.)	Equip Type	Electrode Config	Box Width (in)	Box Height (in)	Box Depth (in)	Gap (mm)	Arc Flash Boundary	Working Distance	Incident Energy (cal/cm2)
SWGR-8000	FPR-8000 (Phase)	15.00	15.64	14.74	15.39	14.50	0.2071	0.0833	SWG	VCBB	30	45	30	152	9' 11"	18"	28.1
	FPR-8000 (Phase)	15.00	15.64	14.74	15.39	14.50	0.2071	0.0833	SWG	VCBB	30	45	30	152	9' 10"	30"	12.0
	FPR-8000 (Phase)	15.00	15.64	14.74	15.39	14.50	0.2071	0.0833	SWG	VCBB	30	45	30	152	9' 10"	32"	10.7
	FPR-8000 (Phase)	15.00	15.64	14.74	15.39	14.50	0.2071	0.0833	SWG	VCBB	30	45	30	152	9' 10"	36"	8.8
	FPR-8000 (Phase)	15.00	15.64	14.74	15.39	14.50	0.2071	0.0833	SWG	VCBB	30	45	30	152	9' 10"	40"	7.4

Table 2 – High Voltage Working Distance

B. Low Voltage Working Distance

If the working distance related to exposure to an abnormal arcing fault and arc flash is reduced by the Qualified Person incident energy can increase significantly due to an inverse squared relationship it has in impacting calculated incident energy. Review Table 3 below.

Bus Name	Protective Device Name	Bus kV	Bus Bolted Fault (kA)	Bus Arcing Fault (kA)	Prot Dev Bolted Fault (kA)	Prot Dev Arcing Fault (kA)	Trip/ Delay Time (sec.)	Breaker Opening Time/Tol (sec.)	Equip Type	Electrode Config	Box Width (in)	Box Height (in)	Box Depth (in)	Gap (mm)	Arc Flash Boundary	Working Distance	Incident Energy (cal/cm2)
MB-8100	FPR-TX1 (Phase)	0.48	49.32	35.21	44.50	31.77	0.2000	0.0833	MCC	VCBB	12	14	10	25	9' 0"	18"	31.1
	FPR-TX1 (Phase)	0.48	49.32	35.21	44.50	31.77	0.2000	0.0833	MCC	VCBB	12	14	10	25	9' 0"	30"	12.3
	FPR-TX1 (Phase)	0.48	49.32	35.21	44.50	31.77	0.2000	0.0833	MCC	VCBB	12	14	10	25	9' 0"	32"	11.0
	FPR-TX1 (Phase)	0.48	49.32	35.21	44.50	31.77	0.2000	0.0833	MCC	VCBB	12	14	10	25	9' 0"	36"	8.9
	FPR-TX1 (Phase)	0.48	49.32	35.21	44.50	31.77	0.2000	0.0833	MCC	VCBB	12	14	10	25	9' 0"	40"	7.3

Table 3 Low Voltage Working Distance

C. High Voltage Relay Maintenance Mode ON and OFF

In the case shown in Table 4, if the maintenance mode has not been programmed and was turned on and the digital relay programming did not change from Group A settings (e.g., properly coordinated) to Group B settings (e.g., no intentional delay) then the Qualified Person would not be adequately protected, they would require Leve 2 arc flash PPE when they are only wearing Level 1 arc flash PPE.

Figure 4 is the single line diagram related to Table 4 below for MB 8100.

Bus Name	Protective Device Name	Maintenance Mode	Bus kV	Bus Bolted Fault (kA)	Bus Arcing Fault (kA)	Prot Dev Bolted Fault (kA)	Prot Dev Arcing Fault (kA)	Trip/ Delay Time (sec.)	Breaker Opening Time/Tol (sec.)	Equip Type	Electrode Config	Box Width (in)	Box Height (in)	Box Depth (in)	Gap (mm)	Arc Flash Boundary	Working Distance	Incident Energy (cal/cm2)
MB-8100	FPR-TX1 (Phase)	OFF	0.48	49.32	35.21	44.50	31.77	0.2000	0.0833	MCC	VCBB	12	14	10	25	9' 0"	18"	31.1
	FPR-TX1 (Phase Maint.)	ON	0.48	49.32	35.21	44.50	31.77	0.0167	0.0833	MCC	VCBB	12	14	10	25	5' 3"	18"	11.4

Table 4 – High Voltage Relay Maintenance Mode On and OFF - Reduction In Incident Energy on MCC

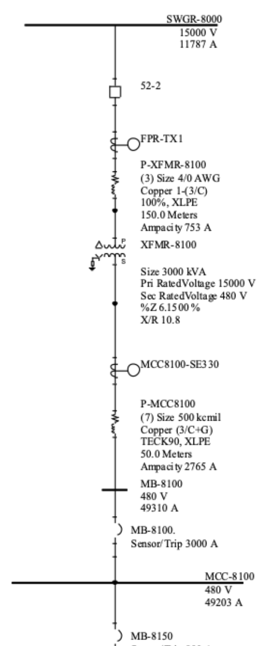

Figure 4 – High & Low Voltage Single Line Diagram

D. TCC High Voltage Relay Maintenance Mode OFF

The Time Current Curve (TCC) in Figure 5 would be the normally coordinated electrical protective device settings. In this case the incident energy on MCC 8100 is calculated to be 31.1 cal/cm² at a working distance of 18 inches.

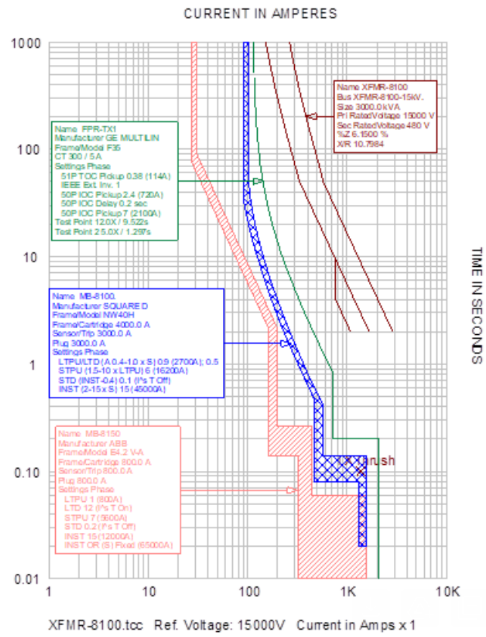

Figure 5 – TCC High Voltage Relay Maintenance Mode ON

The TCC in Figure 6 would be the temporary settings for the FPR-TX1 relay such that the incident energy level expected on MCC 8100 is 11.4 cal/cm^2 at a working distance of 18 inches.

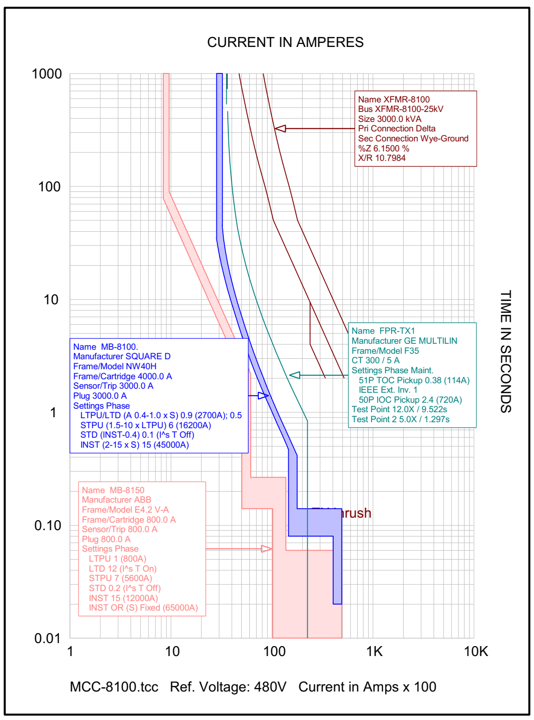

Figure 6 – TCC Low Voltage MCC Maintenance Mode ON

E. Low Voltage Main Breaker Maintenance Mode ON and OFF

In this case in Table 5 below for MCC 8100 its' Main Circuit Breaker's normal settings achieve 15.7 cal/cm^2 of incident energy at a working distance of 18 inches and a maintenance mode setting would be required to reduce the incident energy to 6.9 cal/cm^2 at 18 inches working distance.

Bus Name	Protective Device Name	Maintenance Mode	Bus kV	Bus Bolted Fault (kA)	Bus Arcing Fault (kA)	Prot Dev Bolted Fault (kA)	Prot Dev Arcing Fault (kA)	Trip/ Delay Time (sec.)	Breaker Opening Time/Tol (sec.)	Equip Type	Electrode Config	Box Width (in)	Box Height (in)	Box Depth (in)	Gap (mm)	Arc Flash Boundary	Working Distance	Incident Energy (cal/cm2)
MCC-8100	MB-8100. (Phase)	OFF	0.48	49.21	35.17	44.39	31.72	0.1400	0.0000	MCC	VCBB	12	14	10	25	6' 3"	18"	15.7
	MB-8100. (Maint)	ON	0.48	49.21	35.17	44.39	31.72	0.0600	0.0000	MCC	VCBB	12	14	10	25	3' 11"	18"	6.9

Table 5 – Low Voltage Main Breaker Maintenance Mode ON and OFF

F. High Voltage Arc Flash Relay ON or OFF

As depicted in Table 6 below it demonstrates that if an arc flash relay is not programmed then incident energy could increase by 600%.

Bus Name	Protective Device Name	Arc Flash Detection	Bus kV	Bus Bolted Fault (kA)	Bus Arcing Fault (kA)	Prot Dev Bolted Fault (kA)	Prot Dev Arcing Fault (kA)	Trip/ Delay Time (sec.)	Breaker Opening Time/Tol (sec.)	Equip Type	Electrode Config	Box Width (in)	Box Height (in)	Box Depth (in)	Gap (mm)	Arc Flash Boundary	Working Distance	Incident Energy (cal/cm2)
52-0.	511A-P_Normal (Phase)	OFF	15.00	15.64	14.74	15.39	14.50	0.4815	0.0833	SWG	VCBB	30	45	30	152	14' 8"	3' 0"	17.1
	511A-P_Normal (AFD)	ON	15.00	15.64	14.74	15.39	14.50	0.0010	0.0833	SWG	VCBB	30	45	30	152	4' 9"	3' 0"	2.6

Table 6 – High Voltage Arc Flash Relay ON or OFF

G. TCC Arc Flash Relay Programmed and Active

The TCC in Figure 7 below would be the electrical protective device setting including the arc flash relay. In this case the incident energy on the load side is calculated to be 2.6 cal/cm^2 and energized electrical work performed would only require Level 1 arc flash PPE.

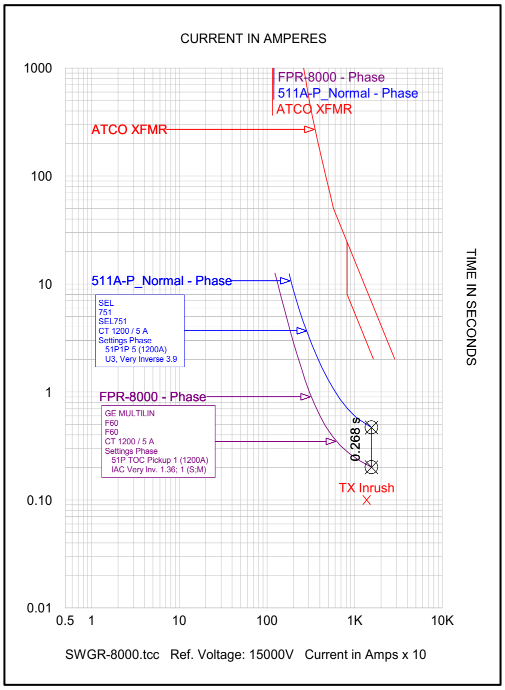

Figure 7 – TCC Arc Flash Relay Programmed and Active

H. TCC Arc Flash Not Active

The TCC if Figure 8 below would be the normal settings for the relay such that the incident energy level expected will be 17.4 cal/cm^2 and a Level 2 arc flash PPE arc flash suit would be required to be worn for energized electrical work tasks.

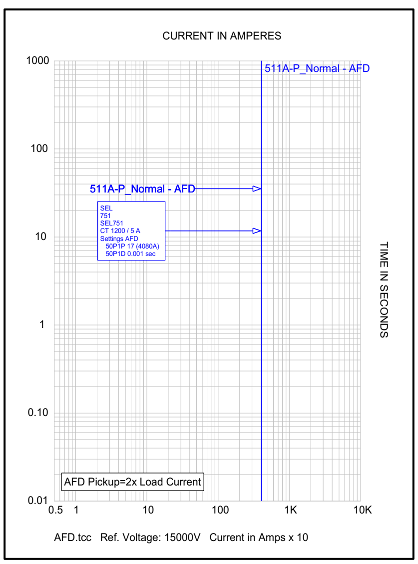

Figure 8 – TCC Arc Flash Not Active

I. Box / Electrode Configuration Impact On Incident Energy

In Table 6 below it illustrates how the calculated incident energy would change if the incorrect IEEE 1584 box/electrode configuration is selected. If the IEEE 1584 Horizontal Conductor/Electrodes inside a metal Box/enclosure (HCB) is used when it is not applicable the table indicates incident energy would increase by over 100%.

Bus Name	Protective Device Name	Bus kV	Bus Bolted Fault (kA)	Bus Arcing Fault (kA)	Prot Dev Bolted Fault (kA)	Prot Dev Arcing Fault (kA)	Trip/ Delay Time (sec.)	Breaker Opening Time/Tol (sec.)	Equip Type	Electrode Config	Box Width (in)	Box Height (in)	Box Depth (in)	Gap (mm)	Arc Flash Boundary	Working Distance	Incident Energy (cal/cm2)
MB-8100	FPR-TX1 (Phase)	0.48	49.32	31.13	44.50	28.09	0.2000	0.0833	MCC	VCB	12	14	10	25	9' 0"	18"	21.2
	FPR-TX1 (Phase)	0.48	49.32	35.21	44.50	31.77	0.2000	0.0833	MCC	VCBB	12	14	10	25	9' 0"	18"	31.1
	FPR-TX1 (Phase)	0.48	49.32	30.90	44.50	27.88	0.2000	0.0833	MCC	HCB	12	14	10	25	8' 8"	18"	42.4

Table 6 – Box / Electrode Configuration Impact On Incident Energy

V. CONCLUSIONS

In two separate cases Qualified Persons were not adequately trained and were making assumptions with respect to incident energy and the arc flash boundary distance provided to them on installed arc flash and shock equipment labels without validation.

Human error probability needs to be managed with the respect to the Qualified Person applying risk control methods. Passive and active "Prevention through Design (PtD)" incident energy reduction methods need technical skills training, confirmation that documented inspection and test procedures have been implemented and that procedures be followed to confirm they are functioning as intended or the actual incident energy could be 300 to 400% higher. A formal Energized Electrical Job Safety Plan (EEJSP) with completed form is a valuable administrative tool to use to have Qualified Persons formally assess hierarchy or risk control methods they have been provided by their employer.

Knowledge and skills training for new electrical equipment the Qualified Person has never been exposed to needs to be funded by the capital project. A Qualified Person may be trained on specific electrical equipment and a specific manufacturer but may not be trained on a different manufacturer of the same electrical equipment or new electrical equipment that is different than an older design. Formal procedures been documented and adding formal Notice signage on the electrical equipment (see Figure 9, 10 and 11 below) can be used to increase awareness to the Qualified Person that they need to ensure incident energy reduction methods installed are used and active.

As illustrated in this paper if the incident energy reduction methods installed are not active the Qualified Person will not be wearing adequate arc flash PPE provided to them to wear and their residual risk with be high. The arc flash boundary would also be a shorter distance.

The Qualified Person must be trained on the electrical equipment and the passive and active incident energy reduction methods installed, follow a procedure and be competent with respect to each manufacturer's operating instructions with enhanced safety features. Retraining or additional training may be required at regular intervals to maintain competency.

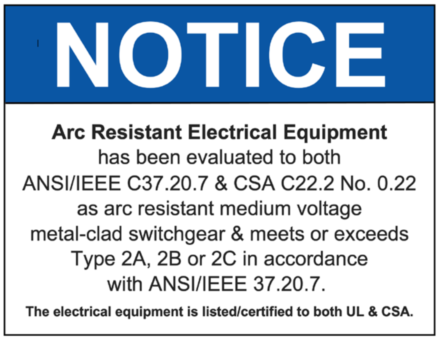

Figure 9 Notice Signage Arc Resistant Electrical Equipment

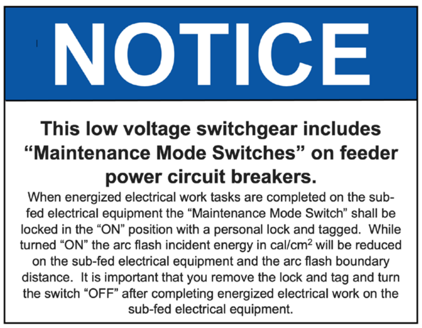

Figure 10- Notice Signage Maintenance Mode Installed

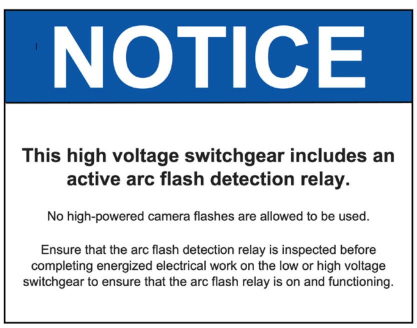

Figure 11 – Notice Signage Arc Flash Relay Installed

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VII. VITA

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Terry has presented on electrical safety at over ninety-five (95) conferences and workshops in Canada, the USA, Australia, India and Italy. Terry has been authoring the "Electrical Safety Measures" articles every two months for Electrical Line Magazine (www.electricalline.com) for over 10 years.

How Artificial Intelligence Can Help Improve Arc Flash Predictive Models

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Abstract – Over the years, various techniques were proposed to predict arc flash incident energy. Empirical models based on test results obtained from arc flash experiments performed in laboratories were developed using statistical methods to fit the experimental data, such as linear and polynomial regression. In recent years, the development of artificial intelligence has brought to light several machine learning (ML) techniques that can be used to train regression models on arbitrary sets of labeled data. In this work, we applied 32 state-of-the-art machine learning techniques on the IEEE 1584-2018 arc flash dataset, used as the learning dataset, and evaluated our models on the EPRI-2021 dataset, used as the holdout dataset. Using training/validation/test splits in the learning dataset, we identified the Bagging regressor as our best ML model, with superior ability to predict incident energy in the learning and holdout datasets when compared to the baseline IEEE 1584-2018 model. When further evaluated and compared with the baseline on the holdout dataset, this ML model achieved a 25 % reduction in the mean absolute error (MAE) between measured and predicted incident energy (MAE: 2.8008 to 2.0949 cal/cm^2). This translated in an improved coefficient of determination (R^2) of 0.3186 for the baseline to 0.7028 for our best ML model. Overall, this work aims to increase electrical workers' safety by proposing ML techniques that could lead to the development of more accurate models for arc flash incident energy prediction. Future work in this field could focus on various topics, such as physics-informed neural networks.

Index Terms — Arc flash, artificial intelligence, machine learning, regression, electrical power engineering

I. INTRODUCTION

The arc flash phenomenon corresponds to the heat and light that are produced following a fault in an electrical power system. This phenomenon can create discharges of thermal energy that can severely burn electrical workers, which can result in major injuries or death. The intensity of the incident energy of an arc flash event is quantified in calories per square centimeter (cal/cm^2) [1]. Arc flash events can occur in open air or inside physical cabinets (boxes). Over the years, attempts have been made to develop equations that can predict this energy based on different input parameters that describe the physical and electrical properties of equipment, using diverse statistical regression analysis techniques.

Starting in the 1980's, Lee's model was developed, which could very conservatively estimate the arc flash incident energy based on a limited set of input parameters: the bolted-fault short-circuit current, the system phase-to-phase voltage, the arc duration and the distance from the arc source (working distance) [2]. The equations were based on measured incident energy and the analysis of the maximum power measured for arc flash events of different fault currents [2]. This method was limited to arcs in open air, was conservative over 600 volts and became more conservative as voltage increased. In the late 1990's, Doughty et al. developed equations that better described the arc flash incident energy below 600 volts both in open air and inside boxes [3]. It was discovered that the heat reflected on the metallic surfaces inside the box was concentrating the heat that was directed towards the worker, thus increasing the incident energy of the arc flash blasts when compared to arc flash events in open air [3]. In the early 2000's, the first iteration of the IEEE 1584 standard was developed: IEEE 1584-2002 [4]. Based on around 300 tests performed in laboratories, regression techniques were applied to the laboratory data to develop equations that could predict the incident energy. In the late 2010's, the second iteration of the IEEE 1584 standard was developed: IEEE 1584-2018 [5]. Based on around 1860 tests performed in laboratories (the dataset that comprises these test results will be referred to as the IEEE 1584-2018 dataset in this article), regression techniques were applied to the laboratory data to develop equations that could more accurately predict the incident energy of arc flash events. In this version of the standard, several new input parameters were introduced, including the electrode configuration, which is a categorical input (feature) that can be one of either 5 choices: (i) VCB: Vertical Conductors inside a

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Box; (ii) VCBB: Vertical Conductors terminated in an insulating Barrier inside a Box; (iii) HCB: Horizontal Conductors inside a Box; (iv) VOA: Vertical conductors in Open Air; or (v) HOA: Horizontal conductors in Open Air.

In 2021, around 300 independent tests done by the Electric Power Research Institute (EPRI) laboratory (the dataset that comprises these test results will be referred to as the EPRI-2021 dataset in this article) showed some limitations with the IEEE 1584-2018 model at medium voltage, where several tests measured 2 to 3 times as much energy as the IEEE 1584-2018 model would predict [6]. Both the IEEE 1584-2018 and EPRI-2021 datasets were also published as open-access on the IEEE DataPort dataset storage platform and can be accessed by any person with a valid IEEE DataPort subscription [7].

In parallel, the field of artificial intelligence (AI) has been the subject of massive research and interest over recent years. As a subset of AI, machine learning (ML) can be described as the field of applications of AI that defines techniques to train models that can automatically learn and improve from experience. Various ML regression techniques have been developed and perfected through the years to train predictive models on any dataset. In this work, our objective is to train multiple ML algorithms on the IEEE 1584-2018 dataset and evaluate the models' performance on both the IEEE 1584-2018 and EPRI-2021 datasets, to see if these techniques can be used to develop more accurate models for arc flash energy prediction. To this end, we developed a pipeline to train and evaluate 32 ML regression methods with various parameters and scaling methods in order to find the model that yields the highest predictive capabilities. To our knowledge, using ML techniques to improve arc flash predictive models has never been attempted.

The rest of this article is organized as follows. Section II describes the key concepts of ML used in the context of regression. Brief descriptions for each of the 32 ML regression methods applied in this article are presented in Section III. The methodology that was developed to perform calculations and evaluate the different ML algorithms is presented in Section IV. Then, Section V shows the results obtained. A discussion on the results and future work is provided in Section VI. Finally, Section VII concludes this article.

II. MACHINE LEARNING FOR REGRESSION

A. Introduction

ML models can be used for various tasks that are split into two different schemas: unsupervised and supervised learning. Unsupervised learning is used when ML models are trained with input features only: the associated outputs or labels are unknown. These kinds of algorithms can be used for tasks such as clustering and association, where the algorithms seek to identify different clusters or groups within the data. On the other hand, supervised learning is used when ML models are trained with input features as well as expected output values. In that case, models are trained to predict the output values given the input values. The most common supervised learning tasks are classification (predicting a category) and regression (predicting a continuous value). For the arc flash prediction problem, we do not use unsupervised learning, as our training data contains input features as well as measured output values from tests performed in laboratories. Instead, we use a supervised learning schema with regression algorithms.

When training a ML model, it is good practice to have two separate datasets: one for model development (we call this a learning dataset) and one for final performance evaluation (we call this a holdout dataset). If the performance of a model is evaluated on the same dataset that was used to train it, a biased performance result could be obtained since the model might have memorized the training data. Differently put, a model showing a very high performance when evaluated on the learning dataset will not necessarily perform well on new never-seen-before data: this concept is called overfitting. To avoid overfitting, we typically evaluate the final model's performance on a completely separate dataset that the model has not been trained on: the holdout dataset. Furthermore, the learning dataset is typically shuffled and split into a training and a test set: the model is trained on the training set, and the various models trained during the study can be compared against one another on the test set. The size of the test set typically varies from 10 % to 20 % of the entire size of the learning dataset: the remainder goes into the training set. Once the final model has been selected as the highest performing model when evaluated on the test set, this final model is retrained on the entire learning dataset and evaluated on the holdout dataset to obtain the final accuracy of the model.

In both the IEEE 1584-2018 and EPRI-2021 datasets, all features are numerical, except the electrode configuration which is a categorical feature. There are multiple ways to handle categorical features as part of ML regression problems. One method is to train a separate sub-regressor for each categorical value and combine the models as part of a meta-ensemble of regressors. Another method commonly used is one-hot encoding, where the categorical feature of N possible values is split into a N-sized binary vector where, for each data point, only the bit corresponding to the current category of the data point is set to 1, and all the other bits are set to 0. Regression algorithms can be trained once categorical features are encoded into numerical feature vectors.

B. Hyperparameter Selection

When training a ML model, lower-level model parameters are optimized in order to predict accurate outputs given the inputs of a dataset. Some additional higher-level parameters are selected during the training process, such as the choice of optimization metric, the learning rate or the input feature scaling method: these higher-level parameters are called hyperparameters. For a given problem, the set of hyperparameters that will result in the highest performance is almost impossible to know in advance. For that reason, a hyperparameter search is typically performed as follows: a combination of hyperparameters is selected, the model is trained, and the performance for this specific set of hyperparameters is obtained, then these steps are repeated several times with different sets of hyperparameters until the set of hyperparameters that results in the highest predictive performance is found.

A common way to evaluate the performance of hyperparameter combinations is by applying k-fold cross-validation (CV). In this approach, the training data is split into k splits: the model is trained on $k-1$ splits (we call these splits the training splits) and evaluated on 1 split (we call this split the validation split) iteratively until every split has been evaluated on. The mean evaluation performance over all validation splits is then used as the comparison metric across different sets of hyperparameters. When data is split into different classes, or when the data has a categorical feature that can be interpreted as a class, a stratified k-fold CV approach can be used, where the folds are split in order to keep the same proportion of classes across splits (in our case, the classes are represented by the electrode configuration: for regressors trained on sets with multiple possible electrode configurations, each split contains a similar distribution of every electrode configuration).

Several strategies can be used to conduct a hyperparameter search. One popular approach is the grid search, where each value to evaluate for every hyperparameter is specified: then, CV is performed for each possible combination of all these hyperparameters. While being very thorough as every single combination is tested, this strategy can become extremely computationally intensive with a large hyperparameter search space. Another popular approach is the random search, where all values to evaluate for each hyperparameter are specified, but only a random subset of the combinations of these hyperparameters gets evaluated. With this strategy, the computational intensity can be varied by adjusting the number of iterations of the random hyperparameter combination sampler. One more interesting approach consists in using the *Optuna* optimization framework, which is an open-source Python package that implements Bayesian hyperparameter optimizations such as Tree Parzen [8]. With this package, the minimum and maximum values of a range can be defined for hyperparameters rather than absolute values along with a number of trials: the optimizer then automatically navigates the hyperparameter search space and finds optimal hyperparameter combinations through successive trial runs, moving through the hyperparameter space in the direction which maximizes (or minimizes) a specified evaluation metric.

C. Input Feature Scaling

Typically, input values are scaled as part of a data pre-processing step before supplying the data to the ML algorithm for training. For reference, in the IEEE 1584-2018 model [5], the input variables are scaled by applying a natural logarithm transformation on them. Note that different input feature scaling methods can yield higher or lower performance on different datasets: the input feature scaling method is a hyperparameter that needs to be optimized as part of the hyperparameter selection process. The scaling methods evaluated in this article are detailed below. Equations (1) to (4) contain the following variables: i represents the input sample index, x_i represents the original value, x_i' represents the scaled value, μ represents the mean value of a feature, σ represents the standard deviation of a feature, x_{min} represents the minimum value of a feature, x_{max} represents the maximum value of a feature, $\tilde{x}$ represents the median value of a feature and IQR represents the interquartile range of a feature ($IQR = Q_3 - Q_1$).

1) *Log*: A natural logarithm is applied to the input data using the following equation:

$$x_i' = \log(x_i) \tag{1}$$

2) *Standard*: A standard scaling (also called standardization) is applied to the input data using the following equation:

$$x_i' = \frac{x_i - \mu}{\sigma} \tag{2}$$

3) *Minmax*: A minmax scaling (also called normalization) is applied to the input data using the following equation:

$$x_i' = \frac{x_i - x_{min}}{x_{max} - x_{min}} \tag{3}$$

4) *Robust:* A robust scaling (which is robust to outliers) is applied to the input data using the following equation:

$$x_i' = \frac{x_i - \tilde{x}}{IQR} \tag{4}$$

D. Performance Evaluation

Several evaluation metrics are used in regression problems in the context of ML. These evaluation metrics are used in CV to select which set of hyperparameters is optimal based on the mean score across all splits. Moreover, some ML regression methods have objective functions (also called cost functions or loss functions), which some can be optimized. The performance evaluation metrics used in this article are detailed below. Equations (5) to (7) contain the following variables: i represents the input sample index, N represents the total number of output values, y_i represents the measured output value (also called the ground truth), $\hat{y}_i$ represents the output value predicted by the model and $\bar{y}$ represents the mean of the measured output values.

1) *Coefficient of Determination (R^2)*: The coefficient of determination, also called the R^2 coefficient, is often treated as the most common and informative metric to evaluate and compare regression models [9]. This coefficient can be calculated with the following formula (higher is better, range is $[-\infty,\ 1]$):

$$R^2 = 1 - \frac{\sum_{i=1}^{N}(y_i - \hat{y}_i)^2}{\sum_{i=1}^{N}(y_i - \bar{y})^2} \tag{5}$$

2) *Mean Absolute Error (MAE)*: This error evaluates the absolute error between the measured and predicted values: it is generally considered to be robust to outliers and noise. The mean absolute error can be calculated with the following formula (lower is better, range is $[0,\ \infty]$):

$$MAE = \frac{1}{N}\sum_{i=1}^{N}|y_i - \hat{y}_i| \tag{6}$$

3) *Root Mean Squared Logarithmic Error (RMSLE)*: This error penalizes underpredictions more than overpredictions. It is well suited for the arc flash regression problem, since it can be used to optimize for models that tend to overpredict incident energy rather than underpredict. The root mean squared logarithmic error (RMSLE) can be calculated with the following formula (lower is better, range is $[0,\ \infty]$):

$$RMSLE = \sqrt{\frac{1}{N}\sum_{i=1}^{N}(\log(y_i + 1) - \log(\hat{y}_i + 1))^2} \tag{7}$$

After a model has been trained, a feature importance analysis can be performed to evaluate which features are the most important for a particular model. The approach we use in this article is feature permutation, where the values of a single feature are randomly shuffled and the degradation of the model's performance is observed across successive iterations. With this method, we can estimate the mean and standard deviation of performance decrease for each feature permutation operation, allowing us to evaluate the relative importance of each feature for the model. The feature permutation results do not reflect the predictive values of features themselves, but how important these features are for a certain model [31].

III. MACHINE LEARNING REGRESSION METHODS

Several ML regression methods have been applied in this paper: this section explains the basic principles behind these methods. Some models are grouped into larger families of models: ensemble, linear and tree-based models. Ensemble models aggregate two or more sub-models in order to produce better predictions. Linear models assume that the output can be predicted via a linear combination of the features. Tree-based models assume that the output can be predicted by learning decision rules inferred from the features.

1) *Ada Boost*: Ensemble model. Meta-estimator where multiple weak learners (decision trees, for example) are trained and combined to create a strong learner: each learner focuses on the errors of the previous one [10].

2) *ARD*: Linear model. Automatic Relevance Determination (ARD) is a Bayesian model which fits the weights of a regression model, using an ARD prior, assuming that these weights can be represented by Gaussian distributions [11].

3) *Bagging*: Ensemble tree-based model. Meta-estimator that fits base regressors on random subsets of the original dataset, then aggregates individual predictions via voting or averaging all predictions. In our case, the base regressors are decision trees [12].

4) *Bayesian Ridge*: Linear model. Variation of a regular Ridge regression which treats coefficients in a probabilistic manner via Bayesian assumptions: the model attempts to estimate a probability distribution for parameters, which can help the regression when working with small or noisy datasets [13].

5) *Decision Tree*: Tree-based model. Splits data into smaller groups based on features that best separate the outcomes. Structures itself via nodes, branches and leaves [14].

6) *Elastic Net*: Linear model. Combines both the Lasso and Ridge techniques to improve the regularization of regression models [15].

7) *Extra Tree*: Tree-based model. Extremely randomized tree regressor, the best splits to separate the samples into two groups are randomly selected across all features [16].

8) *Extra Trees*: Ensemble tree-based model. Meta-estimator that fits multiple extra-trees on different sub-samples of the dataset using averaging techniques [16].

9) *Gamma*: Linear model. Generalized Linear Model (GLM) with a Gamma distribution as its reproductive Exponential Dispersion Model (EDM) [17].

10) *Gaussian Process*: Bayesian method that predicts data using a probabilistic approach. It models data as samples from a Gaussian process, providing predictions along with uncertainties [18].

11) *Gradient Boosting*: Ensemble tree-based model. A series of decision trees are built sequentially, where each new tree corrects the errors made by the previous ones. All the tree's predictions are combined to make a final prediction. The model is optimized by minimizing errors using gradient descent methods [19].

12) *Histogram Gradient Boosting*: Ensemble tree-based model. Variant of Gradient Boosting that uses histograms to speed up the process of building decision trees, making it faster and more efficient on large datasets [20].

13) *Huber*: Linear model. Combines the robustness of median regression with the efficiency of least squares regression using a loss function that is quadratic for small errors and linear for large errors, making it robust to outliers [21].

14) *Kernel Ridge*: Combines Ridge regression with kernel methods to handle non-linear relationships by mapping input data to a higher-dimensional space using a kernel function, then applying Ridge regression in that space [22].

15) k*-Nearest Neighbors*: Predicts a value based on the average of the values from the k nearest training data points to the input [23].

16) *Lars*: Linear model. Least Angle Regression (LARS) is an algorithm used to fit linear regression models that incrementally adds predictors, adjusting coefficients as it goes to select the most relevant features while controlling model complexity [24].

17) *Lasso*: Linear model. Method that adds a penalty equal to the absolute value of the coefficients to the loss function, which helps in feature selection and regularization by shrinking some coefficients to zero [25].

18) *Lasso Lars*: Linear model. Lasso model trained with LARS [24], [25].

19) *Lasso Lars IC*: Linear model. Lasso model trained with LARS using the Akaike Information Criterion or Bayes Information Criterion [24], [25].

20) *Linear*: Linear model. Least squares linear regression finds the best-fitting line by minimizing the sum of the squared differences between observed and predicted values [26].

21) *Multi-Layer Perceptron*: Deep neural network with multiple layers that learns complex patterns by adjusting weights through backpropagation to predict continuous values [27].

22) *Orthogonal Matching Pursuit*: Linear model. Sparse modeling technique that iteratively selects the most relevant predictors while ensuring orthogonality to previously chosen ones [28].

23) *Passive Aggressive*: Linear model. An algorithm that updates model weights aggressively when errors are made, but remains passive and stable when predictions are accurate, adapting quickly to new data [29].

24) *Poisson*: Linear model. GLM with a Poisson distribution as its reproductive EDM [17].

25) *Quantile*: Linear model. Estimates specific quantiles of the output by fitting models that predict different points of the distribution [30].

26) *Random Forest*: Ensemble tree-based model. Builds multiple decision trees and averages their predictions to improve accuracy and reduce overfitting [31].

27) *RANSAC*: Linear model. RANdom SAmple Consensus (RANSAC) fits a model to data by iteratively selecting random subsets, fitting the model, and evaluating its robustness, which helps to handle outliers effectively [32].

28) *Ridge*: Linear model. Ridge regression adds a penalty proportional to the square of the coefficients' magnitude to the

loss function, which helps prevent overfitting by shrinking the coefficients [33].

29) *Stochastic Gradient Descent*: Linear model. Algorithm used to minimize the loss function of a linear regression by updating model parameters iteratively. Unlike traditional gradient descent, which uses the entire dataset for each update, Stochastic Gradient Descent updates parameters using a single training sample at a time [34].

30) *Support Vector Machine*: Finds a function that predicts values while keeping errors within a specified margin, using a hyperplane to fit the data and kernels to handle non-linear relationships [35].

31) *Theil Sen*: Linear model. Fits a line by taking the median of weights found by optimizing on randomly selected subsamples, making it robust to outliers [36].

32) *Tweedie*: Linear model. GLM with a Tweedie distribution as its reproductive EDM [17].

IV. METHODOLOGY

A. Baseline IEEE 1584-2018 Model Evaluation

By implementing the IEEE 1584-2018 model equations [5] and evaluating the results on both the test set and holdout dataset, we evaluated the performance of the IEEE 1584-2018 model to establish our baseline. For this evaluation, we used the calculated arcing current in the IEEE 1584-2018 model equations, not the measured arcing current. Since the datasets only contained a single fault duration value, we did not consider the minimum arcing current step of the calculations, as no fault duration could be inferred for the calculated minimum arcing current value.

B. Experiment Setup

In order to train our best performing model for arc flash energy prediction, an experiment setup was devised (see Fig. 1).

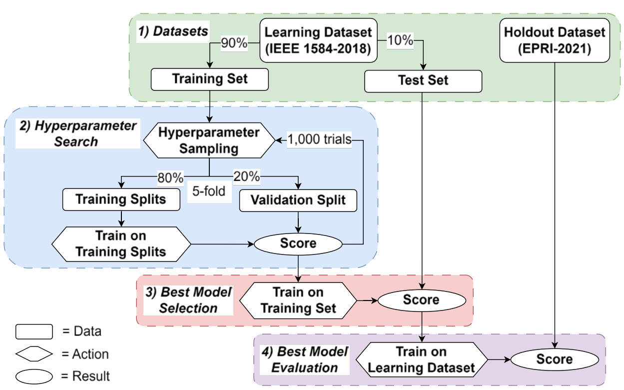

Fig. 1 Experiment Setup. 1) Datasets are processed and split into different sets (green). 2) Hyperparameter searches are performed for all models (blue). 3) All models are trained on the training set and evaluated on the test set (red). 4) Our best model is trained on the learning dataset and evaluated on the holdout dataset (purple).

Multiple input feature scaling methods were described in Section II. C, and we wanted to evaluate the impact of those scaling methods on the performance of the models. For this reason, every model has been trained with 4 different input feature scaling methods: log, standard, minmax & robust. Overall, for 32 ML regression methods, each trained for 6 different sub-regressor configurations, each trained with 2 different sets of box size input features (Height, Width and Depth or CF only), each trained with 4 different normalization methods, we trained a total of 1,536 models. For each of these models, a hyperparameter search has been performed (blue box in Fig. 1). After the best hyperparameters were found, all 1,536 models were trained on the training set and evaluated on the test set to find our best model (red box in Fig. 1). Finally, our best model was trained on the learning dataset and evaluated on the holdout dataset (purple box in Fig. 1). Detailed explanations on the experiment setup are given below.

1) *Datasets:* For this study, the IEEE 1584-2018 dataset was used as the learning dataset and the EPRI-2021 dataset was used as the holdout dataset [7]. The raw learning dataset contained 1,871 data points, while the raw holdout dataset contained 229 data points. Data points where any of the features or output values were missing or invalid were ignored. Two outliers, sequences 1610 and 1611, were identified in the learning dataset by computing the cosine similarity between samples and evaluating where the measured energy was extremely different for very similar input values. For test sequence 1610, the measured incident energy is 60 cal/cm^2, with almost identical input parameters as test sequence 1609 with a measured incident energy of 11.7 cal/cm^2 (except a very minor 0.5 millisecond (0.07 %) difference in duration of fault). For test sequence 1611, the measured incident energy is 129.3 cal/cm^2, with almost identical input parameters as test sequence 1614 with a measured incident energy of 6.5 cal/cm^2 (except a very minor 1.4 millisecond (0.3 %) difference in duration of fault). Due to these anomalous comparative results, test sequences 1610 and 1611 were treated as outliers and were excluded from the learning dataset. After this filtering operation was performed, the learning dataset contained 1,730 valid data points and the holdout dataset contained 212 valid data points. The learning dataset was shuffled and split into a training set and a test set, with a test set size of 10 %, using a stratified splitting strategy to split the different electrode configurations evenly across both sets. One-hot encoding was used to encode the electrode configuration into numerical features when training regressors where multiple electrode configurations could be encountered. In the holdout dataset, the depth of boxes was missing: a value of 36 inches (914.4 millimeters) was assumed for all data points (this depth value was used for all 14.4 kilovolts data points in the learning dataset). All data points where the electrode configuration was set to “Transformer” or “PMH-[…]” were considered as the HCB electrode configuration, as described in the paper which accompanies the dataset [6]. Both for the IEEE 1584-2018 and EPRI-2021 datasets, all box dimensions were converted from inches to millimeters as part of the data pre-processing step. The list of input features used to train the models is detailed below:

- V_{oc}: Line-to-line system voltage (in kilovolts).
- Height: Box height (in millimeters).
- Width: Box width (in millimeters).
- Depth: Box depth (in millimeters).
- G: Electrode gap (in millimeters).
- I_{bf}: Bolted fault short-circuit current (in kiloamperes).
- t: Duration of fault (in milliseconds).

- D: Working distance (in millimeters).
- [VCB, VCBB, HCB, VOA, HOA]: One-hot vector for electrode configurations.
- CF: Enclosure size correction factor (calculated using the IEEE 1584-2018 model equations [5]).

The data was split into different sub-regressor configurations to evaluate if training specific sub-regressors for different splits of data could increase the overall performance of the model. A simple conditional statement can then direct any set of features to the right sub-regressor as part of the ensemble of regressors, and the performance metrics on the combined set of sub-regressors can be evaluated. The following list describes the different sub-regressor configurations considered in this article.

1) *Full*: 1 regressor with the full set of input features: [V_{oc}, Height, Width, Depth, G, I_{bf}, t, D, VCB, VCBB, HCB, VOA, HOA].
2) *Box – Open Air*: 2 regressors, one for arcs inside boxes with the following input features: [V_{oc}, Height, Width, Depth, G, I_{bf}, t, D, VCB, VCBB, HCB], and one for arcs in open air with the following input features: [V_{oc}, G, I_{bf}, t, D, VOA, HOA].
3) *Split Configs*: 5 regressors, one for each electrode configuration (VCB, VCBB, HCB, VOA, HOA), the 3 ones for arcs inside a box with the following input features: [V_{oc}, Height, Width, Depth, G, I_{bf}, t, D], the 2 ones for arcs in open air with the following input features: [V_{oc}, G, I_{bf}, t, D].
4) *LV – MV*: 2 regressors, one for low-voltage (LV) data points and one for medium-voltage (MV) data points, with the same input features: [V_{oc}, Height, Width, Depth, G, I_{bf}, t, D, VCB, VCBB, HCB, VOA, HOA].
5) *Box – Open Air – LV – MV*: 4 regressors, one for LV data points inside a box, one for MV data points inside a box, both with the following input features: [V_{oc}, Height, Width, Depth, G, I_{bf}, t, D, VCB, VCBB, HCB], one for LV data points in open air, one for MV data points in open air, both with the following input features: [V_{oc}, G, I_{bf}, t, D, VOA, HOA].
6) *Split Configs – LV – MV*: 10 regressors, 2 for each electrode configuration for LV & MV data points. The 6 ones for arcs inside a box with the following input features: [V_{oc}, height, width, depth, G, I_{bf}, t, D], the 4 ones for arcs in open air with the following input features: [V_{oc}, G, I_{bf}, t, D].

A threshold of 1 kilovolt for the distinction between the LV and MV sets was chosen (a threshold of 0.6 kilovolts is used in the IEEE 1584-2018 model to switch between equations for LV and MV systems [5], but since multiple data points were on the edge at 0.601 kilovolts and would have been included in the MV set rather than the more appropriate LV set, a higher value of 1 kilovolts was selected). In the IEEE 1584-2018 model [5], the arc flash incident energy equations do not directly use Height, Width and Depth features for arcs inside a box: a hand-crafted feature named CF (Enclosure Size Correction Factor) calculated with Height, Width and Depth is used instead. As part of this work, we wanted to evaluate if models performed better when using the three original Height, Width and Depth features or the hand-crafted CF feature only. To this end, all models are evaluated with these two combinations of input features for regressors that are applied to arcs inside boxes. Fig. 2 shows the number of samples per split for each different sub-regressor configurations considered for the learning dataset (see the $n1$ values) and for the holdout dataset (see the $n2$ values). Note that in the holdout set, due to a limited number of data points, some sub-regressor configurations have no data points ($n2 = 0$). These sub-regressors could therefore not be evaluated on the holdout dataset: the results obtained on the EPRI-2021 dataset shown in Section V are only for the sub-regressor configurations for which $n2 > 0$.

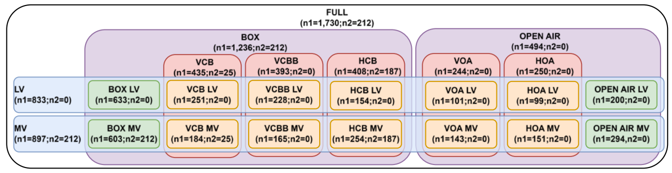

Fig. 2 Sub-Regressor Configurations. White: *1) Full*, Purple: *2) Box – Open Air*, Red: *3) Split Configs*, Blue: *4) LV – MV*, Green: 5) *Box – Open Air – LV – MV,* Orange: *6) Split Configs – LV – MV.*

2) *Hyperparameter Search:* Hyperparameter searches in the training set were performed using the *Optuna* library [8] with 1,000 trials over a comprehensive range of hyperparameters for each regression method. 5-fold stratified CV iterations were performed and the folds with the lowest mean RMSLE on the validation split across all 5 folds were selected as the best hyperparameters.

3) *Best Model Selection:* After CV, the 1,536 models were retrained on the entire training set with the selected hyperparameters and evaluated on the test set: the main results are shown in Table I and Fig. 3. The model with the lowest RMSLE on the test set was selected as our best model.

4) *Best Model Evaluation:* Then, our best model was retrained on the entire learning dataset and evaluated on the holdout dataset: the main results are shown in Table II and Fig. 4. For our best model, a feature importance chart was generated using the feature permutation technique as described in Section II. D, see Fig. 5. This feature permutation evaluation was conducted for 100 iterations on the learning dataset.

C. General

All code for this article was developed in Python using the *Scikit-learn* ML library. Computations were performed in a Linux-based environment on an AMD Ryzen 9 5900X CPU. In order to ensure reproducibility of the results over multiple runs, a random seed with a value of 54,288 has been assigned to all random number generator instances in the code. The total runtime required to perform all calculations for this study was around 200 hours.

V. RESULTS

A. Selection Of Our Best Model

The calculations performed in this study allowed us to find the best performing combinations of regression methods (with the best set of hyperparameters), sub-regressor configuration and scaling methods. We selected the best regression method that yielded the lowest RMSLE on the test set: we show the results in Table I. We found that the best performing model is the Bagging method [12], using the Full sub-regressor configuration and the Minmax scaling method. We also show the performance of the IEEE 1584-2018 baseline model on the test set for comparison. In Table I, improved metric measurements compared to the baseline model are shown in bold.

TABLE I
RESULTS – TEST SET (10% OF IEEE 1584-2018)

Model	R^2	RMSLE	MAE
(a) Our best	**0.6645**	**0.3915**	**2.4239**
(b) Baseline	0.0865	0.5824	3.6142

Fig. 3 (a) shows the predicted (calculated by the model) VS the measured incident energy for our best model and Fig. 3 (b) shows the predicted VS the measured incident energy for the baseline model when evaluated on the test set.

(a)

(b)

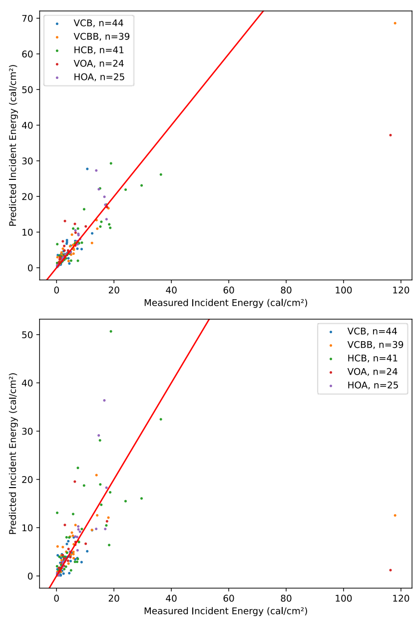

Fig. 3 Predicted VS measured incident energy (cal/cm^2) on the test set. (a) Our best model. (b) Baseline IEEE 1584-2018 model.

B. Evaluation Of Our Best Model

Our best model was then retrained on the learning dataset and evaluated on the holdout dataset: we show the results in Table II. We also show the performance of the IEEE 1584-2018 baseline model on the holdout dataset for comparison. In Table II, improved metric measurements compared to the baseline model are shown in bold.

TABLE II
RESULTS – HOLDOUT DATASET (EPRI-2021)

Model	R^2	RMSLE	MAE
(a) Our best	**0.7028**	0.5113	**2.0949**
(b) Baseline	0.3186	0.5029	2.8008

Fig. 4 (a) shows the predicted VS the measured incident energy for our best model on the EPRI-2021 dataset and Fig. 4 (b) shows the predicted VS the measured incident energy for the IEEE 1584-2018 baseline model on the EPRI-2021 dataset.

(a)

(b)

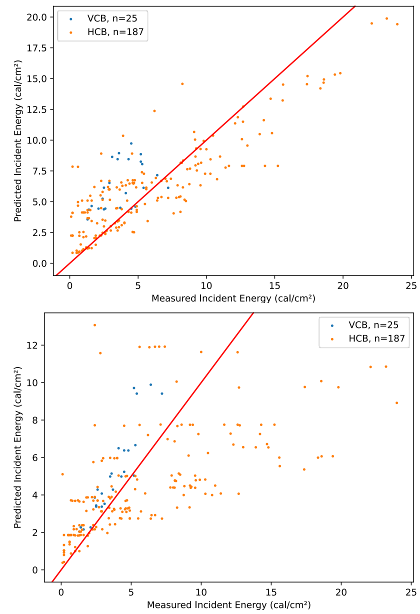

Fig. 4 Predicted VS measured incident energy (cal/cm^2) on the holdout dataset. (a) Our best model. (b) Baseline IEEE 1584-2018 model.

Fig. 5 shows the feature importance chart for our best model when evaluated on the learning dataset. The vertical black line on each bar represents the standard deviation (which represents the error) obtained across 100 feature permutation iterations.

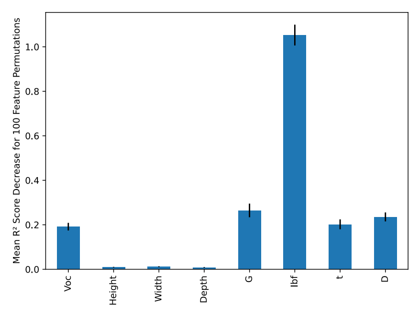

Fig. 5 Feature importance chart of our best model

VI. DISCUSSION

In this work, we wanted to identify the best performing ML regression methods when applied to different sub-regressor configurations and input feature scaling methods. We found that the best performing model architecture was the Bagging method [12], which is an ensemble tree-based method where several base decision trees are trained, and the predictions of those estimators are combined to obtain a final prediction. Furthermore, we found that the best performing sub-regressor configuration is the Full configuration, where a single sub-regressor configuration is used. Also, we found that the Minmax input feature scaling method was the highest performing method, but the feature scaling method remains a hyperparameter that needs to be optimized for each model. Moreover, we found that models using the original Height, Width and Depth variables performed better than those using the hand-crafted CF feature. In Table I, we can see that our best model achieves better performance for the R^2, MAE and RMSLE metrics on the test set when compared to the baseline IEEE 1584-2018 model. In Table II, we found that our best model can achieve better performance for the R^2 and MAE metrics on the holdout dataset when compared to the baseline IEEE 1584-2018 model. Based on the MAE metrics presented in Tables I and II, our model shows a 33 % reduction in the MAE between the measured and predicted energies in cal/cm^2 when compared to the baseline on the test set, and a 25 % reduction on the holdout dataset, which are significant improvements. By observing the feature importance chart of our best model in Fig. 5, we see that the most important feature is I_{bf}, the features of moderate importance are G, D, t and V_{oc}, and the least important features are Width, Height and Depth. The box dimension features have very little impact on prediction performance for our best model, therefore removing these features could make future models easier to apply, with a negligible impact on predictive performance.

Moreover, we wanted to plot the performance of our best model and the baseline on both the test set and holdout dataset. In Figs. 3 and 4, the red line represents an identity line with a slope of 1 intersecting at (0, 0). Assuming a perfect model, all predicted VS measured points would fall directly on this line. Points that fall to the bottom-right of the identity line are underpredicted (the predicted incident energy is lower than the measured incident energy), while points that fall to the top-left of the identity line are overpredicted (the predicted incident energy is higher than the measured incident energy).

While the Bagging regression algorithm yielded the highest performance on the test set and was selected as our best model, there are some drawbacks to tree-based models. Decision trees, even if they are averaged via an ensemble model of multiple trees (in our best model, the outputs of 332 decision trees are averaged to obtain an aggregated arc flash energy prediction), do not provide perfectly smooth or continuous outputs, but piecewise approximations. These models are not well suited for extrapolation with combinations of data that are widely different from what was used to train it. This does not mean that these models are invalid: ensemble decision-tree based models are widely used and applied in the ML regression context. However, these models lack in prediction accuracy when applied to theoretical combinations of inputs that are widely different from the training data (i.e. applying such models with a voltage below 480 volts and a very large arc gap of 254 mm would produce odd results, but these combinations are not expected in real world situations). A possibility for future development would be to focus solely on training ML models that are not based on decision trees and increase the ranges of hyperparameters for those models in the hope to train better models that do not have the theoretical applicability limitations of decision-tree based models. Another possibility would be to calibrate the model via the application of piecewise functions to make the model predictions smoother between ranges of available training data point input combinations. In this study, the ranges of applicability for each feature of our models have not been evaluated. In general, ML models are valid for data points that fall within the range of data points that were used to train it. Therefore, we expect the range of applicability of the models developed in this article to be similar to the ranges found in the IEEE 1584-2018 dataset. We believe that the best way to increase the range of applicability would be to produce training data points for features across a wider range of values by performing more arc flash tests in laboratories. As future work, it would be interesting to perform sensitivity analyses on the models to evaluate the ranges of applicability of these models. Another option would be to apply data augmentation techniques to create synthetic data from the learning data. For example, by assuming that the incident energy is proportional to ${I_{bf}}^2 t/D^2$ (assuming that the I^2t rule applies to the arc flash phenomenon and the inverse-square law for working distance), synthetic data could be created from the learning data and scaled across artificial ranges of I_{bf}, t and D: ML models could learn these relationships between the variables by being trained on the combination of learning + synthetic data.

As shown in Table II, our best model has a slightly higher RMSLE on the holdout dataset when compared to the baseline IEEE 1584-2018 model. Even though RMSLE was chosen as our hyperparameter search selection metric and our best model selection metric as described in Section IV. B., the RMSLE was not optimized directly by the training regression algorithms, as this metric is not available as a loss function of any regression method in the *Scikit-learn* package. Optimizing the RMSLE as a loss function would require a custom implementation of the *Scikit-learn* algorithms, which was not done in this study, but could be explored in the future. This effort could potentially result in the development models where the RMSLE results are further improved.

One of the main drawbacks when training complex ML algorithms is lack of interpretability when compared to typical linear or polynomial regressions. These trained models, in most cases, are represented by “black boxes” where the relationship between the inputs and outputs is not obvious. In our case, our best model is an ensemble tree-based model, where individual decision trees are trained and the predictions of every tree are averaged to obtain a final prediction. It would be possible to explore all decision trees individually to see which decision rules were learned, but this was not done in this study.

Most ML models are trained using high-level programming languages such as Python with specialized libraries such as *Scikit-learn*. The deployment of ML models in commercial arc flash software can be achieved through various means. One avenue is to use the *Sklearn-onnx* library in Python which converts models trained using the *Scikit-learn* library into the universal *ONNX* format, and then implement the *ONNX* Runtime in the Windows software application and use it to make predictions with the model. Note that for each input feature scaling method based on the statistical distribution of input features, the statistical information of the input feature scalers needs to be stored along with the final regressors and applied to all new inputs in order for these regressors to be used.

As future work, a various number of approaches could be evaluated to potentially improve arc flash predictive models. A recent study has proposed the training of an external model called an Error Passing Network (EPN) that can be trained on a base model and that learns to correct the prediction errors of the model [37]. It would be interesting to train an EPN on the base IEEE 1584-2018 model and evaluate the gain in the model’s predictive performance for the base IEEE 1584-2018 model + EPN pair. Another avenue to explore would be Physics-Informed Neural Networks, where neural networks can be guided by physics-based equations during training, which can lead to better predictive models for physics-based phenomena such as arc flash [38]. Another avenue to explore would be to use imputation techniques, such as nearest neighbors imputation, for data points with missing or invalid values, rather than filtering out these data points during the pre-processing step.

Since arc flash incident energy prediction is an ongoing research and industry effort spanning decades and electrical workers' life can be at risk if any model is used wrongly, we discourage the use of custom developed arc flash predictive models that are not widely accepted. We strongly believe that the standards should be iteratively updated through the years and improved upon when more data and better models are developed. We encourage others in the field to propose avenues to further improve arc flash predictive models and hope that the methods and models developed in this article can help advance those efforts.

Finally, the performance of ML models increases when more high-quality data is used for training. We encourage standard development groups and other independent organizations to perform more tests in laboratories, increase the number of data points and include as many input parameters as possible in the datasets to find potential new relationships between new input features and incident energy. In addition, it would be interesting to explore combining different arc flash laboratory measurement datasets together to create a model that could, for example, incorporate the AC vs DC variable as a categorical variable, and to explore merging various high voltage arc flash test datasets in order to develop models that can be applied in a wider voltage range. In this work, we trained models for incident energy prediction only: this same exercise could be performed to develop predictive models for arcing current as well.

VII. CONCLUSIONS

In this work, our objective was to evaluate the potential of training ML regression models to accurately predict arc flash incident energy. We applied several ML regression techniques on published arc flash datasets and trained a variety of models to predict arc flash incident energy with different sub-regressor configurations and input feature scaling methods. Overall, we did find that the Bagging tree-based ensemble regression technique achieved higher performance across several evaluation metrics both on the IEEE 1584-2018 and EPRI-2021 datasets when compared to the baseline IEEE 1584-2018 model. We suggest that the next iteration of the IEEE 1584 standard should explore the use of ML methods, which have been shown in this article to produce highly performant predictive models. We also encourage conducting more experiments and increasing the size of arc flash datasets.

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IX. VITAE

Simon Giard-Leroux, P.Eng., M.Sc. received the bachelor's degree in electrical engineering and the master's degree in computer science from the Université de Sherbrooke, Sherbrooke, Quebec, Canada, in 2016 and 2022, respectively. Since 2017, he occupied various roles as an electrical engineer conducting power system studies and developing software in consulting firms and software companies. Since 2023, he is a Senior Product Manager working on the EasyPower software within Bentley Systems, Inc. in Portland, Oregon, USA. His research interests include power system studies and electrical network analysis, with a focus on using computer science, machine learning and programmatical approaches to tackle challenging issues in the electrical industry.

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Nicolas Raymond, M.Sc. is a Senior Advisor in Real Estate Data Modelling at the city of Laval in Quebec, Canada. Nicolas holds a bachelor's degree in mathematics and a master's degree in computer science. During his master's, his main focus was on the application of machine learning in healthcare, and he developed a model to efficiently monitor cardiac health in childhood cancer survivors. In 2023, he temporarily moved to Edmonton, Alberta, Canada for a year residency at the Alberta Machine Intelligence Institute (Amii), where he applied deep learning to build tools that use genetics to facilitate crop breeding. He recently joined the city of Laval in his home province of Quebec, Canada, where he finds interests in modelling real estate data to achieve fairness and accuracy.

Martin Vallières, Ph.D. received a Ph.D. degree in Medical Physics from McGill University, Montreal, QC, Canada, in 2017, and completed postdoctoral training in France and USA, in 2018 and 2019. He is an Assistant Professor in the Department of Computer Science, Université de Sherbrooke, Sherbrooke, QC, Canada, and a Canada-CIFAR AI Chairholder, since 2020. The overarching goal of his research is centered on the development of clinically actionable models to better personalize cancer treatments and care. Over the course of his career, he has developed multiple prediction models for different types of cancers. His research interests include graph-based integration of heterogeneous medical data types for improved precision medicine.

Advancing the Electrical Safety Culture to the Commercial and Residential Worker

Paper No. ESW2025-15

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Abstract – Electrical injuries and fatalities have plateaued in the last decade after dropping consistently in the previous two decades [1]. One possible explanation is that efforts to reduce electrical incidents in the Industrial sector have been quite effective, while the Commercial and Residential sectors have not made similar progress. Statistics show that Commercial and Residential workers are getting hurt and killed by electricity at greater rates than workers in Industrial Facility environments. This paper examines Occupational Safety and Health Administration (OSHA) fatality statistics from 2011 to 2023 to explore who is getting killed by electricity, discusses differences in the Industrial, Commercial and Residential sectors that could explain these statistics, and proposes that the Electrical Safety Workshop (ESW) and anyone concerned with electrical safety expand their focus to include Commercial and Residential workers.

Index Terms — Electrical Safety, Safety Culture, Residential, Commercial, Electrical Fatality Statistics

I. INTRODUCTION

The disparity in electrical safety culture between the Industrial and Commercial/Residential sectors can be observed by examining two electrical contractors for whom the author of this paper worked. “Company A” consisted of around 100 employees and performed mainly residential and light commercial work. In Company A, “hot work” was encouraged and taught by the older electricians. There was no safety training; in fact, the only training was what could be learned on the job. During the year or so that the author worked for this company, he sustained multiple shocks while performing hot work on 120V and 277V circuits. To Company A, this was par for the course of being an electrician.

“Company B” consisted of around 1200 employees and performed large commercial and industrial new construction and service work. This company had a top down commitment to electrical safety starting with the owner, a former electrician. Company B had a formal training program which included electrical safety training, ensured employees were provided with appropriate personal protective equipment (PPE) at all times, and had a safety department including several full time safety professionals. Hot work was prohibited unless deemed absolutely necessary, in which case a hot work permit had to be approved by the safety department. Company B had a Medical Incident Rate (MIR) significantly below the national average, and injuries and near misses were shared with the entire company as opportunities for improvement.

This example from the personal experience of the author underscores the difference that exists in safety culture and safety practices between Industrial and Commercial / Residential workers and companies. In general, operations and maintenance personnel and contractors employed at Industrial facilities are more likely to resemble Company B, while companies performing Commerical and Residential work are more likely to resemble Company A.

NOTE: The terms “Industrial”, “Commercial”, and “Residential” are used generally. For the purpose of the paper, facilities that could technically be defined as large Commercial sites are included in “Industrial”. This paper draws a correlation between sector and firm size, with “Residential” related to smaller firms, “Commercial” related to small to mid-sized firms, and “Industrial” related to mid-sized to large firms. This correlation may not be true in all cases, but is accurate in general.

II. ELECTRICAL ACCIDENT TRENDS

As indicated in Figures 1 and 2, electrical accidents have plateaued in the last decade after dropping consistently in the previous two decades [1].

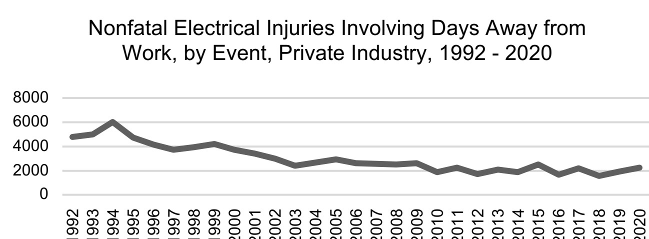

Fig. 1 Non-fatal Electrical Injuries 1992-2020

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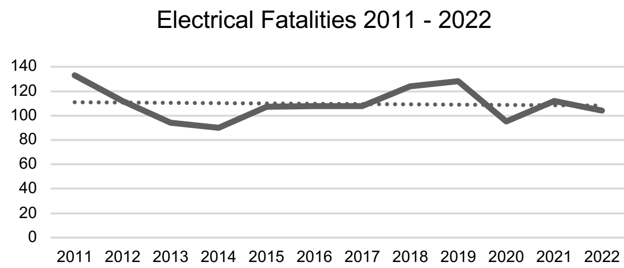

Fig. 2 Fatal Electrical Injuries 2011-2022

III. OSHA Electrical Fatality Statistics 2011 - 2023

The following graphs are created from data from OSHA as provided by the Electrical Safety Foundation (ESFI) and used with permission from ESFI [2].

These graphs were made examining characteristics of each fatality event as compiled by ESFI. Not every characteristic was given for each event, so the following graphs represent a subsection of the overall data set. Refer to Appendix A for more information on graph compilation methodology.

