Reducing Risk when Performing Energized Work on Batteries

David M. Rosewater, *Senior Member, IEEE,*

***Abstract*—Electrical safety guidance in NFPA 70E for work on batteries can be substantially improved. Article 120, Establishing an Electrically Safe Work Condition was originally developed to manage electrical sources that can be de-energized, e.g., facility ac/dc power circuits. Some have inappropriately attempted to apply electrical safety practices intended for power distribution circuits to battery work. This includes attempts to de-energize batteries, verify zero energy, or establish an electrically safe work condition, none of which can be applied to batteries. However, the principles of the control of hazardous energy, including lockout tagout, can and need to be adapted to work on batteries. This paper explores the modifications required to develop a battery hazardous energy control procedure that can protect workers and avoid accidents. The paper also covers several physical properties and engineering controls common in battery systems that affect the battery risk assessment required by NFPA 70E. Lastly, the paper presents a list of changes proposed to electrical safety practices, including those outlined in NFPA 70E, that clarify how to control hazardous energy in batteries, helping to avoid future misapplication of power distribution circuit electrical safety practices to batteries.**

***Index Terms*—risk assessment, energized work, batteries, work practices, workplace safety**

I. Introduction

ELECTRICAL work on batteries is becoming more common with the proliferation of battery-based energy storage systems to support a transition to low-carbon energy sources. Large batteries have been in widespread use in power systems and electric vehicles for over a century, but their relative cost has historically limited their application to backup systems, and niche markets. Mobile applications have been limited to engine start batteries and naval vessels. This has led to a relatively small and stable workforce of specialized battery technicians who have established safety practices independent from the electrician and linemen trades. As batteries have fallen in cost they are more commonly installed in cars, homes, business, and utility applications by a new workforce of battery technicians. This new workforce needs specific guidance for how to safely assemble, maintain, repair, and disassemble battery systems.

The control of hazardous energy in electrical systems has been structured and regulated around lockout/tagout (LOTO) since before the OSHA first passed Code of Federal Regulations (CFR) Part 1910.147 in 1982 [3]. The LOTO system, in its current incarnation, is designed primarily for electricians installing and modifying ac/dc power circuits, though it can be applied to many hazardous energy sources [4]. Electrical LOTO requires a worker to establish an electrically safe work condition by isolating equipment from its energy source and locking the point of isolation to prevent unexpected energization. It then requires a worker to test the circuit to verify zero energy within the work area before starting work. These requirements are based on sound and robust principles of electrical safety to eliminate or reduce the hazard as much as possible before work. Batteries, however, are their own sources of electrical energy and cannot be deenergized like ac/dc power circuits. The requirements of LOTO are not directly applicable to battery systems as they are always energized.

This paper presents a method to modify and supplement the requirements of the LOTO system to eliminate or reduce the hazards of battery systems as much as possible before performing energized electrical work. This method is built on contributions that clarify and refine the battery risk assessment required to identify required personnel protective equipment (PPE) and administrative work controls. Finally, it concludes with a discussion of how to modify existing workplace LOTO programs to cover energized work on batteries.

II. Battery Risk Assessment

Risk assessment aims to understand the likelihood and severity of potential accidents. Workers can then apply controls to make accidents less likely and/or less severe. This can be done through the hierarchy of controls presented in NFPA 70E 2024 Article 110.5(3) [4]: Elimination, Substitution, Engineering controls, Awareness, Administrative controls, and PPE.

Applied to batteries and battery systems, Article 320.3(A)(2) requires that a risk assessment shall be performed prior to any work on a battery system. This risk assessment shall identify the chemical, shock, arc flash, and thermal hazards. Additionally, this risk assessment shall assess the risks associated with the type of tasks to be performed.

Historically, some employers require the preparation of an Energized Electrical Work Permit (EEWP) for any work on

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David M. Rosewater is with the Sandia National Laboratories, Albuquerque, NM 87185 USA (e-mail: dmrose@sandia.gov)

This paper is substantially built on work presented at the 2023 IEEE IAS Electrical Safety Workshop [1]. The contributions to risk assessment were further developed in work presented at the 2023 Battcon Conferance [2].

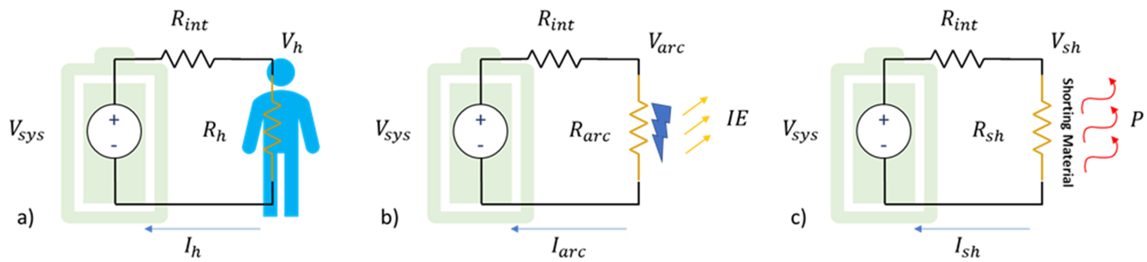

Fig. 1. Summary of hazard models for a) shock, b) arc flash, and c) thermal. Partially adapted from [2].

batteries. The requirements of a battery risk assessment are substantially like the requirements of an EEWP. An EEWP requires the work to be justified, a description of the safe work practices to be employed, the completion/documentation of a pre-job briefing, and energized work approval. The safe work practices and pre-job briefing are industry standard practices for electrical work and documenting them in an EEWP specifically, while helpful, does not necessarily improve safety. Batteries are, as a class of power sources, justified for energized work through Article 110.4(B) Infeasibility [4] in that it is infeasible to perform work on a battery in a de-energized state. Discharging or disassembling batteries to a ‘de-energized’ state is damaging to the battery, hazardous to the worker, or both. Over discharge can cause excessive heat generation or fire in batteries and should not be performed as a means of shock or arc flash mitigation. In general, reducing the charge of a battery does not significantly reduce its electrical hazard for the purpose of electrical work. Some battery types are required to be shipped at a reduced state of charge based on their chemical or potential fire hazards. Some flow batteries, batteries with tanks of liquid electrolyte, are designed to be safely discharged to close to zero energy, though doing so can require specialized equipment and an extended, planned outage.

