DC Systems Working Group

EFCOG ESTG Workshop

Pacific Northwest National Laboratory

July 24-28, 2017

DC WG - History

- On the EFCOG ESTG website
  - See DC Working Group 20140714e.PPTX for:
    - DC Arc Flash WG Phase I – 10/2010
    - DC Systems WG Phase II – 10/2012
    - DC Systems WG Phase III – 7/2014
  - See DC Working Group 20150713d1.PPTX for:
    - DC Systems WG Phase IV – 7/2015
  - See DC Working Group 20160718b3.PPTX for:
    - DC Systems WG Phase V – 7/2016

Agenda

- Review and revise EFCOG Best Practice BP194-DC Arc Flash Calculator from 2016 ESW
  - Incorporate capacitor bank Arc Flash calculator into BP194
- Release Battery Risk Assessment Flowchart as a BP
- Review the LBNL High Energy Ground Stick Standard for Pulsed Power Applications for release as a BP

DC Arc Flash WG 2016 Members

new members in 2016

- Stan Berry, Gary Dreifuerst, Adam Green, Timothy Kuneli, Adam Martinez, Peter McNutt, Lynn Ribaud, Melkie A. Tega, Justin Tokash, Kyle Carr, Thomas Floyd, Martin Iedema, Eugene Ormond, Jason Sempsrott, Gedeon Teame, Michael Utes, Kyle Roberts, Perry Plotkin
- Facilities-ANL, DOE, FNAL, LANL, LBNL, LLNL, Navy, NREL, NSTec, PNNL, SNL

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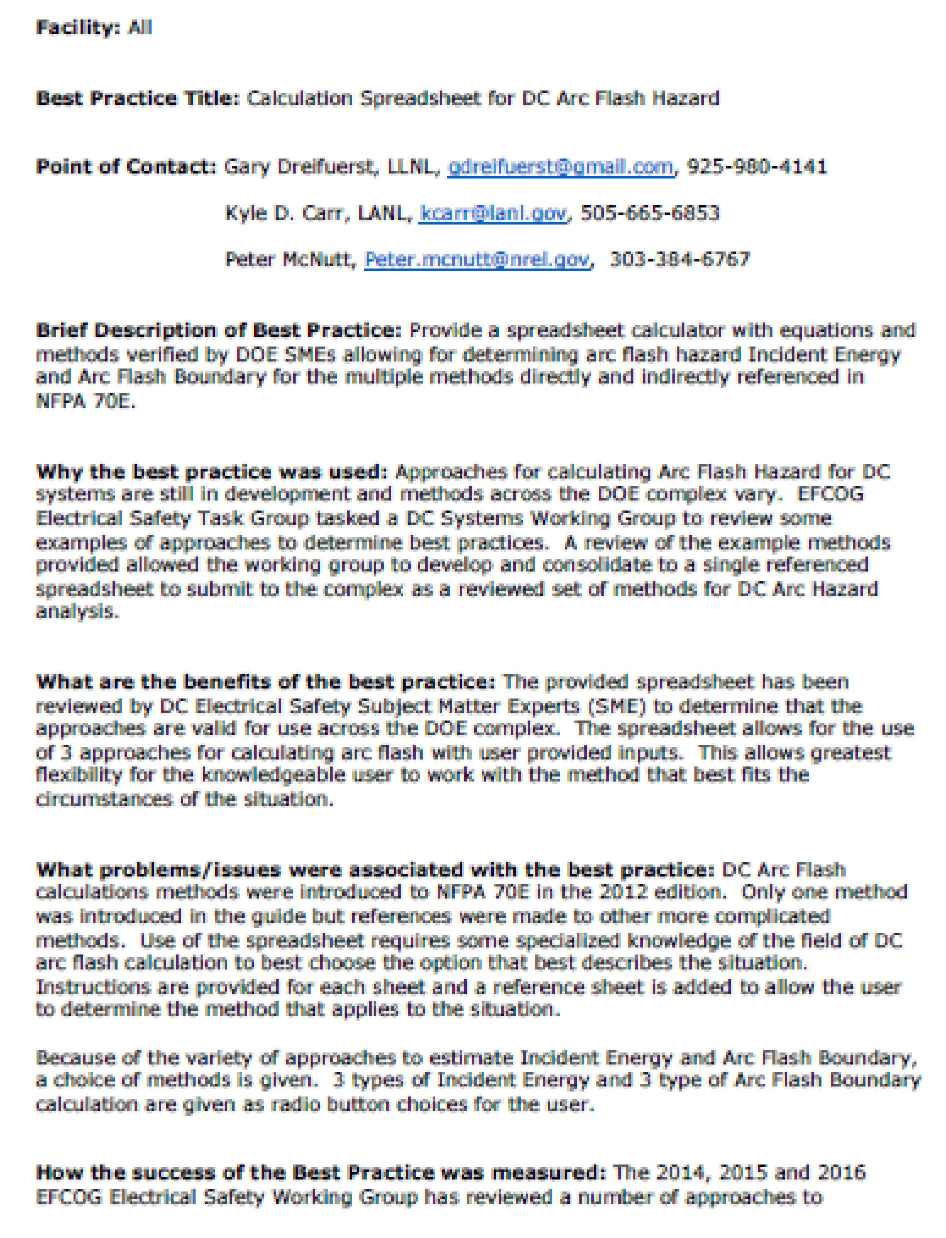
Facility: All

