Arc Flash in Marine Installations

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ABSTRACT--This paper introduces the basics of the arc flash danger and how arc flash hazard reports and equipment labeling protects workers. Arc flash requirements are just beginning to enter the marine world in contrast to shore-side facilities where they are firmly in place. Mitigation techniques to reduce or eliminate an arc's incident energy will be detailed. Estimated ranges of worst-case incident energies at the main switchboard will be detailed based on total online generator size and compared with examples of PPE protective equipment.

INTRODUCTION

The use of electrical energy aboard ships and marine structures has increased in recent decades and is anticipated to grow further. With the increase in energy and power levels, the hazards associated with electrical installations also grows. One of the major hazards is an arc flash event. Knowing about arc flash can protect your employees and your firm from a tragic accident.

An arc flash is a rapid release of energy due to an arcing fault between a bus bar and another bus bar, neutral, or a ground, during which the air is the conductor. While arc flashes can be precipitated at any time, they are much more likely, and the consequences much more severe, while maintenance and repair operations on energized equipment are under way. These operations introduce the compounding effects of bringing personnel into proximity with energized conductors, and the removal of covers from electrical components. In the majority of cases, it is human error rather than equipment failure that leads to the arc flash event. Unintentional arcing in power equipment can inflict several different types of hazards:

- Heat from an arc can cause severe flash burns many feet away (temperatures can reach 19,500°C, four times the temperature at the surface of the sun). [1]
- This massive energy discharge burns the bus bars, vaporizing the copper, causing an explosive volumetric expansion conservatively estimated to have an expansion ratio of 67,000 to 1. [1] Byproducts from the arc, such as molten metal spatter, can cause severe injury.
- Pressure waves caused by the rapid expansion of air and vaporization of metal can distort enclosures and cause doors and cover panels to be ejected with severe force, injuring personnel.
- Sound levels can damage hearing.
- In addition to personnel hazards, an arc flash generally results in equipment damage, which requires clean up and repair, and causes system down time.

Anywhere from 3,500 to 30,000 arc flash incidents occur every year [2] and countless have been investigated. Many of these have revealed new insights into the danger. In particular, a number of accidents occurring at the US Dept. of Energy have been very well documented and the accident reports are available online. [3] [4] [5]

There have been countless studies done on a multitude of aspects of the arc flash danger. However, most of these are focused on shore-side installations. This paper, in contrast, will focus on what is unique for the marine application.

ARC FLASH HAZARD ANALYSIS

An arc flash hazard analysis allows us to quantify the arc flash energy lurking inside each electrical panel. The danger is measured in calories per centimeter squared (cal/cm^2). This is the energy that would

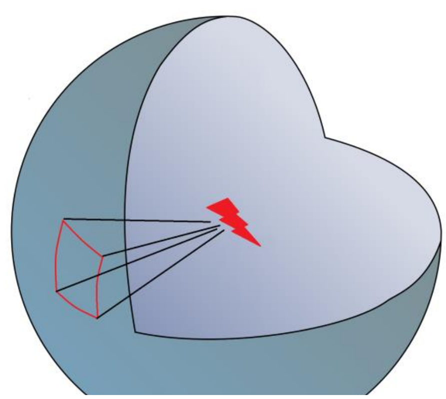

Figure 1: Example of incident energy projected onto a 1 cm^2 surface

potentially be projected onto the front of a worker at roughly arm's length from the electrical arc. See Figure 1.

It has been found that 1.2 cal/cm^2 of thermal energy applied to a person's skin for a short period of time generally produces a second-degree burn, which is not a permanent injury. This threshold is typically used as the upper limit to which personnel may be exposed without extra arc flash specific personal protective equipment (PPE). Arc flashes are generally limited to systems where the bus voltage is equal to or in excess of 208 volts. [6] Lower voltage levels normally will not sustain an arc.