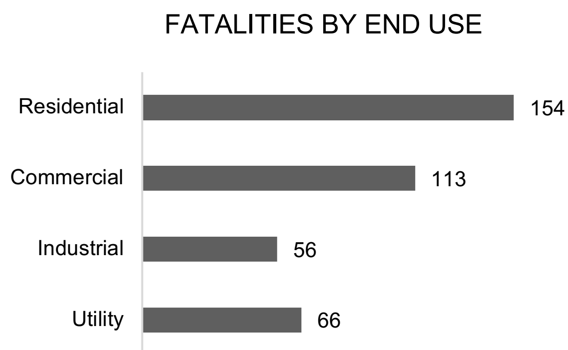

Fig. 3 Fatalities by End Use

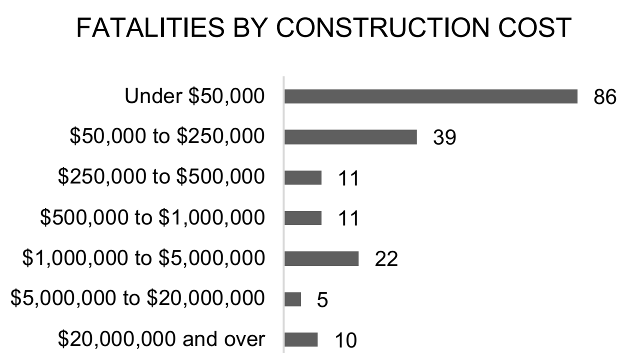

Figure 4. Fatalities by Construction Cost

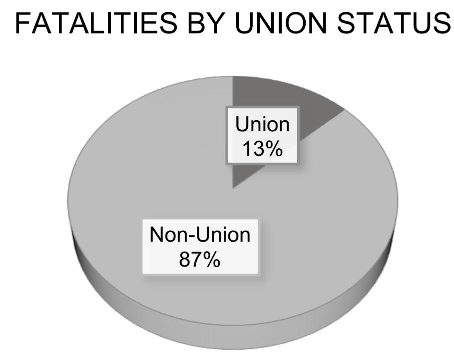

Figure 5. Fatalities by Union Status

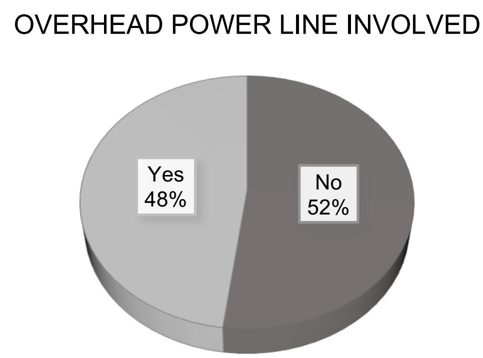

Figure 6. Overhead Line Involved

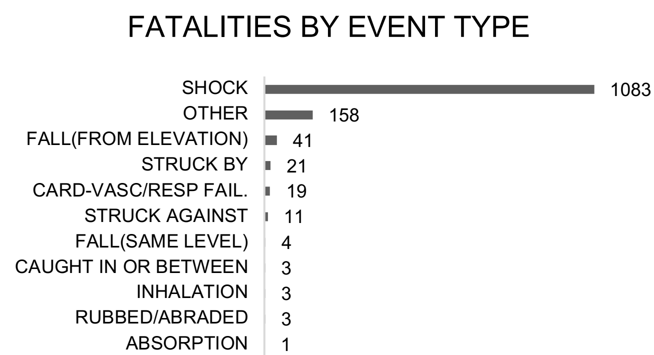

Figure 7. Fatalities by Event Type

A. Who is getting killed by electricity?

Figure 3 indicates that for every fatality of an Industrial worker there are around five Commercial and Residential fatalities. Figure 4 indicates that the majority of deaths occur on lower cost projects, which typically relate to Residential and Commercial projects. Figure 5 indicates that Non-Union workers are more likely to experience a fatality than Union workers, considering that in 2023 28.6% of electricians and 16.2% of all construction workers belonged to a union [3]. Commercial and Residential projects may be less likely to have union requirements, depending on other factors such as the state in which the project is located.

While it can be challenging to categorize electrical fatalities definitively into categories of Industrial, Commercial and Residential, examining characteristics of each fatality indicates that Commercial and Residential workers are bearing the brunt of electrical fatalities.

B. How are electrical fatality accidents occurring?

Almost half of all electrical fatalities are due to contact with an overhead line, and four out of five are due to electrical shock. As discussed in Section IV, Commercial and Residential workers are more likely to be exposed to contact with overhead lines, and less likely to be protected from shock by Electrical Safe Work Programs. This further illuminates the greater toll on Commercial and Residential workers, and offers one explanation as to why electrical fatalities have not dropped in the last decade.

IV. DIFFERENCES IN THE INDUSTRIAL SECTOR VERSUS THE COMMERCIAL AND RESIDENTIAL SECTORS

A. Working Environments

Characteristics of Industrial environments when compared to Commercial and Residential environments could explain why they experience fewer fatalities. Industrial facilities tend to be more controlled environments. Workers report to the same facility every day, often for years at a time. Maintenance and troubleshooting procedures can be well defined for the electrical systems by facility personnel, who are familiar with the system. When new construction is performed or outside contractors are used at an Industrial facility, these companies hold contractors to compliance with stringent safety protocols and have dedicated employees to ensure compliance.

A Commercial construction site is a constantly changing environment. Temporary power systems are rigged (often using temporary overhead 480V lines) and moved around as the building(s) take shape. There is heavy equipment and delivery vehicle traffic with potential to contact overhead lines. For much of the project, there is exposure to the elements including mud and shallow standing water, and long extension cords are run throughout the site for lighting and power tools. This creates ample opportunities for shock events to occur.

Residential construction sites are also constantly changing. They use temporary power systems that are not as large as commercial sites and are typically 240/120V, but they have the same exposure to the elements and use of electrical cords and power tools. There is delivery vehicle traffic and often exposure to overhead power lines. Ladders are used and moved around the site, and especially among non-electrical trades, ladders are often aluminum due to cost and ease of use, presenting an additional exposure to electric shock.

Residential service workers move from location to location almost every day, and may visit multiple homes in a day. Use of ladders and presence of residential overhead service drops create a shock hazard. Hot work may be required to perform troubleshooting, and many residential workers do not think twice about performing hot work since the voltage is “only” 240/120V.

B. Financial Considerations

Industrial facilities are often owned and operated by large corporations with resources budgeted specifically towards safety, including electrical safety. They have dedicated safety personnel and are likely to ensure adequate PPE is provided and used by workers. Insurance costs can be lowered by reducing MIR, creating a financial incentive for large firms to invest in safety.

Mid-sized contractors that perform Commercial work often have safety programs and provide PPE, but do not have the resources of larger firms and may not have dedicated safety professionals. Residential contractors tend to be smaller firms, sometimes consisting of only the owner and a few additional employees. These firms have fewer resources available and safety is not always a priority when a firm is struggling to maintain financial viability. They do not have dedicated safety professionals, and may not provide adequate PPE.

C. Safety Programs and Training

Industrial firms are more likely to have training programs for maintenance and operations workers which include electrical safety training. The repetitive nature of industrial processes allows for well defined Electrical Safe Work Programs that can be tailored to each machine or to the facility electrical system, which remain relatively constant over time. National or multi-national firms often create and enforce ESWPs at all facilities and for all employees.

For operation and maintenance at Commercial facilities, there are typically limited maintenance personnel. A small number of employees or even just one employee are often responsible for performing all maintenance tasks, not just electrical maintenance. These employees are often not trained electricians and may have limited knowledge of electrical systems and electrical safety. These facilities are less likely to have defined Electrical Safe Work Programs.

Training programs may exist for some Commercial and Residential firms, but are not as comprehensive as those provided by Industrial firms. Safety training and specifically electrical safety training may not be included. Smaller firms may have no formal training, and the entry level nature of construction trades means that workers often receive only informal on the job training with no safety component. Bad habits are easily passed down, including poor safety practices.

Examining the differences between the Industrial, Commercial and Residential sectors offers an explanation of the statistics showing greater numbers of electrical incidents among Commercial and Residential workers.

V. ESW IMPACT ON COMMERCIAL AND RESIDENTIAL WORKERS

A. Lack of Commercial and Residential Participation in ESW

Participants in ESW largely represent the Industrial sector. Manufacturing companies, chemical and oil and gas refining plants, web giants and data centers, utilities, research laboratories, and the like make up a large percentage of the attendance roster and presenters. Commercial and Residential firms are not well represented. The reason for this is likely to be largely financial, since as discussed above, these firms often do not employ fulltime safety professionals and engineers, and do not have the resources to send employees to training seminars or conferences such as ESW. While this may be true, has the ESW made enough of an effort to engage the Commercial and Residential sectors?

B. Current ESW Efforts to Impact Commercial and Residential Workers

There are efforts by participants of the ESW to impact workers outside of Industrial facility environments. To cite some examples, the Industrial Applications Subcommittee (IAS) Electrical Safety Committee Construction Subcommittee has presented tutorials and provides mentorship to drive development of papers. It encourages its members to spread word about ESW and promote electrical safety to their clients in order to drive engagement and participation by those who have not participated in the past. The Electrical Safety Foundation (ESFI) is a consistent ESW participant, and has a strong focus on promoting electrical safety to non-electrical workers (around 70% of fatalities are non-electrical workers) and has a campaign to drive awareness of overhead lines (around 50% of fatalities involve contact with an overhead line). [4]

However, more effort is needed in order to advance the electrical safety culture across the entire workforce and create a downward trendline of electrical accidents again.

C. Ways for the ESW to Increase Impact on Commercial and Residential Workers

How can the ESW impact Commercial and Residential workers? This paper does not purport to have all the answers, but the following are some proposed actions that could be taken. Further outreach to contractors could occur, and trade organizations could be engaged. Engagement with Inspector organizations could be increased, as inspectors have a direct touchpoint with contractors across industry sectors. Increased participation by unions could provide valuable insight into current safety practices and areas for improvement. Suppliers and distributors could be engaged to promote electrical safety as they interact with contractors across all industry sectors on a regular basis.

These are only a few ideas, and this paper calls on the vast experience, knowledge and creativity of the audience to explore this crucial question and work to expand the focus of the ESW to advance the electrical safety culture into areas where it has had less of an impact to date.

VI. CONCLUSION

The ESW, along with the electrical industry in general, has done a fantastic job of advancing the electrical safety culture in Industrial Facility environments, but has not impacted Commercial and Residential workers to the same degree. Commercial and Residential workers are getting hurt and killed by electricity at rates greater than Industrial workers. Electrical injuries and fatalities have plateaued in the last decade. It is incumbent on the ESW and those concerned with electrical safety to widen their lens and work to advance the electrical safety culture to Commercial and Residential workers in an effort to push the electrical accident trendline towards zero.

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VIII. VITA

Earl Wiser, P.E. worked as an electrician for five years before attending Texas A&M University where he graduated with a Bachelor of Science in Electrical Engineering. He worked as an Electrical Engineer for an electrical contractor in Dallas for five years and as a Power System Engineer and Principal Engineer for Schneider Electric for five years. Mr. Wiser obtained his Professional Engineer license in 2020 and is now licensed as a P.E. in five states.

Overlooked Dangers - Addressing Electrical Safety for Non-Electrical Workers

Paper No. ESW2025-16

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Abstract – Many advancements have been made to help electrical workers get home safely each day. When looking at statistics, however, it is not just electrical workers who need help to be safe. Over two-thirds (2/3) of workplace electrical fatalities are attributed to non-electrical workers. These are people whose job duties do not seem to put them at a significant risk of electrical shock or an arc flash event, and yet they make up the majority of the electrical injuries and fatalities in the workplace. Why is this happening and how can this trend be stopped? In this paper, the reasons behind non-electrical workers having such high injury and fatality rates will be discussed, and possible solutions to this problem will be explored. Electrical safety isn't just for electricians, it's for everybody. Our country's safety culture needs to expand and address these often-overlooked dangers.

Index Terms — electrical safety, unqualified persons, non-electrical workers, training, electrical safety programs, approach boundaries, awareness, avoidance.

I. INTRODUCTION

When it comes to electrical safety, substantial efforts have been made to lower the risks electrical workers encounter daily. Advancements in personal protective equipment (PPE), tools, equipment designs, and qualification processes all work to provide a safer workplace for electrical occupations. Unfortunately, the risk associated with non-electrical occupations is often neglected. This has led to a striking number of electrical fatalities for non-electrical workers. According to data compiled by the Electrical Safety Foundation International (ESFI), 70% of workplace fatalities involving electricity occurred in non-electrically related occupations between 2011 and 2022 [1]. These numbers clearly show why electrical safety initiatives must address all personnel in the workplace, not just electricians.

Non-electrical occupations, such as laborers, mechanics, roofers, maintenance technicians, and many other careers have the misguided assumption that they are not vulnerable to electrical hazards as a regular part of their livelihood. This is due to a lack of awareness regarding the potential hazards associated with seemingly routine tasks. Improper use of extension cords, interacting with damaged or improperly installed electrical equipment, and contact with overhead power lines are just some of the common incidents that result in non-electrical worker injuries and fatalities every year.

In order to address the unfamiliarity and occasionally blatant disregard for electrical safety, it is vital that all occupations involving potential exposure to electrical hazards (50V to ground or greater) be provided awareness and avoidance training [2]. It is an absolute must for the training to be presented in a format that the worker can grasp, including bridging any language barriers. There are also instances where traditionally non-electrically related occupations are now being expected to do some basic electrical tasks. For those roles, workers should be expected to adhere to task-specific electrical qualifications, with additional training and field work audits to ensure competency as determined necessary based on the risk to the employee [2]. Additionally, qualified electrical workers must be held accountable for their impact on workplace safety. Emphasizing the hazard boundaries, communicating effectively, and ensuring safe working conditions for electrical installations can considerably limit electrical hazard exposure for everyone in the workplace.

II. HAZARD AWARENESS AND AVOIDANCE TRAINING FOR NON-ELECTRICAL WORKERS

Today, the majority of workplaces provide basic electrical safety training, but it's often overly generic and therefore insufficient in providing applicable information for specific roles. Even if it does cover the specific considerations for various roles, the training is normally presented in English. When looking at the demographics most at risk, Hispanic or Latino workers have the highest rate of electrical fatalities [1]. This could be due to a language barrier resulting in unclear instruction being provided. To effectively implement electrical safety training for non-electrical occupations, the individual roles, experiences, and languages of the workers must be considered.

As required by the NFPA 70E, the type and extent of the training should be based on the risk to the employee [2]. The Occupational Safety and Health Standard 1910 Subpart S, Electrical, provides "Typical Occupational Categories of Employees Facing a Higher Than Normal Risk of Electrical Accident" in Table S-4 [3]. This table can provide guidance on which roles need focused electrical safety training, but there are numerous other professions in the workplace that will possibly be exposed to electrical hazards. Non-electrical occupations facing electrical risks include, but are not limited to, blue collar supervisors, industrial machine operators, material handling equipment operators, painters, welders, tree trimmers, and countless others. Electrical hazard awareness and avoidance training should cover fundamental topics that apply to every role,

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but adding specifics pertinent to each job will ensure the training is impactful and memorable.

Some of the most effective training approaches include a recurring combination of classroom-based and on-the-job training, with full re-training provided every 3 years at a minimum [2]. This allows for dedicated time to focus on key electrical safety concepts as well as implementing real world practice, ideally presented in the language workers are most comfortable understanding.

A. Fundamental Topics

Electrical hazard awareness and avoidance training for non-electrical occupations must cover key subjects applicable to any workplace or role. Exploring common electrical injury and fatality circumstances can leave a lasting impression on the importance of following electrically safe work practices. Without establishing a fundamental understanding of the hazards and how to avoid them, electrical injuries and fatalities will continue to impact unqualified worker professions immensely.

1) <u>Electrical Hazard Identification:</u> The first essential electrical safety topic is to clarify how electricity affects the human body, and the possible injuries associated with electrical incidents. Electrical shock, arc flash, and arc blast hazards must be discussed in enough detail to impress the dangers of working around electricity. It is important for non-electrical workers to discuss scenarios that are relevant to their risk of exposure to those hazards. Being able to identify potentially hazardous situations, such as equipment left open or damaged, is crucial to avoiding incidents.

2) <u>Electrical Hazard Boundaries:</u> Anytime there are exposed energized conductors or circuit parts in the workplace, unqualified persons must stay outside of the hazard boundaries for arc flash or electric shock, whichever is greater. Training workers to identify when electrical components are exposed and how to respect the electrical hazard boundaries can mitigate common instances of unprotected personnel approaching hazardous electrical equipment and installations.

3) <u>Lockout/Tagout vs. Electrically Safe Work Conditions:</u> Another common topic that is essential to be addressed is detailing the difference between who is “authorized” to perform lockout/tagout (LOTO) and who is “qualified” to establish electrically safe work conditions in compliance with the NFPA 70E [2]. Unqualified workers must never access enclosures with hazardous electrical systems, even if they are authorized to turn the power off and apply LOTO. If work is to be done within the hazard boundaries of exposed electrical conductors or circuit parts, non-electrical workers need to be trained to enlist the help of qualified persons to verify that all electrical components (50V to ground or greater) are de-energized and safe to approach prior to work.

4) <u>Temporary Power, Cords, and GFCI Use:</u> Many non-electrical occupations utilize extension cords and other temporary power installations frequently. Although a qualified person should oversee the proper installation and maintenance of temporary wiring, it is vital for non-electrical workers to understand how to safely inspect cords for signs of damage prior to use [4]. Unqualified workers must also be educated on identifying when GFCI protection is required, and how to test it before relying on that protection.

5) <u>Electrical Emergency Response:</u> When faced with an emergency, especially involving friends and acquaintances, many people have an innate desire to help. Non-electrical occupations are often unaware that responding to electrical emergencies requires additional consideration to avoid hurting themselves or others in the process. Ideally, another qualified person will be part of the job safety planning and ready to respond in the event of an emergency. When this is not possible, or an incident occurs involving non-electrical workers who failed to recognize that electrical hazards were present, an unqualified person may see the need to act. Contact release training geared specifically to unqualified workers could allow faster emergency response for any electric shock victim, rather than having to wait for a trained qualified person to arrive. Explaining how to safely remove someone receiving an electric shock from the hazardous area without coming into contact directly will lessen the chance of multiple fatalities. This could include the use of insulated rescue hooks, identifying power sources, or finding other non-conductive rescue devices to pull or pry the victim off the circuit. Basic first aid and other emergency response techniques after electrical injuries [5] can also be important topics in non-electrical worker awareness training.

III. QUALIFIED WORKER RESPONSIBILITY

While providing effective electrical hazard awareness and avoidance training to non-electrical occupations is essential, it is also important to reflect on the responsibility of qualified electrical workers. If an electrical worker performs a task in an unsafe manner, they not only put themselves at risk but everyone in the area as well. Holding electrical occupations accountable for their role in workplace electrical safety is central to keeping everyone safe from electrical hazards. In order to be confident that electrical occupations perform their tasks in a safe and compliant manner, employers must establish clear and effective qualification programs. Electrical occupations are required to be trained and evaluated regularly to maintain their qualifications [2]. Training must be completed every three years at a minimum, and field work audits must be performed annually to verify adequate implementation of electrically safe work practices on the job. If an electrical worker fails to implement required electrically safe work practices, they must be re-trained and audited [2] to ensure future work is completed appropriately. Part of being a qualified electrical worker is being able to assess the risk and implement the risk control methods to lessen the likelihood and/or severity of an electrical incident. Qualified electrical workers should be leaders in electrical safety to protect other electrical personnel and non-electrical personnel alike.

However, numerous workplaces still struggle with determining whether a role is considered an electrical or non-electrical occupation. If the worker must perform tasks on or near electrical conductors or circuit parts operating at 50V to ground or greater, they shall be trained and qualified to perform their specific electrical duties [3]. This means many roles that are traditionally considered to be non-electrical occupations actually require becoming qualified workers for certain tasks. Employers can define levels of qualifications to address the overlap in responsibilities. Each role would be expected to pass criteria specific to the limited electrical responsibilities for their job. Levels of qualified electrical workers and their responsibilities need to be documented as part of an organization’s electrical safety program [2]. This would ensure that certain customarily non-electrical occupations can complete particular electrical responsibilities safely and in compliance with applicable industry regulations, codes, and standards.

IV. CONCLUSION

The electrical industry has seen substantial improvements in lowering the risks electrical workers encounter, but they are not the only ones being hurt and killed by electricity. Non-electrical occupations still make up a startling majority of electrical related fatalities in the workplace year after year [1]. The need is clear for electrical safety initiatives to expand and include all personnel in the workplace.

In order to address electrical safety for non-electrical workers, all occupations that have potential exposure to electrical hazards (50V to ground or greater) are required to be trained in hazard awareness and avoidance [2]. For traditionally non-electrically related occupations that have some electrical responsibilities, task-specific electrical qualifications are necessary based on the risk to the employee [2]. Moreover, all qualified electrical workers must be held accountable to electrically safe work practices that impact overall workplace safety.

These methods will assist in lowering the non-electrical occupation fatality rates, but there will always be room for improvement. By following OSHA, the NFPA 70E Standard for Electrical Safety in the Workplace, and other relevant electrical codes and standards, both qualified and unqualified workers can avoid all too common and unnecessary electrical risks.

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VI. VITA

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Practical Battery Arc-Flash Models

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Abstract – Calculating arc flash incident energy (IE) in battery systems can be significantly improved in both accuracy and practicality. Annex D of NFPA 70E has referenced the maximum power transfer method since 2012, which tends to overestimate IE and has led to the overprescription of personal protective equipment for over a decade. Many alternative methods have been proposed but have been either impractical or inaccurate. This confluence of factors means that many battery systems either do not have arc flash labels or are labeled with an arc flash hazard that, if true, would make regular maintenance tasks impractical. This paper develops a practical battery arc flash model that accounts for electrode erosion and self-extinguishing phenomena in different configurations to predict IE. Self-extinguishing time is predicted by modeling the arc length as a random variable and assuming that the arc will extinguish whenever it exceeds a maximum threshold. The probability distribution of the arc length depends on the electrode configuration and the voltage. The proposed method is substantially more accurate than established methods when they are used to predict the IE measured in 250 battery arc flash tests from published literature. This achievement represents a milestone in battery arc flash modeling that will enable appropriate safety controls to be applied to battery work.

Index Terms — batteries, arc-flash, battery arc-flash, risk assessment, safety, electrical work, personal protective equipment, hazard analysis

I. INTRODUCTION

The physics of an electric arc is complex. However, electrical safety requires simple rules and guidelines to protect workers. If a model is too complex, it will not be widely used. If a model is not precise enough, then it will lead to either the over prescription of controls or inadequate controls. This paper attempts to strike a balance between simplicity and precision in calculating battery arc flash incident energy (IE). The goal of this paper is to provide a practical way to calculate battery arc-flash IE with the information available to a battery worker.

With the proliferation of batteries needed for grid scale energy storage it is important to protect battery workers from electrical hazards. Battery arc flash injuries have historically been rare and are difficult to disaggregate from contact thermal injuries in accident data [1]. However, national worker safety standards require arc flash hazard labels on stationary battery systems [2]. The prevailing method to calculate IE in batteries has been the maximum power transfer method described in an informative annex D. 5 of NFPA 70E [2]. Part of the motivation of this paper is that this method is known to overestimate the IE in battery systems leading to the overprescription of personal protective equipment (PPE). While rare, it can also underestimate the IE in cases where the arc current is lower than expected, leading to slower overcurrent protection and hence longer arc duration. More accurate methods have been developed [3] that can provide a better initial estimate of arc current and hence arc time where overcurrent protection is the limiting factor. However, there is a growing body of experimental evidence that self-extinguishing is the primary limiter of arc duration under certain conditions. This paper explores what these conditions may be and develops a model to predict self-extinguishing times.

The remainer of this paper is organized as follows: The relevant physics of electric arcs in air produced by batteries are reviewed in Section II, the published body of battery arc flash experimental data is reviewed in Section III. Methods of dc arc flash calculation, including the novel methods developed for battery arc flash in this paper, are covered in Section IV, and lastly the results of using these methods to predict IE from arc flash tests is presented in Section V.

II. BATTERY ARC FLASH PHYSICS

An electric arc is a continuous discharge of electricity through air that produces light and heat. It occurs when sufficient voltage is applied across a gap between two electrodes, ionizes the gas and creates a conductive plasma channel. The plasma transfers heat rapidly through thermodynamic processes. The arc sustains itself when all forces and energy flows are in a stable operating region. The formal criterion for stability is that the eigen values of the characteristic equation must all be non-positive. More simply put this means that any perturbation to the arc results in a resorting force or energy flow. Looking at the arc's temperature, for the arc to be stable, electrical heat generation must be balanced by heat transfer. There are two stable operating temperatures for electric arcs: where heat generation is balanced by conduction losses (to both the surrounding air and the electrodes), and where it is balanced by radiation losses. Conduction heat transfer is proportional to the temperature difference and its associated stable temperature is around 6000~K [4]. Radiation heat transfer is proportional to the temperature difference to the fourth power, and its associated stable temperature is much higher around 9000~K [4]. We are primarily concerned with the higher temperature arcs as these are more hazardous to workers.

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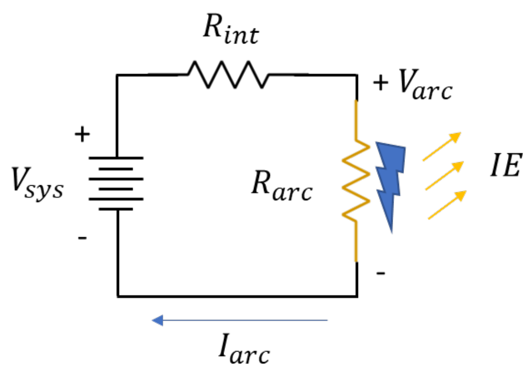

Fig. 1 Battery Arc Flash Hazard Diagram

Instead of delving into complex models of plasma physics, we look at an electric arc as a simple intersection of two equations: a Thévenin equivalent battery model, and an average power arc model. This model only includes an ideal voltage source and a resistor which has the advantage of linearity but the disadvantage of limited applicability. Specifically, this model will not apply to photovoltaic panels or electronic dc power supplies (including rectifiers). Similarly, it assumes that the circuit inductance is negligible which is inaccurate when there is a significant length of cables or wiring in the circuit. Hence, the results that follow will only apply to work performed on the battery itself or in dc panelboards located near the battery.

In this paper, we build on the IE calculation method developed by Ammerman [3] using the Stokes and Oppenlander [4] model, referred to here as the arc resistance model. A diagram of a Thévenin battery model connected to a nonlinear arc resistance model is shown in Fig. 1. This method sets the battery terminal voltage equal to the arc voltage through (1). This equation is solved iteratively by changing the arc current using gradient descent. A spreadsheet to solve this function for I_{arc} and V_{arc} is available [5]. Once solved, the arc voltage, current, time, and working distances are plugged into (2) to determine the IE. The relationship in (2) assumes that the arc is at thermal equilibrium, in that the heat gained by the electrical power of the arc is immediately lost by the arc through thermal radiation.

$$V_{\text{arc}} = (20 + 0.534 z_{\text{g}}) I_{\text{arc}}^{0.12} = V_{\text{sys}} - I_{\text{arc}} R_{\text{int}} \qquad (1)$$

$$IE = \frac{0.239\left(\frac{\text{cal}}{\text{J}}\right)}{4\pi D^2} \int_0^{T_{\text{arc}}} V_{\text{arc}}(t) I_{\text{arc}}(t) dt \qquad (2)$$

where

V_{arc} is the arc voltage (V)
I_{arc} is the arc current (A)
T_{arc} is the arc time (s)
V_{sys} is the battery voltage (V)
R_{int} is the battery internal resistance (Ω)
z_{g} is the electrode gap (mm)
D is the working distance (cm)
IE is the incident energy (cal/cm^2)

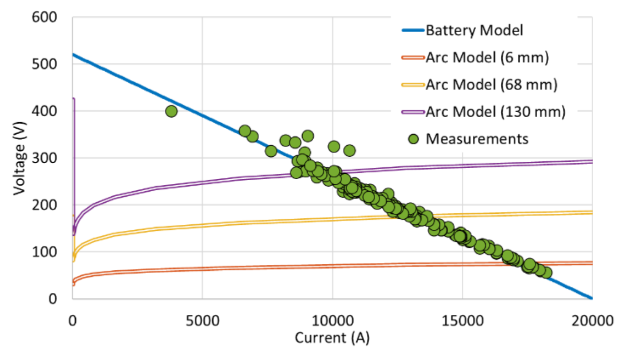

Fig. 2 Battery Arc Flash I-V Data, [6,7]

In general, (1) approximates the arc's average power as a function of arc gap and arc current. We extend the use of this model to represent a stable voltage and current around which an arc operates. Fig. 2 shows current and voltage data collected during inline arc flash experiments on a 520 V battery with a short circuit current of 20 kA. The initial electrode gap was 6 mm. After two seconds the electrodes had burned back to 130 mm. As shown in the I-V data, the stable voltage-current starts at the intersection of the battery model and the 6 mm arc model. As the test progresses, the measured voltage rises and current falls along the battery model line.

The data in Fig. 2 demonstrate that (1) is a relatively accurate approximation of the underlying physics. In Section IV(C) we build on (1) to model how the electrode gap changes over time and then in Section IV(D) we allow the arc to have a random length greater than the electrode gap. First, we review the available experimental data that is used to determine the accuracy of these methods.

III. EXPERIMENTAL DATA

Recent work has surveyed the history of DC arc flash testing [8]. In this paper we investigate an expanded list of references to compare their methodologies and results pertaining to batteries. The drawings in Fig. 3 shows the range of different test configurations used in published works, with the addition of a box in many tests to simulate the arc occurring within an electrical equipment enclosure. Note that of the tests in the literature with a real battery, or a simulated battery with calibrated voltage droop, all were performed with low inductance circuits starting with the battery at rest. This is a good match to our assumed linear battery model, but it would not apply to other power sources (PV or electronics) or to equipment enclosures located far from the batteries with long twisted current carrying wires that would store additional energy in their inductance.

We divide the configurations into three categories: inline, open parallel, and closed parallel. The terminology of open (a.k.a., ‘unbounded’, or ‘in open air’) and closed (a.k.a., ‘terminated in an insulating barrier, or ‘butted into a boundary’) is used for convenience and does not refer to the enclosure’s door position. Convective forces can be ignored for short arcs, meaning that the orientation of the electrodes (horizontal or vertical) does not significantly affect this model. The inline configurations have the current carrying conductors in the

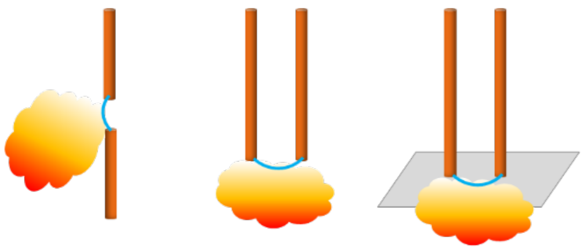

Fig. 3 DC Arc Electrode Configurations
(a) inline, (b) open parallel, (c) closed parallel

same line as the arc. Assuming that the inline conductors extend a significant length away from the arc, as is true in the experimental setups reviewed here, this means that the magnetic forces have a minimal impact on the position of the arc until it moves outside of this line, at which point the direction of Lorentz forces is in a circle around the conductors as dictated by the right-hand rule. The parallel configurations have the current carrying conductors oriented parallel to each-other. This means that the Lorentz forces project the arc away from the source of energy, no matter the polarity of the electrodes. The open parallel configuration allows the arc to be projected past the length of electrodes while the closed parallel configuration terminates the electrodes in an insulating barrier.

A. Inline configurations

Inline configurations (Fig. 3a) were included in the tests performed in [7], and [9–13]. The data provided in [7, 9, and 10], were the most comprehensive as large tables describe every test condition and the results. Data from [11–13] had to be inferred from figures. Because of this, some data points from either arc time or incident energy were missing and those tests are omitted. In total, data from 89 arc flash experiments using inline configurations are analyzed in this paper. These data identify two of the notable phenomena that this paper hopes to address: electrode erosion, and semi-random self-extinguishing time. Electrode erosion, or burn back, has been well documented as important for IE calculation [6] and as a contributing factor for self-extinguishing and is discussed more in Section IV(C). The tests that self-extinguish have a clear trend that higher voltage batteries have longer duration arcs [14] but there is still substantial uncertainty in the arc interrupt time. There was no clear impact of containing the arc within a box on the interrupt time but doing so increased the incident energy measured.

B. Open Parallel Configurations

Parallel configurations without a barrier (Fig. 3b) were included in the tests performed in [9-13]. The spreadsheets in [9-11] could be read from directly, while data from [12] and [13] had to be inferred from the figures. In total, data from 84 arc flash tests using open parallel configurations are analyzed in this paper. These data show that a battery arc between parallel conductors, without a barrier, is extremely short lived compared with the inline configurations. There is a clear trend that higher voltage leads to a longer arc duration. However, the trend is roughly exponential rather than linear. Notably, many experimentalists (e.g., Fechalos [10]) started with parallel electrodes to better represent real battery equipment, but changed to inline electrodes when they could not sustain an arc in the parallel configuration.

C. Closed Parallel Configurations

Parallel configurations with a barrier (Fig. 3c) were included in tests performed in [11], [15] and [16]. Data from [15] was obtained. Data in [16] did not include any self-extinguishing arcs so could not be used to develop models but could be used to verify model accuracy.

Parallel testing was performed by Hildreth in [11] but their results were only organized by average times and their plots did not distinguish which results came from which tests. An interesting observation in [11] was that adding an insulating barrier to the end of the parallel electrodes extended the arc duration: "Arcs extinguished themselves very quickly when allowed to progress to the top of the bus bars where the arc could expand in free space. A barrier was added to confine the arc to the area between the bus bars. This successfully confined the arc and resulted in longer arc times." - Hildreth [11]. In total, data from 77 arc flash tests using closed parallel configurations are analyzed in this paper.

Comparing these results to data from [15] complicates this observation. Instead of simply increasing the arc duration, the barrier appears to increase the uncertainty in self-extinguishing time. The arcs were observed to occasionally stretch away from electrodes, perpendicular to the magnetic forces from the electrodes. Identical tests sustained themselves for a duration ranging from several milliseconds to several seconds.

IV. METHODS

A. Maximum power transfer method

This is the most widely used method to calculate arc flash IE as it requires the least information. Originally published by Doan in 2007 [17] and later included in Annex D of NFPA 70E [2], this method assumes that the arc voltage is exactly half the source voltage.

$$I_{\text{arc}} = I_{\text{bf}}/2 \tag{3}$$

$$IE \approx 0.01 V_{\text{sys}} I_{\text{arc}} \frac{T_{\text{arc}}}{D^2} \tag{4}$$

where

I_{bf} is the bolted fault current (A)

B. Arc resistance method

This method is referenced in NFPA 70E [2] but has seen less wide use than the maximum power method due to the need to know the arc gap and to iteratively solve for the arc resistance and hence power. This is equivalent to the similar formulation in (1) with the simplifying assumptions of a constant arc gap and known arc duration. First published by Ammerman in 2010 [3], this method calculates the arc resistance at the intersection between the battery's discharge curve and the arc high-current / low-voltage curve.

$$R_{\text{arc}} = \frac{20 + 0.534 z_g}{I_{\text{arc}}^{0.88}} \tag{5}$$

$$V_{\text{arc}} = V_{\text{sys}} - I_{\text{arc}} R_{\text{int}} \tag{6}$$

$$IE \approx \frac{I_{\text{arc}}^2 R_{\text{arc}} T_{\text{arc}}}{4\pi D^2} \tag{7}$$

One problem with this method is that the arc gap can change over time with electrode erosion. As was shown in Fig. 2 the initial arc gap was below the maximum power point on the battery's discharge curve. As the arc gap increased, the power increased. So, if the electrode gap is narrower than the max power arc gap, the IE that a worker is exposed to could be between the IE calculated using this method and the maximum power method. Marroquin, et al extended the arc resistance method to predict and account for electrode erosion in IE calculation in [6]. We build on these results in the following sections.

C. Erosion model

Here we begin to develop a novel modification of the arc resistance method by determining the rate of electrode erosion. The growth of the electrode gap is a function of the heat generated by the arc, some of which melts or vaporizes the metal of the electrodes. Previous studies have modeled this rate as proportional to current [6], [8], and [18]. We attempted to model it as proportional to current squared and arc power and both fit the results when the final arc gap is known. However, when predicting what the final arc gap will be, modeling electrode erosion as proportional to current yields the most accurate results. Hence, we use the function shown in (8) to model arc erosion.

$$\frac{dz_g}{dt} = K_{\text{g}} I_{\text{arc}} \tag{8}$$

where

K_{g} is the arc erosion rate constant (mm A^{-1} s^{-1})

We can determine the erosion rate constant of the experiment shown in Fig. 1 by solving the following multi-objective optimization problem with inputs: V_{arc} arc voltage data, I_{arc} arc current data, Φ = 44 cal cm^{-2} the measured total IE at a working distance D of 45.7 cm, z_0 is the initial electrode gap of 6 mm while z_1 is the final electrode gap of 130 mm. The unitless weight Γ is set at 100 to balance how much the optimization tries to fit the I-V data and how much it tries to fit the IE data.

$$\begin{aligned}
&\min_x ||V_{\text{arc}} - \hat{\mathbf{v}}_{\text{arc}}||_2^2 + ||I_{\text{arc}} - \hat{\mathbf{i}}_{\text{arc}}||_2^2 + \Gamma\left(\Phi - \sum \hat{\phi}\right)^2 \\
&\text{s.t. } \hat{\mathbf{v}}_{\text{arc}} = V_{\text{sys}} - \hat{\mathbf{i}}_{\text{arc}} R_{\text{int}} \\
&\qquad \hat{\phi} = 0.239\left(\frac{\text{cal}}{\text{J}}\right)\frac{dt\hat{\mathbf{v}}_{\text{arc}}\hat{\mathbf{i}}_{\text{arc}}}{4\pi D^2} \\
&\qquad \Xi\hat{\mathbf{z}}_{\text{g}} = K_{\text{g}}\hat{\mathbf{i}}_{\text{arc}} \\
&\qquad \hat{\mathbf{z}}_{\text{g}}(0) = z_0 \\
&\qquad \hat{\mathbf{z}}_{\text{g}}(n) = z_1
\end{aligned} \tag{9}$$

where

x is the set of decision variables:

$$x = \left\{\hat{\mathbf{v}}_{\text{arc}}, \hat{\mathbf{i}}_{\text{arc}}, \hat{\phi}, \hat{\mathbf{z}}_{\text{g}}, V_{\text{sys}}, R_{\text{int}}, K_{\text{g}}\right\} \in \mathbb{R}^{4n+3}$$

Ξ is a discrete time difference matrix:

$$\Xi = \frac{1}{\Delta t}\begin{bmatrix} -1 & 1 & 0 & . & . & 0 \\ 0 & -1 & 1 & 0 & . & . \\ & & . & . & & \\ & & & . & . & \\ 0 & & & 0 & -1 & 1 \end{bmatrix}_{n\times(n+1)}$$

This problem is solved in python using pyomo [19] and the interior point, non-linear solver ipopt. The results are shown in Fig. 4. For the 25 mm diameter copper electrodes used in this experiment Kg = 0.00496 mm A^{-1} s^{-1}. This value is used for tests in [7] and [8]. Fechalos [10] used 19 mm copper electrodes and Hildreth [11] used 14.3 mm copper electrodes so their Kg is scaled by the ratio of their cross-sectional areas (Kg = 0.00855 mm A^{-1} s^{-1}, and 0.01517 mm A^{-1} s^{-1} respectively). Fechalos [10] used 19 mm tungsten electrodes for one test and so we scaled Kg by both cross-sectional area and the ratio of densities of each material. This calculation resulted in 0.0073 mm A^{-1} s^{-1} for the tungsten electrode test in [10]. Note that trying to adjust for the heat capacity and melting temperature of tungsten produced an inaccurate underestimation of electrode erosion. These are rough approximations and further testing is required to parameterize this phenomenon. The calculated IE was 44 cal/cm^2 demonstrating that the erosion model can accurately predict experimental outcomes when the arc duration and final arc gap are known.

Solving (1) for z_g provides a real-time estimate of the arc length based on the battery model and measured current. This estimate is distinct from the electrode gap burn back in that it comes from the intersection of the battery discharge curve and the arc model.

$$z_g = \frac{V_{\text{sys}} I_{\text{arc}}^{0.12} - R_{\text{int}} I_{\text{arc}}^{0.88} - 20}{0.534} \tag{10}$$

The arc length estimate, shown in Fig. 4 (c), is observed to jump above the electrode gap, peaking above 200 mm. The random behavior of the arc length estimate suggests a method to predict the self-extinguishing time of an arc. If the arc length behaves like a random variable, then we can predict the likelihood over time that it extends long enough to extinguish itself. The following section explores this potential solution.

D. Arc Length as a Random Variable

A clear trend is observable in the experimental data that arcs self-extinguish [4,14]. Stokes observed the following "... the arc obviously has a tendency to extinguish itself if the source voltage is less than the maximum excursion voltage." and further that the phenomena involved are "essentially random" [4]. Our objective is to use what is known about the battery system (voltage, short circuit current, electrode gap, and configuration) to estimate the self-extinguishing time with quantitative accuracy.

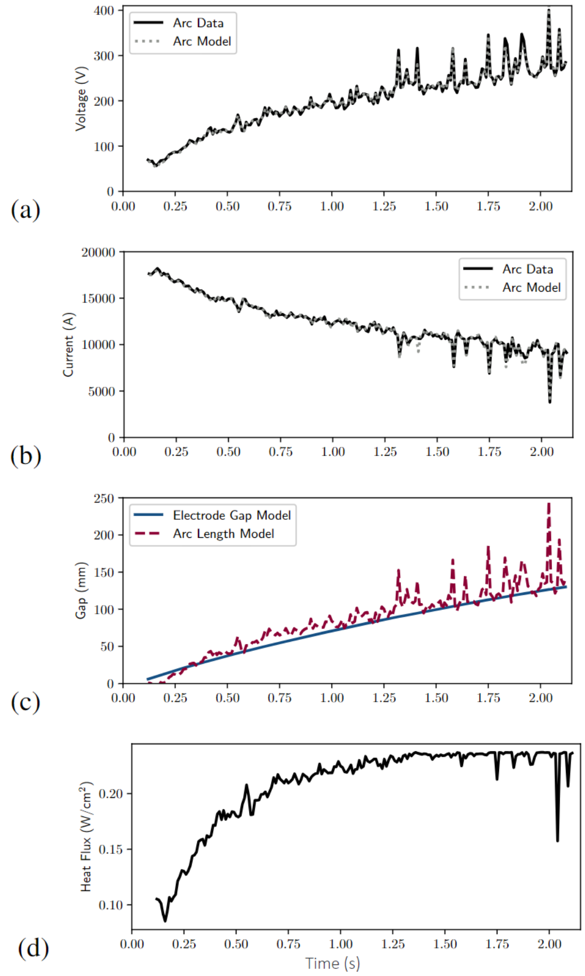

Fig. 4 Arc Model with Electrode Erosion, (a) Arc Voltage, (b) Arc Current, (c) Electrode Gap from (10) and Arc Length from (10), and (d) Arc Heat Flux at a 45 cm (18 in) working distance.

To accomplish this goal, we first model the arc length of inline conductors using a random variable ($\tilde{z}$). The arc length cannot be shorter than the gap between electrodes (z_g). We assume that the arc lengths longer than this minimum are exponentially less likely. The probability density function for the arc length based on this assumption is shown in (11).

$$\rho(\tilde{z}) = \beta e^{\beta(z_g - \tilde{z})} \qquad \tilde{z} \in \mathbb{R} \geq z_g \tag{11}$$

where

- ρ is the arc length probability density function
- $\tilde{z}$ is the random arc length which is a real number ($\mathbb{R}$) greater than the electrode gap (z_g)
- β is a constant describing the distribution with high β corresponding to a short tail (with outcomes tending to be close to z_g), and low β corresponding to a long tail (with outcomes tending to be significantly greater than z_g). See the parameterization functions in the Appendix.

An illustration of two example distributions is shown in Fig. 5.

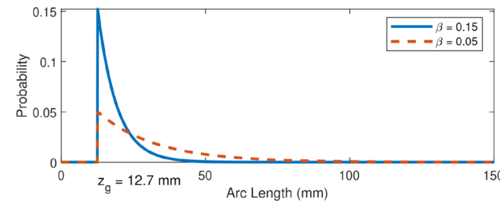

Fig. 5 Example probability distributions for ($\tilde{z}$).

We assume that the maximum arc length is where there is no solution to (1). The maximum arc length of the arc model in [4] occurs at the transition current between the low-current / high-voltage region, and the low-voltage/high-current region as shown in (12). Plugging (12) into (1) provides (13).

$$I_t = 10 + 0.2 z_g \tag{12}$$

$$(20 + 0.534 z_g)(10 + 0.2 z_g)^{0.12} = V_{sys} - (10 + 0.2 z_g) R_{int} \tag{13}$$

where

- I_t is the transition current (A)

The solution to (13) yields the self-extinguishing arc length z' for a given battery, above which no arc can sustain itself [20]. The next step is to calculate β based on measured T_{arc} values in arc flash experiments. To this end, we use (11) to predict the likelihood of the arc self-extinguishing in less than T_{arc} as the probability that $\tilde{z}$ exceeds the arc length limit z' within the time T_{arc}. To integrate (11) with respect to time we need to determine $z_g(t)$. This is done in two ways based on the electrode configuration.

For inline configurations, $z_g(t)$ is dominated by electrode erosion as described in (8). However, determining the arc current using (1) is more complex than needed for the assumed linear source. Again, a linear model limits the applicability of this method to batteries (not PV or electronics) and to low-inductance circuits (i.e., on or near the battery itself). With a known final electrode gap (z_1) and arc time T_{arc} we can use a simple linear approximation for $z_g(t)$ as shown in (14).

$$z_g(t) = z_0 + K_g \int_0^{T_{arc}} I_{arc} dt \approx \left(\frac{z_1 - z_0}{T_{arc}} \right) t + z_0 \tag{14}$$

Plugging the approximation in (14) into (11) and integrating with respect to time yields (15).

$$\rho(\tilde{z}, T_{arc}) \approx \frac{T_{arc}}{z_1 - z_0} e^{\beta(z_1 - \tilde{z})} \tag{15}$$

With this result, we can then calculate the probability $\mathbb{P}$ that the random variable $\tilde{z}$ is greater than the maximum arc length z' causing the arc to self-extinguish. This is calculated by integrating (15) over the arc length from z' to ∞. The result of this calculation is shown in (16). We then solve (16) for the arc duration $\hat{T}_{arc}$, where the probability that the arc self-extinguishes reaches a specified value to produce the time-at-risk equation in (17).

$$\hat{\mathbb{P}}(\tilde{z} \geq z') = \frac{T_{\text{arc}}}{\beta(z_1 - z_0)} e^{\beta(z_1 - z')} \tag{16}$$

$$\hat{T}_{\text{arc}} = \frac{\mathbb{P}(\tilde{z} \geq z')\beta(z_1 - z_0)}{e^{\beta(z_1 - z')}} \tag{17}$$

For each arc flash experiment with a known self-extinguishing time, there exists $\beta \in \mathbb{R}_+$ that solves (16) for values of $\mathbb{P}(\tilde{z} \geq z') \in [0,1]$. This is to say that we can pick the probability we are interested in, e.g., 50% chance of the arc time exceeding estimate or the median result, and calculate $\beta_{50\%}$ as the tuning parameter to model that outcome. These values are a function of voltage and are listed in the Appendix.

While we have a quantitative estimate for $\hat{T}_{\text{arc}}$, it requires a known final electrode gap z_1 to calculate. In practice, we solve for $\hat{T}_{\text{arc}}$ and $\hat{z}_1$ together iteratively by approximating I_{arc} and V_{arc} the same as we did for z_g as shown in (22) and (23). Equations (18) through (21) are simplifying nomenclature.

$$I_0 = I(z_g = z_0) = I(t = 0) \tag{18}$$

$$V_0 = V(z_g = z_0) = V(t = 0) \tag{19}$$

$$I' = I(z_g = z') = I(t = \hat{T}_{\text{arc}}) \tag{20}$$

$$V' = V(z_g = z') = V(t = \hat{T}_{\text{arc}}) \tag{21}$$

$$\hat{V}(t) \approx \frac{V' - V_0}{\hat{T}_{\text{arc}}} t + V_0 \tag{22}$$

$$\hat{I}(t) \approx \frac{I' - I_0}{\hat{T}_{\text{arc}}} t + I_0 \tag{23}$$

$$\hat{z}_1 \approx z_0 + K_{\text{g}} \int_0^{\hat{T}_{\text{arc}}} \hat{I}(t) dt = z_0 + \frac{K_{\text{g}}(I' + I_0)}{2} \hat{T}_{\text{arc}} \tag{24}$$

The time $\hat{T}_{\text{arc}}$ and gap $\hat{z}_1$ are solved for using (17) and (24). Note that many experiments with inline configurations self-extinguish so quickly as to result in no electrode burn back. In these cases, we tend to find a $\hat{z}_1 - z_0$ is a fraction of a millimeter. We can estimate the arc flash current by plugging (22) and (23) into (2) and solving the integral. This yields the surprisingly simple formulation in (25). Because it is a functions of the time-at-risk from (17), (25) is an energy-at-risk (EaR) function. Note that this equation is more complex when considering overcurrent protection interrupting an arc before its self-extinguishing time. This situation is accounted for in the supplemental spreadsheet [5].

$$\begin{aligned} \hat{\text{IE}} &\approx \frac{0.239\left(\frac{\text{cal}}{\text{J}}\right)}{4\pi D^2} \int_0^{\hat{T}_{\text{arc}}} \hat{V}(t)\hat{I}(t)\, dt \\ &= \frac{0.239}{4\pi D^2} \left(\frac{I'V' + I_0 V_0}{3} + \frac{V' I_0 + I' V_0}{6} \right) \hat{T}_{\text{arc}} \end{aligned} \tag{25}$$

E. Arc elongation in parallel configurations

For parallel configurations the electrode gap (z_g) is a constant. Using a constant electrode gap in (11) and integrating with respect to time yields (26). This is then used to calculate the probability $\mathbb{P}$ that the random variable $\tilde{z}$ is greater than the maximum arc length z' causing the arc to self-extinguish. The result of this calculation is shown in (27) We then solve (27) for the arc duration $\hat{T}_{\text{arc}}$, where the probability that the arc self-extinguishes reaches a specified value to produce (28).

$$\rho(\tilde{z}, T_{\text{arc}}) \approx T_{\text{arc}} e^{\beta(z_1 - \tilde{z})} \tag{26}$$

$$\hat{\mathbb{P}}(\tilde{z} \geq z') = \frac{T_{\text{arc}}}{\beta} e^{\beta(z_g - z')} \tag{27}$$

$$\hat{T}_{\text{arc}} = \frac{\mathbb{P}(\tilde{z} \geq z')\beta}{e^{\beta(z_g - z')}} \tag{28}$$

These equations are very similar to (15), (16), and (17) and can be used to estimate arc flash IE in the same way. Instead of needing to estimate z_1, we simply set $z_g = z_0$ and use (2) to calculate IE. Note that the value of β in (28) changes based on the configuration and voltage as shown in the Appendix.

V. RESULTS

The goal of this paper is to develop practical methods to calculate battery arc-flash incident energy. Available to anyone reading this paper [5] is an open-source licensed spreadsheet that is programmed to enable a user to calculate the IE using the methods described in section IV. With automated calculation, the remaining challenge is in determining accurate inputs. We define the information available to an analyst in two tiers 1) electrical only, and 2) electrical + mechanical. An arc in a box coefficient of 1.52 is used for all experiments performed within enclosed spaces based on the calculated value for panelboards [14, 21].

If all that is known about a battery system is its electrical characteristics, then the only method that can be used in the maximum power transfer method (see Section IV-A). This is why it is so widely used, despite its tendency to overestimate the level of the hazard. If the mechanical characteristics of a battery system are known, including the configuration and arc gap, then a much more accurate estimate of IE can be calculated. The simplest method to account for the arc gap is to use the arc resistance method (see Section IV-B). However, this method ignores how arc gaps can change over time and the propensity of arcs to self-extinguish in different configurations.

The proposed method to account for these phenomena is the self-extinguishing method, which combines electrode erosion (see Section IV-C), and arc length as a random variable (see Section IV-D). Fig. 6 shows histograms of the error from using these three methods to predict the IE of 250 tests (see Section III). The self-extinguishing method results are divided between the median estimate c), and the EaR estimate d) where there is a less than 5% chance that the IE is higher than the estimated value. The maximum power transfer method overestimates the IE by 12.6 cal/cm^2 on average, while the mean error of the arc resistance method is 7.5 cal/cm^2. There are a few cases where the arc resistance method underestimates the measured IE, roughly 1.5% of the tests in our dataset. The mean error of the median prediction of the self-extinguishing method is only 0.47 cal/cm^2, however, that is because roughly half (49%) of its predictions underestimate the IE. This is an improvement; however, we still do not want to underestimate the IE that a worker could be exposed to. The mean error of the ≤5% chance EaR prediction of the self-extinguishing method is 3.3 cal/cm^2, with a 0.4% chance (1/250) of underestimating IE by more than 0.1 cal/cm^2. A summary of these results by arc flash PPE category is included in Table I. The maximum power method predicts a higher category than measured in 90% of tests. Compare that to the median self-extinguishing method correctly predicting the PPE category in 75% of tests. The <5% EaR self-extinguishing method still predicts the correct PPE category in 64% of tests but reduces the rate of predicting a lower category from 12% to 0.4%. The improved performance of the self-extinguishing method is acute at low energy. Fig. 7 shows the IE of each test result plotted against the prediction of each method. Below 1.2 cal/cm^2, the maximum power method and arc resistance method tend to overestimate the IE by one to two orders of magnitude. The proposed <5% EaR self-extinguishing method is much better at correctly identifying when a test measures IE below this hazard threshold.

There are several important caveats to keep in mind when reviewing these results. First, as previously stated, the linear model used only applies to batteries (not PV, rectifiers, or DC generators) and only when working on or near the batteries themselves (low inductance circuits), when at rest (not under charge or discharge). Second, the probabilistic model does not fully account for the effect of arc current on the likelihood of self-extinguishing. It is understood that stronger magnetic forces should lead higher bolted fault current batteries to interrupt arcs more quickly. However, current has a more complex effect and we were unable to improve the predictive model by including current (bolted fault or initial arc current) in the model. More experimental data and better models may enable us to account for this in the future and improve our predictions further. Lastly, as a probabilistic prediction, there will be outlier cases that have IE exposure greater than predicted by the model. For example, in the data presented in Fig. 7, there is one case where the <5% chance self-extinguishing model result predicted an IE of 0.5 cal/cm^2 when the actual test measured approximately 2 cal/cm^2. The source report included a surprising observation of this test "Review of high-speed video shows the arc grow substantially towards the calorimeter placed in front of the battery cabinet." We analyzed the current and voltage data from this test and determined that the higher IE was likely due to the effective working distance being reduced from 45.72 cm to roughly 30 cm. Outlier cases can and will happen and are one reason why PPE is the least effective method in the hierarchy of controls [2].

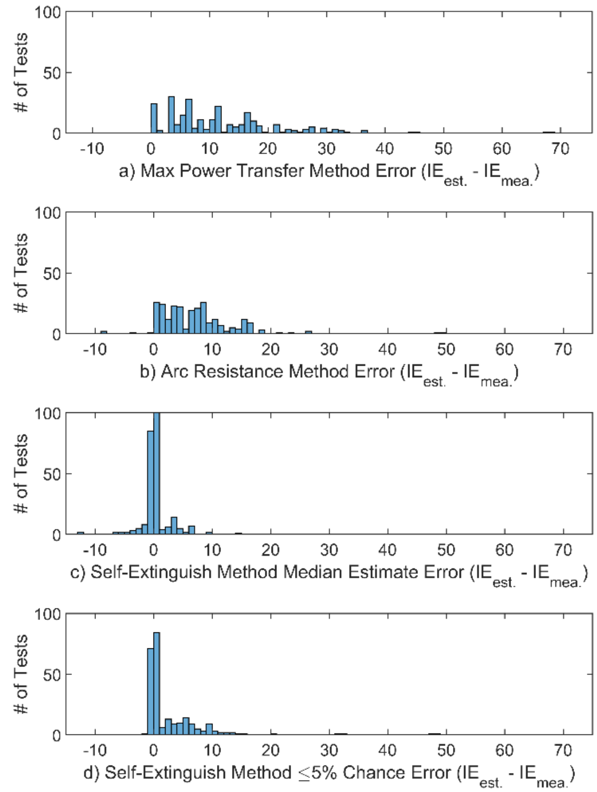

Fig. 6 Prediction error histograms: a) maximum power method, b) arc resistance method, c) median result of the self-extinguish method, and d) ≤ 5% chance result of the self-extinguish method.

VI. CONCLUSION

Practical methods to estimate the arc flash hazard of battery systems are critical to keeping workers safe. We propose a probabilistic, self-extinguishing arc model to predict arc duration. This method uses the battery voltage, short-circuit-current, arc gap, and the electrode configuration as inputs. These inputs are readily available to anyone with the battery specification sheet and a completed design or physical system to look at. Electrode configuration is generalized into three categories: inline, open parallel, and closed parallel (terminated into an insulating barrier). For inline configurations, electrode erosion dominates the process of self-extinguishing, so we use current over time to predict the arc duration and final arc gap. In parallel configurations the process of self-extinguishing is dominated by the Lorentz forces. Terminating parallel conductors in an insulating boundary, such as a breaker, can greatly extend the duration of the arc and make the arc duration more random / less predictable.

The proposed methods are both practical, and more accurate than comparable methods. The self-extinguishing method, tuned to a <5% EaR, has an average prediction error of 3.3 cal/cm^2, compared to 12.6 cal/cm^2 for the maximum power method and 7.5 cal/cm^2 for the arc resistance method. This leads the EaR arc-extinguishing method to perform substantially better when it is used to select arc rated PPE, especially at low energy. This method correctly identifies the minimum category of PPE that would protect a worker in ~64% of tests, with ~36% overestimating the required PPE and a <1% chance of underestimating it. This is a substantial improvement over the maximum power method which overestimates the required PPE in 90% of tests and the arc resistance method that overestimates the required PPE in 87% of tests. Future work will focus on improving calculation of the tuning parameter β. More experimental data in the closed parallel configuration could improve both accuracy and precision of the model.

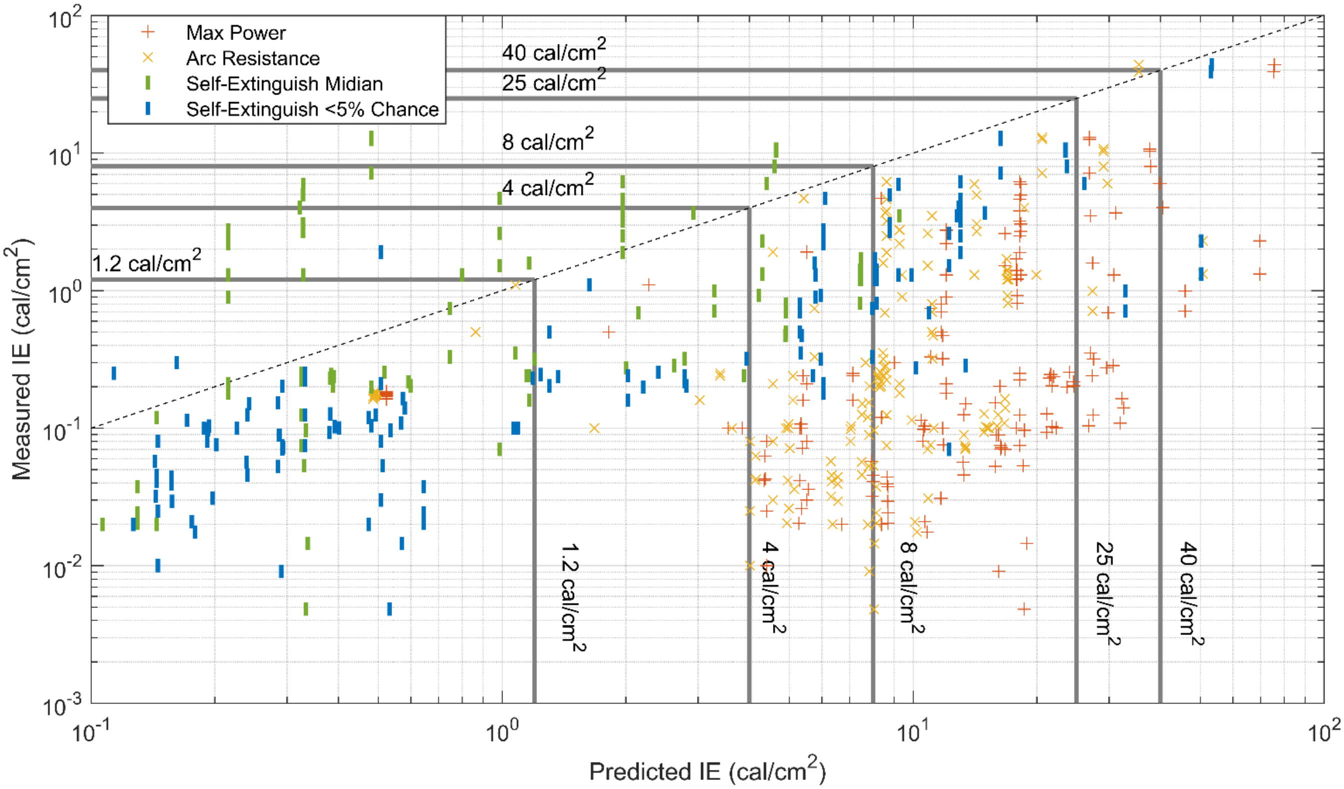

Fig. 7 Comparison of arc flash incident energy predictions and results

TABLE I
RESULTS BY ARC FLASH PPE CATEGORY

Method Predicts Correct PPE Category

	Max Power	Arc Resistance	SE Median	SE <5% EaR
Number	26	30	184	160
%	10.4%	12.0%	73.6%	64.0%

Method Predicts Higher PPE Category

	Max Power	Arc Resistance	SE Median	SE <5% EaR
Number	224	218	41	89
%	89.6%	87.2%	16.4%	35.6%

Method Predicts Lower PPE Category

	Max Power	Arc Resistance	SE Median	SE <5% EaR
Number	0	2	25	1
%	0.0%	0.8%	10.0%	0.4%

Number is out of 250 tests.

VII. ACKNOWLEDGEMENTS

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IX. VITAE

David Rosewater is a Senior Member of the Technical Staff at the Sandia National Laboratories. He received a B.S. and an M.S. in electrical engineering from Montana Tech of the University of Montana, as well as a PhD in electrical and computer engineering from the University of Texas at Austin. His research interests include modeling and simulation, performance testing, safety, and standardization of battery energy storage systems. From 2009 to 2011, he worked at the Idaho National Laboratory developing advanced spectral impedance measurement techniques for hybrid vehicle battery cells. He is a Senior Member in the IEEE and currently chairs the IEEE P2686 working group developing a recommended practice for design and configuration of battery management systems in energy storage applications. David holds a professional engineering license in the state of New Mexico

Lloyd B. Gordon graduated from Texas Tech University in 1981 with a PhD in Electrical Engineering. He started his research career at Lawrence Livermore National Laboratory (DOE), conducting research in topics of pulsed power engineering, plasma physics and dielectric engineering from 1981 to 1986. From 1986 to 1991 he was in the Department of Electrical Engineering at Auburn University, and from 1991 to 1998 was in the Department of Electrical Engineering at the University of Texas at Arlington. From 1998 to 2021 he worked at Los Alamos National Laboratory (DOE). Dr. Gordon has 25 years of experience in experimental high-energy research, 45 years of experience as an educator and trainer, and has focused his efforts on R&D electrical safety over the past 25 years. He has lectured to and trained over 100,000 scientists and engineers throughout the DOE, DOD, NASA, and industry cover the past 35 years in R&D Electrical Safety. Dr. Gordon serves on the NFPA 70E, Chapter 3 task group and is a member of the IEEE 1584, Guide to Arc Flash Calculations. Dr. Gordon is a senior life member of IEEE and has been a member for 54 years.

William Cantor holds both a B.S. degree in Chemical Engineering and an M.S. degree in electrical engineering. He has over 30 years' experience in the stationary battery industry and has been an active participant in the development of related IEEE standards and is an active member of IEEE PES ESSB committee. In addition, Mr. Cantor represents IEEE PES/IAS on various NFPA committees and is an Assistant Teaching Professor at the Pennsylvania State University.