Lastly, the energized work approval signatures required in a EEWP according to NFPA 70E Article 130.2(B)(9) [4] have been critical in aligning the incentives of employers to avoid energized work wherever possible. But requiring these signatures for work on batteries and battery systems can defer or delay regular maintenance, or conversely, make the approval of EEWPs routine. All work within the restricted approach boundary of a battery is energized electrical work and requires a commensurate level of documented safety. Requiring battery technicians to justify and safety officers sign approvals for day-to-day work may reduce the strict scrutiny that is applied to EEWPs and could reduce the effectiveness of whole safety programs.

Based on this reasoning, an EEWP should not be used for work within the restricted approach boundary of a battery as it would be redundant to the battery risk assessment. Instead, employers should recognize that if they own and maintain a battery that, by design, it cannot be worked on in a de-energized state. This energized work should be controlled and documented accordingly but routine justification and approval does not reduce risk. Note that an EEWP is clearly required for any energized work within the restricted approach boundary of battery charging equipment as it can be worked on in a de-energized state, though doing so may require energized work to disconnect it from the battery. The following sections clarify and refine the process of battery risk assessment for: shock, arc flash, and thermal hazards. A flowchart and summary of this process are included in Section III A.

A. Calculating Shock Hazard

Batteries cannot be deenergized. A common design method to reduce the risk of a shock is to operate the battery or battery bank in an ungrounded state as is permitted by NEC 480.13 [5] if there is ground fault detection and indication. Because shock involves an unintended path for current through the human body (see Fig 1 a), the exposed terminals in an ungrounded stationary battery system can be physically separated far enough to make a shock extremely unlikely. NFPA 70E does not currently account for conductor spacing in shock risk assessment as exposed conductors in facility ac and dc power circuits are almost always close to each other or ground [4].

This section presents an interpretation of the limited and restricted approach boundaries (LAB & RAB) for shock hazard in NFPA 70E that accounts for conductor spacing. The additional rules are based on the intuition that, if someone reaches out in both directions and is unable to span a hazardous battery voltage, then the probablity of a shock is very low. A battery shock hazard threshold of 100 V is used as specified in article 320 of NFPA 70E [4]. The lengths prescribed for LAB in Table 130.4(E)(b) [4], are referred to here as the LAB distances, whereas the threshold for qualified workers is referred to as the LAB. If the conductors are spaced close together, as in a panel, then the limited approach boundary is spherical, with a radius derived from the LAB distance. If the conductors are spaced far apart but within two times the LAB distance of each other, then the limited approach boundary is the intersecting space of 2 spheres, each with radius of the LAB distance centered on one of the exposed conductors. If the conductors are spaced more than two times the LAB distance apart, then there is no intersection of the 2 spheres and the limited approach boundary is not specified. The restricted approach boundary measured from the exposed electrical conductors that create a LAB that any part of the worker is currently in. If the worker is not within the LAB, then the RAB is not defined as there is no path for current to flow through them.

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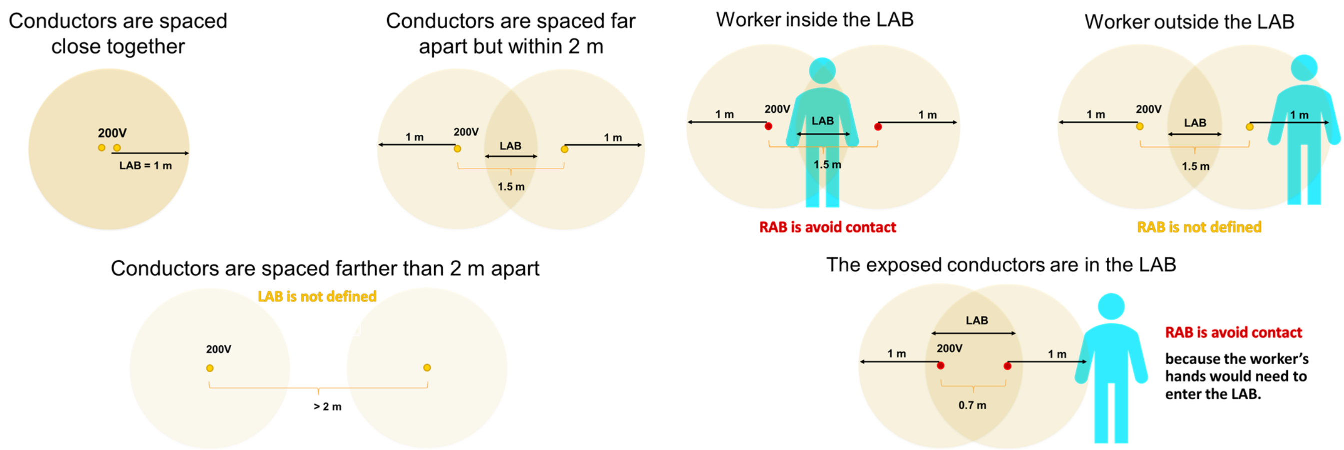

Fig. 2. Limited Approach Boundary (LAB, left), and Restricted Approach Boundary (RAB, right) based on high conductor spacing. Adapted from [2].

Figure 2 shows three examples of limited approach boundaries (LAB) for a 200 V battery string, and how the restricted approach boundary changes depending on the location of the worker [2]. It is critical to remember that the LAB is a minimum boundary and barriers shall be established in reasonable, logical locations to prevent access by unqualified persons.

A high circuit resistance to ground, referred to in the NEC as an impedance grounded system [5], can eliminate the shock hazard between the battery and ground by limiting current in a ground fault to below 40 mA, preventing fibrillation in heart tissue [4], [6]. The minimum resistance to ground for shock protection is therefore 25 Ω / V. However, ground faults are also common and can occur gradually over time. A ground fault in dc systems can result from water leaks, condensation buildup, vermin (e.g., rats, squirrels, snakes), chemical leaks from the batteries, material fatigue or damage, rusting or corrosion, and many other factors. An ungrounded system without a properly installed and tested ground fault identification device should be treated as grounded. Battery charging circuits without ac isolation transformers can present a shock hazard to ground though the ac circuit [7].

Shock PPE requirements are no different between batteries and facility circuits, so they are not reiterated here.

B. Calculating Arc Flash Hazard

While a shock hazard is based on an unintended path for current through the human body, arc flash is based on a path for current through air (see Fig 1 b). Just as with the shock hazard in batteries, the risk of an arc flash is highly dependent on the spacing of electrical conductors. To be hazardous, electrical conductors must be close enough to each other to allow current to pass through air in proximity to a worker. In facility ac/dc power circuits, minimum conductor spacing is driven largely by the insulation properties of air under normal conditions, which is sufficient until a temporary short creates the conditions for an arc. In large stationary battery systems, the conductors are often naturally spaced much farther apart and hence we can consider if an arc is even possible in a circuit. This is a complex problem, but we can calculate a lower bound on conductor spacing above which an arc cannot be sustained.

