Arc-in-a-Box: DC Arc Flash Calculations Using a Simplified Approach

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Abstract
A method is proposed for calculating the incident energy and the arc flash boundary distance for dc systems when an arc is bounded inside a space such as a battery cabinet. The so-called "arc-in-a-box" has a focusing effect in which radiated energy strikes the back and sides of the box, reflecting out in a higher concentration of energy than would be obtained in open air. This multiplying effect increases the level of the electrical hazard and therefore affects the selection of personal protective equipment (PPE) for workers who are potentially exposed to a dc arc flash. The method uses the dc maximum power method and a multiplying factor instead of using distance exponents. The proposed method expands on methods developed by earlier researchers and scientists. It is only valid for the radiated component of heat flux (i.e., energy that is radiated directly out of the box), and for that radiation striking or re-striking the inside of the box. Some background on the development of this method is presented along with a number of formulae and definitions. The need for further testing is explored with some testing procedures being suggested. An example is provided and several references are included.

Introduction

What is a multiplication factor?

Safety requirements stipulate that no work should be done on energized equipment if it can be avoided. For stored energy devices such as batteries, turning off the energy source is not possible, so one must conduct a risk assessment, which includes hazard identification prior to working on a battery system. One element of that hazard identification is to determine the incident energy available at the work task location that could be released in an arc flash event.

The elements and possible consequences of an arc flash are the explosive release of energy in many forms: extreme heat energy (3rd and 4th degree burns), air pressure energy (enough to knock a person over or cause concussion), audible noise energy (enough to cause deafness), and light energy (enough to cause temporary or permanent blindness), and release of poisonous gas (aluminum or copper oxides). Of the possible forms of injury, the greatest danger appears to be from thermal injury. On a battery system installed on open racks, this energy tends to be released in all directions. As shown in Figure 1, a worker standing next to an arc flash event would only be exposed to a portion of the total energy. However, in a battery cabinet almost all of the energy is focused cannon-like in a single direction toward the front of the cabinet, which is where it is open and where a worker is likely to be standing, as shown in Figure 2. This effect is what's known as the "multiplier factor." Whatever amount of energy a person would be exposed to in open air is amplified by the cabinet effect.

Figure 1: arc flash in open air radiates in all directions

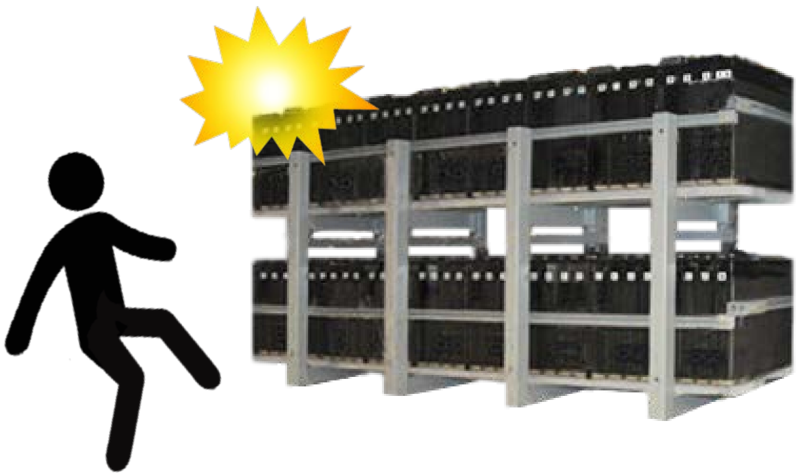


Figure 2: Arc flash in a box concentrates all the energy in one direction.

Incidents of arc flash in battery cabinets are not well documented. Some incidents identified as arc flash do not have all of the attributes described in the preceding paragraph. Some appear to have been hydrogen explosions rather than arc flash, although the consequences can be similar. Battery cabinets come in many forms. Anecdotal evidence suggests that the greatest risk of arc flash is in cabinets in which top-terminal containers are installed. Maintenance activities requiring a worker to reach across terminals and connectors increase the probability of a short circuit and the creation of an arcing current, and thereby an arc flash incident. Cabinet designs with inadequate clearance above the terminals can further increase the likelihood of an incident happening. Front-terminal battery cabinets can significantly lower the risk of an arc flash incident happening.