Best Practice Title: Calculation Spreadsheet for DC Arc Flash Hazard

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Kyle D. Carr, LANL, kcarr@lanl.gov, 505-665-6853

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Brief Description of Best Practice: Provide a spreadsheet calculator with equations and methods verified by DOE SMEs allowing for determining arc flash hazard Incident Energy and Arc Flash Boundary for the multiple methods directly and indirectly referenced in NFPA 70E.

Why the best practice was used: Approaches for calculating Arc Flash Hazard for DC systems are still in development and methods across the DOE complex vary. EFCOG Electrical Safety Task Group tasked a DC Systems Working Group to review some examples of approaches to determine best practices. A review of the example methods provided allowed the working group to develop and consolidate to a single referenced spreadsheet to submit to the complex as a reviewed set of methods for DC Arc Hazard analysis.

What are the benefits of the best practice: The provided spreadsheet has been reviewed by DC Electrical Safety Subject Matter Experts (SME) to determine that the approaches are valid for use across the DOE complex. The spreadsheet allows for the use of 3 approaches for calculating arc flash with user provided inputs. This allows greatest flexibility for the knowledgeable user to work with the method that best fits the circumstances of the situation.

What problems/issues were associated with the best practice: DC Arc Flash calculations methods were introduced to NFPA 70E in the 2012 edition. Only one method was introduced in the guide but references were made to other more complicated methods. Use of the spreadsheet requires some specialized knowledge of the field of DC arc flash calculation to best choose the option that best describes the situation. Instructions are provided for each sheet and a reference sheet is added to allow the user to determine the method that applies to the situation.

Because of the variety of approaches to estimate Incident Energy and Arc Flash Boundary, a choice of methods is given. 3 types of Incident Energy and 3 type of Arc Flash Boundary calculation are given as radio button choices for the user.

How the success of the Best Practice was measured: The 2014, 2015 and 2016 EFCOG Electrical Safety Working Group has reviewed a number of approaches to

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determine the format and use of the attached spreadsheet. A number of SMEs have used this spreadsheet against their own previous calculation and determined that it gives a reliable calculation.

Description of process experience using the Best Practice: The spreadsheet contains 4 individual worksheets for the user.

The first 3 sheets are used for 3 calculation methods from user inputs. Each of the 3 methods allows for a selection of either Open Air, Closed Box (x3) or Closed Box (Wilkens method).

The first sheet allows the user to input System Voltage, System Short Circuit Current, Clearing Time and Working Distance to determine Incident Energy and Arc Flash Boundary using maximum available power as listed in NFPA 70E Informative Annex D.5 and Doan method. This method requires an estimate of maximum clearing time and is extremely conservative. It is also only applicable to linear systems such as constant resistance battery bank models. Gap effects are not considered.

