

Advancement in Arc Flash Related Research and Safety by Design

Dr. P.K. Sen, P.E.
Professor of Engineering
Site Director, PSerc
Colorado School of Mines
Golden, Colorado
psen@mines.edu
303-384-2020

Power Systems Engineering Research Center
Denver, Colorado
February 3, 2009

Purpose of the Presentation

“Arc Flash Hazard”

- ◆ Why are we Concerned about the “Arc Flash Hazard?”
- ◆ How do we Protect “Workers?”
- ◆ What is the State of Arc Flash Hazard Research?

Presentation Outline

- ◆ **Electrical Safety Awareness**
 - ◆ **The Arc Flash Hazard**
- ◆ **Arc Flash Safety Standards & Incident Energy Calculations Techniques**
 - ◆ **NFPA 70E-2004**
 - ◆ **IEEE 1584-2002 and More!!**
- ◆ **Future Challenges & Research Opportunities**

The Beginning of Electrical Hazard Awareness?

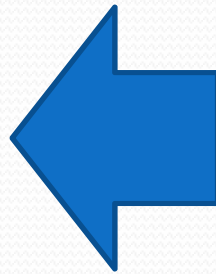
“I introduced into my ears two metal rods with rounded ends and joined them to the terminals of the apparatus. At the moment the circuit was completed, I received a shock in the head – and began to hear a noise – a crackling and boiling. This disagreeable sensation, which I feared might be dangerous, has deterred me so that I have not repeated the experiment.”

Alessandro Volta (1745 – 1827)

Hazards of Electricity

◆ Hazards of Electricity identified by NFPA 70E-2004: *Standard for Electrical Safety in the Workplace.*

- Electrical “Shock”
- Electrical “Arc-Flash”
- Electrical “Arc-Blast”



Electric “Shock” Triangle



Lower Magnitude of Current

For, 110lb Body Weight

$$I_B = \frac{0.116}{\sqrt{t_s}}$$

where,

I_B = Body Current (A)

t_s = Duration Current Exposure (seconds)

Electrical Injury Statistics (1992 – 2002)

**There were 3,378 Worker Fatalities
Caused by Electrical Events**

**Sixth Leading Cause of Workplace
Fatalities in the United States**

**Contact with Overhead
Power Lines:**

1,432 Fatalities (42%)

**There were 47,676 Non-Fatal Electrical
Injuries Documented**

29,046 Electric Shock Injuries

18,360 Burn Injuries

**Reference: J.C. Cawley and G.T. Homce, Trends in Electrical
Injury, 1992-2002, IEEE PCIC Conference Record, 2006,
Paper No. PCIC-2006-38.**

Electrical Burns (Examples)



Arm with third degree burn from high-voltage line.

$$\text{Internal Heat} = I^2 R t$$

What is Arc Flash?



**Outdoor,
Open Air**

What is Arc Flash?



**Indoor,
Enclosed
Box**



What is Arc Flash?

- ◆ An arc flash is a dangerous condition associated with the Release of Energy caused by an Arcing Fault.
- ◆ The amount of energy impressed on a surface, some distance away, as a result of an arcing fault is called the Incident Energy.

Arc Flash Hazards

The Known Hazards Associated with an Arc Flash include:

- **Intense Heat (Thermal Energy)** ★
- **Blast Pressure Waves**
- **High Intensity Sound**
- **Shrapnel**
- **Toxic Vapors**
- **Electromagnetic Radiation**



**More
Research**

Incident (Thermal) Energy

- ◆ Incident energy is a measure of the amount of energy available at a given point during an arc flash event. Incident energy is typically expressed in (Joules) J/cm^2 or (calories) cal/cm^2 .
- ◆ The energy required to produce a **Curable Second Degree Burn** on unprotected skin has been established as: **$5.0 \text{ J}/\text{cm}^2$ ($1.2 \text{ cal}/\text{cm}^2$)**

Factors Influencing Incident Energy Levels

- ◆ **System Conditions, Voltage and Fault Levels**
- ◆ **Protective Devices and Fault Duration**
- ◆ **System Grounding**
- ◆ **Electrode Gap, Orientation and Arc Length**
- ◆ **Size and Shape of Enclosures (Open Air, Box, Cables, etc.)**
- ◆ **Atmospheric Condition**
- ◆ **Energy Transfer Mechanisms**
- ◆ **Distance from the Fault Location**
- ◆ **Misc. Factors**

1st Degree Burn



2nd Degree Burn



3rd Degree Burn



4th Degree Burn



Arc Flash

Hazard Risk Categories

Hazard Risk Category 0	<1.2 cal/cm²
Hazard Risk Category 1	1.2 - 4 cal/cm²
Hazard Risk Category 2	4.1 - 8 cal/ cm²
Hazard Risk Category 3	8.1 - 25 cal/cm²
Hazard Risk Category 4	25.1 - 40 cal/cm²
Risk Not Acceptable	>40.0 cal/cm²