What are the implications for a user?

Once the risk assessment identifies the potential level of incident energy, which is related to the seriousness of a possible injury, one must then determine the likelihood of an incident happening (probability) based on the type of work to be conducted. The risk is related to the combined effect of seriousness and likelihood [1]. An example of how the level of risk is based upon the task to be performed on a battery system was presented at Battcon-2013 [2].

How close will a worker be to the battery?

The answer will factor into the determination of the likelihood of an arc flash event happening. What will – or could – the worker likely touch? The answers to these and similar questions will help determine the level of risk and whether the risk is considered acceptable or not. The arc flash boundary may be considered as coming into effect when a worker is within the limited approach (shock) boundary for the 2012 edition of NFPA 70E – the restricted approach boundary for 2015 edition or the worker is interacting with the equipment in manner that could cause an arc flash incident. When either of these events happens the arc flash boundary comes into effect around the equipment as well as the need for adequately rated personal protective equipment (PPE) – clothing, equipment, such as hard hats and face shields, and insulated tools – that a worker must wear or use in order to perform the task safely.

Background

The first research paper to identify the behavior of dc arc flash was published in a paper by D. R. Doan [3] in 2010. This work extrapolated from what was then known about an ac arc flash. The first description of the so-called "arc-in-a-box" multiplier effect was introduced by R. Wilkins [4] in 2004 and was expanded upon for dc systems by Ammerman et.al. [5] in 2010, and clarified by Fontaine et. al. in 2012 [6]. These calculations were based upon the shape and dimensions of typical switchgear, motor control centers, and panelboards that were available at the time. Table 1 illustrates the typical enclosures that formed the basis for the calculations. For this paper we have identified them as small, medium and large. Unfortunately, none of these appears representative of a typical battery cabinet in use today with the large, medium voltage (MV) switchgear being closest.

Informative Annex D in the 2012 edition of NFPA 70E [7] provides two methods for estimating direct-current incident energy for arc flash calculations. The first is known as the "Maximum Power Method." After giving the formulae for estimating the arc flash energy, it states, "For exposures where the arc is in a box or enclosure, *it would be prudent* to use a multiplying factor of 3 for the resulting incident energy value." [8] This value has been challenged by some who question if a factor of three is arbitrary or based on solid test data. Some think the multiplier is even higher, while others argue that the formulae are already so conservative that the multiplier should be lower. The work of Wilkins, Ammerman and Fontaine referenced above suggest that, depending upon the box size, the multiplying effect could be as high as a factor of approximately 5 for large enclosures.

Table 1: Enclosure types and dimensions (mm/in) based on ac equipment cabinets

Enclosure Type	Enclosure Width mm (in)	Enclosure Height mm (in)	Enclosure Depth mm (in)
Small	305 (12.0)	356 (14.0)	191(7.5)
Medium	508 (20.0)	508 (20.0)	508 (20.0)
Large	1143 (45.0)	762 (30.0)	762 (30.0)

First some definitions

The following terms, abbreviations, and symbols are used in this paper

- **arc flash boundary (AFB)** - Per NFPA 70E [1], this is the distance within which a person could receive a second degree burn if an electrical arc flash were to occur. Officially, it is the distance at which the incident energy density equals 1.2 cal/cm^2 (5.0 J/cm$^{2)}$.

- **thermal Joule (J_{th})** – One Joule is 4.184 calories.

- **Calorie** - The approximate amount of energy needed to raise the temperature of one gram of water by one degree Celsius depending upon the atmospheric pressure and the starting temperature.

  (Note: Under the International System of Units, Joule is the preferred term in place of calorie. However, per NFPA 70E, personal protection equipment is still rated in calories.)

