DC Arc Flash

Lesley Varga, P.E.
President
Quality Standby Services, LLC
E-mail: lesley@qualitystandbyservices.com

Agenda

- Where are we on DC Arc Flash?
- How to Calculate DC Arc Flash (NFPA 70E 2018)
- A Technique for Analyzing Hazards and Risks

NFPA 70E-2018

- NFPA 70E: Standard for Electrical Safety in the Workplace
  - "best practices"
- Article 130 covers arc flash hazards (AC and DC)
- Article 320 Safety Requirements Related to Batteries and Battery Rooms
- Annex D Incident Energy and Arc Flash Boundary Calculation Methods
  - D.5 Direct Current Incident Energy Calculations

NFPA 70E-2018 (Continued)

- Article 130.4 Shock Risk Assessment
  - >50 VDC per Table130.4(D)(b)
- Article 130.5 Arc Flash Risk Assessment
  - Likelihood of occurrence
  - Assess arc flash using tables (category) or calculation method (either not both)
  - Frequency
    - Assess when new
    - Every major upgrade or every 5 years
  - Labeling requirements (also see Article 320)

NFPA 70E-2018 (Continued)

- Article 130.7 Personal and Protective Equipment
  - PPE Category Method
  - Determine likelihood of occurrence, Table 130.5(C)
  - Determine Arc Flash Category & Boundary, Table 130.7(C)(15)(b)
    - Battery voltage and SS current must be in the table
    - If not, use IE calculation Annex D method
  - If above tables are utilized, can use Table 130.7(C)(15)(c) for PPE Selection
    - Otherwise perform the IE calculation Annex D and use Table 130.5(G) for PPE selection

NFPA 70E-2018 (Continued)

- Article 320
  - Signage
    - Arc Flash
    - Shock
    - Thermal
    - Chemical
  - Electrolyte Safety
    - If not handling electrolyte – Safety Glasses only

NFPA 70E-2018 (Continued)

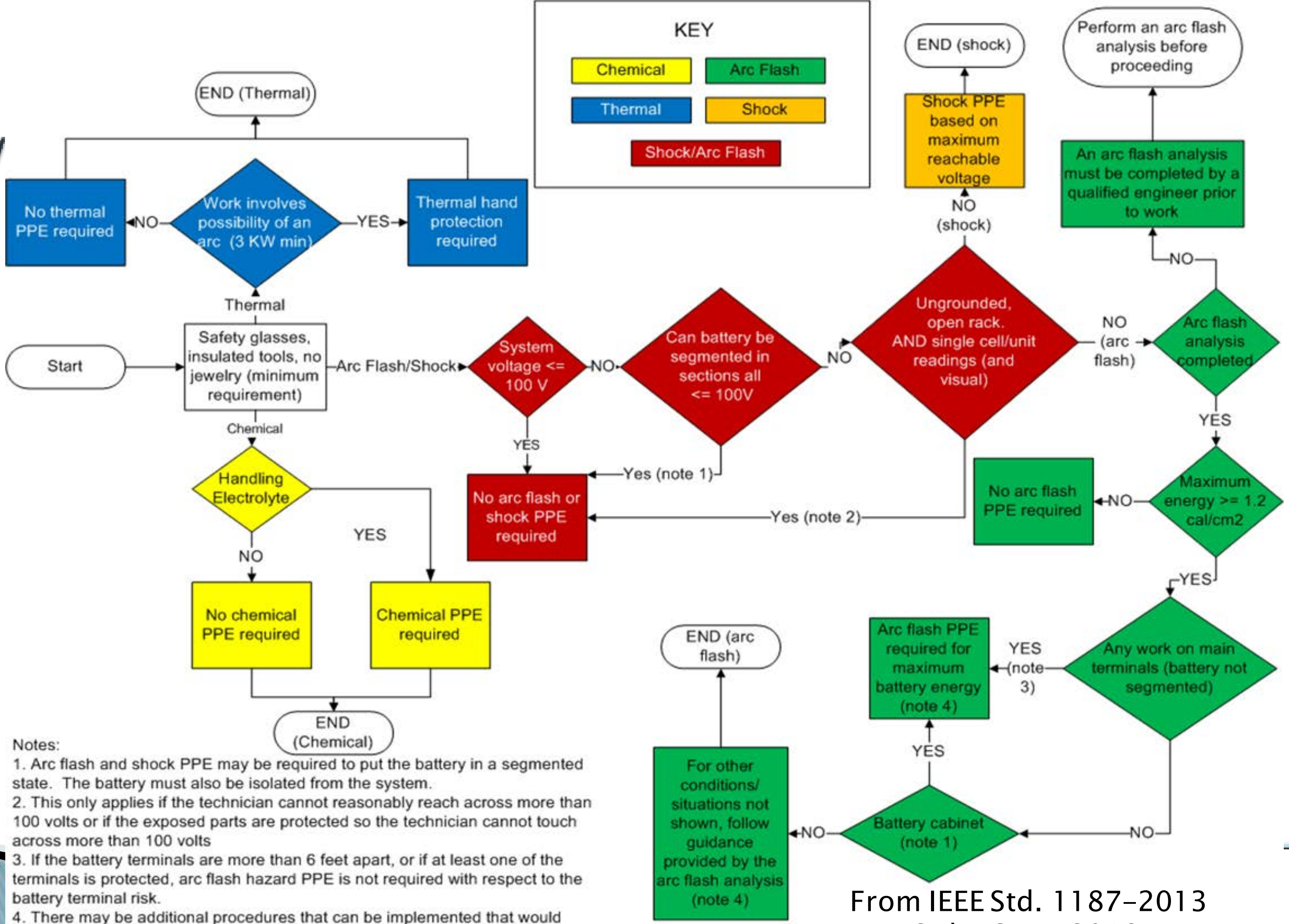
- Annex D
  - Calculations for DC arc flash
  - Very conservative
  - Based on worst case theory

Battery related arc flash

- Not traditionally an issue
- Documented cases?
  - Confusion with large shorts resulting in molten metal
- Many users ignore risk completely
- Users who abide by NFPA 70E often overprotect which results in other safety issues
- Guidance in NFPA 70E is very conservative
  - Limited test data available

PPE Flow Chart for Battery Work

proposed by Stationary Battery Committee



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.