Personal Protective Equipment (PPE) Comparison



**PPE for Hazard Risk
Category 1**



**PPE for Hazard Risk
Category 2**

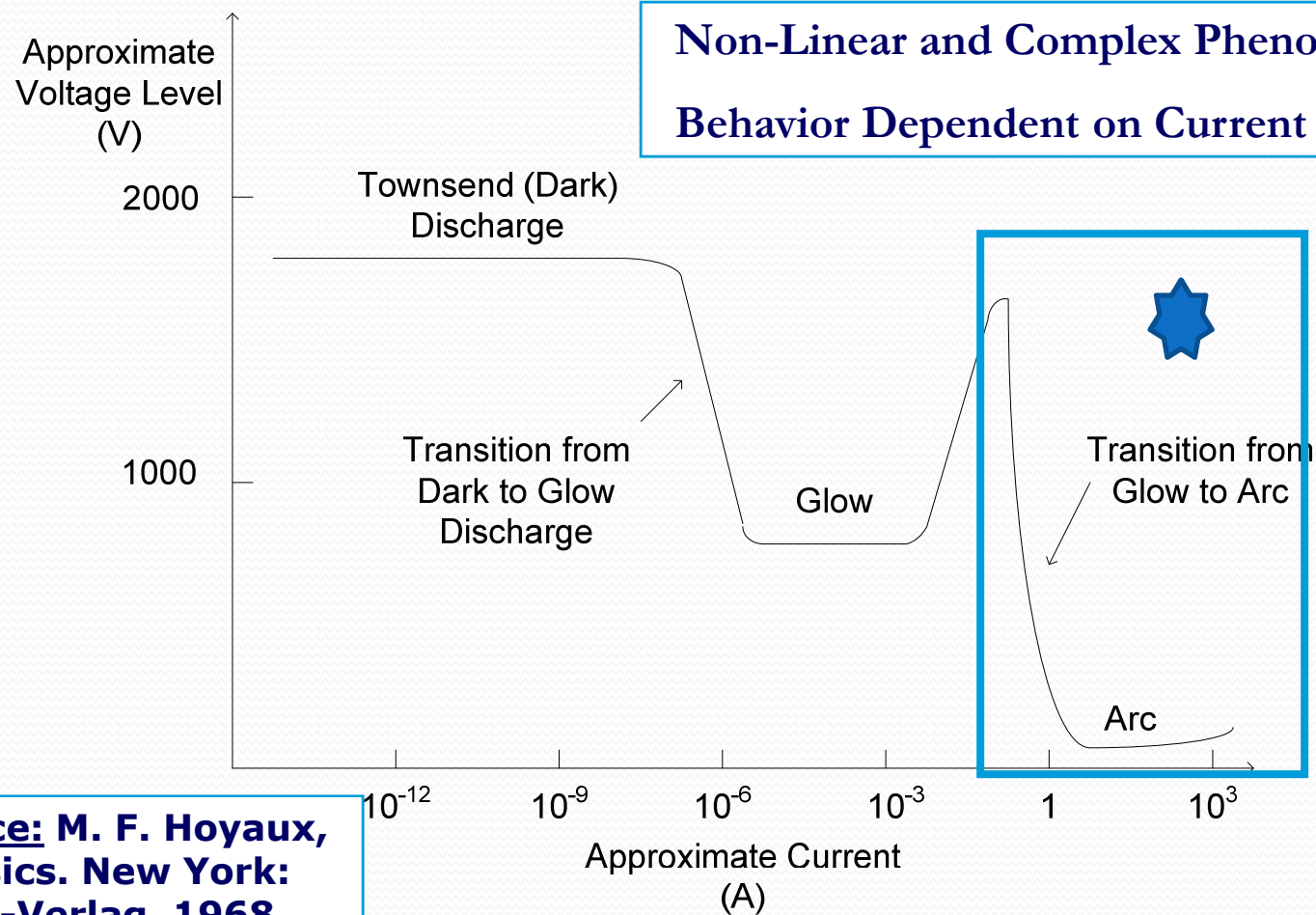


**PPE for Hazard Risk
Category 4**



**PPE for Hazard Risk
Category 3**

Arc Characteristics

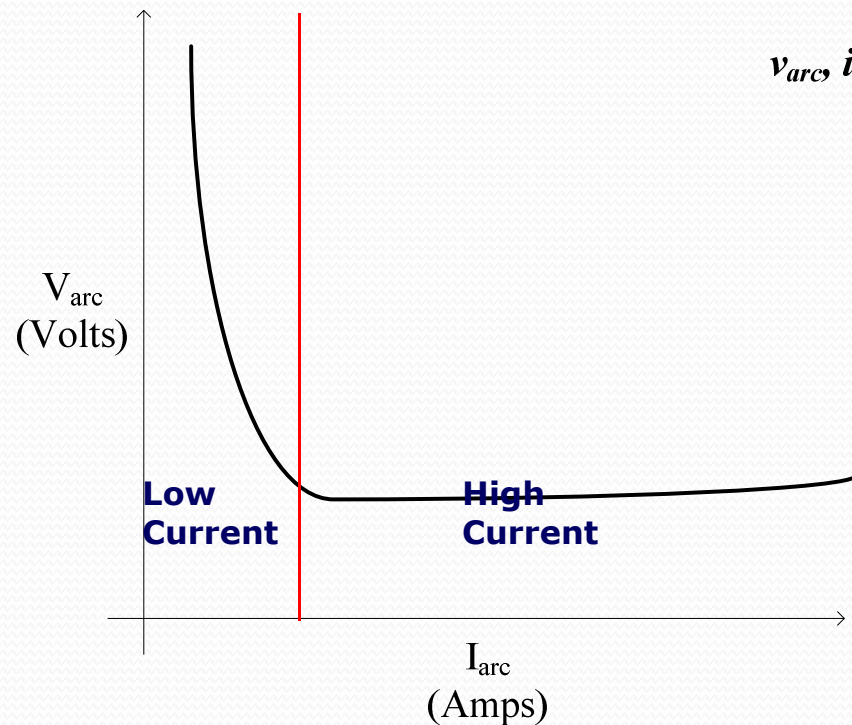


Reference: M. F. Hoyaux,
Arc Physics. New York:
Springer-Verlag, 1968

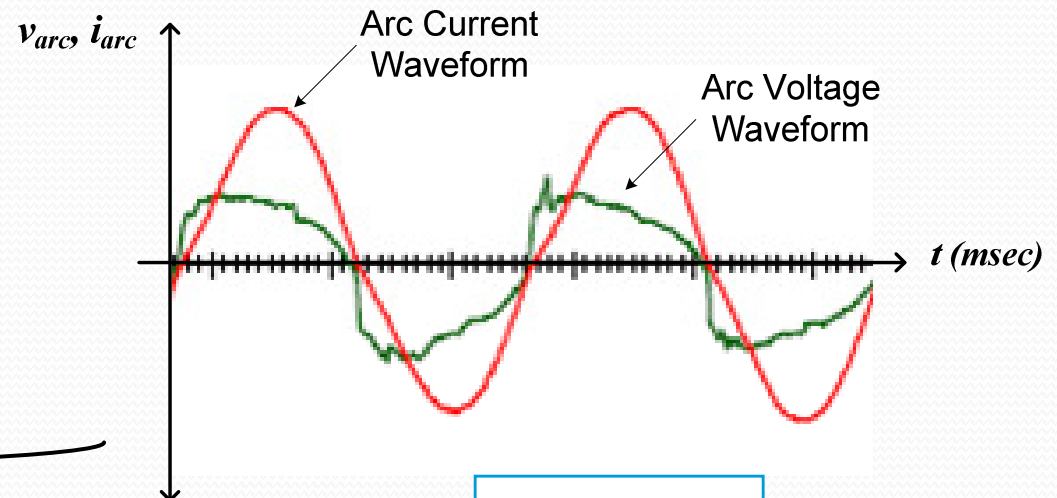
Volt-Ampere Characteristics



Reference: R. F. Ammerman, T. Gammon, P. K. Sen, and J. P. Nelson, "Comparative Study of Arc Modeling and Arc Flash Incident Energy Exposures," IEEE/IAS 55th Annual Petroleum and Chemical Industry Technical Conference, Cincinnati, Ohio, September 2008.



