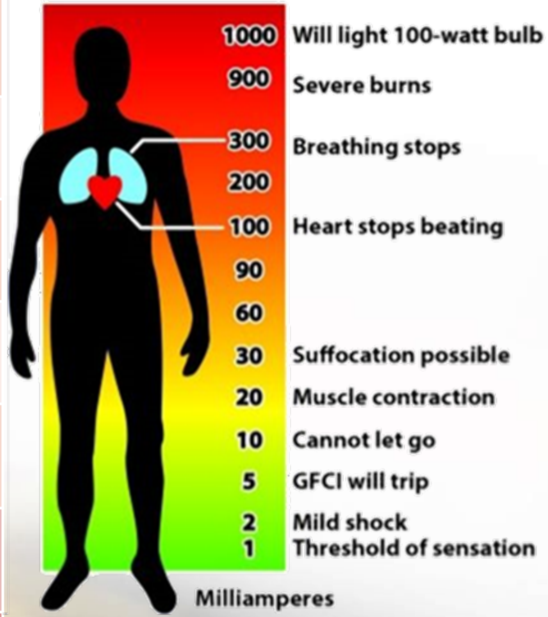
EASTPENN

AMERICAN POWERSYSTEMS

Advancements in DC Shock and Arc Flash Coming to NFPA 70E and IEEE 1584 in the Future Based on Real-World Testing

Effects of Current Through the Body (time-dependent)

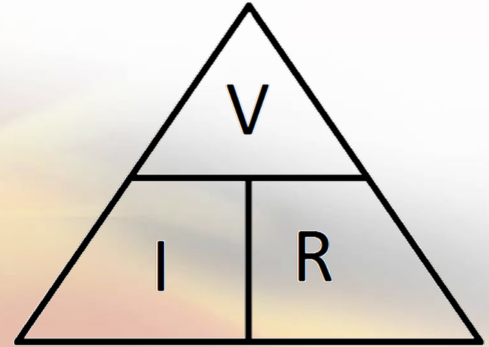
Effect	AC mA	DC mA
Tingling Sensation Perceptible	1/10 - ½	1 - 2
Involuntary Reflex (Let-go current)	½ - 5	2 - 30
Possible Tetany (Unable to Let-go)	5 – 400	30 - 200
Possible Respiratory Arrest (Paralyzed Diaphragm)	30 – 200	170 - 200
Ventricular Fibrillation	50 - 200	200 - 500
Heart Failure	500+	500+
Internal Organs Burn	1500+	1500+



Current Through the Body Calculation

- equivalent human Body Resistance Varies Greatly
  - Average Human Dry Skin R ≈ 20,000 Ω
  - Average Human Wet Skin R ≈ 1,250 Ω
  - Human Sweaty Skin R as low as 500 Ω (Worst-Case w/o Wounds?)
  - Also Varies Arm-to-Arm vs Arm-to-Foot
    - Worst Cases for the Heart are Arm-to- Arm or Left Arm - Foot
- Sample Calculations:
  - 120 VAC rms
    - Dry Skin: I ≈ 6 mA (tingle & let-go)
    - Wet Skin: I ≈ 100 mA (might be deadly)
  - 240 VDC
    - Dry Skin: I ≈ 12 mA (tingle & let-go)
    - Wet Skin: I ≈ 190 mA (hard to let go)