A review of dc-arc models and intendent energy (IE) calculations can be found in [8]. This work describes a complex relationship between arc voltage, arc current, arc resistance, and arc gap. We can synthesize these results to calculate an estimate of the maximum arc gap. Arc physics has two modes that can be described as high-voltage/low-current and low-voltage/high-current modes [9]. The low-voltage/high-current mode, represented in (1), is of more interest in battery system as they are generally lower voltage systems with high fault current. We have omitted electrode material, shape, and orientation from this analysis for simplicity those factors do not determine arc formation.

$$V_{\text{arc}} = (20 + 0.534 z_g)\, I_{\text{arc}}^{0.12} \tag{1}$$

$$I_{\text{t}} = 10 + 0.2 z_g \tag{2}$$

$$V_{\text{t}} = (20 + 0.534 z_g)\,(10 + 0.2 z_g)^{0.12} \tag{3}$$

where V_{arc}, I_{arc}, and z_g are the arc voltage, current, and gap respectively, while I_{t} and V_{t} are the current and voltage where the arc transitions from high-voltage/low-current mode to low-voltage/high-current mode. The transition voltage is the theoretical minimum voltage of the arc though there can be substantial error in this approximation [9]. Solving (3) for z_g is difficult but by plotting them in Fig. 3 we find that the simple linear function with slope 1 mm per volt provides a slightly larger than necessary gap for voltages below 1000 V.

If a battery's voltage is substantially below the minimum voltage for a specified gap, either by (3) or the 1 mm per V approximation, then no arc could be sustained over that gap in open air. For gaps less than this threshold, another important consideration is at what gap length would a sustainable arc be hazardous. This occurs when the power transferred from the battery to the arc incurs an incident energy (IE) greater than the limit (IE_{lim}) 1.2 calories per square centimeter (cal/cm^2), at 46 mm (18 in) working distance (D) over an arc time (T_{arc}) of 2 seconds, assuming no circuit protection [4], [10]. The

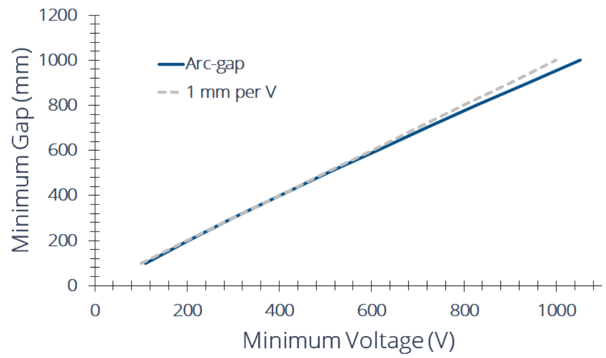

Fig. 3. 1 mm per V arc-gap approximation

TABLE I
ELECTRODE BURN-BACK DURING ARCING TESTS FROM [11] COMPARED TO GAP CALCULATIONS

V_{sys} (V)	R_{int} (mΩ)	Gap 1 (mm)	Gap 2 (mm)	z_{g1} (mm)	z_{g2} (mm)	z_{g3} (mm)	$\frac{z_{g3}}{\text{Gap 2}}$ –
105	15	3	5[a]	105	93	42	8.4
105	15	6	6[b]	105	93	42	7
144	8.4	6	25	144	137	86	3.4
144	8.4	25	25[c]	144	137	86	3.4
260	13	6	69	260	259	207	3.0
520	26	6	130[d]	520	512	499	3.8

Gap 1 is the initial gap in mm before the arc
Gap 2 is the final gap in mm after the arc
[a] The 105V battery with a gap of 3 mm resulted in 4 kA arc fault and sustained for approximately 300 milliseconds.
[b] The 105 V battery with a gap of 6 mm resulted in self-extinguishing in less than 100 milliseconds.
[c] The 144 V battery with a gap of 25 mm resulted in low fault current and blew out quickly
[d] The 520 V battery arc interrupted by circuit breaker after 2 seconds so this is a lower bound on the arc gap

derivation presented in [1] can be used to find this point of intersection, the result of which is shown below.

$$V_{\text{arc}} = \frac{-b \pm \sqrt{b^2 - 4ac}}{2a} \tag{4}$$
$$a = -\frac{0.019 T_{\text{arc}}}{R_{\text{int}} D^2} \quad b = \frac{0.019 T_{\text{arc}} V_{\text{sys}}}{R_{\text{int}} D^2} \quad c = -I E_{\text{lim}}$$

where V_{sys} is the battery's open circuit voltage, and R_{int} is the battery's internal resistance.

To check the validity of these calculations we compare them to experimental data collected by Gray, Robert, and Gauthier in [11]. They ran a series of arc flash experiments on battery systems using vertically spaced copper electrodes. A subset of their data is shown in Table I compared to the gaps calculated with the three proposed methods: 1 mm / V (z_{g1}), per (3) (z_{g2}), and per (4) (z_{g3}). These data show that the maximum arc gap calculated with (4) is conservatively above the ending arc gaps in each experiment by a factor of 3 to 8. This means that wherever conductors are spaced farther than this maximum arc gap apart there is a very low arc flash hazard. Conversely, if they are closer than the maximum arc gap then there is an arc flash hazard magnitude to calculate. This limits the locations of arc flash hazard to those places where exposed electrical conductors are close together.

The effect of arc gap on battery arc flash hazard is better illustrated in Fig. 4 as the current-voltage (IV) curves of the arc-through-air and battery are plotted together. Where the curves intersect are conditions where the battery's voltage and current are sufficient to sustain an arc according to the physics models presented here. By increasing the arc gap in the system design we are able to eliminate the intersection of these curves, thereby making an arc through air extremely unlikely.