X. APPENDIX

The tuning parameter β for inline configurations is calculated as a function of battery voltage as shown in Fig. 8. Of the 89 experiments, a subset of 43 were selected to train the parameter β for inline configurations. The best fit line with the data available was the sum of two power law functions as shown in (29).

$$\beta_{\text{inline}} = aV^b + cV^d \tag{29}$$

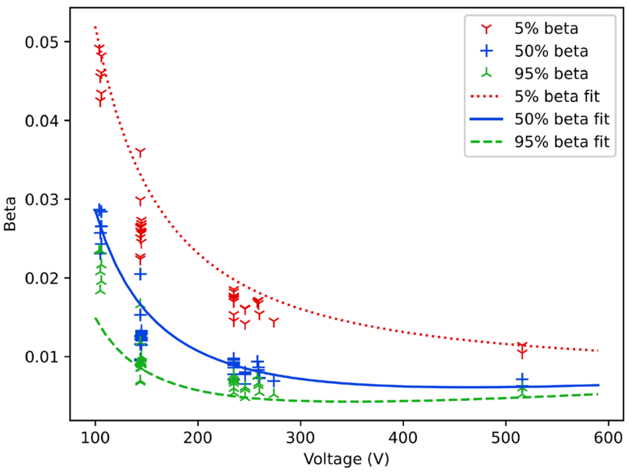

Fig. 8 Beta tuning parameterization for inline configurations

The tuning parameter β for open parallel configurations is calculated as a function of battery voltage as shown in Fig. 9. Of the 84 aggregated experiments, a subset of 65 were selected to train the parameter β for open parallel configurations. The best fit line with the data available was the sum of two power law functions as shown in (30).

$$\beta_{\text{open-parallel}} = aV^b + cV^d \tag{30}$$

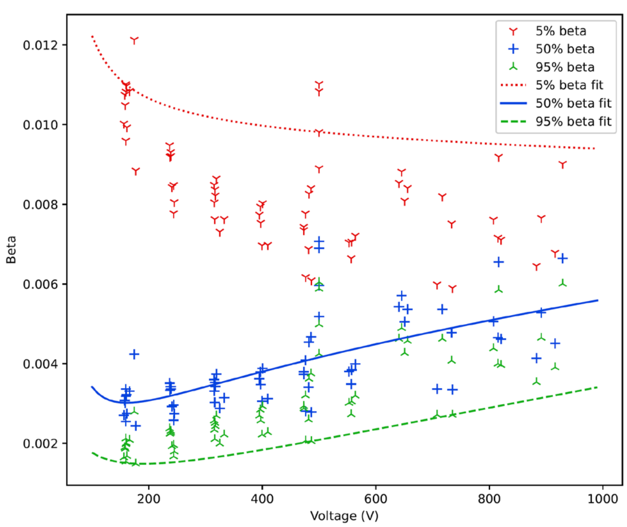

Fig. 9 Beta tuning parameterization for open parallel configurations

The tuning parameter β for closed parallel configurations is calculated as a function of battery voltage as shown in Fig. 10. Of the 77 aggregated experiments, a subset of 22 were selected to train the parameter β for closed parallel configurations. The best fit line with the data available was a linear function as shown in (31).

$$\beta_{\text{closed-parallel}} = aV + b \tag{31}$$

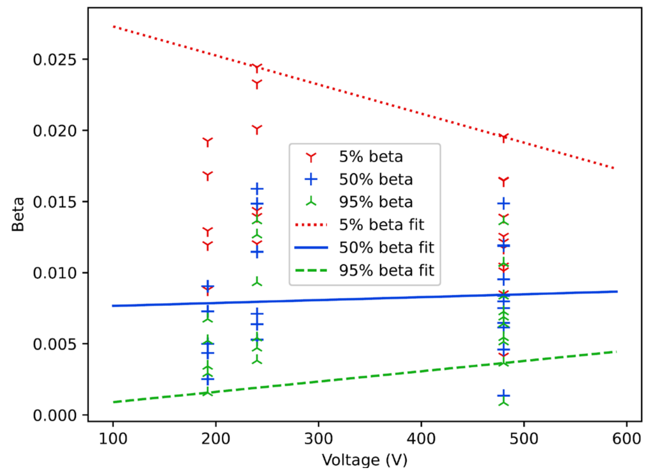

Fig. 10 Beta tuning parameterization for closed parallel configurations.

A summary of the model parameters for each configuration is shown in Table 1.

TABLE II
BETA FUNCTION PARAMETERS FOR (29), (30), AND (31)

Midian parameters $\beta_{50\%}$	a	b	c	d
Inline	46.62	-1.612	8.13E-6	0.9994
Open Parallel	13.29	-1.985	2.51E-4	0.4493
Closed Parallel	2.05E-6	7.46E-3	--	--

<5% chance parameters $\beta_{5\%}$	a	b	c	d
Inline	50	-1.527	0.00781	-3.29E-6
Open Parallel	15.35	-1.999	0.01386	-0.05654
Closed Parallel	-2.04E-5	0.02934	--	--

Workplace Electrical Fatalities 2011 - 2023

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Abstract – Contact with electricity continues to be one of the leading causes of fatalities in the workplace. According to the Occupational Safety and Health Administration, nearly 70% of workplace electrical fatalities occur in non-electrical occupations, which may not require adequate electrical safety training to help prevent fatal electrical injuries [1]. Data compiled from the Bureau of Labor Statistics' Census of Fatal Occupational Injuries found that the construction and natural resources and mining industries have a higher-than-average rate of electrical fatalities compared to other industries, including manufacturing and trade, transportation, and utility industries. This paper examines the commonalities in workplace electrical fatalities, the differences between fatalities in selected industries and occupations, and where improvements can be made in training to prevent these fatal electrical injuries.

Index Terms — electrocution, electrical shock, electrical burn, electrical injury, overhead power lines, occupation, degree of injury, nature of injury, OSHA.

I. INTRODUCTION

According to the Bureau of Labor Statistics' Occupational Injuries and Illnesses and Fatal Injuries Profiles, there is an average of 150 electrically related fatalities each year in the United States [2]. In certain industries and occupations, such as the construction industry, the need for focused electrical safety training information has been identified by highlighting the unique electrical hazards within the industry by the Occupational Safety and Health Administration (OSHA) [3]. While these efforts focus on specific industries, there are many others that have a high risk of electrical incidents where additional awareness efforts can be made.

The author has worked with the Electrical Safety Foundation International to compile data related to workplace electrical incidents to understand the common causes of electrical fatalities in the United States. The data is compiled from two sources, the Bureau of Labor Statistics (BLS) and the OSHA. Each data set provides different insight into the workplace electrical incidents occurring in the United States. The BLS's Census of Fatal Occupational Injuries (CFOI) "provides a comprehensive count of all workplace injuries" [4] and is useful in understanding the rate of electrical incidents. OSHA's Fatality and Catastrophe Investigation Summaries (OSHA 170 form) provides greater detail on the incident including a narrative of the events leading to the fatality. OSHA 170 form is only made available to the public once they "undergo a process for screening personal information and adding keywords," which may result in a delay between when the accident occurred and when the data is made available. This results in a difference in the total number reported incidents compared to the BLS numbers [5].

This paper reviews electrical incidents reported to OSHA and BLS between 2011 and 2023 and categorizes workers involved into two categories: electrical and non-electrical occupations. Electrical occupations are considered occupations that typically receive electrical safety training and are occupations that directly involve electricity. Non-electrical occupations comprise the occupations that do not fall into the electrical occupation category and are more likely not to have electrical safety training. Table 1 shows all electrical occupations as defined by the author.

TABLE 1
ELECTRICAL OCCUPATIONS

Electrical and electronic engineers
Electrical and electronic equipment assemblers
Electrical and electronic technicians
Electric power installers and repairers
Electricians
Electricians' apprentices
Electronic repairers, communications, and industrial equipment
Supervisors in above fields

For those cases where the occupation was recorded as "unknown" or "not listed," the author reviewed the investigation summary to find evidence of the worker's occupation and adjusted the report if possible. A total of 123 reports had the occupation listed as "occupation not reported" after the author's edits. Additionally, relevant cases with the occupations of "groundskeepers and gardeners, except farm" and "chainsaw operators" were combined into "tree trimming occupations" if the worker was completing a tree trimming task when the fatality occurred.

The BLS changed its data collection methods in 2011 resulting in a data gap with previous years [6]. The author selected to compile all workplace incident data beginning in 2011 to stay within the scope of the CFOI.

II. WORKPLACE ELECTRICAL FATALITY TRENDS

A total of 26,285 fatalities were reported in OSHA 170 forms between 2011 and 2023. Out of these fatalities, 1,467 involved electricity, accounting for 5.6% of all fatalities. The percentage of electrical fatalities compared to all fatalities has been steadily decreasing reaching the lowest percentage, 2.71%, in 2020. The

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sharp decline in the percentage of electrical fatalities in 2020 was due to workplace COVID-19 deaths being recorded in the OSHA reports. Figure 1 displays the number of electrical fatalities as reported in OSHA 170 form between 2011 and 2023 compared to the total number of workplace fatalities.

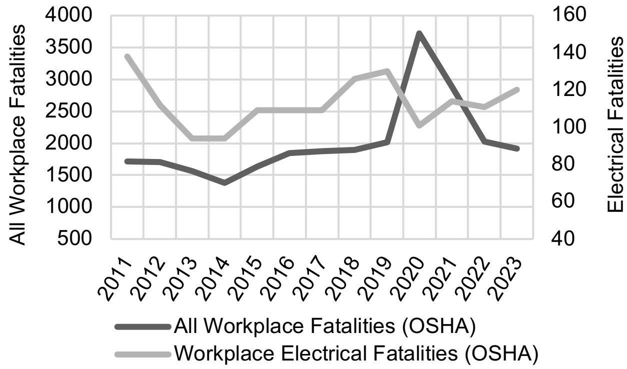

Fig. 1 Workplace Fatalities and Electrical Workplace Fatalities Reported in OSHA 170 Form, 2011 - 2023

The number of electrical fatalities has stayed relatively stable between 2011 and 2023. When reviewing the rate of electrical fatalities across all industries in the United States, the rate, just as the total number of electrical fatalities, has had very little change throughout the years. Figure 2 shows the rate of electrical fatalities compared to the rate of all workplace fatalities. The calculated rate is based on data provided by the BLS. At the time of writing, data is only available from 2011 to 2022.

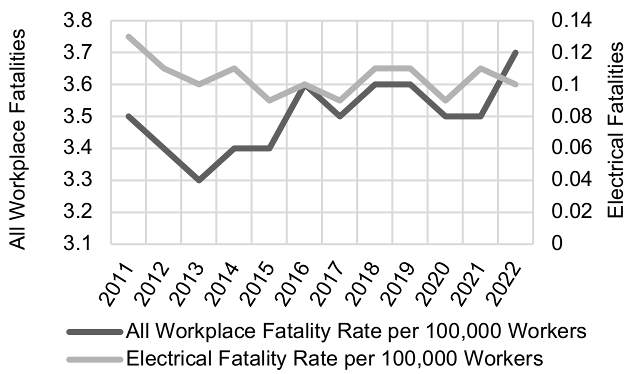

Fig. 2 Workplace Fatality Rate and Electrical Workplace Fatality Rate per 100,000 Workers,
Bureau of Labor Statistics, 2011 - 2022

The rate of electrical fatalities varies per industry. The Bureau of Labor Statistics reported that the "construction," "professional and business services," "natural resources and mining," "trade, transportation, and utilities," and "manufacturing" industries have the highest number of electrical fatalities. The rates of electrical fatalities in these selected industries show that the "construction" and "natural resources and mining" industries consistently have a higher-than-average rate of electrical fatalities compared to all other industries. Figure 3 shows the electrical fatality rate among selected industries. Limited data is available for the 2019 and 2020 collection years due to complications related to data collection by the BLS during the COVID-19 pandemic [7].

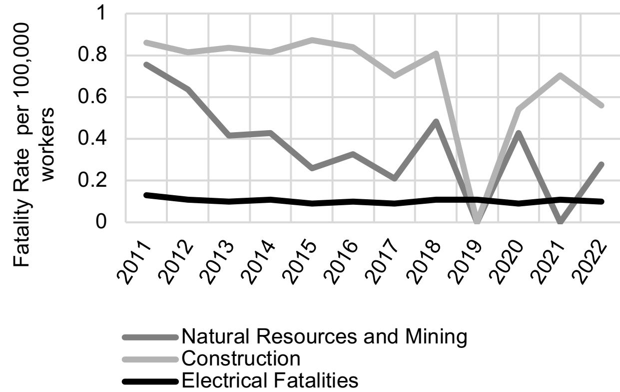

Fig. 3 Rate of Electrical Fatalities per Select Industries,
Bureau of Labor Statistics, 2011 - 2022

Table 2 shows the average electrical fatality rate per 100,000 workers for select industries. The industries with electrical fatalities not listed in the table ("information," "financial activities," "education and health services," "leisure and hospitality," and "other services") have a negligible fatality rate.

TABLE 2
Average Electrical Fatality Rate per 100,000 workers by Select Industry, BLS, 2011 - 2022

Industry	Average Rate
Construction	0.69
Natural Resources and Mining	0.35
Professional and Business Services	0.11
All Industries	0.10
Manufacturing	0.06
Trade, Transportation, and Utilities	0.04

III. ELECTRICAL FATALITIES BY OCCUPATIONS

A total of 1,467 electrically related fatalities were reported in OSHA 170 forms from 2011 to 2022 across 130 different occupations. Of these occupations, a total of 416 fatalities (28%) were in electrical occupations while the remaining 1,051 fatalities during this time were in non-electrical occupations. Figure 4 shows the total fatalities per year by occupation type as reported in OSHA 170 forms. On average, 74% of electrical fatalities between 2011 and 2023 were in non-electrical occupations.

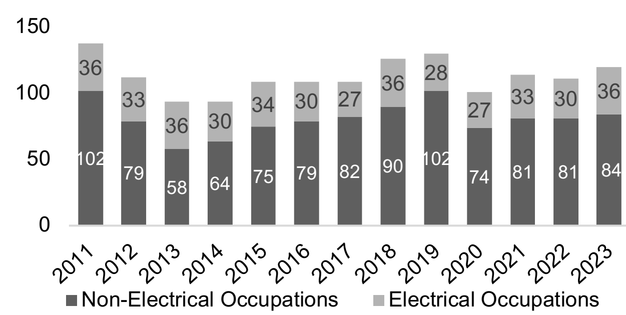

Fig. 4 Electrical Fatalities by Electrical and Non-Elecrical Occupations, OSHA 170 Forms, 2011 – 2023

A total of ten occupations accounted for over 58% of all electrical workplace fatalities with seven of the occupations being non-electrical. Table 3 displays the occupations with 10 or more electrical fatalities between 2011 and 2023.

TABLE 3
Occupations with 10 or more Electrical Fatalities, OSHA 170 Form, 2011 - 2023

Occupations	Fatalities
Electricians	212
Laborers, except construction	142
Construction laborers	131
Occupation not reported	123
Electrical power installers and repairers	122
Tree trimming occupations	64
Electricians' apprentices	45
Heating, air conditioning, and refrig. mechanics	43
Roofers	38
Truck drivers, heavy	35
Painters, construction and maintenance	32
Machinery maintenance occupations	28
Telecomm: line installers and repairers	27
Installers and repairers	23
Electrical and electronic engineers	22
Carpenters	20
Electrical and electronic technicians	17
Welders and cutters	16
Chainsaw operator	14
Helpers, construction trades	14
Supervisors; electricians & power transm. Install	13
Technicians, not elsewhere classified	13
Farm workers	13
Groundskeepers and gardeners, except farm	13
Construction trades, not elsewhere classified	11
Plumbers, pipefitters and steamfitter apprentices	10

Several non-electrical occupations have been experiencing a steady increase in the number of electrical fatalities throughout the years. These occupations include roofers, truck drivers, and painters. Many occupations, including those with an increasing number of electrical fatalities, are occupations and trades typically in the construction industry. Figure 5 shows select occupations where there have been increased numbers of electrical fatalities.

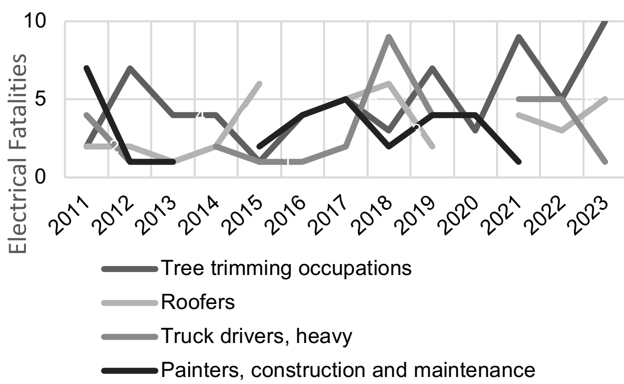

Fig. 5 Select Occupations with Increased Electrical Fatalities, OSHA 170 Forms, 2011 - 2023

The rate of electrical fatalities varied greatly between occupations. The BLS found that electrical occupations had a high rate of electrical fatalities as well as "roofers," "ground maintenance workers," "heating, air conditioning, and refrigeration mechanics," "construction laborers," and "painters" which are non-electrical occupations. Table 4 displays the rate of electrical fatalities in select occupations.

TABLE 4
Average Electrical Fatality Rate per 100,000 workers by Select Occupation, BLS, 2011 - 2022

Industry	Average Rate
Electrical Power Line Installers and Repairers	6.56
Electrician	2.75
Roofers	2.66
Grounds maintenance workers	1.24
Heating, air conditioning, and refrigeration mechanics	0.97
Construction laborer	0.55
Painters, construction and maintenance	0.41
All occupations	0.10

The Bureau of Labor Statistics also reports the location where the electrical fatality occurred. A total of 37% of workplace electrical fatalities occurred in private residences, 31% occurred in industrial places and premises, 12% on streets and highways, 11% in public buildings, 7% on farms, and 1% in places for recreation and sports. Mines and quarries and residential institutions accounted for less than 1% of locations each.

IV. CAUSES OF WORKPLACE FATALITIES

To understand the cause of the electrical fatalities occurring in the workplace in the United States, the author reviewed the narratives for all 1,467 fatalities listed in OSHA 170 forms. A number of commonalities among the fatalities were categorized based on the narrative. Table 5 provides the causes of electrical fatalities along with a detailed explanation of the cause.

A. All Occupations (1,467 Fatalities)

Overhead power line contact is the leading cause of all workplace electrical fatalities, accounting for 48.2% of the fatalities between 2011 and 2022. Unexpected contact with energy accounted for 19.3% of the fatalities and nearby energized equipment contact accounted for 12.7%. The 17 other causes accounted for 19.8% of the fatalities. Figure 6 shows the causes of all electrically related fatalities.

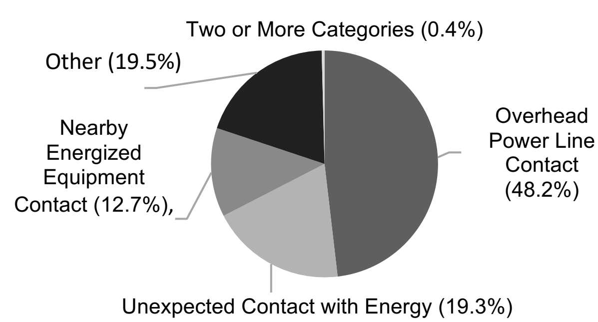

Fig. 6 Causes of Electrical Fatalities, All Occupations, OSHA 170 Form, 2011 – 2023

The reports for overhead power line contact and nearby energized equipment contact account for over 60% of electrical fatalities. Instances of both of these causes of fatalities were either due to the worker not being aware of the energized equipment or due to the worker not understanding the dangers of energized equipment around them.

TABLE 5
Electrical Fatality Causes, OSHA 170 Form, 2011 - 2023

Cause	Description	Fatalities
Overhead Power Line Contact	Fatality was caused due to direct or indirect contact with overhead power lines. Includes arcing from overhead power lines.	707 (48.2% of fatalities)
Unexpected Contact with Energy	Worker unexpectedly came in contact with energized equipment or parts while completing a task. Report may have not included details leading to fatality. Excludes all other causes.	283 (19.3% of fatalities)
Nearby Energized Equipment Contact	Worker came in contact with nearby electrical equipment not being worked on. Includes unintentional contact by extremities or tools. Worker may have not been aware of energized equipment.	186 (12.7% of fatalities)
Working on Energized Parts	Report mentions worker decided to complete work on energized equipment.	60 (4.1% of fatalities)
Ground-Fault	Report mentions ground-fault as the cause of the fatality.	59 (4.0% of fatalities)
Damaged Wiring or Equipment	Fatality caused by damaged wiring or equipment. Includes defective equipment.	46 (3.1% of fatalities)
Troubleshooting / Testing	Worker was conducting troubleshooting or testing when fatality occurred.	38 (2.6% of fatalities)
Worker Mistake	Report mentions a worker making a mistake in the job process that led to the fatality.	29 (2.0% of fatalities)
Arc-Flash or Arc-Blast	Fatality caused specifically by an arc-fault or arc-blast.	16 (1.1% of fatalities)
Underground Power Line Contact	Fatality was caused by contact with an underground power line.	14 (1.0% of fatalities)
Lockout / Tagout Failure	Report mentions worker did not complete a lockout / tagout procedure leading to the fatality.	14 (1.0% of fatalities)
Improper Installation	Worker was killed by improperly installed wiring or devices.	4 (0.3% of fatalities)
Electrical Fire	Fatality was caused specifically by an electrical fire.	3 (0.2% of fatalities)
Backfeed	Fatality was caused specifically by backfeeding.	2 (0.1% of fatalities)
Two or More Causes	Fatality was caused by a combination of two or more of the above causes.	6 (0.4% of fatalities)

B. Electrical Occupation Fatalities (416 Fatalities)

Electrical occupations had a much more varied cause of electrical fatalities. Unexpected contact with energy is the leading cause of electrical occupations fatalities at 27.9% of fatalities. Contact with overhead power lines accounted for 26% of the fatalities while nearby energized equipment contact was the cause of 17.1% of the fatalities. Working on energized parts (8.7%), troubleshooting / testing (5.8%), worker mistakes (5%), arc-flashes / blasts (2.4%), and lockout tagout failure (1.7%) were the other common causes of electrical occupation fatalities. The other nine causes accounted for 5.5% of fatalities.

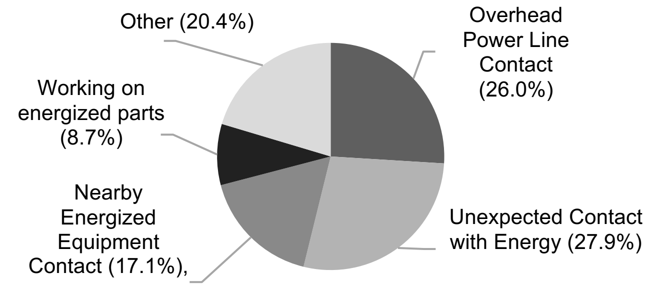

Fig. 7 Causes of Electrical Fatalities, Electrical Occupations, OSHA 170 Form, 2011 – 2023

C. Non-Electrical Occupation Fatalities (1,051 fatalities)

Four causes account for 88.9% of non-electrical occupational fatalities. Overhead power line contact accounted for the majority of non-electrical occupation fatalities at 57%, unexpected contact with energy accounted for 15.9%, nearby energized equipment contact accounted for 10.9%, and ground faults accounted for 5% of all fatalities. Eight other causes accounted for 10.9% of fatalities while two or more causes accounted for 0.2%.

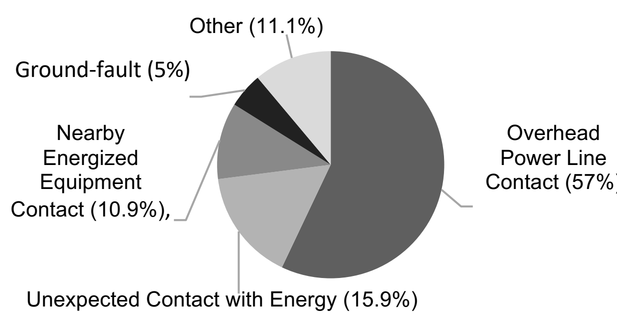

Fig. 8 Causes of Electrical Fatalities, Non-Electrical Occupations, OSHA 170 Form, 2011 – 2023

V. HOW TO PREVENT ELECTRICAL FATALITIES

Five of the top causes of electrical fatalities across all occupations in the workplace account for almost 90% of all electrical fatalities. In many cases, these fatalities can be prevented by raising awareness of the electrical hazards on the worksite.

A. Overhead Power Line Contact

Overhead power line contact is the leading cause of workplace electrical fatalities. Overhead power line contact accounts for 48.2% of all electrical fatalities, 26% of electrical occupation fatalities, and 57% of non-electrical occupations. Overhead power line contacts are unique because in many cases the fatality occurred when the power line was clearly visible.

A total of 87% of overhead power line contact fatalities are in non-electrical occupations. The leading occupations with overhead power line contact are laborers, except construction (12.2%), construction laborers (12.2%), electrical power installers and repairers (12.02%), tree trimming occupations (8.25%), roofers (4.67%), and truck drivers, heavy (4.24%). All occupations should be reminded to "always look up" to be aware of the overhead power line in the area of work. Tree trimmers, roofers, and construction laborers need to be aware of items that may be in contact with overhead power lines that may be energized. Proactive measures can also be taken on jobsites to visually identify and mark hazards and adjust travel areas to avoid overhead power lines. All occupations should be taught to assume all wires are energized to reduce accidental contact.

B. Unexpected Contact with Energy

Unexpected contact with energy is the second leading cause of electrical fatalities in the workplace accounting for 19.3% of all electrical fatalities, 27.9% of electrical occupation fatalities, and 15.9% of non-electrical occupation fatalities. This cause of electrical fatalities is broad, and the source of shock or energized equipment contact may be varied. In some cases, the narrative provided in the OSHA 170 form may not provide context related to what the source of contact was.

Electricians accounted for 27.56% of unexpected contact with energy fatalities. Laborers, except construction (6.36%), construction laborers (5.65%), heating, air conditioning, and refrigeration mechanics (4.59%), and electrical power installers and repairers (4.24%) are the occupations with the highest percentage of unexpected contact with energy fatalities.

Connected safety devices, permanently installed safety controls, preventative and remotely monitored maintenance, and keeping unqualified workers from electrical and energized equipment rooms can help prevent these electrical fatalities. Additionally, ensuring electrical occupation workers follow the hierarchy of controls to prevent complacency can reduce the number of electrical fatalities within this cause.

C. Nearby Energized Equipment Contact

Nearby energized equipment contact accounted for 12.7% of all electrical fatalities, 17.1% of electrical occupation fatalities, and 15.9% of non-electrical occupation fatalities. In all of these fatalities, the worker died due to contact with energized equipment that is not the original equipment being worked on. The energized contact could have been caused by a body part or tool coming into contact with external equipment near where the worker was working.

Electricians accounted for 20.41% of the nearby energized equipment contact. Laborers, except construction (8.60%), electricians' apprentices (7.53%), heating, air conditioning, and refrigeration mechanics (6.99%), and machinery maintenance occupations (5.91%) were the occupations with the highest percentage of nearby energized equipment fatalities.

All workers should have an understanding of the potential dangers of electricity. Workers should also be aware of the equipment around them, not just the work they are completing. It is important that workers be fully aware of the general area where they are working to avoid accidental contact with energy. Workers should also remember to follow proper testing procedures when completing work.

D. Working on Energized Parts

Working on energized parts accounted for 4.1% of all electrical fatalities in the workplace, 8.7% of electrical occupation fatalities, and 2.28% of non-electrical occupational fatalities. These fatalities occurred when electrical occupations did not follow the proper energized work procedures or when non-electrical workers were completing work that they were not qualified to complete.

Electricians accounted for 46.67% of the working on energized parts fatalities. Heating, air conditioning, and refrigeration mechanics (8.33%), construction laborer (5%), and electricians' apprentices (5%) accounted for the highest percentage of occupations with working on energized parts fatalities.

Electrical occupations must remember to always follow the proper procedures when completing energized work. It is important to remember that electrical work should only be completed by qualified workers with proper training.

E. Ground-Fault

Ground-faults accounted for 4% of all electrical fatalities in the workplace, 1.44% of electrical occupation fatalities, and 5.04% of non-electrical occupation fatalities. In all cases, the ground-fault fatalities occurred when tools or extension cords experienced a ground-fault.

Laborers, except construction, accounted for 18.64% of ground-fault fatalities. Construction laborers (10.17%), plumbers, pipefitters and steamfitters and their apprentices (11.86%), electricians (5.08%), and welders and cutters (5.08%) accounted for the occupations with the highest percentage of ground-faults.

All the ground-fault-related fatalities were caused by a lack of ground-fault circuit interrupters. The fatalities related to ground-faults occurred when tools or temporary wiring was used outdoors or in wet conditions. Workers should always use properly tested ground-fault protection when using electrical equipment. Additional steps can also be made to ensure the integrity of grounding equipment through monitoring.

VI. CONCLUSION

Electrical fatalities continue to be a leading cause of fatalities in the workplace. Between 2011 and 2022, the rate of electrical fatalities has not had a significant decline and has remained relatively stagnant. On average, 74% of electrically related fatalities occur in non-electrical occupations and 48.19% of fatalities can be prevented by visually checking for overhead power lines.

Overhead power line contact and nearby energized equipment contact accounted for 60.87% of electrical fatalities. Both of these causes can be prevented by reminding all workers of the dangers of overhead power lines and reminding workers to be aware of their surroundings. Both of these causes do have a significant impact on non-electrical occupations. It is important to always ensure that electrical work is completed by qualified workers who have received proper training to complete the job.

Additional work can be done to raise awareness for all workers on the potential dangers of electricity. The 19.3% of fatalities that occurred due to unexpected contact with electricity and the 4.1% of fatalities that occurred due to workers completing work while the equipment they are working on is energized can also be reduced. By warning workers about the dangers of energized equipment and ensuring they are following the hierarchy of controls, there can be a reduction in the number of these fatalities. Further, complacency may be an issue for electrical occupations completing jobs.

To prevent electrical fatalities on the job site it is important to always look up to identify and avoid overhead power lines and be aware of all surroundings. Following proper testing procedures on not only the device being worked on but also the area around the worksite to prevent accidental contact with energized equipment is important. The most common causes of electrical fatalities are the most available. It is important that all workers understand the dangers of electrical contact. Qualified electrical workers should try to combat complacency, and non-electrical occupations should be trained to understand normal operating conditions and be aware of the limitations of their training and capability for electrical work. Properly using widely available technology, such as ground-fault protection [8], has been shown to reduce the number of fatalities caused by accidental electrical contact [9]. Newly available technology such as predictive maintenance through connected devices, wearables, and permanently installed safety devices can help reduce the number of human contact with energized devices and thus prevent electrical fatalities on the job site.

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VIII. VITA

Daniel Majano is the Senior Program Manager at the Electrical Safety Foundation International (ESFI). He develops and manages programs to help reduce the number of electrically related fatalities in the workplace, home, and community. He has led ESFI’s effort to compile workplace and residential electrical safety data to guide ESFI’s awareness materials. He is a graduate of George Mason University and was the 2024 recipient of the IEEE IAS Electrical Safety Committee Young Professional Achievement Award.

APPENDEX A: ALL OCCUPATIONS INVOLVED IN ELECTRICAL FATALITIES, OSHA 170 FORM, 2011 – 2023

Occupation	Fatalities	Occupation	Fatalities
Electricians	212	Drywall Installers	2
Laborers, except Construction	142	Drillers, Earth	2
Construction Laborer	131	Insulation Workers	2
Occupation not Reported	123	Supervisors and Proprietors, Sales Occupations	2
Electrical Power Installers and Repairers	122	Managers and administrators, N.E.C.*	2
Tree Trimming Occupations	64	Supervisors, Production Occupations	2
Electricians' Apprentices	45	Managers, Farms, except Horticultural	2
Heating, Air Conditioning, and Refrigeration Mechanics	43	Mechanical Engineering Technicians	2
Roofers	38	Elevator Operators	2
Truck Drivers, Heavy	35	Sheet Metal Worker Apprentices	1
Painters, Construction and Maintenance	32	Diver	1
Machinery Maintenance Occupations	28	Machinist Apprentices	1
Telecomm: Line Installers and Repairers	27	Heavy Equipment Mechanics	1
Installers and Repairers	23	Fire Fighter	1
Electrical and Electronic Engineers	22	Washing, Cleaning and Pickling Machine Operators	1
Carpenters	20	Airplane Pilots and Navigators	1
Electrical and Electronic Technicians	17	Managers, Properties and Real Estate	1
Welders and Cutters	16	Furnace, Kiln and Oven Operators	1
Chainsaw Operator	14	Driver-Sales Workers	1
Helpers, Construction Trades	14	Boilermakers	1
Supervisors: Electricians and Power Transmission Install.	13	Mechanical Engineers	1
Groundskeepers and Gardeners, except Farm	13	Sales Representatives, Mining, Manufacturing, and Wholesale	1
Farm Workers	13	Highway Maintenance Worker	1
Technicians, N.E.C.*	13	Buyers, Wholesale and Retail Trade except Farm Products	1
Construction trades, N.E.C.*	11	Miscellaneous Plant and System Operators	1
Plumber, Pipefitter and Steamfitter Apprentices	10	Designers	1

Plumbers, Pipefitters and Steamfitters	9	Chief Executives and General Administrators, Public Admin.	1
Janitors and Cleaners	8	Maids and Housemen	1
Farmers, except Horticultural	7	Aircraft Mechanics, excluding Engine	1
Drillers, Oil Well	7	Surveyors and Mapping Scientists	1
Electronic Repairers, Communications. and Industrial Equipment	7	Bakers	1
Electrical and Electronic Equipment Assemblers	6	Railroad Conductors and Yardmasters	1
Concrete and Terrazzo Finishers	6	Operations and Systems Researchers and Analysts	1
Assemblers	5	Crane Operator	1
Equipment Operator: Heavy	5	Order Clerks	1
Roof Repair: Shingle	5	Roofers: Helpers	1
Elevator Installers and Repairers	5	Bartenders	1
Crane and Tower Operators	5	Separating, Filtering, Clarifying, Precipitating, and Still Machine Setters, Operators, and Tenders	1
Misc. Electrical and Electronic Equipment Repairers	5	Earth, Environmental and Marine Science Teachers	1
Machine Operators, not Specified	4	Specified Mechanics and Repairers	1
Agricultural and Food Scientists	4	Hand Painting, Coating and Decorating Occupations	1
Truck Driver: Heavy/Tractor-Trailer	4	Structural Metal Workers	1
Brickmasons and Stonemasons	3	Health Aides, except Nursing	1
Helpers, Mechanics and Repairers	3	Supervisors, Cleaning and Building Service Workers	1
Telecomm: Equipment Install/Repair, Not Line Installer	3	Business, Commerce and Marketing Teachers	1
Production Helpers	3	Supervisors, Forestry and Logging Workers	1
Supervisors, N.E.C.*	3	Engineering Technicians, N.E.C.*	1
Roof Repair: Sheet Metal	3	Machinists	1
Paving, Surfacing and Tamping Equipment Operators	3	Biological Technicians	1
Forestry Workers, except Logging	3	Supervisors; Brickmasons, Stonemasons, Tilesetters	1
Fabricating Machine Operators, N.E.C.*	3	Printing Machine Operators	1
Agriculture and Forestry Teachers	3	Surveying and Mapping Technicians	1
Supervisors, Farm Workers	3	Production Coordinators	1
Not Applicable	3	Garbage Collectors	1
Not Specified Mechanics and Repairers	3	Cooks, except Short Order	1

Water and Sewage Treatment Plant Operators	3	Management Related Occupations, N.E.C.*	1
Freight, Stock and Material Handlers, N.E.C.*	2	Public Transportation Attendants	1
Hand Cutting and Trimming Occupations	2	Hazardous Materials Removal Worker	1
Aerial Lift Operator	2	Pest Control Occupations	1
Drilling and Boring Machine Operators	2	Truck Drivers, Light	1
Structural Iron and Steel Worker	2	Pipelayer	1
Hoist and Winch Operators	2	Plasterers	1
Supervisors, Related Agricultural Occupations	2	Industrial Machinery Repairers	1
Horticultural Specialty Farmers	2	Adjusters and Calibrators	1
Communications Equipment Operators, N.E.C.*	2	Industrial Truck and Tractor Equipment Operators	1

*Not Elsewhere Classified (N.E.C.)

Best Practices for Implementation of Temporary Protective Grounding on Electrical Systems

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Abstract – Temporary protective grounding (TPG), or personal protective grounding (PPG), is one of the cornerstones of electrical safety. However, correct interpretation of the applicable standards may be difficult, and proper field implementation may be cumbersome. The intent of this paper is to provide guidance on how to interpret the significant industry standards (e.g., ASTM F855, ASTM F2249, IEEE 1048, IEEE 1246, NFPA 70E), regulations (e.g., OSHA, NESC), and to present best field practices are for implementation. It gives recommendations on proper sizing, hardware, and system requirements of TPG. The paper includes applications for overhead line circuits (up to 500 kV), and enclosed equipment (up to 35 kV) applicable to general industry, electric utilities, and oil and gas.

Index Terms — de-energized work, electrical safety, electric shock, body current, temporary protective grounding, TPG, PPG, G&T, grounding switch, *ac* induction, induced current, induced voltage, arc flash.

I. INTRODUCTION

Temporary protective grounding (TPG), or personal protective grounding (PPG), is one of the most applied risk controls for worker protection during de-energized work to protect against electric shock and arc flash due to accidental reenergization and other hazards. Unfortunately, due to the large variety of applications, power system configurations, ratings, and variety of industry standards, many individuals struggle in connecting all the information and applying it correctly. This puts a lot of pressure on end users, manufacturers, and test laboratories. Additionally, the available material is not easy to digest, and it could be quite expensive to test or model TPG field configurations. Some small companies do not have access to an engineering department or staff with extensive TPG experience, and they may need to outsource resources. Proper training in TPG is a must.

Understanding of the power system's ratings is important when prescribing TPG applications. Hardware of a certain gauge and length that performs well at certain fault current magnitudes, X/R ratios, may fail at different system ratings. Also, proper periodic maintenance of TPG hardware is advised to avoid failure and accidents.

In the paper, TPG is a generic term that covers overhead applications, enclosed applications, and underground applications. Sometimes, TPG encompasses grounding devices (G&Ts, grounding switches) when used in the context of a regulation that allows it.

On the other hand, special conductive clothing for vicinity working has been developed as a secondary protection in the case of a TPG failure or its inappropriate application. This paper also aims to introduce personal protective equipment (PPE).

II. DE-ENERGIZED WORK HAZARDS

Workers that perform tasks on electric systems employ de-energized work methods for their maintenance and construction operations. A de-energized circuit is not free from hazards and caution is advised. The following are common hazards that may be present during de-energized work:

a. Electric shock due to *ac* induced current/voltage, accidental circuit re-energization, faults on adjacent circuits, lightning strikes, etc.
b. Direct electric contact with nearby energized circuits due to inadequate clearance
c. Placement of TPG on an energized conductor
d. Burns from ignited TPG jumpers and/or arc flash due to TPG failure
e. Personnel struck by TPG cable whipping due to electromagnetic forces
f. Burns due to fires on vegetation due to ac induced current or fault current
g. Trip hazards with TPG jumpers laid on the ground
h. Injuries/fatalities from falls while applying TPGs when working aloft
i. Smoke and metal vapor inhaling

The main purposes of TPG are:

a. To establish an equipotential zone (EPZ) to control electric shock hazards
b. TPG shall have low impedance/resistance so relaying systems operate correctly, and isolate the intended circuit within the intended time delay

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c. TPG hardware must remain operational after the event and not cause an open circuit due to overheating or mechanical forces or arc flash

Figure 1 shows an example of a test performed at a high current laboratory to certify the performance of double 4/0 AWG TPG under fault current conditions at 51,6 kA rms symmetrical for 30 cycles, with an X/R of 30. In this example, one TPG jumper was exposed and failed to sustain the energy (broken clamp, arc flash and explosion). The top clamp failed and detached from the jumper, which caused an arcing fault, ignited the conductor jacket, and caused a fire. This demonstrates the hazardous conditions that a failed TPG could cause in the field and may expose workers to hazards. During the test, the TPG hardware vibrates and moves violently due to the electromagnetic forces. It also overheats rapidly. Due to the asymmetry ratio of the dc offset, the hardware was subjected to maximum peak current of 128.6 kA. Also, copper expands 30,000 to 67,000 times in volume as it vaporizes from solid to a gas state. This contributes to arc jets and explosion forces.

During a fault, the peak current of the first cycles has the largest magnitude and forces and may break or disconnect the TPG hardware. If not, the subsequent cycles maintain vibration and overheating so the hardware could also fail during that timeframe. Typical hardware fails occur on clamp jaws, ferrules, conductor, clamping hardware (studs, stirrups, etc.) and conductor jacket ignition.

Figure 1 – Example of double 4/0 TPG test failure (top- clamp break, explosion; bottom - arc flash and gassing)

The main requirements of TPG are:

a. To reduce the body current (I_b) of an individual to a tolerable value during exposure
b. Sustain electromagnetic forces and not break
c. Withstand thermal heating and not melt, ignite, or break
d. Meet other hardware requirements per industry standards (e.g., ASTM F855 [1], IEC 61219 [2])

Per IEEE 80 [3], the tolerable body current, I_b (in A), for preventing heart ventricular fibrillation (99.5% of population, 50 kg or 110 lb weight), at exposure time t, in seconds, is determined by Equation (1). Based on (1), a tolerable exposure voltage (V_e, in V) can be calculated and when assigning a body resistance and applying Ohm's law. This value can be used during laboratory testing for pass/fail criteria during TPG hardware testing.

$$I_b = \frac{0.116}{\sqrt{t}} \quad (1)$$

For example, at 30 cycles (0.5 s, typical at transmission level), the tolerable body current limit is 164 mA. If the body resistance is assumed to be 1,000 Ω (other values may be used; body resistance varies [3]), then the exposure voltage V_e tolerable limit is 164 V. If during a laboratory test this limit is exceeded, then an electric shock hazard may be present, and the hardware may not be suitable for the given application. If the time of exposure is larger (such as in distribution, industrial applications, ac induction applications), the tolerable I_b limit is less. Careful consideration is required when a particular piece of TPG hardware is evaluated for different system parameters. In scenarios with *ac* induced current, there is no relaying system available to trip the adjacent circuit causing the *ac* induction, and the time t of exposure could be several seconds, corresponding to a very low limit of tolerable I_b. For example, at 3 s exposure, the I_b tolerable limit is 67 mA, or 67 V of V_e (59% reduction).

Calculations of voltage exposure in field TPG configurations based solely on resistance produce large errors as the voltage developed across TPG hardware (due to a fault) has a large component due to the reactance of the TPG conductor(s). The reactance of the TPG increases with length (also coiling, multiple conductors), and with the number of TPG jumpers per phase. IEEE 1246 [4] explains TPG 'K' factor method in depth for calculating exposure voltage V_e of a given TPG field configuration.

III. REGULATIONS AND CHALLENGES

Safety regulations involving TPG vary considerably per region of the world and complicates end user understanding. It also makes it difficult for some grounding equipment and methods to be applied in different jurisdictions. Examples include but are not limited to whether TPGs may be applied by hand, with insulating protective equipment (IPE), or a live-line tool, and if grounding (earthing) switches count as TPG, or should be used in conjunction with TPG, or cannot be used alone as temporary grounding.

In the USA, OSHA regulates TPGs for general industry with 29 CFR 1910.333 [5], 1910.335 [6]. 29 CFR 1910, Subpart S [7] cites NFPA 70E [8] as a consensus standard that may be consulted for compliance. TPGs are covered in NFPA 70E [8] Sections 120.4, 120.5, 250.3. Table 130.7(C) deems the application and removal of TPG an arc flash prone activity. Table 130.7(E), and Sections 250.1-250.3 recommend periodic testing of TPG assemblies. Section 360 covers capacitor temporary grounding.

Similarly, in the USA, TPGs for the electric utility industry are regulated by 29 CFR 1910.269 [9] (including line clearance trimming),1926.962 [10], and IEEE C2 (NESC) [11]. General arborist operations cover TPG practices under ANSI Z133 [12].

TPG rules for the telecommunication sector are covered under 1910.268 [13]. See 1910.268(m)(4).

TPG for inland Oil & Gas industry is regulated per OSHA 1910 [7] and 1926 [14]. Offshore operations are regulated by other acts and vary per sea region. TPG for mining operations is regulated by MSHA, 30 CFR [15]. For example, TPGs for coal mines are covered under Subpart 75.705-1.

Several accidents have been reported in the industry where a crane contacted a live power line. 29 CFR 1926.1407[16] through 1926.1411 [17] cover appropriate TPG controls when cranes operate near power lines, or when a crane must be moved under a power line. Contractors must contact power line operators and request to de-energize lines and apply TPG if work is conducted within the permissible distance. Distances vary based on qualifications of the crane operator, presence of a spotter, crane controls, etc.

When a TPG work hazard is not addressed by a specific OSHA standard, the General duty clause of the OSH Act applies (Section 5.a.l) [18].

In Europe, the European Union Directive 2014/35/EU [19] regulates the use of TPG.

Many regulations lack a proper definition of "equipotential zone" (EPZ) and its shortcomings turn into field confusion, training deficiencies, and accidents. An EPZ is a region of a worksite in which the equipment has been bonded and grounded such that an individual will experience very little differences of electric potential (below tolerable limits) while in contact with different items within the worksite and therefore that individual has a very low risk of electric shock. Misunderstanding of application of EPZ may expose individuals to the risk of becoming in series with the path of electrical current and being injured. An example is the misconception that all the earth is at the same electrical potential. During a fault, electric current is injected or extracted at different points of the surface, and it splits between different mediums. Soil has varying resistance, or resistivity, and when electric current passes through it, it causes surface voltages (touch voltage, ground potential rise GPR, etc.). If the resistivity is high, then a surface voltage may develop that could injure or kill an individual.

Regulations are sometimes vague as to whether a de-energized circuit is prone to electrical hazards. ac induction is a silent killer, and many people lose their lives because they were trained to deem a circuit safe to touch when deenergized and grounded ("if it is grounded then it is dead" philosophy) [20]. Rather, training should state that if a circuit is de-energized and grounded, it may not be safe. Some regulations such as 1910.269 [9] mention that the risk of *ac* induced voltage must be assessed when determining if a circuit that has been de-energized and grounded is safe to approach.

There is a close relationship between TPGs, arc flash, lockout & tagout (LOTO), and minimum approach distance (MAD). NFPA 70E [8] equivalent term for MAD is Restricted Approach Boundary (RAB). Some regulations fail to establish a direct connection between them. TPGs are control means to transition an electric circuit from energized, to de-energized and grounded. Attaching and removing TPG are considered live work activities Workers apply TPG with PPE, insulating protective equipment (IPE), and live line tools and adhere to the MAD. After the circuit has been declared LOTO and cleared, then MAD is no longer applicable, and the arc flash exposure is eliminated.

In the USA, OSHA [9] does not permit the sole use of grounding switches as TPG. Some exceptions exist such as gas insulated switchgear (GIS) due to its unique construction and difficulty of accessing the bus. Another example of an exception is metal-clad switchgear where IEEE C37.20.6 [21] devices (e.g., G&Ts) are allowed. Some countries in Europe and Latin America allow the use of earthing switches as TPG or to be used in conjunction with TPG. Other countries do a mixture of methods.

Low voltage TPG practices vary greatly around the world. In the US, OSHA 1910.269 [9] addresses that at 600 V or less, the worker can use insulating equipment for applying TPG instead of a live line tool. In addition, Live-line tools are mandatory over 600 V. OSHA Instruction CPL 2-1.38 [22] mentions the challenges in applying TPGs on systems 600 V and under when the circuit has not been constructed to accommodate TPGs, or when the short circuit duty is so high that is impractical to size TPG hardware to sustain large thermal requirements and electromagnetic forces (e.g., 80 kA). In Europe, LV systems (overhead, enclosed) are built to accommodate TPGs and apply special TPG jumpers and clamps.

During some equipment testing such as high potential testing, TPGs must be removed after connecting the test equipment. Regulations such as 1910.269 [9] require that the TPGs are installed first with a live line tool, the test equipment is connected after, and then the TPGs are removed with a live line tool, leaving the test equipment connected. During the test, personnel must maintain MAD, and the live conductors may only be approached with IPE or with live line tools.

IV. INDUSTRY STANDARDS AND CHALLENGES

Industry standards for hardware and application guides that cover TPG must be followed with caution. Not all standards can be used in conjunction with each other. Some limitations apply. The main recognized methods for applying TPG in overhead, underground, and enclosed applications are [4] [23]:

a. Bracket grounding (source grounding)
b. Worksite grounding (single point grounding)
c. Worksite bracket grounding (multi-point grounding)
d. Combination grounding

TPG jumpers can be applied in a variety of configurations [4] [23]:

a. Parallel
b. Balanced (or 'T')
c. Cluster
d. Unbalanced (or daisy chain)
e. Single-phase

It matters where the worker is positioned in comparison with the location of TPGs. The body current I_b exposure of the individual increases when the distance between the person and the TPG increases. It also increases if the worker is between the source and the TPG vs. if the TPG is between the source and the worker.

The main standards that cover TPG and bonding hardware include ASTM F855 [1], ASTM F2321 [24], IEEE 386 [25], and IEC 61230 [26]. Ratings vary based on fault current, X/R ratio (*dc* offset), duration, and some based-on voltage too.

The main standards that cover grounding equipment such as G&T devices and grounding (earthing) switches include IEEE C37.20.6 [21], and IEC 62271-102 [27].

The main standards that cover TPG field applications include but are not limited to IEEE 1048 (overhead lines) [23], IEEE 1246 (substations) [4], IEEE 1268 [28] (mobile substations), IEEE C2 (NESC) (overhead lines) [11], and NFPA 70E [8] (general industry).

Consult MAD (RAB) when applying TPG per IEEE 516 [29], NESC [11], IEC 61472 [30], NFPA 70E [8], and ANSI Z133 [12].

Consult arc flash exposure estimates for applying TPG per IEEE 1584 [31], and NESC [11].

Sometimes workers applying TPG may have exposure to high electric field (*E*) strength, and magnetic field strength (*B*) from nearby energized circuits. Consult occupational limits per ICNIRP [32], IEEE C95.1 [33], and IEEE C95.6 [34]. Exposure to non-ionizing radiation from live antennas when applying TPG is a thermal and electric shock hazard. Consult occupational limits for SAR per ICNIRP [35] and NESC [11].

Manufacturing standards such as ASTM F855 [1] state that using the ratings for field application is out of scope. This puts the responsibility on the end user to determine whether the hardware can or cannot be applied to a specific field situation. The most common approaches to determine if a given TPG set or grounding equipment meet system requirements and TPG configuration are:

a. Test the exact TPG configuration and system ratings at a high current test laboratory
b. Use TPGs within the limited testing parameters of an industry standard (e.g., ASTM F855 [1], IEEE C37.20.6 [21])
c. Used advanced simulation software

For option (a), the laboratory testing option can be costly. It is recommended for TPG applications of multiple jumpers per phase as the current split is difficult to predict. For example, a bundle of two TPG per phase doesn’t mean that the current splits 50/50% per jumper as some training and technical papers incorrectly present. Small differences in jumper length, clamping force and resistance between clamping points may cause current distribution of 70/30% up to 90/10% just to give some idea of the asymmetry that causes hardware failures. Option (a) is also helpful in high current applications, such as Grade 5H to 7H hardware [1].

There are several organizations that perform TPG testing and evaluation and some of their reports are freely accessible to the public or subject to membership. An examples include Georgia Tech’s NEETRAC [36].

In option (b), some field cases may be applicable within the boundaries of testing of an industry standard. For example, applications of single jumpers per phase of short length of about 15 ft or less match closely the performance of hardware tested per ASTM F855 [1], which is tested with jumpers of 3 m length. The problem with longer TPG jumpers or TPG with multiple conductors per phase is that ASTM F855 [1] will not be able to represent accurate performance due to the excessive electromagnetic forces, and voltage drop. Hardware failure is common.

Grounding devices (G&Ts, grounding switches) must be adequately designed to meet system requirements including fault duty growth. Accidents have occurred where people used G&T of inadequate ratings. For example, according to IEEE C37.20.6 [21], G&Ts must be sized to withstand the maximum peak current (or asymmetrical total current); they also must meet or exceed the closing and latching capability of the circuit breaker they are intended to replace. A periodic maintenance program must ensure that the equipment ratings are maintained. G&Ts should not be modified by users as there is a risk that the hardware may not sustain the system ratings. Replacing a jumper model or adding a ground stud (an modifying design) on the G&T may compromise the system and cause failure. Users must adjust work methods to accommodate the capabilities of the equipment. There are options in the marketplace for remote racking of G&Ts by using specialized external motorized drives that add distance between the operator and the equipment to be serviced.

According to IEC 62271-102 [27], grounding (earthing) switches must be specified to meet system short-circuit making current (I_{ma}) and rated peak withstand current in case of accidental energization. The Class (E0, E1, E2) determines the number of short-circuit making operations without major maintenance. The switches also must meet the system induced current switching requirements. For example, a 245 kV earthing switch, Class A, must withstand 80 A rms of electromagnetic coupling current, and 1.25 A rms of electrostatic coupling current. Because of this capability, grounding switches can be used to aid workers to close a circuit with high ac induction prior to applying TPG, and to remove TPG prior to opening the switch at the end of the job. Ac induction has caused multiple accidents in multi-line corridors due to workers drawing very long arcs while applying/removing TPGs [20]. The worker can be distracted and either contact a nearby live part, or the arc may extend enough to reach the worker or a live part and cause a system fault. See Figure 2.

Figure 2 – Example of an arc caused by ac induction while removing TPGs on a 345 kV line in a T-line corridor

Grounding switches may lose alignment with time and increase contact resistance, which can lead to catastrophic failure during a fault due to overheating. Grounding switches need periodic blade adjustment and realignment, addition of conductive joint compound, and contact resistance testing.

Consult ANSI/NETA Maintenance Testing Specifications (MTS) [37] and manufacturer recommendations.

Option (c) is still a valid way to predict TPG performance. The best practice is to use software that utilizes a semi-empirical model and apply K-factors per IEEE 1246 [4]. Another way is to use multi-fields finite element analysis software for simulating voltage exposure and electromagnetic forces. However, this method requires a high level of expertise, and access to data from laboratory tests.

The *dc* offset of the fault current, represented by the X/R ratio of the fault circuit, defines the magnitude of the peak current I_p that will produce electromagnetic (Lorentz) forces that TPGs are subjected to. See Equation (2) for first peak current [38].

$$I_p = I_{sym,rms} \cdot \sqrt{2} \cdot \left(1 + e^{\frac{-\omega t}{X/R}}\right) \tag{2}$$

Per Equation (2), the larger the X/R ratio, the larger the peak current. X/R ratio varies per location in the circuit, and per fault type (e.g., single line-to-ground). In a SLG fault, the peak current happens every ½ cycle (8 ms at 60 Hz). The direction of the force alternates direction and turns into a 120 Hz vibration that could break TPG hardware. Figure 3 shows the whipping action of triple TPG (unrestrained) jumpers due to electromagnetic forces at a 50-kA test, X/R of 30, single phase, for 0.5 s. Figure 4 shows before/after photos and failure.

The magnitude of the peaks of the current decreases with time as the *dc* offset reduces to zero. In DLG and three-phase (TPH) faults the interaction of forces is more complex as forces from multiple conductors add up vectorially with phase shifts.

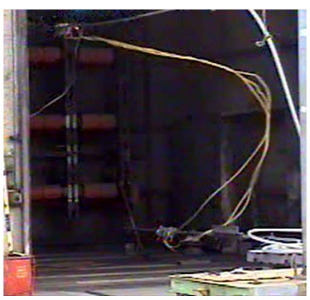

Figure 3 – Electromechanical forces on triple TPG jumpers during a 50-kA high current test

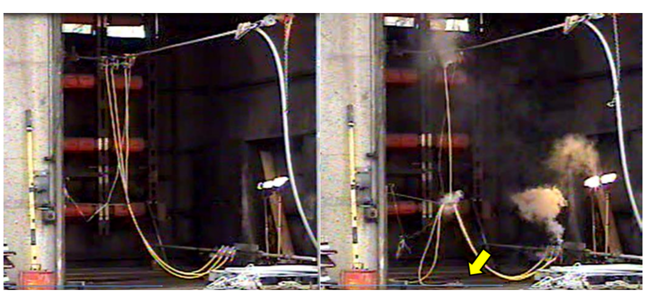

Figure 4 – Mechanical failure of triple TPG configuration, 50-kA test (left: before; right: after)

Examples of typical ranges of X/R values for real circuits are 5 or less for UHV/EHV transmission, 5 to 12 for HV transmission, 60 and below for distribution, and 100 and below for generation [39]. Standards such as ASTM F855 [1] include tests with only one conductor and an X/R ratio of 17 for standard ratings, or high (Grade 'H') X/R of 30. IEEE 386 [25] covers MV underground/cable applications including elbow type TPGs. This standard has single-phase tests with parameters that vary depending on the system voltage such as X/R of 6 or 20, rms symmetrical fault current of 3.5/10/20/40 kA, and duration of 0.17 s or 3 s.

Periodic testing and in-service inspection of TPG assemblies is recommended per ASTM F2249 [40] and NFPA 70E [8]. Several tests were conducted over the years on failed TPG sets at the laboratory, and reference measurements are posted in tables in ASTM F2249 [40] that determine the value of electrical resistance (R_{max} limits) to which a TPG shows signs of impending failure and removal from service is advised. There are no test equipment standards available, so user caution is advised when selecting test equipment. Some testing instruments may be sensitive to clamping force, location of the clamp on the test instrument ports, coiling of the TPG jumper. The best practice is to select four-point resistance measurement devices. See Table I for an example of periodic testing of TPG.

TABLE I
EXAMPLES OF FIELD ELECTRICAL TESTING OF TPG

Test Set	Configuration	R measured (Ω)	R_{max} limit [a] (20 °C) (Ω)	Test Result
1	4/0 AWG, 25 ft, C-clamp to steel beam clamp	0.0361	1.6718	Pass
2	2/0 AWG, 15 ft, duckbill to duckbill	2.3671	1.6083	Fail

[a] Per ASTM 2249 [37]

V. BEST FIELD PRACTICES

This section covers best practices for applying TPGs and grounding devices. Periodic review of work practices is advised for companies to remain current as the field of temporary grounding is in constant development.

It is recommended to complete a grounding plan and discuss it during a pre-job briefing meeting before applying temporary grounding. Identify all possible sources of de-energization and points of isolation. Identify sources of ac induction. Select the best method (bracket grounding, worksite grounding, etc.) and location of the master grounds and bonding. Follow IEEE 1048 [23] and IEEE 1246 [4] for more guidance. Place master grounds the closest to the workers to reduce body current I_b exposure.

Fault duration is important as TPGs may need to be tested per system requirements at the laboratory. Common practice is to size TPGs according to backup relaying clearing times. Typical backup clearing times for transmission are 300 ms. Some sub-transmission line configurations (e.g., 69 kV) range between 250 ms up to 2 s. Distribution and industrial relaying applications have backup clearing times that range from 250 ms up to 3 s due to current time interval coordination (CTI) of overcurrent protective elements. Reclosing time is typically not accounted in TPG sizing due to two reasons; one is it is common practice to block the reclose function of protective schemes during de-energized work, and second, even if the circuit recloses accidentally, it is considered a separate fault event due to the dead time interval between faults. Differential schemes (87L, 87T, 87Z, 87V), teleprotection schemes (permissive overreaching transfer trip POTT, etc.), and current reversal schemes have typical fast clearing times between 167 ms (10 cycles) and 300 ms.

Fault current growth is a factor to consider when sizing TPGs and grounding devices. Periodic assessments may be required. In general industry applications, a facility with a power transformer may experience little change of fault current on the low side unless the transformer is replaced with one of lower impedance, or a transformer is added in parallel operation. Periodicity can be set as every 3 to 5 years review.

In transmission applications, fault current growth could vary widely. Due to the addition of new power lines and generation, fault growth could change in one year between 5 to 50%, so a more frequent review period, such as yearly, is recommended. A lot of utilities have reached very high current values (e.g., 63 kA) and ASTM 7H Grade [1] TPG hardware is common. For that reason, utilities sometimes apply procedures to perform power line switching to reduce fault current levels prior to applying TPG, or sometimes report fault current changes across T-lines so crews may place TPGs at a given line section.

Distribution feeder systems have many challenges. First, fault current is very difficult to estimate because feeder sections are constantly switched and the source impedance, and line conductor gauges vary per line section. Short circuit strength changes constantly. Second, the fault current magnitude is high closer to the substation, and it is very low at the tail of the feeders. Some utilities oversimplify TPG requirements and may end up with a large size and heavy duty 'one fits all' approach TPG set that may create fatigue and stress on the line workers; that may be an overkill on the broader portion of the feeder system. Or the utility may use different sizes of TPG that require more training and leave room for mistakes from workers. Periodicity for TPG assessments in feeder systems is recommended on a yearly or biannual basis.

When working on MV concentric neutral cables, be cautious with trapped charge due to the capacitance of the cables after de-energizing. Make sure an EPZ is established before workers approach cable sheaths, conductors, etc. For splicing operations, there are special cable cutting tools, or spiking tools, with a pin that pierces the cable and shunts the sheath and conductor before cutting in case the cable is energized. This causes the protection system to trip and protects the worker. The spiking tool can perform the cutting with the operator at a distance, so if a fault were to occur, the person won't be affected by arc energy or electric shock hazards. Designs with capacitive points for voltage measuring (with a live-line tool) at cable elbows are also recommended.

In generation plants, fault current duties shouldn't change much due to the impedance of the generator step-up transformer unit (GSU), unless more generating units are added, switchgear configuration is modified, or if the GSU is replaced with a different impedance unit. Common practice is to avoid adding fault contributions from local generating units and assume LOTO controls are in place when generators are offline. Recommended periodicity of TPG studies is every five years (authors' recommendation) or each time the plant configuration changes the fault current over 10%.

Deactivate the reclosing function (ANSI 79) of the circuit relaying prior to applying temporary grounding.

Always inspect the TPGs and grounding devices daily prior to use. Some jobs may take days or weeks.

Always apply and remove TPG in the right order with a live-line tool and respect MAD (RAB). Make sure the voltage sensing tool is operational prior to applying TPG. Request clearance from system operator, de-energize the circuit, and test for dead with a voltmeter and a live line tool. Apply TPGs on the grounded end first and build the configuration towards the phase conductor last. Remove TPG in opposite order.

Use a double-hotstick method if it is needed to place TPG jumpers between phase conductors (e.g., unbalanced configuration). Some regulations allow placing TPG with rubber gloves and protector gloves (e.g., at 600V or below per [9]), but caution is needed. Use appropriate arc rated (AR) PPE (e.g., AR gloves, AR/FR clothing, AR head protection).

Brush the conductor and grounded source surfaces (with a special live line tool brush) before applying TPG clamps. Some TPG clamps have serrated jaws for improving contact. Weathered steel and painted steel offers poor electrical connection (high resistance).

Apply proper barricading of the EPZ and the temporary grounding electrodes, if applied. During a fault, current can be injected into the ground and touch and step voltages will develop across the surface. Outside the EPZ, the voltage gradients may exceed tolerable values and pose electric shock hazards.

Do not always assume that a circuit that is de-energized and that is grounded is dead. Conduct an assessment and determine if ac induction may be present and apply proper controls. Examples include proper bonding and establishment of the EPZ, use IPE, use live-line tools and switch to a live work method, use conductive clothing [1067] [41], etc. OSHA states that an ac induction hazard is present if the worker exposure exceeds 6 mA of body current [7].

Conductive clothing is (flame and arc resistant) PPE that can help workers reduce their exposure to high electric (E) fields (Faraday cage effect) when applying TPG near other high voltage energized parts and meet occupational limits [32] [33]. There is also a special type of conductive clothing designed to protect against ac induced current [42]. This PPE shunts the ac induced current (that it is rated for, e.g. 50 A) and reduces the body current (under 6 mA) in case of accidental contact with ac induced current. By maintaining the body current low, the wearer can self-extract from the circuit with ac induction (avoid electric shock, muscle contraction, asphyxia) [42]. ASTM Task Group WK70226 produced a PPE standard specification that will be published in 2025, and IEEE 1067 [41] is under review to include this type of PPE.

Users should determine if they want to rate their TPG according to withstand rating or ultimate rating. For example, according to ASTM F855 [1], a Grade '5' TPG (X/R of 1.8), 4/0 AWG, at 30 cycles, has a withstand rating of 30 kA symmetrical, and an ultimate rating of 42 kA symmetrical. The basis of using withstand rating is that the TPG can be returned to service upon inspection after sustaining an event, and the ultimate rating does not (permanent damage). Grade 'H' (X/R of 30) TPGs only have ultimate rating.

Define what are acceptable ground sources to apply TPG and if an order of merit exists. For example, in overhead line applications a multi-grounded shield wire or multi-grounded neutral wire offers less resistance to remote earth than a driven temporary ground rod.

Verify that clamping hardware such as grounding stirrups and grounding studs are properly rated and that they can accommodate the quantity of required clamps. For example, some metal-clad switchgear requires two ground studs in the ground bus to accommodate double TPG in high current applications.

For G&Ts, some companies color code equipment for the fault current and voltage application so personnel avoid using the wrong G&T with a lesser rating. Some equipment has been designed to avoid this issue by design by sizing differently the G&T primary terminals and jumper cable terminals.

Create simple TPG tables for workers to reduce human error when reading them (Table II). For example, a company may decide to do a one size fits all after conducting grounding and fault analysis. The benefits are less parts in field use to choose. Disadvantages are that the hardware that the employee needs to carry may be heavier and cause fatigue or injuries. Another approach is to list the circuits and post the TPG requirements per circuit. See Table II. The disadvantages are handling more TPG inventory and the need to properly train the workforce to read the tables. With this approach it is recommended to alert workers about situations in which they should contact engineering. Examples include TPGs required when there is transformer paralleling, or when the system fault level exceeds the ratings of available TPGs, and the system operator needs to conduct system switching to reduce the fault current.

TABLE II
EXAMPLE OF TPG REQUIREMENTS FOR OVERHEAD LINES

Line ID	Nominal Voltage (kV)	Line Length (mi)	Fault Current			TPG Required 4/0 AWG	
			Maximum Fault Current (kA)	X/R	Type	No. per phase	Max Length (ft)
A	69	14.5	17.5	15.0	SLG TPH	1	25
B	115	28.3	36.1	8.7	SLG TPH	2	25
C	230	72.4	28.6	5.3	SLG TPH	1	25

When it is required to apply double and triple TPGs per phase conductor, place the clamps as close as possible. See Figure 5.

In bundled phase conductors, Figure 6, apply TPGs to different bundle sub-conductors. Users may add jumpers between sub-conductors or review if the conductive properties of bundling hardware and conductor yokes are sufficient to carry fault current.

If there is a possibility of applying TPGs on flexible or rigid conductors for a given application, the flexible conductor option offers a safety buffer. Upon a fault, the flexible conductor will move and absorb some of the energy and less energy will be transferred to the TPG hardware compared to connecting to a rigid bus. An example is placing TPGs on circuit breaker stranded jumpers in a substation instead of applying them on the tubular (pipe) bus. See Figure 6.

When applying TPGs, it is best to use the shortest TPG leads possible (and not coiled). That will reduce the reactance of the cables and the voltage that can be developed across the TPG.

Many accidents are reported due to applying TPGs on live buses and equipment. Ensure that workers perform a pre-job brief form, identify the circuit to work on properly, and verify absence of voltage with a live-line tool prior to applying TPGs. Tag the circuit to be worked on, some people come and work on the wrong circuit after a lunch break and contact energized parts.

Some grounding stirrups are more heavy duty than grounding studs. Stirrups have two attachment points to the bus. However, both solutions are acceptable provided there is testing to justify the configuration.