The arc flash hazard analysis is a natural extension from two related studies that may already be required for the installation:

- Short circuit study
- Circuit breaker coordination study

If you have these two common studies, you already have the basis to perform an arc flash hazard analysis.

EBDG has extensive experience performing these arc flash studies for marine electrical systems. We utilize a powerful software package called SKM Power Tools for Windows™ to perform the arc flash calculations. Nevertheless, an intimate understanding of the electrical engineering underlying this software is critical in its application.

The purpose of calculating the arc flash numbers is not to have them buried in a report for the life of the system. In contrast, the numbers become an active and ongoing part of safety procedures by being labeled on the electrical equipment. These labels warn the front-line worker of the danger. See Figure 2 and Figure 3.

In concert with arc flash training and a broader electrical safety program, workers are educated about what level of personal protective equipment is required for the various levels of arc flash danger, specifically the incident energy levels listed in cal/cm^2.

REGULATORY REQUIREMENTS

Even shore-side, there aren't any clear-cut regulatory requirements for arc flash studies or arc flash safety practices. But tragic high-profile accidents and the ensuing fines and lawsuits have made them common practice onshore. As a result, National Fire Protection Association (NFPA) Standard 70E has become the consensus standard for workplace electrical safety. Organizations are guided by the policies and procedures in this standard.