Ohm's Law



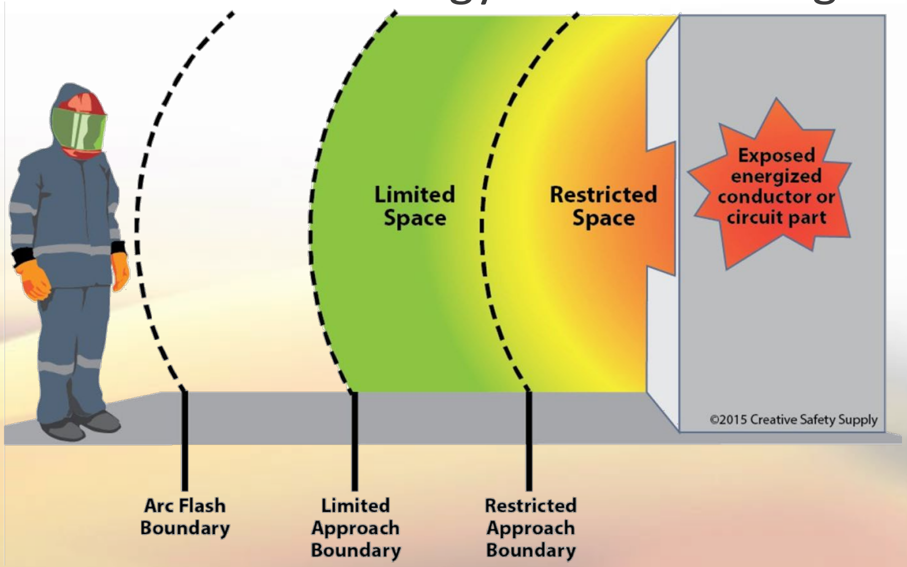
I = V/R

V = IR

R = V/I

Shock and Arc-Flash/Blast Boundaries

- Restricted Approach Boundary: Shock Protection Required
  - Reserved for Qualified Persons Only
- Limited Approach Boundary: Qualified vs Unqualified/Escorted
- Arc Flash Boundary: Arc Flash Protection Required
  - Distance at Which Incident Energy Causes 2nd-Degree Burn (1.2 cal/cm^2)



DC Shock Risk Table

- Determine the Boundaries from Table 16 of the Safety Policy
  - Tables Derived From NFPA 70E-2021 Article 130

This will be going back to 100 VDC in NFPA 70E-2024

<table>
<tr><th>System Voltage</th><th>Limited Approach Boundary for Exposed Fixed Circuit Part</th><th>Restricted Approach Boundary</th></tr>
<tr><td>0 – 50 V
(12, 24, 48 VDC)</td><td colspan="2">not specified</td></tr>
<tr><td>51 – 300 V
(125, 250 VDC)</td><td rowspan="2">3’6”</td><td>Avoid Contact</td></tr>
<tr><td>301 – 1,000 VDC
(med-large UPS)</td><td>1’</td></tr>
</table>

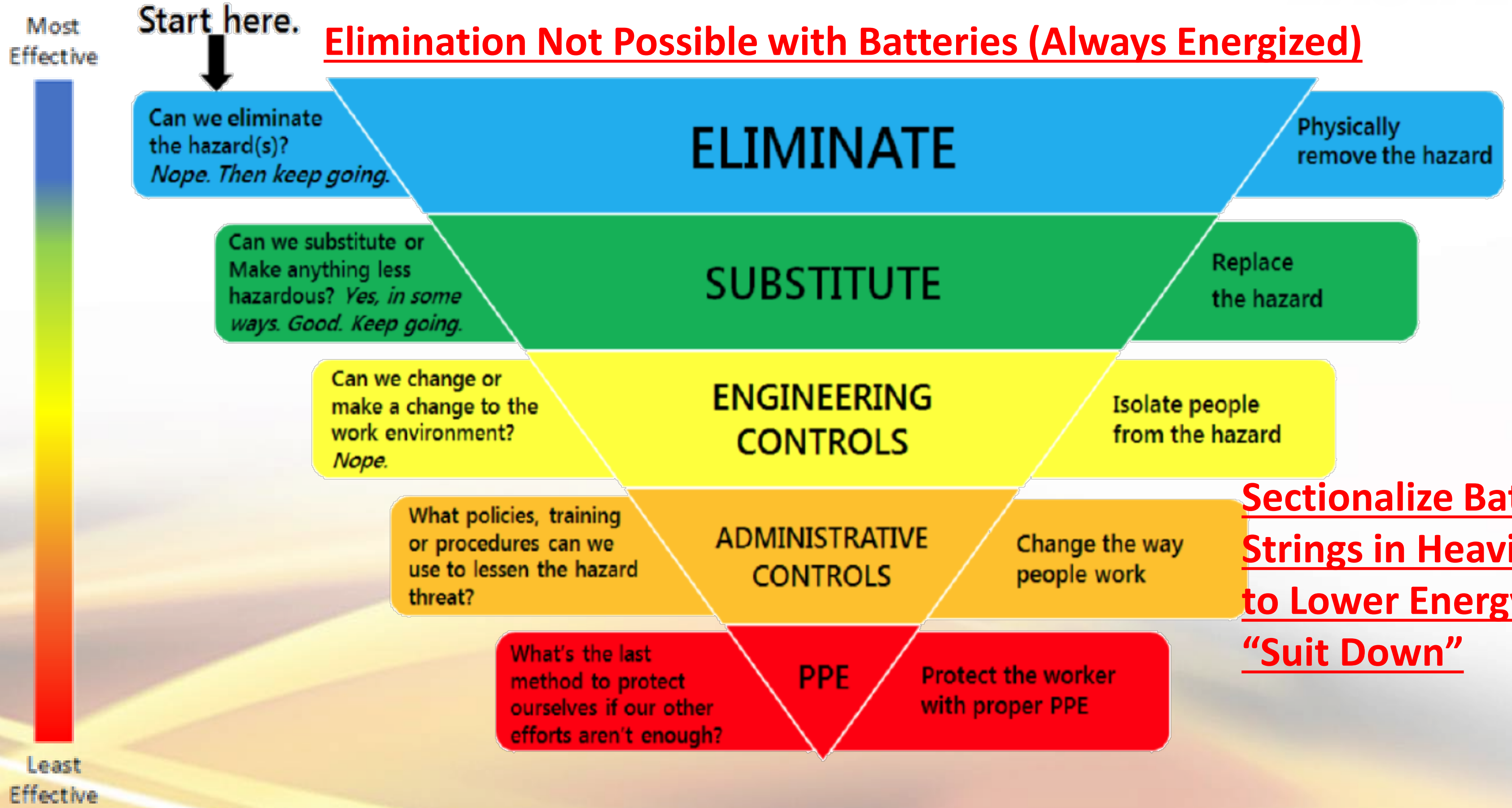
Arc-Flash PPE Categories (From NFPA 70E Article 130)