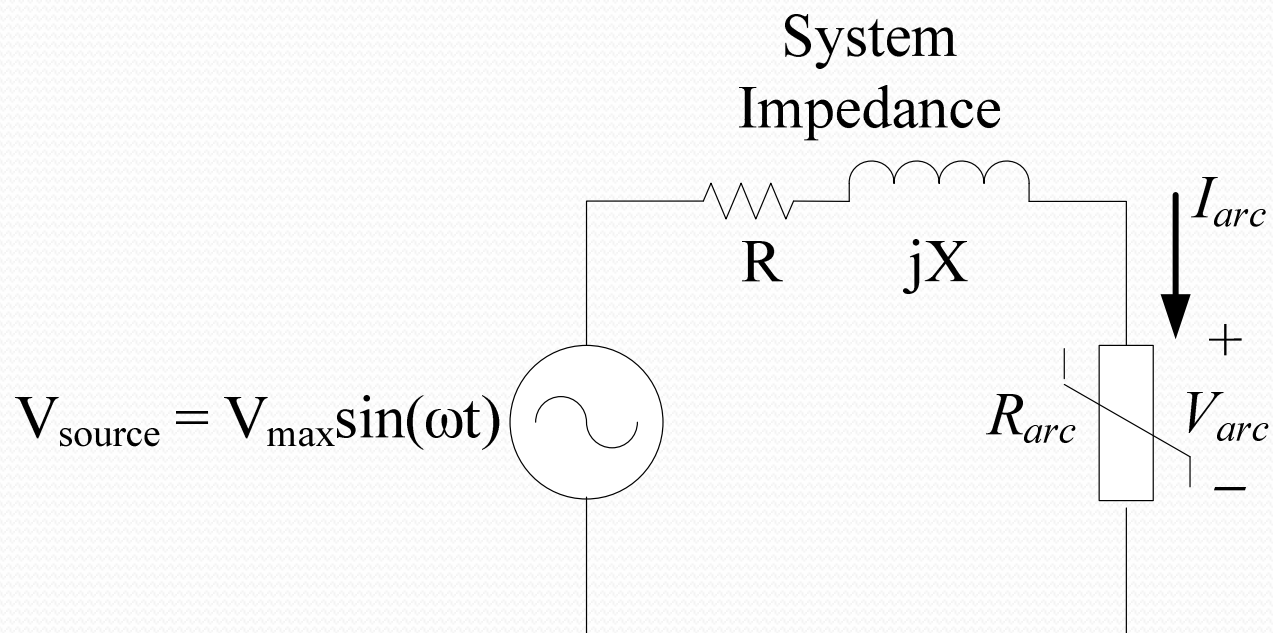
DC Arc Characteristics



**Non-Linear
Harmonics
Resistance**

AC Arc Characteristics

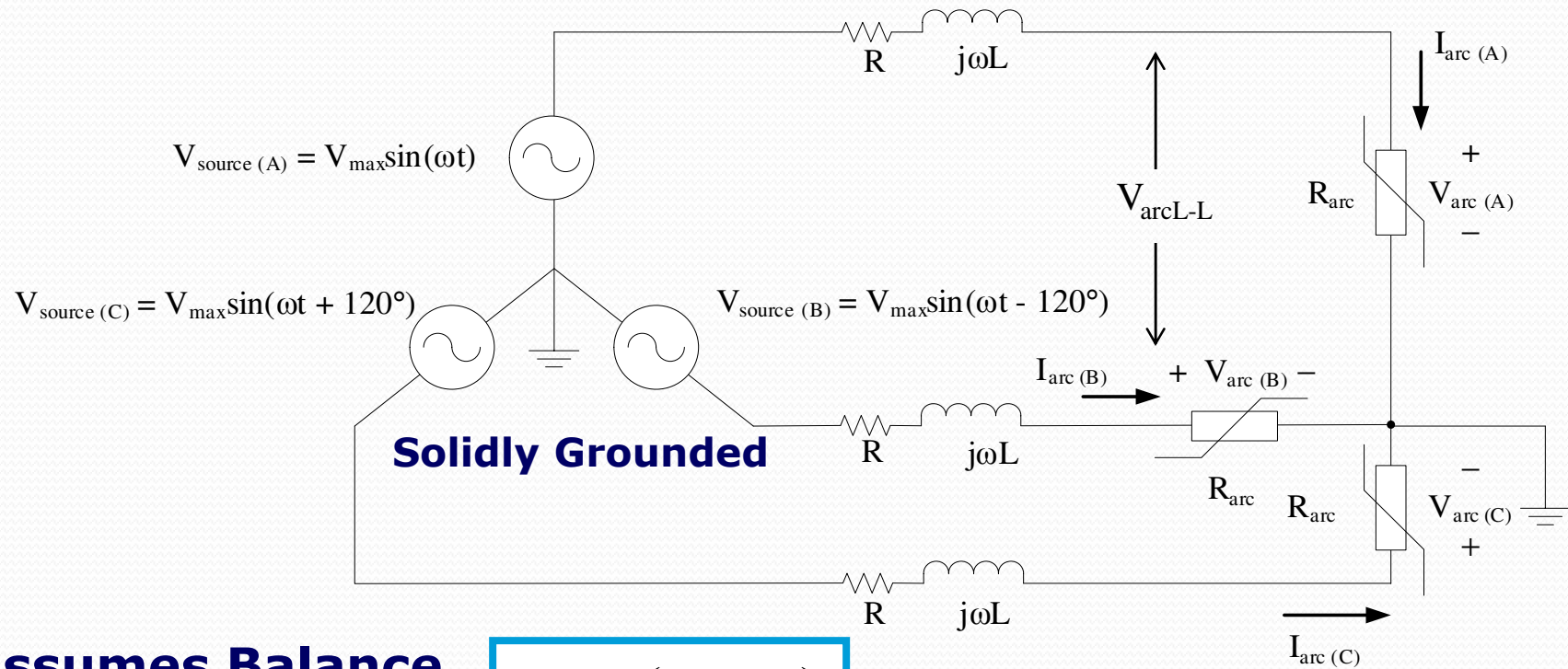
Single-Phase Equivalent Circuit Model



**Simple Looking
But Actually
Very Complex**

$$R_{\text{arc}} = \frac{V_{\text{arc}}}{I_{\text{arc}}}$$

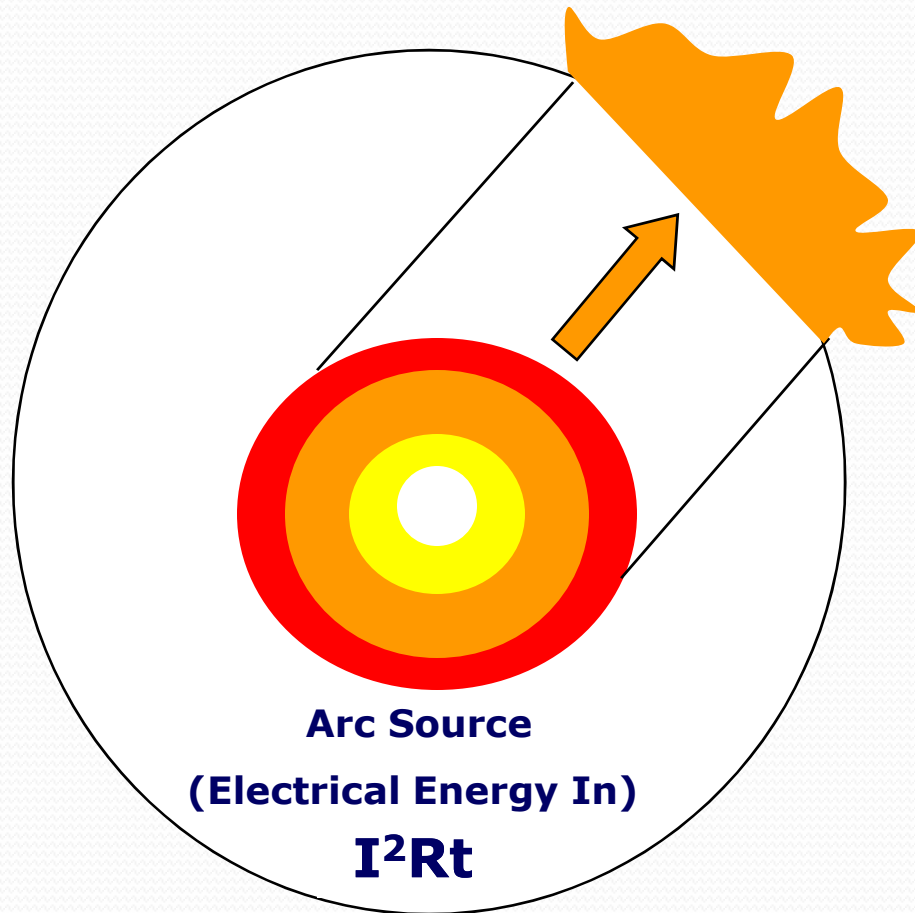
Three-Phase Equivalent Circuit Model



**Assumes Balance,
Another Degree of