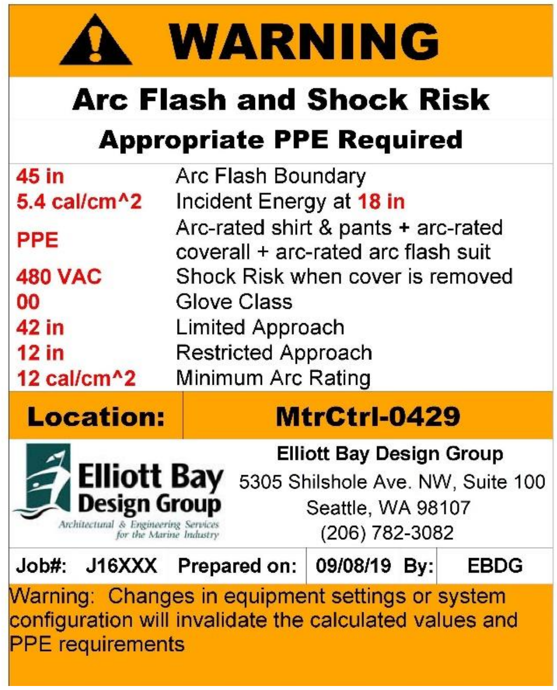

Figure 2: Example of an arc flash label

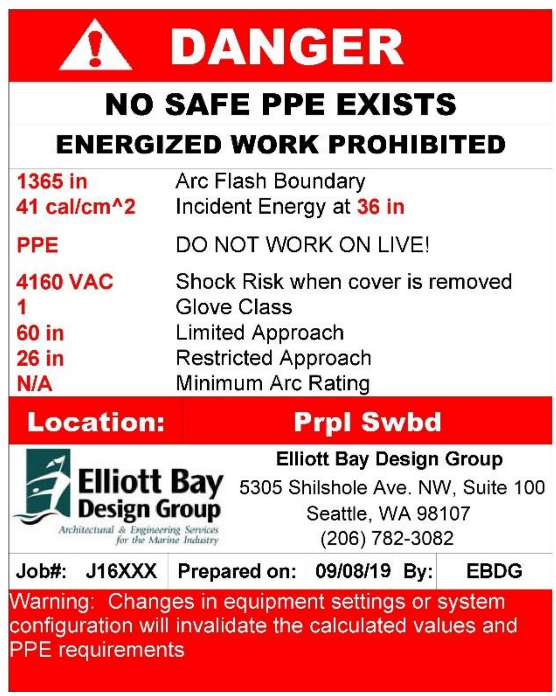

Figure 3: Example of an arc flash label

Marine standards have historically not addressed arc flashes but are also beginning to add arc flash requirements. DNV now requires arc resistant switchgear for medium voltage systems and generator sections of low voltage IMO compliant systems (Rules For Classification – Ships, 2019, 4-8-2/9.2.2, 4-8-4/1.1.5, and 4-8-4/2.2.1). In 2014, ABS added the requirements for both arc resistant switchgear and arc flash hazard analyses for systems greater than 1000V [Currently MVR 2020 4-8-1/5.1.7(b) and 4-8-5/3.7.4(e)]. Lloyd's Register added an entire section dedicated to arc flash safety (Rules and Regulations for the Classification of Ships, 2019, Part 6, Chapter 2, Section 8). This requires arc flash studies to be performed even for low voltages. BV requires arc resistant switchgear for medium voltage applications (C-2-13/6.2.5)

In 2014, a variety of marine arc flash safety requirements were created by the Institute of Electrical and Electronics Engineers (IEEE): IEEE Std 45.5, Recommended Practice for Electrical Installations on Shipboard -- Safety Considerations. IEEE 45 has had numerous sections called out by 46 CFR (Code of Federal Regulations) for many decades. So, this set of standards may have the strongest connection to those who develop United States Coast Guard regulations, and those who must abide by them.

MARINE OPERATOR EFFORTS

While not yet broadly required by regulation, several marine operators have initiated arc flash investigation and mitigation efforts.

In 2013, the Canadian Coast Guard published a tender notice for arc flash studies. [7] They implemented arc flash safety procedures on two vessels and have been working to expand to additional vessels.

In 2014, the US Army Corps of Engineers began requiring vessels to meet arc flash standards (ER 385-1-100). [8] This has been implemented on numerous vessels.

EBDG completed arc flash studies for all six of TxDOT's Galveston ferries in 2016. [9] Shore-side studies had already been performed for the terminals and shore-side maintenance buildings. [10]

ARC FLASH HISTORY

Over the last three decades, arc flash safety practices have gone from almost unheard of to fairly universal for shore-side facilities. Avoiding them has become increasingly expensive. The following timeline demonstrates this continuing trend:

- 1981, Ralph Lee published the first formulas for hazard calculations
- 1991, arc flash was first defined by OSHA
- 1995, DuPont undertook arc flash R&D
- 1995, the ASTM Arc Test Method was developed
- 1995, NFPA 70E defined an arc flash boundary
- 1998, ASTM developed standards for PPE testing
- 1999, Arc flash rated PPE appeared on the market
- 2000, NFPA 70E expanded arc flash requirements
- 2002, NEC began requiring arc flash hazard warning labels
- 2002, IEEE 1584 Guide for Performing Arc Flash Hazard Calculations first published
- 2004, NFPA 70E referenced IEEE 1584
- 2011, OSHA fined the US Postal Service $6.2 million for arc flash violations [11]
- 2011, An arc flash victim settled for $13.9 million with Reading Materials, Inc. [12]
- 2013, An injured worker received an award of $7 million involving Qualcomm [13]
- 2014, IEEE 45.5, IEEE Recommended Practice for Electrical Installations on Shipboard—Safety Considerations released.
- 2018, Revision of IEEE 1584 released, incorporating refinements resulting from additional testing and analysis.

ARC FLASH AND MARINE DESIGN

Space comes at a premium on a ship. For control and monitoring purposes, switchboards are often placed inside the engine control room. But even for low voltage switchboards, arc flash calculations are revealing that the incident energy levels are much higher than thought. An accident in such a location could not only lead to significant injury but make continued operation from the location very challenging.

Concerns regarding such an arc flash are especially sensitive with regards to the main generator breakers. Should an arc flash develop on the input bus bar to a generator circuit breaker, the circuit breaker cannot interrupt that flow. During an arc, the conductive ionized air called plasma flows through the inside of the switchboard. If an arc starts in one location, it can be assumed that it will propagate to other locations.