Assess ungrounded systems carefully. Typically, if a person applies a TPG in one phase of an energized ungrounded system, the fault current may be so low (e.g., 15 A) that no damage will be observable on the TPG. Some ungrounded systems are designed not to trip under SLG conditions. Furthermore, when the person applies the second TPG jumper a larger fault current may be observed. For that reason, TPGs may need to be sized by the double line-to-ground (DLG) fault magnitude. Also consider that after placing the first grounding jumper, a neutral shift may occur, and the ungrounded phases may experience a neutral shift and exhibit line-to-line voltage. Caution is advised when selecting the MAD.

Figure 5 – Example of placement of multiple TPG jumpers on a single-phase conductor

Figure 6 – Example of placement of multiple TPG jumpers on a two-bundled phase conductor

Carefully specify the TPG jacket type. Jackets are for mechanical endurance, and they are only rated 600 V (or less). Clear plastic jackets are good for visual inspection of outer conductor strands, but they are too stiff and perform poorly for installation in cold climates. Customized jackets with customer information help deter copper theft.

When performing visual inspection on TPGs, look for cracked clamps, loose ferrules, loose nuts, kinks, bulges, broken strands, past signs of arcing, etc. Tag the hardware as defective. Remove from service and either ship to the shop or destroy and dispose. See Figure 7.

When working on substation capacitor banks, de-energize and wait some time (typically 5 to 10 minutes) for the capacitor to discharge and verify absence of voltage with a live-line tool. Then ground. NFPA 70E [8], Article 360 and Annex R, cover 'soft' and 'hard' grounding of capacitors for various uses.

In applications with very large fault current and X/R (e.g., 50 to 63 kA), where TPG sizing is not available or impractical, it is recommended to consider a procedure for switching the system configuration so the fault current is reduced, so TPGs can be sized and applied properly. Examples include sectionalizing buses, avoiding power transformer paralleling, etc. Another solution is to place TPG grounds at locations of lower fault current (overhead lines, enclosed switchgear).

Figure 7 – Example of failed TPGs during visual inspection – defective jacket (left), cut strands (right)

Do not touch TPG hardware due to electric shock hazards including *ac* induction. Never position the worker's body in series between items at different electrical potentials, or between the conductors and the TPG hardware. Secure loose TPG jumpers with a rope to prevent whipping action due to a fault. TPG on the ground could also become tripping hazards. Avoid coiling the TPG jumper as it increases the inductive reactance of the cable and therefore it increases the voltage drop across the TPG and poses an electric shock risk to the workers. Coiling also amplifies the electromagnetic forces that the TPG is subjected to. See Figure 8.

The best practice for rating TPGs is to perform laboratory testing with a particular field TPG configuration. Other approaches such as interpreting industry standards or performing simulations are possible but caution must be exercised with experienced staff.

In metal enclosed and metal-clad switchgear applications manually racking grounding equipment (G&T) with open door doesn't remove the hazards of arc flash exposure due to equipment maintenance conditions. See NFPA 70E [8]. Some G&T designs allow for closed door racking. Grounding switches are available in the IEC world but there is no available standard in the ANSI world. Future development is needed to accommodate solutions to facilitate grounding.

Old facilities in the general industry and power plants lack provisions of TPG attachments. Therefore, it is cumbersome to apply TPGs. Solutions vary depending on regulations. Some solutions include isolation at LV circuits to de-energize the MV circuits, so TPG attachments such as ball studs can be installed to facilitate future jobs. Whenever that is not a possibility, another option is to isolate the MV equipment by removing circuit breaker carts in switchgear, and then applying PPE and IPE so the workers can install the TPG attachments, and then proceeding with installing the TPGs, and continuing the work as de-energized.

Figure 8 – Example of unsecured vs secured TPG jumpers

Generator contributions to fault current can be excluded from TPG calculations with proper generator LOTO procedures, so there is assurance that the excitation system and prime mover are disabled. This helps in reducing TPG requirements as generators may add high fault contribution.

Applying temporary grounding to low voltage systems (e.g., 600 V and below) varies greatly based on local regulations. Some regions like the US allow grounding with certain provisions. OSHA states [9] [22] that TPG may be applied if the circuits have been designed with appropriate clearances to place ground clamps, jumpers, and grounding switches. Also, it states that TPG can only be applied if the hardware can sustain the fault current; caution is advised on LV systems with very high fault current [22]. If the system is de-energized but not grounded, workers must isolate the circuit, test for absence of voltage, and apply lockout & tagout. Isolation can be performed by opening disconnects, removing fuses, clipping conductors, etc.

In Europe, it is more common to apply temporary grounding to LV systems because they are built with provisions. Same TPG configurations apply, such as bracket grounding, worksite grounding, etc. There are specially designed LV TPG clusters that can be applied with live-line tools. There are also TPG options for aerial bundled cable (the UK uses an insulated adapter to an insulated piercing connector). However, all these TPG sets are rated for low fault current ratings of 15 kA and below.

When work is to be performed on an aerial platform with a non-insulating boom, the best practice is to apply bonding between the metallic grid of the bucket and the power line. In this way, the conductor is bridging the worker, so that ensures equipotentiality. For bucket bonding jumper, it is best to select a breakaway bond which is a mechanical fuse element placed in series with the bonding jumper. This facilitates worker extraction from the worksite in case the boom needs to be lowered due to an emergency or an accident.

Some EPZs contain conductive matting to provide a large surface where large amounts of people can work, and material can be stored. Examples include conductor stringing sites for overhead and underground power lines, mobile substations, and optical fiber splicing. A common misunderstood concept is that EPZ matting should be fault carrying [23]. Therefore, temporary electrodes shall be placed and bonded to the platform on one side of the matting only. TPGs must be placed between the phase conductors and the temporary electrode side of the matting. The goal is to avoid creating paths of transiting fault current across the matting. Its main purpose is to provide equipotentiality. Further details are covered in IEEE 1048 [23].

For temporary grounding of mechanical equipment and vehicle grounding, consult IEEE 1048 [23] and IEEE 1246 [4].

TPG training of workers should have demonstration of the task by the trainees and oversight from an instructor. Many training modules consist of an electronic slide deck with a few figures, pictures and bullet points; and the students don't get the chance to familiarize themselves with the exact equipment, TPG hardware and tools used in the field. Analysis of field accidents [20] proved that many incidents could've been prevented by using live-line tools, placing/removing TPG in the right order, and maintaining MAD.

VI. CONCLUSIONS

Adequate application of TPG in the field requires good understanding of how industry manufacturing standards, application guides, and regulations align together. This is not easily achievable. The goal of this paper is to serve as a good starting point to guide people in the aspects of TPG that should be incorporated in field operations and safety programs. The guidance is intended for users, manufacturers, and test laboratories.

Accidents due to inadequate implementation of TPG are preventable. The challenge is to focus on allocating limited resources and budget on aspects of TPG that will greatly impact and improve the safety of workers.

Users should choose a proper method for determining the ratings of their TPGs. Industry standards such as ASTM F855 [1] state that they are not applicable to field applications. Typically, TPG hardware, studs, and stirrups do not perform at ASTM F855 [1] ratings in field applications with long jumper length or with multiple TPG jumpers per phase. Therefore, users should choose a method such as laboratory testing, using an industry standard within boundary limitations, or by using specialized simulating software. TPG de-rating may be required.

The first cycles of the fault current offer the highest peak current I_p and electromagnetic forces that challenge the integrity of TPG hardware and causes failures. Also, the voltage that develops across the TPG has a large reactance component that may cause the exposure voltage V_e to exceed tolerable limits when the TPG length or number of jumpers per phase is increased.

The concept of equipotential zone (EPZ) is very important and misunderstood in industry. Regulations address this definition vaguely. Because of this issue, workers may fail to identify if a worksite maintains equipotentiality and may place themselves in series with the circuit and get injured. Always ensure EPZs are installed with adequate TPG configuration, sizes and bonding. Also, maintain a short distance between TPGs and workers to reduce the body current in case of accidental energization.

Ac induction and direct electrical contact while applying TPG are the top electrical hazards and causes of accidents. People are more familiar with direct contact but not with ac induced current and voltage. Therefore, companies should incorporate ac induction hazards in their TPG programs.

The creation of a grounding plan during the planning stage of the job is of upmost importance. Some jobs require the application of tens of grounds, and the order of application matters. Review the grounding plan during the pre-job briefing.

Installing and removing TPG is a live work activity, and it is not exempt from the hazards of direct electrical contact and arc flash. Therefore, it is recommended to apply MAD, use properly rated live-line tools, properly rated IPE, AR/FR clothing, AR gloves as required, AR face protection as required, etc.

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VIII. VITAE

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Inadequate Engineering Controls Can Expose Workers to Hazards

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Abstract – Two recent electrical incidents demonstrate how the design of equipment encouraged electrical workers to take actions that violated NFPA 70E principles. The features that encouraged non-compliant work execution will be described, as well as how the equipment was improved to facilitate safe work practices. Design-stage processes that help identify features that will foster rather than compromise safe work practices will be identified as well.

Index Terms — Troubleshooting, repair, deranged equipment, time pressure, electric shock, arc flash NFPA 70E

I. INTRODUCTION

The design of electrical equipment is driven by many factors. The key factor has certainly always been the intended use of the equipment, and cost has never been too far behind. Early on, safety became another significant factor, and even a century ago it drove innovations that at the very least could be leveraged for market advantage. See figure 1.

Ideally this attention to detail would have so thoroughly pervaded electrical equipment design that Prevention through Design, also known as Safety by Design, principles are always consistently applied in the development of all electrical equipment. Too often, though, suboptimal equipment design contributes to putting workers in harm's way or encouraging the choice of less than adequate means and methods. Two examples of this contributed to instances of electrically inadequate work at Fermilab in 2024.

Fermilab is a Research and Development laboratory established by the U. S. Atomic Energy Commission in 1967 which continues its research mission today under the auspices of the U. S. Department of Energy. Among the lab's accomplishments are the first direct observations of the Bottom and Top quarks and the Tau neutrino. It continues in operation today with a primary mission to observe and quantify the many unusual properties of neutrinos, which may lead to a better understanding of fundamental particle physics. The electrical equipment at Fermilab ranges from the unique and exotic needed to accelerate protons to 99.999% of the speed of light, as well as much more familiar equipment that distributes power across the 6800 acre site, keeps the buildings warm and dry and keeps the building occupants comfortable.

Figure 1: Safety Switch Advertisement

II. EQUIPMENT EXAMPLES

A. The Legacy Design

Among the ranks of exotic equipment is the 400 MeV Linear Accelerator, or Linac, which gives Fermilab's proton beam its first real burst of speed The protons are propelled by radio-frequency energy through a series of drift tubes in nine vacuum chambers, or "tanks." The Linac has been in regular operation since 1971, and with a few exceptions, most of the original equipment remains in service today.

The radio-frequency energy for each of the nine tanks come from a radio-frequency amplifiers based on designs used for broadcast applications. The amplifiers' accommodations for worker safety are typical of the era in which they were built.

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Figure 2: Crowbar Cabinet

Each amplifier has a crowbar cabinet, see figure 2, The crowbar cabinet detects arcs in the modulator that drives the RF power amplifier and triggers a mercury-based ignitron switch that instantly shorts the modulator capacitor bank to ground to avoid damaging the power amplifier tube and inhibits further operation of that RF section.

Located in the bottom center of this crowbar cabinet is a smaller enclosure known as the crowbar assembly. This assembly contains two 120 VAC to low voltage DC power supplies and the control logic that triggers the ignitron firing circuit which draws current from a 120 VAC to 385 VDC power supply it also contains. The location of this assembly is shown in figures 3 and 4.

The 120 VAC power to each crowbar assembly is supplied by a control power circuit with a 20-ampere circuit breaker that serves several other control-type loads at its particular RF amplifier. Age has made several of the other loads on these control circuits susceptible to failure when the power to them is cycled, so several years prior, the Linac electrical maintenance team (LEMT) replaced an external terminal strips on the crowbar assemblies with MS-type connectors, allowing the power to be removed from the assemblies under the cord and plug exception in OSHA 1910.147(a)(2)(iii)(A) without interrupting power to the other failure-prone loads.

On the day of the incident, the LEMT replaced a failed power amplifier driver tube at Linac Radio Frequency Station 3 (LRF3). Upon completion of this task, LRF3 was still not operating correctly and diagnostics with a good driver tube in place indicated that the crowbar assembly had also failed. A member of that team proceeded to remove the crowbar assembly so a spare assembly could be installed.

As can be seen from Figures 3 and 4, an installed crowbar assembly is in an ergonomically challenging location. It is not only located at the very bottom of the crowbar cabinet, but the fixed vertical column between the two doors is directly in front of its MS connector.

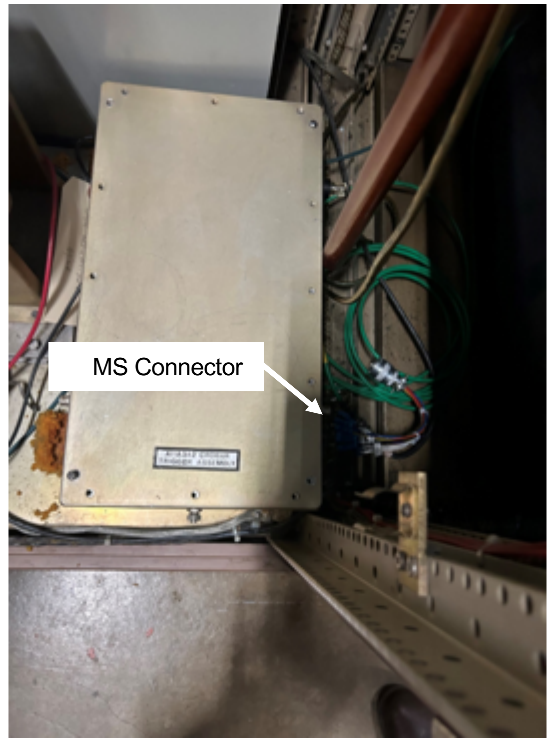

Figure 3: Bottom Left Interior of Crowbar Cabinet

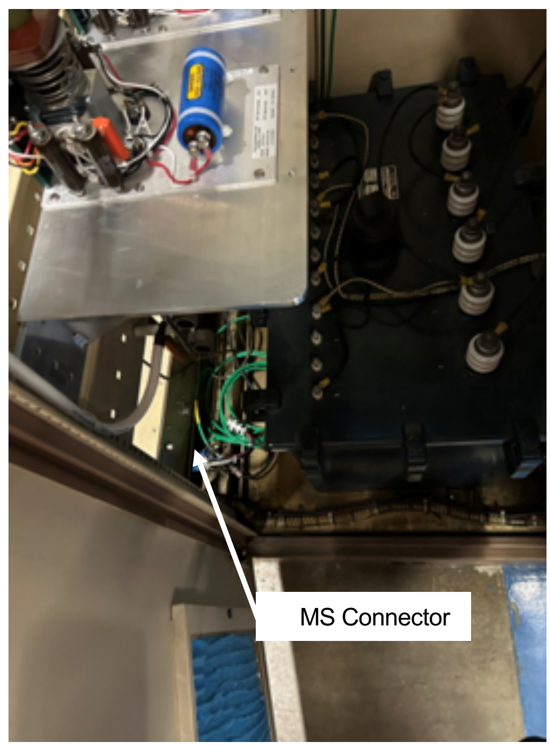

Figure 4: Bottom Right Interior of Crowbar Cabinet

The LEMT member found it impossible to reach the connector and still be able to exert the force needed to twist its locking ring, so he decided to shift the crowbar assembly to the left to better access the connector. To shift the crowbar assembly over, its mounting bolt needed to be removed first. Figure 5 shows the location of that bolt:

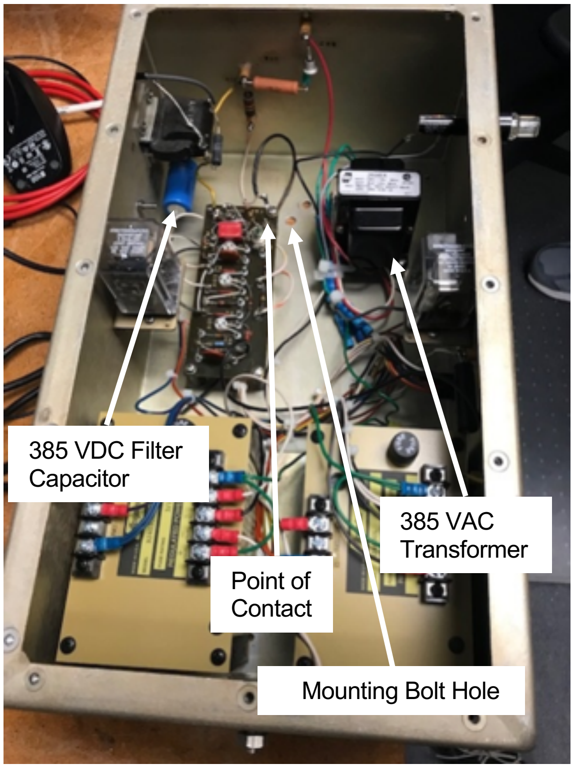

Figure 5: Crowbar Assembly Interior

The crowbar assembly mounting hole is indeed located inside the assembly enclosure, so the LEMT member removed the cover and proceeded to remove the bolt. Prior practice in the Linac had not identified any hazardous energy inside the crowbar assembly that would require additional protective measures. As the LEMT member removed the bolt, hand contact was made with a point on the printed circuit board energized at 385 VDC. The LEMT member did not immediately recognize the sensation as a shock and proceeded to shift the crowbar assembly and unplug the MS connector. After completing the replacement, the LEMT member mentioned that he might have received a DC shock and the event investigation was initiated.

The transformer producing the 385 VAC is rated 25 watts, for a full load amperage of 63 mA, which exceeds the 40 mA threshold in NFPA 70E 350.9(2), and the 20 μF filter capacitor stores 1.5 Joules of energy, which exceeds the 1 Joule threshold in NFPA 70E 350.(9)(3)(b). No injury occurred, and there was no noticeable mark at the point of contact with the LEMT member's hand.

B. The Modern Design

Suboptimal equipment design is not relegated to history. A second incident occurred about a month before the LRF3 event. While the LRF3 crowbar assembly is, if not unique, at least not ordinary, this one involved a very common piece of equipment – a sump pump controller located in Fermilab's Main Injector Service Building 40 (MI-40). When the Main Injector was constructed in the early 1990s, a simplex (one pump) sump pump was installed in the beam tunnel there. Because this tunnel is considered a radiation area, access is prohibited when the proton beam is operating in the Main Injector, and at other times it is restricted to minimize exposure to residual radiation. For over two decades any failures of this simplex controller or its pump required a quick shutdown of the proton beam and repair work in an area that was potentially more radiologically active than optimal.

To mitigate this problem, replacements of the MI-40 simplex sump pump and a similar one at the MI-62 service building with duplex (two pump) sump pumps were planned for the annual summer shutdown in 2020. The duplex controller shown in Figures 6 and 7 was purchased and installed at MI-40.

This duplex controller was built by one firm in 2019 and was purchased and relabeled by a second firm, which then sold it to Fermilab in the summer of 2020, which was at the height of the COVID-19 pandemic. The lapse of time and turnover of engineering and procurement personnel has made it difficult to determine when, why, and by whom certain decisions were made during the acquisition process, but this duplex controller did not conform in several ways to the specifications in the Request for Proposals. It is likely that supply chain constraints from the pandemic were a factor in those decisions.

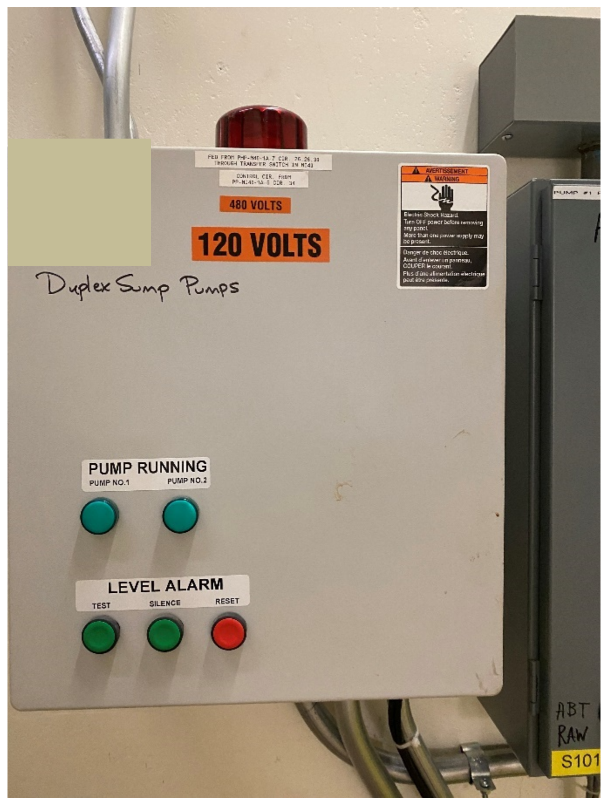

Figure 6: MI-40 Duplex Controller Exterior

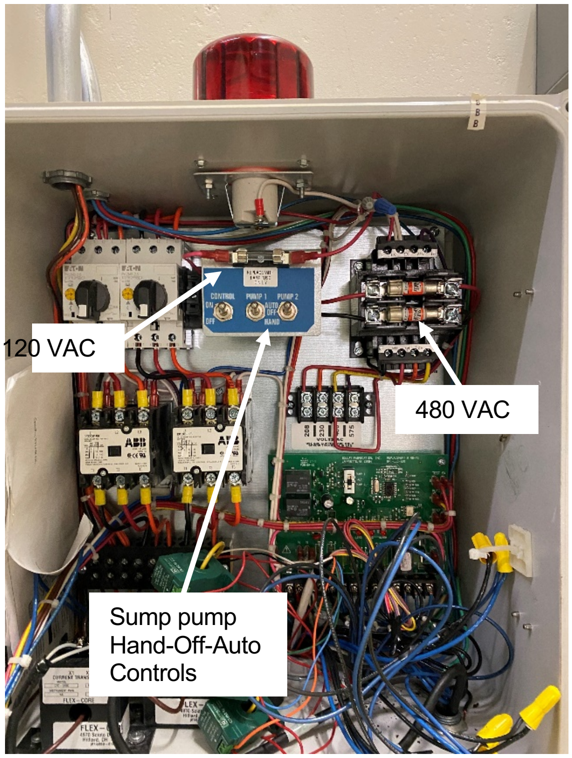

Figure 7: MI-40 Duplex Controller Interior

When this incident occurred, failure of this duplex sump pump had caused minor flooding of the MI-40 beam tunnel, which shut down proton beam operation. Measures not relevant to this subject were taken to address possible radiological issues with the water in the tunnel, which once completed, allowed three facility electricians to enter the tunnel with mechanics and radiological staff to determine why the duplex sumps weren't functioning correctly. Because of the radiological status of the area, the entry team wore protective clothing made of HDPE fibers but did not bring electrical PPE with them to avoid the risk of radiologically contaminating it.

Once the entry team had reached the duplex pumps, a visual inspection confirmed that the water level had come nowhere close to any vulnerable equipment. The obvious first step in troubleshooting a sump pump system is to run the pumps manually. With few exceptions, all sump pump controllers at Fermilab have exterior Hand-Off-Auto (HOA) pump controls that permit the basic functioning of the pump(s) to be tested without any exposure to electrical hazards. These exterior controls are required by the lab's standard pump controller specifications.

The lead electrician, E1, had more than a decade of experience at the lab and led the troubleshooting. E1 opened the duplex controller without performing LOTO or donning electrical hazard PPE. Faced with the HOA controls inside the cabinet, he asked the two other electricians, E2 and E3, both of whom had only a few months of experience at the lab, if they thought it was safe to reach in and operate the HOA switches. With their concurrence, E1 operated the switches. Once those tests were done, E1 closed the panel and completed the work to correct the problem, which was tangled cords for the sump level sensing floats. After the entry team exited the beamline enclosure, one of the radiological support team members described the incident to a member of the lab's general safety staff. Based on inspection of a spare duplex controller identical to the ones for MI-40 and MI-62, it was determined that E1 had been within the Restricted Approach Boundary for 480 volts without proper electrical hazard PPE, so an event review was initiated.

III. INCIDENT REVIEW RESULTS

A. Linac LRF3 Crowbar Assembly

During the 2024 summer shutdown, all six RF stations that use this crowbar assembly and the nine crowbar assemblies (six in service, three spare) were retrofitted to no longer require the internal mounting bolt. A grounding strap was added in each RF station and an external grounding stud was added to each crowbar assembly to provide any grounding connection that the mounting bolt might have previously provided. Inspections were performed and discussions with LEMT members were held to identify any similar ergonomic or mounting issues, but none were found.

More extensive renovations and upgrades were not considered because the existing Linac will be soon replaced by a new superconducting Linac, which is being presently constructed by the Proton Improvement Plan II (PIP-II) project. The results of this incident review were shared with the PIP-II project, other facilities at Fermilab that use RF equipment, and with other Department of Energy Sites.

B. MI-40 Duplex Sump Pump Controller

The inspection of the identical spare duplex controller found that the internal HOA switches have a momentary, spring return action for the Hand position. With a momentary action on that switch, it would not be possible to place the controller in LOTO, operate the switch to the Hand position, and then remove LOTO and return power to the controller to check pump function. Plans were developed and materials purchased to retrofit these two controllers and the spare with external HOA switches. This was performed during a regularly-scheduled maintenance shutdown of the Main Injector. See Figure 8. Four other sump pump controllers without external controls have retrofits planned.

Figure 8: Retrofitted Mi-40 Duplex Controller

There are many locations, such as municipal lift stations in public areas, where unhindered access to system controls is unwise. There are serval common ways to restrict access to system controls without unnecessarily exposing workers to electrical hazards:

- Key-operated external switches
- Lockable blister boxes or “speakeasy” doors with systems controls beneath them
- Double-door panels with lockable exterior doors, behind which are located interior door panels with the controls and indicators mounted on them that block exposure to potentially energized conductors or circuit parts.

A review of the catalog of the original manufacturer revealed that they did offer sump pump controllers with external HOA controls, such as the one in Figure 9 that would have been completely suitable for the MI-40 application:

Figure 9: Duplex Controller with External HOA

This firm “…saw the need for quality cost effective control panels, suitable for almost any environment. The Series 2 controls were designed to fill that need.” Figure 6 shows the Series 2 controller that was installed at MI-40. While it is true that with the proper electrical hazard PPE these panels could be used without an uncontrolled exposure to hazardous energy, there remains a significant difference between even a “controlled” exposure to hazardous energy and no exposure to it at all. The Hierarchy of Controls in NFPA 70E 110.1(H)(3) make it clear that the Engineering Control of the closed control panel is preferable to relying on personal protective equipment.

IV. WORK PLANNING AND CONTROL

A key element for protecting workers from hazards of any sort is thorough work planning and control. In both of the instances described, the work planning was inadequate. In the first case, the original work scope was well planned, but when the additional scope of replacing the crowbar assembly was identified, no pause was taken to identify the hazards and implement mitigations. In the second case the work planning deficiencies were more systemic and beyond the scope of this paper. No procedures or steps were developed to direct the workers’ activities once they had accessed the sump area, which troubleshooting activities were permitted and which weren’t, or to identify at what point work should stop.

V. CONCLUSIONS

While it is difficult to imagine a situation in which the design or condition of equipment can be the sole reason for an uncontrolled exposure to hazardous energy, it certainly can, as these two events demonstrate, make it more difficult to perform work in an electrically safe manner.

NFPA 70E Informative Annex O, *Safety-Related Design Requirements,* recommends in O2.2 that “design option decisions should facilitate the ability to eliminate hazards or reduce the risk….” Design decisions can readily impact the ability of many people to perform work in both a safe and an efficacious manner. As illustrated by the second example, design decisions are not only made by equipment manufacturers, but are also made by those who select the equipment that will be included in the design of specific facilities. Design decisions that place obstacles to the safe performance of work are effectively decisions to encourage work to be performed unsafely.

The electrical industry since its infancy has sought ways to protect both the public and workers in the electrical industry from the hazards electricity poses. Many product designs have advanced this cause, but until they are actually installed and used, they will not have any beneficial effect. In some instances it may take codes and regulations to drive implementation, but codes and regulations remain minimum requirements. The Hierarchy of Control will never be as prescriptive as other parts of our codes and standards, but it is hard to overstate how its principles can help design professionals focus on how their design choices will affect the people who interact with the results.

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VII. VITA

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Lightning Safety Advocacy Programs

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Abstract – Lightning strikes present a risk, resulting in deaths and injuries annually. Lightning injuries, like electrical injuries can have brain injury and chronic pain, but unlike electrical injuries, lightning injuries do not have major burns or amputations. This study is divided into two stages. The first stage presents the mechanisms of lightning injuries, including *i*) direct strike, *ii*) touch voltage, *iii*) side flash, *iv*) step voltage, *v*) upward unconnected leader, and *vi*) trauma associated with the air expansion near the lightning channel. The second stage of the study is dedicated to presenting the main results of lightning safety advocacy programs, which combine engineering components, such as the protection of structures against lightning (LPS) and storm warning systems, with behavioral actions, such as training, alerts, the creation of councils, and governmental policies. The 2011 Runyanya Primary School tragedy in Uganda, where a lightning strike killed 18 students and injured 38, led to the establishment of International Lightning Safety Day - ILSD (28 June), highlighting the need for global awareness. This study also proposes ways for government involvement, especially in developing countries, to improve lightning prevention and protection, emphasizing the importance of integrated and multidisciplinary approaches.

Index Terms — Lightning safety, Lightning injuries, Lightning safety advocacy programs.

I. INTRODUCTION

Lightning is responsible for numerous accidents worldwide, causing a wide range of issues, including power supply interruptions, physical damage to structures, fires, equipment failures, and other significant disruptions [1], [2], [3]. Estimating the global number of fatalities due to lightning remains a challenge, as most data is derived from news reports, which are often imprecise. According to Ron Holle (2023), has consistently published studies estimating an annual global average of 24,000 lightning-related deaths [4]. Similarly, recent analyses by Chris Vagasky et al. (2024), utilizing data from lightning location networks that detect over two million lightning events annually (including cloud-to-cloud and cloud-to-ground discharges), estimate global fatalities to range between 6,000 and 24,000 per year [5]. In terms of property damage, insurance reports indicate an average annual cost exceeding US$ 900 million in the United States alone, according to the Insurance Information Institute (2021).

This paper examines the mechanisms of lightning-related injuries and highlights major Lightning Safety Advocacy Programs worldwide, emphasizing their efforts to reduce injuries and, most critically, fatalities caused by lightning.

Fortunately, deaths and injuries from lightning have decreased in recent decades, particularly in developed countries. This decline is attributed to several factors, including population shifts from rural to urban areas, the automation of agricultural processes that reduce the number of exposed workers, widespread dissemination of lightning safety information, improved building protection, and better-equipped healthcare systems capable of treating lightning-related injuries [6], [7], [8]. For example, in the United States, annual lightning-related deaths have declined from approximately 50 fatalities in the early 2000s to around 12 deaths in recent years (2023 and 2024), according to data from the National Lightning Safety Council.

However, in developing countries, the reduction in lightning-related deaths has not followed the same trajectory. Vulnerable populations in these regions often depend on subsistence agriculture, live in inadequately protected buildings, and lack access to safe transportation, leaving them significantly more exposed to lightning hazards [9], [10], [11], [12].

Additionally, limited knowledge about lightning safety, coupled with cultural beliefs and myths, exacerbates the risks. As population growth continues in these countries, more people are exposed to lightning hazards. This exposure, combined with inadequate or non-existent healthcare systems, has led to persistently high—and in some cases increasing—numbers of deaths and injuries caused by lightning.

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II. MECHANISMS OF LIGHTNING INJURIES

Knowing the mechanisms of injuries caused by lightning and the frequency of each occurrence is very important, as it allows for the definition of protective measures to prevent them. Figure 1 shows the six main types of damage to living things caused by lightning.

As shown in Fig. 1, the six main mechanisms of lightning injury are:

a) **Direct strike**: Contrary to what many believe, a direct strike is the least common mechanism, accounting for perhaps only 3-5% of deaths [13]. A direct injury occurs when the lightning connects directly with the victim, typically in open areas. While it might be assumed that direct strikes are more likely to cause fatalities than other mechanisms, this has not been demonstrated in any studies.

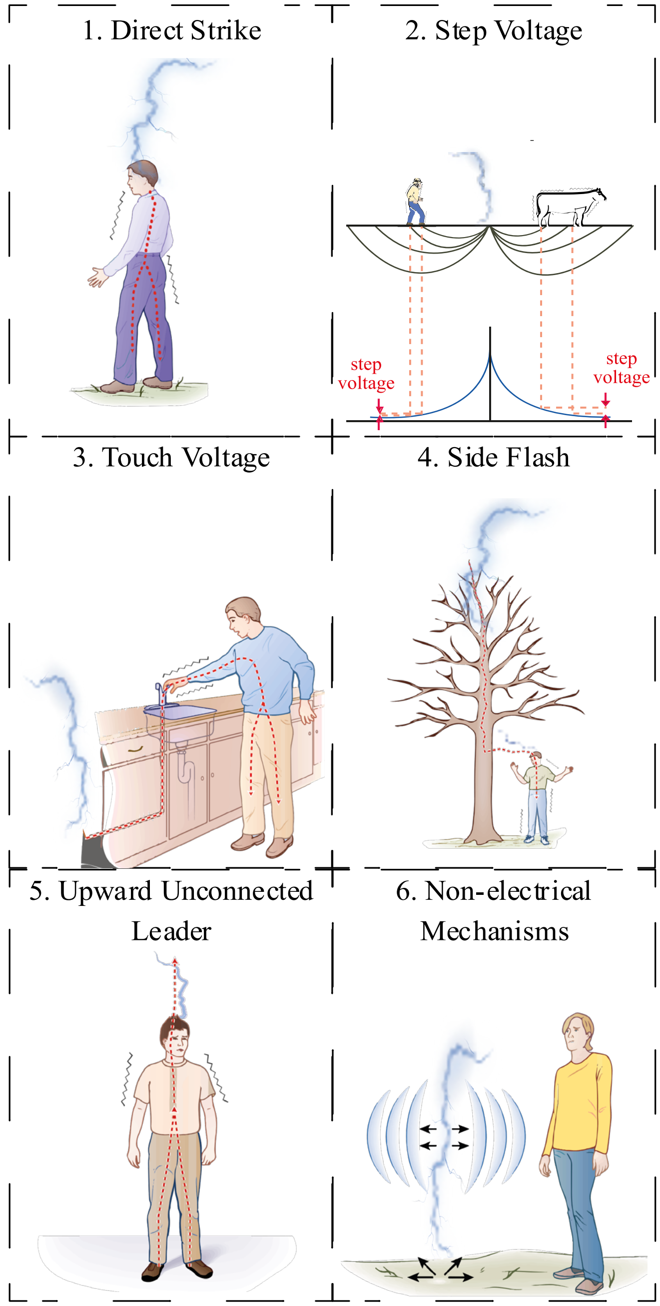
b) **Step voltage or ground potential**: (lightning current traveling through the ground) occurs when lightning strikes the ground or an object connected to the ground, and its current spreads across the earth. This current creates ground potential that can injure people nearby. It can affect many people, both inside and outside unprotected buildings. Typical examples are field workers, children in classrooms, people in outdoor sports or worshippers in open-air churches. Animal deaths due to step voltage are also widespread. Since the distance between animals' front and hind legs is significant and the electric current typically follows a path that involves the heart, animal deaths in open fields due to lightning strikes are frequently observed.

c) **Touch voltage**: This occurs when a person is in contact with conductive paths such as metal pipes, wired telephones or appliances, headphones, or wiring, whether outdoors or inside structures or outdoor structures such as metal bleachers or fences. Touch voltage can also happen when animals gather near long, ungrounded wire fences [14], [15].

d) **Side flashes**: These occur when trees, poles, towers, or other tall objects are struck by lightning, and part of the lightning's current jumps to a person standing nearby. Examples include someone seeking shelter from the rain under a tree, in a parking lot with a metal structure, or standing very close to the down conductors of a Lightning Protection System (LPS) [16], [17].

e) **Upward Unconnected Leader** (UUL): Electrical storms contain electromagnetic solid fields. Whenever a storm moves through an area, opposite charges are induced in objects on the ground near the cloud, including trees, towers, people, and animals. Upward leaders typically emerge from these objects as upward-directed discharges seeking to connect with the descending lightning channel. Even if the connection with the downward leader does not occur, the upward leader—now called "unconnected"—carries enough energy to cause injuries that have been theoretically and clinically documented. Figure 2 shows the situation of an Upward Unconnected Leader (UUL) causing harm to a man [18], [19], [20], [21].

f) **Barotrauma**: Blunt trauma has also been suggested as a mechanism of injury from lightning. When lightning travels through the air, it causes rapid heating and expansion of the air, and anything nearby may experience a concussive force similar to being near an explosion [22], [23].



Figs. 1 Mechanisms of lightning injury. Source: Adapted from Cooper et al. (2016) [24].

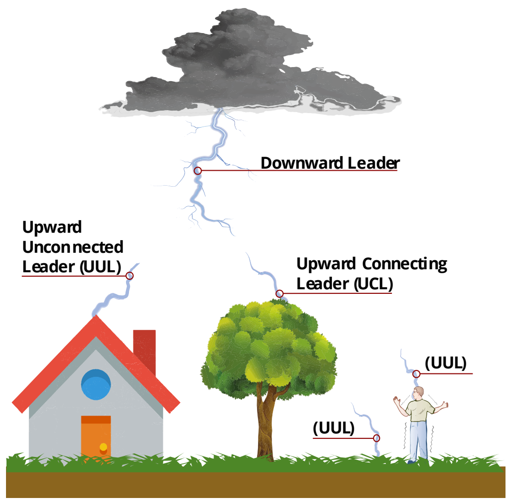


Fig. 2 Victim from Upward Unconnected Leader (UUL).

Many still believe that direct lightning strikes are responsible for most lightning-related deaths. However, some studies conducted in developed countries [13], [25] have shown that direct strikes account for only 3 to 5% of deaths. According to these studies, step voltages and side flashes are responsible for more than half of the fatalities, followed by touch voltages and upward leaders. Lastly, direct strikes and barotrauma account for the fewest deaths, as shown in Figure 3.

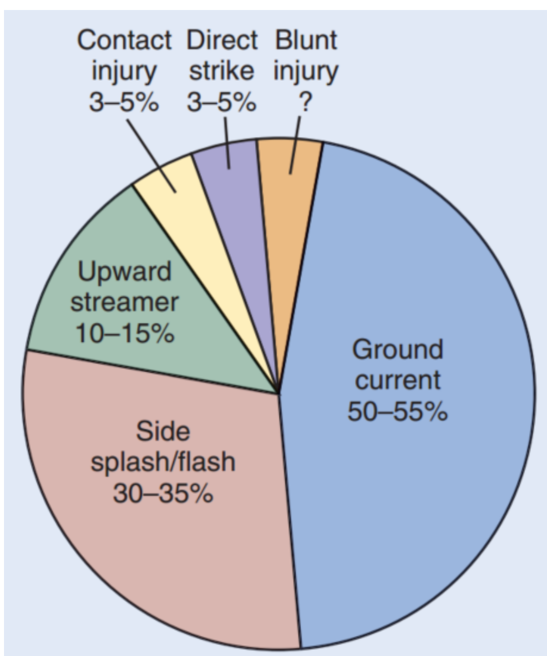


Fig. 3 Mechanisms of lightning injury. Source: [13], [25].

Some studies have examined a seventh mechanism. For example, Blumenthal, R. and West, N. J. (2017) [26] explained that barotrauma caused by lightning is comparable to a 5 kg dynamite explosion. There can also be shrapnel from lightning damaged trees or other objects that cause injuries. There are cases of people being "thrown" due to the abrupt expansion of air near the lightning channel, resulting in musculoskeletal injuries.

There are various types of injuries that lightning strikes can cause, ranging from burns to cardiac issues and neurological impacts. In situations with multiple victims, first responders should focus on those who appear lifeless, applying cardiopulmonary resuscitation (CPR) if they are trained to do so. An ongoing study in Brazil, which analyzed 413 victims of lightning-related accidents between 2019 and 2023, showed a distribution as presented in Figure 4.

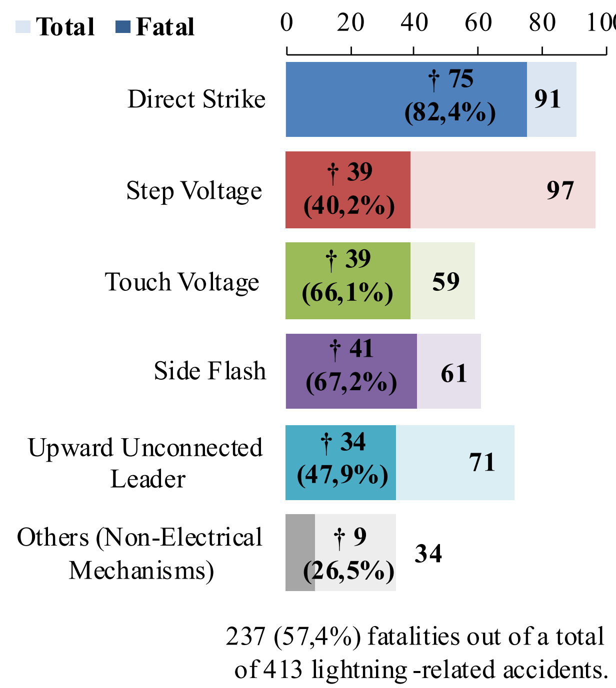


Fig. 4 Distribution of lightning injury mechanisms

These numbers show that, in developing countries, direct lightning strikes are still responsible for many accidents, followed by those caused by step voltage. Accidents caused by unconnected upward leaders are also significant, although difficult to identify. Direct strikes are the leading cause of lightning-related deaths, while step voltage, touch voltage, side flash, and unconnected upward leader incidents show similar and closely aligned numbers. Identifying each mechanism is highly subjective, but a special methodology was used to reduce data uncertainty.

III. LIGHTNING SAFETY ADVOCACY PROGRAMS

Even with the decrease in lightning-related deaths, especially in developed countries, many lightning safety advocacy programs have been created to further reduce accidents.

Since the 1980s, starting with groundbreaking efforts in Japan and extending to initiatives in countries like France, Italy, and the United States, where researchers developed safety guidelines and advocacy programs, there has been a sustained push to reduce lightning-related risks. One notable initiative is Lightning

Safety Week (2001-2015 NOAA), which led to establishing the National Lightning Safety Council (NLSC) in 2015, which played an essential role in preventing atmospheric electricity hazards. On a global scale, important programs include “The African Centers for Lightning and Electromagnetics Network” (ACLENet) in Africa, “The Zambian Centre for Lightning Information and Research” (ZaCLIR) in Zambia, “South Asian Lightning Network” (SALNet) in South Asia, “Latin American Lightning and Education Network” (LALENet) in Latin America, and the emerging “Association of Lightning Protection and Warning Professionals” (APPAR) in Brazil [27].

A. USA National Lightning Safety Council

The National Lightning Safety Council in the USA grew out of the Lightning Safety Awareness Team which was created to advance lightning safety by raising awareness and providing education. It comprises lightning safety experts from multiple disciplines dedicated to saving lives, reducing injuries, and safeguarding property from lightning hazards. The Council collaborates with its partners in both broadcast and print media to deliver accurate and current information on lightning-related deaths, injuries, and incidents year-round. Additionally, the Council leverages its annual National Lightning Safety Awareness Week, held during the last week of June, as a critical opportunity to engage with the media, outdoor recreation organizations, and government agencies to inform the public about the risks of lightning and strategies for staying safe [28], [29].

B. The African Centres for Lightning and Electromagnetics Network (ACLENet)

ACLENet (The African Centres for Lightning and Electromagnetics Network) is a not-for-profit organization with national centers across Africa registered as non-governmental organizations (NGOs) or companies limited by guarantee. ACLENet operates within the cultural frameworks of each African country to accomplish the following objectives [30]:

1) *Assess the impact of lightning on the citizens and economy of each nation.*
2) *Collaborate with governments to ensure that lightning protection systems for new schools and other critical infrastructure comply with relevant safety codes.*
3) *Educate teachers, parents, students, and the public on lightning safety.*
4) *Partner with universities to train future lightning safety experts within Africa.*
5) *Enhance the training and professional qualifications of engineers, architects, and electricians in lightning protection.*
6) *Guide code-compliant lightning protection for utilities and other critical economic sectors.*
7) *Improve access to accurate and timely lightning data, weather forecasts, and warnings.*

Since its founding in 2014, ACLENet has been actively involved in designing and installing lightning protection systems for schools in Uganda, in collaboration with the Ugandan government. Additionally, the organization has conducted educational initiatives on lightning science and safety, targeting both the public and school communities (Fig. 05). Since 2016, these efforts have safeguarded over 16,000 students, teachers, and their families.

One of their missions is to document the extent of the problem by collecting news reports of lightning incidents.

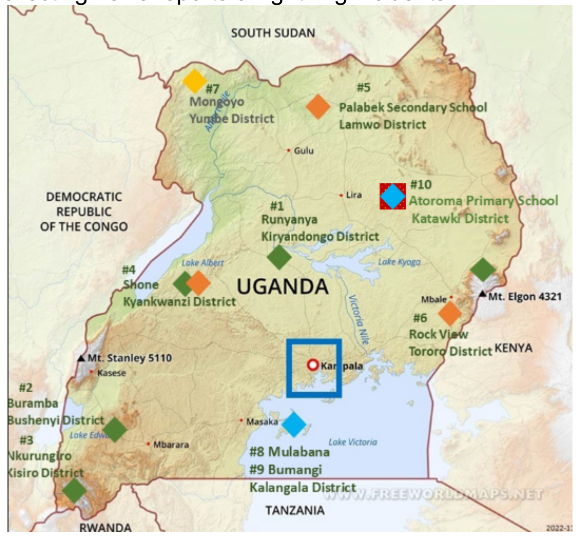


Fig. 5 - Schools across Uganda that are now safe from lightning. Source: [31].

C. The Zambian Centre for Lightning Information and Research (ZaCLIR)

Another institution in Africa is also active in lightning research and safety, the ACLENet Zambian Centre for Lightning Information and Research Organization (ZaCLIR). has criticized the government for its slow progress in supporting lightning safety awareness campaigns nationwide. Recently, Luapula Province has seen a concerning increase in lightning-related deaths, with more than nine fatalities reported this year alone.

In an exclusive interview with the Zambian Business Times (ZBT), Foster Chileshe Lubasi, the Director of ZaCLIR and a lightning research scientist, expressed frustration over the lack of support from the Disaster Management and Mitigation Unit (DMMU). She explained that for the past three years, ZaCLIR has been trying to collaborate with the DMMU to launch nationwide lightning safety awareness initiatives, but the unit's response has been discouraging.

Lubasi noted that ZaCLIR is planning how to effectively start the campaign, hoping the government will eventually offer its support. She also mentioned that ZaCLIR is conducting a research project in collaboration with the University of the Witwatersrand in South Africa to study indigenous knowledge about lightning. The partnership with South African universities is precious because they have more advanced equipment and well-established lightning research laboratories [32].

D. South Asian Lightning Network (SALNet)

In South Asia, various institutions from Afghanistan, Bangladesh, Bhutan, India, Maldives, Nepal, Pakistan, and Sri Lanka have formed SALNet—the South Asian Lightning Network—a non-profit organization dedicated to lightning safety and protection across the region [33]. SALNet serves as a platform for education, research, advisory services, and outreach to all interested individuals and institutions. The organization's headquarters is based in Kathmandu, Nepal.

SALNet was founded to advance scientific research and technological innovation, foster sound engineering and technical practices, and promote the dissemination of knowledge and public awareness regarding lightning safety. The overarching aim is to reduce injuries, fatalities, and property damage caused by lightning in South Asia through the following actions:

1) They support creating lightning research, education, and awareness centers throughout the South Asian region.

2) Providing these centers with information on funding opportunities and technical and operational management guidance.

3) Assisting centers in organizing research and engineering training programs on the latest global developments to enhance expertise and achieve scientific excellence.

4) Sharing information and data on the latest international standards and guidelines among the centers to encourage sound research and engineering practices while preventing the spread of fraudulent products and technologies that have been scientifically discredited.

5) Facilitating the training of medical professionals in lightning-related post-trauma treatment.

6) Promoting collaborations between research institutions and industry.

7) Supporting establishing a region-wide lightning and storm detection system and developing methods to effectively communicate forecasting and real-time weather information to the general public.

E. Latin American Lightning and Education Network (LALENet)

In Latin America, LALENet—The Latin American Lightning and Education Network—is a non-profit organization focused on raising awareness about the dangers of thunderstorms and the many accidents that occur in the poorest rural villages across Central and South America. LALENet is committed to reducing lightning-related deaths, injuries, and property damage through education and improving existing infrastructure, aligning with internationally recognized safety standards.

F. Association of Lightning Protection and Warning Professionals (APPAR)

In Brazil, APPAR (Association of Lightning Protection and Warning Professionals) [34] is an emerging organization with the following core activities:

1) Promoting, organizing, and raising awareness about ILSD - International Lightning Safety Day, observed on June 28;

2) Publishing articles in journals, conferences, and magazines;

3) Delivering presentations at technical events;

4) Developing initiatives to provide free lightning protection projects for low-income communities;

5) Creating a repository of news related to lightning accidents in Brazil;

6) Establishing and maintaining relationships with the National Lightning Safety Council (NLSC) and ACLENet;

7) Producing safety guidelines on lightning protection for organizations and institutions such as city governments, fire departments, and clubs;

8) Creating public outreach materials on lightning hazards, including i) videos outlining basic safety rules, ii) children's books to educate about lightning risks, iii) live webinars, and iv) videos explaining lightning formation with a focus on personal safety;

9) Collaborating with print and digital media to disseminate statistics on lightning-related deaths and injuries to raise public awareness.

In December 2024, a children's book was released showing the dangers of lightning illustrated for children (Fig. 6) [35].

Fig. 6 - Cover of a children's book about lightning protection. Source [35].

IV. LIGHTNING RESEARCH

Although lightning strikes are increasingly well understood within the scientific community, significant research challenges continue thanks to the development of various measurement systems. For example, researchers have developed methods such as capturing lightning discharges using small rockets launched toward charged clouds, installing monitored towers in high-risk locations, and deploying increasingly precise sensors to detect and analyze lightning parameters. This growing body of research is regularly presented and discussed at scientific conferences, such as the International Conference on Lightning Protection (ICLP)—the 37th edition of which was held in Dresden, Germany, in September 2024—and the International Symposium on Lightning Protection (SIPDA), with its 18th edition scheduled for Thessaloniki, Greece, in September 2025.

V. CHALLENGES FACED BY LIGHTNING SAFETY ADVOCACY PROGRAMS

Despite these advancements, lightning claims live, particularly in developing and underdeveloped countries [32], [36], [37]. Awareness programs about the dangers of lightning are crucial, especially in educating the public on protective behavioral measures both in open areas and within homes. These programs also seek to engage governments in the issues, improve safety standards by ensuring that only scientifically proven systems are included in official guidelines, and enhance public education—particularly among children, using specialized educational materials. Specific events like the International

Lightning Safety Day (ILSD) further emphasize the importance of lightning safety.

The ILSD was observed in several countries around the world on June 28 (or on nearby dates) to commemorate the tragic incident of June 28, 2011, when a single lightning strike killed 18 children and injured 38 others at Runyanya School in Uganda. This remains the most significant lightning-related accident involving children and the second deadliest lightning incident globally on record (WMO reference).

In the United States, the National Lightning Safety Council (NLSC) recognizes National Lightning Safety Awareness Week, which began in 2001, well before the Ugandan tragedy. This weeklong observance provides a vital opportunity to educate the public about lightning safety. On its website, the NLSC encourages visitors to explore NOAA's (National Oceanic and Atmospheric Administration) extensive resources on lightning safety to further their understanding of the issue.

ACLENet, one of the key promoters of ILSD, frequently organizes international events involving more than 25 countries, sharing vital lightning safety information and advocating for protective measures globally.

VI. LIGHTNING SAFETY GUIDELINES

Lightning safety guidelines encompass two critical components: the formulation of a comprehensive lightning safety plan and the adoption of individual safety behaviors during thunderstorms, both indoors and outdoors.

A. Developing a Lightning Safety Plan

A well-structured lightning safety plan is essential for ensuring the safety of individuals, especially during outdoor activities. Key elements include:

1. **Monitoring Weather Conditions**: Always check weather forecasts before planning outdoor activities. If thunderstorms are predicted, adjust plans accordingly. Even in the absence of a storm warning, identify lightning-safe areas in advance and estimate the time required to reach them.
2. **Evacuation Plans**: Ensure evacuation plans provide sufficient time to guide co-workers, team members, or children to safety. For large venues, such as stadiums, develop extensive safety strategies, including:
    a) Real-time weather monitoring systems.
    b) Clearly marked signage for lightning-safe zones.
    c) Safety instructions provided in event programs or through public announcements.

B. Outdoor Safety Behaviors

When outdoors during a thunderstorm, prioritize reaching a lightning-safe area, such as a substantial building or a fully enclosed metal vehicle. Follow these specific behaviors:

1. **Evacuate Immediately**: Cease all activities, including work, sports, or walking, and head to a safe location.
2. **Seek Appropriate Shelter**: Opt for a building with a Lightning Protection System (LPS). If unavailable, choose a concrete or masonry structure, or stay inside an all-metal vehicle.
3. **Avoid Tall Objects and Open Areas**: Steer clear of trees, towers, and other tall structures to minimize the risk of side flashes.
4. **Minimize Exposure**: Avoid open vehicles, such as motorcycles, bicycles, and uncovered tractors. Refrain from standing on truck beds or in convertible cars.
5. **Maintain Safe Distances**: Keep at least three meters away from metal poles, fences, gates, and other conductive objects.
6. **Avoid Heightening Risks**: Do not carry items that increase your height, such as umbrellas or children on your shoulders, when moving to safety.

C. Indoor Safety Behaviors

Even indoors, specific precautions can reduce the risk of injury during a thunderstorm:

1. **Stay Away from Openings**: Avoid proximity to windows, doors, roofs, or balconies, especially those with metal frames.
2. **Avoid Electrical Appliances**: Refrain from touching plugged-in appliances, such as refrigerators, stoves, and computers.
3. **Avoid Plumbing**: Do not shower or use water fixtures, especially if they are connected to metal pipes.
4. **Refrain from Using Certain Devices**: Avoid using wired phones, plugged-in cell phones, or electrical grooming devices like hairdryers.
5. **Postpone Electrical Work**: Do not perform tasks on electrical systems, even indoors, during a storm.
6. **Unplug Electronics in Advance**: Disconnect sensitive electronics, such as televisions or stereo systems, before the storm approaches.
7. **Inspect Surge Protection Devices**: Between storm periods, verify that Surge Protection Devices (SPDs) are properly installed in electrical panels.

By combining these guidelines with broader public education initiatives, individuals and organizations can significantly reduce the risks associated with lightning strikes.

VII. CONCLUSIONS

This study described the main mechanisms of lightning-related injuries and their statistical distribution. It also introduced the major Lightning Safety Advocacy Programs (LSAP) around the world and the activities they are conducting. Lightning injury prevention requires both lightning safe areas that individuals can evacuate to and behavioral education so individuals can learn measures that will decrease their risk of injury.

Lightning Safety Advocacy programs can be instrumental in both activities, working with governments to provide lightning safe areas and educating the public and schoolchildren about lightning safety behaviors.

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IX. VITAE

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Do You Know Who You Are Working For?

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Abstract – Do you know who you are working for? Do you know who is working for you? Two simple, yet important questions when working in environments that contain electrical hazards. Exposed electrical hazards can result in tragedy and continues to be an issue based on the number of workers seriously injured or killed from exposure to and/or contact with such hazards. Though there are many approaches to mitigate these risks, one of the biggest areas of opportunity in industry today remains the complex and challenging work dynamics at play when work is performed by a company at a host employer site. These dynamics exist between the host employer and company, as well as the individual workers. Failure to understand and a lack of robust systems to control these dynamics will jeopardize the safety goals of both employers.

Index terms – Arc Flash, Contractor, Electrical Safety Program, Electrical Safety Management, Host Employer, Risk Management, Risk Assessment, Worksite Coordination

I. INTRODUCTION

This paper will include a case study involving an exposed electrical hazard occurring at a host employer site to a subcontract employee, which resulted in a tragic and life altering injury, significantly impacting both companies. The paper will explore the legal and risk management implications of such an event, the need for safety management systems, programs, training and tools, as well as an analysis of the applicable electrical standards and regulations. The paper will conclude with a discussion of the pitfalls, error traps, and challenges that exist for both the host employer and service provider, as well as risk control methods and best practices to mitigate these risks.

II. CASE FOR CHANGE

Over the last thirty years, there is no doubt that improvements have been made on the overall quest to protect people from electrical hazards, especially in the workplace. From the many advancements in technology, engineering controls, regulations and standards, advancements in safe work practices, worker training and personal protective equipment (PPE), to the adoption and application of human and organizational performance techniques (HOP)… to name just a few.

Despite the unwavering commitment and tremendous efforts by the many dedicated professionals and organizations who have been leaders in this space, significant incidents and fatalities (SIF) still occur and happen at good companies with great people. However, this should not be a surprise to industry. The Electrical Safety Foundation International (ESFI) has, for years, conducted studies and published data on workplace electrical injury statistics [1]. In the Workplace Fatalities and Injuries 2003 – 2021 report, ESFI illustrates that a visible step change was seen from 2003 to 2013 in the number of Fatal Electrical Injuries, but unfortunately the progress beyond this point has certainly slowed and/or remains flat (See Figure 1).

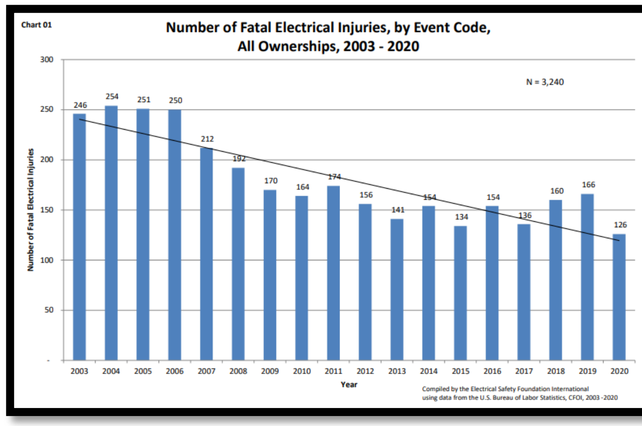

Figure 1. ESFI Workplace Fatalities and Injuries 2003 – 2021 report, (Chart 01, page 34)

The report also indicates a noticeable improvement in nonfatal electrical injuries from 1992 to 2012 but unfortunately a similar pattern of the limited, to flat progress is very visible. (See Figure 2).

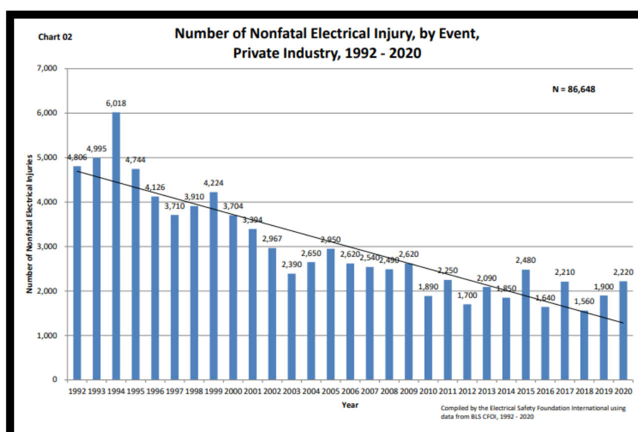

Figure 2. ESFI Workplace Fatalities and Injuries 2003 – 2021 report, Chart 02, page 35)

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While there are many causal factors and opportunities to explore, the primary purpose of this paper by the authors is to share the painful, but important lessons learned from experiencing a tragic accident, as well as sharing insights and perspectives from the host employer (customer) and service provider (contractor) points of view that will provide tangible takeaways for any organization that shares a passion for learning and is committed to sending everyone home injury free, every day!

III. THE ACCIDENT

On December 19th, 2020, an electrical services technician was seriously injured at customer location in Texas. The work scope for the subcontractor consisted of conducting a visual inspection of electrical equipment at a university CEP (central energy plant) during winter break. The customer was a third-party operations and maintenance company that managed the central energy plant and the annual maintenance outage. This job was part of the final startup assurance effort and crucial to finishing up the planned shutdown, as well as restoring power to the facility before the Christmas holiday.

The assignment was considered a low-risk and simple task to the 5-year NETA (National Electric Testing Association) technician. He arrived around 7:30 am and began visually inspecting the electrical equipment and components inside of the facility (central energy plant). At approximately 9:00 am, he was finished with the work inside the facility. He then updated his customer contact (third party operations and maintenance company) and inquired what equipment was left remaining.

He was instructed that the substation outside was the only equipment remaining to inspect. However, unknowingly to the third-party operations and maintenance company employee, the switchgear in scope was not fully ready for maintenance and placed in an electrically safe working condition. Earlier that morning, a university employee tasked with isolating the electric power to the substation was unable to get the circuit breaker de-energized. As a result, he isolated the equipment downstream, which left a cabinet feeding the 12.47kV switchgear lineup energized.

The subcontractor proceeded to the substation where he found the power distribution equipment unsecured and unlocked. He began inspecting the switchgear lineup and was nearing completion when he opened the door to an energized compartment and experienced a significant arc flash event.

The electrical fault tripped the equipment on the upstream utility side, and the technician fell face first into the lower cabinet. The host employer employees and other contractors responded quickly by summoning 911, removing the injured worker from the equipment and attempted first aid care until local emergency medical services arrived.

However, the site was not adequately prepared for an electrical emergency (i.e., no emergency response plan, or proper rescue equipment existed, nor were there personnel on site proficient on methods and techniques for responding to electrical injury).

Despite swift efforts from emergency medical technicians and critical care team in the emergency room (ER), the extent of the injuries was catastrophic and resulted in bilateral amputation of both hands shortly upon arriving at the hospital. The twenty-five-year-old technician survived the life altering event and has subsequently undergone more than a dozen follow up surgeries and ongoing rehabilitation therapy.

IV. OSHA INVESTIGATION AND FINDINGS

OSHA's (Occupational Safety & Health Administration), Subpart E. 1904.39 standard requires employers to report workplace injuries involving a fatality within eight hours, and injuries that result in hospitalization, amputation and/or loss of an eye within twenty-four hours. As required, a serious event report (SER) notification was made by the subcontractor employee's employer, to OSHA. The area office quickly responded to the SER and assigned a CSHO (compliance safety & health officer) to investigate worksite. Due to the complexity and seriousness of the event, OSHA launched a multi-employer investigation that consisted of numerous site visits, worker interviews, comprehensive information requests related to electrical safety and control of hazardous energy programs, company safe work procedures and employee training records. OSHA also requested evidence of supervisor engagement, and that the employer's health and safety programs are enforced.

After six months, the agency concluded the investigation and levied several citations against both the host employer company and injured contractor's company. The alleged violations were classified as "serious" for non-compliance of the Federal OSHA standard for Power Generation, Transmission and Distribution (1910.269, Subpart R) [3]. The citations targeted multi-employer worksite failures specifically for the host employer (third-party operations and maintenance provider of the central energy plant) and the contractor (inspection/testing company) for violations on both sides to ensure a safe working condition was established, verified and maintained.

Although OSHA does not have a standard specific to contractor safety management, in 1999, OSHA created compliance directive, CPL 2.0 124 as a multi-employer citation policy for CSHO's to follow when conducting an enforcement investigation. Section X is the Multi-Employer Worksite Policy and OSHA generally follows two steps for determining enforcement action. The first step is to determine the role the employer(s) may have had, as the host employer is often cited as the controlling employer, as the equipment owner (host) has an obligation to ensure that the contractor uses qualified persons to perform hazardous tasks. Employers may have multiple roles, which can lead to citations for each role. The second step is to determine if the actions taken of each employer met their obligations [4].

The four roles that OSHA categorizes in the enforcement policy for citing employers are as follows:

1. *Creating: the employer that caused a hazardous condition that violates an OSHA standard.*
2. *Exposing: an employer whose own employees are exposed to the hazardous condition.*
3. *Correcting: an employer who is engaged in a common undertaking, on the same worksite as the exposing employer and is responsible for correcting a hazard.*
4. *Controlling: an employer who has general supervisory authority over the worksite, including the power and ability to correct safety violations or can require others to correct them.*

In 2014, OSHA released a revision to Subpart R,1910.269 (a)(3) – Information Transfer that requires the host employer and the contract employer to provide certain type of information that are important for performing live-line and other work on or near utility-type equipment. None of the companies involved in this event properly managed worksite coordination, communication, electrical safety, job safety planning, pre-job briefing and control of hazardous energy correctly, etc. Lastly, since federal OSHA does not have enforcement jurisdiction over a state institution, the university who owned and operated the power distribution equipment (i.e., the system operator who in this case was the creating, exposing and could have been the correcting employer) escaped without any regulatory accountability in the form of OSHA citations and penalties. In addition, they were also protected from civil litigation due to state sovereign immunity and had limited liability protections for workers compensation.

V. WORKSITE COORDINATION & THE ELECTRICAL SAFETY PROGRAM

The event above was ripe with significant gaps and shortcomings on all parties involved. The limited engagement and responsibility (or lack thereof) regarding the university created and left a dangerous trap that was ripe with error-likely situations. Due to the reasons listed above, OSHA held accountable the third-party operations and maintenance company as the "host employer" and the inspection/testing company as the "contractor" and found both liable for violations that existed at the worksite as part of the investigation. In this case, the host employer drastically lacked a formal outage/shutdown management system, work coordination process or safety and health programs that are vital to executing this type of work safely (i.e., electrical safety, switching procedures, group lockout/tagout, emergency response plan, etc.). The contractor company involved had a well written electrical safety program (ESP) and a long-standing reputation for a commitment to electrical safe work practices. However, due to several factors associated with this event, the technician was complacent and failed to apply critical principles, procedures and controls. The company's ESP outlined requirements for lockout/tagout, job safety planning, pre-job safety briefing, establishing (or verifying) an electrical safe working condition, etc. and the ESP was reinforced with instructor led training for Qualified Electrical Workers.