A prominent critique of using an arc gap for battery risk assessment is that a dropped or misplaced tool could partly bridge the gap between conductors, invalidating the calculations. First, the use of insulated tools is a minimum requirement of any electrical work on batteries. Second, in many large stationary batteries, the layout is large enough that a long pipe, rod, or rail would be needed to span the gap from negative to positive terminals and those kinds of construction materials should not be taken near a battery. Third, the experimental procedure in [11] essentially demonstrated the scenario of concern would not produce a hazardous arc. Each experiment was initiated with a small gage wire installed between the electrodes that would rapidly melt thereby initiating the arc. In cases where the arc gap is too big, the shorting material is quickly melted or ejected, and the gap is restored. These arc gap calculations should not be applied to ac circuits. DC circuits in general, and battery circuits in specific [12], tend to have very low inductance due to lack of transformers. If a battery circuit has a substantial inductance, orders of magnitude higher than what was observed in [11], then the initial fault current could store energy in the circuit that, when the temporary short is removed, could increase the arc flash hazard.

Once we have determined that an arc flash hazard exists in a circuit, there are several methods available to calculate its magnitude [4], [11], [13]. This is an ongoing area of modeling research. Arc flash PPE requirements are no different between batteries and facility circuits, so they are not reiterated here.

C. Calculating Thermal Hazard

Like arc flash, thermal hazards are a result of accidental short circuit scenarios across a gap. However, thermal hazards do not involve an arc through air but rather through shorting material (e.g., wrench, screwdriver, busbar), as shown in Fig. 1 c. Because the short does not need to ionize air, thermal hazards are also present at low voltage. While not as explosive as an arc, a high thermal hazard can still project droplets of molten metal, so eye protection and non-melting clothing are required. When performing thermal hazard risk assessment, it is important to consider what specific shorting material is under consideration. In some cases, the thermal hazard can be eliminated or substituted simply by carefully selecting what is brought near the battery. For example, it is now a best practice to use digital multi-meters that are themselves insulated against high voltage so setting them on the battery terminals by accident would not cause a short. As work on batteries is substantially comprised of assembling and disassembling strings of cells; the busbars, tabs, cables, and wires are often the primary shorting articles of concern.

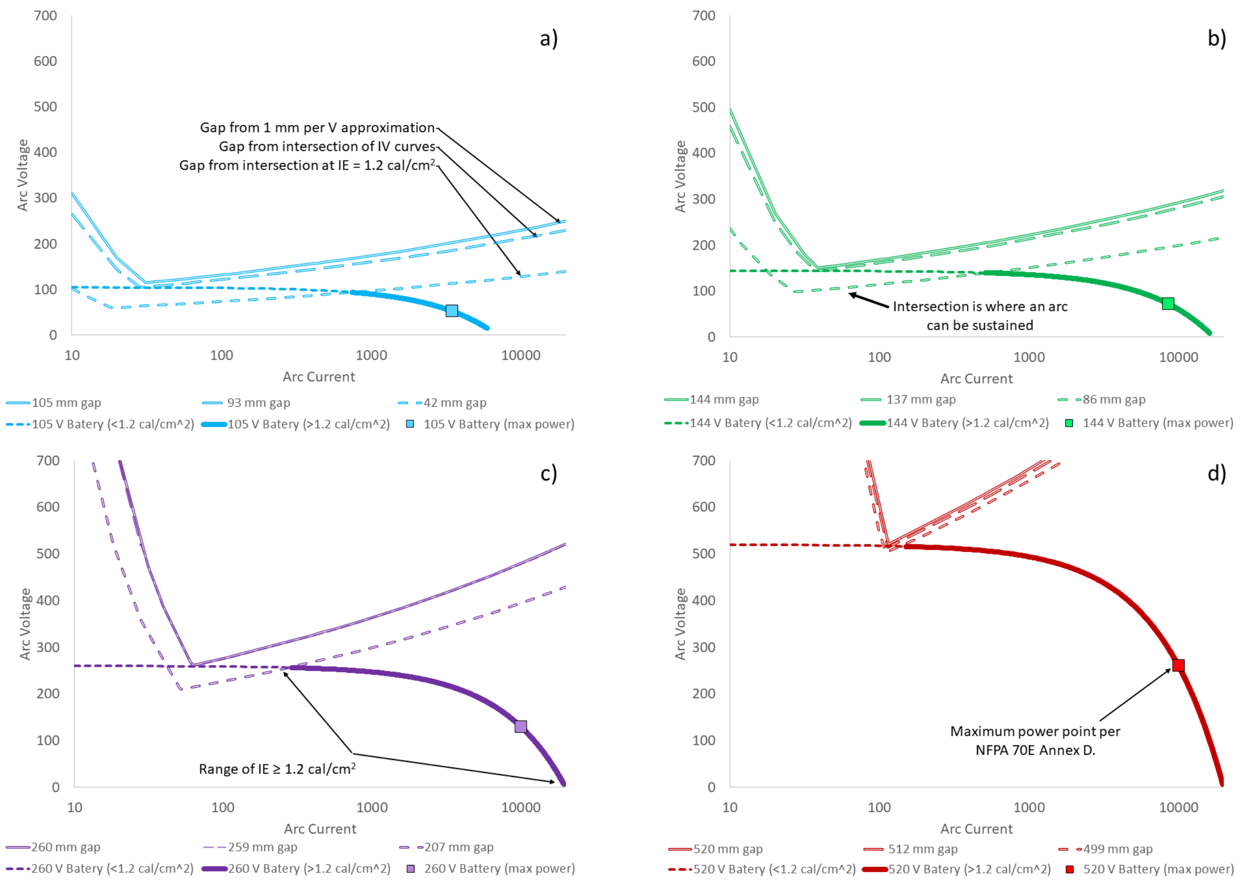

Fig. 4. Arc-gap / battery IV curves for example batteries: a) 105 V battery, b) 144 V battery, c) 260 V battery, d) 520 V battery. Partially adapted from [2].

Further, the work needs to involve a possible short circuit for there to be a thermal hazard. Work involves possible short-circuit when there are two or more exposed battery terminals within a proximity that could be spanned by a shorting article of concern used in or proximate to the work. The battery enclosure itself could act as a short circuit conductor if the battery is grounded.

Thinking carefully about the shorting material and where the short could occur can yield various methods for reducing or controlling the thermal hazard. One method is to control the hazard is to simply cover nearby exposed battery terminals with insulating materials prior to attempting to install or remove a busbar. Another common approach is to use engineered battery packs or racks that allow a battery to be plugged into the circuit rather than having to build the circuit around the battery. This makes it difficult to imagine what material could short the battery during assembly and makes it difficult for a battery to be connected in reverse. If viable, these engineering methods of hazardous energy control should be applied before the risk assessment.