Thus, the worst-case assumption is usually that an arc initiating elsewhere will propagate to the input terminals of a generator circuit breaker. In fact, that worst-case may assume that it propagates to the maximum number of generators that might be online. The possibility of this scenario may lead to the construction of low voltage switchboards with generator entrance cubicles built to medium voltage switchgear standards. Medium voltage standards physically segregate the entrance cubicles and make such propagation from another location extremely unlikely.

Another option is to push major power equipment outside of a manned space like a control room, thus separating crew members from a potential arcing event. While mitigating arc risk, such relocation will increase remote control and monitoring requirements so that crew have the same capabilities as if the switchboard had not been moved.

As vessel electrical systems become more complex, arc flash dangers can both increase or decrease with new technologies. This is especially the case with DC propulsion grids, AC or DC drive systems and new energy storage technology.

Specific to the electrical power system design itself, there are a myriad of enhancements and mitigation techniques to reduce or eliminate the arc flash danger. EBDG can help customers navigate the complexity of such methods:

- Zone-selective interlocking (ZSI)
- Differential relaying
- Energy-reducing maintenance switch
- Mitigation system, like ABB's Arc Vault™
- Arc flash optical relays
- High-resistance grounding
- Current-limiting fuses or circuit breakers
- Arc Resistant Switchgear
- IEC 61850 networking of protection relays
- Line reactors
- Prohibiting energized work on certain panels

ARC FLASH AND GENERATOR SIZE

Caution: *The following estimates of arc flash energies based on ship service or propulsion generator size are for preliminary assessment only. Nothing contained herein shall be taken to replace a more detailed analysis of arc flash energies for the purposes of ensuring workplace safety.*

As discussed, the likely worst-case arc flash numbers for a vessel will likely occur at the entrance cubicles where a switchboard receives its power from onboard AC generators. While in no way meant to replace the need for an arc flash study, at a very preliminary level, generator size can be used to approximate that worst-case arc flash energy number.

A few assumptions are necessary (a fuller set can be found in Appendix A). First, the arc is assumed to last for only two seconds. This comes straight out of the 2015 NFPA 70E which indicates this is a sound assumption if the egress of the person performing the energized work is not inhibited. The capability for quick egress needs to be ensured for any energized work that is performed.

Secondly, on many vessels, the AC generators are located near the switchboards receiving power. The resistance supplied by that short run of often very thick cables is usually quite low. Further, it is usually rather small compared to the internal resistance of the generator itself. Eliminating the cable resistances from the calculation will usually lead to only slightly higher arc flash numbers, a conservative approach.

The internal resistance that the generator provides is also a complex set of calculations and depends on a number of variables. In "Understanding Arc Flash Hazards" [14], equations were detailed that underlie IEEE Standard 1584-2002 [15]. In the initial phase of the arc, the arc is primarily a function of the initial peak prospective short circuit current. This peak current is essentially a function of what is termed the subtransient reactance of the generator. This internal resistance varies from machine to machine. Based on our review of numerous generator data sheets over time, this value is often between 0.10 and 0.15 per unit. Some outliers can be found in the range of 0.075 to 0.20. Based on these ranges, Figure 4 through Figure 6 show the approximate worst-case arc flash energies based on total online generator power for 208V, 480V and 600V systems.