How is the multiplying factor determined?

MODIFIED DC MAXIMUM POWER METHOD EQUATIONS

For the steady state condition, maximum power in a dc circuit arc occurs when the arc resistance equals the system resistance or the watts of the arc equals 0.25 (¼) times the bolted-fault watts, 0.25 W_{bf} (0.25 x V_{sys} x I_{bf}). There are 4.184 thermal calories per Joule – therefore a factor of 0.239 is used for converting from Joules to thermal calories and 1/4π equals (0.079577). Therefore, the multiplier before Equation 1 should be 0.00951 (0.5 x 0.239 x 0.079577) and the multiplier before Equation 2 should be 0.004755. The maximum power method equations have also been modified by including the multiplying factor variable M_f in the equations as shown below.

$\mathbf{IE_m = 0.00951 \times V_{sys} \times I_{arc} \times M_f \times T_{arc}/D_{cm}^2}$ [Equation 1]

(Not rounded off to 0.01)

$\mathbf{I_{arc} = 0.5 \times I_{bf}}$ **[5]**

$\mathbf{IE_m = 0.004755 \times V_{sys} \times I_{bf} \times M_f \times T_{arc}/D_{cm}^2}$ [Equation 2]

Where:

IE_m = estimated dc arc flash energy at the maximum power point, cal/cm^2

I_{arc} = dc arcing current, Amperes

I_{bf} = dc system bolted fault current, Amperes

V_{sys} = dc system voltage, Volts

T_{arc} = total clearing time for dc arcing current, arcing time, sec.

D_{cm} = working distance, cm

M_f = multiplying factor

1.0 for arc-in-open-air

Use the value from Equation 8 below or 3.0 for arc-in-a-box effect where more conservative (less than 24 inches).

DC ARC FLASH BOUNDARY DISTANCE EQUATIONS

$\mathbf{D_{afb\_cm} = [(0.003963) \times M_f \times V_{sys} \times I_{bf} \times T_{arc}]^{0.5}}$ [Equation 3]

$\mathbf{D_{afb\_in} = (0.000614 \times M_f \times V_{sys} \times I_{bf} \times T_{arc})^{0.5}}$ [Equation 4]

$\mathbf{D_{afb\_ft} = (4.264 \times 10^{-6} \times M_f \times W_{bf} \times T_{arc})^{1/2}}$ [Equation 5]

$\mathbf{D_{afb\_in} = (614 \times M_f \times MW_{bf} \times T_{arc})^{1/2}}$ [Equation 6]

$\mathbf{D_{afb\_ft} = (4.264 \times M_f \times MW_{bf} \times T_{arc})^{1/2}}$ [Equation 7]

Where:

$\mathbf{D_{afb\_in}}$ = arc flash boundary, inches
$\mathbf{D_{afb\_ft}}$ = arc flash boundary, feet
$\mathbf{M_f}$ = multiplying factor

Table 2. Typical working distance in inches, millimeters, and centimeters that can be used in calculating dc arc flash incident energy.

Distance from Arc		
(inches)	**(mm)**	**(cm)**
36	910	91.0
24	610	61.0
18	455	45.5

MULTIPLYING FACTOR EQUATIONS FOR DC ARC FLASH CALCULATIONS

$\mathbf{M_f = (k4\pi)/(1 + [A_{in}/D_{in}]^2)}$ [Equation 8]

Ain = 0.03937a, inches [Equation 9]

Where:

a = a characteristic dimension that lets us represent the arc-plus-box as a single heat source in mm. The values of "*a*" were determined by R. Wilkins [4] and are given in Table 3 of this report for the specific equipment categories from IEEE 1584™. The value of "*a*" depends upon the type of equipment used.

k = a dimensionless correction factor determined by R. Wilkins [3]. The values are given in Table 3 of this paper for the specific equipment categories from IEEE 1584™. The value of *k* depends on the situation (arc-in-open-air or arc-in-a-box) and on the type of equipment used.