Complexity**

$$R_{\text{arc}} \approx \left(\frac{V_{\text{arcL-L}}}{\sqrt{3} I_{\text{arc}}} \right)$$

Law of Conservation of Energy



Energy Out

- Heat (Conduction, Convection, and Radiation)
- Pressure Wave
- Sound
- Electromagnetic Radiation
- etc..

Arc Flash Regulations, Codes, Standards, and Guides

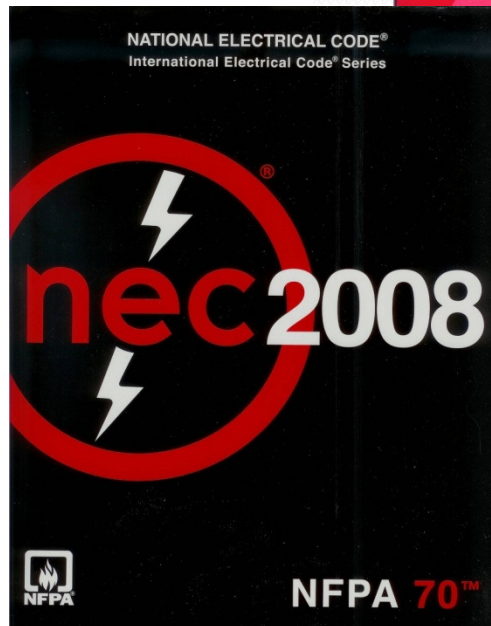
Arc Flash Regulations, Codes, Standards, and Guides