The thermal hazard in a battery system is proportional to the maximum power that could be delivered to the shorting material. The calculation for maximum power is shown below. A thermal hazard is considered to be present if the maximum power to a short (P) is greater than 1000 W.

$$I_{\text{sh}} = \frac{V_{\text{sys}}}{2R_{\text{int}}} \tag{5}$$

$$P = V_{\text{sys}} I_{\text{sh}} = \frac{V_{\text{sys}}^2}{2R_{\text{int}}} \tag{6}$$

where I_{sh} is the current from a battery at the point of max power transfer.

The threshold of 1000 W in batteries is based on a distinction between uninterruptable computer power supplies with thermal hazards in the 100s of watts and car starter batteries with thermal hazards in the 10 kW range [6]. Some large format 12 V batteries for stationary applications can have a thermal hazard in the range of 60-80 kW. The 1000 W threshold was reproduced in [1] with reasonable assumptions about the dimensions of a copper bus bar, the time and temperature it takes to burn skin, and human reaction times to hot surfaces. Note that an arc flash hazard, if present, supersedes a thermal hazard as it requires more protection.

Hand protection should, unless justified, be worn where there is possible exposure to a thermal electrical hazard. Again, PPE is only for when the hazard cannot be eliminated or controlled in some other way. Light-duty leather gloves, heavy-duty leather gloves, or arc-rated leather gloves should be worn where required for thermal protection. Shock and arc flash PPE provide protection from thermal hazards. Using insulated tools when working around batteries significantly reduces the risk of short circuit, and therefor thermal burns, but does not prevent short circuits caused by things other than the worker's tools. Workers should never wear jewelry around batteries or battery systems.

Note that the mechanical hazards of shorted material being ejected from a circuit are highly situational and not as energetic as intuition might suggest. Hildreth and Feeney performed several tests on loose tools dropped on the gap in a 125 V battery bus [13]. They performed two tests with a wrench and two tests with a copper bus bar and "all cases the tool was immediately ejected from the test chamber without excessive force." Safety glasses are sufficient to prevent severe injury from the low velocity projection of shorted materials described in the tests in [13]. This may not hold for higher voltage or higher power batteries.

An employer should justify alternative hand protection or proscription of thermal hand protection based on increased exposure to chemical or other hazards. Performing measurements with a bulb hydrometer in flooded cells for example requires chemical safety gloves, even if a thermal hazard is present. Additionally, many of the tasks involved in the assembly of batteries requires very fine manual dexterity to perform safely. Assembly of small lithium-ion batteries is an example where the fire risks associated with an accidental short circuit are much greater than the thermal burn risks to the worker. An accidental short could lead to a battery fire that exposes workers to smoke inhalation and, if the fire were to spread, many more workers to a fire hazard. The manual dexterity lost by wearing thermal hand protection can increase the likelihood of a short circuit leading to greater overall risk to the worker and others. Just as is commonly done for arc flash, overcurrent protection can be highly effective for reducing the thermal hazard in battery strings. Appropriately sized fuses and breakers will trip the battery circuit before equipment damage can occur, which can also limit the energy delivered to the shorted material. If the shorting material is low resistance, then the short circuit current will be higher leading to a rapid trip. If the shorting material is high resistance, then it will heat more slowly allowing time for the worker to pull their hand away to prevent or limit injury.

III. Electrical Work on Batteries

This section describes best practices for working on energized battery systems. Not all work on battery systems involves entering the restricted approach boundary of a battery. Working on the dc circuits that a battery feeds or on battery chargers are examples of where traditional LOTO procedures and requirements can be applied without issue. Indeed, it is common practice, especially in electric vehicle batteries, to electrically isolate the external terminals of the battery module unless and until it is connected and in use. In these cases, it is fully possible to work on the dc circuit and even the exterior of the battery module in a de-energized, electrically safe, state with zero energy. Though, if there has been damage to the battery module it may be best to treat it as if the isolation circuit has failed until it can be verified.

As batteries cannot be de-energized, work on the batteries themselves will necessarily involve some degree of energized electrical work. The principles of safely working on batteries are analogous to the principles of LOTO, in that all sources of electrical energy should be controlled in such a way as to minimize worker exposure to electrical hazards [4]. However, rather than establishing an electrically safe work condition, someone performing work on a battery system can only establish a lower risk work condition. This is done by electrically isolating the batteries, which are each their own small source of electrical energy, from each other through a process of segmentation, partitioning, or sectionalizing. A battery sectionalizing procedure is therefore an adaptation of the intent of a LOTO procedure for the unique combination of hazards present in battery systems.

This approach to battery electrical work can be combined with existing LOTO programs to adequately reduce the risk of electrical injury in the workplace. Workers who are already familiar with LOTO can be trained for battery work more quickly if the structure and principles of electrical safety are demonstrably similar. Lastly, just as many ac power systems have been designed to enable workers to perform LOTO without exposure to electrical hazards, future battery systems can be designed to enable sectionalizing without exposure to shock or arc flash hazards and with minimal exposure to thermal hazards.

A. *Battery risk assessment process*

This section summarizes and streamlines the process for battery risk assessment as shown in Fig. 5. This risk assessment applies only to the electrical hazards of batteries. Chemical hazards should be assessed independently based on the battery type and task. The process starts with the minimum requirements of safety gasses, insulated tools, non-melting clothing, and no jewelry. It then analyzes thermal risk by assessing possible shorting articles and circuit locations. If the potential for a short circuit can be eliminated or controlled, or if the short circuit power of a given location is below 1 kW, then thermal hand protection is not required. When assessing shock hazard the process is to identify where a worker could potentially contact a voltage differential of more than 100 V with greater than 40 mA available short circuit current. If that is not possible then there is no shock or arc flash PPE required. If it is possible, but the battery can be sectionalized without the worker being exposed to a shock or arc flash hazard, then there is still no shock or arc flash PPE required but a procedure for sectionalizing should be developed. If sectionalizing the battery involves exposure, then shock PPE is based on the voltage differential of exposed conductors within reach. To assess arc flash hazard, the first step is to calculate the maximum arc gap based on the battery's voltage and bolted fault current. If the battery circuit is designed such that all exposed electrical conductors are spaced farther than the maximum arc gap, or the calculated incident energy is below 1.2 cal/cm^2, then the arc flash risk in the battery system is low. If there is a gap narrower than the maximum arc gap, and the calculated incident energy is greater than 1.2 cal/cm^2, then the worker should wear arc flash PPE based on its calculated incident energy.