There is one caveat to the assertion that generator entrance cubicles present the greatest incident energy level. In cases where a step-down transformer is relatively large in comparison to the on-line

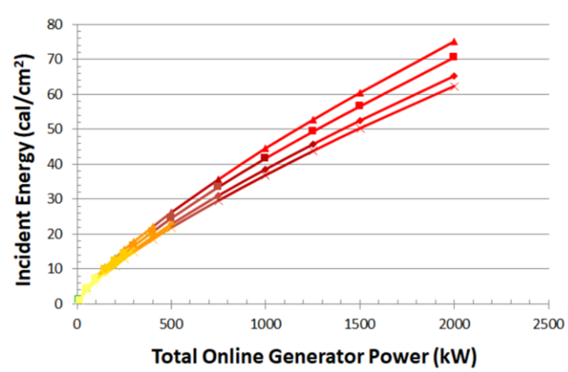

Figure 4: Incoming Switchboard Worst-Case Arc Flash Energy Ranges, 208V

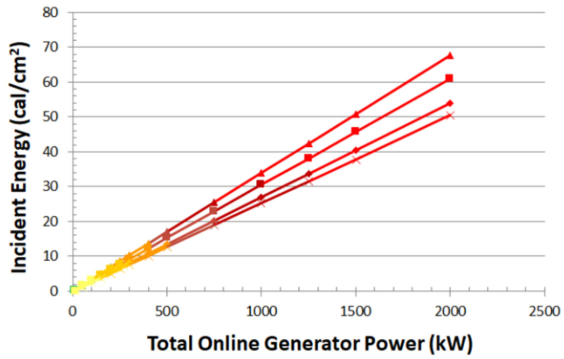

Figure 5: Incoming Switchboard Worst-Case Arc Flash Energy Ranges, 480V

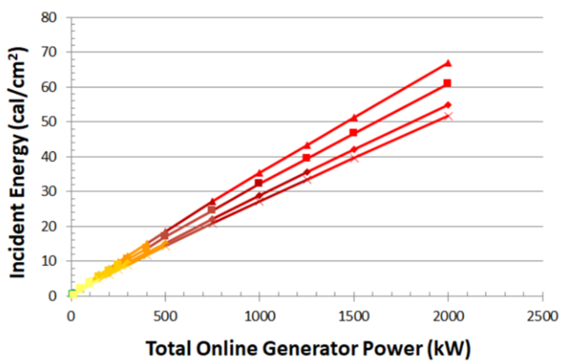

Figure 6: Incoming Switchboard Worst-Case Arc Flash Energy Ranges, 600V

generation capacity, the secondary side of the transformer may present a greater incident energy. This is because the increased current, rather than reduced voltage, has a more significant impact on incident energy level.

PPE RANGES

To put the preceding estimated incident energy levels in perspective, it is helpful to compare them to ratings of clothing and personal protective equipment (PPE) available for use during work on energized electrical equipment. NFPA 70E Annex H provides guidance on arc rated clothing and PPE for several thresholds up to 40 cal/cm^2. See Figure 7 and Figure 8 for two examples.

Each threshold represents an increase in the level of protection, and consequent increase in complexity, weight, and expense. Clothing and PPE combinations for incident energies up to 12 cal/cm^2 are modest additions to a typical shipboard environment. Incident energies between 12 cal/cm^2 and 40 cal/cm^2 are available, but require a more significant investment in use, donning and removal, storage, and care. PPE and arc rated clothing for incident energies above 40 cal/cm^2 are not

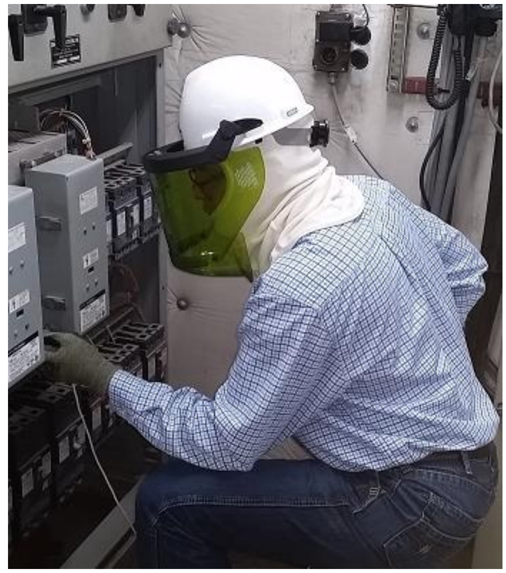

Figure 7: One of the Authors with Arc Flash PPE Protecting up to 12 cal/cm^2 (including special arc flash gloves, shirt and jeans)

Figure 8: Typical Arc Flash PPE Protecting up to 40 cal/cm^2

recognized, and energized work should not be performed on systems with this incident energy level.