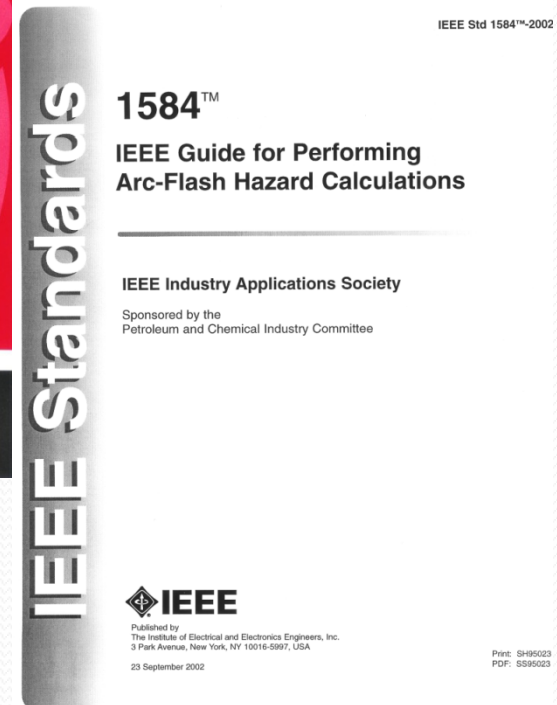
29

Parts 1910 (§ 1910.1000 to End)
Revised as of July 1, 2005

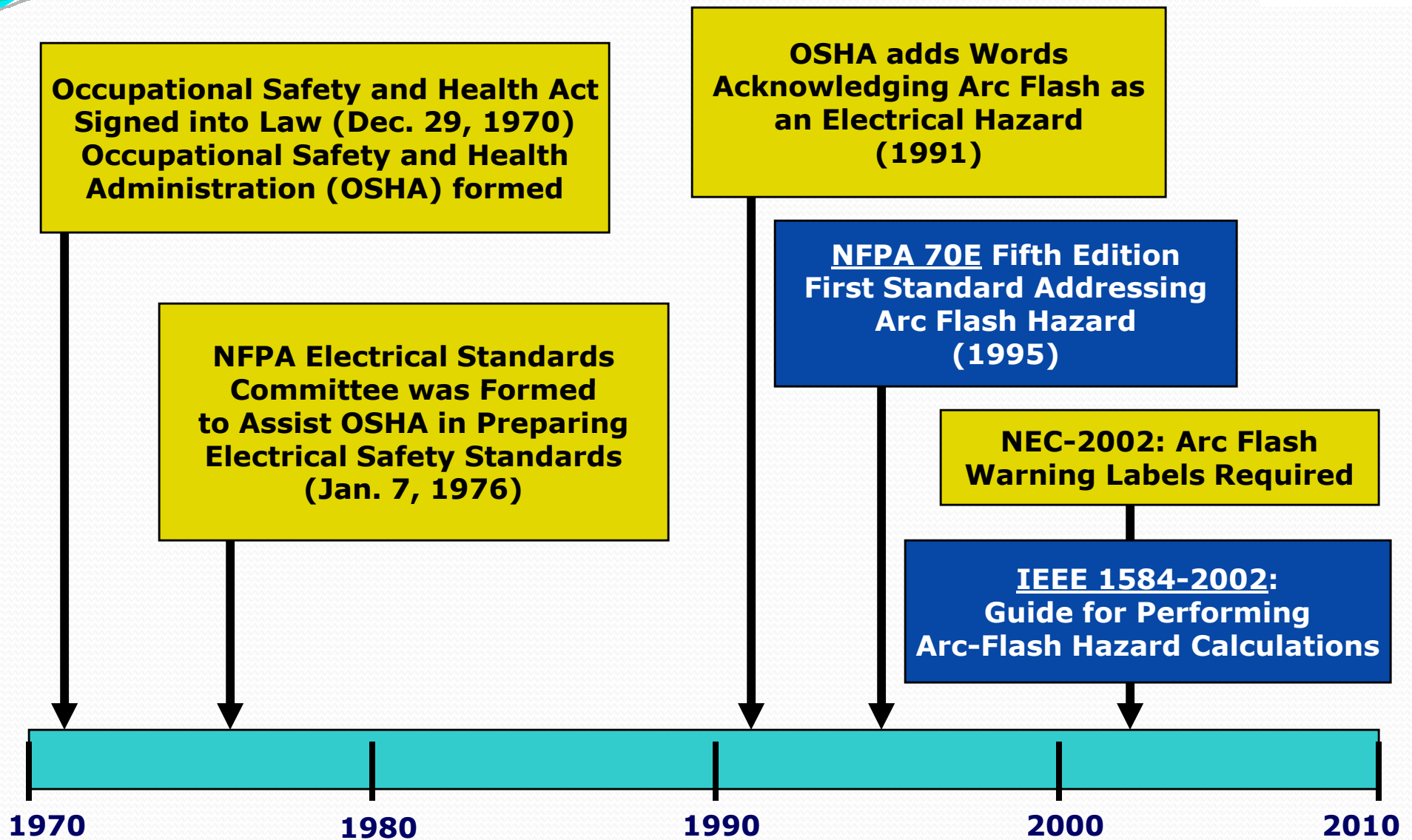
Labor



NESCR?



Evolution of Arc Flash Standards



OSHA and NFPA 70E

OSHA is the “shall”

- OSHA regulations are Federal law and shall be followed. Written in performance-based language.

NFPA 70E is the “how”

- NFPA 70E is recognized as the tool that illustrates how an employer might accomplish the objectives defined by the OSHA performance-oriented language.

OSHA

29 CFR 1910.132(d)(1): “The employer shall assess the workplace to determine if hazards are present, or are likely to be present, which necessitate the use of personal protective equipment (PPE). If such hazards are present, or likely to be present, the employer shall: Select, and have each affected employee use, the types of PPE that will protect the affected employee from the hazards identified in the hazard assessment;”



WARNING

Arc Flash and Shock Hazard Appropriate PPE Required

FLASH PROTECTION

Flash Hazard at **18 inches**
Min. Arc Rating: **0.08 cal/cm²**
Flash Protection Boundary: **3 inch**
Clothing Category: Category 0
VR Gloves-Tools, Proper Clothes
W/Safety Glasses

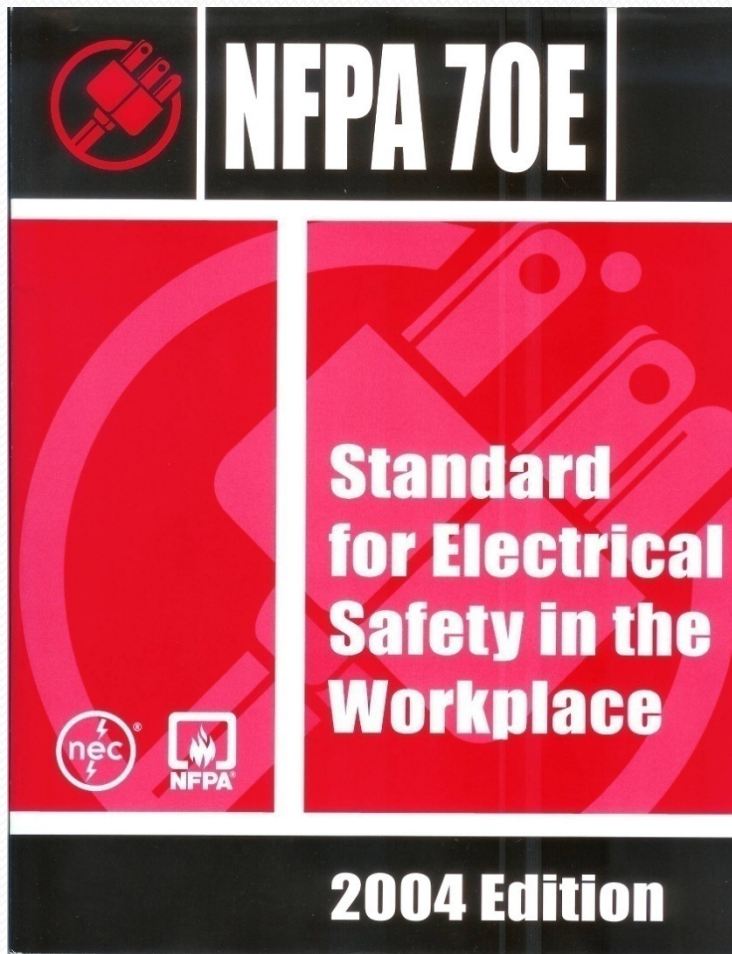
SHOCK PROTECTION

Shock Hazard when
cover is removed **480 VAC**
Limited Approach **42 inch**
Restricted Approach **12 inch**
Prohibited Approach **1 inch**