The second sheet Allows for the input of a custom value for arcing voltage and arcing current as well as an optional input for Photovoltaic Cell Temperature compensation on available energy. This allows the computation for non-linear systems such as PV arrays which would otherwise be underestimated for available energy.

The third sheet is an improvement on the first sheet Doan method by allowing the entry of a Gap into the method. This refines the worst case Maximum Power method to a more realistic estimate of arcing current. The method is referenced but not described in NFPA 70E Informational Annex D.5. The reference is the Ammerman, et.al, application of the Stokes and Oppenlander equations for DC arc current commonly referred to as the Ammerman equations.

The last sheet is a list of references for methods.

The user determines the correct sheet as follows:

If the gap for the possible fault is uncertain or varied, or the gap effects are not important to the answer, and the system is modeled as a resistive system, such as for the Battery Compartment of a UPS, the first sheet is applicable.

If the system is modeled as a non-linear system, such as a Photovoltaic Array, then the second sheet is applicable.

If the system is linear and the gap is well established and important to the solution, such as the bus work in a UPS Cabinet, then the third sheet is applicable.

BP194 tab 1-Doan DC calculator

This is a physics estimate only. It is not based on experimental data but has been verified to be a conservative calculation of incident energy. Please note that this will show the maximum incident energy possible based on the inputs. This method also uses the conservative rounding of coefficients used by Doan [1] and NFPA 70E-2015 Section D.5.1 [2]. Closed box approximations based on NFPA 70E-2015 Section D.5.1 or the calculated closed box approximation from Wilkins, et. al. [3] as described by Ammerman, et. al. [4] are available using the radio buttons.

Caution: These equations are based on maximum power point for a linear system and will not represent non-linear systems accurately such as Photovoltaic systems or Voltage Regulated systems such as battery chargers, UPS rectifiers or VFD buses under load. Higher incident energy values may occur if clearing time increases due to the time current curve (TCC) characteristics of any protective devices.

- ○ Open Air
- ● Closed Box - NFPA 70E 2015 D.5.1
- ○ Closed Box - Wilkins - Large Switchgear (MV)
- ○ Closed Box - Wilkins - Medium Switchgear (LV)
- ○ Closed Box - Wilkins - Small Panel (LV)

Vsys	540	V	[system open circuit voltage]	
Ibf	3000	A	[bolted fault short circuit current]	
Iarc	1500	A	[arcing current for maximum power point]	
Tarc	2	s	[arc clearing time]	
D	45.5	cm	[working distance]	
	18	in		
CFWD	3.00		[configuration factor at working distance]	
CFAFB	3.00		[configuration factor at arc flash boundary]	
IEm	23.48	cal/cm^2		
AFB	201.2	cm	79.2	in

References

[1] NFPA 70E, *Standard for Electrical Safety in the Workplace*, 2015

[2] "Arc Flash Calculations for Exposures to DC Systems," Doan, D.R.,

Doan DC Calculator | NL DC Calculator | SO DC Calculator | Equation Referen

BP194 tab 2-NL DC calculator

Arc Flash Energy - DC Bus - Max Energy Point - Non-Linear Systems

Enter data in blue cells - Read answers in orange cells

This is a physics estimate only. Please note that this will show the maximum incident energy possible based on the inputs. This method also uses the conservative rounding of coefficients used by Doan [1] and NFPA 70E-2015 Section D.5.1 [2]. Closed box approximations based on NFPA 70E-2015 Section D.5.1 or the calculated closed box approximation from Wilkins, et. al. [3] as described by Ammerman, et. al. [4] are available using the radio buttons. Photovoltaic Temperature Correction is per Enrique, el. al. [5].

These equations are based on maximum power point manually entered and may represent both linear and non-linear systems accurately such as Photovoltaic systems or Voltage Regulated systems such as battery chargers, UPS rectifiers or VFD buses under load. Higher incident energy values may occur if clearing time increases due to the time current curve (TCC) characteristics of any protective devices.