$\mathbf{D_{in}}$ = distance from the arc flash source, inches.

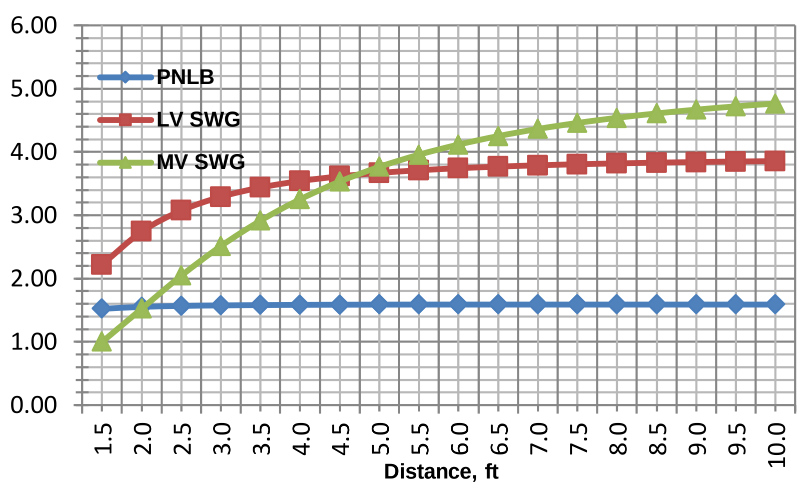
Table 3. Parameters for use in Calculating Multiplying Factors for Arc-in-a-Box Effect

	Width		Height		Depth		Area of inner surface		a	A_{in}	k
	(mm)	(in.)	(mm)	(in.)	(mm)	(in.)	(mm^2)	($in.^2$)	(mm)	(mm)	N/A
PNLB (Small)	305	12.0	356	14.0	191	7.5	361082	560	100	3.937	0.127
LV SWG (Medium)	508	20.0	508	20.0	508	20.0	1290320	2000	400	15.748	0.312
MV SWG (Large)	1143	45.0	762	30.0	762	30.0	3774186	5850	950	37.4015	0.416

Note: PNLB means panelboard, LV SWG means low voltage switchboard, and MV SWG means medium voltage switchgear.

Figure 3 below graphically shows how the multiplying factors for the different equipment categories in IEEE 1584™ change with distance. As can be seen for panelboards, the curve is fairly flat and for all practical purposes a multiplying factor of 1.6 can be used. At around 9 ft, the multiplying factor for low voltage switchgear levels off at a value of 3.85. However for medium voltage switchgear, the multiplying factor at 10 feet is still increasing, though at a slower rate. This multiplying factor peaks out around 5.23 somewhere at a distance greater than 500 feet. The test data on which IEEE 1584™ was based was taken over a range of 12 to 72 inches. It should be noted that a multiplying factor of less than 1 should never be used, as it is the multiplying factor for an arc-in-open-air. Battery cabinets are probably best represented by the MV switchgear category.

Figure 3 Multiplying Factors vs. Distance



EXAMPLE

It should be noted that the multiplying factor, M_f is dependent upon the type of distribution equipment used, and the distance from the arc. Therefore, an iterative process has to be used to determine the arc flash boundary distance. An initial value of M_f must be set. An initial value of 3 is suggested. Then based on this initial value an arc flash boundary distance is calculated, using an equation given above for dc systems. This value is then plugged into a multiplying factor equation, Equation 8 above using values of *a* and *k* for the appropriate class of equipment given in Table 3 above. The process is continued until the value converges sufficiently. An example of this process is given Figure 4 and in Table 4 below using parameters taken from an example in D. R. Doan· [3] but using values for *a* and *k* for MV switchgear, which is the closest equipment category to a battery cabinet.

Figure 4. Example of arc flash in a dc circuit using the iterative method.