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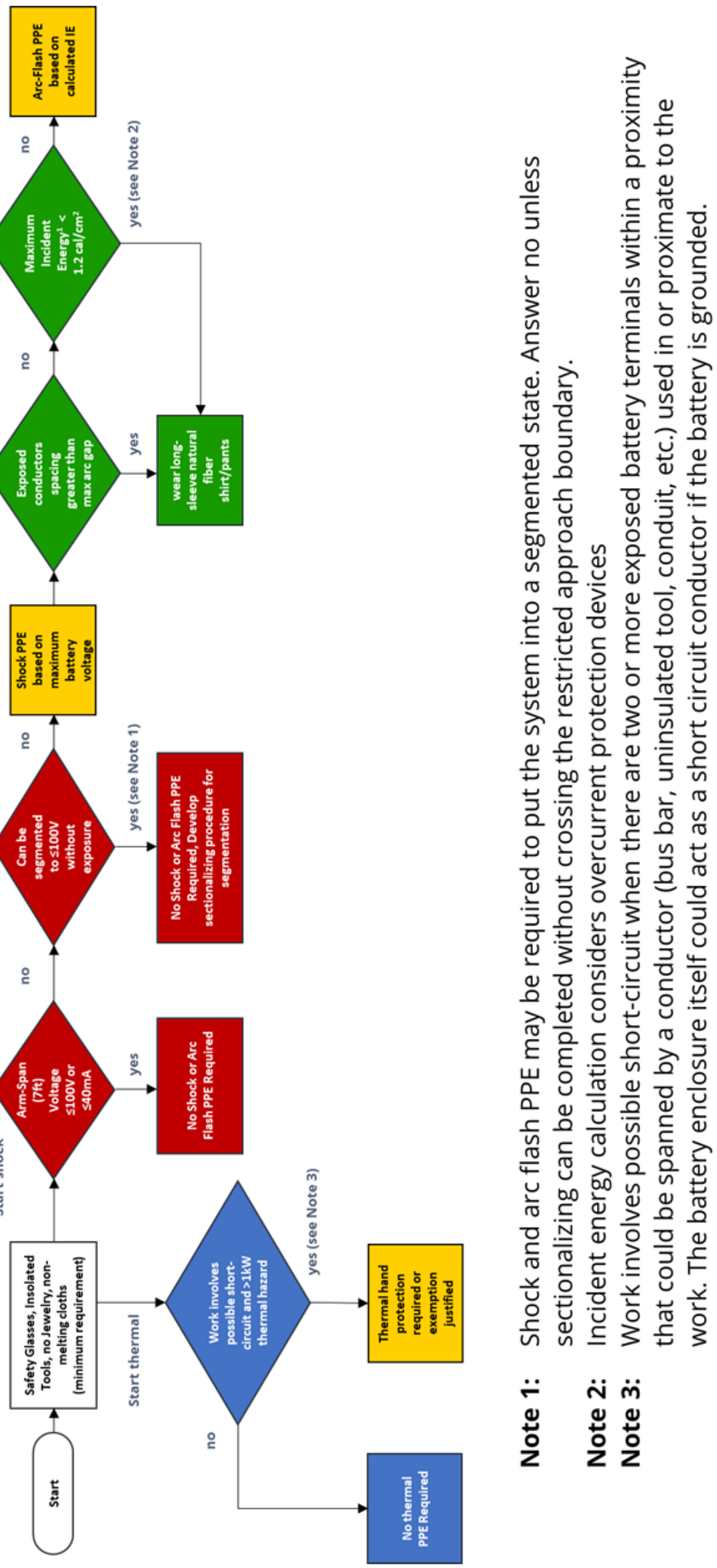

Fig. 5. Battery risk assessment flow chart.

B. Establishing a Lower Risk Work Condition in Batteries

As batteries cannot be de-energized, a battery sectionalizing procedure does not work to establish or verify an electrically safe work condition. Instead, it reduces the risk of injury by splitting a battery into lower voltage, lower energy segments. The provisions of NFPA 70 E, Article 120 [4] should be applied to work on batteries with the following additions / modifications. Authoritative 'shall' language is used here to align with the language of Article 120.

1) Sectionalizing Procedure: Employees performing circuit manipulation of batteries shall plan work to minimize exposure to shock and arc flash hazards. The work plan shall identify the order that battery circuit connections or disconnections are to be made and any resulting changes in the dc voltage, limited approach boundary, restricted approach boundary, shock PPE, arc flash incident energy, arc flash boundary, and arc flash PPE. An illustration of the steps of a sectionalizing procedure are shown in Fig. 6. A sectionalizing procedure shall address the flowing:
   a) Sectionalizing a battery shall, unless justified, start with any means of disconnection that does not expose the worker to a shock or arc flash hazard. The battery's terminal connections (most positive and most negative) shall then, unless justified, be disconnected, followed by inter-rack/inter-tier jumper cables and intercell ties.
   b) Employees shall wear the identified PPE until after a circuit disconnection is performed that reduces the level of shock or arc flash hazard. If a circuit disconnection is hidden from view, then a negative test for conductivity is required.
   c) When returning a battery to service, employees shall wear the identified PPE prior to making any circuit connection that increases the level of shock or arc flash hazard.

2) Identification of disconnecting means: Circuit interrupt switches and plugs that do not expose the worker to a shock or arc flash hazard when maintained and operated properly are permitted circuit disconnecting means in batteries. Plugs and cables that do not accept a lock shall be secured with a plug box or cable lockout device. Intercell busbars are permitted to be used as disconnecting means but must be held in a locked box or cabinet. When removing a busbar during a sectionalizing procedure, the