- ○ Open Air
- ● Closed Box - NFPA 70E 2015 D.5.1
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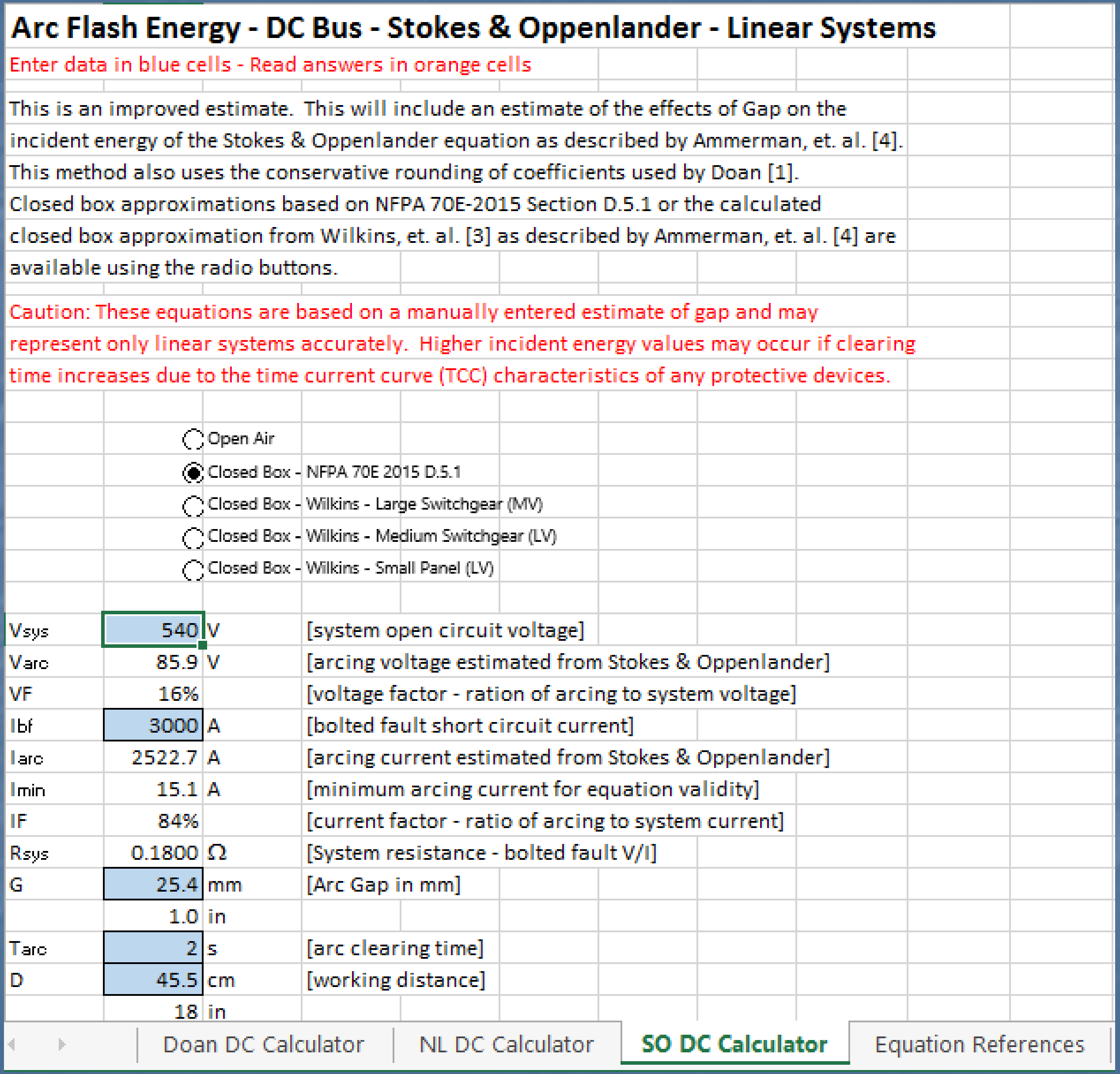
- ○ Closed Box - Wilkins - Small Panel (LV)