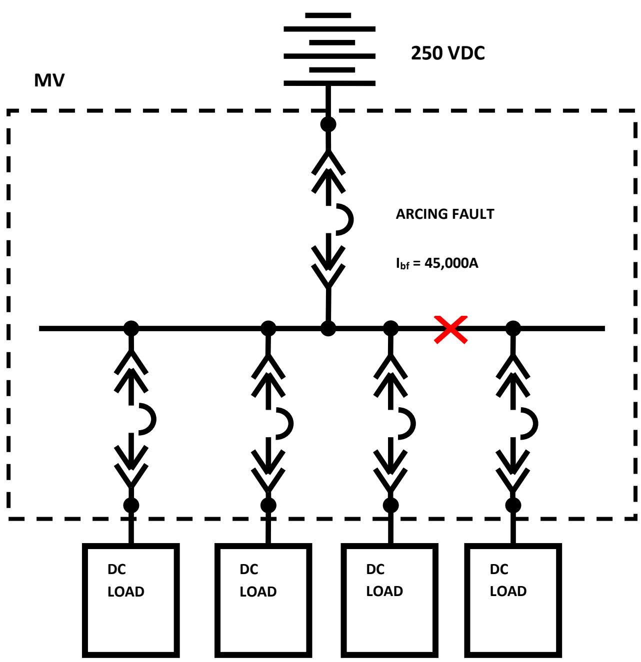


Table 3. Example of determining arc flash boundary based on a medium sized enclosure.				
K	0.416	0.416	0.416	0.416
π	3.142	3.142	3.142	3.142
A	37.4	37.4	37.4	37.4
D	3	101.8	106.3	107.2
M_f	-	3.27	3.33	3.34
V_{sys_dc}	250	250	250	250
I_{bf}	45000	45000	45000	45000
T_{arc}	0.5	0.5	0.5	0.5
M_f	3.27	3.33	3.34	3.34
D_{afb_in} (ft)	101.8 (8.48)	106.3 (8.86)	107.2 (8.93)	107.4 (8.95)