HTR #2 OVN CNV

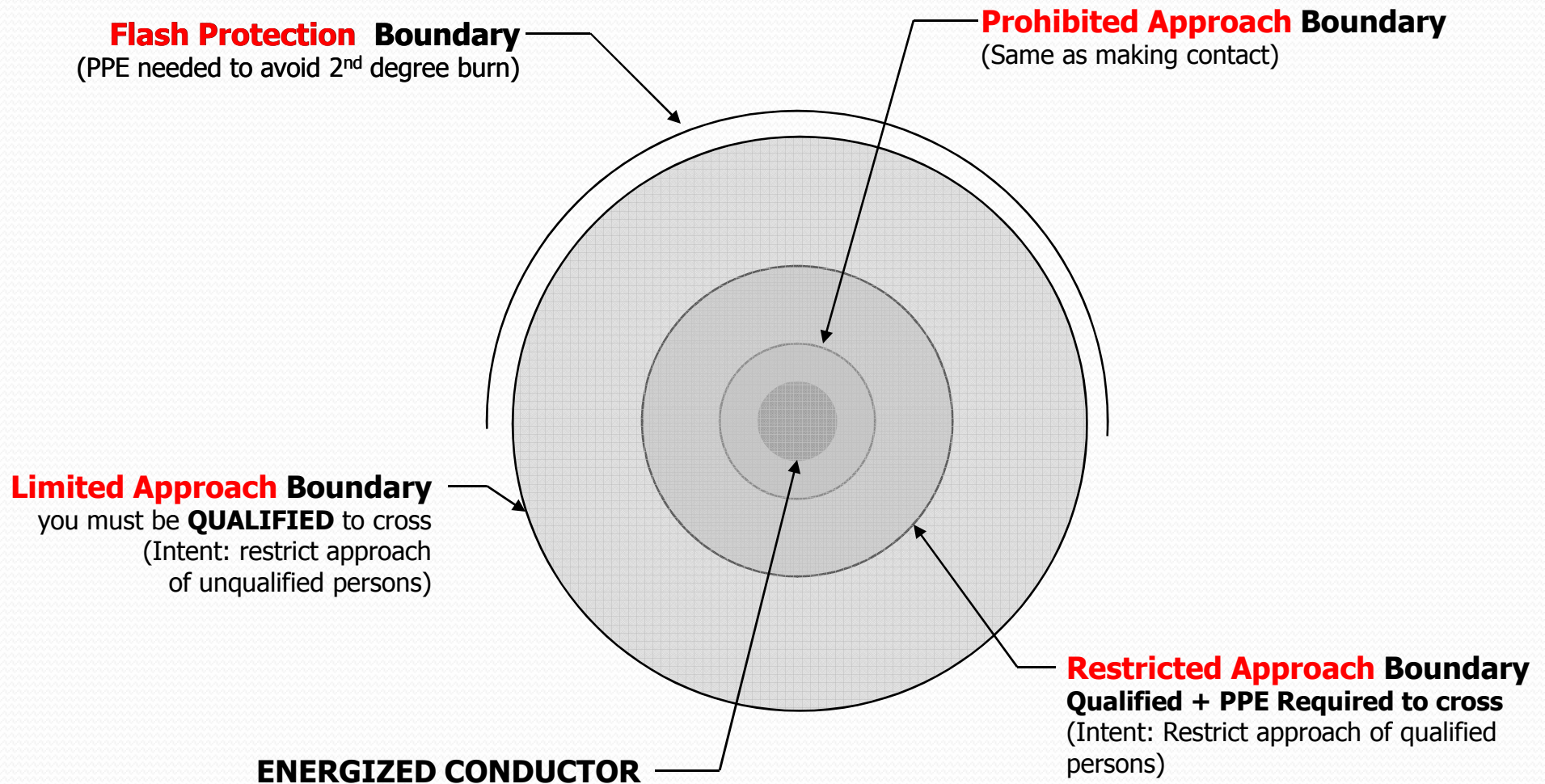
FED FROM BUS DUCT

NFPA 70E – Standard for Electrical Safety in the Workplace

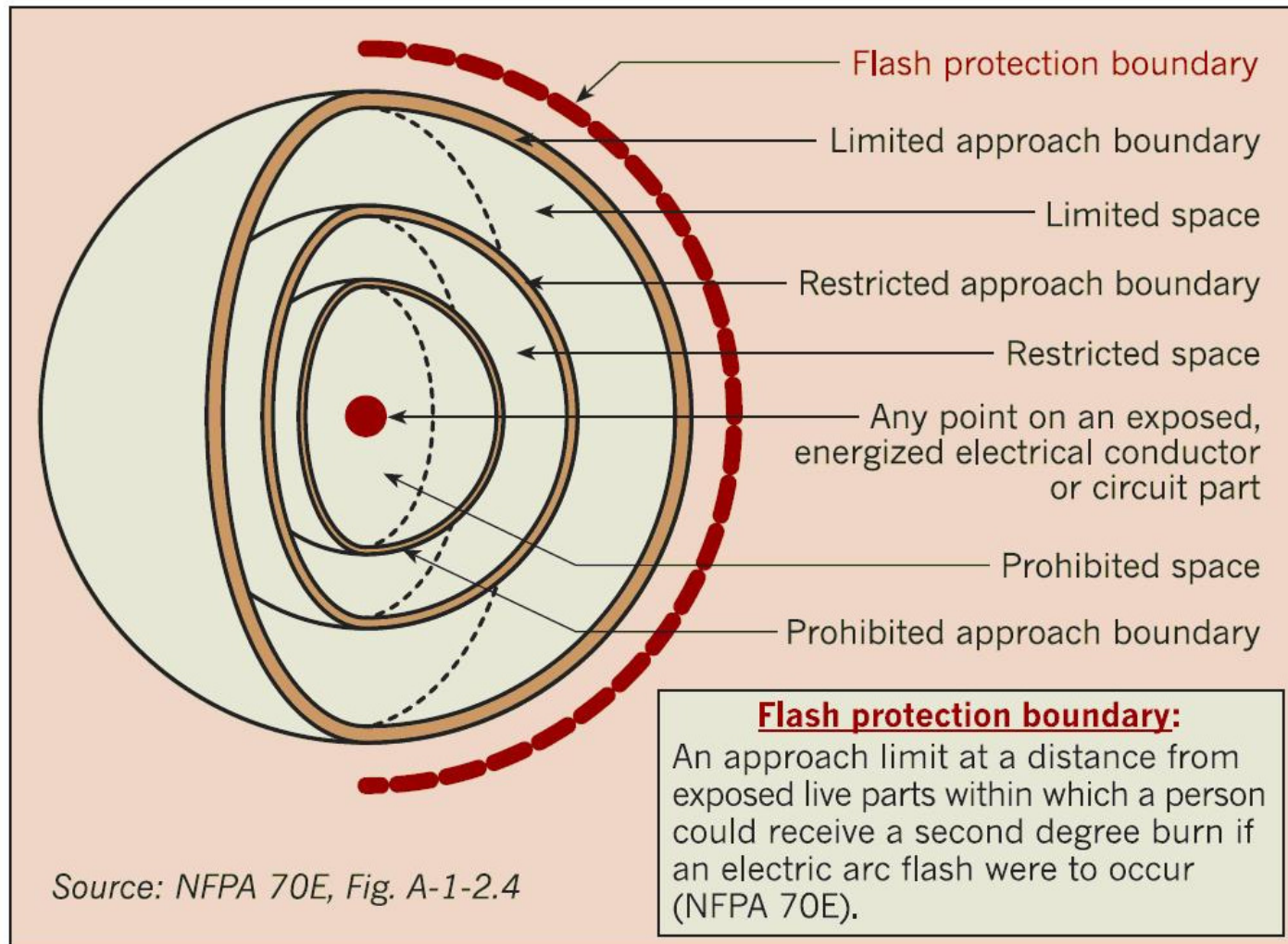


- ◆ Focuses on Protecting people
- ◆ Identifies requirements that are considered necessary to provide a workplace that is generally free of electrical hazards