Vsys	1000	V	[system open circuit voltage]
Varc	815	V	[arcing voltage estimated from max power curve]
VF	82%		[voltage factor - ration of arcing to system voltage]
Ibf	8.87	A	[bolted fault short circuit current]
Iarc	8.3	A	[arcing current estimated from max power curve]
IF	94%		[current factor - ratio of arcing to system current]
Tarc	2	s	[arc clearing time]
D	61	cm	[working distance]
	24	in	
$KT\text{-}P_{MAX}$	-0.43%	/°C	[temperature coefficient at Pmax point - for PV only]
Tmin	-25	°C	[min temperature]
TF	121.5%		[temperature factor - for PV only]

Doan DC Calculator | **NL DC Calculator** | SO DC Calculator | Equation Referenc

BP194 tab 3-SO DC calculator



BP194 tab 4-Equation References

Equations used in calculations for reference:

References

[1] NFPA 70E, *Standard for Electrical Safety in the Workplace*, 2015

D.5.1 $I_{arc} = 0.5 \times I_{bf}$

$IE_m = 0.01 \times V_{sys} \times I_{arc} \times T_{arc} / D^2$

I_{arc} = arcing current (A)

I_{bf} = system bolted fault current (A)

IE_m = estimated dc arc flash incident energy (cal/cm^2)

V_{sys} = system voltage (V)

T_{arc} = arcing time (s)

D = working distance (cm)

For arc in a box, multiply IE_m by 3

[2] "Arc Flash Calculations for Exposures to DC Systems," Doan, D.R., *IEEE Transactions on Industrial Applications,* Vol. 46, No. 6.

(7) $IE_{max\ power} = 0.005 \times (V_{sys}^2 / R_{sys}) \times T_{arc} / D^2$

$IE_{max\ power}$ = estimated dc arc flash incident energy (cal/cm^2)

R_{sys} = system resistance (Ω)

V_{sys} = system voltage (V)

T_{arc} = arcing time (s)

D = working distance (cm)

For arc in a box, multiply IE_m by 3

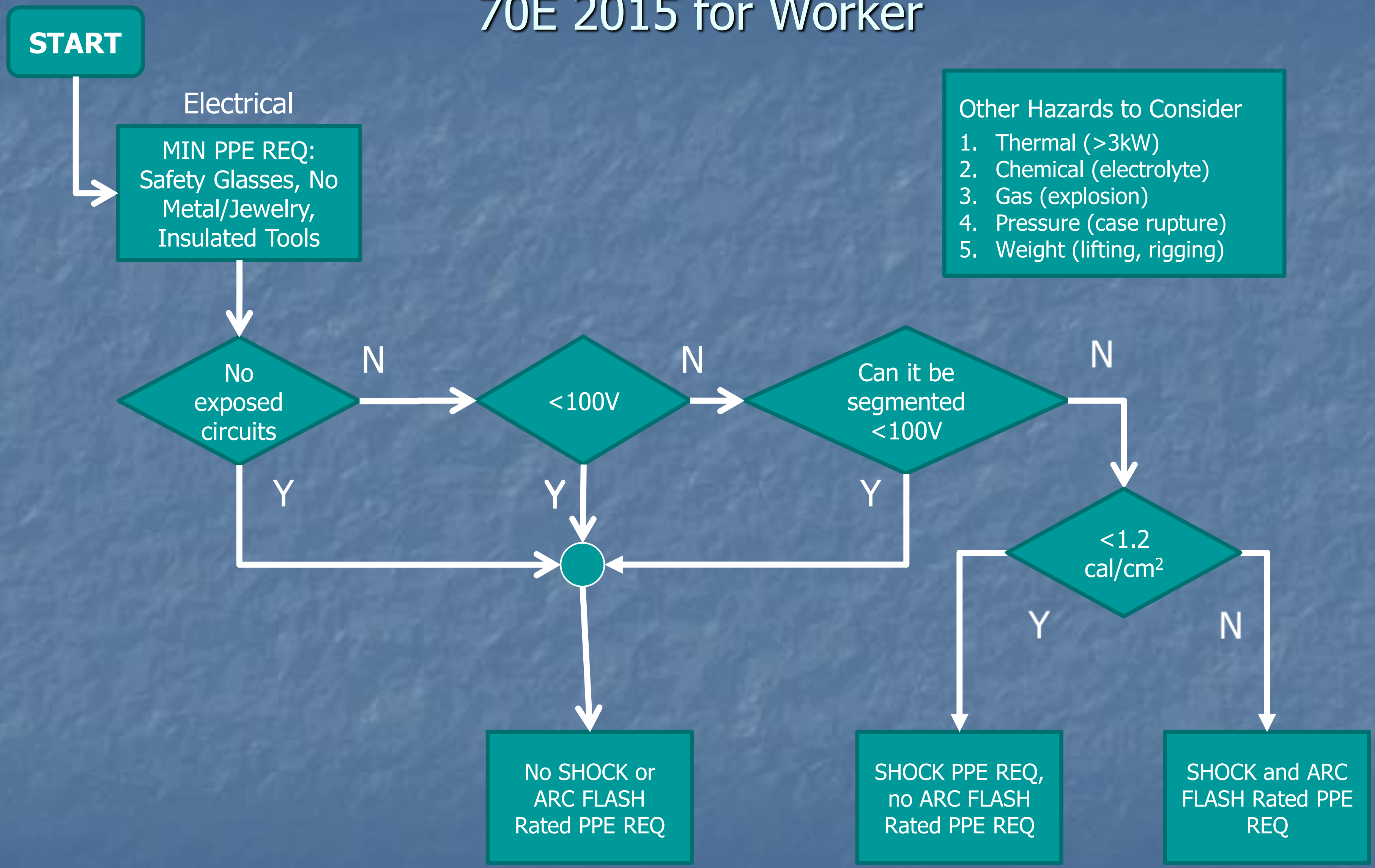
[3] "Simple Improved Equations for Arc Flash Analysis," Wilkins, R., *IEEE Electrical Safety Forum,* posted August 30, 2004.