Human and organizational performance factors also affected decision making of the technician at the time of the job. Such as, the technician had never been to this customer jobsite and the normal technician who serviced this customer was out sick. He was assigned the task last minute on a Friday afternoon, and it was the Saturday before the Christmas holiday. He had just recently gotten engaged and was scheduled to go on a vacation with his new fiancé and family following the completion of the job. When he arrived at the site that morning, he observed other contractors performing work inside of electrical panels. Also, there was no visible signs of power to the central energy plant, all the locks were removed from electrical equipment doors and panels/covers were also opened exposing circuit parts and conductors. Lastly, he made a dangerous assumption based on all these factors that the equipment was in an electrically safe working condition and did not exercise test before touch. OSHA can hold an employer accountable for violations discovered in the work environment related to electrical safety, especially post injury or alleged complaint. However, OSHA does not prescriptively provide a good roadmap for an effective electrical safety program. This is why employers should leverage standards such as NFPA 70E in developing and/or updating the Electrical Safety Program, as well as the NESC (National Electrical Safety Code) for utilities.

Although OSHA has requirements in 1910.269 specific to responsibilities for host employer and contractors, the language is lacking prescriptive direction on how. NFPA 70E does a better job with defining the roles for each and connecting the importance to the ESP (electrical safety program). In addition, the 2018 update of NFPA 70E added guidance on human performance in Informative Annex Q. The information is well written and a great resource addition to any company's overall health and safety program, not just electrical safety.

VI. LEGAL / RISK MANAGEMENT

When there is a failure in understanding who the contractor is working for, negative impacts are seen in areas besides the actual fatality or injury. While all engagements need a contract or terms and conditions setting out job scope and expectations, it is crucial to have such written documentation in the event a fatality or significant event occurs. This written documentation sets the stage as to the legal and risk consequences that the contractor could face in the event of a tragedy occurring. Such consequences can be experienced through, but not limited to, regulatory investigations, litigation, insurance coverage issues, fractured client relationships, internal corrective actions, and tarnish to the contractor's internal and external reputation.

Prior to signing a contract and especially prior to engaging in any work with a host employer, the contractor must understand the scope of the work that is expected to be performed, as well as the safety management systems, programs, and training necessary to complete the job safely. This means that the contractor understands what the safety expectations are for both the host employer and its own team. Once the contractor has that understanding, it is the contractor's responsibility to ensure that every person working on that job under the contractor's control is qualified and trained to perform the task at hand.

Even when the host employer has prescriptive compliance requirements regarding their safety responsibilities and the safety functions that they are to perform, it is the contractor's job to "check the checker" and make sure that those safe work practices are implemented (i.e., trust but verify). However, it is generally unlikely that employees who are directly overseeing the work (host employer) and/or performing the work (contractor) are included in the contractual agreement discussions and term and condition review, which results in it also being highly unlikely that important information relative to safety is incorporated into the safety planning and execution of the work. As Benjamin Franklin is famously attributed for saying, "If you fail to plan, you are planning to fail"

Notably, the U.S. Department of Labor specifically calls out the direct and indirect financial impact that serious injuries have, citing that employers pay almost one billion dollars per week solely for direct workers compensation costs [5]. Additionally, the National Safety Council published staggering figures on days lost in 2022 due to work related injuries at 108 million days lost and estimated another 60 million days lost in future years for these work-related injuries [6].

Listed below are other frequent consequences resulting from SIFs:

A. Regulatory Investigations

A SIF, especially those that are life altering, could trigger a state or federal OSHA investigation. This presents a significant distraction to a host employer and/or contractor due to requests for documentation and employee interviews. While the investigation could last up to 6 months [7], a host employer and/or contractor could continue to experience distractions through negotiating citations and their resulting seriousness, as well as abatement exercises. Depending on the severity of the SIF being investigated, the host employer and/or contractor could face an order to shut down operations. While that may be extreme and draconian, the possibility of an operations shut down could occur. In this event, is either the host employer and/or contractor prepared for the impacts to their respective employees and customers?

B. Litigation

In the event of a SIF, the host employer and/or contractor must be prepared for litigation. The impacted employee or subcontractor could sue the host employer and/or contractor. In the event the host employer is sued, the contractor should expect to be countersued by the host employer under the indemnification provision of the contract. While a lawsuit will strain or end the relationship, there could be greater impacts with having to make litigation disclosures on client specific questionnaires, in addition to disclosures for lending institutions and investors.

C. Insurance Coverage

Depending on the nature of the SIF, especially if such SIF is considered a “shock loss,” the contractor may be faced with filing claims under its auto, workers compensation, general liability, and/or umbrella policies. Depending on whether the contractor has insurance coverage, it will then be faced with a deductible/retention payment and future impacts to insurance renewals by virtue of having a loss to report. These impacts could be higher premiums and collateral obligations. Further, there are notable insurance considerations involving litigation. If the contractor is sued due to the SIF, it may or may not have coverage to pay damages, additionally the contractor may lack coverage for payment of litigation expenses.

D. Fractured Client Relationships

Often a contractor will fail to understand that one SIF will have ripple effects throughout their entire customer base. If a contractor is required to register with a third-party compliance monitoring portal, such as AVETTA© or ISN©, once OSHA logs are uploaded, all clients will know about the SIF. This means that a contractor’s GREEN “GO” status (i.e. all of the contractor’s safety programs, insurance, etc. meet the client requirements) will automatically default to RED “STOP“ (i.e. one or more of the contractor’s safety programs, insurance, etc. do not meet client requirements). When that occurs, the contractor will have to seek a variance to remove the RED “STOP” label. Should the variance not be granted, the contractor will be precluded from working at that client site for an indefinite period. Notably, should the contractor receive a questionnaire with safety questions prior to uploading OSHA logs to these portals, the contractor may be obligated to disclose citations at an earlier time, thereby accelerating the contractor’s preclusion from the client site. Although contractors generally must participate in third-party portals to gain work opportunities, no system exists where contractors can look at the grade or safety programs of the host employers they are going to work for.

E. Internal Corrective Actions

If a SIF occurs, the contractor may be required to re-evaluate training for both classroom and hands-on practicums. Training will need to be assessed as to whether such is adequate and effective, as well as a determination will need to be made as to whether certain employees need to be retrained. Additionally, the contractor may have to purchase new equipment should a piece of equipment be a contributory factor to the SIF.

With the most consequential corrective actions, the contractor may be faced with administering disciplinary action for the injured employee and their managers depending on whether a lifesaving/cardinal rule was violated. This discipline could be seen as providing a written warning to the impacted employee and their management team, suspending the involved employees without pay, reducing bonus compensation, and employment termination.

F. Internal and External Reputation

While it may seem selfish and uncaring when a contractor is faced with a SIF, the contractor must be vigilant as to the impact such events have on their reputation. Are the event and underlying factors so appalling that the contractor’s employees lose faith in management and seek employment elsewhere? Contractors often can experience retention issues after a SIF, especially if employees no longer believe in the contractor’s safety programs and initiatives.

Conversely, are the event and underlying factors so egregious that there will be a negative impact to the contractor’s external reputation thereby tarnishing the contractor “brand” in the community, industry, and among its various clients? In the age of social media, which lends itself to an environment where news, accurate or inaccurate, travels at the speed of sound, contractors must remain on guard as to the information that is being disseminated. Often with SIFs, contractors are best served engaging with a public relations firm that has the expertise to manage the crisis at hand.

F. Estimated Total Cost

Underlying to all these impacts are increased financial obligations. The “OSHA’s Safety Pays Program” provides a helpful calculator to show the estimated cost of occupational injuries.

The calculator begins the exercise by asking for (1) injury type or workers' compensation costs; (2) profit margin; and (3) number of injuries. Using the SIF discussed above, the following inputs were inserted into the calculator: (1) injury type—amputation; (2) profit margin—40%; and (3) number of injuries. Using the SIF discussed above, the following inputs were inserted into the calculator: (1) injury type—amputation; (2) profit margin—40%; and (3) number of injuries—1 [8].

Injury Type	Instances	Direct Cost	Indirect Cost	Total Cost	Additional Sales (Indirect)	Additional Sales (TOTAL)
Amputation	1	$96,003	$105,603	$201,606	$264,008	$504,014

Figure 3. OSHA Safety Pays Program, Individual Injury Estimator

The extent to which a contractor pays the direct costs depends on the nature of the contractor's workers' compensation insurance policy. The contractor always pays the indirect costs.

Regardless of any monies a contractor thinks it may save by taking a short cut with training, making assumptions that a subcontractor's specific training was adequate, going "cheap" on having appropriate PPE or tools, the contractor will be wrong.

Every impact has a financial consequence. For example, maybe the contractor has legal fees for litigation covered through its insurance carrier, however, a contractor's legal spend for an OSHA investigation is not covered by insurance. Additionally, one day of lost labor could impact service level agreements across a contractor's entire client portfolio, which could place the contractor in breach with clients that were not even involved with the SIF. As the old saying goes, never be penny wise but pound foolish!

G. Human Impact

It would be short sighted not to discuss the human toll a SIF causes on a contractor's employees. These human impacts are more than the emotional and physical impacts to the employee directly involved in the SIF; such impacts can be seen throughout the organization, as well as the family of the impacted person.. It is important for contractors to offer on-site counselors and use of Employee Assistance Programs (EAP) to the entire workforce.

VII. CONCLUSION

A. Progress Is Slowing

The number of electrical fatalities and non-fatal electrical injuries have declined over the last three decades, but in recent years that progress has slowed. A potential contributor may be that less companies are developing internal maintenance team capabilities and investing in internal talent has also dwindled over time. As a result, the need for electrical contractors and specialty subcontractors will remain steady and may even increase. This will require employers to ensure that their electrical safety program is equipped with the appropriate principles, procedures and controls to prevent such tragedies as discussed in this paper. OSHA alone will not get you there.

B. Host Employer Challenges

The host employer must be careful to ensure that the contractor (or subcontractor) is qualified from both a technical/execution perspective, but also a safety capability. This cannot solely be gleaned from relying on a review of the contractor's injury / illness rates or loss run history. It is also important not to base all decision making for awarding a contractor a job based on its numerical score or grade in a third-party portal or relying on the reputation that a respectable contractor carries that they are the expert.

The best method is to apply a balanced approach that utilizes the said methods above, but also compliments those measures with formal assurance of the electrical safety program, training of qualified workers, safety culture/leadership commitment. If during a discussion on the contractor's electrical safety program it is conveyed that they follow the customer's program and requirements to keep workers safe, that should serve as a warning. Ultimately reviewing in advance the job safety plan, conducting in field safety assessments (inspect what you expect) during work and providing post job feedback is crucial for leading to the outcome of sending everyone home alive and well.

C. Contractor Pitfalls

Contractors must be prudent in understanding that regardless of the fact that it is the customer's site and equipment, they may not be the expert. That may be the very reason they are hiring the contractor is they lack in house expertise and/or the internal resources. It is critical that contractor electrical safety program elements consist of provisions to ensure control of hazardous energy (lockout/tagout), effective communication/pre-job briefings, provisions for lone worker operations and human performance training on error likely situations at a customer location (i.e., no electrical drawings exist, labels are outdated or missing, missed isolation point in a lockout/tagout, grounds missing, like equipment hazards, etc.).

Contractor safe work plans must include pre-job safety briefings and an element for verifying control of hazardous energy, as well as documenting where/how an electrical safe working condition has been verified. A peer check is a good method to apply to help ensure that the qualified person verifying an electrical safe working condition is in fact properly established does not make a mistake.

Some companies are even using technology for lone work situations where an employee does not have another qualified person at the job site. This allows the worker to review the safe work plan and energy control verification as part of the pre-job briefing virtually with a supervisor (or qualified designee) via cell phone or tablet. Electronic safe work permitting systems can also be built out with stop gaps and triggers to ensure safe work practices are followed. Other companies are exploring wearable technologies designed to alert a worker when a potential electrical hazard is in close proximity.

Ultimately, the last line of defense still relies on administrative controls. The process of verifying an electrical safe working condition at the point of work (i.e. test before touch) is paramount and sadly, yet so many times remains the difference between a worker going home injury free or a experiencing a tragedy.

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X. VITA

Jeremy Presnal graduated from Indiana State University with a Bachelor of Science degree in Occupational Safety & Health Management. He has been working as an environmental, health and safety (EHS) professional for 22 years in the energy industry, with serving the last 10 of those years in a corporate and senior EHS leadership level roles. During his career he has been heavily involved in electrical safety committees focused on developing and implementing effective electrical safety programs. He is an active member of IEEE, current chair of IEEE IAS ESW – Occupational Safety and Health (OSH) subcommittee, past presenter at ESW 2019 and 2020, a professional member of ASSP (American Society of Safety Professionals) and past Administrator of the American Society of Safety Professionals UPS (Utilities Practice Specialty). He is a Certified Safety Professional (CSP), Certified Electrical Safety Compliance Professional (CESCP), Construction Health & Safety Technician (CHST), Occupational Hygiene & Safety Technician (OHST), OSHA VPP Special Government Employee (SGE) and holds other professional safety and training certifications. He enjoys traveling and spending time with his wife (who is a far superior EHS Professional) and three kids.

Kim Drake-Loy is the Chief Legal / Risk Officer of Kim Drake-Loy, Chief Legal & Risk Officer for SHERMCO, is a dedicated professional at SHERMCO, where she has been instrumental in transforming the organization into a recognized leader in the industry. Her tenacity and exceptional follow-through have led to the implementation of a robust contract management system, a sustainable licensing program and improved data capture and reporting processes, as well as successful management of OSHA investigations and complex litigation. Kim fosters a culture of compliance, ensuring that every team member feels valued and empowered to contribute. Her unwavering commitment to safety emphasizes the importance of a healthy work environment, which she believes encourages engagement in compliance practices. In addition to her operational achievements, Kim is passionate about the intricacies of compliance parameters and the significance of understanding the workforce, including employees and third-party partners. Kim's expertise and dedication make her an influential voice within the compliance community, where she advocates for best practices and continuous improvement. A graduate of Trinity University and Texas Tech School of Law, she enjoys traveling and spending quality time with her husband and dog, exemplifying a balanced and active lifestyle.

Medium Voltage Motor Starter Meltdown Incident

Paper No. ESW2025-26

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Abstract – This document discusses the meltdown of a medium voltage synch/transfer motor starter in a processing facility. The root cause of the meltdown is discussed, the ensuing damage that occurred, and the cleanup operation to restore the equipment. The catastrophic failure of a medium voltage MCC starter not only destroyed the failed starter but contaminated the entire power distribution building and the equipment inside it, resulting in an extended outage for cleanup and repair, costing downtime and loss of opportunity.

Index Terms — Starters, smoke, soot, thermal failure

I. INTRODUCTION

Approximately eleven (11) months after initial commissioning at a new electric compressor station one of starters failed. The main breaker of the station had tripped on an arc flash event. Initially the only indication of the failure to operations was that the compressors tripped and would not start. When operations opened the power distribution building door a plume of black acrid smoke poured out. The building was too hot to enter for more than a few seconds. The failed starter door was bowed out. The plastic light fixture above the failed starter plastic cover had plastic strings melted from it hanging in the air. The smoke alarm was also melted and dripped down. The building was full of a black oily soot stuck to the walls. The control cables running in cable tray above the medium voltage (MV) motor starter assembly were melted with the black insulation dripping down through the cable tray on to the starter assembly.

II. THE MEDIUM VOLTAGE ASSEMBLY CONSTRUCTION

The new remote electric compressor station consisted of two (2) 5000HP electric compressors running on 4,160V. The system utilized a 3000HP starting VFD with two (2) sync-transfer motor starters sourced from a 15MVA OA/FA transformer. The equipment was housed in a new Power Distribution Center (PDC) building with a low voltage MCC, a UPS, a station PLC. The manufacturer has thousands of these synch-transfer starters installed without any operational incidents.

The sync-transfer motor starter consists of a 800A VFD starting contactor and an 800A fused protected bypass (run) contactor physically stacked on each other. Each contactor was isolated from the respective bus by an isolation switch above the contactor compartment.

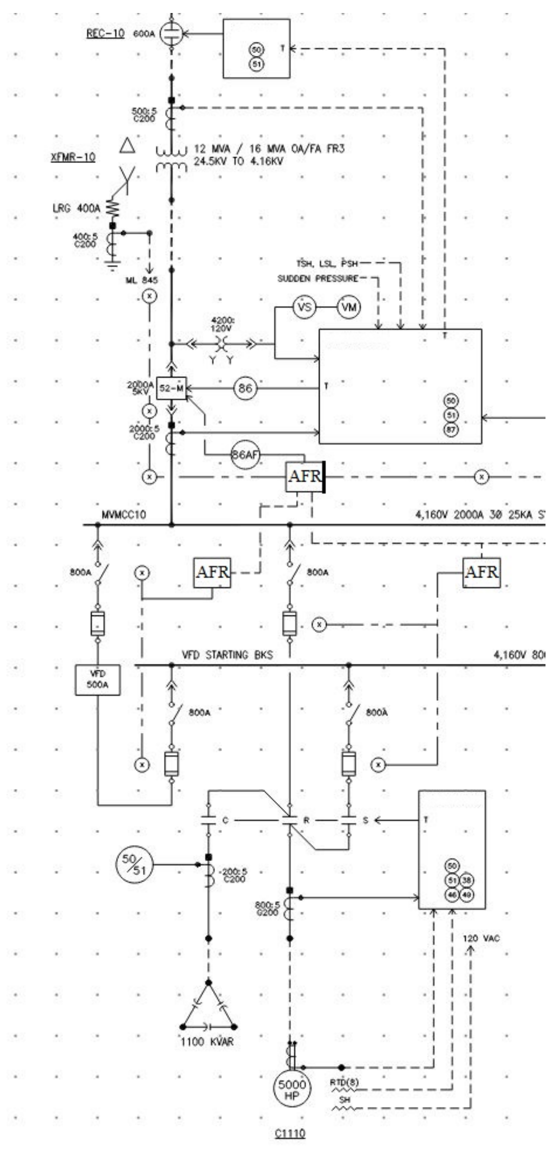

Fig. 1 System Oneline Diagram

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Each cubicle was protected by a light and current arc-flash protection scheme as well as over-current protection.

Two (2) smoke detectors were installed in the PDC and wired back to the station PLC in the PDC building. There were also two building temperature sensors in the building wired to the station PLC in the PDC building.

Fig. 2 Healthy Synch/Transfer Motor Starter during testing

III. THE INCIDENT

The investigation found that the lower B phase termination of the upper VFD contactor had loosened. The other terminations on the destroyed contactor were still intact and tight. The lower B phase termination was together but loose. The burned and highly heated metal behind the B phase termination pointed to the origin of the failure. During the commissioning of the station the failed bypass contactor had been replaced by field personnel. The termination is difficult to access with a wrench. The root cause settled into one or more of three events that loosened the connection: the termination was over-torqued during the field replacement and failed, the flex connection to the contactor was damaged, the contactor had never been applied with DC voltage on the coil, and/or the cable termination lug had been stressed.

Fig. 3 Loosened “B” phase connection on the remnants of the bypass contactor

This loose termination became an extremely high impedance heat source and the resulting heat melted the polymer out of the VFD contactor and conductors on to the enclosure floor. The insulation of the cabling between the contactors melted or burned away. The polymer within the insulating lining had melted or burned away. The arc flash sensor on the side wall melted. All of this while the unit was still running! The resulting heat had melted the resin out of the bypass contactor producing smoke that coated then entire upper area (about five foot above floor) of the Power Distribution Center (PDC) building. This soot was greasy and smeared when rubbed. The Glastic insulating panels had melted exposing the fiberglass within.

Fig. 4 Burned out enclosure

A loose connection such as this creates a higher impedance through the connection essentially creating a heat source. Joule’s First Law states the power (heat) generated by an electrical conductor is proportional to the resistance of the conductor and the square of the current, otherwise referred to as I^2R. As the connection heats up over time, it continues to loosen as the expansion of the hardware of the joint expands, allowing items such as lock washers and nuts to lose their initial force holding the connection together. This will continue until the conductor heat exceeds the temperature limits of the conductor insulation, resulting in insulation failure.

As seen in this instance, the heat generated was sufficient to degrade the Glastic back panel which has a Underwriters Laboratory temperature index ratings from 120C to 210C. NEMA GPO-3 Glastic typically carries a 130C rating and is indicated typically by the red color seen in the photos. The resulting heat was enough that the metal backplane surface was scorched through the Glastic material as shown above. This would put the temperature maximum of the product at 130C or 266F. Exceeding these temperatures the resin would begin to liquify and degrade the material.

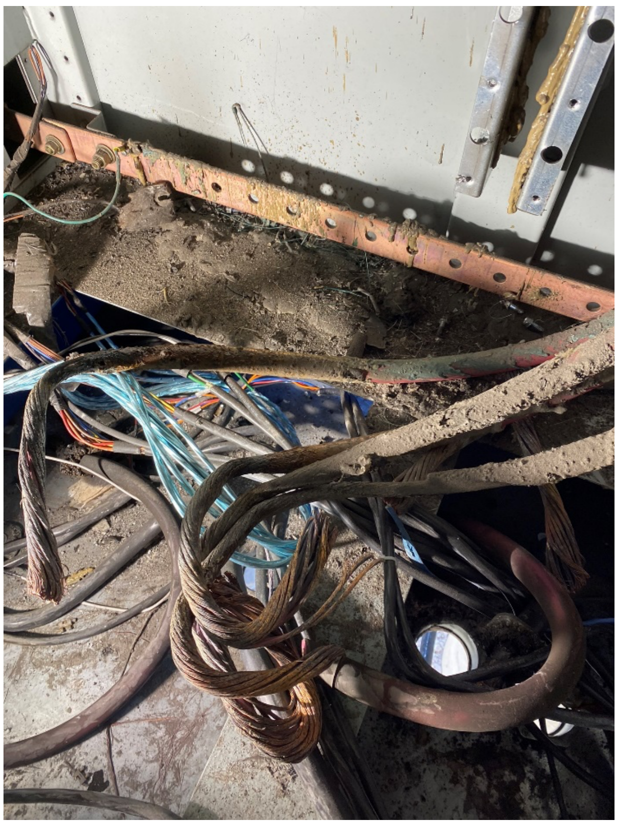

Fig. 5 Burned out enclosure

Finally, with the insulation on the conductors either melted or burned away the dielectric properties of the air reduced until an arc was produced. The resulting arc flash passed through the upper bus openings triggering an arc flash trip event on the main breaker. The arc flash also transferred energy onto the station PLC control wiring that destroyed two discrete modules and the network switch. The transferred energy from the arc flash also damaged the motor protective relay.

During the investigation it was discovered that the PDC building smoke and temperature alarms as well as the alarms from the relays were never configured in the operation’s HMI for alarm and status. Thus, operations were completely unaware of the situation.

Fig. 6 Soot remnant on walls after cleaning

It took nine (9) days to wipe up the soot from the PDC, the MV starter assembly, the MCC, VFD enclosures, etc. Nine (9) days, 40 sets of hands to cleanup, 3600+ manhours. Nine (9) days of down time and no income or productivity. Thankfully, the manufacturer had a direct replacement unit available to rebuild the failed starter. This reassembly was completed on the eighth day of the cleanup.

Fig. 7 Soot remnant inside an VFD

IV. SOME LESSONS LEARNED

Equipment failure could lead to contamination of all devices within the PDC building and the related downtime and chemical damage.

Take extreme care when torquing or verifying torque of terminations within the equipment, especially when there is restricted space and linear forces are difficult to maintain. Test them and document them.

Add the PDC building smoke alarms, building temperature, relay alarms, HRG alerts, and other PDC health status events to the manned operator HMI system and indication of abnormal conditions.

Never wire PLC controls into MV enclosures. Bring auxiliary contacts out to remote IO or interposing relays in a remote location. A remote module or relay is easier to replace than IO cards and back plane.

Use fiber optic cabling between the MV equipment and the station PLC to avoid the destruction of the network switch.

Use arc flash relays that have an internal event history and self check the integrity of the sensor or loop. The type used lost the indication of a trip when the power was removed from the PDC building.

Be aware of cable tray routing over the top of equipment as a failure of the equipment below could impact the cable insulation.

Purchase electronic equipment with coated circuit boards.

Purchase plated bus to protect copper from potential chemical contamination.

V. CONCLUSIONS

This equipment had been IR scanned after startup without detecting any issues. The arc flash detection sensors within the enclosure had melted away as a result of the heat. An abnormal termination could / will produce heat, smoke, and even some noise. The consequences of not preventing, detecting or notification of these failures early is astronomical.

The lessons learned from this incident led to a more critical evaluation of the combined systems installed within PDC buildings and the ways to mitigate reoccurrence of this event. This evaluation criteria could be used on similar sites and installations. Some options could lead to application of newer technologies like continuous thermal monitoring (CTM) systems. Also, a more critical analysis of the arc flash system installation, IR scanning procedures and reports, internal wiring practices with PDC building and component selection could be applied.

Thermal events like the one described here can be difficult to detect and have a devastating effect on operations due to the extended time needed to repair. The investment required for additional systems or components+, upgraded inspections, and mitigating the impact on other systems is highly recommended.

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VII. VITAE

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It's Time to Move the Needle in Electrical Safety

Paper No. ESW2025-27

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Abstract - After more than 30 years of steady decline in occupational fatalities from exposure to electrical hazards in the U.S., the trend for more than 10 years has been flat. This plateau is not unique to fatalities from electrical hazards. The data for all occupational fatalities shows a downward trend since the passage of the Occupational Safety and Health Act in 1970. However, the trend in reducing fatalities from all occupational fatalities for the past 25 years has been flat. Leading safety organizations, including OSHA, NIOSH, the American Society of Safety Engineers, the National Safety Council, and individual experts in safety management, have new approaches to reduce occupational fatalities further. This paper will review some efforts to address the flattened trend in all occupational fatalities, including Serious Injury and Fatality Prevention, Prevention through Design, and Safety Risk Management, and discuss how they can be applied to improve the effectiveness of safe electrical work practices provided by OSHA regulations, NFPA 70E and other industry standards on electrical safety.

Index terms – Electrical Safety, Electrical Safety Program, Electrical Safety Management, Risk Management, Risk Assessment, Hazard Identification

I. INTRODUCTION

Since the passage of the Occupational Safety and Health Act in 1970, the discussion of occupational electrical safety in the U.S. has focused mainly on compliance with safe work practices in OSHA regulations and industry consensus standards, such as NFPA 70E. Regulations and standards provide minimum requirements. Compliance with minimum requirements may create an illusion that potential exposure to hazardous electrical energy is reduced to as low as reasonably practicable (ALARP).

Over the past 20 years, thought leaders in safety management have expressed concern about the trend in occupational fatality prevention in the U.S. As shown in Figs. 1 and 2, both the number of fatal injuries from all causes and the fatalities from exposure to hazardous electrical energy have flattened.

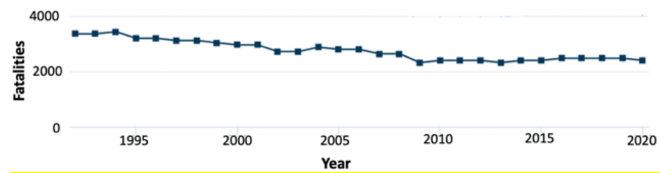

Fig. 1. The trend in Occupational Fatalities from all causes in the U.S. 1990-2020

"Moving the needle" or bending the curve downward in occupational electrical fatalities will require electrical safety leaders to explore and implement strategies that take electrical safety programs beyond simply complying with electrical safety regulations, codes, and standards. Fortunately, new intervention strategies being applied to the bigger concern for all occupational fatalities are available. Electrical safety will need to facilitate or assess the application, specifically to electrical safety, of strategies developed to address the bigger issue of the flattened trend in all occupational fatalities. Applying these and other strategies only to electrical safety is likely, not sustainable, as top management support is required, and it would be more appropriate for top management to understand these strategies apply to the management of all safety risks in the organization

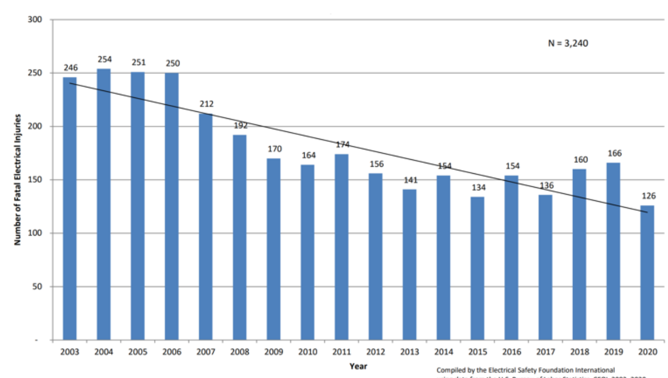

Fig. 2. The trend in Occupational Fatalities from Exposure to Electrical Hazards in the U.S. 2003-2020

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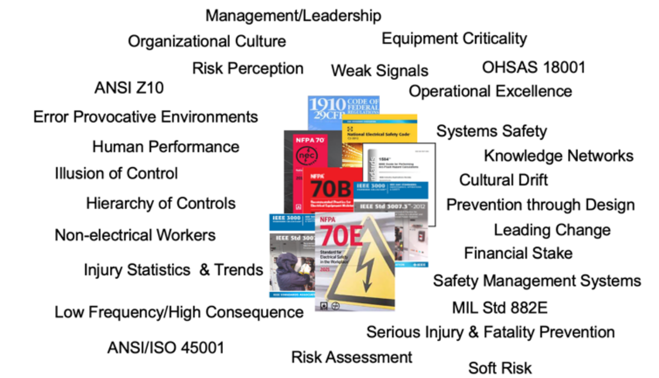

Fig. 3. The topics in the space are essential to managing the risk of exposure to hazardous energy and complement the requirements in electrical safety-related regulations, codes, and standards

Some organizations may tend to "silo" electrical safety practices, creating a disconnect from issues impacting all occupational hazards and risks. The topics in the space outside the collage of electrical safety regulations, codes, and standards in Fig. 3 are relevant to managing electrical safety but either are not addressed or not discussed in detail in the electrical safety resources. This paper discusses five intervention strategies developed outside the context of the electrical safety regulations, codes, and standards that could be integrated into a more comprehensive approach to managing the risk of exposure to hazardous electrical energy.

II. FROM INJURIES TO CONTROLS

From Table I lost time injuries from exposure to hazardous electrical energy cause .06% of all lost time injuries. The very low frequency of electrical injuries means that electrical injuries are few and far between for most organizations. Monitoring the number of electrical injuries is not an effective indicator of electrical safety program quality. Monitoring and reporting electrical injuries are lagging indicators ineffective in managing low-frequency events. A combination of lagging and leading indicators can provide a balanced scorecard for managing continual improvement in occupational safety management. A balanced scorecard of leading and lagging indicators aims to provide insight into an organization's electrical safety initiatives. A balanced scorecard combines leading and lagging indicators to develop a more comprehensive assessment of electrical safety performance and how it can be improved. Lopez, Esposito, Walaski, and others are helping educate safety professionals in designing and applying balanced scorecards for safety management. Standard ANSI Z16.1, *Method of Recording and Measuring Work Injury Experience* originated in the 1930s and was most recently updated in 2022 [1]. This latest revision reflects the evolution and recent research impacting lagging and leading indicators and the design and implementation of a balanced safety metrics scorecard. Integrating the recommendations in this standard into electrical safety programs will help electrical safety leaders identify gaps and opportunities to reduce potential exposure to hazardous electrical energy.

TABLE I
Comparison of select Non-fatal Occupational Injuries in the U.S 2019, based on U.S. BLS Economic News Release, 2019

Type of Non-Fatal Injury	No. of Injuries (2019)
Total	2,814,000
Sprains, Strains & Tears	295,180
Musculoskeletal Disorders	275,590
Falls on Same Level	153,140
Struck by Object	134,620
Falls to Lower Level	91,070
Assault/Violent Act by Person	30090
Highway Accidents	33390
Assault/Violent Act by Animal	14390
Electric Shock & Burn	1900
Fires & Explosions	1700

III. FROM TRIR TO INCLUDE SIF

Total Recordable Incident Rate (TRIR) is a standard safety metric in the U.S. It is defined as the number of work-related injuries per 100 full-time workers during a one-year period. TRIR does not differentiate between a back sprain and an electrocution. For more than ten years, leading safety organizations, including the National Safety Council, the American Society of Safety Professionals, and thought leaders in safety management have brought attention to workplace hazards that have exceptionally high potential of disabling or fatal injury [2] [3]. The intervention strategy, Serious Injury and Fatality (SIF) Prevention, is designed to help employers ensure that low-frequency, high-consequence risks that comprise a small component of TRIR risks are appropriately managed. An organization will typically identify eight to ten hazards in its operations with SIF potential. The dangers with SIF potential may vary depending on the nature of operations, but exposure to hazardous electrical energy is common to nearly all industries and processes. SIF prevention programs help ensure top management is fully committed to the effective management of low-frequency, high-consequence hazards. Having top management support for a SIF Prevention Program will help ensure support for an effective electrical safety program.

IV. FROM PROTECTION TO MORE PREVENTION (PTD)

In July 2007, the National Institute for Safety and Health (NIOSH) convened a workshop to obtain the views of various stakeholders on a major initiative to "create a sustainable national strategy for Prevention through Design ." One product of the workshop was a statement for Prevention through Design, as shown in Fig. 4. NIOSH launched the PtD initiative on the premise that the U.S. is lagging in the comprehensive application of widely recognized and accepted hazard control measures. It is generally accepted that engineering solutions that eliminate or reduce the frequency or severity of exposures are the most effective measures in safeguarding worker safety. Eliminating or reducing the frequency or severity of potential exposure to hazardous electrical energy in design processes, the risk of injury is reduced for the life of the installation. Safe work practices are still needed unless the hazard is permanently eliminated, but the likelihood of exposure is reduced and less dependent on safe work practices.

Prevention through Design (PtD):

Addressing occupational safety and health needs in the design and redesign processes to prevent or minimize work-related hazards and risks associated with the construction, manufacture, use, maintenance, and disposal of facilities, materials, and equipment.

Fig 4.
NIOSH Statement On Prevention Through Design

ANSI/ASSP Standard 590.3-2021 *Prevention through Design: Guidelines for Addressing Occupational Hazards and Risks in Design and Redesign Processes* is a state-of-the-art resource that can help electrical safety leaders reduce the risk of exposure to hazardous electrical energy in capital projects, facility renovations, and incident investigation recommendations [4].

V. FROM ELECTRICIANS TO ALL WORKERS

We live in an electrical world, with nearly every aspect of modern business and commerce dependent on electrical technologies and interactions with tools, appliances, equipment, and systems having some element of inherently hazardous electrical energy. Although the degree of risks ranges from little to great, it is the norm today that all people in the workplace have some risk of injury from electrical energy.

Misperceptions of who may be at risk for electrical injuries may limit the achievement of the potential for injury prevention and the application of best practices for preventing these injuries. Taylor et al. noted that managers and administrators, painters, truck drivers, farm workers, groundskeepers, and gardeners are among the top 10 occupations having the most fatal electrical injuries [5]. Workplace electrical safety programs must address electrical safety for all workers, not just workers whose responsibilities involve working on or near energized electrical circuits. For these non-electrical workers, the exposure to electrical hazards ranges from using common portable tools and appliances to unintentional contact with overhead power lines during routine work activities.

This raises the questions: What is the workplace? What workers are at risk of electrical injury? Do existing electrical safety programs encompass all workplaces and all workers? Article 90.1 of NFPA70E states, "The purpose of this standard is to provide a practical safe working area for employees relative to the hazards arising from the use of electricity." The scope description in Article 90.2 further narrows the application of the standard with this statement: "This standard addresses electrical safety requirements…for the practical safeguarding of employees during activities such as the installation, operation, maintenance, and demolition of electric conductors, electric equipment, signaling and communications conductors and equipment, and raceways" [6]. Strict adherence to the boundaries in these statements would limit application of this standard to workers whose job description, such as construction laborers, roofers, and agricultural workers may involve potential exposure to energized electrical equipment and systems. Could any of the requirements in the standard apply to other workers? What could be the impact if there was more effort to facilitate the application to other workers with potential exposure to electrical hazards in their work activities?

VI. FROM COMPLIANCE TO RISK

Since the passage of the Occupational Safety and Health Act in 1970, the discussion of occupational safety in the U.S. has focused mainly on compliance with safe work practices in OSHA regulations and industry consensus standards. Regulations and standards provide minimum requirements. Compliance with minimum requirements may create an illusion that risk is reduced to as low as reasonably practicable (ALARP). Peterson was one of the first thought leaders in safety management to voice concerns about having a compliance-based safety management process [7]. A gap may exist between risk reduction achieved from compliance with minimum requirements versus risk reduction achieved by other means. ALARP expectations will vary from company to company and change over time, impacted by various forces, including social consciousness, competitive environments, and top management goals.

Mendleoff and Staatsky have shown that the countries in the European Union with top management commitment for risk assessments have a significantly lower occupational fatality rate than the U.S. [8]. Manuele noted the risk-based approach is the cornerstone of the E.U. approach to occupational safety management [2]. The American Society of Safety Professionals, OSHA, and other safety institutions have promoted a risk-based approach as critical to further improvement in injury and fatality reduction [9].

In a compliance-based culture, organizations adhere to standards and regulations, which can lead to a "check the box" approach to comply with the minimum requirements provided by standards and regulations. A risk-based approach helps identify risks that remain even after achieving compliance. The residual risks can then be assessed to determine if additional controls are warranted. Risk assessments should be conducted in all aspects of the life cycle of an installation, process, or component, including capital program design reviews, equipment specifications, tool selection, job planning, and training programs

VII. CONCLUSION

The downward trend in occupational electrical fatalities in the U.S. has been flat for over 10 years. Other countries, especially those in the European Union, that have placed more emphasis on risk assessments in design processes have demonstrated the ability to achieve significantly lower occupational fatality rates than the U.S. Moving the needle in occupational electrical fatalities will require electrical safety leaders and top management to critique past and current methods to manage the risk of exposure to hazardous electrical energy. Strategies are available to address the greater concern for the flattened trend of occupational fatalities from all hazards. Top management should nurture an electrical safety culture that breaks down barriers that can lead the organization to allow electrical safety to be a siloed function and create a more effective solution to electrical safety that embraces advanced safety management, as illustrated in Fig. 5.

Fig. 5. Implementing electrical safety practices and advanced safety management can result in a more comprehensive solution for managing exposure to hazardous electrical energy versus implementing electrical safety practices alone.

The embracement of advanced safety management will provide opportunities for stakeholders in electrical safety to focus on applying evolving concepts in safety management to the unique challenges of reducing exposure to hazardous electrical energy.

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VIII. VITA

H. Landis "Lanny" Floyd II (A'72–M'73–SM'91–F'00–LF'15) received a Bachelor of Science degree in electrical engineering from Virginia Polytechnic Institute and State University, Blacksburg, VA, USA, in 1973. His 45+ year career with DuPont, Wilmington, DE, USA, focused on electrical system reliability and electrical safety in the construction, operation, and maintenance of DuPont facilities worldwide. He retired in 2014 as Principal Consultant Electrical Safety and Technology and Global Electrical Safety Competency Leader. He is currently an Adjunct Faculty Member with the Engineering Graduate School of Advanced Safety Engineering and Management, The University of Alabama at Birmingham, Birmingham, AL, USA, and a Principal Consultant with Electrical Safety Group Inc., Elkton, MD, USA. He has published or presented more than 100 technical papers, magazine articles, tutorials, and workshop presentations on occupational electrical safety. Mr. Floyd is a professional member of the American Society of Safety Professionals, a Certified Safety Professional, a Certified Electrical Safety Compliance Professional, a Certified Utility Safety Professional, a Certified Maintenance and Reliability Professional, a Certified Reliability Leader, and a registered Professional Engineer in Delaware, Pennsylvania, Michigan, and Texas.

Have We Solved the Arc Flash Problem?

Paper No. ESW2025-28

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Abstract – Some recent papers and presentations have been written to suggest that the electrical arc flash hazard is a low probability risk and therefore not the hazard to electrical workers or their employers it once was. They have argued with little evidence to support this conclusion that this hazard has essentially been mitigated. This paper will present a counter argument with evidence that advocates for electrical workers that we are far from achieving our goal of proper worker education and protection.

Index Terms — Arc Flash, Enforcement, Data Collection, Jurisdiction, Electrical Safe Work Practices, PPE.

I. INTRODUCTION

It is important that factual representations of the arc flash hazard are used in training and hazard mitigation, rather than sensationalized stories. However, it is equally important not to understate the hazard. As well, it is important to understand the data that exists as related to electrical hazards and whether it is indicative that arc flash hazards are appropriately mitigated by the vast majority of electrical workers and their employers.

Electrical workplace fatalities in the United States (U.S.) have been hovering between 126-166 per year since 2015. This number is down significantly from 20 years ago, when the 2004 annual electrical workplace fatality number was 254 [1]. In the author's experience, this lowering of fatalities over the years has resulted in less attention to electrical hazards, not only in industry, but also in safety and enforcement. For example, electrical hasn't occupied a space in the top 10 Occupational Safety and Health Administration (OSHA) citations list since 2017.

While fatalities are often focused on, non-fatal injuries are very often life-changing events. In a similar comparison as fatalities of nearly 20 years, non-fatal injuries haven't changed as drastically. 2020 in the U.S workplace saw 2,220 non-fatal electrical injuries involving days away from work (an increase over 2019). 2004 saw 2,650 injuries [1].

During a 2024 IEEE Electrical Safety Workshop (ESW) presentation, a statement was made indicating that we have solved the arc flash problem. The statement was made in support of the "*possible myths, legends, anecdotal stories, errors, or facts*" that *"There are several arc flash fatalities per day/month/year."* The presenter maintained that a lack of Federal OSHA citations was evidence that the industry does not have a problem with arc flash incidents. Although it is agreed that some popular statements exist that over state arc flash occurrences, it can also be proven that arc flash incidents are still occurring at a significant rate, and that the arc flash hazards are not being adequately addressed in many facilities.

The authors' experiences with various facilities throughout the United States and the world indicate that the recognition and mitigation of electrical hazards is still a serious problem, and this includes the arc flash hazard. We present the problems associated with citing OSHA data as insufficient to draw strong conclusions and add anecdotal data from our experiences to reinforce the need to continually sound the alarm regarding the arc flash hazard.

II. OSHA DATA ALONE IS INSUFFICIENT

It is important to realize the limitations of OSHA data based on their mission, scope, and jurisdiction.

1) *OSHA is an enforcement agency and not a data collection agency.* Although OSHA collaborates with National Institute for Occupational Safety and Health (NIOSH) to study workplace hazards and develop solutions, the Bureau of Labor Statistics (BLS) is the data collector and NIOSH uses the data in their research to apply science and expertise to prevent workplace hazards. The BLS has the responsibility to provide accurate, objective, and relevant statistical information. Of course, much of their ability and effectiveness can be impacted by the executive branch of government.

2) *OSHA's jurisdiction is limited for small companies with 10 or fewer employees:* The small business exemption allows these companies to forego recordkeeping requirements such as injury and illness reports and logs. Over 60% of America's small businesses are made up of 10 or fewer employees [2].

3) *OSHA's jurisdiction does not cover self-employed individuals.* Approximately 16.2 million people or 10.1% of the US workforce is self-employed [3]. BLS published an article in 2019 which looked at injury, illness and fatality data from 1992-2016. BLS states that In 2016, the fatal injury rate for self-employed workers, 13.1 fatalities per 100,000 full-time equivalent workers, was more than 4 times the rate for wage and salary workers, which was 3.0 fatalities [4].

4) *OSHA's jurisdiction does not cover immediate family members of farm employers.*

5) *OSHA's jurisdiction does not cover workplaces regulated by other federal agencies such as Mine Safety and Health Administration (MSHA), Department of Transportation (DOT) or Department of Energy (DOE).* There are 2.9 million workers or 1.9% of the American workforce employed by federal

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agencies. These agencies may or may not report injury and fatality data to agencies such as the Bureau of Labor Statistics.

6) *Federal OSHA's jurisdiction does not cover State OSHA Plans in 22 states.* While State OSHA agencies do issue citations and fines, this data is not included in Federal OSHA reporting.

7) *OSHA's jurisdiction does not cover state or local governments employees.* There are 19.58 million state and local government employees in the US in 2023 [5]. To provide just one example of the occupational safety enforcement that state and local government employees receive, the state of Ohio started the Public Employee Risk Reduction (P.E.R.R.P.) program as a state-level OSHA-like program for public employees. P.E.R.R.P. has six officers to cover all the public employees in the entire state of Ohio. There is evidence that there are often not enough resources for P.E.R.R.P. to even investigate fatalities within the state's public employee system.

In addition to the workplaces not covered by OSHA; occupational law to fight enforcement agencies such as OSHA is big business. The author was most recently in attendance as a presenter at a corporate safety conference for one of the largest service organizations in the U.S. A presentation of considerable interest to the author was put in front of the large group from a lawyer representing an occupational law firm that the service provider employs. The lawyer's presentation was on how to handle OSHA when an injury or fatality occurs and how not to incur citations. He proudly recounted a case he had represented that involved a double fatality which because of the way it was submitted through OSHA's online system, OSHA never came to the site of the fatality, and no citations were issued. This begs the question; how many injuries and fatalities never receive OSHA citations to be recorded?

The authors reviewed the OSHA Injury Tracking Application (ITA) data report released for 2023. The ITA is the recommended method of reporting an injury or fatality by most occupational lawyers, since the employer controls the narrative and can't be asked direct questions. The following are 26 injuries found related to arc flash in the report. An additional 8 were identified in the report that are not listed here, and 12 more would need additional research to validate as arc flash-related [7].

A. Sawmill, arc flash from disconnecting power at transformer, electrician injured, 1st degree burns on left hand and right cheek, 2022.
B. Light gauge metal manufacturing, maintenance tech was troubleshooting a power failure at the condenser for air conditioning unit. While checking wiring continuity there was a flash and 2nd degree burns to his face and hands, 2022.
C. Food processing, maintenance technician was shutting off a circuit breaker when the breaker failed causing an arc flash, resulted in thermal burn to left wrist, 2022.
D. Foundry, maintenance manager was transferring connections between panels while it was energized and created an arc flash. Caused third degree burns to the face right hand and right arm, 2022.
E. Liquid coatings, industrial machinery mechanics, proper LOTO was not used, buss rail was energized, resulting in arc flash burns, 2022.
F. Shipyard, foreman, inspected the new equipment for proper installation in preparation to energize the new switch. Employee opened the door to the wrong switch, which not isolated and was live. Employee connected one test lead of the [insulation resistance tester] and was connecting the second test lead when the meter exploded in his face. The employee was hit with arc [flash] to the face, neck, and right hand causing second degree burns, 2022.
G. Power utility, IC and foreman. Worker tried to insert the [newly wired] plug into existing 480V welding receptacle that was live, arc flash occurred when seating the plug. Electrical burns on hands and fingers, 2022.
H. County power distribution, lineman, arc flash and explosion from a failed transformer bushing. Damage to eyes and ears, 2022.
I. Metal fabricating, maintenance technician, doing electrical work in the shop when arc flash occurred, resulting in eye damage, 2022.
J. Adhesive tape manufacturer, group leader and apprentice were replacing an HVAC soft starter. After lockout tagout and during the installation one of the workers drilled into the bucket. This caused contact with a previously unknown live bus located behind the bucket. The contact caused an arc flash incident which resulted in both workers being burned. Workers sustained burns to hands, arms, and face, 2022.
K. Gas well machinery and equipment, electrical technician reached in VFD cabinet to measure allen wrench size and cabinet was energized. Employee suffered burns to hands and fingers, 2022.
L. Courier service, maintenance journeyman, was replacing mcc bucket when arc flash occurred, causing 1st and 2nd degree burns on hands, 2022.
M. Steel and wire drawing, employee found wires, undid the connectors for liquidtight and pushed into the electrical box when the arc flash occurred. The panel on the front of the box flew off and struck the employee in the head. Employee pushed wires into the electrical box without using a meter to check whether it was energized. Employee failed to de-energize equipment or even make attempt to prior to performing repairs. Right eye and temple area impact causing blurred vision in the right eye with limited peripheral vision. Slight laceration and contusion above right eye at the temple. Temporarily loss of vision and hearing due to the arc blast, 2022.
N. Sawmill, millwright. Employee was outside the caged restricted area around switchgear transformer when electrician replaced a fuse. Fuse blew electrician exited caged area and walked away. Employee then entered fenced area where he attempted to test for voltage. As he approached to test it then arced to his tester resulting in a loud bang and arc causing burns to his hands neck face and ears, 2022.
O. Winery, winery worker. Employee was sanitizing about 2 feet away from a pump panel with three outlets. The far right outlet experienced an arc flash (contained within the electrical box). The force from the arc flash made contact with the employee in the chest region. Employee experienced minor soreness. No injuries beyond first aid were sustained, 2022.

P. Liquid and dry bulk manufacturing, electrician. Removed cover on 480V panel and turned back. Arc flash occurred. Burns to both eyes, 2022.
Q. Power generation, journeyman electrician. Employee was inspecting hoist, opened breaker panel and arc flash occurred, burns to face, 2022.
R. Power construction management, lineman. Employee was attempting to place a lightning arrestor onto a t-bushing in a switching cabinet when a failure occurred resulting in arc flash. 1st and 2nd degree burns were sustained. Foreman also sustained medial meniscus tear to the right knee from falling due to arc flash, 2022.
S. Cold forging, maintenance. Employee went to change out middle saddle on fuse holder when wrench made contact to hot side which caused an arc flash. Employee received severe burns to multiple parts of body, 2022.
T. Utility. While replacing an insulator on a CR bank pole, an arc flash occurred. The employee sustained burns to face ears and neck, 2022.
U. Bracket manufacturing, maintenance technician. Employee was working on an energized 480V breaker and received an arc flash. 2nd degree burns to hand, 2022.
V. Clinic, senior building maintenance technician. The employee was working on a rooftop HVAC unit taking current readings for the compressors. A wire in the unit shorted out and caused an arc flash, burning the employee 's hand and arm, 2022.
W. Lumber, nightshift maintenance. Employee was checking a breaker with a meter when arc flash occurred. Eye injury, 2022.
X. Food preparation, maintenance. Employee stated he cut power to the production line and when he tested it with his meter, the 480V arced to his right hand and right side of his face. Burn to head, chin, arm, wrist, and hand, 2022.
Y. Auto manufacturing, Maintenance technician, working on 480v control panel. The breaker on the outside of the PDP was shut off, but the three-phase coming in was not shut off. Technician was wearing arc flash suit, one arc flash glove and safety glasses. As technician was disconnecting wires on the hot side two wires touched together causing an arc flash. Technician received electrical burns on their bare hand and face, 2022.
Z. Motor vehicle seat manufacturer, maintenance technician. Employee was working on panel and was changing fuse and in the process the connector was loose and a cable came out and touched the cabinet and created an arc flash in his face, 2022.

III. DATA POINTS

The question remains, how many injuries and fatalities are really occurring?

The data varies depending on the source you look at, and this is one of the issues the authors have with confirming data. For example:

- Electrical Safety Foundation International (ESFI) states 2011-2022, 1,322 workplace fatalities involving electricity occurred (citing OSHA) [6]. It is worth noting that ESFI attributes only 1% of these fatalities to arc-flash / blast.
- IAEI puts the number electrical fatalities at 1,501 from 2011-2020 [1].

And the above is only fatality data; the authors found data on injuries that ranged between 2,380 [6] and 2,220 [1] for the U.S. workplace in 2020, to name just two data sources. BLS states that in private industry for electricians, there were 7,270 nonfatal injury and illness cases involving days away from work in 2020 [4]. While this includes all causes, there is very little data on how many of these injuries had an electrical root cause.

IV. IN-FIELD OBSERVATIONS

Even if it is agreed that injuries and fatalities are down from previous years, can this decline be attributed to proper work practices, training, PPE, and safety by design? The authors have observed some workplaces in the past few years that seem to be contrary to statements that the arc flash problem is solved, and that there's nothing more to worry about. In fact, they seem to be an injury or fatality waiting to happen.

- This example is a county government (public employer, not covered by OSHA). The safety director and maintenance manager were interested in improving their workplace electrical safety, as they have no written electrical safety program, no electrical safe work practice training for their maintenance technicians, and the technicians have no PPE for the electrical work they do, working on an aging infrastructure. The maintenance manager (with an electrical background) stated that he had heard something about arc flash 20 years ago, but didn't really know much about it, to even help his employees.
- This example is private industry (covered by OSHA). The author recently visited some facilities for a Fortune 1000 company. The electricians have had safe work practices classroom training and have been issued PPE. Beyond the classroom, there is no demonstration of skills per NFPA 70E, and no supervision observing the implementation of electrical safe work practices. Almost all issued PPE was found to be new in the package, never having been used. In one case the author observed an electrician enter an energized 3-phase electrical panel, applying no safe work practices, no PPE, no insulated tools and an apprentice in tow.

These examples help illustrate the persistence of complacency and ignorance with regard to arc flash hazards in the workplace.

Authors investigated an event in 2019 that was not recorded by OSHA and were retained to provide a forensic electrical analysis for the client to enhance their electrical safety program and training. The accident resulted in 3rd degree burns on 15% of the victim's body and 130 stitches. It was caused by the failure of a 60 amp disconnect switch feeding a pin and sleeve receptacle (welding outlet) in which the door was blown off and lacerated the victim's arm.

V. CONCLUSIONS

The authors of this paper do not claim to be experts in data collection and statistics. However, there are obviously inconsistencies in the collection of [electrical] injury and fatality data. Even though the number and frequency of arc flash injuries and fatalities may have been reduced, there still exists many facilities that are not taking any significant action to address the hazard and many more that do not take nearly sufficient enough steps to reduce it.

The arguments and examples of accidents in this paper clearly demonstrate that the arc flash hazard is still a significant hazard with sufficient probability and such serious consequences that the problem is far from solved. Safety professionals must continuously emphasize electrical safety training and work practices to address it. Likewise, electrical engineering and maintenance professionals must design systems to reduce this hazard to levels where it no longer poses the serious consequences it currently does in most facilities.

Arc flash events are sensational and ought to be feared. It is our purpose to encourage the further examination of the data, and to keep trying to find solutions to reduce the electrical hazards in our workplaces, covered by OSHA or not.

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VII. VITA

Karl Cunningham, a father of 12 and grandfather of 26, has been a plant and project engineer and project manager for a fortune 500 company most of his 42-year career. His work includes designing, constructing and starting-up mega-project industrial facilities internationally, working in over 20 different countries. He also served as an apprentice program coordinator, evaluator and instructor for 14 years while working as a plant engineer in the early part of his career in Northern New York state. Karl is on Code Making Panel 12 of NFPA 70 National Electrical Code and the technical committees for NFPA 70B and 70E. He has authored and led electrical safety programs for most of his career. He is a senior member of the IEEE and has presented several papers at past Electrical Safety Workshops. He was also published in ASEE (American Society of Engineering Education) for his Experiential Learning Program and published in the International Aluminum Industry journal.

Michael Kovacic is a full-time Occupational Safety Instructor and Consultant with over 30 years of experience in the electrical safety industry. He has participated in and managed teams for safety audits for millions of square feet of facilities, representing heavy industrial facilities for global corporations and government organizations. He is involved in the development of several computer database applications which aid in the record keeping and reporting portions of the assessment function. He has participated in arc flash hazard calculations for numerous facilities and has background in accident investigation and legal assistance. His extensive knowledge of standards, DOD/DOE requirements, Army, Navy and Air Force safety programs, has enabled him to conduct standard and customized courses on the OSHA Standards, the National Electrical Code, and NFPA 70E for the U.S. Department of Labor at the OSHA Training Institute in Chicago, IL., various State OSHA Departments, Federal Aviation Administration (FAA), Bureau of Worker's Compensation (Ohio) and numerous major private corporations. He has authored electrical safety programs for major corporations and government entities around the world, including a truly reconciled ANSI (NFPA 70E) and IEC (EN 50110) program. He is a member of IAEI, IEEE and NFPA and a voting member of ASTM F-18 Committee.

Artificial Intelligence in Electrical Safety: Now and the Future

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Abstract – Artificial intelligence (AI), while in its infancy, has and continues to play a major role in transforming electrical safety, especially within electrical maintenance and electrical safety management systems. AI utilizes advanced analytics and machine learning techniques to analyze historical or real-time data to identify patterns and anomalies that are used to detect potential electrical hazards or workmanship issues. Organizations may then take preventive measures, minimize electrical accidents, and create a safer working environment while potentially identifying leading indicators.

AI enhances the efficiency of electrical maintenance by continuously monitoring and diagnosing changes in deterioration levels before faults occur. It is anticipated that AI may predict the date and times of potential failures due to the ever-increasing historical database on numerous assets – allowing for condition-based maintenance instead of unplanned outages. AI also automates the analysis of certain electrical safety management systems, such as data from safety inspections and incidents, enabling quicker identification of safety gaps through corrective measures. Additionally, AI algorithms can provide real-time monitoring of electrical safety parameters, ensuring compliance with electrical safety regulations and electrical safety standards.

The paper discusses the potential for using AI to generate electrical work permits and reviews, quality checks on medium voltage joints, and PPE compliance. To highlight the potential of AI, this abstract was written using AI, allowing the engineers time to focus on other electrical safety endeavors.

Index Terms — electrical safety, artificial intelligence, machine learning, electric shock, equipment assessment, outage, fault, short-circuit, predictive analytics, LOTO, lockout tagout

I. INTRODUCTION

Artificial Intelligence (AI) is a cutting-edge technology that is expected to impact various industries throughout the world. AI deployments are increasing efficiency, improving quality, and advancing global technology. Previous connections and learnings likely would not have been possible without AI due to the analysis of vast amounts of data that a human could not comprehend. AI is the tool that is advantageous to further enhance and improve electrical safety work practices.

This paper aims to summarize the present state of utilizing AI in the electrical safety industry and attempt to predict future use cases in this space.

This paper is not comprehensive and is solely the opinions of the authors. There may be more applications that are not covered in this paper that will be critical to advancing electrical safety and more may develop as the technology advances and matures.

II. UNDERSTANDING AI AND THE LIMITATIONS OF USE

A. Artificial Intelligence

Intelligence is the ability of a human to process data to gain knowledge and perform skills that impact themselves, their community, or humankind. It is what makes humans human. Artificial intelligence is the ability of a machine to mimic human intelligence by processing data and interpreting it to be able to communicate in a human-like manner [1]. Arthur Samuel, electrical engineer and professor, used extensive coding and large amounts of data from many games of checkers to create a computer-based "checkers player." In 1962, after playing multiple games against itself, the program was able to defeat checker's expert player, Robert Nealey [2]. This type of computing is a subset of AI known as "machine learning" and is demonstrated by the example shown in Fig. *1*. Where traditional programming languages take data, write a program and provide an output (e.g., if, then, else program), AI uses data and outputs to generate a program [3].

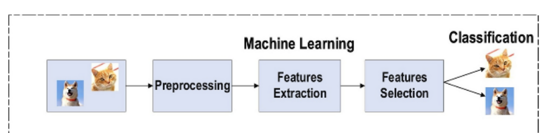

Fig. 1: Machine Learning *[4]*

Understanding and modeling the human brain and its functioning led to the creation of parallel and multi-level processing in the form of neural networks. Whereas machine learning may typically require some user input (e.g., like, dislike, thumbs-up, thumbs-down) to improve accuracy, deep learning uses neutral networks to be largely autonomous [5]. This allows a streamlined process that can manage substantially larger amounts of data compared to machine learning as shown in Fig. *2* [6]. It does, however, require substantially more processing power and time.

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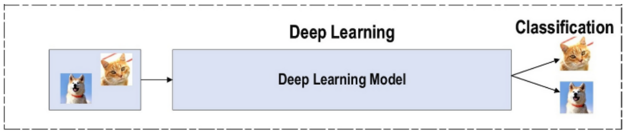

Fig. 2: Deep Learning *[4]*

Artificial intelligence, machine learning, and deep learning are summarized in Fig. *3*.

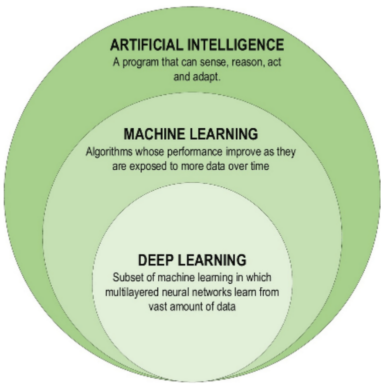

Fig. 3: Relationship between Artificial Intelligence, Machine Learning, and Deep Learning *[5]*

B. Limitations and Considerations

The end user shall always bear the responsibility for their own safety, and while AI can be a tool to improve and minimize mistakes, each person should own their safety. AI is a tool to double check and supplement specialist knowledge and work products, but the worker should always verify the output of any program prior to subjecting themselves to a hazard.

One study of the use of AI in business, the first of its kind, was performed by a management consulting group in collaboration with the Havard Business School, MIT Sloan School of Management, University of Warwick, and the Wharton School at the University of Pennsylvania [7]. There are three key takeaways to the study that influence the ideas within this paper. Firstly, the study found that 90% of the participants improved their results when AI was used to advance their area of expertise, as the authors are suggesting in this paper. The participants were able to apply their judgement, experience, and skills to direct the AI in creative ideation. Secondly, when used to solve a business problem (job function), their performance dropped 23% compared to the group that did not use AI. When offered basic AI training, the participants' performance dropped 29% compared to 16% for the participants not exposed to basic training. This highlights the challenge of blindly trusting AI outputs or demonstrating false confidence in the use of AI. Thirdly, AI is advanced enough to be strong in certain simple repetitive tasks. When the participants altered the output of areas where AI provided strong results, the quality of the work decreased. The study found that for every 10% that the participants departed from the AI output, quality decreased by 17%. The findings from the study shall be considered carefully when adopting the recommendations made in this paper.

III. ARTIFICIAL INTELLIGENCE IN ELECTRICAL SAFETY PRESENT STATE

A. Case Study

A petrochemical plant on the North Slope, Alaska, used manned aircraft (helicopters) to capture images of civil, mechanical, and electrical infrastructure for condition monitoring purposes by subject matter experts (SMEs). Extreme weather conditions and the need for more intrusive imaging resulted in the use of unmanned aerial vehicles (UAV) with light detection and ranging (LiDAR) and ground penetrating radar (GPR). The result was a substantial repository of data in various formats and, more importantly, records of interpretation, trending and analysis of this data by SMEs. The petrochemical plant teamed up with a software expert company that also had a large repository of data and interpretation. They used this repository of data to train the AI. Today, the AI is able to process the images being fed from the UAV and categorized defects such as missing hardware, cracking, and movements [8].


Fig. 4: General image captured by UAV [9]

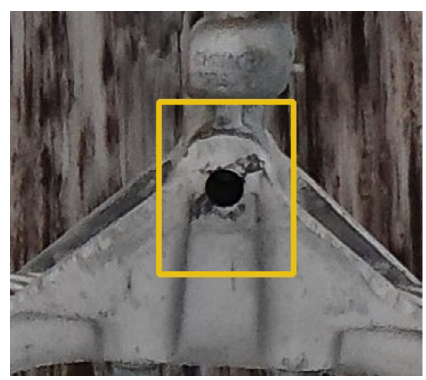
Fig. 5: Image interpreted by AI showing a missing part [9]

The principles adopted by this case study are used to propose applications where AI could be used in electrical safety for creative ideation and problem solving under the supervision of a SME.

IV. AI OPPORTUNITIES IN ELECTRICAL SAFETY: MAINTENANCE AND OPERATIONS

A. Power Systems

AI can be used to analyze data in real time that would normally require a human to intervene at some point in the power system. These applications normally start rather inaccurately during development since the algorithm needs large amounts of data to improve accuracy over time. For example, if a data set has 10 data points, it will likely not be as accurate for all cases as a data set of 100 data points. The 100 data point data set will not be as accurate for all cases as a data set with 1,000 data points. The algorithms will get better, more accurate, and faster as more data gets added to it; however, a SME has to decide on the criteria such as “good,” “bad,” “acceptable,” “reject” on the initial data set and possibly at intervals of data set expansion. This is referred to as “training the model.” The SME must give the initial reference point on both sides of the spectrum for the algorithm to begin its “pass/fail” analysis. Fig. *6* shows some of the most common types of information needed for AI inputs.

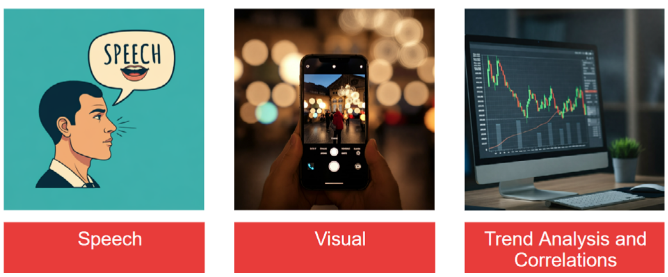

Fig. 6: Example of different types of data that can be analyzed by AI. Note these images were generated by AI.

1) *Power System Design:*

Using AI in the future, power system designs can be automatically generated with a single click of a button in commercial software packages. The software package will utilize a machine learning algorithm and may search via multiple databases pertaining to feedback and failure rates while constantly updating the design using real world data. This “one click” design can include full load flow, protection system coordination, arc flash calculations, and the associated drawings and labels. By clicking “one button” in the software package, a design package can be generated that will have high reliability and proven success. Components would be chosen along with their particular settings. The physical layout prints will also be generated based on the provided physical constraints (space, landmarks, other obstructions).

2) *Power System Operation and Analysis*

Presently, a human has to download and analyze oscillography and status information for transient power system disturbances typically presented in a Common format for Transient Data Exchange (COMTRADE) file. After making sense of the data, take action to restore, stabilize, or return redundancy to the network. Many of these events are repetitive and the information is globally standardized; however, the action required to remediate the transient or fault varies from network to network. If a SME used AI to analyze data in real time and train the AI on the subsequent actions (both permitted and prohibited), then the AI can act faster and process far more complex power system iterations than ever possible from a human. When the system is mature and nuisance trips and false interpretations are addressed, the AI can directly send a trip signal or transfer signal to protect the equipment from catastrophically failing prior to it failing. Fig. *7* and Fig. *8* show examples of trends that can be gathered and actions taken.