LOOKING AHEAD

The definitive guide for performing arc flash energy calculations in the United States, IEEE-1584, was revised and reissued in 2018. It builds upon the foundation created by IEEE-1584-2002, and work prior to that. It is based upon approximately 1700 experimental trials, versus the approximately 300 trials of the 2002 version, and provides higher fidelity results than the previous version.

From the vessel owner's prospective, the most significant difference between the 2002 and 2018 versions of the standard is incorporation of the geometric configuration of the electrical conductors, enclosures, and worker. The geometric orientations determine which sets of equations to use in determining the incident energy, and thus have a significant impact on the results. The ramification is that this information must be collected from a vessel or design while preparing an arc flash study.

The collection of large quantities of geometric data adds to the already intensive effort required during a ship check to collect electrical information on all relevant components. This expands the time and costs of performing an arc flash energy evaluation.

CONCLUSION

Arc flashes can be quite dangerous, but that danger can be mitigated, and workers can be protected. Arc flash requirements are already entering the marine world and their impact will only increase. EBDG can quantify the danger and be part of the process to reduce or even eliminate it.

The reduction or elimination of the arc flash danger can be implemented with existing systems. But like a lot of things, it’s often much easier during an initial design or major upgrade. So, when it comes to major investments in electrical systems, analyzing the arc flash angle now will help protect your investment from the approach of arc flash standards in the future.

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ABOUT THE AUTHORS

Will Ayers has been working in the marine field as an electrical engineer for almost twenty years. Will currently serves as Chief Electrical Engineer and Technical Manager at Elliott Bay Design Group in Seattle, Washington. A graduate of the University of Washington with a BSEE, Will has excelled in vessel electrical system studies, electrical system software modeling, and all levels of system design on a marine vessel. Beginning in 2016, Will has led the completion of arc flash studies for six vessels. Those studies ranged from smaller ship service power systems for direct drive vessels, a large DC-DC diesel-electric vessel with separate ship service power, and a large AC-AC diesel-electric vessel with integrated ship service power.

Taylor Herinckx began his career in 2006 as a naval architect with Elliott Bay Design Group in Seattle. His BS degree in Naval Architecture and Marine Engineering from Webb Institute laid the foundation for his progressive transition to electrical engineering. Taylor has primarily performed electrical work for approximately eight years, focusing on electrical system new designs, modernizations, and construction oversight. He holds professional engineering licenses in both naval architecture/marine engineering and electrical engineering.

APPENDIX A: WORST-CASE ARC FLASH CALCULATION ASSUMPTIONS

- Voltages are less than 1000V
- Arc in a box multiple used (switchboard)
- The system has sufficient voltage and prospective short circuit current for the arc to be self-sustaining
- Calculation at 85% of bolted fault current is not needed because the switchboard arc is assumed to be at line terminals of online generator circuit breakers and arcing for 2 seconds for worst case
- Synchronous AC generator is 4-pole, 1800rpm
- 18" working distance is assumed for switchboards based on 2015 NFPA 70E Table 130.7(C)(15)(A)(b)
- Ungrounded or high-resistance grounded system
- An ungrounded 208V system is not very common but a grounded wye 208V system would result in similar worst-case numbers
- All motors feeding back into the fault would be of the induction type and thus only contributing arcing current for five cycles. Motors have been assumed to account for an additional 10% of generator arcing current during the initial 250 msec of the fault.
- Arcing current based on a step-change input from subtransient levels for 250msec to 3X of rated current for the remaining 1750msec