NFPA 70E Approach Boundaries



NFPA 70E Approach Boundaries



Arc Flash Hazard Calculations

Arc Flash Assessment Methods

- ◆ **NFPA 70E – 2004: Table Method**
- ◆ **NFPA 70E – 2004: Equations**
- ◆ **IEEE 1584 – 2002 Equations**

Calculating Flash Protection

Boundary Distances

The following methods are used to determine the minimum approach distances for voltages less than 600 V. D_C is called the Flash Protection Boundary distance.

For $I_{SC} \times t \leq 5000 \text{ A}\cdot\text{s}$

$$D_C = 4 \text{ feet}$$

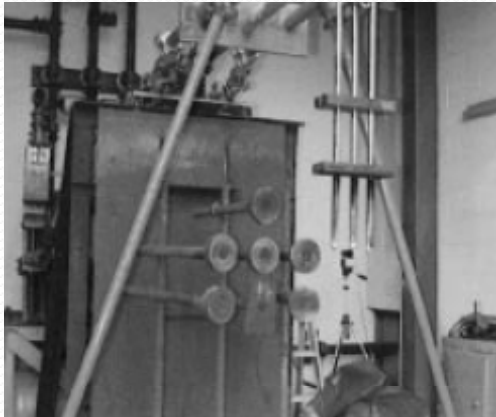
For $I_{SC} \times t > 5000 \text{ A}\cdot\text{s}$

$$D_C = [2.65 \times \text{MVA}_{bf} \times t]^{1/2} \quad (1)$$

$$D_C = [53 \times \text{MVA} \times t]^{1/2} \quad (2)$$

Where: MVA_{bf} = Maximum fault MVA
MVA = Transformer MVA
 t = Fault duration (seconds)

Reference: R. L. Doughty, T. E. Neal, and H. L. Floyd, "Predicting Incident Energy to Better Manage the Electric Arc Hazard on 600 V Power Distribution Systems," *IEEE Transactions on Industry Applications*, vol 36, No. 1, January/February 2000, pp 257-269.



Open Arc Test Setup

Test Setup

- ◆ Vertical Parallel Electrodes: 1.25" side by side spacing
- ◆ System Test Voltages: 600 V
- ◆ Bolted Fault Current: 16 – 50 kA
- ◆ Arcs Initiated using 10 AWG wire connected between the ends of the electrodes
- ◆ Incident Energy: 24 inches from source, measured using an array of seven copper calorimeters

Arc-in-the Box Test Setup



NFPA 70E

Incident Energy Calculations

$$E_{MA} = 5271 (D_A)^{-1.9593} (t_A) [0.0016 F^2 - 0.0076 F + 0.8938]$$

$$E_{MB} = 1038.7 (D_B)^{-1.4738} (t_B) [0.0093 F^2 - 0.3453 F + 5.9675]$$

Where,

E_{MA}	maximum <u>open air</u> incident energy (cal/cm ²)
E_{MB}	maximum <u>20 in. cubic box</u> incident energy (cal/cm ²)
D_A, D_B	distance from arc electrodes, in. (for distances 18 in. and greater)
t_A, t_B	arc duration, sec.
F	short-circuit current kA (for the range of <u>16 kA to 50 kA</u>)

(Used to predict incident energy on 3-phase systems rated 600 V and below.)

IEEE 1584-2002

IEEE Std 1584™-2002

IEEE Standards

1584™

**IEEE Guide for Performing
Arc-Flash Hazard Calculations**

IEEE Industry Applications Society

Sponsored by the
Petroleum and Chemical Industry Committee



Published by
The Institute of Electrical and Electronics Engineers, Inc.
3 Park Avenue, New York, NY 10016-5997, USA

23 September 2002

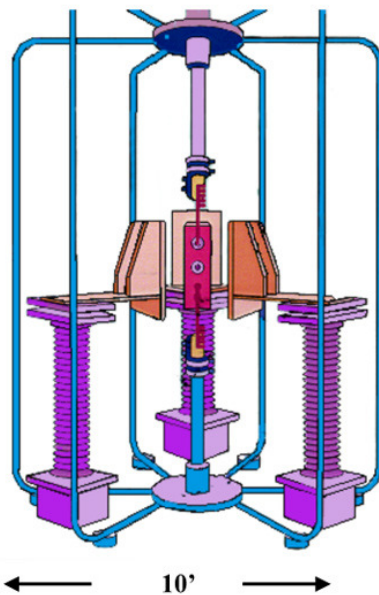
Print: SH95023
PDF: SS95023

Addresses Arc Flash Hazard Calculations

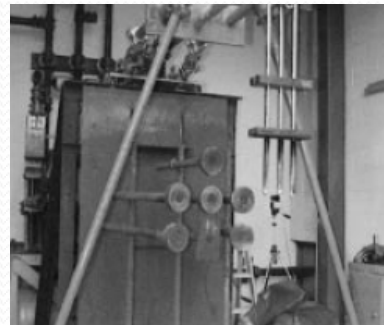
- **Arcing Fault**
- **Incident Energy**
- **Flash Boundary**

Overview of Arc Test Program

ASTM F1959



1Φ Arc in Air Test Setup



3Φ Arc in Air Test Setup



3Φ Arc-in-the Box Test Setup

Three Basic Test Setups

- Independent Test Data
- Wider Range of Variables Tested
- Incident Energy: measured using an array of seven copper calorimeters
- Phase Currents and Voltages measured digitally
- Arc Energy computed by integrating Arc Power over the Arc Duration

Arcing Current Calculations

System Voltage Under 1000V:

$$\lg(I_a) = K + 0.662 \lg(I_{bf}) + 0.0966 V + 0.000526 G + 0.5588 V \lg(I_{bf}) - 0.00304 G \lg(I_{bf})$$