Doan DC Calculator | NL DC Calculator | SO DC Calculator | **Equation References**

- Evaluate Battery Flow Chart a BP - See next slide

Battery Risk Assessment Flowchart

70E 2015 for Worker



Ground Hook (Stick) Safety July 2017 Update needed

- Review LBNL Ground Hook Safety documents. Recommend as draft for sites that have no requirements in place. (This is a design/assembly consideration document, not how to handle sticks document).

ORPS ANL Capacitor Incident

SC--ASO-ANLE-ANLEAPS-2017-0003 20170718

- Second degree burn to worker's fingertips following ground attachment to cap.
- 10kVdc, 305uF, 15kJ single bushing cap
- Released later that day from Argonne Medical Clinic
- Would an ESTG BP on capacitor safety be warranted?

ORPS ANL Capacitor Incident
continued

- On July 18, 2017, at approximately 1335, two Advanced Photon Source Accelerator Systems Division employees were testing capacitors (305uF/10kV each) for a beamline pulsed magnet power supply project a High Voltage Test Stand.
- The two employees had just finished testing one capacitor, which was believed to be in a safe state. One employee went to attach a safety ground across the capacitor. The capacitor was in fact not safely discharged, and an arc flash occurred when the employee tried to attach a safing clip lead with his hand.

Ground Hook (Stick) Safety

- Review ISA High Energy Discharge Stick Standard for Pulsed Power Applications.
- Simplify calculations for user friendliness.
- Sites should be able to provide proof that calculations have been completed, even if vendor completed calcs. Sites shall have independent verification of calculations as this is a safety system.