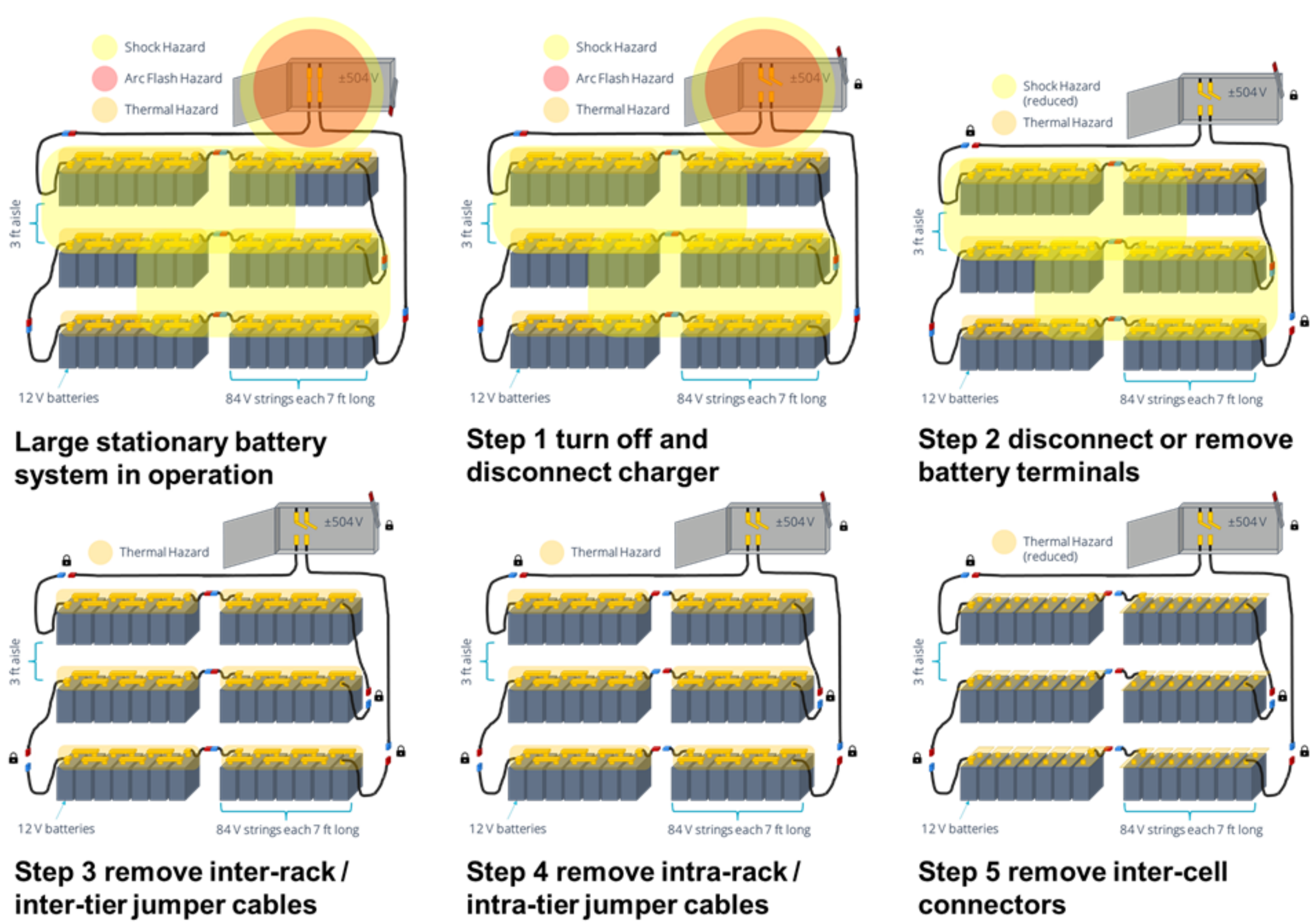

Fig. 6. Example of sectionalizing a large, multi-tier battery. Figure Notes: In Step 1 the panel should be closed but is shown open only for illustration. The lock symbols represent applying a cable lock. Step 4 does not change the hazard level and so locks are not required. The cells are still energized after Step 5, but the level of risk is substantially reduced.

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employee shall entirely remove the bus bar and store it away from the battery to prevent accidental short circuit. In some complex sectionalizing procedures, it may make sense to store bus bars in a locked box or cabinet to make accidental reenergization less likely. Note that intercell busbars and cables are interchangeable so locking them does not prevent a replacement from being installed. However, their presence or absence in a battery string is visibly verifiable before entering the limited area. There are also many of them in a battery string, so it is a multi-step, labor-intensive process to re-install them once removed. These factors reduce the risk of shock and arc flash to a level like applying a lock.

3) Simple Battery Sectionalizing: A battery sectionalizing procedure that involves only a qualified person(s) sectionalizing a single battery with a single charger for the sole purpose of safeguarding employees from exposure to electrical hazards shall be considered to be a simple battery sectionalizing procedure. Simple battery sectionalizing procedures shall not be required to be written for each application. Each worker shall be responsible for their own battery sectionalizing procedure.
4) Complex Battery Sectionalizing: a complex battery sectionalizing procedure shall be permitted where one or more of the following exists: a. Any electrical work on a battery charger (non-battery electrical work covered by traditional LOTO), b. Multiple battery strings connected in parallel, c. Multiple battery chargers connected in parallel, d. Multiple single string batteries with chargers located near each other, e. Multiple energy sources (excluding the battery), f. Multiple crews, g. Multiple crafts, h. Multiple locations, i. Multiple employers, j. Multiple disconnecting means, k. Multiple sequences, or l. Job or task that requires more than one work period.
5) De-energizing Equipment (shutdown): The procedure shall not de-energize the batteries. The procedure shall instead sectionalize the batteries.
6) Stored Energy: The procedure shall not release the energy stored in the batteries as this would damage them and expose workers to additional hazards.
7) Verification: The procedure shall not require that the batteries be operated (charged or discharged) prior to or after sectionalizing as this can introduce additional hazards.
8) Testing: Batteries will have voltage after sectionalizing so testing them for voltage is not required. The purpose of testing in a battery sectionalizing procedure is to verify that the disconnecting means electrically isolates two points in the battery circuit.

   a) If the disconnecting means can be visually verified by the presence/absence of a cable or busbar, or the disconnection of a plug, then testing is not required.
   b) If the disconnecting means is hidden from view or its state could be confused, such as the internal mechanism of a switch, then the procedure shall establish the following:
      i) Test instrument to be used, the required PPE, and the person who will use it to verify the proper operation of the test instrument on a known connection before and after its use
      ii) Requirement to define the limited and restricted approach boundaries
      iii) Requirement to test for conductivity before touching the two exposed conductors that are separated by the disconnecting means
      iv) Requirement to retest for conductivity when circuit conditions change or when the job location has been left unattended
      v) Planning considerations that include methods of verification where there is no accessible exposed point to take conductivity measurements
9) Process for Establishing and Verifying a Lower Risk Work Condition in Batteries. Note that, while this process is like the process for establishing and verifying an electrically safe work condition, it is not equivalent. Batteries will always have the potential for short-circuit which can be electrically hazardous even at low voltage. Establishing and verifying a lower risk work condition in batteries shall include all of the following steps, which shall be performed in the order presented, if feasible:
   a) Determine the number, configuration, and voltage of batteries in series and parallel, and the number, configuration, and voltage of battery chargers. Determine if there are any batteries or chargers nearby that could be confused for the battery being worked on. Check applicable up-to-date drawings, diagrams, and identification tags.
   b) Turn off any/all battery chargers for the associated battery and open their ac and/or dc disconnecting device(s).
   c) Where possible, visually verify that all blades of the disconnecting devices are fully open or that drawout type circuit breakers are withdrawn to the test or fully disconnected position.
   d) Apply lockout/tagout devices to the battery charger disconnection means
   e) Sectionalize the battery in accordance with a documented and established procedure
   f) When required, verify the absence of conductivity with an adequately rated portable meter.