Fig. 7: Machine learning example analyzing trend data. Note this image was generated by AI.

Fig. 8: Anomaly detection example by ML to determine health of assets. Note these images were generated by AI.

3) *Sensors and other forms of monitoring*

Online Partial Discharge (OLPD) sensors such as transient earth voltage sensors, ultrasonic sensors, and high frequency current transformers can be used as inputs to train AI algorithms. These types of sensors have been used for several decades and deep learning may identify trends even between frequency and time domains to detect underlaying or previously unknown outcomes autonomously. This is similarly true for transformer oil analysis, especially on dissolved gas analysis, furan analysis or degree of polymerizations of paper insulation. An excellent example on the potential for success in this area is the famous and groundbreaking research from 2018 where deep learning used retinal fundus imaging from over 284k patients to accurately predict cardiovascular risk factors [10].

Such principles extend to the analysis of data from temperature, voltage, current, vibration, rotational, flux, and other sensors. The SME can either train AI or supervise the output from deep learning to determine the "health" of the equipment through predictive analytics. The algorithm will analyze an ever-increasing database of historical information and compare it against the measurements to determine if the asset is showing signs of degradation and eventual failure. Site operations can then begin to plan pre-emptive remediation prior to a failure and thus minimizing downtime and operational risk.

V. AI OPPORTUNITIES IN ELECTRICAL SAFETY: WORK PRACTICES

Utilizing AI can enhance electrical safety programs and work practices to better protect electrical workers. Visual and audio inputs via cameras, microphones or even cellular phones connected to an app can be used to detect missing equipment, inadequate PPE, and equipment or installation defects [8].

A. Inadequate PPE Check

Permanently mounted cameras or an app-based mobile device photograph can be used to detect whether a worker is wearing appropriate PPE or not prior to entering a cabinet and potentially exposing themselves to electrical hazards. A gating process can be implemented such that the worker does not gain authorization to begin work without getting approval from the AI algorithm within an app or computer program. This gating process can ensure the worker is wearing the appropriate level of PPE based on their task at hand, especially if the Job Safety Plan (JSP) is established and integrated into the AI. This approval process can be applied to both scenarios where the worker is wearing too little or insufficient PPE ("under-protected") for that task AND if they are wearing too much PPE ("overprotected"). One may argue that being "overprotected" is a good thing; however, overprotection may result in the worker losing critical dexterity to complete the task, resulting in a higher risk for mistakes. For example, at higher levels of arc flash protection, older or entry level PPE is typically thicker, bulkier, cumbersome, and potentially less mobile with a narrower peripheral view (note: this isn't necessarily the case for newer higher end flash suits). The worker is physically taxing themselves more than necessary and actually hindering themselves to a point where it may affect their ability to complete the task safely without incident.

It is critical to ensure the task at hand is completed with equipment that is most appropriate based on industry standards, regulations, experience, and internal or contractually agreed work requirements. Fig. 9 depicts a potential photograph or video capture that could be submitted for work approval. Notice that the larger "red" box and the smaller "yellow" box identify insufficient PPE prior to starting the work. The goal is for AI to identify these shortcomings prior to the worker entering the arc flash boundary and shock boundary. In contrast to Fig. *9*, Fig. *10* demonstrates a full approval for a proper PPE for the task at hand. Notice all the different items the AI can analyze. Visual cues can make it easy to identify what was and was not analyzed and what is missing v. meeting the requirements. In a mature, established, and extensively vetted system, the AI can not only become the final authorizing authority for all work that exposes workers to electrical hazards but can continuously monitor all activities with the authority to "stop-work" when safety rules are violated.

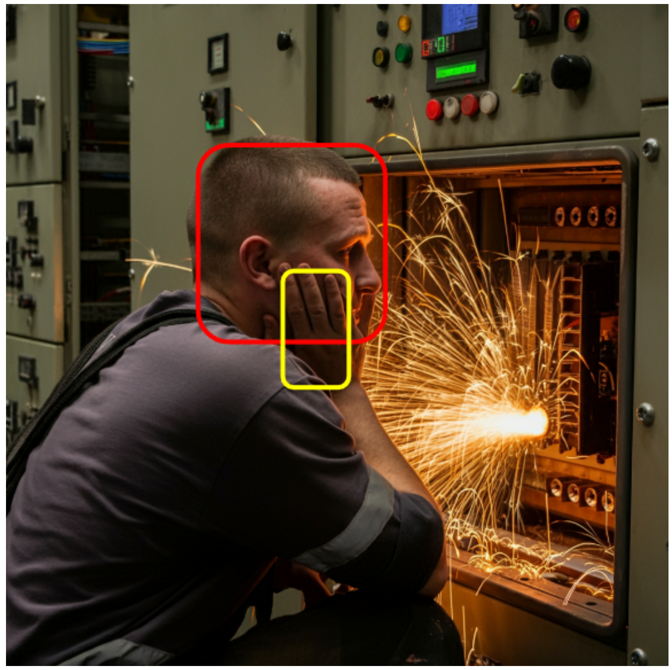

Fig. 9: Inadequate PPE example. Note this image was generated by AI. !

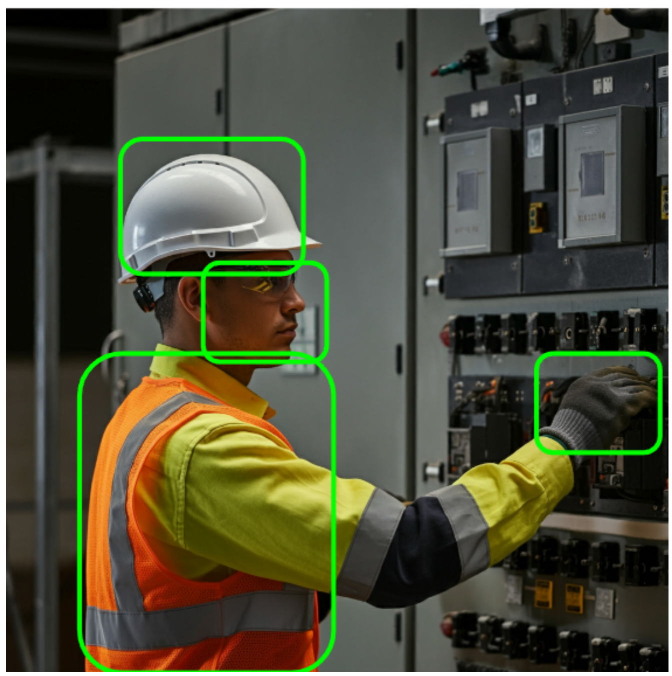

Fig. 10: Example of AI approved PPE required to perform the task. Note this image was generated by AI.

B. LOTO and Electrical Work Permit Generation and Verification

Another application for AI in Electrical Safety is the automatic generation of a Lock-Out Tag-Out (LOTO) plan and Electrical Work Permit. By selecting what task is performed on which equipment, a comprehensive LOTO plan and work permit is automatically generated by a computer program or mobile app. All isolation points would be identified, together with locations and applicable drawings provided by a single click of a button on a screen. A tool like this would save hours of time on a daily basis and improve work efficiency. Additionally, it should minimize errors as long as the database and drawings are updated and accurate. Again, at the infancy stages of training the AI, the SME should verify all outputs and documentation from the AI prior to beginning any work.

By automating LOTO and Electrical Work Permits, the quality and completeness should be consistent across all assets and all workers/supervisors, eliminating human errors and knowledge gaps between employees. It is, however, critical that the drawings, templates, and asset names are verified to be correct at the onset of a project and at routine intervals, especially when equipment changes occur.

Fig. *11* shows an Electrical Work Permit example that is automatically cross-referenced with the one-line diagram (single line diagram). In this example, there are 3 sources that the AI identified in the drawings and then verified that these matched the work permit. Had the worker missed an energy source, AI could have detected it and flagged it or denied the work permit. This tool can be a critical tool to help prevent workers from entering cabinets with outdated drawings or incorrect information that fail to identify an alternate source. In advanced applications, the user can take photographs of the equipment and cross reference it to the work permit and the single line diagram to have a triple verification that the hazardous energy sources are, in fact, identified.

If the photograph identifies unexpected equipment, the program can alert the worker of a potential additional source that requires LOTO prior to beginning the task, thereby eliminating a potential injury or fatality.

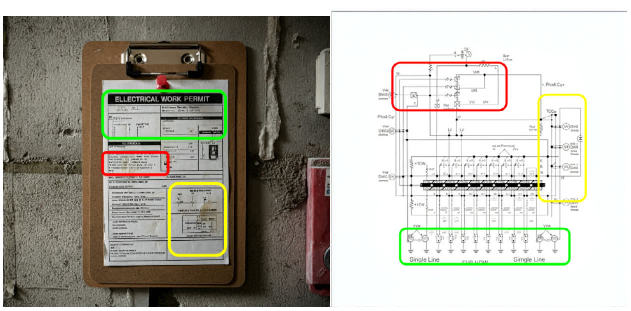

Fig. 11: Example of AI analysis of source identification for a LOTO plan. Note this image was generated by AI.

C. Power Cable Termination Defect Detection

AI has the potential to identify cable defects during construction or maintenance. The process of terminating a medium voltage or high voltage cable is a highly skilled expertise that only trained individuals on those specific cables and terminations should perform. To verify the quality of these splices, terminations, or cable joints, photographs can be taken at each step of this process for a complete 360-degree view of the termination/splice/joint as different layers get connected from two cables. Continuous videography and advanced intrusive imaging has potential in this application as well. The AI maintains the quality control hold points at each step before permitting the next step of the cable termination. As more images get uploaded to the database, the AI algorithm improves its ability to detect minute defects that the human eye cannot identify or that a worker incidentally misses. AI would drastically improve the cable splice/joint quality and reduce the infant mortality rates of such joints prior to completion and testing

Fig. *12* shows a snapshot of a potential cable jointing AI-analyzed photo. In this example, the AI algorithm detected a defect in the semiconductor (semicon or insulation screen) layer transition and would reject this joint. The jointer would be required to start over and not put this part of the cable in service. The other aspects of this cable is approved and determined to be of high quality. By minimizing failures, the electrical safety at the site should improve due to a reduced risk of failures due to poor quality.

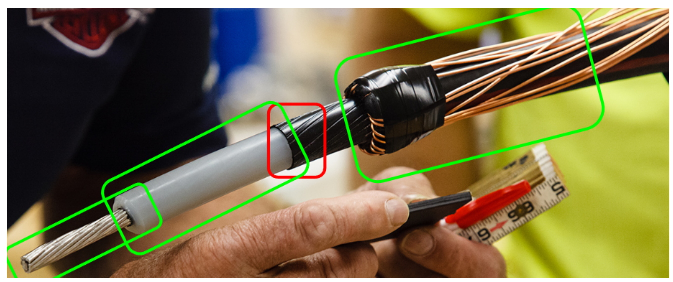

Fig. 12: Example of AI analyzed cable termination and defect identification. Note this image was generated by AI.

D. Control Wiring Factory Quality Verification

AI could be trained to detect improperly terminated control wires. Fig. *13* and Fig. *14* demonstrate potential AI analyzed photographs related to control cable wiring quality and acceptance. Fig. *13* shows a "wire stinger" at one of the control cable wire terminations as the wire enters the terminal block. Note this stray strand does not get terminated and is outside the terminal block hole and its plane. The other cables were approved and determined to be an adequate installation.

While unlikely, it's possible for that stray strand ("stinger") to contact a nearby metallic component, creating a short-circuit that could result in incorrect control signals and maloperations. At higher voltages this type of wiring defect could result in an arc flash.

With AI analyzing these installations, the need to perform a "pull" test on the wires can be removed. Pull tests potentially result in establishing a bad connection depending on the force used during pulling. It is difficult to consistently pull at the correct force per the manufacturer's instruction; also, it is common for the inspector to pull the wire with excessive force, potentially damaging the wire or inadvertently disturbing the connection. A photograph can analyze the entire panel and verify each wire is properly connected based on the depth of the termination, the insulation gaps, and any observance of improper terminations, such as stray strands. Wire labels can also be verified via photographs and cross referenced to drawings to further verify that each wire with the label is terminated at the correct terminal block location. Again, this greatly improves the equipment quality and further reduces the testing required from the factory to the site.

Fig. *14* shows AI verifying the type of wire is correct based on the cables' factory-printed labeling, the wire routing is correct and properly secured, and that each of the wires are properly terminated to the terminal block in the correct locations.

Fig. 13: Example of AI analyzed auxiliary terminations. Green is approved and Red is identified as a defect.

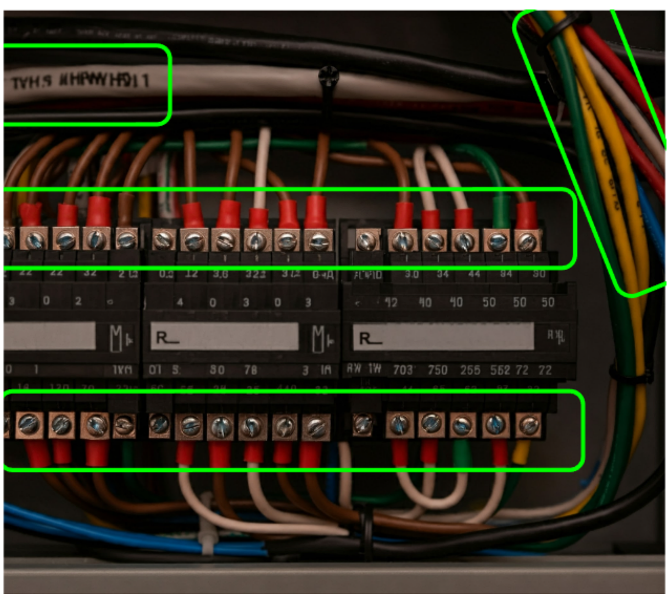

Fig. 14: Example of AI analyzed auxiliary control terminations in a terminal block. Green is approved and no defects were found. Note this image was generated by AI.

E. Bolt Torque Verification

The correct torquing of installations is an essential safety element. AI can be trained on bolt torque verification on busbars, terminations, busway joints, etc. Proper bolt torquing or lack thereof is a constant plague in the electrical industry. Improper torquing can result in poor connections, leading to a high resistance connection (HRC) that reduces the expected equipment life due to elevated temperatures [11]. If the HRC gets worse, thermal events can occur that will impact equipment reliability.

On the other spectrum, if bolt torque is excessive and above the manufacturer's recommendation, bolts can crack or break, resulting in zero compressive force due to bolts and relying solely on the mechanical structure to provide compression (if any). Again, the worst-case result of a broken bolt (or multiple bolts) is an open circuit or arcing to continue current flow which can develop into an arc flash or other thermal event.

The use of AI when verifying bolt torque can be achieved by photographing the bolts and having the algorithm count the threads showing the length of the bolt protruding through the connection and verifying there is a compression washer and the appropriate nut. AI can automatically check each of these items via photographs based on their database of acceptable and failing images. Fig. *15* shows an AI bolt checking example that has passed two bolt torque checks but also failed two. Notice this can be performed at the factory prior to shipment to site, at the integrator (if one is used) or during commissioning or onsite maintenance after work has been completed. The AI check can be set to prevent work order closeout if these photographs and approvals are not uploaded. The program can also not provide authorization to reenergize without final approval, minimizing poor or inadequate installations and preventing a future failure.

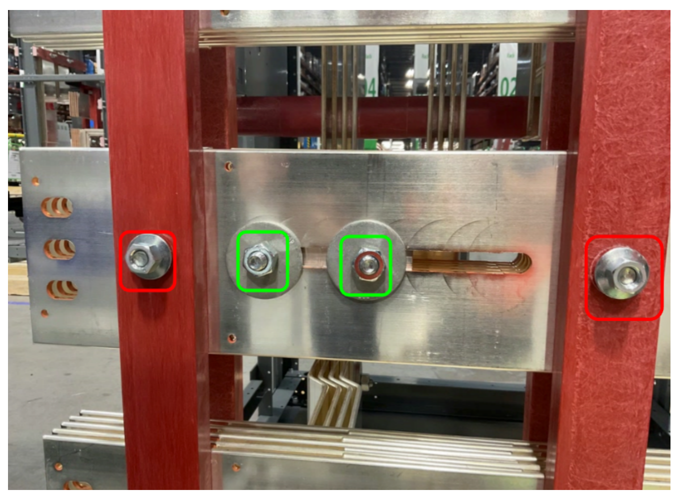

Fig. 15: Example of AI analyzed bolt torque. Green is approved and Red is identified as a defect.

VI. FUTURE WORK

Future work includes refining algorithms and developing AI capabilities in commercial grade applications. These applications will require a large database of good and bad examples to refine assessments of various types of equipment.

Pilot installations for several industries will be required to ensure the AI algorithms are fine-tuned and accurate. Sharing installation photos and data will need to be navigated carefully to avoid any confidentiality concerns and data leakage, but these concerns can be overcome. Manufacturers and consultants are key players in providing AI training until generative AI outputs become stable.

VII. CONCLUSIONS

If properly applied and developed, the benefits to utilizing AI in electrical safe work practices outweigh any potential negatives - especially once the algorithms are trained, vetted, and periodically tested for safety. AI at first will require humans to help it determine whether the input data is “acceptable” or “rejected” but over time, this process will become refined as the algorithm learns acceptable and unacceptable data autonomously. Deep learning can be used to identify trends and solutions that humans have not considered as yet. Humans must trial such learnings before permitting an AI to function autonomously. Various applications have been presented in key areas of electrical safety that include construction, maintenance, and safety management systems that can reduce electrical worker injuries while advancing electrical safety. Many of these applications are presently being developed and piloted in several facilities.

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IX. VITAE

Jay Prigmore (**SM’17 M’07**) received his bachelor’s degree in electrical engineering from Lamar University. He received his M.S. and Ph.D. degrees from Arizona State University.

He is presently employed at Google as an Electrical Quality Engineer - Senior Technical Program Manager. He has given IEEE invited lectures on arc flash mitigation techniques. He developed a peer-reviewed arc flash mitigation device which won “product of the year” in electrical safety. He was previously employed at G&W Electric Company where he was responsible for short-circuit protection devices, their manufacture and applications. Jay has testified over 15 times in both U.S. litigation and international arbitration courts related to incident investigations.

He is a founding member of NFPA 78 and 1078 which provide guidance on performing electrical inspections and the qualifications of electrical inspectors, respectively. Dr. Prigmore has authored prior ESW papers and published IEEE articles on solid state circuit breakers and incident energy reduction techniques. Dr. Prigmore presently holds twelve professional engineering licenses and was the 2024 IEEE Electrical Safety Workshop Chair.

Zarheer Jooma (**SM’17, M’16**) is a professional engineer and partner at e-Hazard. He holds a master’s degree (cum-laude) in electrical engineering, has convened and chaired arc flash and other electrical safety standards, and is a member of both ASTM F18 and IEC TC-78. Zarheer performs electrical network design, arc flash studies, electrical safety training, incident investigations, and auditing. He has published several peer-reviewed papers on Electrical Safety, spoken at numerous conferences both locally and internationally, contributed to wording on the NFPA70E standard, and is actively engaged as a subject matter expert on the IEEE1584 suite of standards. He is the technical paper review chair for two of the IEEE journals and chair for the IEEE Electrical Safety Workshop 2025.

Induced Energy on Communication Cable

Paper No. ESW2025-31

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Abstract – A 500kV transmission line failure caused a 20kA ground-fault, which induced voltage onto a buried communication line. As a result, equipment damage occurred two miles away from the initial ground-fault.

Index Terms — High Voltage, utility ground-fault, communications, short-circuit current, equipment damage.

I. INTRODUCTION

The Hanford Site, a sprawling complex measuring approximately half the size of the state of Rhode Island, is one of the largest environmental cleanup sites in the United States. Located in Southeastern Washington State, this site plays a crucial role in efforts to manage and remediate legacy waste from past nuclear production activities. The site's expanse covers 580 square miles, encompassing a diverse array of facilities and infrastructure that support its operations. The Hanford site employs approximately 13,000 workers, maintains and provides utility services to over 800 buildings, and is home to hundreds of miles of outside plant telecommunications and electrical cable infrastructure.

Positioned on the southern portion of the 580-square-mile site is the Pacific Northwest's only commercial nuclear energy facility. This boiling water reactor produces millions of megawatt hours of energy annually for consumption by nearly 1.5 million local and regional customers through a network of overhead high-voltage electrical lines.

II. DESCRIPTION OF EVENT

The Hanford Information Management (IM) Network Operations Center received alerts indicating that telecommunications equipment within two facilities on the Hanford Site had become unreachable. Recognizing the potential severity of the situation, IM organizational senior leadership was promptly informed, and a team of support staff was dispatched to the affected area to conduct troubleshooting and repair efforts.

Upon arrival, the support staff engaged with building occupants to gather firsthand accounts of the incident. Occupants reported experiencing what they described as a power surge on the incoming telecommunication lines. This surge resulted in significant damage to interior equipment, rendering it inoperable. Although there was no fire, the extent of the damage was substantial enough to warrant the dispatch of the Hanford Fire Department. Their presence was necessary to ensure the safety of the facility and its occupants, as well as to prevent any potential escalation of the situation.

Information technology personnel conducted a thorough investigation to identify the root cause of the equipment failure. This investigation involved collaboration with the electrical utility responsible for the power infrastructure in the area. Through discussions and analysis, it was determined that the incident was triggered by a ground fault on a 500kVAC overhead transmission line. This line intersected the underground communications cable that fed the affected facilities, approximately two miles away.

The utility company confirmed that a failure had occurred on the 500kV line at the same time the issues were reported at the Hanford facilities. During the event, the utility recorded a substantial fault current of 20kA flowing to the ground. Further investigation revealed that the cause of the fault was bird excretions, commonly referred to as "streamers." These streamers can create conductive paths across insulators, leading to flashovers and subsequent ground faults.

The incident underscored the vulnerability of the communication infrastructure to external electrical disturbances, particularly those originating from high-voltage power lines. It also highlighted the need for improved coordination and communication between the utility and the facilities to ensure rapid identification and resolution of such issues. The findings from this event have informed subsequent corrective actions and preventive measures to enhance the resilience of the site's telecommunications systems.

III. ANALYSIS

The incident at the Hanford Site revealed a significant, yet previously unrecognized, potential hazard associated with the intersection of high-voltage overhead power lines and other transmission distribution system cabling, such as telecommunication lines. This hazard is particularly pronounced in scenarios where a ground fault occurs on a high-voltage system, as it can lead to the induction of voltage onto nearby transmission cabling systems. This induced voltage can propagate into personnel-occupied facilities, posing risks of personal injury and property damage. The following factors contributed to this hazard:

- Telecommunication protectors were not properly bonded to a common ground within the facilities. Telecommunication protectors are designed to shield sensitive equipment from voltage surges by providing a

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path to ground. However, if these protectors are not adequately bonded to a common ground, their effectiveness is significantly diminished. This inadequate bonding can result in elevated voltages being transmitted to equipment, increasing the risk of damage and potential safety hazards for personnel.

- The grounding of telecommunication outside plant cabling was found to be insufficient, as it relied solely on the pedestal enclosure without any supplemental grounding measures, such as ground rods. Ground rods provide a low-resistance path to earth, which is essential for dissipating induced voltages safely. The absence of such supplemental grounding means that any induced voltage from nearby high-voltage lines can remain within the system, leading to potential overvoltage conditions that can damage equipment and pose safety risks.
- A significant factor contributing to the hazard was the lack of awareness regarding the potential for induced voltages in the vicinity of high-voltage power lines. This lack of awareness extended to both the utility providers and the facility management teams, resulting in a gap in preparedness and preventive measures. Without a clear understanding of the risks, there was no driver to implement necessary safeguards or to develop response protocols to address such incidents effectively.

The implications of this unrecognized hazard are far-reaching. Induced voltages can lead to:

- Personal Injury: Elevated voltages in facilities can result in electric shocks or other injuries to personnel, particularly if they come into contact with affected equipment.
- Property Damage: Sensitive electronic equipment is particularly vulnerable to overvoltage conditions, which can lead to significant damage, costly repairs, and operational downtime.
- Operational Disruptions: The failure of communication systems can disrupt critical operations where reliable communication is essential for safety and coordination.

IV. CORRECTIVE ACTIONS AND RECOMMENDATIONS

To address the vulnerabilities identified in the incident and to reduce the likelihood of future occurrences, a series of corrective actions and recommendations have been developed. These measures focus on improving the design, installation, and management of telecommunication and electrical infrastructure at the Hanford Site, to enhance the safety and reliability of the telecommunication and electrical infrastructure.

Comprehensive Grounding and Bonding: A critical step in mitigating the risk of induced voltages is to ensure that all telecommunication protectors and cabling are properly bonded to a common ground. This involves:

1. Standardizing Grounding Practices: Establishing standardized procedures for grounding telecommunication systems across all facilities.
2. Supplemental Grounding Measures: Implementing additional grounding measures, such as the installation of ground rods, to provide redundancy and enhance the overall effectiveness of the grounding system.
3. Regular Inspections and Maintenance: Conducting regular inspections and maintenance of grounding systems to ensure their integrity and performance over time.

Infrastructure Assessment: a thorough assessment of the existing infrastructure is essential to identify and rectify potential vulnerabilities. This involves:

1. Comprehensive Site Surveys: Conducting detailed surveys of all telecommunication and electrical infrastructure to assess their current condition and identify areas of concern. This includes evaluating the proximity of high-voltage lines to communication cables and assessing the adequacy of existing grounding systems.
2. Risk Analysis and Mitigation Planning: Performing risk analyses to understand the potential impact of identified vulnerabilities and developing mitigation plans to address them. This may involve rerouting cables, enhancing shielding, or implementing additional protective measures.

Awareness and Training Programs: implement training programs to raise awareness among utility and facility personnel about the risks of induced voltages and the importance of proper grounding and bonding practices.

Design and Installation Improvement: The incident highlighted several failures in the design and installation of the telecommunication infrastructure that contributed to the event. Addressing these failures involves:

1. Design Review and Improvement: Conducting a thorough review of the design specifications for telecommunication systems to identify and rectify any deficiencies. This includes ensuring that all systems are designed with adequate grounding and shielding.
2. Installation Best Practices: Implementing best practices for the installation of telecommunication and electrical systems, including proper routing and separation of cables to minimize the risk of induced voltages.
3. Establishing control processes to ensure that all installations meet the required standards and specifications.

V. VITA

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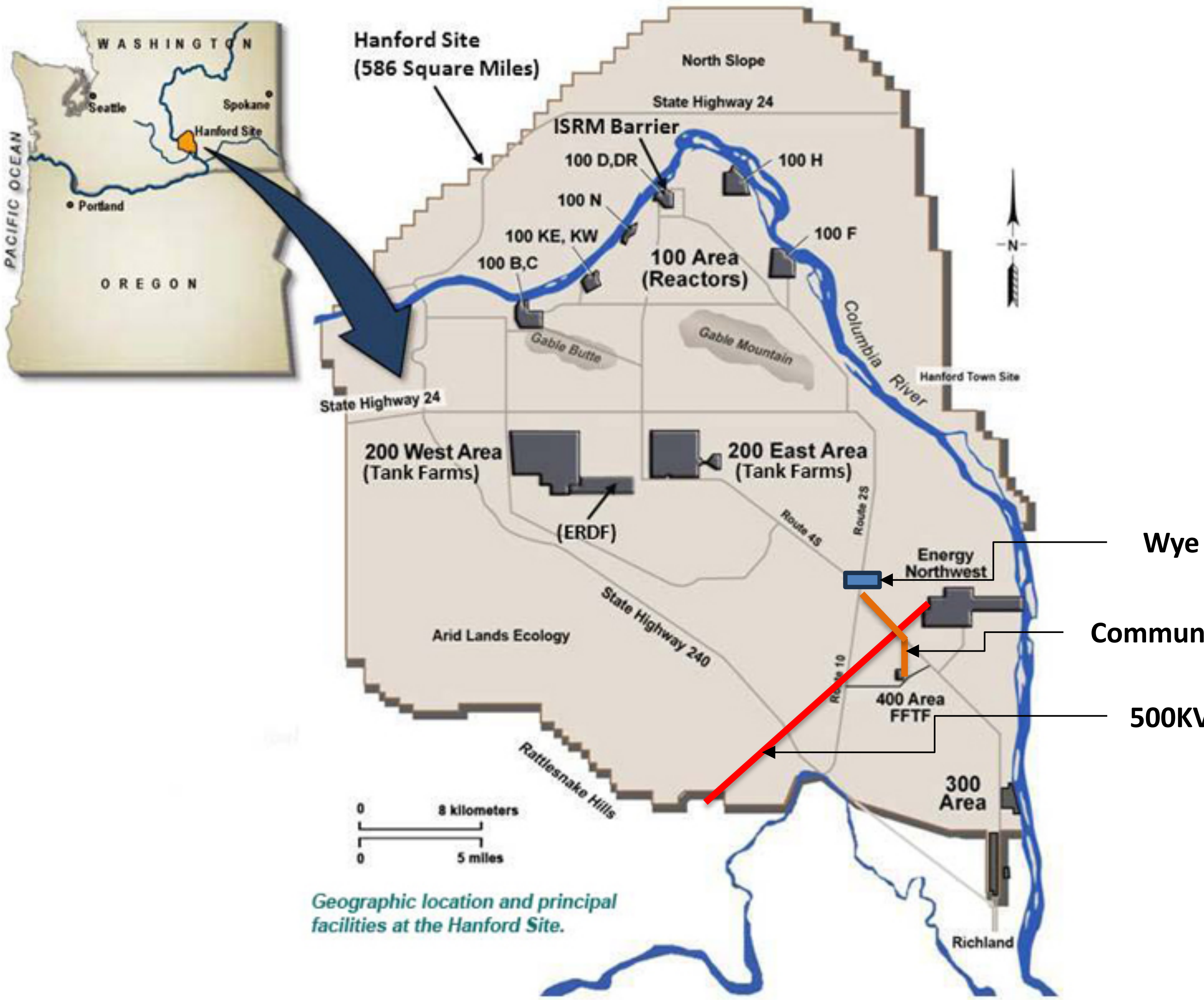
Appendix A: Site Map



Geographic location and principal facilities at the Hanford Site.

Practical Application of the Energized Electrical Work Permit Process

Paper No. ESW2025-32

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Abstract – The Energized Electrical Work Permit (EEWP) process was a significant revision to NFPA 70E and has served as a valuable tool in preventing or minimizing hazards exposure and injuries, and in eliminating jobs that cannot be justified as needing to be done while the circuit is energized. Since its introduction, its application has varied site to site and company to company. Some are very effective, and some are not. This paper intends to provide insight, from the submitter of the proposal for its introduction into 70E, on what the EEWP is and where it came from, the original intent and objectives, benefits, simplified guidance on its application, things that make it most and least effective, and ways to incorporate it into your electrical safety program to get the most benefit.

Index Terms —Energized Electrical Work Permit Process, Energized Electrical Work Permit Form, Energized Work, Energized Work Justification

I. INTRODUCTION

There are several work activities that are subject to permitting processes that have been around for some time and are well established. The permitting process for each is intended to identify the hazards, assess the risk to personnel and employ appropriate control methods to prevent exposure and injury. Examples include Confined Space Entry, Line Breaking, Hot Work (ignition sources created) and Excavation.

With each, there are some activities where the permit is not required. For example, a low-pressure water line to a sink in the kitchen would not require a line breaking permit because the hazards and risks are low enough that it is acceptable to be done without one. There would be no improvement in the level of safety by going through the permitting process. Your office is a confined space, but it is designed for human occupancy with very low hazards and risks, therefore that confined space would not require a permit to enter. A confined space containing a hazardous material, acid for example, would not be designed for human occupancy and would carry high hazards and risks. A permit would be required to enter that space.

In 1998, a large chemical company recognized the need to develop and apply a similar work permitting process to electrical jobs having high hazards and risks. An EEWP process and permit form was developed for energized electrical work and written into their Electrical Safety Program policies. It was expected that a significant benefit would be realized in the exposure and protection afforded the electricians. It was also expected that with the additional, formal review and approval required that jobs previously performed energized would be done at a later time when de-energized, or not at all. Either way, the level of safety and the hazards exposure, and risk to electricians would be reduced or eliminated. Both expectations were realized. And, as with the other work permitting processes, there were exceptions to requiring an EEWP. Those exceptions were based on the level of hazards and risks of exposure and injury, and if any additional level of safety would be realized by going through the EEWP process compared to not.

Soon after, two proposals were submitted to NFPA to revise the then upcoming 2004 edition of NFPA 70E, one for the EEWP process and one for the EEWP form. With some revision from the original submission and help from members of the committee, both were accepted and became a new requirement.

The Energized Electrical Work Permit (EEWP) process was a significant revision to NFPA 70E and has served as a valuable tool in preventing or minimizing hazards exposure and injuries, and in eliminating jobs that cannot be justified as needing to be done while the circuit is energized.

This paper is offered to provide guidance on what the author believes is the most practical way to apply an EEWP process and as a result, realize the most benefit.

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II. WHAT IS AN ENERGIZED ELECTRICAL WORK PERMIT PROCESS?

Similar to other work activities that require a permitting process, the EEWP is a systematic procedure that describes the process to follow in order to protect individuals performing work that exposes them to electrical hazards. Its intent is both to ensure individuals performing energized electrical work are protected and, more significantly and by far the greater benefit, eliminating jobs that cannot be justified as needing to be done while the circuit is energized. It also describes the type of work that would not require an EEWP.

III. THE ORIGINAL EEWP PROCESS AND FORM

The EEWP process was introduced using two proposals to modify the 2004 edition of NFPA 70E.

The first proposal was a description of the process itself to be added to the body of the standard as mandatory text. It described when the EEWP process would apply and the exceptions to requiring a permit to perform energized work. It contained four parts.

1) The first part was to be completed by the person requesting the work to be done while energized, providing a detailed description of the work and the reasons why it cannot be done de-energized. Many times, it is decided that the energized work cannot be justified and the EEWP process stops at this point.
2) The second part was a listing of steps to conduct a formal risk assessment of the work. This risk assessment was to be done by the people performing the work. It covered the arc flash and shock hazards, protective clothing and equipment needed, the safe approach boundaries, considerations for unqualified persons, the training and preparation needed and finally a concurrence by them that they believe the work can be done safely. If the individuals doing the job did not agree that the work can be done safely, the permit would be returned to the requester for further evaluation and justification.
3) The third part was a listing of appropriate members of management that were required to review and sign the form approving the work to be done energized. This section would require approval from the senior management and represented a third opportunity to eliminate the energized work if those individuals were not willing to authorize putting individuals at risk when an alternative exists or can be determined.
4) The fourth part was exceptions to the EEWP requirement providing a description of the types of jobs that did not require an EEWP to be performed while energized. Those included testing, troubleshooting, voltage measuring, etc. that require the circuit to be live to perform such work. It also required that those performing such work be qualified using appropriate safe work practices and PPE.

The second proposal was an example EEWP form to be added to Annex J that would be available as a non-mandatory but one that would be acceptable for use. It followed the same steps as the EEWP process description and served as documentation of those steps, but did not include the discussion on exceptions.

The original EEWP process viewed high hazard and risk jobs as being those needing a permit. This would either force a formal risk assessment and help ensure a good outcome or would determine the work cannot be done safely while energized and the job eliminated from being done while energized. With that, exposure to people is eliminated, serving as the more significant benefit of the process.

IV. NFPA 70E REVISIONS SINCE INTRODUCED

While revisions have been made to the EEWP process in subsequent revisions to NFPA 70E, the original intent and process remains largely the same.

Text was added to require a EEWP when work is being done within the restricted approach boundary, adding an element of where the individual is when work is performed.

Text was also added to require an EEWP where the energized conductors are not exposed, but an increased likelihood of injury from exposure to an arc flash hazard exists. This recognizes that a person can be exposed to arc flash hazards even when there are no exposed conductors, and the equipment is fully enclosed. This concept was added to several other sections of 70E to recognize this and protect people.

Formal electric shock and arc flash risk assessment processes were added to other sections of 70E. These processes were used to replace most of the risk assessment steps in the second part of the EEWP process and form, to be more complete and consistent with the balance of the document. Evidence of a completed job briefing was also added to this part.

Revisions have been made to the EEWP exemptions section that keep testing, troubleshooting, or voltage measuring but added three other items. 1) thermography, ultrasound or visual inspection, 2) access to or egress from an energized equipment area if no work is to be done, and 3) general housekeeping and other non-electrical tasks, all three with the requirement that the restricted approach boundary not be crossed. As written, this would require an EEWP for the three situations listed if the restricted approach boundary is crossed but would not for testing, troubleshooting, or voltage measurement.

Revisions have also been made to the EEWP form to mirror those in the EEWP process described here. And it still does not contain any information related to EEWP exemptions.

V. DECIDE WHICH JOBS REQUIRE A PERMIT

Which jobs require an EEWP, and which do not should be determined by the site and should depend on the level of hazards and risk of injury to personnel.

Several factors are involved, and that determination will vary from company to company and from site to site within the same company. But regardless of the decision on which jobs require a permit and which do not, those making the decision remain responsible for those decisions and the outcomes of any work at the site, permit or not. Also, none of the determinations would prohibit requiring a permit should a situation arise that warrants one, even for those previously exempt.

One determining factor is the knowledge, skills, experience and level of expertise of those who will be performing the energized work. Larger sites with highly trained and skilled individuals, having experience with higher hazard and risk tasks may determine that jobs that would require a permit at sites with lower levels of training and experience, would not at their site.

Another factor is the type of work to be done and the associated hazards and risks. 70E recognizes two types of "energized electrical work", 1) testing and troubleshooting, and 2) maintenance, parts replacement, circuit modification type work. Since the maintenance, parts replacement, circuit modification work carries a much higher level of hazard and risk, in general, this work would require an EEWP. Also, this is the type of work that should be eliminated from being done while energized, as not being justified during the EEWP process. Testing and troubleshooting work, as indicated in the exemptions to the permit requirement, have a much lower level of hazard and risk and generally would not require a permit.

Realizing that no job done energized is without risk, another factor is the "risk tolerance" at the site. Even the testing and troubleshooting jobs done energized have some level of hazard and risk. In general, it is normally determined that even though the risk is not zero, for these jobs it is low enough to be acceptable and the jobs done without a permit. This risk tolerance normally will be higher at the larger, more highly skilled sites and lower at the smaller, less skilled sites.

In all cases, permit or not, those performing the work while energized must be qualified to do so and use proper safe work practices and appropriate personal and other electrical protective equipment.

VI. ENERGIZED ELECTRICAL WORK JUSTIFICATION

NFPA 70E requires electrical circuits having electrical hazards be put into an electrically safe work condition unless de-energizing is infeasible due to equipment design or operational limitations or introduces additional hazards or increased risk. These condition descriptions are broad, open to interpretation, and sometimes not applied to realize the greatest benefit.

The justification for energized work, and for exposing individuals to electrical hazards should be closely scrutinized and highly challenged. Convenience or avoiding cost or production loss are not acceptable justifications. The only true justification is when there is not other option. The justification process for energized work should be made so difficult that people do everything they can to avoid performing the work while energized. Only then will the jobs that are truly justified be identified.

There is a misconception that once you go through the process of getting a fully approved EEWP, people are protected and energized work can be done safely, and you can rest assured that no one will get hurt. As long as the conductors are energized, there is risk of injury from electrical hazards. Going through the EEWP process may drive the risk to a very low level but, if the work is done energized, it is never zero. The only way to completely eliminate the risk of injury from electrical hazards is to perform the work deenergized by creating an electrically safe work condition. Unless energized work is truly justified, there is no acceptable reason for putting someone at risk, even if the risk is very low.

One important element of the justification of energized work is the management approval process. The description of the work to be done and the perceived justification should be reviewed and require approval from senior levels of management. The higher the level of required management review and approval, the more valid the justification process will be. If the EEWP process requires approvals from top levels of management, such as Senior Director, Vice President or President, those requesting the EEWP will be very cautious on seeking approval for an EEWP that may not be totally justified, and most of the time will find some alternative to allowing energized electrical work to be done. The higher the level of management review and approval, the more energized electrical work will be eliminated. If energized work is truly justified, it can be justified to anyone, including the President at 2:00 AM on Saturday morning. If the justification is not that clear, the work should not be allowed to be done while energized.

If someone is allowed to be put at risk and that person is injured, what would the justification be? If someone asks why the injured person was allowed to be put at risk for a job not fully justified, you will not have an acceptable answer.

VII. ENERGIZED WORK IS SOMETIMES UNAVOIDABLE

While every effort should be made to perform work on electrical equipment while de-energized, it is recognized that energized electrical work is sometimes unavoidable. For most sites, these cases should be rare and considered the exception and not the rule.

Whether or not energized work is unavoidable would also depend on the type of facility, electrical equipment, and work to be done. Some examples include battery banks, solar cells systems, wind turbines, UPS systems, capacitors and electric vehicles. Testing and troubleshooting activities may require the circuit to be energized. And conductors are always treated as energized until proven otherwise when performing absence of voltage testing for the purpose of establishing an electrically safe work condition.

Because of the unique hazards and the fact that most work on these has to be done while energized, special precautions and control methods must be used to protect people from injury. These would include equipment and hazards specific training, personal and other protective equipment and tools, unique and specialized work practices and procedures and demonstration of learned skills. Only those with the specialized skills should be allowed to work on these systems.

VIII. CONCLUSIONS

The Energized Electrical Work Permit (EEWP) Process was a significant revision to NFPA 70E and has served as a valuable tool in preventing or minimizing hazards exposure and injuries, and in eliminating jobs that cannot be justified as needing to be done while the circuit is energized. When applied correctly, the process significantly reduces exposure to electrical hazards and risk to personnel. When it is not, it becomes nothing more than a check in the box and the real benefit of the process is lost. This paper provides guidance on how to implement the process for the most benefit. By doing so, the risk of exposure and injury are significantly reduced or eliminated, and those jobs that cannot be justified to be done energized simply go away. If the energized electrical work is justified, the EEWP process forces a formal and thorough risk assessment, identifying the hazards, likelihood of injury to personnel and proper control methods to be used to protect individuals. Either way, when this process is used properly, the people involved will be protected.

IX. WHAT YOU SHOULD DO

1) If you don’t already have one, implement an Energized Electrical Work Permit Process.

2) Decide what jobs are subject to a permit and which are exempt.

3) Avoid implementing an EEWP process that routinely issues permits for jobs that don’t have to be done energized and are not completely justified. If EEWP’s are common and routine, it becomes a “check the box” activity severely diluting the significance of the process.

4) Scrutinize and challenge the justification for each job being planned to be done while the circuit is energized.

5) Require the highest levels of Senior Management for review and approvals.

6) Educate the highest levels of Senior Management on the potential consequences that could result, including injury severity, damage to critical electrical infrastructure, and extent and duration of disruption to operations.

7) Make the process so difficult that people do everything they can to avoid doing energized work.

8) Recognize that there are some cases where energized work cannot be avoided and provide proper protection for individuals.

X. ACKNOWLEDGEMENTS

I would like to recognize and thank Michael Callanan who was the IBEW representative on the 70E Committee at the time this was introduced. His input and guidance on helping determine the final version of the process description and permit form was key to getting committee approval for the concept.

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NFPA 70E-2024, *Electrical Safety in the Workplace*

XII. VITA

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A Comparison Of Fabric Arc Ratings And The Performance Of Arc Rated Clothing Exposed To Arc Flashes Generated Using Ac And Dc Energy Sources

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Abstract – The predominance of DC energy sources (e.g. electric vehicles, photovoltaic power generation, uninterruptable power systems, etc.) is growing rapidly throughout the world. As such, workers in a variety of industries are being faced with a growing risk of exposure to arc flashes generated from these DC sources. However, all Standard Test Methods for determining arc ratings of products are based solely on AC energy, leaving a large unknown in the protective properties of all types of arc-rated clothing. In this paper, the arc ratings of various fabrics are identified and compared using both traditional AC open air arc rating methodologies and novel DC testing methodologies. Further, various commercially available arc rated garments were exposed to both AC and DC arcs to study the differences of full garment response to the two types of arcs. With a clearer understanding of the different reaction and protective performance values, best practices and updates to various international standards are proposed to ensure worker safety when dealing with the rapidly growing risk of arc flashes from DC energy sources. The arcs used in this study were open air, vertical electrode arcs. Other arcing techniques including box arc, ejected arc, and other electrode configurations were not employed in this study.

Index Terms — Arc Flash, Arc Rating, AC Energy, DC Energy, DC Arc Flash, ATPV, Arc Rated, ASTM F1959, IEC 61482.

I. INTRODUCTION

Protective clothing for electrical workers has been subject to standardized testing to determine its arc rating for twenty-five years, since the first edition of ASTM F1959 was published in 1999 [1]. Several subsequent revisions to that standard, along with the release of its European counterpart, IEC 61482-1-1 [2], have all been based in the same theoretical approach to arc ratings. Likewise, Standards for evaluation of various other types of arc rated PPE (e.g. Gloves, Face Protection, Fall Protection, and full garment evaluations) have all been based in the same theoretical approach to arc ratings. That approach has been to expose products, or the materials of their construction, to an electric arc generated using an AC power source.

Many entities rely heavily on accurate Arc Ratings in PPE for a variety of reasons. Fabric and Garment Manufacturers rely on accurate Arc Ratings to properly label their products. Those product labels convey critical information about protective properties of the fabric or garment and are imperative for product liability. Employers rely on accurate Arc Ratings to ensure that they are complying with relevant local, state, and federal requirements for providing their employees with proper PPE to match the incident energy for their equipment [3]. And, perhaps most importantly, end-users, the wearers of Arc Rated (AR) clothing, rely intimately on the accuracy of the Arc Rating on their

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garment label to ensure they return home safely after each day on the job.

With so many entities relying on the accuracy of the arc rating in a product label, it is imperative that the labeled arc rating represent the true protective properties of the garment. Today, every arc rating listed on an Arc Rated PPE label, worldwide, was established using AC energy. That leaves PPE manufacturers, employers, and end users uninformed about protection if exposed to DC arcs. This study aims to explore any differences between arc ratings generated using standard AC sources to those generated using DC sources. This first phase study only aims to explore and report any differences found. The intent is to educate both PPE manufacturers and end users about similarities or differences in order to increase awareness about protective properties of arc rated PPE when there is a potential for exposure to DC arc flash hazards.

II. SHIFT FROM AC TO DC

The shift from alternating current (AC) to direct current (DC) energy reflects a broader transformation in how we generate, distribute, and consume electricity. The shift is driven by both technological advancements and energy needs. Historically, AC has been the dominant form of electricity for power distribution due to its ability to travel long distances efficiently, facilitated by transformers that can easily step voltage levels up or down. However, the rise of renewable energy sources, particularly solar power, has highlighted the advantages of DC [4]. Solar panels generate electricity in DC form and converting it to AC for grid use introduces inefficiencies and energy losses.

Moreover, the increasing prevalence of energy storage systems, like batteries, which inherently operate on DC, further supports the case for a transition to more widespread use of DC power sources. As electric vehicles (EVs) gain popularity, their reliance on DC for charging and operation underscores a growing demand for DC infrastructure. Innovations in DC technology, including the development of DC microgrids, promise to enhance energy efficiencies, reduce transmission losses, and simplify the integration of various renewable energy sources [4]. The push for a cleaner, more efficient landscape has sparked interest in reevaluating our current power distribution frameworks, highlighting the potential for DC to play a crucial role in a sustainable energy future [5].

III. MATERIALS AND METHODS

Five different woven arc rated fabrics were selected for study and genericized as Fabric A through Fabric E for identification purposes. Fabrics A and B are comprised of a multi-fiber flame-resistant blend. Fabrics C and D are FR-treated cotton or cotton-rich fabrics; and Fabric E is a tri-laminate fabric, as shown in Table I. All selected fabrics were Navy in color.

These fabrics were deliberately selected based on overall market significance, while still providing a range of fiber content and construction. Fabrics were selected based on an anticipated arc rating of at least 8 calories. Fabric E was specifically selected to provide a single-layer fabric option with significantly higher arc ratings. In previous (unpublished) work by the authors, where subtle differences were found at the lower arc ratings, those differences were exacerbated in fabrics with higher arc ratings.

All samples of each fabric were taken from a single roll, so as to eliminate roll-to-roll or lot-to-lot variation as a factor in the study.

TABLE I

Products Selected for Testing

Sample ID	Composition	Nominal Weight (oz/yd^2)	Fabric Construction
Fabric A	Multi-Fiber FR blend	5.3	Twill
Fabric B	Multi-Fiber FR blend	6.1	Ripstop
Fabric C	Cotton/Nylon Blend	7.0	Twill
Fabric D	Cotton	9.0	Twill
Fabric E	Polyester/ePTFE	9.0	Trilaminate

AC arc testing was carried out precisely as prescribed in ASTM F1959/F1959M-24b. DC arc testing was carried out in a similar fashion, using ASTM F1959 apparatus, but modified to include a DC energy source. All specimens were tested in a single layer.

The Standard test method for determining the arc thermal protective rating of a fabric system requires a test fixture and instrumented (calorimeters) panels. In such test, the AC power source (50 or 60Hz) is sufficiently high voltage (approx. 2 kV) with a series reactive impedance to provide a stable arcing current of 8000A RMS. Based on the panel distance of 305 mm from the arc, the resultant heat flux on the fabric is approximately 45 cal/cm²s.

For this project, the AC source was replaced with a DC source of equal capacity. This was achieved by using a standard diode three-phase (6 pulse) full-wave bridge rectifier. The use of a three-phase bridge rectifier provides a stable DC voltage and current with less than 5% ripple without additional filtering. The R_{limit} resistor was adjusted to provide nominal 8000A DC arcing current to maintain the same heat flux as with the AC circuit. A simplified circuit diagram is shown in Fig 1.

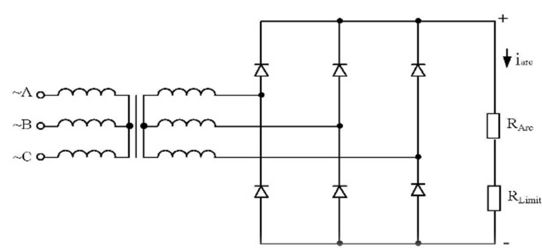

Fig 1: Three-phase full-wave rectifier

As prescribed in ASTM F1959 [1], all samples were washed three times and dried once using AATCC Laboratory Procedure

1, with wash procedure 3, temperature IV, drying procedure Aiii prior to cutting test specimens.

A variety of testing decisions were informed by knowledge of previously published variability in arc ratings [6]. To reduce the impact of variability on our conclusions, each fabric was tested six times – three times standard AC and three times experimental DC – for its arc rating. Testing was carried out over 6 consecutive testing dates in a manner such that no other testing was performed on the apparatus during the course of the study.

The six-day study was broken generally into three “DC days” and three “AC days”. The days were roughly alternated between AC and DC testing dates so that subtle trends in panel conditions or other environmental factors did not confound results for or against either AC or DC testing at the beginning or end of study. DC arc rating tests were carried out on days 1, 4, & 5 and AC arc rating tests were carried out on days 2, 3, & 6. There was a minor technical issue in the lab, unrelated to the study, which limited the number of tests carried out on Day 5. As such, only three of the five DC tests for Day-5 were completed that day. The remaining two tests were completed at the beginning of Test Day 6 before switching to AC to conclude the study.

Additionally, a limited set of commercially available arc-rated garments were exposed to DC arcs to compare the performance of other garment components beyond the fabric arc rating. These garments were placed on non-instrumented manikins, and evaluations were limited solely to qualitative visual assessments.

IV. RESULTS

The individual AC arc ratings and DC arc ratings of each fabric is shown in Table II. The average AC and DC ratings of each fabric is shown in Table III, along with a relative comparison between AC and DC arc ratings.

TABLE II

Individual Arc Ratings (AC and DC)

	AC Arc Ratings			DC Arc Ratings		
Sample ID	Rep 1	Rep 2	Rep 3	Rep 1	Rep 2	Rep 3
Fabric A	10.4	10.4	11.0	11.1	10.8	11.1
Fabric B	10.6	11.4	11.4	9.9	11.7	11.4
Fabric C	9.5	9.8	9.6	9.1	9.8	10.2
Fabric D	11.7	11.9	11.4	11.5	11.1	12.3
Fabric E	32.0	32.2	33.1	34.0	33.0	33.0

TABLE III

Average Arc Ratings (AC and DC), and Relative Comparison

Sample ID	AC Arc Rating	DC Arc Rating	Difference
Fabric A	10.6 (11)	11.0 (11)	+0.4 (0)
Fabric B	11.1 (11)	11.0 (11)	-0.1 (0)
Fabric C	9.6	9.7	+0.1
Fabric D	11.7 (12)	11.6 (12)	-0.1 (0)
Fabric E	32.4 (32)	33.3 (33)	+0.9 (+1)

Although all the results shown in Table III provide precision to the nearest 0.1 cal/cm^2 for comparison, the numbers in parentheses indicate the reported arc rating according to ASTM F1959, which requires results above 10 to be rounded to the nearest whole number. This comparison further solidifies the relative similarity of AC arc ratings to DC arc ratings, for this set of fabrics.

Fig 2 illustrates these values, and the relative difference between AC and DC arc ratings for all fabrics.

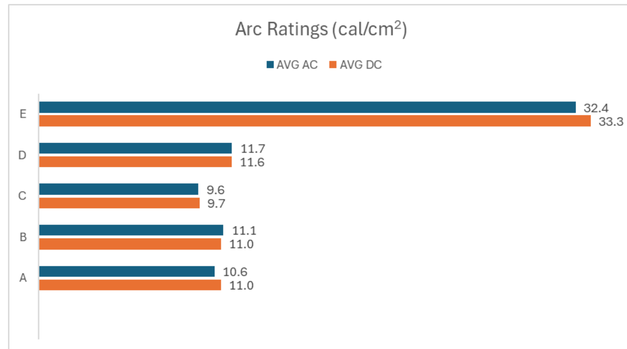

Fig 2. Average arc rating comparison of AC and DC for Fabrics A-E

Overall, the results show effectively no difference between AC and DC arc ratings for the fabrics studied.

The limited garment testing further supports the findings that arc ratings are unchanged when exposed to AC or DC energy sources. There was no notable difference in the qualitative observations made on garments or their components of construction (fabrics, seams/sewing thread, closures, trim and findings, etc.). Fig 3 shows a daily wear garment configuration before and after exposure to a DC arc flash. Response to the arc was identical to that experienced in a standard AC arc flash.


Fig 3. Example Arc-Rated daily wear before and after exposure to DC Arc Flash

V. DISCUSSION

The data very clearly suggests that there is no appreciable difference between arc ratings generated using AC energy and those generated using DC energy with this electrode configuration.

Previous studies have shown it to be very common to see double-digit percent variation in arc ratings over a series of months or years, and from lot-to-lot [6]. As such, it was important for this study to eliminate as many variables as possible, keeping all else equal when switching from AC to DC power supply.

Studying each fabric individually, we confirm that our efforts to reduce inherent variability were successful. There was no clear trend of an arc rating (either AC or DC) of a given increasing or decreasing consistently over successive testing dates.

When comparing the ASTM F1959 reported arc ratings (parenthetic data in Table III), it is most evident that the variation between AC and DC is well within the anticipated variation of the test. Three of the five test fabrics (Fabric A, Fabric B, and Fabric D) averaged exactly the same reported arc rating. These three fabrics show very good precision and indicate precisely no difference in arc ratings generated using AC and DC energy sources.

Fig. 4, Fig. 5, and Fig. 6 depict comparisons between AC and DC arc ratings for Fabric A, Fabric B, and Fabric D, respectively. They illustrate the precision of each type of arc rating for these fabrics and the lack of discernible difference between their average AC and DC arc rating.

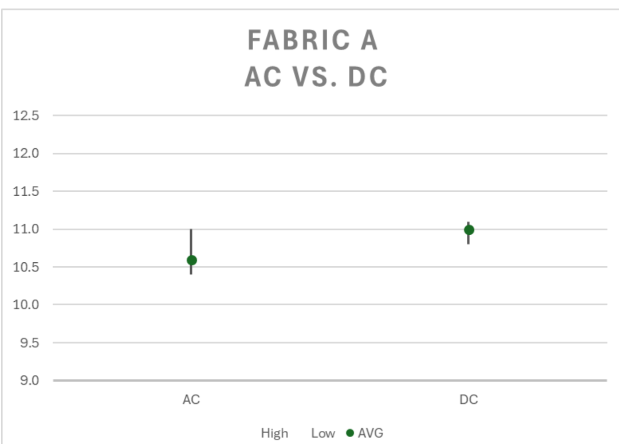

Fig. 4 Fabric A arc ratings, AC and DC, average and range

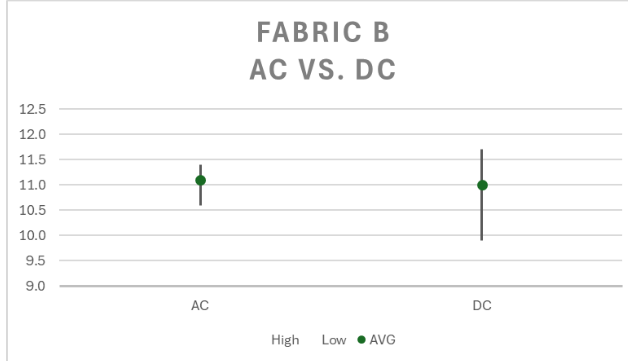

Fig 5. Fabric B arc ratings, AC and DC, average and range

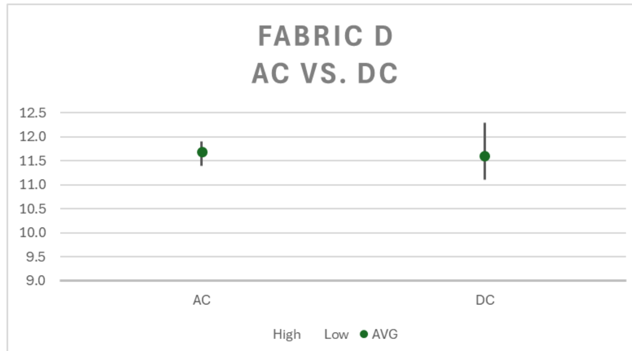

Fig. 6 Fabric D arc ratings, AC and DC, average and range

One of the five, and the only one reported with 0.1 cal/cm^2 precision because its value is below 10, (Fabric C) only showed a 0.1 cal/cm^2 difference. The comparison of AC to DC arc ratings for Fabric C is depicted in Fig. 7. At the relatively moderate arc rating of 9.6 or 9.7 cal/cm^2, a variation of 0.1 cal/cm^2 is well within the normal variation of the test and these results are considered effectively equal.

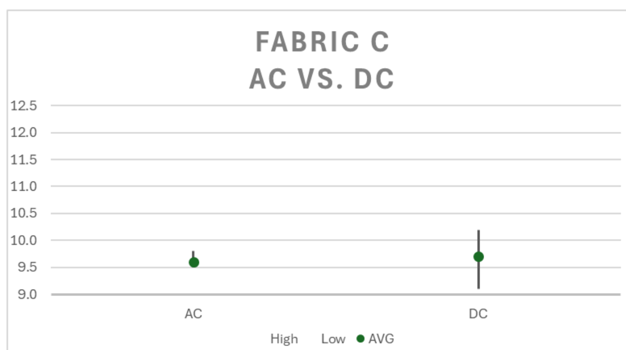

Fig. 7 Fabric C arc ratings, AC and DC, average and range

One of the five (Fabric D) showed a 1 cal/cm^2 difference. While the 1 cal/cm^2 difference is the largest absolute difference of the study, it was not the largest relative difference. The comparison of AC to DC arc ratings for Fabric E is depicted in Fig. 8. At the relatively higher arc rating of 32 or 33 cal/cm^2, such a variation is well within the normal variation of the test and these results are considered effectively equal.

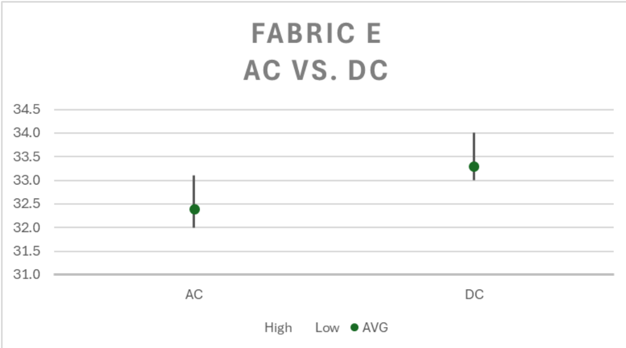

Fig. 8 Fabric E arc ratings, AC and DC, average and range

VI. CONCLUSIONS

Our research studied the relative arc ratings of fabrics when those ratings were determined using either AC energy or DC energy in order to shed light on an unknown area of mitigating risk with the use of arc rated clothing.

Results show that for single layer arc rated fabrics, at least the five fabrics evaluated in this study, there is no significant difference between arc ratings when exposed to AC arcs vs DC arcs. This is a rather encouraging start to what should become a more inclusive study but based on the initial findings, users of Arc Rated clothing can be reassured that the protection level cited in the garment label is representative of the expected performance in an arc exposure, regardless of the type of energy source, AC or DC.

While this testing was specifically carried out using ASTM F1959/F1959M-24B, the authors assume that resulting trends would mirror identically if calculated under IEC 61482-1-1.

Although repeating the multiple established variability studies conducted in the past was not an intended purpose of this study, our results also seem to indicate that arc ratings are no more or less variable when comparing ratings generated with AC versus DC arcs. In fact, the variation revealed by this study suggests that variability between arc ratings is markedly reduced when conducting multiple arc ratings on the same fabric in very rapid succession. Removing the variables associated with long spans of time (and presumably dozens of other tests) between two arc ratings on the same fabric appears to significantly reduce variation in arc ratings. This seems to indicate that much of the variability in arc ratings comes from non-fabric factors.

Based on the findings of this study, all stakeholders can be confident in the existing arc rating found on PPE labels, regardless of the energy source. Fabric makers and PPE manufacturers can confidently carry on labeling their products as tested according to ASTM F1959/F1959M or IEC 61482-1-1. Employers can feel confident in the protection they are providing their employees, assuming the PPE matches the arc flash hazard, regardless of whether that arc hazard is from an AC or DC energy source. And, most importantly, end-users can confidently wear arc rated clothing, knowing that the arc rating in the label applies to both AC and DC arc hazards.

VII. PATH FORWARD

While the results of this study are quite encouraging, it's important to understand that it was a very limited sample set. The authors recognize that the fabrics selected are all single-layer and all had ATPV results, as expected. It is unknown if or how the ratings would compare for multi-layer fabric systems or for systems that are prone to breakopen, such that the arc rating is EBT.

It is also important to recognize that the protective envelope is not limited to upper and lower torso protective garments. The full protective ensemble should be studied in a similar manner before the potential for differences in protection are dismissed. As such, the testing should be extended to other types of PPE before expanding conclusions beyond fabric arc ratings.

A similar study can be planned using ASTM F2675/F2675M for evaluation of arc ratings on hand protective products [7]. While the authors would anticipate similar results confirming minimal differences in arc ratings, we must recognize differences in the testing methodologies. ASTM F2675/F2675M evaluates specimens of whole hand protective devices, which may respond quite differently than flat fabric panels when exposed to thermal energy of an arc flash. Likewise, the materials of construction for hand protective devices (often leather or coated textiles) can differ significantly from fabrics evaluated in this study.

Perhaps more importantly, it will be critical to perform a similar study on face protection products according to ASTM F2178/F2178M [8]. Face protection products rely heavily on restriction of infrared radiation passing through the faceshield. If the spectral properties of a DC arc differ significantly from an AC arc, so too can the protective performance. As such, it will be important to carefully study the differences in arc ratings of face protective products when exposed to AC and DC arcs.

VIII. ACKNOWLEDGEMENTS

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Electrical Vehicles and Li-ion Battery Manufacturing – What are the actual risks for workers?

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Abstract – The current industry transition from internal combustion engine vehicles to electric vehicles introduces a whole new set of lithium-ion battery related risks to vehicles and battery manufacturers. Very few standards, guidelines, or even best practices are available to help occupational health and safety (OH&S) personnel develop safe work practices to address these risks.

This paper presents a powersports vehicle manufacturer's perspective on assessing these emerging risks to the electric vehicle and high-voltage battery manufacturing process. The paper covers the risks of shock, arc flash, chemical and thermal runaway and the associated mitigation measures implemented. Finally, the paper presents the training structure adopted and an overview of the training content.

Index Terms — Lithium-ion batteries, Electric vehicles manufacturing, risks assessment, work practices, workplace safety, training.

I. INTRODUCTION

For a manufacturer of conventional internal combustion engine vehicles, adding electric vehicles to its lineup also introduces new or unfamiliar risks. These risks, which are not traditionally found on internal combustion engine assembly lines, are both electrical, such as the risk of shock and arc flash, and non-electrical, such as chemical exposure from the Li-ion cell electrolyte and thermal runaway.

Unfortunately, unlike traditional risks, there are still very few standards, guidelines, regulations, or even best practices that address battery or EV manufacturing risks. And news coverage and the Internet present spectacular images of EV or industrial fires. The result is a distorted picture that is far from the actual level of risk workers face during battery manufacturing and EV assembly. As a result, assembly line workers, technical staff, and even senior management had a high level of anxiety towards working with Li-ion technology.

This paper presents the steps that were taken to assess these new risks, how they were mitigated, and some of the control measures that were put in place to ensure worker safety.

II. STEPPING INTO UNCHARTERED TERRITORY

A conventional approach to developing new procedures in occupational health and safety is to search the Web. After all, why reinvent the wheel when similar procedures have probably already been written and generously made available to everyone? Of course, the point is not to copy a procedure in its entirety, but to draw inspiration from it, to see how others faced with the same or similar problem(s) have structured their approaches. At the same time, regulations, applicable standards and best practices in the sector or industry can be consulted in order to write a procedure adapted to one's own needs.