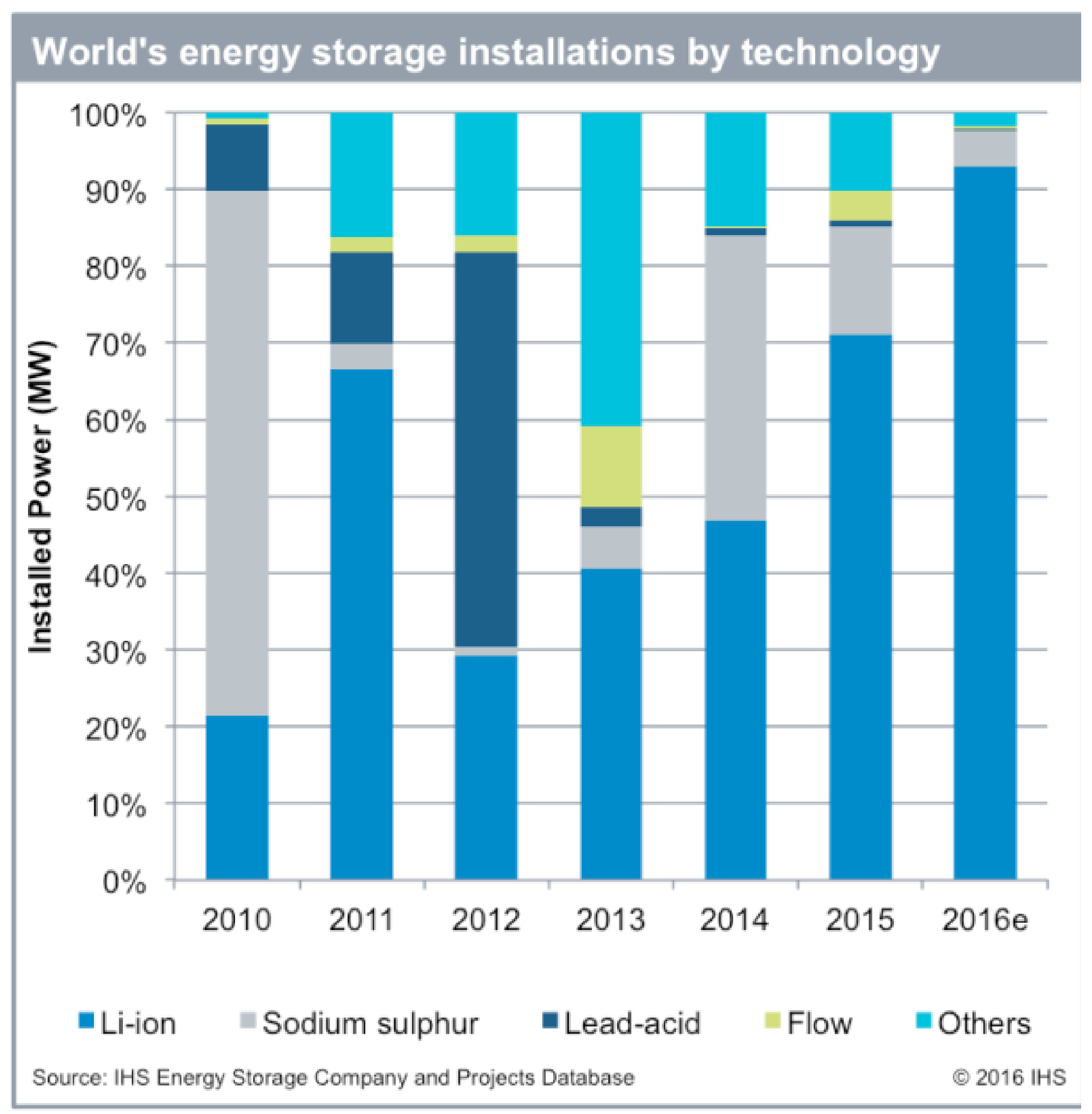
Ground Hook (Stick) Safety

- Verify ASTM F711 has mechanical and electrical testing intervals of two years as applicable. (Up to each site as some sites feel these are not being used as live line tools).

DC Testing Safety

- Possible BP for the applications where bipolar, unipolar, grounded and ungrounded systems are encountered. This is true of DC bus in adjustable speed drives, utility-interfaced inverters, battery chargers and PV systems.
- PPE choices for voltage protection may require Class 1 gloves for 1kVDC systems.

Where are Utility DC systems going?



Increased by 20% since 2015 to reach 2 GW

Where is the NEC going for Energy?

- Existing code structure
  - 690 Solar Photovoltaic (PV) Systems
  - 692 Fuel Cell Systems
  - 694 Wind Electric Systems
  - 705 Interconnected Electric Power Production Sources
  - 708 Critical Operations Power Systems
- New for 2017 proposed

  - Article 691 - Large-Scale Photovoltaic (PV) Electric Supply Stations
  - Article 706 - Energy Storage Systems (ESS)
  - Article 712 - Direct Current Microgrids
  - Article 710 - Microgrid

QUESTIONS?