From IEEE Std. 1187-2013
IEEE Std. 1657- 2018

70E Annex D.5 DC Incident Energy Calculation

Arc Flash Calculations for Exposures to DC Systems

Paper No. ESW2007-19

Daniel R. Doan, PE
Sr. Member IEEE
DuPont Engineering
PO Box 80723
Wilmington, DE 19880 USA
doan@ieee.org

This paper appears in: Industry Applications, IEEE Transactions on
Issue Date: Nov.-Dec. 2010
Volume: 46 Issue:6
On page(s): 2299 - 2302

Abstract – Electrical systems with AC voltage have been shown to exhibit arc flash incident energy during faults. Are there arc flash hazards related to DC systems, such as battery banks for UPS or drives, or DC buses used in chemical processes? Methods are available to estimate arc flash energy of AC exposures, but not DC. This paper will show the basic equations for maximum power from a DC arc, and the resulting estimated arc flash incident energy. Research is required to find accurate values, but until research is completed, these equations can help the engineer provide a preliminary estimate of the thermal energy values for applying protective clothing for these exposures.

environment. All these variables make it difficult to estimate the true arc flash energy exposure for a worker.

II. BASIC EQUATIONS

A DC system can be modeled as shown in Figure 1. The source can be simply modeled as a system voltage and impedance. To begin an estimate, it is necessary to make some assumptions. During the arc we can work under the assumption of a steady state of current, so that we can use the resistance of the system and the resistance in the arc for calculations. Any inductance in the system would tend to

Annex D.5: DC Incident Energy Calculation

- Maximum Power Method:
  - This method is based on the concept that the maximum power possible in a dc arc will occur when the arcing voltage is ½ the system voltage
  - Applies to dc systems up to 1000V
  - *"…this calculation is conservatively high in estimating the arc flash value."*

DC Arc Flash Incident Energy

- $IE = 0.01 \times Vsys \times Iarc \times Tarc/D^2$
  - Vsys =system voltage, nominal
  - Iarc = 0.5 x Ibf
    - Ibf = bolted fault current = battery short circuit
  - Tarc = arcing time; 2 sec, Table 130.7(C)(15)(b)
  - D = working distance, cm; 18”, Table 130.7(C)(15)(b)
  - *Note: for battery cabinets/enclosures multipliers are used (e.g. 3x)*

Short Circuit Current

- *Obtain the battery short circuit current from the battery manufacturer*
- Annex D.5.3: A conservative approach…is to assume the maximum short circuit current is 10 X the 1 minute rate (to 1.75 vpc at 25˚C) of the battery

$$I_{arc} = 0.5 \times I_{ss} \ (I_{bf})$$

Actual DC Arc Flash Testing

U.S. DEPARTMENT OF ENERGY - BONNEVILLE POWER ADMINISTRATION

BPA F 5450.05
(10-94)

ENGINEERING AND TECHNICAL SERVICES REPORT

TITLE			DATE	REPORT NO.
DC ARC FLASH: 125V, 1300 AMP-HOUR BATTERY			May 11, 2017	TEST-17-051
			AUTHOR J. G. Hildreth – TEST-MODA	
			Assisted By D.J. Fujita – TEST-MODA D.J. Mullen – TEST-MODA P.C. Anderson – TEST-MODA	
REQ ORG. TECC	PAGES 90	L.P./W.O. 16-114	REVIEWED BY S. Khem – TEST-MODA	

SUMMARY:

From Bonneville Power Authority
Test -17-051
DC Arc Flash

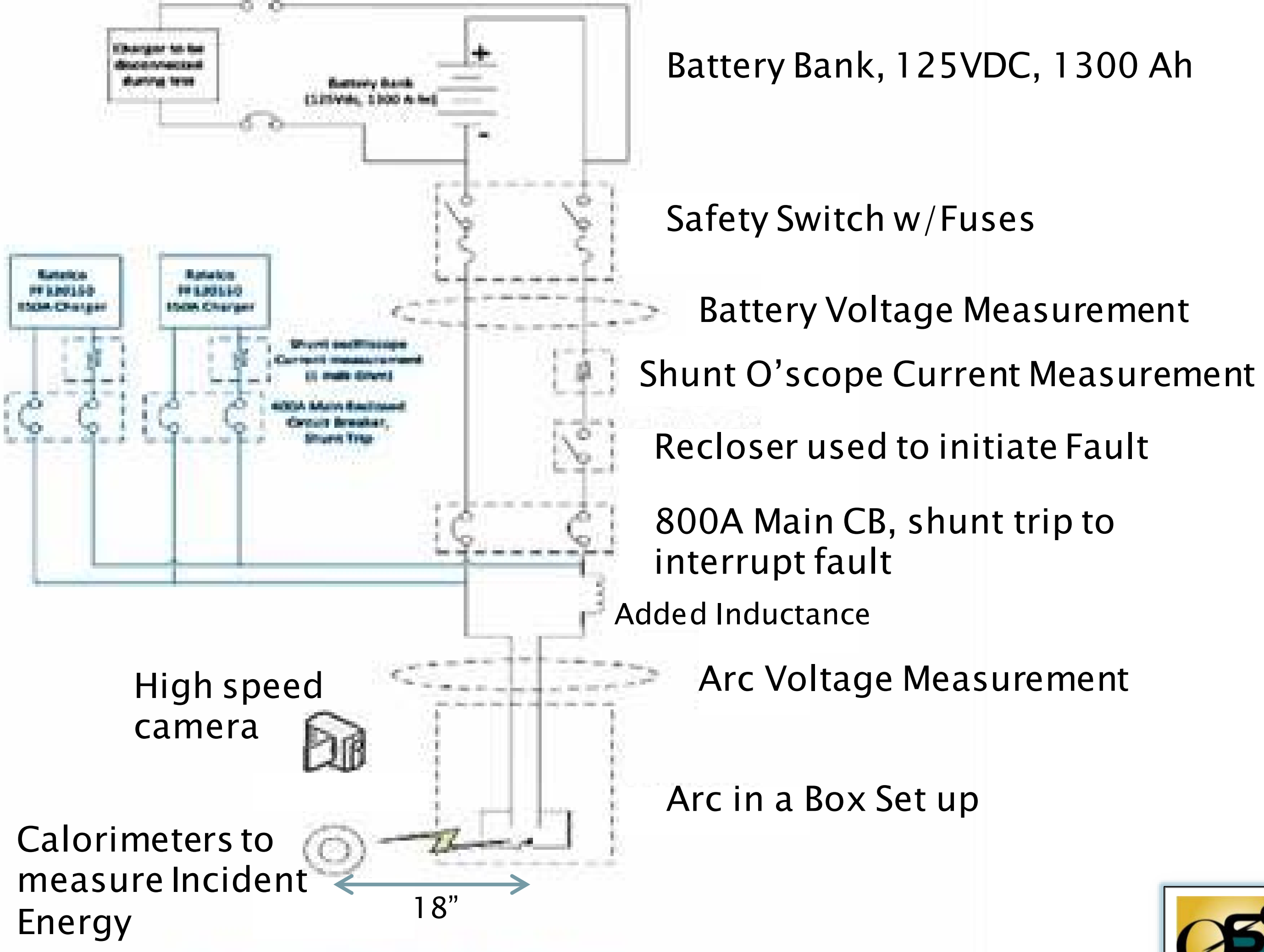


Figure 1 – Arc Flash Circuit Configuration.

From Bonneville Power Authority
Test -17-051
DC Arc Flash

Battery

The power source for this series of tests consists of a battery bank made up of flooded lead acid batteries. The battery, one of the largest used at BPA, was removed from service at Raver substation. It has a rating of 125V and 1,300 ampere-hours. Its short circuit capacity is 11,000A. The manufacturer is C&D. The battery was installed in a standard 40-foot shipping container equipped with active ventilation and a hydrogen gas monitor.

125 VDC, 60 cell Battery 1300Ah Short Circuit= 11,000 Amps

From Bonneville Power Authority
Test -17-051
DC Arc Flash

Table 1 - (continued) – Summary of Test Results

Test Number	Description	Voltage (Vdc)	Gap (inch)	No-Ox	Fuse Wire	Duration (s)	Self Extinguish	Peak Current (A)	Mean Arcing Current (A)	Energy (Cal/cm^2)
	Vertical Rod-to-Rod Gap									
38	Arc between copper rods	125	0.25	N	4 #24	0.338	Y	5344	3098	0.46
39	Arc, Repeat with 2 fuse wires	125	0.25	N	2 #24	0.165	Y	?	?	0.18
40	Arc, same as #39	125	0.25	N	2 #24	0.249	Y	4606	3336	0.35
41	Arc, same as #39	125	0.25	N	2 #24	0.267	Y	4493	3269	0.35
42	Arc, same as #39	125	0.25	N	2 #24	0.274	Y	4645	3275	0.43
43	Arc, added no-ox, #22 wire	125	0.25	Y	2 #22	0.004	Y	3480	1912	0.00
44	Arc, same as #43	125	0.25	Y	2 #22	0.026	Y	4094	1800	0.04
45	Arc, single #16 fuse wire	125	0.25	Y	1 #16	0.054	Y	6064	2998	0.07
46	Arc, same as #45	125	0.25	Y	1 #16	0.297	Y	6156	3234	0.24
47	Arc, same as #45	125	0.25	Y	1 #16	0.308	Y	6098	3151	0.23
	Bolted Fault									
48	Bolted Fault	125	N/A	N/A	N/A	0.015	N/A	7814	N/A	N/A
49	Bolted Fault	125	N/A	N/A	N/A	0.015	N/A	7850	N/A	N/A
	Installed Actual DC Panel									
50	Arc, smallest gap (0.9")	125	0.9	N	1 #16	0.011	Y	6177	3223	0.00
51	Arc, repeat #50	125	0.9	N	1 #16	0.009	Y	6124	3590	0.00
52	Arc, repeat #50	125	0.9	N	1 #16	0.020	Y	6091	1977	0.00
53	No Arc, steel plate bolted one e	125	N/A	N	Steel	N/A	N/A	N/A	N/A	0.00
54	Arc, steel plate bolted one end	125	N/A	N	Steel	0.171	Y	6714	4003	0.55
55	Arc, repeat #54	125	N/A	N	Steel	0.162	Y	7375	4470	0.23
56	Arc, wrench bolted one end	125	N/A	N	Wrench	0.342	Y	7231	4813	0.21
57	Arc, repeat #56	125	N/A	N	Wrench	0.266	Y	7231	4813	0.21
58	Arc, repeat #56	125	N/A	N	Wrench	0.518	Y	7216	5298	0.32
	arc re-established itself					0.114	Y	5827	3442	
59	Arc, screws between bus bars ar	125	N/A	N	Screws	0.064	Y	3025	1580	0.03
60	Arc, repeat #59, bigger screws	125	N/A	N	Screws	0.285	Y	7337	4199	0.09