C. Additional Protective Measures

If additional protective measures are required, they should be selected and implemented according to the hierarchy discussed above. Common engineering controls in batteries, and how to account for them in the risk assessment, include the following:

1) Disconnects: Mid-string and terminal disconnects that do not expose the worker to an electrical hazard can be used to sectionalize a battery into lower voltage segments. If a circuit disconnection is hidden from view, then a negative test for conductivity should be

performed. The US NEC, article 480.7(C), requires mid-string disconnects for all batteries exceeding 240 V to be disconnected into segments below 240 V dc [5]. The shock, arc flash, and thermal risk for any following tasks are then determined based on the voltage and short circuit current of the battery segments.

2) Overcurrent Protection: Mid-string breakers, fuses, or contactors may be used to reduce arc flash and thermal risk. To be accounted for in a battery risk assessment, such devices must be rated to interrupt the battery's short circuit current and be listed. The arc flash, and thermal risk for any following tasks are then determined based on the reduced duration of an arc or short circuit, calculated according to the overcurrent protection's time-to-trip curve. One-half bolted fault current is commonly used but the maximum hazard can occur anywhere from just below the minimum trip current to the bolted fault current.
3) Barriers: Battery terminals may be covered with barriers to prevent accidental contact or short circuit. To be accounted for in a battery risk assessment, barriers should be rated for the battery's nominal voltage and installed correctly. The description of the work to be performed should then include removal and replacement of terminal barriers.

IV. Conclusion

This paper clarifies and elaborates on the battery risk assessment required by NFPA 70E. Calculating and controlling shock, arc flash, and thermal hazards in battery systems is complex but critically important to prevent workplace accidents. Electrical hazards in batteries are mitigated by the physical separation of voltage, by their ability to operate ungrounded (or with high resistance to ground), and the ability to electrically isolate batteries from each other to reduce voltage and available current. While the best method of controlling electrical hazards is through a LOTO program, the requirements of LOTO cannot be directly applied to batteries as they are always energized by design. However, the principles of hazardous energy control on which LOTO programs are built can be applied to batteries. Instead of establishing an electrically safe work condition, a battery sectionalizing procedure can establish a lower risk working condition. Instead of verifying zero energy, all electrical work on batteries is energized electrical work that is controlled based on the magnitude and type of risk. Therefore, sectionalizing a battery into lower voltage, lower energy, segments can almost entirely eliminate the shock and arc flash hazards, and substantially reduce the thermal hazards of a large battery system. The remaining hazards can be controlled through basic PPE such as insulated tools, safety glasses, and leather gloves.

Updating an existing workplace LOTO program to account for the controls appropriate to batteries can be easily accomplished with supplemental training. Rather than training battery technicians without prior electrical safety knowledge, basing battery safety training on existing LOTO principles will allow employers to provide additional training for only those employees who perform work on battery system. Similarly, LOTO program audits can include battery safety practices and training without the need to create an oversight program from scratch. Controls for the chemical, mechanical, and fire hazards of batteries will still require training based on the specific battery type and formfactor of a given workplace.

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References

[1] D. M. Rosewater, "Reducing Risk when Performing Energized Work on Batteries," *2023 IEEE IAS Electrical Safety Workshop (ESW)*, March, 2023, Reno, NV

[2] D. M. Rosewater, "Reducing Risk in the Design of Batteries," *2023 Battcon Conference*, May, 2023, Orlando, FL

[3] *The control of hazardous energy (lockout/tagout)*, OSHA 29 CFR 1910.147, 1989

[4] *Standard for Electrical Safety in the Workplace*, NFPA 70E, 2024.

[5] *National Electrical Code*, NFPA 70, 2020.

[6] L. B. Gordon, L. Cartelli and N. Graham, "A Complete Electrical Shock Hazard Classification System and Its Application," *in IEEE Transactions on Industry Applications*, vol. 54, no. 6, pp. 6554-6565, Nov.-Dec. 2018, doi: 10.1109/TIA.2018.2803768.

[7] *IEEE Recommended Practice for Personnel Qualifications for Installation and Maintenance of Stationary Batteries*, IEEE Std 1657-2018 (Revision of IEEE Std 1657-2009), 25 May 2018, doi: 10.1109/IEEESTD.2018.8365914.

[8] R. F. Ammerman, T. Gammon, P. K. Sen, and J. P. Nelson, "DC-Arc Models and Incident-Energy Calculations," *in IEEE Transactions on Industry Applications*, vol. 46, no. 5, pp. 1810-1819, Sept.-Oct. 2010, doi: 10.1109/TIA.2010.2057497.

[9] A. D. Stokes and W. T. Oppenlander, "Electric arcs in open air," *J. Phys. D: Appl. Phys.* Vol 24, pp. 26-35, 6 April 1990

[10] D. R. Doan, "Arc Flash Calculations for Exposures to DC Systems," *in IEEE Transactions on Industry Applications*, vol. 46, no. 6, pp. 2299-2302, Nov.-Dec. 2010, doi: 10.1109/TIA.2010.2070480.

[11] K. Gray, S. Robert, and T. L. Gauthier, "Low Voltage 100–500 Vdc Arc Flash Testing," *2020 IEEE IAS Electrical Safety Workshop (ESW)*, 2020, pp. 1-7, doi: 10.1109/ESW42757.2020.9188336.

[12] A. Marroquin and T. McKinch, "Methods for Evaluating DC Arc Flash Incident Energy in Energy Storage Systems," *2023 IEEE IAS Electrical Safety Workshop (ESW)*, March, 2023, Reno, NV

[13] J. G. Hildreth and K. Feeney, "Arc Flash Hazards of 125 Vdc Station Battery Systems," *2018 IEEE Power & Energy Society General Meeting (PESGM)*, 2018, pp. 1-5, doi: 10.1109/PESGM.2018.8586181.