Unfortunately, this conventional approach doesn't work when it comes to the risks associated with lithium-ion technology! In fact, it's hard to find any procedures or information documents on how to manage these risks from an occupational health and safety perspective. None of the automaker websites we consulted have published such documents, except for the manufacturer-specific Emergency Response Guides for each electric vehicle. However, these guides are aimed at firefighters and first responders and cover the steps involved in securing an electric vehicle after an accident.

In the absence of working procedures, are there any standards or guidelines on the risks associated with lithium-ion? Yes and no! There are dozens of standards on the functional safety, design or performance of electric vehicles, batteries, charging stations and the various components of electric vehicles. But what about standards (mandatory or informative) or best practice guides for worker safety? For now, only a few European countries have EV Standards as part of their H&S Acts [2], [3], [4]. However, some standards bodies have recognized the existence of a "normative desert", i.e. sectors where there are few or no standards. For example, the American National Standards Institute (ANSI) has published its Roadmap of Standards and Codes for Electric Vehicles at Scale [5]. In this document, ANSI identified 37 gaps where standards could be developed or improved. Unfortunately, while some of these gaps relate to safety in general (functional, fire, or storage), none of them directly relate to working safely with vehicles or batteries.

Another example comes from the British Standards Institution (BSI Group), which specifically analyzed the global landscape of safety standards for battery manufacturing and vehicle design and use [6]. However, they did not look at the vehicle manufacturing aspects. They looked at a total of 324 standards and also identified areas with gaps. For example, there are no OHS standards covering the manufacture of modules or batteries. The BSI then developed a series of

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three Publicly Available Specifications (PAS) to quickly fill the gaps identified, in a format similar to a standard but without the status of one. Of particular relevance are PAS 7060 [7] on the design and use of batteries and PAS 7061 [8] on the safe handling of battery packs and modules.

There are also examples from a Canadian OHS research institute [9] and a provincial regulatory body [10], who analyzed all available standards, laws, and regulations (within their jurisdiction) to come up with an interpretation of preventive measures related to electric vehicles and batteries.

Finally, of course, there are the NFPA 70E / CSA Z462 electrical safety standards. However, the preamble to these standards excludes vehicles from their scope. Nevertheless, these standards remain the benchmark for electrical safety, and their voluntary application to electric vehicle risk management seems inevitable. One possible interpretation, however, is that a battery is subject to the standard during its manufacturing process. But at what point on the assembly line does a battery cease to be a battery and become a vehicle? Perhaps it would be appropriate in a future version of the standards to clarify this aspect or to better define the scope of these standards in the growing context of electric vehicles.

III. RISKS

A battery is a device that converts chemical energy into electrical energy. And vice versa if we are talking about a rechargeable battery. Compared to relatively safe low-voltage rechargeable (aka secondary) alkaline and lead-acid batteries, an equivalent lithium-ion cell can deliver about 4 times more energy for the same weight (gravimetric energy density) and about twice as much energy in the same space (volumetric energy density). Unfortunately, to achieve this level of performance, lithium-ion chemistry is much less stable. And while the risks of electrical shock and arc flash are relatively well understood, the unique nature of dc current in electric vehicles, as well as the risks of chemical and thermal runaway, are new risks to manage.

A. Risk of shock

In general, the risk of electric shock is controlled by creating a safe electrical working condition by isolating energy sources and locking them out to prevent re-energization. However, batteries are their own source of electrical energy and cannot be in a "zero energy" state [11], especially because lithium-ion technology always requires a minimum state of charge level below which the cells become so damaged that they could catch fire if recharged.

Another fundamental difference in the risk of electric shock when working on electric vehicles is that, unlike normally grounded ac systems found in residential and commercial/industrial environments, where touching a single energized conductor poses a risk, ungrounded dc circuits (such as those used to power EV traction motors) require touching both the positive and negative conductors at the same time to complete the circuit. To achieve this, the relatively high-voltage ungrounded dc system must have a double fault, i.e. current leakage from both the positive and negative sides at the same time at two different points in the system, and a worker must touch both components at the same time! What's more, this electrical system, made up of all the high voltage components such as the battery, motor, inverter and on-board charger, are all electrically connected. A double fault in such a system, even in two different places, would most likely result in a short circuit and blowing the battery main fuse, quickly eliminating the hazard. Under these conditions, the probability of all these conditions occurring on a vehicle or battery assembly line is very low.

At this point it is important to explain that there are international standards for the transport of Li-ion cells and batteries; UN 3480/3481 [12], [13]. These standards state that the state of charge of cells or batteries must not exceed 30% of the charge capacity for air transport and 50% for ground transport (there are exceptions). However, BRP has made a corporate decision not to exceed 30% charge capacity for all shipping purposes. In practice, this means that our pallets of raw cells are delivered to us with a maximum charge of 30%. Our batteries and EVs are assembled and then delivered to dealers with the same 30% maximum charge, but this is not the case for all EV manufacturers.

The risk of electric shock in the battery assembly process is different from that in vehicle assembly, but also poses little risk to workers. The battery assembly process is robotic. Individual cells are assembled into modules with a voltage (at 30% SOC) of approximately 45 Vdc. Individual modules are therefore not considered a shock hazard. The modules are then assembled into their battery pack and busbars are connected between the modules also using a robotic process. In fact, the installation of the busbars connects all the modules in series, increasing the total voltage to around 350 Vdc at 30% SOC. Finally, the battery is closed before leaving the robotic cell. The battery assembly workers are therefore not exposed to high voltage under normal, expected assembly conditions.

The finished batteries then pass through the final quality control station on the assembly line. At this point, a final check is made to ensure that the two contactors on the positive and negative poles are in the "open" position, i.e. the battery is deactivated, and that the relatively high voltage contained in the battery cannot be touched at any of the battery's external contact points.

These batteries will eventually end up on vehicle assembly lines. Their safe deactivation state is guaranteed throughout the vehicle assembly line by the impossibility of obtaining the conditions necessary to activate the battery. The main condition being that the 12V battery is not connected throughout the assembly process. And without a 12V power source the high-voltage battery cannot be activated.

It's only at the very last assembly station, the functional quality control, that the vehicle and its battery are fully activated. But at this stage, the vehicle is as safe as if it were activated by its future owner. All in all, the risk of shock to production workers is minimal in both battery and vehicle assembly.

B. Arc flash risks

One might think that the risk of arc flash would be easy to manage, thanks to the CSA Z462 / NFPA70E standards, which provide a reference framework for calculating the incident energy. The result of this calculation will have a direct impact on the choice of protective equipment, the arc-resistant PPE to be worn and the work procedures to be developed. However, the reality is less obvious.

Several authors [14], [15], [16], [17] report differences between ac and dc arcs and overestimates of incident dc arc energy levels calculated using the ac arc calculation method suggested by the standards. And while this approach offers the advantage of better protecting workers from arc flash hazards, it can also, as we will see below, give a false impression of the existence of a risk when in fact the risk is minimal.

At the beginning of the battery design project, the initial incident energy calculations were performed in-house by electrical engineers. These initial results were calculated using the maximum power (also known as the Doan method) and Stokes and Oppenlander methods as suggested by the standard and gave results ranging from 1.5 to 7.1 cal/cm2. As a result, battery R&D procedures were designed with the risk of arc flash in mind, and personal protective equipment was incorporated into work procedures to control this risk. In an R&D context, this was highly desirable to anticipate the additional risks associated with the uncertainty of prototype development.

However, with manufacturing production approaching, it became important to clarify the actual incident energy level more precisely in order to adapt work procedures and PPE requirements for workers potentially exposed to arc flash. It was essential to ensure that the workers were adequately protected without burdening them with excessively conservative, uncomfortable personal protective equipment, which would itself have been a source of additional risk.

To ensure a comprehensive and accurate assessment of the risk, an external firm with expertise in dc arc calculations was commissioned. The calculations were validated using the maximum power and Stokes and Oppenlander methods, with results ranging from 1.3 to 4.2 cal/cm². Furthermore, the actual incident energy of dc arcs was calculated to be between 0.3 and 0.4 cal/cm² for our 8.9 kWh battery. These low incident energy levels provided reassurance that the arc flash risk to workers was minimal. The calculated results, which are 3 to 10 times lower than those obtained using the maximum power method, are similar to the results reported in the literature. This significant difference in incident energy also demonstrates the need for NFPA 70E / CSA Z462 standards to consider, in a future version, these differences in the calculation of ac versus dc arcs and suggests a more suitable calculation method for dc arcs.

C. Chemical risk

The risk of chemical burns is essentially linked to the electrolyte in Li-ion cells, which is a relatively strong base with a pH of around 10-11. Due to intellectual property considerations, the Li-ion cell manufacturer's Safety Data Sheet (SDS) does not provide the product composition. The SDS does, however, indicate the CAS number corresponding to $LiPF_6$, which is the electrolyte most commonly used in Li-ion cells today, according to the literature.

There is currently a paucity of information available regarding the risk of worker exposure caused by electrolyte leakage from Li-ion cells. However, one reference found [18] indicates that the risk is minimal due to the limited quantity of liquid electrolyte present in each cell, with most of the liquid being absorbed into the cell material's porosity. Moreover, leakage will only occur if the cell envelope is compromised. Additionally, each cell is contained within its own compartment of the module, which will contain any electrolyte leakage.

The second chemical risk posed by Li-ion cells is related to the risk of thermal runaway, which we'll look at later, and involves exposure to toxic fumes and gases in addition to fire.

Several studies have been conducted to identify the chemical compounds emitted during the initial thermal runaway gassing and possible combustion of the gases vented by lithium-ion cells [18] [19] [21] [22]. The data demonstrate that the gases emitted are highly variable, depending on numerous parameters. These include the type of chemistry (NMC, LFP, NCA, etc.), cell format (cylindrical, prismatic, pouch, etc.), state of charge (SoC), and the way the cell has been heated (penetration, slow heating, flame, etc.). The quantities and toxicity of the gases emitted also vary considerably, with the most frequently reported being CO2, CO, H2, and hydrocarbons. This significant variability in results can be attributed, at least in part, to the lack of consensus on test conditions [23].

In terms of worker protection, the challenge lies in providing adequate protection against harmful gas exposure. This is due to the fact that regulations require respiratory protection to be selected according to the precise level of contaminants to which workers are exposed. However, due to the unavailability of this data from either the literature or the Li-ion cell supplier, an internal study was conducted to characterize the gases emitted by the cells. The study enabled a comparison of each component with the local regulatory exposure limit. Once the required protection factor and appropriate filter cartridge had been selected, the type of respiratory protection could be chosen.

D. Thermal runaway risks

Thermal runaway of Li-ion cells is the most important risk to manage in the context of battery or electric vehicle manufacturing. Unlike the electrical risks of shock and arc flash, which can only occur in very specific contexts, thermal runaway can occur anywhere at any time. Thermal runaway is defined as the overheating of a cell caused by the uncontrolled chemical reaction of its internal components. After reaching a tipping point, this chemical degradation is exponential, with the temperature rising several hundred degrees in a matter of seconds. The cell then ruptures, releasing a large amount of flammable gases that can ignite under the right conditions [24].

The main causes of thermal runaway are:

- Internal short circuits (due to cell aging or manufacturing defects) or external short circuit.
- Physical damages (leading to short circuits)
- Overheating (i.e. repeated charge and discharge cycles, poor BMS design)
- Overcharging

Some of these causes, such as cell aging or overcharging, are irrelevant in a manufacturing context, or cell defects, which are rare events and beyond our control. Overheating, on the other hand, is directly related to module and battery design. For example, by using a honeycomb module matrix the cells are individually wrapped. In this way, a thin plastic wall and air voids act as a thermal insulator, limiting the amount of heat that can be transferred to adjacent cells.

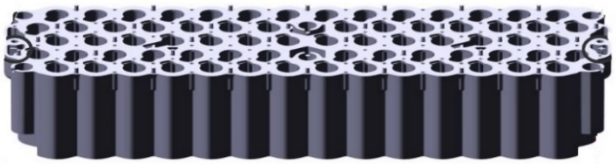

Fig. 1
Honeycomb matrix for modules.

It is reasonable to conclude that the most probable cause of thermal runaway is any other cause that could result in external short circuits to cells, modules, batteries, or high-voltage components, or penetration/crushing of cells/modules that causes internal short circuits. For instance, the interval between the receipt of the raw cells and their insertion into the modules represents a period of heightened vulnerability. This is because the cells are shipped on pallets packed in cardboard boxes and handled manually. They can be damaged by a forklift truck, dropped on the floor, or short-circuited by falling bunched together or by a metal object.

Subsequently, the module and battery assembly line are highly robotized, which minimizes the risk of thermal runaway. However, it is essential to plan for potential emergency scenarios and develop an intervention procedure for each robotized cell to reach and remove any module that may be in thermal runaway.

Subsequent stages of electric vehicle production present a reduced risk of thermal runaway. Remember that the batteries are deactivated (at their terminals) at the end of the production process. The batteries are then placed in UN 38.3-certified crates, which are designed to withstand a free fall of 1.2 meters (four feet). Upon arrival at the vehicle production facilities, the batteries, still deactivated, are integrated into the vehicles. The vehicles are fully activated only once, at the final quality control station. They are then prepared for packing and placed in transport crates.

This particular mode of transportation can potentially lead to incidents where a battery could be damaged by the forks of a forklift, or if crates fall during the transfer or loading of a truck.

Fig. 2
Powersport vehicles stacked crates.

To assess if a battery has been damaged during transport a process was developed to safely inspect the vehicle and its battery by a duly trained employee and confirm that no fault codes is present in the battery. This is a crucial aspect, as per the regulations governing the transportation of dangerous goods, once a Li-ion battery is damaged, it cannot continue its journey by regular transport. It then becomes a hazardous material and must be transported in accordance with this more stringent regulation.

Furthermore, we have developed a technical guide for all production sites and distribution centers. This guide outlines the design requirements of a safe quarantine area for the temporary storage of damaged vehicles or batteries to monitor for the development of thermal runaway. It is also essential that the designated safe area is capable of retaining or channeling water, or alternatively, that it is a watertight container capable of submerging a burning vehicle. It is important to consider the recovery of extinguishing water from lithium-ion fires, which may be classified as hazardous material depending on local environmental regulations [25]. Currently, there is conflicting data on the toxicity of extinguishing water [26] [27] [28]. The NFPA has initiated a research project to better understand the environmental impacts of Li-ion fires compared to other types of fire [29].

It is important to note that one of the primary reasons for the 30% charge limit for transporting lithium-ion components is based on the findings of multiple studies [21], [24] which have demonstrated a direct correlation between a cell state of charge and the intensity of the runaway exothermic reaction. As previously stated, the gases released by the cell are flammable, but they do not ignite in all circumstances. The overall conclusion of these studies is that when a cell is charged above 50%, the temperatures reached, and the gases emitted are more likely to ignite than when thermal runaway occurs at less than 50% state of charge. In light of these considerations, a 30% charge limit represents an acceptable compromise between runaway safety and other technical criteria, such as cell longevity in prolonged storage.

Batteries and electric vehicle fires represent the most controversial and high-profile aspects of lithium-ion batteries. Furthermore, this is the aspect that raises the most questions and concerns among employees. Nevertheless, the frequency of incidents involving electric vehicles is considerably lower than that of fires in vehicles with internal combustion engines [30], [31], [32]. However, the level of attention given to these incidents in the media and online can lead to a distorted perception of the actual risk of thermal runaway. One of the reasons for the increased concern with Li-ion EV fires as compared to internal combustion engine (ICE) vehicle fires is the ability to rapidly extinguish most fires involving traditional vehicles by starving them of oxygen. This is not the case with a Li-ion fire, as all Li-ion chemistries used in EVs produce their own oxygen, to one degree or another. While EV fires are much less frequent than ICE vehicle fires and are not prone to the rare explosive event that can occur with traditional fuel vehicles, they do last longer and require monitoring for a longer period after initial extinguishment to ensure that reignition does not occur.

In the event of a significant incident being reported in the media, it is essential that we are prepared to address these concerns and provide clear and concise explanations to both our employees and management regarding the similarities and differences between the reported incident and our own operational reality. Inquiries such as: Is it possible that a similar event could occur here? What measures have been implemented to prevent and manage such an incident? What conclusions can we draw from this incident? In the context of limited experience with Li-ion battery risk management, these questions are understandable and reflect a higher level of uncertainty. The lack of available information makes it challenging to benchmark one's own occupational health and safety (OHS) performance against other industry players.

IV. TRAINING

For an employer, the introduction of a new technology, such as lithium-ion batteries, necessitates the swift identification of potential hazards, an evaluation of their associated risks, and the implementation of control measures. Training has always been a complementary but equally essential element in the arsenal of risk control measures. It has become imperative to provide training to all personnel who work with, on, or around our batteries or electric vehicles. It was therefore crucial to base this new training program on a system that had already been established in other environments.

A search of the relevant literature revealed several documents dealing with training for working with electric vehicles. Some are national standards, while others are simply proposed guides to industry practice in mechanical repair shops. With the exception of one document, all of the identified sources are from European countries. Only one North American guide is available from the National Institute for Automotive Service Excellence [33]. Moreover, most of these documents pertain to the safety of working on electric vehicles in mechanical repair shops, which does not reflect the reality of electric vehicle manufacturing.

After careful consideration, the decision was made in favor of the German standard DGUV 209-093, "Training for work on vehicles with high voltage systems" [34]. The key benefit of this informative standard is that it recommends training levels based on the level of risk, rather than on the tasks to be performed. This offers greater flexibility in its application. Furthermore, the standard outlines training recommendations for working with relatively high-voltage systems in research, development, and manufacturing. It also addresses training for working with series production vehicles. This standard is therefore more suited to manufacturing production and recognizes the difference between the higher risks of working on prototypes in R&D compared to working on production vehicles.

In accordance with the DGUV standard, there are four distinct levels of competency for performing various tasks, with the levels increasing in accordance with the associated risk:

Level 0: Is an informative and introductory overview of electric vehicles (EVs), covering fundamental electrical concepts, the various components of an EV, the four main risks, the EV ecosystem, and the energy transition. This information session is open to all employees and does not allow to perform any tasks on an electric vehicle.

Level 1: This course is designed for individuals without a background in electricity or related fields. It offers a simple introduction to fundamental concepts and techniques. The course provides a straightforward explanation of fundamental concepts related to electricity, including voltage, amperage, and resistance. It also covers the functions of key electric vehicle components, such as the cell, module, battery, inverter, converter, and charger, as well as the notion of stranded energy in the battery. Furthermore, it delineates the four main risks and the protective measures that have been implemented to safeguard against them. The course also covers the signs to look out for in the event of thermal runaway and the emergency measures that should be taken. All personnel working on vehicles or deactivated batteries, including assembly line workers, logistics personnel, industrial engineers, and quality assurance personnel, are required to complete this training. The training allows workers to perform vehicle assembly on an assembly line or to transport vehicles or batteries. In summary, to work on or near vehicles or batteries that are deactivated by default and cannot be activated.

Level 2: This is a more technical level of training, essentially repeating the content of Level 1 but with greater depth of coverage. Furthermore, the course covers the various battery and vehicle protection systems, including the Battery Management System (BMS), Insulation Monitoring Device (IMD), High Voltage Interlock Loop (HVIL), and First Responder Cut Loop (FRCL). Finally, the course explains the procedure for verifying that the battery has been deactivated before making any mechanical repairs on systems that may be in motion (drive systems, cooling, brakes, etc.). The training includes both theoretical and practical components for verifying deactivation. It is designed for team leaders, department supervisors, technicians, mechanics, and operators at final quality control stations. In summary, this training equips workers with the knowledge and skills to safely and effectively work on mechanical components of vehicles whose high-voltage battery may have been activated at some point and requires confirmation of deactivation.

Level 3: This training is for individuals with a solid electrical or electromechanical experience and provides the knowledge needed to troubleshoot and diagnose problems on vehicles. For example, to address issues in vehicles that have not passed the commissioning tests. This training allows personnel to work on a vehicle or battery that is activated or could potentially be energized. Furthermore, the training encompasses the procedures for activating and deactivating batteries, as well as the accountability for ensuring deactivation before delegating a mechanical task to a Level 2 worker. This training is intended for a select group of electrical engineers or electromechanics who are called upon to provide diagnostic support on assembly lines, or for individuals working in R&D.

In addition to the training programs on the hazards of batteries and vehicles, our training department also offers courses designed to meet the specific requirements of various workstations and tasks.

V. CONCLUSIONS

The introduction of new risks into an industrial environment presents a unique set of challenges. Conventional risks are supported by a comprehensive set of standards, guidelines, and best practices, and the preventive measures are well established and widely understood. However, when these risks emerge alongside a new technology such as lithium-ion, which has an evolving standards ecosystem, the challenge becomes significant.

In summary, here are the four OH&S corporate guidelines than have been developed for battery and electric vehicles manufacturing:

1. **Electrical risks**
   - Shock risks.
     - In battery and EV manufacturing
     - In commissioning tests
     - From a fire hose
   - Arc flash risks.
2. **Thermal runaway and Li-ion fire management**
   To determine the best type of equipment to detect and mitigate Li-ion fires.
   - Thermal, gas and smoke detectors
   - Fire extinguisher and extinguishing agents.
   - Fire blankets.
   - Safe quarantine areas
   - Dipping tank
3. **Emergency response plan**
   - Custom made evacuation trailer to take an EV from the assembly line outside to a safe area.
   - Respiratory protection
   - Thermal event emergency procedures for all probable scenarios from raw cells reception and storage to battery and EV manufacturing and shipping.
4. **Training**
   - EV Levels 0, 1, 2, 3 courses
   - Selection, use and care of electrical gloves
   - Minor thermal events first responder
   - Battery and EV repair
   - Crated vehicle damage assessment
   - Transport of hazardous materials and Li-ion battery recycling

This paper demonstrated that through a systematic and pragmatic approach, it is possible to gather sufficient information on the main risks identified to ultimately develop our own standards.

Furthermore, we have outlined areas for improvement in current standards that would benefit from a more robust framework for the electric vehicle and battery sectors. It is only a matter of time before additional standards are developed. In the interim, this lack of guidance increases the necessity for manufacturers to develop and test their own OH&S standards. In either case, it would be beneficial for the entire electric vehicle and battery manufacturing industry to have a few more guides to fall back on.

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VII. VITA

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Safety Culture or Compliance?

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Abstract – Many organizations have developed their safety programs for compliance with regulations and standards. This is often due to high level managers viewing the regulations as bureaucratic requirements that increase costs and impede progress yet recognizing that regulatory compliance is necessary to avoid fines. However, this paper will discuss how the approach to safety for regulatory compliance fails to achieve a safe work culture. Some symptoms of organizations that do not have a culture of safety are given and techniques used at organizations that appear to have created a safety culture are also provided. Finally, an understanding of how the safe work culture creates business value for the organization is also explained.

Index Terms — Safety culture, regulatory compliance, business case for safety.

I. INTRODUCTION

In working with a multitude number of organizations the authors have encountered few organizations that have a very positive safety environment. Yet, most organizations have policies and programs as dictated by OSHA regulations and NFPA 70E. These organizations state that safety is one of their core values – "safety first" is the rule. Despite these statements and their efforts to adhere to OSHA and consensus safety standards, they struggle to see consistent safe behaviors among their workers.

Upon closer examination of the companies, the authors began to distinguish that the behavioral differences could be attributed to achieving a safety culture as oppose to safety compliance. As these behaviors were recorded it became evident that there was a clear divide between the organizations that achieved a safety culture and those that sought compliance. This held true in sub-organizations as well where one department or area of a company achieves safety culture and others are stuck seeking compliance. .

II. WHAT IS SAFETY CULTURE

A. Start with "Culture" Definitions [1]

1a the customary beliefs, social forms, and material traits of a racial, religious, or social group

*also***:** the characteristic features of everyday existence (such as diversions or a way of life) shared by people in a place or time

popular *culture*

Southern *culture*

b: the set of shared attitudes, values, goals, and practices that characterizes an institution or organization

a corporate *culture* focused on the bottom line

c: the set of values, conventions, or social practices associated with a particular field, activity, or societal characteristic

studying the effect of computers on print *culture*

Changing the *culture* of materialism will take time …— Peggy O'Mara

d: the integrated pattern of human knowledge, belief, and behavior that depends upon the capacity for learning and transmitting knowledge to succeeding generations

2a: enlightenment and excellence of taste acquired by intellectual and aesthetic training

b: acquaintance with and taste in fine arts, humanities, and broad aspects of science as distinguished from vocational and technical skills

a person of *culture*

3: the act or process of cultivating living material (such as bacteria or viruses) in prepared nutrient media

Also: a product of such cultivation

4: cultivation, tillage

We ought to blame the *culture*, not the soil. - Alexander Pope

5: the act of developing the intellectual and moral faculties especially by education

6: expert care and training

beauty *culture*

We should not choose just one of these definitions but should allow the impact of each of these definitions to provide insight into what we want to achieve and even how to achieve it. Here are some considerations for each given definition to consider in the context of worker safety:

1a The customary beliefs regarding safety can be that accidents happen, we try to minimize, we report on them, or it can be that accidents are always preventable, we must design and re-design our facilities and work methods to prevent them, always anticipating.
b The shared values must be that accidents are preventable and they impact the bottom line more than any other business

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aspect. Goals are to make the workplace safe and without incident.

c The values are set by investing in safety. It is the first consideration of every employee and funds are invested in making safety improvements – always moving up the hierarchy of controls.

d The integrated pattern of behavior is that safety considerations and moving up the hierarchy of controls to elimination is a constant life-long, never-ending mission. Every employee is to be recruited with that in mind and trained in the same way.

2a Enlightenment and excellence in safety is acquired by the intellectual and aesthetic training.

b Acquaintance with and taste in safety science to understand and control all hazards and to include root causes analysis with a mission to eliminate or completely control.

3 The act of cultivating an attitude that embraces safety as a first thought before action.

4 We cannot blame the employees for their bad decisions when the culture doesn't support otherwise.

5 Training, training, training.

6 External expert resources utilized beyond classroom training to provide solid support in the work methods as well as equipment and systems re-design to move up the hierarchy.

B. Safety Culture in Professional Reference

Reason (1997) defined Safety Culture as meeting four criteria:

(1) Reporting Culture, one where employees freely report errors and near-misses;

(2) Just Culture, a non-punitive, trusting environment, where the system rather than the employee is held accountable for errors;

(3) Flexible Culture, where employees are so well-trained and where their skills, experience, and abilities, are so well respected, that management is able to cede control to front line experts under conditions of crisis; and

(4) Learning Culture, where the organization is able to draw the right conclusions and implement changes as needed based on data from its safety information systems.

Together, these criteria create an Informed Culture, where managers and operators have full awareness of all the factors that affect safety in a system. Informed Culture is, essentially, a Safety Culture.

C. Safety Proficiency

Evidence of achieving this safety culture is similar to psycholinguistics [2][3] where proficient multilinguals can reach a level of fluency where they not only think in their second, third and additional languages but they do not even actively decide which language to think in. Instead, the language of thought tends to be determined automatically by context, social cues, and habitual patterns.

Similarly, when a safety culture is achieved the vast majority of persons "apply safe work practices" without making an active decision to think about safety. They automatically identify hazards, assess risks, and apply appropriate controls. They also bring this safety thinking to their home and recreational activities.

When employees enter public buildings, they will notice where the AEDs are located. They will encourage others to use the handrails when ascending or descending stairs. They will lift with their knees. They will ensure they have working smoke alarms in their homes.

III. EVIDENCE OF COMPLIANCE ONLY

The evidence offered here is a list of statements or acts that have been found by the authors to indicate the organization is only trying to comply with rules and standards and not actively encouraging a safety culture.

1) *"Where does it say we need to do that?"* This statement is all too often heard from plant managers and supervisors and completely undermines the desired safety behavior to eliminate and mitigate hazards. If a person identifies a hazard, a good safety culture will expect action to be taken to move up the hierarch of controls to control the hazard. When this question is asked, it is specifically considering only what is required by a written standard or law – it is negating the actual safety consideration.

2) *Lack of Thoroughness in Root Causes Analysis (or none at all) that looks for and stops at procedural failures by employees.* All causes need to be identified and addressed. This doesn't mean that we ignore employee errors but we must drive out the fear of admitting failures so they can be learned from as to why the employee failed.

3) *"Isn't PPE sufficient?"* Over dependency on PPE is selecting the least effective safety control and limits the necessary analysis for moving up the hierarchy of controls.

4) *"Well this is the design, we have to live with it."* Recognizing hazards inherent in the design need to be seriously considered for change re-design or replacement.

5) *"They/We are trained professionals and understand how to work on this live."* A trained professional who understands the hazards of live work and values their life would choose to NOT work on it live.

6) *"We've never had an incident before."* Living in "lucky land" does not mean that your luck will continue into the future.

7) *"We don't have a budget for that."* Safety should not be thought of as a budgetary item. Budget must be found to address hazards. Organizations with strong safety culture have much better budgetary control of the safety related expenses. The business case for safety has been clearly established by the ASSE [5] for the returns in addressing hazards.

8) *"That takes too long."* Avoiding safety procedures because it will impact production doesn't realize the impact on production when there is an incident that stops it – let alone hurts a person.

9) *Supervisors that turn the other cheek, allowing workers to bypass safety procedures.* This completely undermines compliance as well as development of safety culture.

10) *"It's common sense."* Common sense doesn't exist anymore – it's now uncommon sense. Nothing can be assumed – including common sense.

11) *"We can't foresee every possible hazard."* This excuse undermines the risk assessment process and job briefing efforts that are effective in identifying and communicating hazards and risk mitigation techniques.

12) *"Accidents happen, that's why they are called accidents.*" The foundational philosophy of a strong safety culture is that every incident is preventable.

13) *"Is that a legal requirement or a recommendation?*" This response in the face of a recognized hazard and a recommended mitigation is an obvious attempt to only comply to a minimum legally enforcable OSHA rule.

14) *"We'll address that if it becomes an issue.*" Waiting to react when hazards and mitigations are known is a dangerous reactive approach.

15) *"We don't need retraining or refresher training, our employees know it."* This is overconfidence in employees and forgetting what got you there. Continued training of employees is a challenge as it can become monotonous and seemingly ineffective. Employees seldom retain more than 20% of the information presented in training. It is important to continue to train and find effective ways to reinforce the learnings.

16) *"We have more important business priorities otherwise we won't be here to employ safe workpractices."* In the words of former CEO Paul O'Neil – "If you can manage safety, you can't manage." The root cause problem solving skills and safe work planning (anticipation) skills to manage safety apply to all business problems.

17) *"Our industry is inherently hazardous."* This excuse for accidents prevents organizations from implementing measures to mitigate and control the hazards.

18) *"We haven't had any complaints."* The assumption that formal complaints would come forward if there were hazards that needed to be addressed is an excuse to not drive a proactive approach that is the basis of a strong safety culture.

19) *"We follow the industry standard practices."* This is resting on mediocrity where a strong safety culture is always striving higher.

20) *"We've always done it that way."* Failure to recognize the opportunities for continuous improvement that is driven by a strong safety culture.

21) *"It was a freak accident no one could have prevented."* A strong safety culture is built on the premise that all incidents are preventable. Any compromise of that postulate will cause the safety culture to crumble.

22) *"People need to be more careful."* When we assume it is only a people issue then we fail to move up the hierarchy of controls in the best possible manner.

23) *"We will address safety issues at the next review."* This sends the message that safety is just a segregated subject to be put in a priority list with other business strategies and objectives. A strong safety culture is built when management makes it an all encompassing necessity. It must permeate everything we do.

24) *"We're focusing on (growth, profits, market share, costs, etc.).* Like the previous point, safety must be all encompassing and permeating all mandates.

25) *"The safety measures make it impossible to perform our work in a cost-effective manner."* Blaming good safety practices for higher costs or slower execution demonstrates an lack of appreciation for the moral and business value of preventing injuries and loss of life.

26) *"There's too much red-tape already."* Viewing forms and permits as time-wasting bureaucracy rather than effective tools to assist in risk assessment and control measure selection clearly displays a lack of culture and inclusion of safety tools.

27) *"We don't want to scare people from the job."* Treating discussions or training on hazards as a pretense for maintaining morale and preventing worry. A well-trained workforce is essential for establishing a strong safety culture. The workers, when well trained, are best positioned to provide good ideas for improvement.

28) *"That's not my job, that's up to the safety department or other supervisors."* A strong safety culture empowers everyone with "stop work" authority. As well, their job includes safe work practices for everything they do. The safety department just feeds them with tools and aids.

29) *"Electricians are trained to know how to work with electricity."* Assumes that experienced electricians don't need further training or safety reinforcement. On-going training and reinforcement for all employees is a trademark evidence of strong safety organizations. Note that it is mostly persons assumed to be qualified persons getting killed by electrical hazards.

30) *"They are engineers, they don't need electrical safety training."* Assumes that engineers will not expose themselves to electrical hazards. It also fails to recognize that to move up the hierarchy of controls often requires engineers to design out the hazard, substitute for the hazard, reduce the hazard, or utilize engineering controls to better control the hazard.

31) *"Our equipment is new (or very good) and built with latest safety features."* This asserts that current equipment is adequate, regardless of wear, technological advancements, or worker feedback.

32) *"Our (electrical) recordables are very low, I don't see the need for more safety training or initiatives."* This is often a statement from top management for safety in general and for electrical safety specifically. Such statement clearly indicates that the company is in a reactive mode and not proactive. This is repeated more significantly in the area of electrical safety due to the low ratio of reported incidents to serious injury/fatality.

33) *"Just train us on the rules from OSHA/NFPA 70E."* This is an obvious indication of safety compliance over culture. It also falsely assumes, particularly in the case of NFPA 70E [7], that it is a set of prescriptive rules that can be simply followed. This fails to recognize the concepts dictated by the standard to move up the hierarchy of controls, consider conditions of maintenance, perform risk assessment, and recognize all hazards.

34) *"We don't need to worry about the (electrical) contractors. They are trained experts in their field and know better than us."* In addition to violating NFPA 70E [7] with this statement, it fails to take responsibility and ownership of safety for everyone working at the facility. It also fails to recognize the impact contractors can have on the employee workforce. Safety responsibility cannot be contracted out.

If you hear these statements in your organization, then you have evidence of lacking a safety culture. Your organization is, at best, attempting to comply with OSHA and perhaps some consensus standards. These excuses reflect a lack of commitment to safety and can be signs that an organization is prioritizing convenience, cost, or productivity over the well-being of its employees and perhaps the public.

IV. EVIDENCE OF SAFETY CULTURE

This list of statements and behaviors are more often found in organizations that have achieved a safety culture.

1) *Is there a hazard and how can we eliminate it or control it?* This is consistent with following the hierarchy of controls.

2) *"We must consider safety in all of our designs and equipment purchases."* This is a mandate to move up the hierarchy of safety controls.

3) *"The hazard elimination shall be our top priority."* Again, a mandate for the top hierarchy of safety controls.

4) *"We must stop production when hazards appear."* This is a clear indication that production does not take precedence over safety.

5) *"Everyone has "stop work" authority."* Another clear indication that safety is a priority and every employee is enabled.

6) *"Safety (prevention) by design shall be the foundation of our approach to all projects."* This takes the focus away from capital cost and places safety as a foundational value. If the cost can't be justified with a "safety by design" approach then it is not a justifiable expense/project.

7) *Safety best practices are deployed before they become required by OSHA or consensus standards.* The standards are reactive in that they are written in the blood of injuries and fatalities after they have occurred and provided the substantiation for change. A good example of this are NFPA 70E requirements for arc flash hazards. Arc flash was a known hazard of electricity since just after the 19th century. It wasn't until a groundbreaking paper by Ralph Lee in 1982 did people even consider it in safety programs. Even then, NFPA 70E did not address it in the standard until the 1995 version. Likewise, Charles Daziel's 1961 GFCI invention to address his well documentation substantiation did not make it into the NEC until 1968.

8) *Upgrade old facilities to address hazards despite grandfathering allowances.* Even OSHA recognizes that grandfathering has to be limited (see CFR 1910.302(b)). One example is equipment grounding conductors – the single most important and simple thing we can do to protect people from shock.

9) *"I do not ever want to be forced to make a call to an employee's loved ones."* This demonstrates management of a company that has care for their employees and their families and have strong convictions to ensure their safety.

V. STEPS TO BUILD THE SAFETY CULTURE

Below are listed some things that organizations displaying stronger safety culture either have in place or implemented during an early period to develop that culture.

1) *Train, Train, Train*. To build a safety culture requires a lot more training than your compliance organizations. Organizations that succeeded performed retraining on an annual basis coupled with supporting weekly single point lessons. Training must go beyond safety training and include technical skills training as well.

2) *Make safety and knowledge of safe work practices fun and frequent*. In class and on-line weekly quizzes with prizes for correct answers keep people thinking about safety and the skills they need.

3) *Have a strong Root Causes Analysis response to all maintenance and safety events.* Investigations need to be quick and thorough, investigating all contributing and possible causes. Avoiding blame and driving out fear for individual actions and focusing on why those actions were made and how they could be changed in the future even if it means a design change.

4) *Exhaustive written safety program that is not limited in page count.* The written safety program needs to be exhaustive and easy for people to reference to find answers. It should also be in the hands of every worker and foundational to their training. Page counts are not important as it is not a book one reads, it is a reference book where one looks up specific subjects for answers.

5) *Ensure you have a strong preventive maintenance program*. Maintenance and safety go hand in hand. This was a driving factor in NFPA 70B Standard for Electrical Equipment Maintenance [4] becoming a standard. A good safety culture cannot be built in a company that doesn't recognize the need for good preventive maintenance – it's a contradiction. Poor maintenance is shouting to the workers that the company doesn't care.

6) *Demonstrations of skills by workers are assessed in detail*. This requires a detailed skills assessment sheet or score card to do so. It normally requires 3rd party assessments to ensure partiality is limited.

7) *Observations of work tasks are regularly performed.* These observations follow along the same approach for detail assessment as the demonstration of skills. They also provide an opportunity for coaching improvements. Use of a 3rd party expert observer also provides valuable input.

8) *Develop safety awareness for employee use at home and for their family.* There is an endless list of ways to encourage safe behavior at home from issuing fire alarms, providing first aid and CPR training that is open to family members, providing defensive driving training that is open to family members, issuing PPE for home use, etc. Employees are three times more likely to be injured at home than at work. If it is truly a culture, it happens in their lives 24/7, regardless of where they are.

9) *The employee hiring process considers the safety attitude*. This can be especially difficult because job seekers put on their automatic safety answering machine to address direct questions about safety. Interviewers need to be skilled to ask open-ended questions that determine the true value of safety to the persons being interviewed. Note that a developing safety culture will begin to attract people because of the high positive morale that it creates – word will get out quickly.

VI. VALUE OF THE SAFETY CULTURE

The argument to develop a safety culture within companies provides a twofold benefit: it ensures the overall success of the business and the safety of the employee. The American Society of Safety Engineers [5] found a direct, positive correlation between investment in safety, health and environmental management programs and its subsequent return on investment. The direct returns include savings on worker's compensation benefit claims, civil liability damages, litigation expenses, lost time and production of an injured employee, improved productivity and employee morale, and winning/losing bids. There is also a possible personal cost for managers prosecuted under a criminal law.

ASSE also touches on the hidden and/or shared costs that go beyond those that appear in a company's ledger. These "costs" may not necessarily be monetary in nature, such as the long-term impact on the injured/killed person and their family, as well as fellow employees that witnessed, or are otherwise affected by, the accident. The public reputation of the company in question can also be effected. The massive free flow of information over social media from frequent and/or serious accidents can impact building, expansion, and/or operating permits or cause a PR nightmare for a business.

Furthermore, the shared costs are those that are paid by society or "externalized" by a company, such as when medical insurance pays for the injured employee's medical costs. This eventually gets passed on to people in the form of higher medical insurance premiums. Society saves as a whole with fewer accidents leading to fewer requirements for medical personnel and services. In addition to shared costs, workplace injury losses were estimated at one-quarter of each dollar of pre-tax corporate profits, while indirect costs are thought to be as much as 20 times higher than direct costs.

ASSE cites a 2001 Liberty Mutual report in which 61% of executives surveyed say $3 or more is saved for each $1 invested in workplace safety. ASSE presented 14 specific company examples of cost savings from investing in safety programs, in addition to other examples of significant improvement in safety statistics without translation to cost. Developing a strong safety culture is the best way to maximize these business benefits.

It has been established by Caskey and Ozel [6] that companies that compromise workplace safety through cuts in safety related expenditures and increased demands on employee productivity in order to meet earnings expectations have a higher injury rate than those that miss expectations or largely exceed them. Injury rates are 12.7% higher in such companies. The rates are even higher in companies that are non-union, in states where worker compensation premiums are not tied to claims, and/or companies without dependence on government contracts tied to safety performance.

The decisions of executives to cut safety and maintenance expenses can have long-term negative consequences for the company's performance. Companies with a confident long-term outlook will continue to invest in safety for the returns they will gain.

Once a safety culture is established, the company gains significant benefit through high employee morale. It is common for people to look forward to their work and desire to make an impact. This engagement increases productivity and further benefits the company. A true win-win.

VII. CONCLUSIONS

This paper describes the traits of organizations simply seeking compliance with safety standards vs organizations seeking to establish a strong safety culture. Some methods are proposed to help organizations build their safety culture. And, finally, the business case for why this culture is important is also demonstrated. Organizations that achieve the safety culture have high morale and employee productivity.

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IX. VITA

Karl Cunningham, a father of 12 and grandfather of 25, has been a plant and project engineer and project manager for a fortune 500 company most of his 42 year career. His work includes designing, constructing and starting-up mega-project industrial facilities internationally, working in over 20 different countries. He also served as an apprentice program coordinator, evaluator and instructor for 14 years while working as a plant engineer in the early part of his career in Northern New York state. Karl is on Code Making Panel 12 of NFPA 70 National Electrical Code and the technical committees for NFPA 70B and 70E. He has authored and led electrical safety programs for most of his career. He is a senior member of the IEEE and has presented several papers at past Electrical Safety Workshops. He was also published in ASEE (American Society of Engineering Education) for his Experiential Learning Program and published in the International Aluminium Industry journal.

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An AI Integrated Robotic System for Safe Operation in High Voltage Distribution Panel

Paper No. ESW2025-37

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Abstract – In high-voltage (22kV) distribution panels within substations or industrial facilities, electricians performing internal maintenance typically de-energize the power supply, confirm the absence of voltage using a voltage detector, and then discharge the accumulated charge in circuits or equipment by attaching portable earthing clamps to the R-S-T(or A-B-C) terminals. Despite these precautions, several electrocution incidents occur annually due to misinterpretation of the power equipment status, mistakenly proceeding with work under the assumption that the system is de-energized while it remains energized. Additionally, human error can lead to sudden circuit shorting, causing arc flash incidents that pose severe risks, such as burns, explosions, and fires. This research proposes the development of a robotic system capable of performing these hazardous tasks autonomously to prevent such incidents. The robotic system consists of a voltage detecting module, an earthing module, a gripper, a depth camera, and an orthogonal robotic manipulator. The voltage detecting module contacts the R-S-T terminals to verify the de-energized state, while the earthing module safely discharges the R-S-T terminals. A depth camera, employing a instance segmentation algorithm, precisely identifies the positions of the R-S-T terminals, allowing the robotic system to navigate and position the voltage detecting and earthing modules accurately. The efficacy of this robotic system was validated in real-world conditions, demonstrating that the automated voltage detecting and earthing process could reduce the risk of electrocution for electrical technicians.

Index Terms — Distribution Panel, R-S-T Terminals, Robotic System, Voltage Detecting. Earthing, Instance Segmentation

I. INTRODUCTION

A typical 22kV distribution panel includes power installations such as R-S-T three-phase terminal busbars, through which current flows from the Load Break Switch (LBS) to the Metering Outfitting Facility (MOF). During necessary maintenance inside the distribution panel, standard safety procedures are followed. The operator, equipped with appropriate safety gear, de-energizes the distribution panel and uses a contact voltage detector to ensure no current is present in the R-S-T terminals. Once confirmed, portable earthing clamps are directly secured to the R-S-T terminals to dissipate any residual charge, creating a safe environment for maintenance work inside the distribution panel.

Ensuring the safety of electricians in high-voltage environments is of utmost importance. Although safety procedures are in place, the manual process of voltage detecting and earthing in distribution panels still has the potential for human error. Particularly during earthing operations, arc flash incidents can occur due to insulation faults, improper equipment selection, or operator error, causing unexpected circuit shorting. This sudden release of electrical energy and high temperatures can result in severe burns, explosions, fires, and other critical risks. To prevent such hazards, strict adherence to safety procedures and protective measures is essential. Human errors can stem from insufficient training, poor judgment, and inadequate supervision, especially when technicians work under time constraints or in hazardous environments. Therefore, exploring safer approaches to voltage detecting and earthing operations is crucial to minimize human error and enhance overall safety.

Various studies have proposed methods for safer voltage detecting and earthing operations. For instance, reliable earthing system implementation [1], ensuring personnel safety during earthing and ground faults in power systems [2], and the use of embedded earthing switches to perform grounding without removing distribution panels [3] have been explored. However, these methods typically require direct human involvement, leaving inherent risks unchanged. Notably, there has been no reported research on an automated system that can perform voltage detecting and earthing operations without human intervention.

This study proposes automating the voltage detecting and earthing process of high-voltage distribution panels using an AI-integrated robotic system called earthing robot. First, the R-S-T terminals are identified using an instance segmentation algorithm with a depth camera, and the precise 3D target position is estimated through a back-projection technique. The cartesian manipulator of earthing robot then moves to the target location, autonomously performing voltage detecting and earthing using the robot's specialized voltage detectng and earthing modules.

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II. 3D TARGET POSITION ESTIMATION SYSTEM FOR R-S-T TERMINALS

To enable the automatic voltage detecting and earthing process of the earthing robot, accurate estimation of the 3D position of the R-S-T terminals on the distribution board is crucial. This ensures precise movement of the earthing module and voltage detecting module to the target location. In this study, an instance segmentation algorithm was utilized to identify the pixel positions of the terminals. The Euclidean distance was measured using a depth camera, and the data was subsequently converted into 3D relative coordinates to estimate the target position.

A. Recognizing terminals using instance segmentation

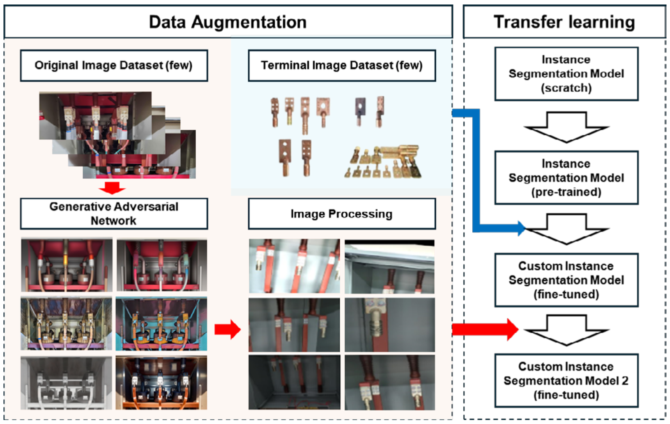


Fig. 1 Training process of instance segmentation to avoid overfitting

Fig. 2 Result of terminal instance segmentation in real time

Training an instance segmentation model using deep learning typically requires a large dataset of images of R-S-T terminals. However, no open-source datasets for R-S-T terminals are currently available, and capturing images of high-voltage distribution panels involves significant challenges, including the risk of electric shock and security concerns. Consequently, training the model with a limited amount of image data may lead to overfitting. Moreover, the recognition rate for terminals with different designs in untrained distribution panel environments is likely to be low, potentially resulting in detection failures. To address these limitations, this study proposes an enhanced learning process for the instance segmentation model, as illustrated in Fig. 1.

First, this study utilized a lightweight segmentation model pre-trained that had been trained on various base-class objects, and applied transfer learning with our training data to fine-tune the model. To enable recognition of terminal designs not present in the original dataset, a generative adversarial network (GAN) was employed to randomly generate distribution panels with diverse designs. Additionally, image processing techniques were used to augment the dataset, creating model robust to various distances, lighting conditions, and camera noise. During this process, the model was initially trained on images of the terminals themselves, followed by training on full images of distribution panels. This stepwise approach allowed the model to first learn the basic patterns of the terminals before progressing to distinguish terminals within complex distribution panel environments, thus enhancing the generalization ability. As a result, a customized instance segmentation model was developed, capable of accurately recognizing the pixel coordinates of the R-S-T terminals with a confidence level exceeding 0.8 in real-time on simulated distribution panels. This is illustrated in Fig. 2, where the locations of the terminals are marked with red boxes.

B. Determine the 3D terminal position in the world coordinate system

After the terminals are recognized using the instance segmentation model, the proportions of the terminals enable the RGB camera to identify the target pixel position, specifically the center point of the terminals. The stereo based depth camera employs two infrared cameras to calculate the Euclidean distance d to the object at the specified pixel coordinate, based on the principle of stereo vision. Accurate 3D coordinates of the terminal's center relative to the camera are obtained by compensating for the distortion caused by the camera lens and back-projecting the points from the camera coordinate system to the world coordinate system. This process utilizes the corrected pixel coordinates (a_u, b_u) and the Euclidean distance d. The equation for correcting the distorted pixel coordinates is provided below:

$$a_d = a_u(1 + k_1 r_u^2 + k_2 r_u^4 + k_3 r_u^6) + 2p_1 a_u b_u + p_2(r_u^2 + 2a_u^2) \quad (1)$$

$$b_d = b_u(1 + k_1 r_u^2 + k_2 r_u^4 + k_3 r_u^6) + 2p_2 a_u b_u + p_1(r_u^2 + 2b_u^2) \quad (2)$$

where

α_d, b_d	The corrected pixel coordinates after distortion correction.
α_u, b_u	The undistorted pixel coordinates (ideal coordinates before distortion).
r_u	radial distance from the distortion center to the undistorted pixel
k_1, k_2, k_3	The radial distortion coefficients
p_1, p_2	The tangential distortion coefficients

The equation above has been adjusted to account for both radial distortion[6], where pixels shift outward or inward depending on the distance $r_u = \sqrt{a_u + b_u}$ from the center of the image, and tangential distortion, which occurs when the lens and image sensor are not aligned. The corrected pixel coordinates (a_u, b_u)can be converted to the world coordinate system (x, y, z) using the focal length f_x and f_y along the x and y axes, and the pixel coordinates of the center of the image center (c_x, c_y) as shown in the equation below.

$$z = \frac{d}{\sqrt{\left(\frac{a_u - c_x}{f_x}\right)^2 + \left(\frac{b_u - c_y}{f_y}\right)^2 + 1}} \tag{3}$$

$$\begin{bmatrix} x \\ y \\ z \end{bmatrix} = \begin{bmatrix} 1/f_x & 0 & c_x/f_x \\ 0 & 1/f_y & c_y/f_y \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} a_u \\ b_u \\ z \end{bmatrix} \tag{4}$$

where

x, y, z	The 3D coordinates of the point in the camera's world coordinate system.
f_x, f_y	The focal lengths of the camera along the x and y axes
c_x, c_y	The pixel coordinates of the optical center of the camera
d	The actual physical depth or distance to the object being observed in the real world.

III. AUTOMATED PROCESSES OF SAFE OPERATION USING MODULE BASED ROBOTIC SYSTEM

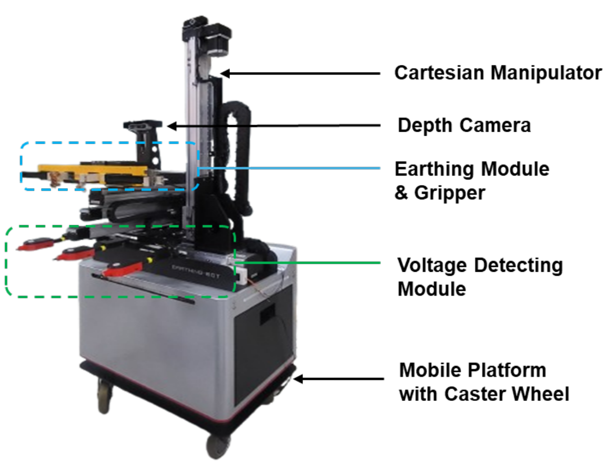


Fig. 3 Configuration of the earthing robot

The overall configuration of the earthing robot consists of a stepper motor-driven cartesian manipulator mounted on a mobile platform with caster wheels, as illustrated in Fig. 3. The end of the cartesian manipulator is equipped with a depth camera and a gripper, while the voltage detecting module is positioned at the bottom of the y-axis linear motor. The gripper is responsible for lifting and maneuvering the earthing module to ground the R-S-T terminals, discharging any residual charge. The depth camera, a stereo-based model, determines the relative positions of the R-S-T terminals in front of the earthing robot. The mobile platform includes a control box that houses the built-in controller, PC, and power system. A handle is provided to manually position the robot in front of the distribution panel.

A. Mechanism of voltage detecting module

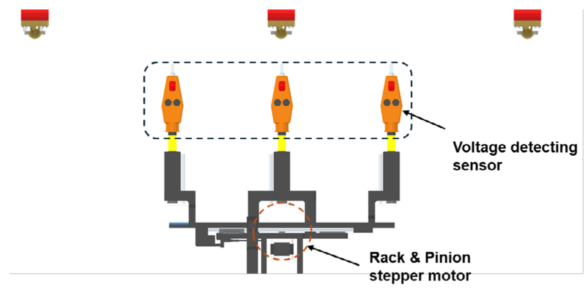


Fig. 4 Configuration of voltage detecting module

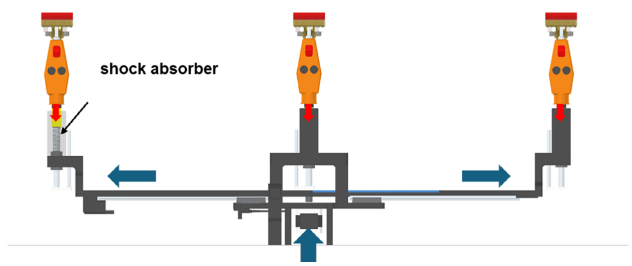


Fig. 5 Voltage Detecting Module that Performs safe operation by Contacting the R-S-T Terminals

The voltage detecting module, depicted in Fig. 4, comprises three voltage detecting sensors mounted on shock-absorbing springs. These sensors are positioned at the ends of the robot system, actuated by stepper motors and rack-and-pinion gears. The sensors detect current non-contact from approximately 30 cm within a range of 3.3 kV to 30 kV and transmit warning commands to a PC via wireless communication. The module is attached to the end of the cartesian manipulator, allowing free translational movement within the manipulator's workspace. Due to variations in the phase spacing and positions of the R-S-T terminals across distribution panels in different substations, the 3D positions of the terminals are determined using the terminal recognition algorithm described in Section II. Based on the detected phase spacing, the rack-and-pinion gear and cartesian manipulator are controlled to ensure simultaneous contact of all three sensors with the R-S-T terminals. To mitigate the risk of electric shock in the presence of residual charge, the module's body is constructed from fully rated insulating material capable of withstanding voltages up to 22 kV, safety for both the operator and the robot.

B. Mechanism of earthing module and gripper module

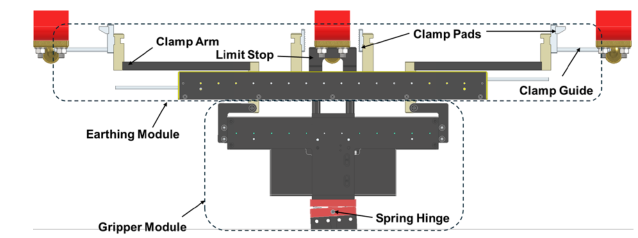


Fig. 6 Configuration of earthing module

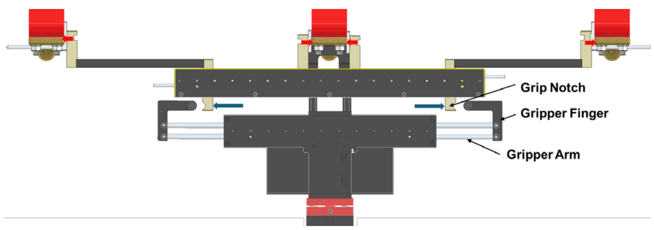


Fig. 7 Earthing module that performs safe operation of the R-S-T terminals

The configuration of the grounding module is illustrated in Fig. 6. The gripper, powered by a stepper motor, features adjustable finger spacing to enable translational movement of the grounding module when secured in the grip notch. Adjusting finger spacing also alters the gap between the clamp pads, which is designed with a spring mechanism to accommodate terminals with varying spacings. This design accounts for the typical axial spacing of 30 to 40 cm found in 22kV distribution panels. When the clamp pad contacts a terminal, it discharges residual charge through the grounding wire. The wire, sized between 80 mm² and 150 mm², is selected to ensure sufficient mechanical strength and current capacity for reliably grounding 22 kV terminals.

After the depth camera identifies the target location of the S terminal, the cartesian manipulator positions the module so that the limit stops mounted on the module contact the terminal's center. The clamp pads then adjust their spacing through finger operation, as depicted in Fig 7, with the center pad narrowing and the outer pads widening. Once the clamp pads contact the terminal, any residual charge is discharged through the grounding wire. The gripper fingers subsequently release the grounding module, allowing the module to remain securely attached to the terminal via the spring mechanism on the clamp. During retrieval, the gripper fingers re-engage with the module, reversing the grounding process to disconnect the module from the terminal.

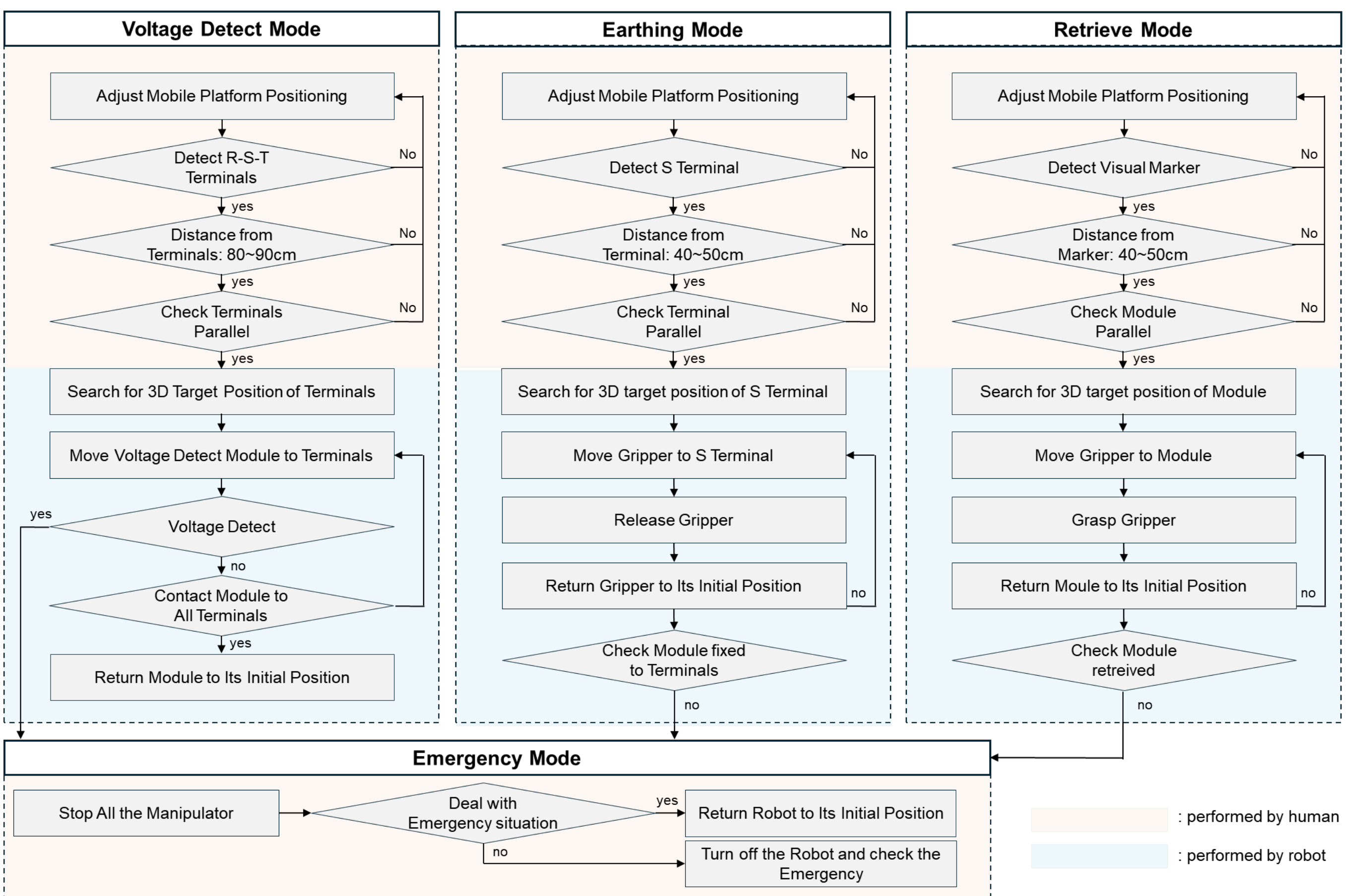


Fig. 8. Flow chart of the robotic system for safe operation

C. Automated process for safe voltage detecting and earthing operation by earthing robot

The flowchart illustrating the safe inspection and earthing process performed by the earthing robot is shown in Fig. 8. The robot's mobile platform is equipped with non-motorized caster wheels, requiring manual positioning by the user to ensure that the terminal or module enters the cartesian manipulator's workspace. The depth camera continuously determines the robot's relative position to the terminals in real time. Once three predefined conditions are satisfied, the initial positioning is deemed complete, allowing the robot to proceed with hazardous electrification and earthing tasks.

In test mode, the robot maintains a minimum safety distance of 80 centimeters and advances until the tester contacts the terminal. If current is detected during the approach, the non-contact voltage detecting sensor wirelessly signals the robot to immediately enter emergency stop mode. This halts all manipulator movements and triggers an audible warning to alert the operator to the hazard.

After completing the inspection, the robot transitions to earthing mode, moving as close as possible to the distribution panel. The gripper positions the earthing module on the terminal, and the depth camera verifies the module's placement. If the module is not properly positioned, the system switches to emergency mode.

Finally, in retrieval mode, the robot automatically retrieves the installed earthing module. The module's position is confirmed by using the visual marker[7] attached to it, and the system reverses the earthing mechanism sequence to remove it. The depth camera then verifies whether the module has been successfully retrieved. If retrieval is unsuccessful, the system again switches to emergency mode. This automated process enables operators to safely conduct earthing and testing tasks with the earthing robot.

IV. EXPERIMENTS AND RESULTS

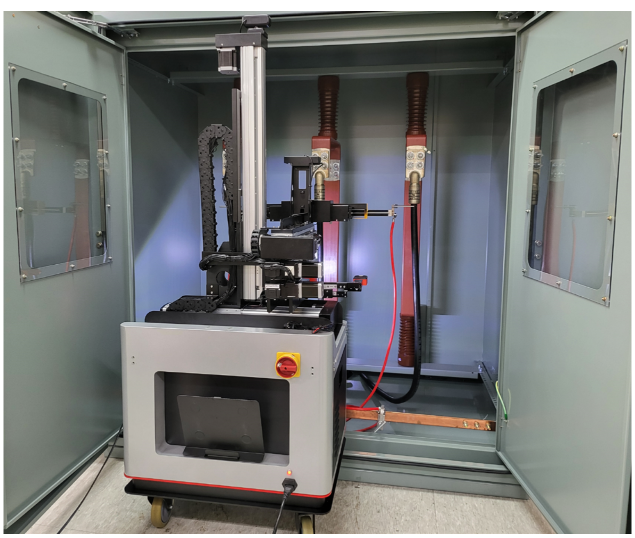
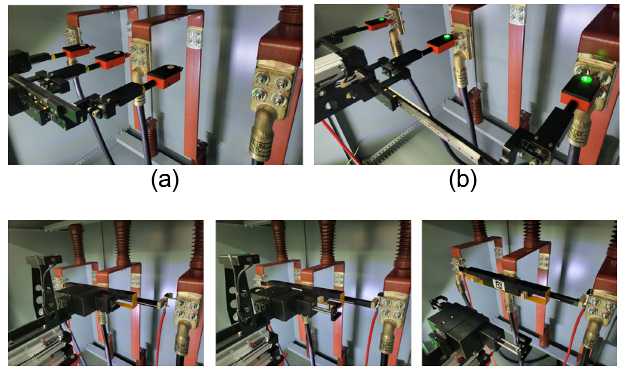


Fig. 9 Experiments setup for earthing robot to perform voltage detecting and earthing



(a) (b)

(c) (d) (e)

Fig. 10 Process of the voltage detecting (a) through (b) and earthing (c) through (e)

To validate the feasibility of the proposed grounding robot, tests were conducted using a mock-up switchboard designed in accordance with the IEC 62271-200 standard to perform voltage detecting and grounding tasks, as illustrated in Fig. 9. The instance segmentation model used to identify the 3D target locations of the terminals was initially trained on a dataset comprising images of 20 different types of terminals, each with a resolution of 640×480 pixels. Five real-world switchboard images were augmented to 100 images using a generative adversarial network (GAN) and subsequently expanded to 2,000 images through image processing techniques. This dataset was divided into 70% training data, 20% validation data, and 10% test data for model training. Key hyperparameters for the training process included a batch size of 4 and 100 epochs. The customized segmentation model achieved a sampling rate of approximately 40 Hz, enabling accurate estimation of terminal locations.

To further validate the feasibility of the proposed voltage detecting and grounding process, five first-time users conducted grounding tasks under the guidance of the robot. Each participant repeated the test 20 times, resulting in a total of 100 trials. The voltage detecting process succeeded in all 100 trials, and the grounding process also achieved a perfect success rate of 100 out of 100 trials. These results demonstrate the feasibility and high reliability of the grounding robot. However, as all tests were conducted under uniform environmental conditions, additional validation is required to assess the system's response to unexpected variables or environmental factors.

Additionally, if the robot fails to apply the ground clamp due to external disturbances, the cartesian manipulator cannot retrieve the module autonomously, requiring the human operator to intervene manually, which poses potential safety risks. Therefore, further research is necessary to enhance the system's reliability and achieve a higher success rate. Future studies will focus on performance evaluation in diverse working environments and long-term reliability testing to derive more comprehensive experimental results.