From Bonneville
Power Authority
Test -17-051
DC Arc Flash

Test 56

In tests with the actual DC panel, the tool was fixed to one bus bar such that it was touching the other. Once the arc was established, it burned away the bus bar and the end of the tool until there was a sufficient gap to extinguish the arc. The maximum incident energy from this configuration was 0.32 Cal/cm^2.

Figure 17 – Wrench Fixed to a Bus Bar in the Panel, Before and After Arc.

Compare to Incident Energy Calculation

From Bonneville Power Authority
Test -17-051
DC Arc Flash

TEST-17-051
Page 7

The following assumptions are made when estimating the incident energy using Equation 1:

- The distance is 18-inches (45.7 cm)
- System bolted fault current is the maximum short circuit current of the battery, 10,747 A
- Arcing current is 50% of the bolted fault current (maximum power transfer theorem)
- System voltage is the nominal 125 Vdc
- Arcing time is 2 seconds
- A multiplier of 1.6 is applied to the calculated incident energy to account for the enclosure's tendency to direct the energy.

The resulting incident energy for the above assumptions is **10.3 Cal/cm^2**.

Test Results vs Calculated IE

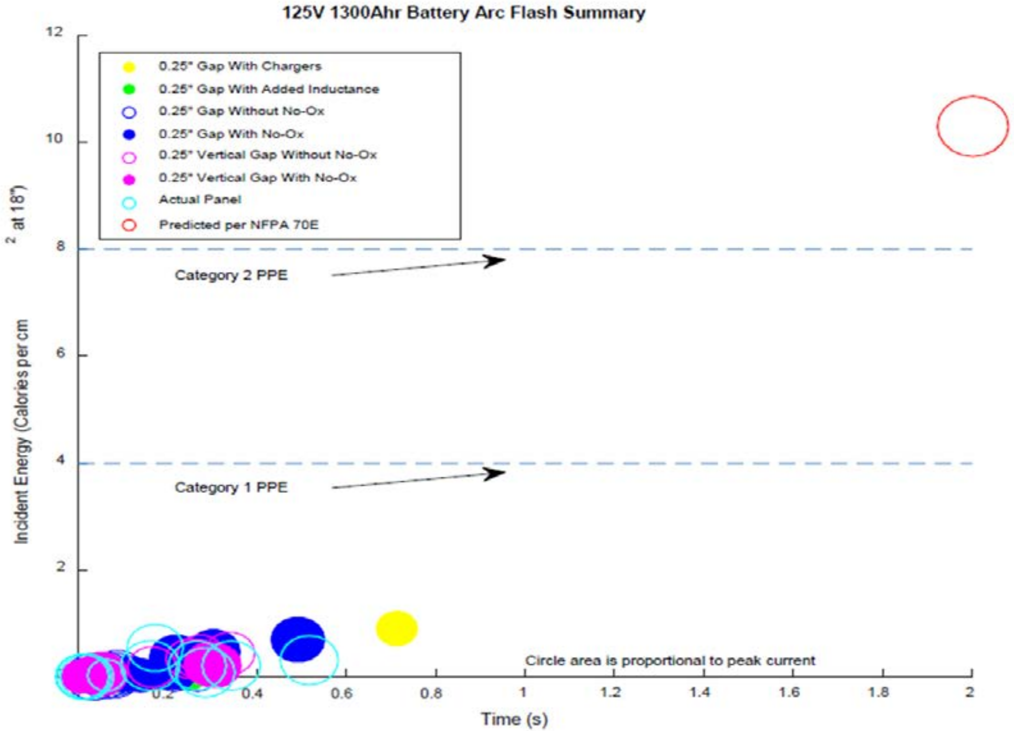


Figure 3 – Measured Incident Energy versus NFPA Calculated Value

From Bonneville
Power Authority
Test -17-051
DC Arc Flash

A Technique for Analyzing Hazards and Risks Associated with Battery Systems

Analyzing Hazards and Risks

- Battery System Hazards and Risk Ranking
  - A technique to highlight operations of high hazard and high risk
- Job Hazard Analysis / Job Safety Analysis
  - Assigns hazards and risks rankings for basic steps
  - Identifies steps of highest concern
  - Identifies required PPE
- Examples

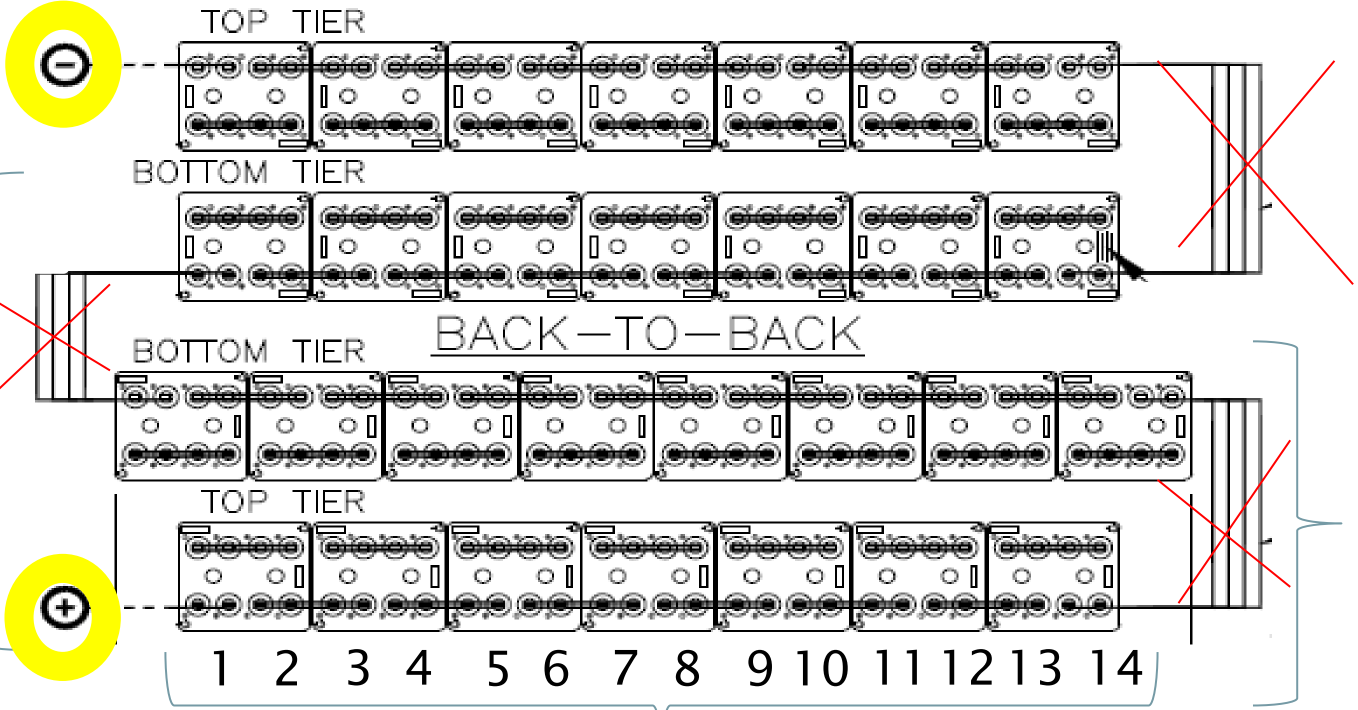
Battery Installations: What are the Risks?

- Shock hazard:
  - For strings operating at >50 VDC nominal, under normal conditions
    - It should be presumed that there is an unacceptable risk of injury from shock or thermal hazards (arc flash, electrical burn, or thermal burn) from exposure to energized conductors and circuit parts operating at greater than or equal to 50 volts.
- Arc flash hazard:
  - Dependent upon the task
  - The battery positive and negative terminal location
  - Is the string/system grounded

Battery Installations: What are the Risks?

- Chemical hazard
  - Handling of electrolyte (water and sulfuric acid)
- Thermal hazard
  - A burn as a result of a short
- Lifting and handling hazards
  - Material handling equipment and manual efforts

120V Utility Battery System Shock Hazard



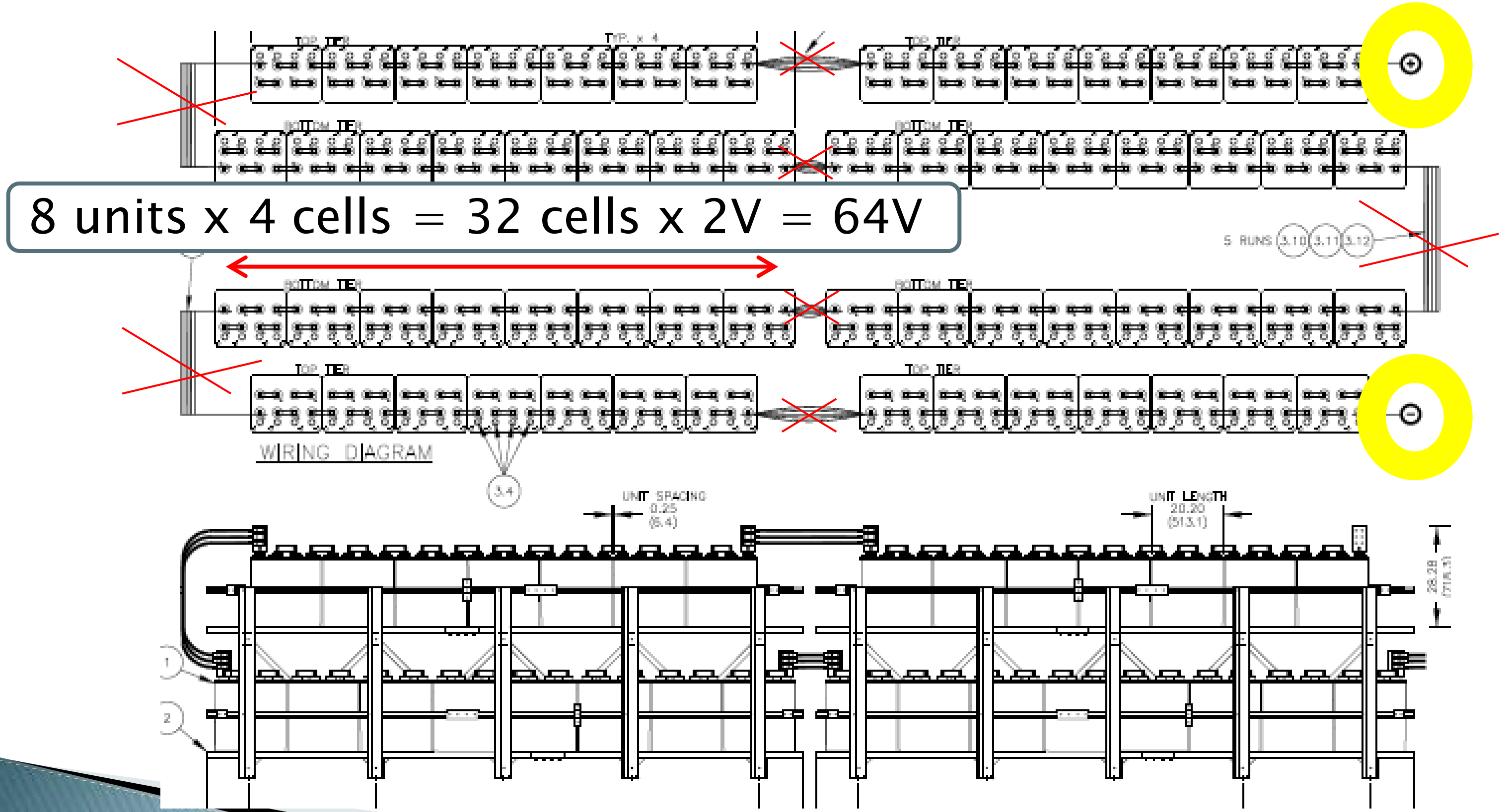
Do not connect until final step

Including the back rack bottom tier = 44 cells total x 2 = 88 VDC

Including the bottom tier: 16 cells + 14 cells = 30 cells x 2 VDC= 60VDC

14 cells x 2 V = 28 VDC

240 Cell UPS Wet Cell Battery



Biggest Risk at Positive and Negative

Hazard and Risk

- Organize the job tasks
  - For each step, identify the hazard that may be encountered
  - For each hazard,
    - determine the severity of the hazard
    - determine the risk or likelihood of occurrence
    - determine the PPE required, tools and equipment needed, and other mitigation techniques

Hazard and Risk Rankings

HAZARD SEVERITY RANKING		
1	Low hazard	Can cause local/temporary irritation
2	Low to moderate	
3	Moderate hazard	Can cause minor injury, local aid sufficient
4	Moderate to high	
5	High hazard	Can cause major injury, professional aid required
RISK PROBABILITY RANKING		
1	Low risk	Unlikely to occur
2	Low to moderate	
3	Moderate risk	Possible to occur without mitigation
4	Moderate to high	
5	High risk	Likely to occur without mitigation

Hazard and Risk Ranking Table

Hazard Ranking	1	2	3	4	5
			X		
Risk Ranking	1	2	3	4	5
Combined Ranking	1	4	9	16	25

- Combined ranking 1 = low hazard + low risk
- Combined ranking 9 = moderate hazard + moderate risk
- Combined ranking 25 = high hazard + high risk

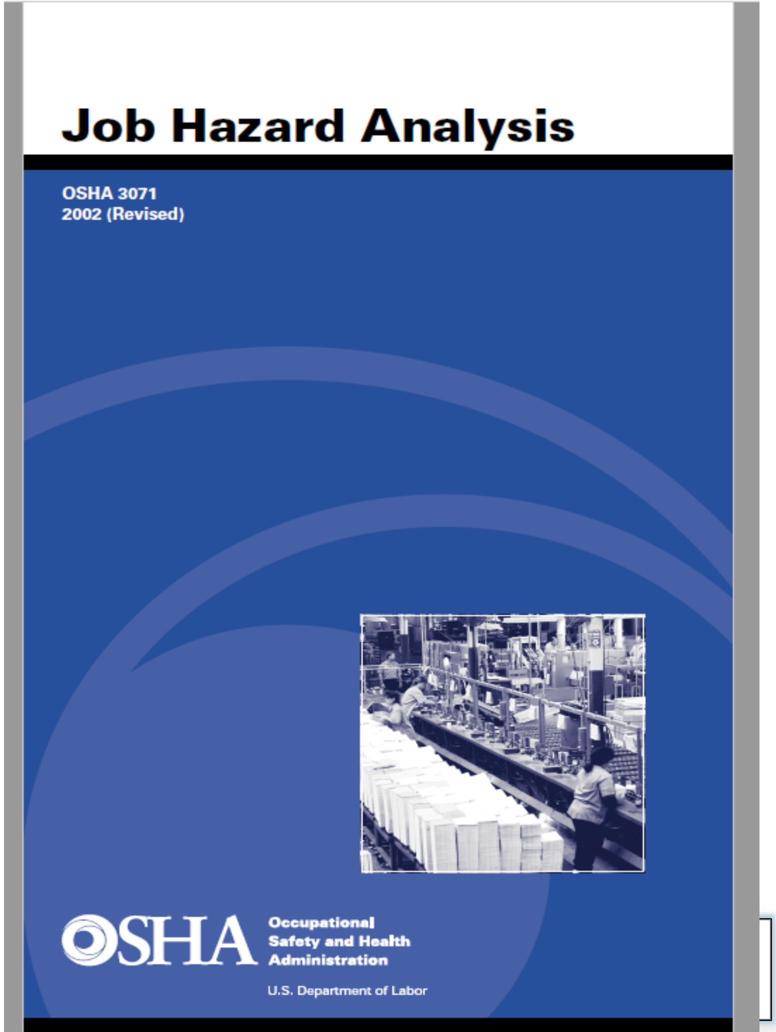
Hazard and Risk Ranking Table

Risk and Hazard Ranking Matrix

		Hazard ranking	Risk ranking	Combined ranking
Battery installation	Electrical hazard - electric shock	3	3	9
	Heavy lifting - physical injury	3	3	9
	Drop hazard - physical injury	4	2	8
	Equipment hazard - forklift safety	4	2	8
	Equipment hazard - ladder safety	3	2	6
	Electrical hazard - arc flash incident	5	1	5
	Chemical hazard - acid spill in eyes	3	1	3
	Chemical hazard - acid spill on skin	1	1	1

Job Hazard Analysis

- A Job Hazard Analysis, “JHA” is a process of taking a critical look at the basic steps of a job to identify the hazards. Once the hazards are identified, implement methods to eliminate or reduce to an acceptable risk level.

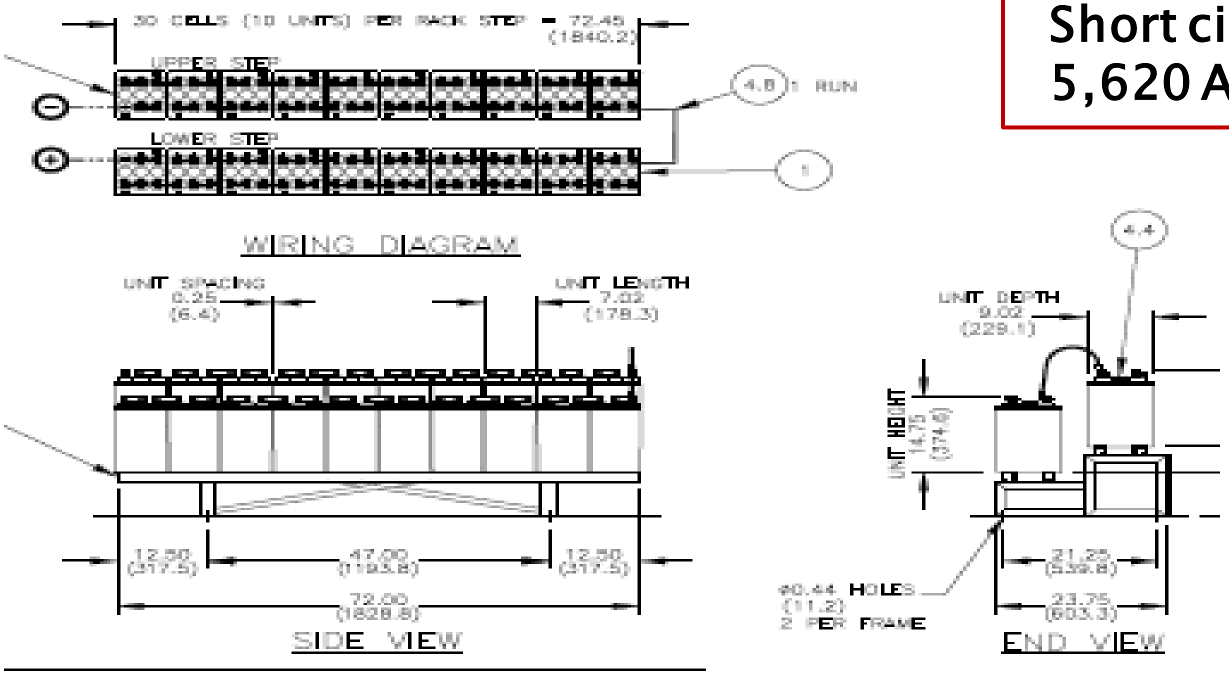


Basic Process of JHA

- Step One: Select the job/ task
- Step Two: Breakdown the job into successive basic steps
- Step Three: Identify the hazards and likelihood of occurrence in each step
- Step Four: Eliminate or reduce the hazards

EXAMPLE VLA (Wet Cell) 120VDC, 60 Cell Installation

470 AH battery
Short circuit =
5,620 Amps



Arc Flash PPE – Calculation

- 120VDC, 470 Ampere hour battery system
  - Short circuit provided by the manufacturer: 5,620 amps

- The Job is installing a new string, while this task is not directly listed in NFPA 70E Table 130.5 (C), it can be assumed there is a potential risk of arc flash
- Using PPE Category Method:
- Table 130.7(C)(15)(b) shows Arc Flash PPE category 2 is required
- Table 130.7(C)(15)(c) shows category 2 = 8 cal/cm^2

DC Incident Energy (IE) Calculation

- Battery short circuit current: 5,620 amps
- Isc = 5,620 amps, where Iarc = Isc/2 = 2,810 Amps
- Vsys = 120 VDC
- D = 18”, 45.72 cm
- T = 2 sec
- $IE = 0.01 \times Vsys \times Iarc \times Tarc/D^2$
- IE = .01 x 120 x 2,810 x .0009567 = <u>3.2 cal/cm²</u>

DC Incident Energy (IE) Calculation

- *Using Battery 1 Minute Rate* (594A) to 1.75vpc=
  - 5,940 amps
- Isc = 5,940 amps, where Iarc = Isc/2 = 2,970 Amps
- Vsys = 120 VDC
- D = 18", 45.72 cm
- T = 2 sec
- $IE = 0.01 \times Vsys \times Iarc \times Tarc/D^2$
- IE = .01 x 120 x 2,970 x .0009567 = <u>3.4 cal/cm²</u>

Arc Rated Clothing and PPE

- Per Category Method, Table 130.7(C)(15)(c) specifies minimum arc rated clothing of 8 <u>cal/cm²</u>

- Per IE Analysis Method, Table 130.5(G), select: 1.2 to 12 cal/cm^2 section:
- Arc rated clothing and equipment greater or equal to the determined incident energy ($\geq$ 3.2 cal/cm^2)

Standard PPE

- Safety glasses with side shields
- Safety shoes
- Eye wash device or station
- Acid neutralizer
- Insulated tools
- Leather gloves
- FR long sleeve shirt and pants
- Calibrated instruments

Additional PPE and Equipment

- Electrically rated gloves and blankets when shock hazard exists
- Proper arc flash rated PPE when arc flash hazard exists
- Acid resistant apron and gloves, face shield and/or goggles when chemical hazard exists

VLA (Wet Cell) 120VDC, 60 Cell Installation

- Job Hazard Analysis Basic Steps:
  - Receive battery and rack
  - Transport to installation location
  - Assemble rack
  - Load cells onto rack
  - Assemble battery hardware
  - Terminate charger to battery
  - Data gather for initial installation

JHA

- Receive battery and rack

Basic steps	Potential Hazards	Hazard Ranking (how bad)	Risk Ranking (how likely)	Combined Ranking	Safe job procedures , Mitigation & PPE
Unload delivery truck/pallet movement	Injury due to forklift or pallet jack	2	2	4	Forklift and/or pallet operating safety training, spill response kit/means available, Std. PPE
Inspection of equipment	Trip hazard	1	1	1	Precautions based upon any visible damage, Std. PPE
	chemical hazard from leaking electrolyte	2	1	2	+ Chemical PPE if needed

JHA

- Complete Rack & Load Cells

Basic steps	Potential Hazards	Hazard Ranking (how bad)	Risk Ranking (how likely)	Combined Ranking	Safe job procedures , Mitigation & PPE
Ground rack	Airborne particles	1	1	1	Utilize dust mask for buffing paint (at rack ground location), proper tool use, Std. PPE
Unpack cells & prep for install	Injury due to mechanical hazards	2	2	4	Maintain body positioning and footing; maintain awareness of surrounding, Std. PPE, spill response available
Install/load new cells onto rack	Injury due to drop and lifting	1	2	2	Maintain body positioning and footing; verify lifting equipment is of adequate rating and maintained; follow manufacturer's instructions, Std. PPE
	Chemical hazard due to electrolyte	3	3	9	+ Chemical PPE, spill response available

JHA

Installation of Cells

Basic steps	Potential Hazards	Hazard Ranking (how bad)	Risk Ranking (how likely)	Combined Ranking	Safe job procedures , Mitigation & PPE
Clean cell posts, apply no-ox grease	Chemical exposure	1	1	1	Follow manufacturer's instructions, see no-ox-id grease Safety Data Sheet (SDS), Std. PPE + Chemical PPE, appropriate gloves
Install new battery connectors and hardware	Electrical hazard: shock and/or thermal	2	2	4	Follow mfg. instructions, Std. PPE, work on cell groups $<$50VDC, appropriate gloves. Leave connection open between cell groups.
Torque the connections	Electrical hazard: shock and/or thermal	2	3	6	Utilize insulated tools, follow mfg. instructions, Std. PPE, work on cell groups $<$50VDC
Terminate and torque the inter-tier and inter-rack cables & connectors	Electrical hazard: shock and arc flash	4	3	12	Required PPE per IE calculation (arc rating $\geq$ 3.2 cal/cm^2, utilize protective blankets to terminate one connection at a time

JHA

- Terminate Battery to Charger

Basic steps	Potential Hazards	Hazard Ranking (how bad)	Risk Ranking (how likely)	Combined Ranking	Safe job procedures , Mitigation & PPE
Obtain connection resistance readings to verify proper torque	Electrical hazard: shock	3	2	6	Follow instructions, proper use of digital low resistance ohmmeter (DLRO), Std. PPE, appropriate gloves
Obtain open circuit voltage of each cell	Electrical hazard: Shock	2	1	2	Proper use of DMM, Std. PPE, appropriate gloves
Terminate positive and negative cables (feeders) from charger	Electrical hazard: shock and arc flash	4	3	12	Verify LOTO on de-energized charger, verify DC output breaker of charger open, verify voltage polarity, PPE per IE calculation (arc rating $\geq$ 3.2 cal/cm^2, utilize protective blankets

Conclusion

- Stationary batteries are used throughout our industrial world
- There are hazards associated with stationary batteries
- Every installation should be evaluated for potential hazards, risks and likelihood of occurrence
- Information concerning the risks should be provided and/or posted with the battery installation
- Work on battery systems should be performed by knowledgeable personnel with proper training, tools and PPE

Thank you

Lesley Varga, P.E.
President
Quality Standby Services, LLC

Standby DC Power Systems
Engineer, Furnish and Install Services

Quality Standby Services

Standby Power Products for the Telecom, UPS and Utility Applications

Engineer and Furnish

- All battery types
- Chargers and ancillary equipment
- Battery Monitors

Application and System Design

- Registered Electrical PE
- Electrical Contractor License

Field Services

- Installation Services
- Start-up Service and Inspection
- Battery Testing
- Maintenance Contracts
- Battery Disposal
- 24 Hour Emergency Service

MARIETTA, GA (770) 916-1747
WWW.QUALITYSTANDBYSERVCICES.COM