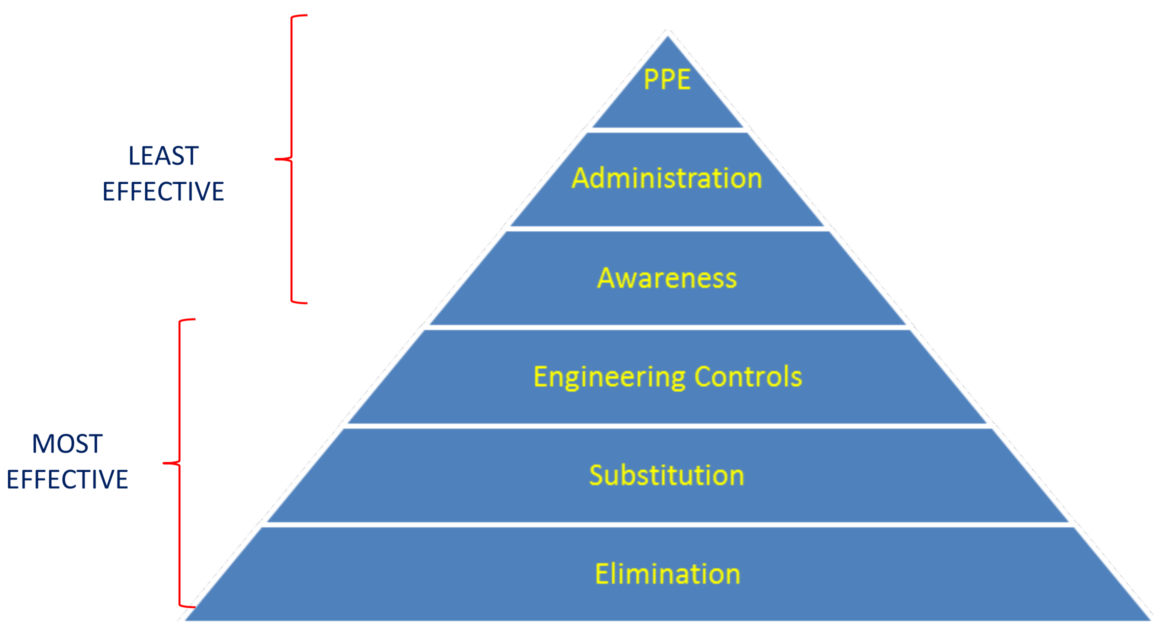
Summary and Conclusions

"Arc-in-a-box" has a focusing effect in which radiated energy from an arc flash strikes the back and sides of the box, reflecting out a higher concentration of energy than would be obtained in open air. Nobody has actually tested or calculated the multiplier effect on a "typical battery" cabinet. Wilkins [4] developed a model for calculating the multiplier effect based on test data using boxes that were available boxes at the time. The models are not representative of battery cabinets but may be the best information we have to date.

Top terminal batteries in a cabinet pose a higher degree of risk than front terminal batteries, but this paper has focused on the top terminal architectures. Variables can include the distance of the fault from the sides of an enclosure and the distance between the fault and the front of the cabinet. This paper has tried to provide a simplified approach to making the calculation using the modified maximum power method.

The implications for users are that the calculations based on the modified maximum power method can give higher incident energy values and greater arc flash boundaries based on the multiplier effect. For a typical 3-phase UPS battery at the working distance the level of PPE required may be very high. Therefore, solutions need to be considered based on the design of the battery system, including such things as segmenting the battery into lower voltage segments or providing effective barriers between the user and the battery.

Figure 5: Arc Flash mitigation, least effective at the top to most effective method at the bottom. Personal Protective Equipment is the last resort.



The knowledge of how arc flash behaves on dc systems is still in its infancy. Credible testing is necessary to characterize dc arc flash. Stake-holders in the battery industry need to step forward with suggestions for test procedures and with the money to finance the testing. Until that is done, the safety of workers on battery systems will continue to be theoretical and may require a very high level of PPE. This all came about as a result of a paper presented by Ralph Lee many years ago. [9]

References

[1] NFPA 70E, *Standard for Electrical Safety in the Workplace, 2012 Edition.*

[2] Cantor, W. and McCluer, S, "DC Arc Flash: 2013 Regulatory Updates and Recommended Battery Risk Assessment Guidelines," Battcon 2013 – *Conference Proceedings, International Stationary Battery Conference*, May 2013, pages 1-1 to 1-10.

[3] Doan, D. R., "Arc Flash Calculations for Exposures to DC Systems", *IEEE Transactions on Industrial Applications,* Volume 46, Issue 6, 2010, page(s): 2299–2302.

[4] Wilkins, R., "Simple improved equations for arc flash hazard analysis", *IEEE Electrical Safety Forum*, posted August 30, 2004.

[5] Ammerman, R. F., Gammon, T., Sen, P.K., and Nelson, J.P., "DC arc models and incident energy calculations", *IEEE Transactions on Industry Applications*, Vol. 46, No. 5, Sept/Oct 2010, pages 1810-1819.

[6] Fontaine, M.D., and Watt P., DC Arc Flash Calculations, Using a Simplified Approach, IEEE 2012 Electrical Safety Workshop, paper ESW2012-25.

[7] NFPA 70E®, 2012, *Standard for Electrical Safety in the Workplace,* D.8.1.1, page 70E-71.

[8] Doughty, R. L., Neal, T. E., Dear, T. A., and Bingham, A. H., "Testing update on protective clothing and equipment for electric arc exposure", *IEEE Industry Applications Mag.*, Vol. 5, Issue 1, Jan/Feb 1999, pages 37–49.

[9] Lee, R., "The Other Electrical Hazard: Electrical Arc Blast Burns", *IEEE Trans. Industrial Applications,* Vol. 1A-18. No. 3, Page 246, May/June 1982