V. CONCLUSIONS

This study developed an AI-integrated robotic system, referred to as the earthing robot, to automate voltage detecting and earthing processes in high-voltage distribution panels, significantly enhancing electrician safety. The robotic system was tested in real-world scenarios and demonstrated its potential to mitigate the risk of electrocution. By automating these safety-critical operations, technicians are no longer directly exposed to high-voltage components, thereby reducing human error and improving overall operational safety.

Despite these advancements, the system is not yet fully autonomous. Tasks such as opening the distribution panel, connecting the earthing clamps to the terminals, and positioning the robot still require human supervision and control. This reliance on human intervention introduces potential risks due to operational or judgment errors. To address these limitations, future research should prioritize increasing the robot's autonomy, minimizing human involvement, and further enhancing operational safety.

In conclusion, while the robotic system developed in this study represents a significant step forward in safer high-voltage maintenance, achieving full automation remains a necessary goal to eliminate hazards. The findings of this study provide a robust foundation for the future development of fully autonomous robotic systems for safe operations in high-voltage distribution panels.

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Crime and Punishment… And Electricity – A Study on Court Cases in Finland Involving Electrical Safety in 2013–2023

Paper No. ESW2025-38

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Abstract – As use of electric power imposes shock, arc flash and fire hazards to workers and the users of the electrical installations as well as to bystanders. Electrical work is strictly regulated in industrialized countries. Exact requirements for both the installations and the competence of the electricians vary country by country. Neglecting the regulations can lead to criminal charges or damage judgments. In this paper, 74 Finnish court cases involving electrical safety are classified and analyzed from a technical and safety perspective. The cases include workplace safety offenses, self-made illegal electrical installations as well as plain electricity thefts. If prosecuted, the trial leads to a guilty verdict in almost every case. If no actual accident happens, persons making illegal installations are typically receive a small fine, but in work safety negligence or systematic illegal contracting the perpetrator can be convicted with jail time or a suspended sentence. In the most severe case reviewed, an improperly installed underfloor heating cable causing a structural fire, killing three adolescent girls However this did not lead to criminal conviction as the offense had passed the statute of limitations. The conclusions of these reviews can be used in improving work safety by learning from incidents and focusing electrical inspections, as well as comparing legal systems and safety legislation to other countries.

Index Terms — electrical safety legislation, work safety, electricity theft.

I. INTRODUCTION

As the use of electric power imposes shock, arc flash, and fire hazards to workers, users of the electrical installations, and bystanders, electrical work is strictly regulated in industrialized countries. Exact requirements for both the installations and the competence of the electricians vary from country to country. Neglecting the regulations can lead to criminal charges or damages judgments.

This paper examines Finnish court cases involving electrical safety. Finland is one of the Nordic countries in Europe, an industrialized country with population of 5.6 million and GDP per capita of 54,000 USD. Fatal electrical accidents are rare in Finland (0–2 casualties per year). Typical fatal accidents involve climbing onto an electric train or a burglary aiming for copper theft. For instance, in years 2020–2022 there were six casualties, of which one was a work accident, two were copper theft and three were young persons climbing on a train at an electrified railway yard. [1] The number of electrical accidents has declined in 40 years from over 10 accidents per year to only few cases per year probably due to improved safety culture, replacing uninsulated overhead lines with insulated lines and ground cabling as well as introducing mandatory safety devices such as GFCI's, and safety wall sockets prohibiting a foreign objects being pushed into wall sockets [2].

The Finnish electrical safety legislation consists of the main law, The Finnish Electrical Safety Act [3] and government decrees which define more technical details and are easier to update than an act, which requires long process in the parliament. For instance, Government Decree on Electrical Work and Operational Work of Electrical Installations [4] defines essential safety requirements in electrical work as well as the top-level course topics which shall be studied in vocational and engineering degrees leading to electrical competences and Government Decree on Electrical Installations defining the essential safety requirements for electrical installations as well as the main requirements for the commissioning and its documentation [5].

The legal system in Finland is a civil law system. The courts are divided in two main systems: one for crime and civil cases (general courts) and one for handling complaints on decisions of the authorities (administrative courts). The first one includes district courts, courts of appeal and the Supreme Court. The second one consists of administrative courts and the Supreme Administrative Court. There exist also courts for special areas such as the Market Court, the Labor Court and the Insurance Court [6].

One distinct feature which limits the use of the court system in civil cases is that in Finnish legal system, the loser of the court case must pay the legal expenses of the winning party [7]. Especially if the case is complex, and the argument concerns a four-digit amount, risk of having to pay 5-digit amount of legal expenses makes it usually unfeasible to file a case unless winning it is almost certain.

In this paper, crime and civil cases involving electrical safety are reviewed to build a picture on which kind of misconduct leads to criminal prosecution or civil argument cases.

II. MATERIAL AND METHODS

For this paper, a request for information was filed to Legal Register Centre of Finnish government, for all criminal and civil cases from years 2013–2023 where the word electrical safety

(Finnish: *sähköturvallisuus*) or electric shock or arc flash or electrical accident is mentioned. In reply, a list of court cases where the word is mentioned in the verdict was received. The individual verdicts were ordered from the appropriate courts. In Finland, the verdicts are publicly available, but they are to be ordered from the court. The keyword search included also the inflectional forms of the keywords, as in Finnish language words are inflected (e.g. *sähköturvallisuus* = electrical safety, *sähköturvallisuuden* = of electrical safety).

Researching a longer time span than 10 past years (2013-2023) would require manual work in all specific court archives, as the Legal Register Centre holds record of only 10-years' time.

From the results, which included 54 criminal cases and 20 civil cases, cases which involved one of the keywords, but the case itself has nothing to do with electricity or electrical safety (for instance, a theft where the electrical safety training certificate was stolen among other items), were pruned out manually.

III. RESULTS

A. The civil action cases

In the 23 civil action verdicts from the data, three were from the court of appeals and one from the Supreme Court, resulting in 20 individual court cases. In 7 of the cases, electricity or electrical safety played only minor role or remained unclear and was barely mentioned in the verdict.

From the remaining 13 cases, 11 were disputes in property transactions: typically, there were self-made or dangerous installations, and the buyer of the house wanted to get a price compensation for getting them fixed by a professional.

In one case, which was appealed to the Supreme Court, a grocery store entrepreneur had rented part of a building for his business since February 2011 and due to an error in electrical installations, the refrigerator of the cold storage of the grocery store was connected in parallel with the energy meter, so the refrigerator ran with unmetered electrical power between 2000–2012 at substantial cost to the plaintiff. The grocery store owner agreed to pay for the electricity he had used in 2011-2012, but the utility company filed a claim for the owner of the building that the property company should pay for the electricity used in 2000–2011. The building was connected to the grid in 1960. The maker of the connection bypassing the meter is unknown. In October 2025, the district court sentenced the owner of the property to pay the unmetered electricity (67,000 EUR ≈ 72,000 USD) to the utility company. The owner appealed, but the court of appeals did not change the verdict in April 2017. The owner of the building appealed to the Supreme Court. The Supreme Court decided that as the maker of the bypass is unknown and Electrical Safety Act has no specific section on bypassing the meter or neither does the utility agreement, the owner of the building is not liable for the unmetered electricity consumption of the previous tenant.

One case dealt with electrical fire safety of a wheel loader. A skid-steer loader caught fire in Siilinjärvi in May 2018, which destroyed a cowhouse and killed 32 cows. The insurance company demanded a 983,841 EUR (1,054,000 USD) and the farmer demanded 72,965 EUR (78,000 USD) of compensations from the manufacturer via product liability legislation for the damages. However, the district court sentenced that there is not enough evidence that the fire was caused by design or manufacturing error and rejected the claim. The farmer and the insurance company have appealed to the court of appeals, but as of November 2024, the appeal has not been tried.

B. The Levi Fire case in April 2019

The most famous case involving electrical safety was the Levi cabin fire, in which three teenage girls died from a fire of an electrical origin. In the accident, an improperly installed floor heating cable caused a fire at night, and 10-, 12- and 14-year old children, who were sleeping upstairs, died inside while their 17-year old sister who was sleeping downstairs was rescued and managed to call the fire brigade. The heating cable had several installation errors according to the accident investigation report [8]:

- The minimum allowed bending radius of the cable was neglected while installing.
- The cable ties used for mounting the cable to the metal mesh under the floor were tightened too much.
- Part of the cable was mounted using clamps which depressed the cable (See Figure 1).
- The cable was laid and bent in a overly tight pattern (causing too much heating power per unit area).
- The cable was partially installed inside a heat insulating material.
- The cable was mounted directly to the wood in some places.

When the cable was installed, using a GFCI and an aluminum foil under the cable was not mandatory, as is the current situation. A GFCI could have possibly, but not necessarily, prevented the fire, as the sheath of the cable is safety grounded.

Fig. 1 The floor heating cable was mounted with clamps which depressed the cable (Image: Lapland Police)

There exists no court case as for the actual suspected crimes, installing the cable without proper competence and installing it against the installation manual resulting in hazard, the limitation period for pressing criminal charges was expired. The expiration time for the severest types of crimes which could be considered in the case, negligent homicide and gross negligent homicide, are 5 and 10 years respectively. As the suspected installation was carried out in year 2005 [9] and the actual fire took place in April 2019 [8], it was not possible to file criminal charges against the electrician and the building contractor involved in the case. As fires killing multiple people, especially children, are not common in Finland, the case drew lots of media attention [10], [11], [12], [13]. A lack of criminal charges does not hinder filing a damage compensation claim case as a civil action, but since the Finnish legal system does not recognize punitive damage compensations, but only actual lost money (or physical or mental pain) can be compensated, it is usually impractical to file a civil case in such accidents. In June 2021, the district court of Itä-Uusimaa confirmed a mediation between the relatives of the deceased children and the electrician, for the damage compensations.

For improving electrical safety, the case is a grave reminder that negligence while doing electrical installations can cause fatal consequences 14 years after the actual installation.

C. Criminal cases involving electrical safety

Criminal cases involving electrical safety are more common than civil cases. In the keyword search, 54 cases were found, including 16 appealed cases.

In many cases, the case itself had nothing to do with electricity or electrical safety. For instance, in one theft an electrical safety training certificate was stolen among other items in a wallet, and in another, electrical safety is mentioned once when discussing an environmental violation when recycling glass from old cathode ray tubes. After pruning such cases, 41 cases of which 12 were appealed, were left for closer examination.

The crime types in the prosecution vary from negligent homicide to violation of electrical safety provisions. Most of the cases, where the main crime has to do something with electrical safety, the crime type is *violation of electrical safety provisions* or *causing danger*. Typically, if the end result is not inherently dangerous but the actor has no formal qualification for the electric work, the crime type is *violation of electrical safety provisions*. If someone gets an electric shock or there are bare live parts from where someone could easily get an electric shock, the crime is more severe, *causing danger*.

Crimes which are not considered especially severe are typically punished by fines. The fines are scaled to the monthly income of the perpetrator.

From the 41 cases, 7 were electricity thefts. Because of smart meters have been installed to all electricity connections in the beginning of 2010’s, the utility company can on a daily basis track if the power output from a distribution transformer does not match to the electricity meters of the customer’s connected to the transformer.

The sentences from the electricity thefts are presented in Table 1. In Finland, a day-fine system like in France and other Nordic countries, is used. One day-fine resembles losing the income of one day salary and is calculated from the net income of the perpetrator. If the perpetrator has no income, one day-fine is €6 euros.

TABLE I
SENTENCES FROM STEALING ELECTRICITY

Punishment	Crime
Day-fine 30 * 14 € = 420 €	A man had connected electric power with an extension cord from the house laundry to his apartment, for couple of days.
Day-fine 30 * 6 € = 180 €	A resident (an electrician) connected electric power to his house by himself, stealing electricity wort 3.25 €.
Day-fine 60 * 26 € = 1560 €	Electric power was cut off due to unpaid bills, after which the resident of the house connected them again bypassing the meter multiple times.
40 day-fines, of 8 € for the other and 19 € for the other	Two men bypassed the energy meter in their apartment.
Day-fine 50 * 6 € = 300 €	The resident connected his house to an overhead powerline by himself. The sentence includes a sentence for negligent driving.
80 days of conditional imprisonment	Some electrical loads were connected by bypassing the energy meter, resulting in stealing electricity worth 5107 €.
65 days of conditional imprisonment	The resident of an apartment stole electricity from a distribution box. The sentence includes a sentence for driving while intoxicated.

The punishments are relatively mild which is common in Nordic countries. Typically, if the perpetrator is first-timer and the crime is not gross, imprisonment sentences under 2 years are given as conditional imprisonments, which means the perpetrator is jailed only if he or she commits another crime during the conditional imprisonment. The only case involving electrical safety where the perpetrator was sentenced to jail was a series of crimes where the perpetrator did electrical contracting for over 3 years without the training and work experience required by law. The main crime type was aggravated fraud, as he got customers by pretending to be a qualified electrician. The perpetrator was convicted to some other financial crimes in the same trial, resulting in absolute imprisonment. Four of the installations he made caused immediate danger, and they were convicted as causing danger.

The crimes involving electricity by crime type are listed in Table 2. In many court cases, there are multiple crimes which are sentenced in the same trial. For instance, if committing an aggravated narcotics offence includes illegal installations, the more severe of the crimes is considered as the main crime type. For instance, growing large amount of cannabis for sale is illegal in Finland and is considered an aggravated narcotics offence. In the two cases listed in Table 2, growing cannabis involved illegal electrical installations, and the perpetrator(s) was convicted for violation of electrical safety provisions also.

TABLE II
CRIME TYPES WITH CRIMES INVOLVING ELECTRICAL SAFETY

Cases	Main crime type
12	Causing danger
8	Occupational safety and health offence
6	Theft
5	Violation of electrical safety provisions
3	Aggravated fraud
2	Aggravated narcotics offence
2	Negligent endangerment
1	Negligent homicide

1	Construction violation
1	Aggravated criminal damage

The most common main crime type involving electrical safety is causing danger. From the 12 instances, 6 involved connecting an electric stove in a potentially lethal way by mixing one of the phase conductors and the protect earth (PE) conductor, making the stove chassis live with 230 volts respect to the ground. The common reason was that a normal construction or renovation worker disconnected the stove to make floor or mat installations and did not know how to connect the wires when connecting the stove back. The stoves in Finland are typically connected with a screw terminal, making it easy for a layman to make a lethal connection. Mixing the phase conductor and PE (in TN-S distribution systems) or PEN (in TN-C distribution systems) conductor is most common lethal installation error and causes immediate danger by making the chassis of the equipment live. The only fatal accident in the criminal case list, the negligent homicide from year 2013, was caused when a plumber mixed phase L3 and the PE connector, making the body of the boiler being installed live.

In houses built before year 1989 in Finland the TN-C earthing system [14] with combined neutral and protect earth (PEN) conductor was used in all electrical installations and GFCI's were not used (Figure 2). Since year 1989, the TN-C-S system became mandatory (Figure 3).

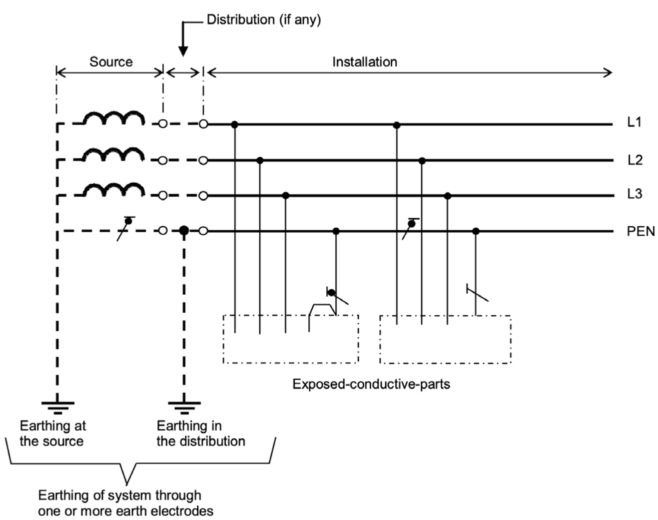

Fig. 2 The TN-C earthing system used in buildings till the year 1989. All loads and socket-outlets are connected to a phase or phases and to PEN conductor. (Image: IEC 60364-1 [14])

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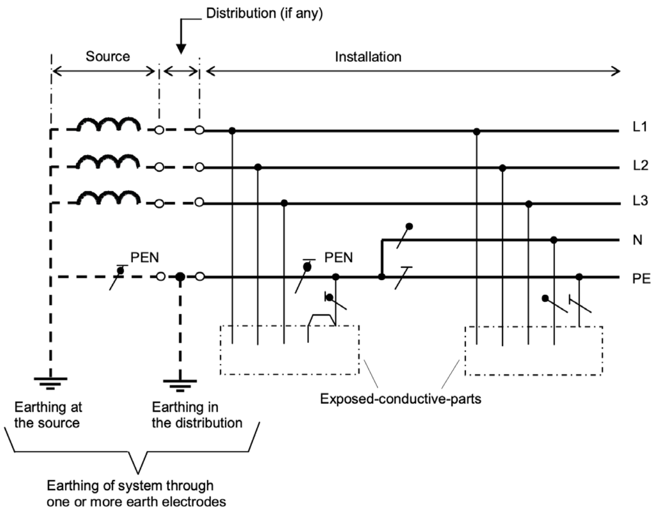

Fig. 3 The TN-C-S earthing system used in buildings since the year 1989. The main board is fed with the TN-C system (L1-L3 + PEN), and the PEN conductor is split to N and PE conductors. (Image: IEC 60364-1 [14])

In the TN-C-S system, all loads and socket-outlets are equipped to separate safety earthing conductor (PE, protect earth) which bonds the chassis of Class I (safety grounded) device to the same potential with the distribution system earth. With the TN-C-S system, mixing the PE and one of the phases with each other will leave the chassis of the device energized. With the TN-C system, the PEN conductor is connected to the chassis of the Class I equipment (PE) as well as the neutral pole of the device (N). The TN-C-S system is considered safer as the PE conductor has distinct yellow-green coloring and in the TN-C system, a broken PEN conductor will cause the chassis of the device to come energized via the internal circuit of the device. If the L and PEN conductors are intermixed when connecting the load or the wall socket, the chassis of the device will directly have 230 V voltage in respect to the ground potential.

The instances of the second most common main crime type, occupational safety and health offence, are listed in Table 3. In all the cases, the punishment was 20–60 day-fines. In two cases, the company was also sentenced to pay fines.

TABLE III
SENTENCES FROM OCCUPATIONAL HEALTH AND SAFETY OFFENCES

Punishment	Crime
Day-fine 60 * 39 € = 2340 € for the foreman, 40 * 37 € = 1480 € for the CEO	Three workers were severely injured from an electric shock while unloading a truck on a construction site so that the boom of the crane got too close to a 110 kV transmission line.

Day-fine 25 * 95 € = 2375 € for the electrical work supervisor	A cleaner got an electric shock from a lighting track with a missing terminal at the end. The shock led to *complex regional pain syndrome*.
Day-fine 25 * 73 € = 1825 € for the foreman, 50 * 44 € = 2200 € for the HSEQ coordinator	Due to neglected safety planning, a non-electrical worker got too close to 110 kV part and an electric arc was lit between him and the part.
Day-fine 25 * 20 € = 500 € for the foreman	While working with district heating piping, a 400 V ground cable was lifted a little with a crane. The insulation was damaged which led to an arc flash causing burns to worker's hand.
Day-fine 50 * 6 € = 300 € for the CEO	A gas station worker got an electric shock from a deep fryer which had already been reported faulty by other employees.
Day-fine 30 * 38 € = 1140 € for the safety supervisor and 6000 € fine for the company	A worker got an electric shock when erecting a street light pole, when the pole got too close to a 20 kV overhead line.
Day-fine 20 * 40 € = 800 € for the foreman, 20 * 39 € = 780 € for head of work safety and 20 * 59 € = 1180 € for project manager	An electrician fell 5 meters in a power plant due to two loose bolts in a structure over a generator.
Day-fine 50 * 340 € = 17000 € for CEO who was also electrical work supervisor, 50 * 352 € = 17600 € for foreman and 30000 € fine for the company.	An electrician stepped on a 20 kV busbar on a transformer which was assumed to be de-energized for dismantling.

One peculiar observation in the occupational health and safety offences was that in six of eight cases, the victims were non-electrical workers. Of two electrical workers, one was a falling accident not involving electrical cause and the other was an electrician working on a site where a transformer was to be dismantled – a work which could be done by a non-electrical worker. Although the number of cases is low, this is in line with observations in the United States: for instance, only 27% of workplace electrical fatalities are working in electrical occupations. [15] Therefore it has been suggested that the all workers, not just electrical workers, should be trained on how to avoid electrical hazards. [16]

Furthermore, someone was found guilty in every case and convicted to a fine. This is not surprising, as according to district court statistics, 95 % of criminal charges in Finnish courts lead to conviction. [17] The rate is high as in Finland there is no option to plea bargaining outside court, although some crimes, like minor assault, can be settled with mediation.

IV. CONCLUSIONS

Most of the civil lawsuits concerning electrical safety are disputes in property transactions, for fixing self-made or dangerous installations from the previous owner.

In criminal lawsuits, a prominent type of endangerment is a case where a layman (carpenter or other construction worker) detaches an electric stove and connects it back to the connector in the wall after finishing their work. If the phase conductor and protect earth conductor are mixed with each other, the full mains voltage prevails in the frame of the stove and touching it would cause a lethal electric shock.

Such accidents could be prevented by emphasizing the importance of using trained electricians, enforcing plug-and-socket connectors for household equipment such as boilers and stoves as well as enforcing the use of GFCIs in all household electric circuits.

Enforcing the use of GFCIs is probably an efficient way to combat severe accidents caused by wrongful installations, as the device will trip in case where a person gets an electric shock from a chassis of wrongly connected stove or boiler. One challenge is that for many devices which are connected with a screw terminal, a GFCI is not mandatory in the panelboard. Currently, the Finnish installation standard SFS 6000:2022 [18] requires GFCIs only in wall sockets and lighting circuits.

For occupational health and safety offences leading to injuries, the punishments were typically same magnitude (30 day-fines) than for stealing electricity worth negligent amount of money. Theft is a deliberate act and work safety offences are typically a result of negligence, although causing a physical injury can be argued to be more severe result than a company losing electricity for a one-digit amount of money.

With only a few exceptions, all the crime cases involving electrical safety do happen with nonelectrical professions. Raising awareness for electrical risks for nonelectrical work as well as the fact that electricity theft is noticed in days due to smart metering, could increase electrical safety and raise the bar for conducting illicit acts involving electricity.

V. ACKNOWLEDGEMENTS

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VII. VITA

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Currently, Linja-aho is a full-time electrical safety consultant and textbook author, focusing on battery and electric vehicle safety and testing laboratory accreditation assessment. In the IEC, Linja-aho is the chair of working groups IEC TC 1 MT 100, which maintains the international electrotechnical vocabulary on fundamental concepts and IEC PC 128 WG 2, which aims at developing an international standard on safety of operating electrical installations.

Using AI and VR for Electrical Safety Training

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Abstract - In response to the continuing electrical workplace incidents and in particular the stagnant electrical shock death rates ~120/year over the last 11 years [1], there is a critical need to accelerate and "revolutionize" electrical safety training methodologies. This abstract proposes a holistic approach that integrates Artificial Intelligence (AI) into both the design and delivery of training programs. This is done by combining the Systematic Approach for Training (SAT) with the ADDIE (Analysis, Design, Development, Implementation, and Evaluation) process. The following 3 aspects of electrical safety training can bring real and sustainable improvements to the electrical sector.

(1) Using an innovative technique- Systematic Approach for Training (SAT) process to improve performance in the design and development of high impact and valuable electrical safety training.

(2) Using Technology such as Artificial Intelligence (AI) in the construct of that training.

(3) Incorporating leading edge Technology such as Virtual Reality / Augmented Reality (VR/AR) in addition to hands on training in the implementation and evaluation phase of ADDIE (Analysis, Design, Development, Implementation, and Evaluation) for electrical safety training.

If the SAT process is used properly, especially in the Analysis and Design phase coupled with the appropriate technology, electrical safety training will be far more effective. Then it comes down to a quality delivery and using the appropriate modern technology technologies in such a manner as to make it impactful, and effective. By incorporating this approach electrical safety training can provide a significant return on investment (ROI).

Index terms – Electrical Safety, training effectiveness, systematic approach, ADDIE, training design, Virtual Reality, Augmented Reality, Artificial Reality

I. INTRODUCTION

Electrical safety remains a critical concern in workplaces across various industries. Despite advancements in our technology and safety protocols outlined in the latest revisions of OSHA or NFPA 70E/CSA Z462, the rate of electrical-related incidents, particularly fatal electrical shocks, has remained alarmingly consistent. According to the Electrical Safety Foundation International (ESFI), approximately 120 deaths per year have been attributed to electrical shocks over the past 11 years. This stagnant mortality rate underscores the urgent need for a paradigm shift in electrical safety training methodologies. Given that equipment design, enforcement and field observations are taking place the variable remaining is with how we train the people.

Traditional approaches to electrical safety training, while foundational, have not kept pace with the rapidly evolving technological landscape. The persistence of workplace electrical incidents suggests that current training methods may be insufficient in effectively conveying critical safety information or in fostering lasting behavioral changes among workers. As such, there is a pressing need to revolutionize and accelerate the development and delivery of effective electrical safety training programs.

This paper proposes a holistic approach to electrical safety training that leverages cutting-edge technologies and established educational frameworks. By integrating Artificial Intelligence (AI) into both the design and delivery of training programs, the aim is to create a more dynamic, personalized, and effective learning experience. This approach combines the Systematic Approach for Training (SAT) with the ADDIE (Analysis, Design, Development, Implementation, and Evaluation) process, enhanced by AI and immersive technologies.

The proposed methodology focuses on three key aspects:

1. Utilization of the Systematic Approach for Training (SAT) process to improve the design and development of high-impact electrical safety training.

2. Integration of Artificial Intelligence (AI) in the construction and customization of training materials.

3. Incorporation of Virtual Reality (VR) and Augmented Reality (AR) technologies, alongside hands-on training, in the implementation and evaluation phases of the ADDIE process.

By addressing these aspects, we aim to create a comprehensive and innovative approach to electrical safety training that can bring about real and sustainable improvements in workplace safety from the smallest companies to large corporations and facilities. This paper will explore the theoretical foundations, methodological approach, and potential outcomes of this integrated training framework, providing a roadmap for revolutionizing electrical safety education in the modern workplace.

II. SAT/ADDIE – INSTRUCTIONAL DESIGN MODEL

The Systematic Approach for Training (SAT) serves as the foundational framework for our proposed methodology. SAT is a comprehensive, iterative process that ensures training programs are designed, developed, and delivered in a manner that effectively meets the needs of both learners and organizations. The SAT process ensures that the people being trained get the training they need to improve performance. The training given is aligned with organizational goals and policies. Trainees are evaluated as well as the training process is set up for continuous improvement.

Various models exist to aid in instructional design such as ADDIE, Gagne's, Merrill's and many others. All methods have pros/cons however a tried and true method over the last 40+ years is the ADDIE process. It is also the most widely used due to flexibility and its ability to integrate new technology [2].

The ADDIE model [3] consists of 5 phases:

<u>Analysis</u>- In this phase we determine what the training need is. How do we do this?

a. We determine if there is a training need based on observations, audits, requests from technicians/supervisors, or recent industry or personal failures.
b. We determine the audience that will be trained
c. We determine the evaluation method to be used in order to determine if training hit the mark.

<u>Design</u>- Based on the analysis, learning objectives are developed and exam questions written. In this area most focus on cognitive and psychomotor skills; however, based on the above stagnation in electrical fatalities the affective domain must be considered and incorporated into the training material and performance scenarios. The Affective Domain is the "Behaviors" to be considered.

Objectives are 3 parts:

a. Condition- What is the scenario for the task
   Example: Given an energized 480Volts AC(VAC) Power Panel troubleshooting scenario
b. Behavior- What do you want the technician to do
   Example: Demonstrate the ability to select the proper Personal Protective Equipment PPE
c. Standard- What standard should the technician be trained and evaluated to. Be specific in this case.
   Example: In Accordance with the NFPA 70E section art. 130.7 / CSA Z462 Clause 4.3.7
   All together the objective would be written as - Given an energized 480VAC Power Panel troubleshooting scenario, Demonstrate the ability to select the proper PPE In accordance with (IAW) NFPA70E section art. 130.7. or CSA Z462 Clause 4.3.7

<u>Development</u>- This is the phase where Training materials, including content, assessments, and supporting resources, are created in this phase. For electrical safety training, this may include developing the classroom material, presentation and the practical exercises- scenario-based exercises, interactive simulations. They also build the mockups or set up the environment for the exercises. All the material is then approved by the line supervision after incorporating any comments. This is a collaborative effort between the instructional designer and the actual technicians/supervision in the field.

<u>Implementation</u>- The training program is delivered to the target audience. This phase considers various delivery methods, including classroom instruction, e-learning modules, and hands-on practical sessions. Administering of the examination and the performance evaluation is also accomplished. The goal in this phase is "Mastery" of the objectives. To help with this mastery examination/performance evaluations are crucial to hold participants accountable for the learning process.

<u>Evaluation-</u> The effectiveness of the training program is assessed through various metrics, including learner feedback, knowledge retention rates, and improvements in workplace safety indicators. This phase ensures continuous improvement of the training program. Using the ADDIE approach in all phases ensures that high quality training will be performed and evaluated. This is crucial to Electrical Safety training. The training needs to fit the trainees and the evaluation needs to test both cognitive and skills.

III. ARTIFICIAL INTELLIGENCE

Artificial Intelligence (AI) is leveraged to enhance various aspects of the training development and delivery process, making the learning experience more personalized, adaptive, and effective.

Key Applications of AI in Electrical Safety Training:

1. Content Creation:
a. AI algorithms can analyze vast amounts of electrical safety data, incident reports, and industry standards to generate relevant and up-to-date training content. The input and output of these "Prompts" are limited based on Token size. What is a Token [4]? Generally a token is a word. Large Language Model (LLM) AI's use tokens to analyze and return a response to a user. Some AI models limit the input to a few thousand tokens, while others are hundreds of thousands of tokens.

When using AI to help in creating content the user needs to match up the appropriate AI to the amount of data (Tokens) that will be analyzed by the AI. Are you uploading a procedure, policy etc? If your AI is limited you will need to truncate your input into multiple sessions.

b. Example of using AI to generate content: The instructional designer can assign the AI the Role of an Instructional Designer and then ask the AI to generate 10, 3 part objectives with an even mix of cognitive and performance based objectives utilizing your company's procedure and NFPA 70E / CSA Z462 as a standard.

Once the 10 objectives are developed the instructional designer can then prompt the AI to develop the lesson plan material including Power Point Slides. Example prompt would be using the 5 cognitive objectives develop the lesson plan to teach these objectives. After the lesson plan material is completed you can then ask the AI to develop the (Visual Basic) VBA code to provide however many slides based on the material in the lesson plan.

One key note in using prompts is the need to be iterative in the process. Rarely can you ask a prompt that will give you everything you need. At times, the material provided by the AI is in error and will need to be corrected. For example if the LLM you used to develop the above gives just a sketch/outline of the lesson plan or you desire a more detail in the material, ask the AI to provide more detail based on your need to support your training.

Once you have Objectives, Lesson Plan, you can develop exam questions. For example: ask the AI to develop 5 multiple choice questions per cognitive objective with answers and plausible distractors. You may have to iterate this some to fine tune your questions.

After this you are ready to have AI generate your laboratory/field training activities. As above use a prompt to have the AI develop a comprehensive performance training activity using available mock up equipment you have. Inside of 20 minutes the above material can be generated and edited to support a high quality training session that utilizes classroom and hands on exercises. Is this expedited approach with AI important? Yes. It allows the instructional designer to have a more comprehensive framework with which to start with allowing the designer to focus more on student centered innovation vice template formats and basic material.

2. Personalized Learning:
   a. Machine learning algorithms can assess individual learner profiles, including prior knowledge, learning styles, and job-specific requirements with a pre and post-assessments.
   b. Adaptive learning systems then will create customized training sequences that address each learner's unique needs and knowledge gaps.

3. Intelligent Assessment (Adaptive Assessment) [5]:
   a. Using the questions developed above AI can provide the adaptive assessment and provide real-time feedback on learner performance.
   b. Predictive analytics identify areas where learners may need additional support or practice.

4. Framework of design facilitates a collateral duty:
A supervisor in small organizations that have no training support can use this approach with very little training and create high quality training the technicians need in a very short period. This allows the supervisor to focus on their primary responsibilities and yet provide high quality and comprehensive training materials that are student centered and needs based.

IV. USE OF VIRTUAL REALITY/AUGMENTED REALITY IN ELECTRICAL SAFETY TRAINING

Virtual Reality (VR) and Augmented Reality (AR) technologies are integrated into the training program to provide an immersive, hands-on learning experiences that simulate real-world electrical hazards and safety procedures. Kolb's Experiential Learning Theory [6] emphasizes the importance of engaging a learner on an emotional level. This engagement can enhance their attitude towards learning and improve their motivation. VR engages the user on an emotional level with near total immersion into the scenario.

1. Hazard Recognition:
   - Many providers of training in the healthcare [7] and maintenance industry are using VR [8] to place the trainees into an environment that simulate various workplace scenarios, allowing learners to identify and assess electrical hazards in a safe, and controlled setting. VR scenarios can safely demonstrate the consequences of electrical safety violations, creating impactful learning experiences without real-world risks. This starts to impart a lasting impact via the affective domain.

   - AR overlays can highlight potential dangers in real work environments during on-site training.

2. Procedural Training - VR simulations guide learners through step-by-step procedures for tasks such as lockout/tagout, equipment inspection, and emergency response. The USAF is pioneering the integration of VR/AR into their maintenance training program [9]. The generation today are comfortable with the VR/AR technology which then makes this approach a natural extension of their existing level of knowledge.
- Haptic feedback in VR controllers can simulate the physical sensations of handling electrical equipment. This leads to the development of a cognitive muscle memory in the technician.

3. Collaborative Training:
   - Multi-user VR environments enable team-based training exercises, fostering communication and coordination in electrical safety training. There are many available platforms that set up a virtual classroom which allows training to take place on a global level. These Virtual Classrooms have tables for avatars to sit at for up to 80+ people at a time. For those who do not have a VR headset, a monitor at the head of the VR table is provided to allow those people to participate, very similar to a video conference call. The virtual classroom has a whiteboard area where people can individually go to and run slide presentations, show videos and such. The immersive nature of VR improves the engagement [10] as well as the motivation and enjoyment of the training session. Additionally, VR can change behaviors (Affective Domain) in safety training.

4. Integration with Hands-on Training:

VR/AR technologies offer significant advantages. This technology is designed to complement not replace traditional hands-on training. The proposed methodology incorporates a blended approach:

- VR/AR simulations prepare learners for hands-on sessions, reducing the learning curve and improving safety during practical training. Using VR/AR will help the trainee gain proficiency as well as muscle memory prior to performing the tasks in the real environment.
- At a Nuclear power facility a class I recently taught using VR on a vacuum circuit breaker shortened the class by 67% (3 weeks to 1 week) and lowered the hours of maintenance through proficiency by 38% (32 hours to 18 hours). The students used 3D modeling and VR software prior to actual performance and assessment in the laboratory. This technique allowed the trainees to gain sufficient proficiency and confidence in maintenance that transferred into the plant when doing the maintenance.
- Hands-on training reinforces skills learned in VR/AR environments and addresses aspects of electrical work that require physical electrical hazard interactions. There is some tactile difference between VR and real world application, however, the conversion to real world is small in comparison to no VR access.
- AR can be used during hands-on training to provide real-time guidance and safety reminders.

By combining the SAT process, AI, and VR/AR technologies, this methodology aims to create a quickly produced, comprehensive, flexible, and highly effective approach to electrical safety training. The synergy between these components addresses the complexities of modern electrical work environments and the diverse needs of learners, potentially leading to significant improvements in worker behavior and workplace safety outcomes.

V. CONCLUSIONS

The approach in using SAT/ADDIE will aid the industry in providing high quality, consistent training with measurable results that will improve worker performance.
The proposed AI-integrated approach to electrical safety training represents a significant paradigm shift in how we prepare workers for the challenges of the electrical industry. The introduction of AI into safety training allows for an unprecedented level of personalization while maintaining scalability in an efficient time frame. This addresses a long-standing challenge in training program design – the tension between standardization for consistency and customization for effectiveness within the shortest timeframe as possible. Training programs can now adapt in real-time to individual learning styles, prior knowledge, and job-specific requirements, possibly leading to more engaged learners, changed behaviors and better knowledge retention.
Safe Exposure to High-Risk Scenarios. VR simulations allow trainees to experience and respond to dangerous situations without physical risk. Workers can develop critical decision-making skills and emotional resilience for high-stress situations, potentially reducing freeze responses in real emergencies. The challenge is ensuring that the psychological impact of realistic hazard simulations is managed appropriately, particularly for trainees who may find such experiences distressing.
Technical Infrastructure Requirements for using AI, VR/AR require a certain level of technological infrastructure. There's a risk of creating a "digital divide" in safety training quality between well-resourced and under-resourced organizations or regions. The cost and technical skill required are continuing to be reduced to a scalable solution that can deliver the benefits of the technology without requiring a significant capital investment. The shift to AI-driven systems requires new skillsets among training developers and administrators. Organizations will need to invest in upskilling their training personnel or recruiting individuals with AI and data analysis skills. The challenge will be in bridging the knowledge gap between traditional safety training expertise and the technical skills required for AI, VR/AR-integrated systems.

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VIII. VITA

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How to Be the Employee in Charge (EIC) for a High Voltage TASK

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Abstract – This paper will examine some of the responsibilities that are required to become the Designated Person called the Employee in Charge (EIC) for a High Voltage task or switching operation. This is a very critical responsibility for a qualified person to oversee a High Voltage task or switching operation and be responsible for the safety of all personnel involved on the job. Frequently, in High Voltage training classes, a question is asked as to how to become the Employee in Charge (EIC) and what is involved once you are assigned to that position. A lot of people do not understand the seriousness and importance of this position.

All High Voltage jobs require that there be a designated person called the Employee in Charge (EIC), prior to starting the job. This is a specialized leadership role that requires proper training and technical understanding of High Voltage systems with good communication skills. It does not require that this person be the supervisor on the job.

Index Terms — Employee in Charge (EIC), Designated Person, High Voltage Systems

I. INTRODUCTION

The Employee in Charge (EIC) is the Designated Employee as defined in OSHA 1910.269(x). [1] That person is defined as:

Designated Employee (Designated Person)

An employee (or person) who is assigned by the employer to perform specific duties under the terms of this section and who has sufficient knowledge of the construction and operation of the equipment, and the hazards involved, to perform his or her duties safely.

This person must be a qualified High Voltage person, per their company's procedures, to perform this job.

National Fire Protection Association (NFPA) 70E® [2] gives the definition of a Qualified Person as shown in Fig 1 Qualified Person.

Qualified Person.

One who has demonstrated skills and knowledge related to the construction and operation of electrical equipment and installations and has received safety training to identify the hazards and reduce the associated risk.

Fig 1 Qualified Person

NFPA 70®, 70E®, and Standard for Electrical Safety in the Workplace® are registered trademarks of the National Fire Protection Association, Quincy, MA.

Therefore, given the definition of a Designated employee as defined in OSHA 1910.269(x), the EIC person must be a qualified High Voltage person to perform this role. However, the key item is that person does not have to be a supervisor. It can be any member of the team doing the work. [3] OSHA and consensus standards National Electric Safety Code (NESC) C2-2023 make it a point to require an EIC on all High Voltage job sites. [4]

The NEC code states that a "designated person shall be in charge of the operation of the equipment and lines and shall be responsible for their safe operation." It also states that if "more than one person is engaged in work on or in the vicinity of the same equipment or line, one person shall be designated as in charge of the work to be performed. Where there are separate work locations, one person may be designated at each location." An example of this would be a complex lock out switching operation in which crews have to be stationed in multiple control houses or locations to perform the lock out. However, if this is the case, it is very important that the EIC persons at the various locations maintain full communication between them while the job is being performed. It is also very important that the written switching order be followed exactly as written. If it becomes necessary to deviate from the written plan, the job must be stopped, the plan rewritten and approved, and the job started over again. A new job briefing planning meeting must then be held with all the people involved in the job. In effect, it becomes a brand-new job.

II. ROLES AND RESPONSIBILITIES OF EIC

There are four basic roles and responsibilities of the EIC when performing a High Voltage task or switching operation. [5] These will now be examined in more detail.

A. Conducts Job Briefings

Prior to starting a job, there must be a group job briefing meeting led by the EIC to review the job plan details with all the people involved in the job. There may be additional meetings required for things like shift change or personnel change or if there is a change in job scope. The EIC must fully understand the task, procedures, and the specific responsibilities of each person on the team. This is where the communication skills of the EIC become very important. Everyone needs to fully understand their responsibilities. When using more than one EIC due to remote locations, one person must be designated as the Master EIC who is responsible for the entire job.

Things to be covered in this meeting are listed below:

1) Details and scope of the work.
2) All hazards that may be present. These could be more than electrical like weather when working outdoors.
3) All applicable safety rules. These would include any special rules associated with the operating process.
4) PPE and tools that are needed to safely perform the task. A job risk analysis needs to be performed for the task to be done. The result of that analysis needs to be reviewed in this job briefing meeting
5) Sequence of events. If performing switching, a written switching order needs to be available for all people. One good suggestion for this item is when the EIC reads the instruction, the person receiving it repeats it back. This will help to make sure the instruction was received correctly.
6) Grounding. Anytime a ground cable is applied by any person involved in the job, be it a company person or a contractor, the location of the ground cable must be included on the written switching order. This will help ensure that it is removed before power is applied. The EIC needs to make sure this happens for all ground cables that may be applied. At the end of the job, all ground cables need to be accounted for.

B. Ensures Everyone Follows All Safety Rules and Procedures

The EIC needs to make it clear that everyone must follow the instructions on all safety rules and only do things when specifically directed by the EIC. This would include any unique special safety rules associated with the process. No work is to be performed without the direct approval of the EIC person. Communication is critical when performing High Voltage tasks or switching operations. Any miscommunication can lead to a very serious incident.

C. Determines What Safety Precautions Are Necessary

These will be specific to the job site and the company. Each job will have specific safety precautions, beyond the High Voltage ones, that will need to be followed. It is very important that the EIC understands these precautions so everyone can be directed to follow them. It is very important that the EIC have a very detailed knowledge of the process in which the work is being performed. Additional things that can help in this area would be the arc flash labels and the Tables in NFPA 70 E Standard. These will help define the Personal Protective Equipment that may be needed for the job. However, it is very important that the EIC have a very good understanding of the process for which the work is being done.

D. Obtains and Releases All Clearances

This needs to be done for both upstream and downstream customers. A High Voltage breaker cannot be arbitrarily opened or closed. The work needs to be coordinated with the upstream and downstream customers and the steps need to be defined on a written switching order or a Job Safety Analysis (JSA). Everyone on the job needs to know what steps will be taken to perform the work needed. This is another area where communication skills are critical so both upstream and downstream customers know what to expect.

III. TASKS ONLY A QUALIFIED PERSON MAY PERFORM

The following are tasks that only a qualified High Voltage person can perform. [5] It is important that the EIC understands these qualifications to keep people from getting hurt while performing the tasks needed for the job.

A. Test Energy Sources

Prior to applying any grounds, it is very important to perform a Live-Dead-Live test to make sure all feeds and any back feeds have been turned off. This must be done prior to applying the grounds on the circuit.

B. Be the High Voltage EIC

To be the High Voltage EIC, that person must be a qualified High Voltage person.

C. Perform Work on Energized Equipment

Doing a Live-Dead-Live test or applying the grounds on the circuit is considered performing work on energized equipment as it has not been put into an electrical safe work condition.

D. Act As Observer

Whenever live-line High Voltage work is performed, an observer must be present. This person serves two functions. One is to check the person doing the work is doing it correctly. The second is to be the safety person should something go wrong. This person must be a qualified High Voltage person. The key thing is this person must stay outside the work area. Therefore, if something does go wrong, they can be available to come in and perform the rescue function.

E. Escort Unqualified People into The Area

Sometimes it is necessary to bring an unqualified High Voltage worker into the work area while the job is ongoing. If this needs to be done, that person must be escorted by a qualified High Voltage person. That escort person must provisionally qualify the unqualified High Voltage worker by explaining all the various high voltage hazards in the area. That qualified person's primary responsibility is to watch over the unqualified worker. That person cannot get actively involved in the job task that is being done. The EIC has total responsibility to safeguard the person in their care.

IV. CONCLUSIONS

When one is chosen for the position of Employee in Charge (EIC), by the employer, it is a very important part of the assignment work needed to perform a High Voltage task or switching operation. That person needs to be trained not only in technical skills but also in communication skills with a full understanding of the process involved. Each company has their own procedures for what is needed to be trained in High Voltage work for demonstrated competence in according to OSHA and NFPA 70E such as PPE, control of hazardous energy, hazardous communication, etc. Communication skills are a special unique training required to become an EIC.

V. ACKNOWLEDGEMENTS

I would like to recognize all the many students in the electrical High Voltage safety classes who have participated in the discussions on the role of the Employee in Charge (EIC) for High Voltage systems. Their comments brought many different perspectives as to the role of the EIC to help keep people safe when working around High Voltage systems.

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VII. VITA

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Joe Rachford retired from a lengthy career in the steel industry. Towards the end of his career, he designed a brand new skills based technical training program for electrical and mechanical craft people. Prior to that, he was responsible for all power distribution systems in the plant from the incoming 345 kV lines down to the 480-volt distribution breakers. Over the years, he served in a wide variety of electrical maintenance managerial positions for power distribution, drives systems, and instrumentation for a power generating station.

He holds a BSEE degree from the University of Cincinnati and a MS Management degree from Purdue University. He is a Senior member of IEEE and a Life Member of American Iron and Steel Technology (AIST). He holds one patent and has presented several technical papers to IEEE, NETA and AIST.

Investigation of the Quality of Electrical Installations in Commercial Properties in Brazil

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Abstract – In 2023 alone, ABRACOPEL - the Brazilian Association for Awareness of Electrical Hazards, recorded 2,089 electrical accidents in Brazil, including fires, electric shocks, and lightning strikes, resulting in 781 deaths. It was observed that most accidents are related to the poor quality of electrical installations. Until the time of this study, there was no published document describing the quality of Brazilian building electrical installations. This research aimed to map and evaluate the quality of electrical installations by identifying the main deficiencies and promote awareness of the need for improvements. The methodology involved the application of 494 questionnaires in different states and regions of Brazil, covering urban and rural areas. The study reveals that few properties have electrical drawings, and many installations are done by unqualified professionals. While grounding systems and circuit breakers are common, the lack of residual current and surge protection devices poses significant safety risks. The conclusions highlight the urgent need for awareness and implementation of electrical safety measures in commercial properties to ensure user protection and installation efficiency.

Keywords — Electrical Installation Quality; Commercial Properties; Brazil; Safety Standards; Grounding and Protection Systems.

I. INTRODUCTION

Electricity power distribution is a fundamental aspect of any building, whether residential or commercial [1], [2], [3], [4]. In commercial properties, where the electricity demand is greater and the amount of people is significant, ensuring that electrical installations comply with technical standards becomes even more critical [5], [6], [7], [8]. This study aims to investigate the current state of electrical installations in commercial properties in Brazil, focusing on critical elements such as electrical designs, protective devices, installation practices, and the condition of electrical cables. The objective is to identify possible security gaps, raise awareness, and promote measures that guarantee the integrity and security of these environments.

II. METHODOLOGY

The survey was conducted by professionals collaborating with Abracopel, who had been trained remotely on the established guidelines and evaluation criteria.

Four hundred ninety-four completed questionnaires were obtained, representing a comprehensive sample distributed across all regions of the Brazilian territory, including the Federal District. The investigation covered different states and provinces, providing a detailed analysis of the conditions of electrical installations in commercial properties. The sample included properties in urban and rural areas, allowing comparisons between these two contexts. Furthermore, properties were categorized according to the size of the cities, using the number of inhabitants as a classification criterion.

Data collection was carried out through structured questionnaires, which addressed aspects such as location of the property, type of property, purpose, age, functional area, type of construction, existence of an electrical drawing, execution of installations, protection against overcurrent and surges, grounding system, use of relocatable power tap and extension cords, renovations carried out, perception of safety, occurrence of accidents and presence of photovoltaic generation systems.

The data was tabulated and analyzed, allowing the identification of trends, security gaps, and relevant factors related to electrical installations in commercial properties in Brazil. This study seeks to provide an overview of the characteristics and conditions of electrical installations, contributing to the formulation of initiatives aimed at improving electrical safety, protecting users, and preventing accidents.

III. RESULTS AND DISCUSSIONS

Analysis of survey data reveals essential disparities in the distribution of respondents in different regions of the country and population groups. The geographic distribution of respondents (Table 1) shows that the majority are concentrated in the Southeast region of Brazil, with 254 respondents, equivalent to 51% of the total. However, when the data are adjusted for population, the Southeast has 3.0 respondents per million inhabitants, a higher proportion than the national average of 2.4 respondents per million. This concentration may be related to the region's high population density and more robust economic development, which attracts more commercial infrastructure and corresponding electrical installations.

TABLE I
DISTRIBUTION OF RESPONDENTS BY REGION IN RELATION TO POPULATION

Region	Responses	Population (x 1 mill.)	Respondents (per mill. inh.)
North	33	17.4	1.9
Northeast	105	54.7	1.9
Southeast	254	84.8	3.0
South	58	29.9	1.9
Central-west	44	16.3	2.7
Total Respondents	494	203.1	2.4

On the other hand, regions such as the North and Northeast, despite representing together a significant part of the Brazilian population (72.1 million inhabitants), have only 1.9 respondents per million inhabitants, suggesting lower participation in the research. The Central-West region, with a density of 2.7 respondents per million, also presents a proportionally high participation, which may reflect this region's rapid economic and urban growth. The classification of population areas (Table 2) reinforces the observation that most respondents inhabit large metropolitan areas, with 98 respondents in areas with more than 5 million inhabitants and 106 in areas with 1 to 5 million inhabitants, resulting in a high participation rate (4.8 and 5.0 respondents per million inhabitants, respectively). These densely populated urban areas tend to have large commercial enterprises, often requiring more complex and standardized electrical installations. These results explain the greater participation of respondents in these ranges, given the likely greater regulatory control and inspection in more economically developed areas.

TABLE II
DISTRIBUTION OF RESPONDENTS BY URBAN POPULATION (INHABITANTS), SIZE AND DENSITY

Area and Pop. Range	Respondents	Population (x1 mill.)	Respondents (per mill. inh.)
Urban: More than 5 M	98	20.5	4.8
Urban: More than 1 M up to 5 M	106	21.0	5.0
Urban: More than 500 k up to 1 M	64	17.9	3.6
Urban: More than 100k up to 500 k	131	58.0	2.3
Urban: Up to 100k	81	85.7	0.9
Rural	14	-	-
Total Respondents	494	203.1	2.4

Nevertheless, urban areas with less than 100 thousand inhabitants have only 0.9 respondents per million inhabitants, suggesting less formalization and possible underreporting of electrical problems in regions with lower population density. Rural areas, which constitute only 3% of respondents, also reflect limited participation, which may be related to the low concentration of commercial enterprises and the lower regulatory requirements in terms of the adequacy of electrical installations.

The comparison between the density of respondents and population groups reinforces the disparity in the quality and safety of electrical installations between more urbanized regions and those with lower population density. The most densely populated areas and the most significant commercial infrastructure demonstrate greater adherence to standardized practices, such as grounding, circuit breakers, and surge protection systems. However, a substantial number of properties still need a formal electrical drawing (49%), which reveals a critical gap in the planning and execution of installations.

A. General Building Information

Section 3.A presents an overview of the distribution and characteristics of the commercial buildings analyzed. Most respondents are concentrated in the Southeast region, with 51% of responses. However, when adjusting the data by population, the Southeast has a higher proportion of respondents per million inhabitants (3.0), suggesting greater formalization and awareness about the electrical conditions of commercial installations. The North and Northeast regions, with 1.9 respondents per million inhabitants, have lower adherence, possibly related to barriers to accessing information and resources for improvements in electrical installations.

In terms of property location, 78% are located on high-traffic streets or avenues, which indicates the predominance of commercial areas with greater movement and, possibly, greater demand for electricity. However, 43% of properties are residential converted to commercial use, a situation that presents significant challenges in terms of adapting electrical installations to support the new demand. This underscores the need for innovative solutions in the field. Furthermore, 21% of properties are over 30 years old, which implies a growing need for renovations and updates to facilities as electrical safety standards evolve.

Regarding the design and technical responsibility and execution of electrical installations, 174 respondents (36%) answered "YES" that the building has an electrical drawing, while 238 (49%) answered "NO" and 76 (11%) were unable to answer. Among the 36% of respondents who answered "YES" to the existence of a drawing, 23% responded that electrical engineers or electrical technicians did not prepare the electrical drawing. It is concluded in this study that only 25% of commercial electrical installations (123 responses out of 448) have electrical drawings with adequate technical responsibility, demonstrating the possibility that 75% of commercial electrical installations in Brazil have uncontrolled risks.

Some questionnaires were not fully completed by respondents, resulting in variations in the total number of answers for certain questions. This is reflected in some tables, where fewer responses are recorded than the 494 questionnaires collected overall. Factors such as a lack of specific knowledge, perceived irrelevance of certain questions, or intentional omission of information may have contributed to this discrepancy. These variations were carefully considered during data analysis to ensure the reliability and consistency of the findings.

TABLE III
SURVEY OF PROPERTY CHARACTERISTICS, OWNERSHIP, AND ELECTRICAL INSTALLATION PRACTICES IN BRAZIL.

1 – Region.		
Answer	N	%
Southeast	254	51%
Northeast	105	21%
South	58	12%
Central-West	44	9%
North	33	7%
Total Respondents (Brazil)	494	100%

2 – Population Area (inhabitants).		
Answer	N	%
Urban: More than 5 M	98	20%
Urban: More than 1 M up to 5 M	106	21%
Urban: More than 500 k up to 1 M.	64	13%
Urban: More than 100k up to 500 k	131	27%
Urban: Up to 100k	81	16%
Rural	14	3%
Total Respondents (Brazil)	494	100%

3 – Location in the city.		
Answer	N	%
High-traffic Street/avenue	387	78%
Gallery or adapted warehouses	24	5%
Large shopping mall	4	1%
Small or medium-sized shopping mall	2	0%
Other	77	16%
Total Respondents	494	100%

4 – Ownership type.		
Answer	N	%
Own property	248	50%
Rent property	192	39%
Loaned property	15	3%
Shared property	18	4%
Other	21	4%
Total Respondents	494	100%

5 – Designation.		
Answer	N	%
Residential (house) converted to commercial	212	43%
Commercial: Living room	72	15%
Business: Store	61	12%
Commercial: Warehouse	37	7%
Commercial: Deposit / Storage	16	3%
Commercial: Building Floor	14	3%
Other	82	17%
Total Respondents	494	100%

6 – Age.		
Answer	N	%
Up to 1 year old	17	3%
1 to 5 years old.	66	13%
6 to 10 years old	72	15%
11 to 15 years old	65	13%
16 to 20 years old	65	13%
21 to 25 years old	45	9%
26 to 30 years old	35	7%
More than 30 years old	104	21%
No information	25	5%
Total Respondents	494	100%

7 – Usable Area.		
Answer	N	%
Up to 49 m²	87	18%
50 to 100 m²	146	30%
101 to 200 m²	92	19%
201 to 300 m²	41	8%
301 to 500 m²	35	7%
501 to 1,000 m²	33	7%
More than 1.000 m²	60	12%
Total Respondents	494	100%

8 – Construction Responsibility in Electrical Installations.		
Answer	N	%
Construction company or contractor	158	32%
Foreman or bricklayer	149	30%
Self-build	54	11%
Collective effort	8	2%
No information	125	25%
Total Respondents	494	100%

9 – First Commercial Facility on the Property.		
Answer	N	%
Yes	249	50%
No	142	29%
No information	103	21%
Total Respondents	494	100%

10 – Inclusion of Electrical System Design.		
Answer	N	%
No	238	49%
Yes	174	36%
No information	76	16%
Total Respondents	488	100%

11 – Person/Entity Responsible for Electrical Installation Design.		
Answer	N	%
Electrical engineer	104	65%
Electrical technician	19	12%
Civil engineer	15	9%
Architect	3	2%
Other	3	2%
No information	17	11%
Total Respondents	161	100%

12 – Responsibility for Execution of Electrical Installations.		
Answer	N	%
Electrician	48	30%
Electrical engineer	39	24%
Electrical technician	25	16%
Construction company or contractor	23	14%
Civil engineer	6	4%
Foreman or bricklayer	1	1%
Other	2	1%
No information	17	11%
Total Respondents	161	100%

B. *Characteristics of Electrical Installations*

Analysis of the electrical characteristics of commercial buildings demonstrates significant gaps in compliance with safety standards. The absence of a functional grounding system, reported in 41% of properties, is one of the most critical points, as this system is essential to prevent electric shocks and protect equipment and users. Furthermore, 4% of installations do not have overcurrent protection, and 60% of properties do not have residual differential protection devices (RCD), exposing occupants to high risks of electrical accidents.

Protection against voltage surges is also insufficient, with 59% (Table 4) of properties without surge protection devices (SPD). These data are alarming, especially in commercial environments, where failure in electrical installations can result in significant financial losses and serious accidents. These results highlight the need for more excellent supervision and awareness of the importance of complying with technical standards, such as Standard (NBR 5410) - Electrical installations of buildings Low voltage [9], to guarantee the safety of installations.

TABLE IV
ELECTRICAL INSTALLATION SAFETY AND INFRASTRUCTURE IN BRAZILIAN PROPERTIES

13 – Existence of a functional grounding system.		
Answer	N	%
Yes	201	44%
No	191	41%
No information	69	15%
Total Respondents	461	100%

14 – Existence of a main electrical distribution panel.		
Answer	N	%
Yes	427	93%
No	28	6%
No information	6	1%
Total Respondents	461	100%

15 – Type of overcurrent protection in the main distribution panel or other distribution panels within the electrical installation.		
Answer	N	%
Circuit Breaker (main protection)	323	78%
Circuit Breaker (individual circuit protection)	308	75%
Fuse (main protection)	31	8%
Fuse (individual circuit protection)	27	7%
No overcurrent protection	17	4%
Total Respondents	413	100%

16 – Type of residual current protection in the electrical installation distribution panel.		
Answer	N	%
Main RCD	107	26%
RCD for group of circuits	66	16%
RCD for individual circuit	41	10%
No RCD	246	60%
Total Respondents	413	100%

17 – Type of surge protection devices (SPDs) in the main distribution panel of the electrical installation.		
Answer	N	%
No SPD	244	59%
Main SPD protected by the main circuit breaker	136	33%
Main SPD protected by its own circuit breaker	51	12%
Main SPD protected by a fuse	10	2%
Total Respondents	413	100%

18 – Existence of a color-coding system for identifying electrical conductors.		
Answer	N	%
Yes	215	50%
Partially	106	25%
No	93	22%
No information	14	3%
Total Respondents	428	100%

19 – Existence of protective earth (PE) conductors.		
Answer	N	%
Yes (at all outlets and equipment)	189	44%
Partially (at only some outlets and equipment)	108	25%
No	131	31%
Total Respondents	428	100%

C. Information on the Use and Maintenance of Electrical Installations

Regarding the use and maintenance of electrical installations, it is alarming that 26% of properties have never had electrical renovations. Coupled with the advanced age of certain buildings, this raises serious concerns about safety and functionality. Additionally, it is concerning that 54% of commercial buildings have no electrical drawings for renovation. This lack of planning could lead to execution failures and poor component choices.

Relocatable power tap is still used every day, with 38% (Table 5) of installations using them temporarily or permanently, which increases the risk of overload and fires. These results reveal the need to invest in adequate electrical infrastructure to avoid improvised solutions that could compromise safety.

TABLE V
INFORMATION ABOUT USE AND MAINTENANCE OF ELECTRICAL INSTALLATIONS

20 – Existence of '*non-standard relocatable power tap*' or similar adapters connected to the installation.		
Answer	N	%
There are no non-standard multi-plug adapters	219	52%
There are temporarily installed non-standard multi-plug adapters	99	24%
There are permanently installed non-standard multi-plug adapters	60	14%
No information available	40	10%
Total Respondents	418	100%

21 – Existence of (certified) relocatable power tap in use.		
Answer	Responses	%
Permanently installed	129	31%
No extension cords or power strips	127	30%
Temporarily installed	108	26%
No information available	54	13%
Total Respondents	418	100%

22 – Years since last electrical renovation (partial or full).		
Answer	N	%
No renovation done	108	26%
Within the last year	60	14%
More than 1 year and up to 5 years	98	23%
More than 5 years and up to 10 years	53	13%
More than 10 years	38	9%
No information	61	15%
Total Respondents	418	100%

23 – Electrical Drawing Created for the Renovation.		
Answer	N	%
No	135	54%
Yes	78	31%
No Information	36	14%
Total Respondents	249	100%

24 – Renovation of Electrical Installations: Percentage of Building Area.		
Answer	N	%
Up to 25%	101	44%
26% to 50%	46	20%
51% to 75%	32	14%
76% to 100%	53	23%
Total Respondents	232	100%

25 - Reasons for Electrical Installation Renovation		
Answer	N	%
Expansion	125	54%
Preventive maintenance	77	33%
Energy savings (energy/electrical efficiency)	31	13%
Maintenance recommended by a professional	24	10%
Installation of alternative energy systems (such as photovoltaic)	13	6%
Frequent tripping of circuit breakers	11	5%
Electrical installation accident with fire or fire hazard due to overload	7	3%
Accidents in the building involving electric shock	5	2%
Electrical installation accident with short circuit at outlets	5	2%
Other	28	12%
Total Respondents	232	100%

26 – Report on Electric Shock Incidents in the Property's Installations.		
Answer	N	%
No	257	65%
Yes, without consequences	71	18%
Yes, with seriousness	3	1%
Yes, with fatality	1	0%
No information	63	16%
Total Respondents	395	100%

27 – Occurrence of Fire or Fire Hazard of Electrical Origin on the Property.		
Answer	N	%
No	326	83%
Yes, fire hazard	17	4%
Yes, small-scale fire (partially affected areas of the property)	13	3%
Yes, large-scale fire (affected the entire property)	3	1%
No information available	40	10%
Total Respondents	395	100%

D. *Information on the Use and Maintenance of Electrical Installations*

Section D focused on the implementation of photovoltaic (PV) systems in commercial properties, with only 11% (Table 6) of the properties analyzed having adopted this technology. This relatively low number may be attributed to a lack of incentives or the perception of high upfront costs for implementing renewable energy technologies. Of the properties with PV systems, 81% have protection on both the direct current (DC) and alternating current (AC) sides, demonstrating good compliance with safety standards. However, 19% of these systems showed protection failures, underscoring the crucial need for reinforcement in supervision and technical guidance during the installation of photovoltaic systems to ensure safety and compliance.

Furthermore, 58% of the electrical installations of properties that adopted PV systems were suitable to accommodate this technology. This promising information indicates the adaptation of existing electrical infrastructures to support new energy demands. However, 26% of properties that did not undergo readjustment represent a potential risk of system failures, as sizing and adaptation are essential to guarantee the safety and efficient performance of photovoltaic installations.

TABLE VI
INFORMATION ON PHOTOVOLTAIC SYSTEMS IN BUILDINGS.

29 – Existence of a Photovoltaic System in Commercial Property.		
Answer	N	%
No	341	89%
Yes	44	11%
Total Respondents	385	100%

30 – Technical Responsibility for the Design and Installation of the Photovoltaic System.		
Answer	Responses	%
Electrical engineering office	24	56%
Construction company or contractor	6	14%
Electrical technician	6	14%
Civil engineering office	0	0%
Architecture office	0	0%
Unknown	6	14%
Other	1	2%
Total Respondents	43	100%

31 – Existence of Adequate Protection in the Photovoltaic System.		
Answer	N	%
Yes, on the DC side and the AC side	35	81%
Partially, only on the DC side	1	2%
Partially, only on the AC side	1	2%
The only protection in the PV system is in the inverters	1	2%
No information	5	12%
Total Respondents	43	100%

32 – Adaptation of Electrical Installation for Photovoltaic System.		
Answer	N	%
Yes	25	58%
No	11	26%
No Information	7	16%
Total Respondents	43	100%

IV. CONCLUSIONS

This study underscores the critical need for improved electrical safety standards and practices in Brazilian commercial properties. The findings reveal that only 35% of properties possess an electrical drawing, and a significant proportion of installations are carried out by unqualified professionals. While 44% of properties have functional grounding systems and most use thermomagnetic circuit breakers, essential safety devices like residual current devices (RCDs) and surge protection devices (SPDs) are absent in 60% and 59% of properties, respectively. These gaps substantially increase the risks of electric shocks, equipment damage, and financial losses.

Addressing these deficiencies requires coordinated efforts among policymakers, regulatory agencies, and industry stakeholders. Emphasis should be placed on creating public policies to encourage the formalization and supervision of electrical installations, particularly in less densely populated regions where compliance rates are lower. Awareness campaigns and professional training initiatives are essential to promoting adherence to safety standards and highlighting the role of qualified professionals in improving electrical safety.

The integration of photovoltaic systems, adopted by only 11% of the analyzed properties, presents an opportunity to enhance sustainability. However, the study also identifies risks associated with inadequate system adaptations, as 26% of properties with photovoltaic systems lacked proper adjustments. Ensuring rigorous compliance with safety standards is crucial to maximizing the benefits of these technologies.

The findings provide a foundation for developing targeted interventions to improve electrical safety and efficiency in commercial properties across Brazil. Future research should evaluate the impact of these measures and explore innovations in electrical safety technologies to ensure continued progress toward safer and more sustainable infrastructure.

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VII. VITA

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