- Arc Flash Boundary: $\leq$1.2 cal/cm^2, 2nd degree burn threshold
  - Minimum required to work on live voltages: Natural fiber (cotton, wool, rayon) clothes
  - Long sleeves required to reach into battery/electrical cabinets
- Arc Flash PPE Category (was HRC) 1: 4 cal/cm^2, ATPV (Arc Thermal Performance Value)
- Arc Flash PPE Category 2: 8 cal/cm^2
  - PPE Category "2+": 12 cal/cm^2
- Arc Flash PPE Category 3: 25 cal/cm^2
- Arc Flash PPE Category 4: 40 cal/cm^2

helmet/shield good to 12 cal/cm^2, – can be used with 12 cal/cm^2 clothing/coverall

Another Way of Looking at Electrical Safety

Elimination Not Possible with Batteries (Always Energized)



Sectionalize Battery Strings in Heavier Gear to Lower Energy, then "Suit Down"

DC Arc-Flash Risk Analysis

- NFPA 70E Allows Arc-Flash Analysis by Tables in Article 130 **or** by Annex D.5 Calculations (see Next Pages), but Not Both to try to Get the "Best" Result

Nominal DC Voltage	Fault Current	Arc-Flash Boundary	Risk Category
0 - 100V	Any	N/A	N/A
100 - 250V	<4 kA	3'	2 - (8 cal/cm^2)
	≥4 kA and <7 kA	4'	2 - (8 cal/cm^2)
	≥7 kA and <15 kA	6'	3 - (25 cal/cm^2)
250 - 600V	<1.5 kA	3'	2 - (8 cal/cm^2)
	≥1.5 kA and <3 kA	4'	2 - (8 cal/cm^2)
	≥3 kA and <7 kA	6'	3 - (25 cal/cm^2)
	≥7 kA and <10 kA	8'	4 - (40 cal/cm^2)

This will be going up to 150 V in NFPA 70E-2024

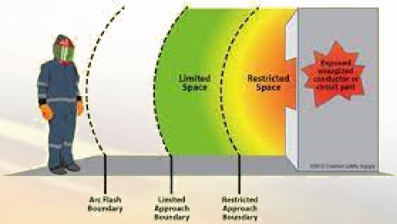
How DC Arc-Flash cal/cm² is Calculated per NFPA 70E, and BPA & Hydro Quebec Studies

- Formula from NFPA 70E: $E_{i-m} = 0.01 \times V_{nom} \times \frac{I_{sc}}{2} \times \frac{t_{arc}}{d^2}$
  - *d* is usually defined as 18”, but in cm (45.72)
  - Based on NFPA 70E, + BPA & Hydro Quebec studies, max t_{arc} =
    - 0.025 s for most breakers (unless known otherwise), when applicable
    - 0.326 s ≤ 100 V_{dc}
    - 100 V_{dc} < 0.715 s < 150 V_{dc}
    - 150 V_{dc} ≤ 1.37 s < 270 V_{dc}
    - ≥ 270 V_{dc} = 2 seconds

  - Simplifying the Equation: $E_{i-m} = 0.000002392 \times V_{nom} \times I_{sc} \times t_{arc}$

How Arc-Flash Boundary is Calculated per NFPA 70E, and BPA & Hydro Quebec Studies