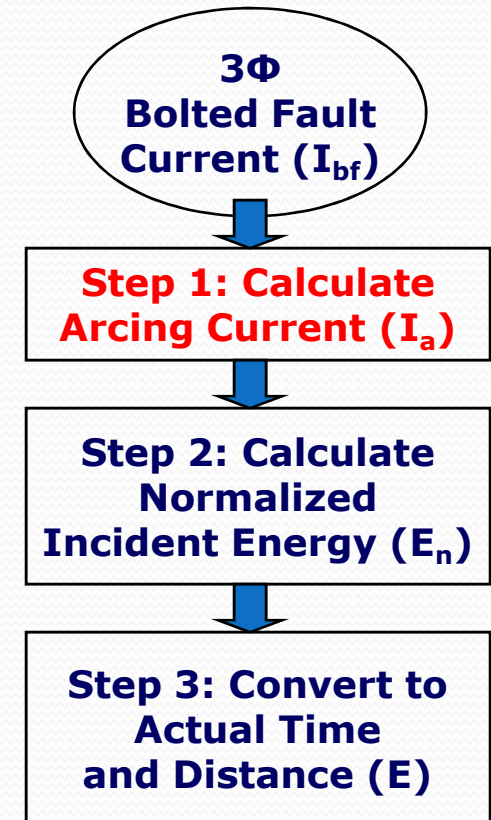
System Voltage Over 1000V:

$$\lg(I_a) = 0.00402 + 0.983 \lg(I_{bf})$$

$$I_a = 10^{\lg(I_a)}$$

Where,

I_a	arcing current (kA)
K	(- 0.153) for open configurations and (- 0.097) for box configurations
I_{bf}	bolted 3 ϕ fault current (symmetrical rms (kA))
V	system voltage (kV)
G	gap between conductors (mm) (Table I)
lg	log with a base 10



IEEE 1584

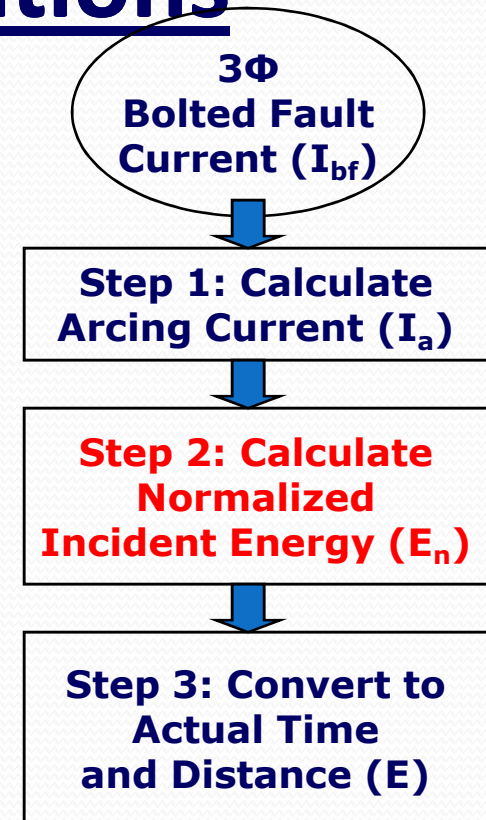
Incident Energy Calculations

$$\lg(E_n) = K_1 + K_2 + 1.081 \lg(I_a) + 0.0011 G$$

$$E_n = 10^{\lg(E_n)}$$

Where,

E_n normalized incident energy (J/cm²)
 K_1 (− 0.792) for open configurations and
 (− 0.555) for box configurations
 K_2 (0) for ungrounded
& high-resistance grounded systems
 (− 0.113) for grounded systems
 G gap between conductors (mm) (Table I)



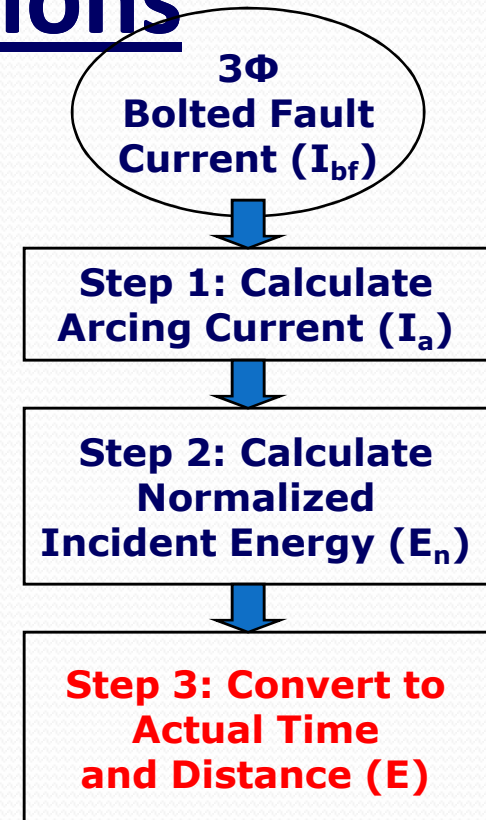
IEEE 1584

Incident Energy Calculations

$$E = C_f E_n (t/0.2) (610^x/D^x)$$

Where,

E	incident energy (cal/cm ²)
C _f	calculation factor 1.0 for voltages <u>above 1 kV</u> 1.5 for voltages <u>below 1 kV</u>
E _n	normalized incident energy
t	arcing time (sec)
D	distance from the possible arc point to the person (mm)
x	distance exponent (Table I)



Quick Comparison of Arc Flash Standards

	NFPA 70E - 2004	IEEE 1584 - 2002
Voltage Range	208 V – 600 V	208 – 15 kV
Current Range	16 kA – 50 kA	0.7 kA – 106 kA
Arc Duration	No Limit	No Limit
Installations	Open Air, Cubic Box	Open Air, Cubic Box, Cable Bus
Working Distance	18 inches +	18 inches +

Data Collection for Arc Flash

Required Parameter	NFPA 70E	IEEE 1584
System Nominal Voltage	X	X
Gap Between Conductors		X
Distance Factor		X
System Grounding		X
Open/Enclosed Equipment	X	X
Working Distance	X	X
Coordination Information	X	X

Incident Energy Calculations

For situations where the voltage is over 15 kV or the gap or bolted fault current is outside the range of IEEE 1584 model parameters, the Lee method can be applied. The method estimates incident energy semi-empirically based on a theoretical maximum value of power dissipated by arcing faults.

$$E = (0.512 \times 10^6) V I_{bf} (t/D^2)$$

where:

E = Incident energy (cal/cm²)

V = Voltage (line-to-line kV)

I_{bf} = Bolted fault current (kA)

t = Arc time (seconds)

D = