DC Systems Working Group

EFCOG ESSG

National Renewable Energy Laboratory

July 14-18, 2014

Best Practices

- DC Arc Flash WG Phase I – 10/2010
  - Basis –Proposal
  - Status
- DC Systems WG Phase II – 10/2012
  - Basis – Need for AHJ Decision for DC Systems
  - Product – Consensus Paper
- DC Systems WG Phase III – 7/2014
  - Proposal to restructure part of Chapter 3 of 70E
  - Compare DC Arc Flash calculation approaches
  - Provide a Battery Flowchart for Risk Assessment

DC Arc Flash WG 2010 Members

- Cliff Ashley, Andrew Burbelo, Sjef Bennink, Todd Bischoff, Jeremy Bynum, Douglas Coffland, Gary Dreifuerst, Jim Durnan, Lloyd Gordon, Kurt Kranz, Jerry Lane, Mark Mathews, Bert Manzlak, Troy McCuskey, Jacqueline Mirabal, Earl Myott, Thomas Nehring, Sanjay Sanan, Joshua Siems, Bobby Sparks, Richard Waters

DC Arc Flash WG Deliverables – Phase I

- Best Practices
  - DOE Handbook – R&D
  - Station Power – 125Vdc
- Research Recommendations
  - Field Measurements on existing systems
  - Skunk Works
- New Proposals for NFPA 70E - 2012

DC Applications

Company	Model	Voltage	Power [kW]	Energy [kWh]	Weight [kg]	Type
GM	Volt	365	111	16	181	Lithium Ion
GM	EV1	312	105	16	450	Lead acid
Toyota	Prius	202	37.9	1.31	29.1	Nickel-metal Hydride
Nissan	Leaf	408	90	28.8	300	Lithium Ion
Tesla	Roadster	375	185	53	450	Lithium Ion
Mercedes	SLS Ecell	400	480	48		Lithium Ion
TEPCO	Level III	500	50			EV charger connector
USN	Albacore	710	11190			Silver Zinc

DC Publications - Doan

- **Arc Flash Calculations for Exposures to DC Systems-**ESW2007-19
- Duke Power-Kinectrics testing had difficulty in establishing and maintaining an arc in excess of 0.5 in at 130V and 2.0 in at 260V. Isc was > 20kA at 230V.
- IE_{max} power = $0.005 * (V_{sys}^2 / R_{sys}) * T_{arc} / R^2$

- **Examples**
  - **UPS**
  - **Substation battery**
  - **Electrochemical cell**

Voltage	Isc	Iarc	Tarc [s]	IEmax
350	10k	5k	0.2 - fuse	1.2
135	1.34k	669	2.0 – no OL	0.9
250	45k	22.5k	0.5 – CB	7.5

High Current DC Testing

- In searching the internet for examples of high current testing, the following two videos show Robert K. Golka conducting Fireball experiments first using submarine batteries and finally a complete WWII class submarine, USS Silversides (SS-236).
- Viewing his experimental video may be useful to us because it illustrates how difficult it is to create and sustain an expanding arc flash plasma, which would be a threat to an electrical worker.
- His experiments regularly generate substantial glowing objects in his quest to create ball lightning.

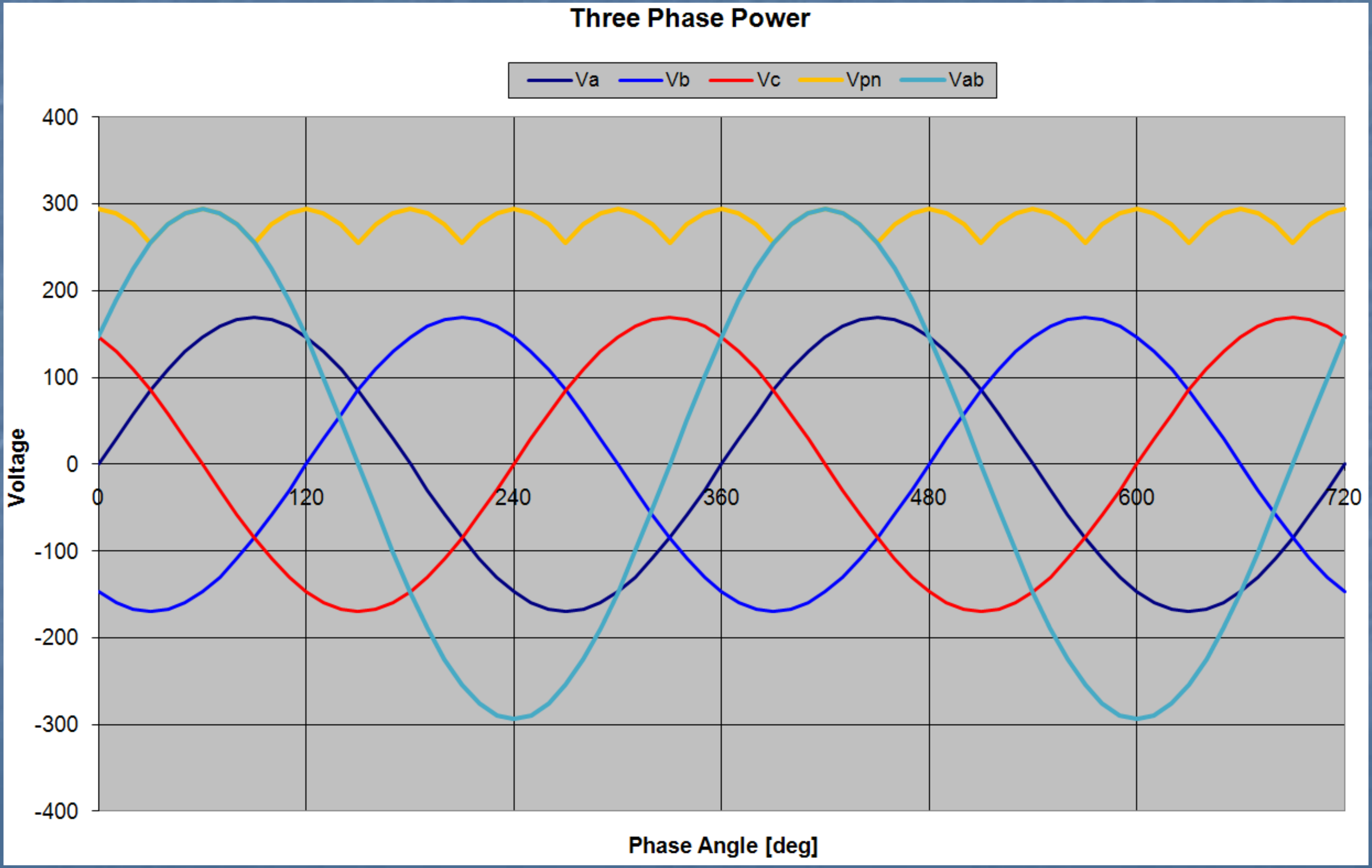
- Golka 1994, 20 battery cells, 25kAh, 42V, 5kA – 8kA, 1050 lbs each, 300 cells in a nuclear submarine
- Golka 1995 USS Silversides (SS-236), 260V-330V, 6kA-8kA

Test	Voltage estimate	Current estimate	Location
20 cells	42V	5kA-8kA	Warehouse
Full system	260V-330V	6kA-8kA	Silversides

AC Faults with DC Effects

- Three Phase Faults may have currents that excite the Arc Flash Plasma with the same non-zero crossing waveforms that are characteristic of DC Faults
- A voltage (current) zero-crossing exists for all single phase faults, this includes:
  - LL, LN, LG, LLG (Va, Vb, Vc, Vab)
- No voltage (current) zero-crossing exists for the LLL fault.
  - LLL (Vpn) See Vpn on the next slide

AC Fault Waveforms



DC WG 2012 Members

- Les Bermudez, Stan Berry, Stuart Bloom, Nasser Dehkordi, Terry Dembrowski, Gary Dreifuerst, Kevin Dressman, Tom Duran, John Franchere, Chuck Gaus, Bobby Gray, Lloyd Gordon, Kurt Kranz, John Lacenere, Mark Mathews, George Powell, Lynn Ribaud, Sal Sferrazza, Bobby Sparks, Robert Spang, Gary Sundby, Pat Tran, Mike Utes

DC Systems Working Group
Phase II

- Best Practices - EFCOG Website
- The fundamental principle of this best practice is based on the general approach: "work controls, such as engineering & administrative controls will yield better protection for workers than a singular focus on calculations."

- Recommendations of Working Group

"NFPA 70E 2012 provides the reference model for working on DC battery systems safely. It uses the best available information to quantify and mitigate the risk. It is what we have to work with and it should be used. When more research is done, that information will be used to improve the model as appropriate. 2 seconds is a reasonable starting point for exposure to an arc incident. Sound professional judgment needs to be used when applying the 2 second exposure time. For example, if the worker is a highly confined space, 2 seconds is likely not appropriate. Finally, we all need to keep in mind that there has never been a documented sustained arc flash incident involving a DC battery system . In light of this fact, 2 seconds is a very conservative factor and should be considered safe until research or an event proves otherwise."

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Phase II

- Arc Flash - Incident Energy Calculation
- Hazard Classification Analysis
  - Issues covered
    - Arc Flash
    - Molten Ejected Metal, primary hazard for low voltage high current banks (Welding PPE)
    - Thermal Contact Burn (Heavy duty leather gloves)
  - Issues not covered
    - Arc Blast, Electrical Shock, Weight (Lifting)
    - Chemical, Battery Gas Explosion

DC Systems Working Group
Phase II

- Equipment
  - Stationary UPS
  - Portable UPS
  - Battery Banks (including Submarines)
  - Other DC Systems (e.g. capacitors and inductors)

DC Systems Working Group
Phase II

- Drivers
  - 10 CFR 851
  - OSHA
  - NFPA 70E 2004 & 2012
  - NFPA 70 NEC
- DOE Guidance Documents
  - DOE Electrical Safety Handbook

DC Systems Working Group Phase II

- Definitions:
  - Arc Flash Boundary: When an arc hazard exists, an approach limit at a distance from a prospective arc source within which a person could receive a second degree burn if an electrical arc flash were to occur.
  - The WG interpretation is that this applies to dc systems with greater than 100V as the distance at which the incident energy equals 1.2 cal/cm^2 (5 J/cm^2).
  - Arc (IEEE) : A continuous luminous discharge of electricity across an insulating medium, usually accompanied by the partial volatilization of the electrodes.

DC Systems Working Group
Phase II

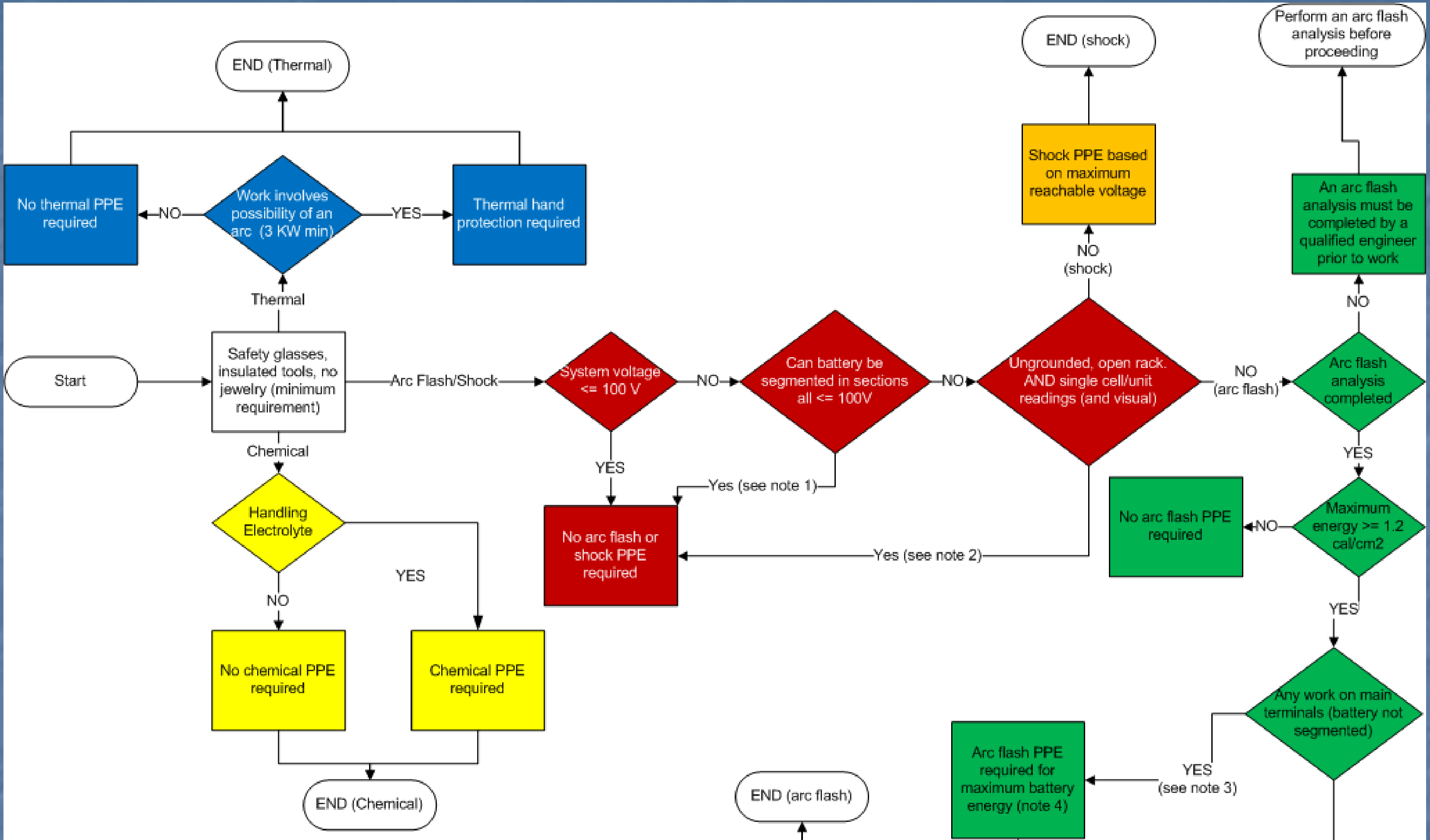
- No national consensus standard exists for DC arc flash calculations. Three calculation approaches may be used as chosen by the site AHJ.

Type	Technique	Reference	Comment
Bruce Power	Empirical Arc testing	NFPA reference	Empirical, measured
Ammerman	Arc model	IEEE paper	Theoretical
Doan	Max power transfer	NFPA70E-2012	Usually conservative, theoretical

DC Systems Working Group
Phase II

- DC Hazard assessment tools
  - IEEE Stationary Battery Working Group, Flowchart
  - Doan’s Excel calculator based on NFPA 70E 2012
  - Example Battery planning packages LANL and PNNL
  - Separate Best Practice (ISA)
    - Capacitor & Inductor arc flash boundary calculations.

IEEE Stationary Battery Working Group, Flowchart, Phase II



Notes:
1. Arc flash and shock PPE may be required to put the battery in a segmented state. The battery must also be isolated from the system.
2. This only applies if the technician cannot reasonably reach across more than 100 volts or if the exposed parts are protected so the technician cannot touch across more than 100 volts
3. If the battery terminals are more than 6 feet apart, or if at least one of the terminals is protected, arc flash hazard PPE is not required with respect to the battery terminal risk.
4. There may be additional procedures that can be implemented that would further reduce the arc hazard risk and required PPE.

Doan's Excel calculator based on NFPA 70E 2012 Phase II

Arc Flash Energy - DC Bus - Max Power Point

Enter data in blue cells, answer in orange cell.

This is an estimate only - not based on testing.
This spreadsheet estimates the arc flash energy if the arcing fault current is at the maximum power point for a DC circuit arc.
Higher arc flash energy may occur at other arcing current values, depending on the protective device time-current curve.

Any worker exposed to potential arc flash hazards should wear FR garments; a minimum Class 1 (4 cal/sqcm rating) PPE is recommended for any DC exposures.

V open circuit	600	volts	(open circuit voltage of source)
Isc	5000	amps	(short circuit current of source)
Rs	0.12	ohms	(system resistance)
Varc max power	300	volts	(voltage of arc at maximum power point)
Iarc	2500	amps	(arcing current at maximum power point)
Trip/Open time	2	sec	(time for protective device to open circuit when Iarc flowing, or expected arc duration)
Rarc	0.12	ohms	(resistance of arc at max power point)
Parc	750000	watts	(power in arc)
Earc	1500000	watt-sec	(maximum energy in arc)
	358509	cal	
Working Distance	18	inches	45.7 cm
IE max	13.7	cal/sqcm	(estimated incident energy at point of maximum power in arc, at Working Distance from arc)

Units

1 Calorie =	4.184	Joules
1 Joule =	1	Watt-sec

Energy = Power x time

Surface of sphere: 4 x Pi x R^2

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Phase II

- Arc Flash Calculations assumptions
  - 100% State of Charge of Battery
  - Use the manufacturer's short circuit rating (< 1 second rate), if not available estimate the short circuit current at 20x 1 hour rate, or (battery voltage)/(internal resistance)
  - Batteries in equipment use factor of 3x (arc-in-a-box), on a rack use factor of 1x
  - Fuse or circuit breaker characteristics must include DC rating

References, Phase II

- "DC Arc Flash, The Implications of the NFPA 70E 2012 on Battery Maintenance", W. Cantor, P. Zakielarz, M. Spina 2012
- "Arc flash calculations for exposures to DC systems", Doan, D.R. 2007
- "DC arc models and incident energy calculations", Ammerman, R.F. 2009
- IEEE Stationary Battery Working Group, Flowchart

DC Systems Working Group
Phase II

- Future topics for next EFCOG
  - Draft white paper (capacitors & inductors) sent out for WG peer review
  - White paper-Using NFPA 70E 2012 and UPS safe work practices posted on EFCOG web-site

DC Systems Working Group
Phase II

- Topics for next EFCOG (Phase III)
  - R&D Equipment
  - PVs & Fuel Cells
  - Power backup battery systems
  - EVs
    - Charging Stations for EVs
    - Used vehicle batteries in power utility
  - Installation requirements for batteries into NEC?

DC Arc Flash WG 2014 Members

- Gerald Alfano, Erika Barraza, Stan Berry, Christopher Brooks, Dwight Clayton, Gary Dreifuerst, Andrew Drutel, Patrick Foy, Lloyd Gordon, Adam Green, Kurt Kranz, John Lacenere, Eugene Ormond, John Scott, Mariko Shirazi, John Sines, Alan Tatum, Joshua Usher, James Wright

DC Arc Flash WG Deliverables – Phase III

- Modify NFPA 70E - 2018
  - Group 1 - Restructure Articles 330, 340
  - Group 2 - Add Evaluation of DC Arc Flash Calculation Methods to Annex D
  - Group 3 - Add Battery Risk Assessment Flowchart to Article 320
- Evaluation of Testing Recommendations
  - Support DC Arc Flash Calculations Methods

DC Arc Flash WG Future Plans
Phase III – Topics for Phase IV

- Perform same treatment of Article 320 – Batteries as WG changes to Articles 330 and 340
- Incorporate Fuel Cell and Photovoltaic systems into Chapter 3.
- Refine reviews of calculation approaches for DC Arc Flash as test data is made available

EFCOG DC Working Group 1: Modify NFPA 70E

Erika Barraza
Dwight Clayton
Gary Dreifuerst
Patrick Foy
Lloyd Gordon
Eugene Ormond
Alan Tatum

Proposal to Modify NFPA 70E, Chapter 3, Phase III

Article 90.3 note regarding chapter 3:

- *Safety requirements for special equipment; supplements and/or modifies Chapter 1*
- Articles 310 and 320 are addressed by specific NFPA 70E task groups
- Articles 330, 340, and 350 are the responsibility of the NFPA 70E DC Task Group

Chapter 3 Safety Requirements for Special Equipment (present Table of Contents)

- Article 310 Safety-Related Work Practices for Electrolytic Cells
- Article 320 Safety Requirements Related to Batteries and Battery Rooms
- Article 330 Safety-Related Work Practices for Use of Lasers
  - ANSI Z136 covers lasers
- Article 340 Safety-Related Work Practices: Power Electronic Equipment
  - Largely a tutorial on hazard thresholds, but much of the information is incorrect, redundant, or irrelevant
- Article 350 Safety-Related Work Requirements: Research and Development Laboratories

Chapter 3 Safety Requirements for Special Equipment (proposed Article 330 Title and Content)

- Article 330 Safety Requirements for DC Electrical Hazards
  - Add thermal burn threshold table (Appendix F, DOE Electrical Safety Handbook)
  - Add shock threshold table (Appendix F, DOE Electrical Safety Handbook)
  - Move Approach Boundary for DC Shock Protection, Table 130.4(C)(b)
  - Add arc flash threshold table (Appendix F, DOE Electrical Safety Handbook)
  - Move H/RC Classification Table (for DC Arc Flash), Table 130.7(C)(15)(b)
  - Capacitor and inductor safety
  - Reference to ionizing radiation (X-rays)

Chapter 3 Safety Requirements for Special Equipment (proposed Article 340 Title and Content)

- Article 340 Safety Requirements for Sub-rf and rf Hazards
  - Low frequency ac sources – 1 Hz to 3 kHz (other than 60 Hz)
  - RF sources >3 kHz
  - Zero voltage verification for sub-rf and rf
  - Reference to non-ionizing radiation (radar, communication, microwave, etc.): IEEE C95

Next Steps - Group 1

- EFCOG DC Working Group will rewrite Articles 330 and 340 by the end of CY 2014 and submit to the NFPA 70E DC Task Group
- NFPA 70E DC Task Group submits proposals

DC Arc Hazard Evaluation Methods - Team Members

Best Practices – Working Group 2

- John Lacenere - Facilitator
- Kurt Kranz
- Adam Green
- James Wright
- Andrew Drutel
- Mariko Shirazi
- John Scott

DC Arc Hazard Evaluation Methods

References:

- 2014 Doble Engineering – 81st International Conference of Doble Clients: "Dc Arc Flash. The Known and Unknown and the impact on Battery Maintenance Activities" Cantor
- Kinectrics Report K-418079-RA-001-R00 (10/12/2011) – "DC Arc Flash Hazard Analysis Service for PNNL", Cheng, Keyes
- IEEE/2010 TIA Vol.46, #5: "DC–Arc Models and Incident-Energy Calculations", Ammerman, Gammon, Sen, Nelson
- 2011 (BattCon?) – "The Limitations of the Maximum Power Method of Calculating DC Energy", Fontaine
- IEEE/2010 TIA Vol.46, #6: "Arc Flash Calculations for Exposures to DC Systems", Doan (NFPA 70E/2012 Annex D)
- INL (5/10/2012): "DC Arc Flash Calculation Tool", Ferguson, Whipple, et.al.
- 2011 APTA Conference: "Arc Hazard Assessment for DC Applications in the Transit Industry", Cheng, Cress, Minini

DC Arc Hazard Evaluation Methods

Comparison Table – DC Arcs and Arc Flash

Method	Empirical/ Theoretical	Applicability			Testing Recommendations
		PV	Batt	DC PS	
NFPA 70E (Doan)	Theoretical	N ?	Y	Y	Author recommends additional testing
Ammerman	Energy = T Iarc = E	Y ?	Y	Y	Author recommends additional testing
INL (Ammerman)	Energy = T Iarc = E	Y ?	Y	Y	Author recommends additional testing
Kinectrics (CMBC)	Empirical	N	Y ?	Y	Data points unclear 300-600 VDC
Kinectrics (Bruce Power)	E – 1-phase times 1.25	N	Y ?	Y	Data points unclear ArcPro® is a Kinectrics product 100-300 VDC
IEEE 1584	E – 3-phase AC Calc.	N	N	N	Not recommended for DC Arc Flash calculations

DC Arc Hazard Evaluation Methods

Observations:

- Doan and Ammerman result in similar (within 8%) incident energies for a battery system, using ***constant clearing time of 2 seconds***, 130 – 260 V, and 0.5 – 2 inch gaps. Estimates were significantly higher than measured test data over these conditions (Kinectrics Bruce Power data – comparative results presented in 2014 Cantor Doble paper)
- Ammerman may result in more accurate incident energies than Doan in cases where clearing time is dependent on Iarc (e.g. determined from TCC).
- INL Mathcad / EXCEL tool is useful for computing Iarc and resulting incident energy for the Ammerman method

Recommendations:

- Recommend more testing to evaluate accuracy of existing models and/or develop additional empirical models. Insufficient data points currently available to validate models.
- Need to determine applicability of models to PV and other DC sources

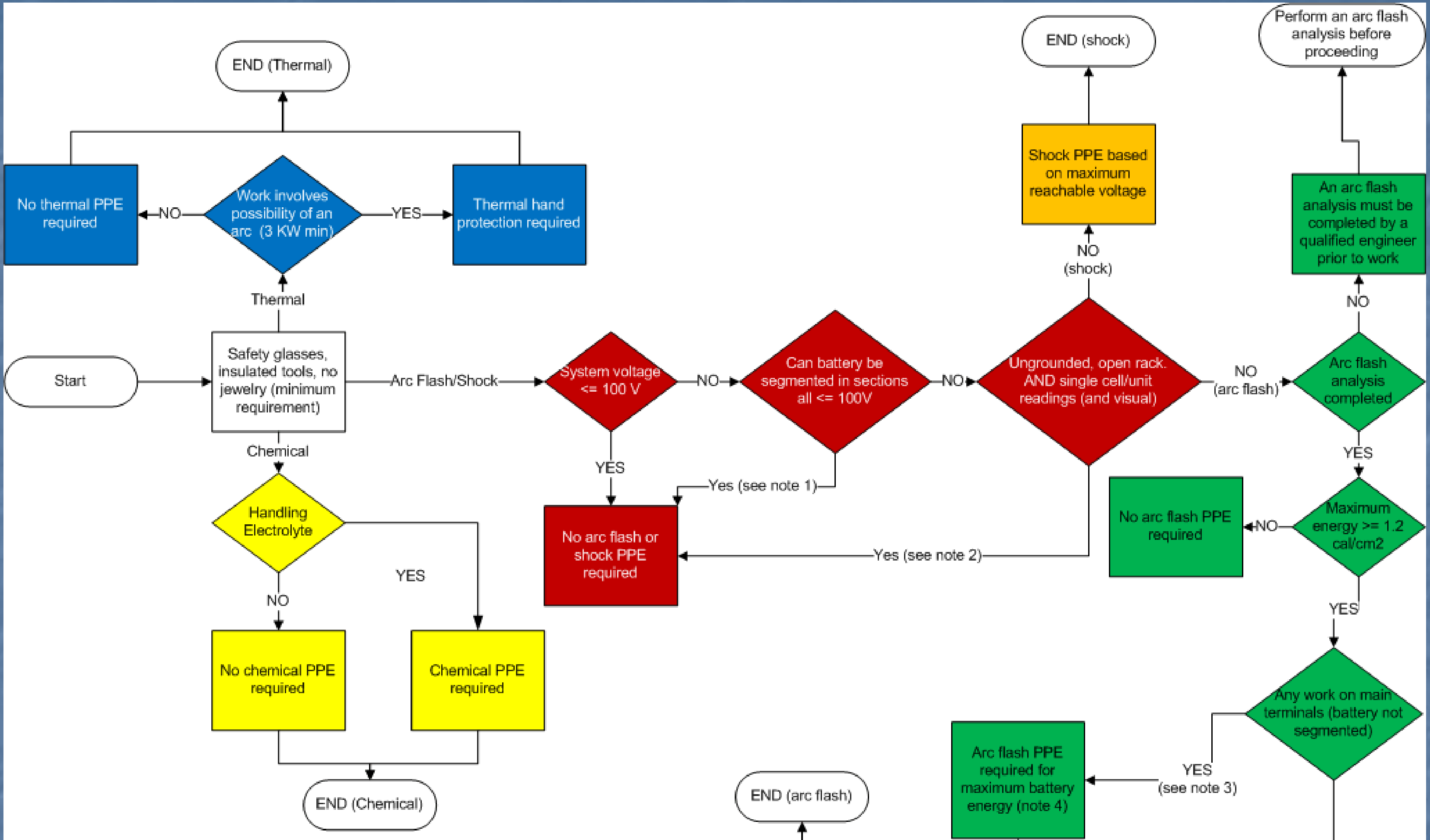
Battery Risk Assessment Group 3

- Stan Berry
- John Sines
- Gerald Alfano
- Joshua Usher

Battery Risk Assessment Flowchart

- References for Flowchart
  - DC Arc Flash. The Known and Unknown and the Impact on Battery Maintenance Activities, Cantor, 2014.
  - DC Working Group 20121001d
  - DC Arc Flash. 2013 Regulatory Updates and Recommended Battery Risk Assessment Guidelines, Canto and McCluer, 2013

IEEE Stationary Battery Working Group, Flowchart, Phase II



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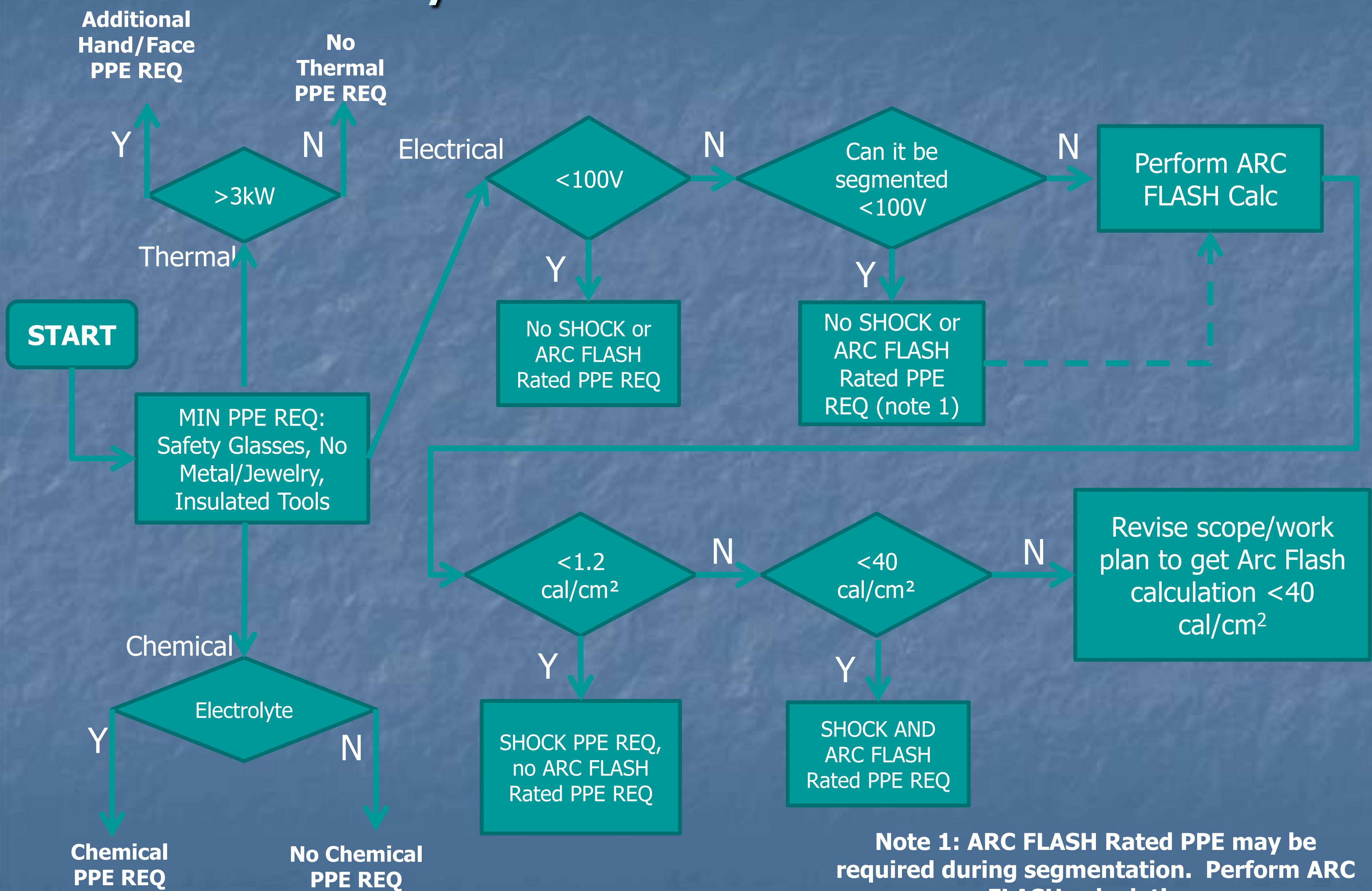
Battery Risk Assessment Flowchart



Note 1: ARC FLASH Rated PPE may be required during segmentation. Perform ARC FLASH calculation.

Battery Risk Assessment
Group 3

- Future Work
  - Incorporate testing data as refinement of the DC voltage limit for the threshold of DC Arc Flash