- Algebraically Rework Formula: $d(\mathrm{cm}) = \sqrt{\dfrac{0.01 \times V_{nom} \times I_{sc} \times t_{arc}}{2 \times E_{i-m}}}$
  - The incident Energy ($E_{i\text{-}m}$) to set the arc-flash boundary is 1.2 cal/cm^2
  - Based on NFPA 70E, + BPA & Hydro Quebec studies, max t_{arc} =
    - 0.025 s for most breakers (unless known otherwise), when applicable
    - 0.326 s ≤ 100 V_{dc}
    - 100 V_{dc} < 0.715 s < 150 V_{dc}
    - 150 V_{dc} ≤ 1.37 s < 270 V_{dc}
    - ≥ 270 V_{dc} = 2 seconds



  - Simplifying the Equation: $d\ (in) = \sqrt{0.0006458 \times V_{nom} \times I_{sc} \times t_{arc}}$

Sample DC Arc-Flash Max Power Method Calculations

Battery Model	VDC	Cat	Arc-Flash Boundary	Short Circuit Amps	cal/cm² @ 18"
MCTII-4000	2	N/A	3	26,653	0.04
MCTII-4000	24	N/A	12	26,653	0.5
MCTII-4000	48	N/A	16	26,653	1.0
KCR-15	2	N/A	2	7,407	0.01
KCR-15	120	1	20	7,407	1.5
HR5500ET	12	N/A	3	4,786	0.04
HR5500ET	120	N/A	16	4,786	1.0
HR5500ET	240	1	32	4,786	3.8
HR5500ET	480	2+	54	4,786	11.0
AVR125-33	2	N/A	2	11,131	0.02
AVR125-33	48	N/A	11	11,131	0.4
AVR125-33	120	1	25	11,131	2.3
AVR125-33	240	2+	49	11,131	8.8
AVR125-33	480	4	83	11,131	25.6

Kinectrics 2007 Bruce Power Study

- Report No. K-012623-RA-0002-R00
- 125 and 260 VDC Systems
- Incident Energy Measured at Various Distances, but not 18”
- Showed Max Power Method Seriously Overestimated Incident Energy

BPA Study

Bonneville POWER ADMINISTRATION

- IEEE PES General Meeting 2018, paper 8586181
- 1,300 Ah nominal 125 VDC (133 V Float) Lead-Acid Battery
  - Listed Bolted Fault Short Circuit Current of 11,000 A
- 60 Tests
- Maximum Arc Flash Sustain Time was 0.715 seconds
  - Ranged from 0.004 s up to 0.715 seconds
- Maximum Arc Flash Energy was 0.9 cal/cm^2 at 18”
  - Ranged from unmeasurable low up to 0.9
  - Below 1.2 cal/cm^2 Level Where Special Clothing Required
  - NFPA 70E Annex D.5 Max Power Method Predicted 10.3 cal/cm^2
- Measured Max Arc Fault Current Ranged from 1,923-7,850 A

Hydro Quebec First Study

- IEEE IAS 2020 Electrical Safety Workshop (ESW), paper 14
- 69 Tests, both “Arc in a Box” and Open Air, at 105, 144, 260, and 520 VDC

V_{nom} (V)	V_{arc} (V)	I_{sc} (A)	$I_{arc\text{-}peak}$ (A)	t (s)	18” $E_{measured}$ (cal/cm²)	18” $E_{Ammerman\text{-}iterative}$ (cal/cm²)	18” $E_{Doan\text{-}MaxPower\text{-}2s}$ (cal/cm²)	18” $E_{MaxPower\text{-}tvary}$ (cal/cm²)
105	59-65	7,000	2,900-4,000	0.04-0.33	0.02-0.24	0.8	3.5	0.6
144	78-124	17,000	900-8,000	0.02-0.49	0.005-1.7	3.0	11.7	4.2
260	112-132	20,000	8,600-10,900	0.75-1.37	6.0-10.7	12.0	24.9	17.0
520	181-184	20,000	11,000	2+	39.0-44.0	45	49.8	49.8

What’s Next?

- NFPA 70E-2027 to have New Formula/Method for DC Arc Flash Calculation Based on the Testing Shown in the Previous Two Slides; + 2022 Additional Testing done by Hydro Quebec (to be published in 2023 for IEEE IAS ESW), and 2022 Testing done by C&C Power on a UPS Battery Cabinet (to be published in 2023 for Battcon)
- IEEE 1584 Will Get Upgraded in the Next Edition with the Same Types of Calculations
- Both of These Changes Will Allow Canned Arc-Flash Programs (like ETAP, etc.) to Greatly Improve Their DC Arc Flash Portions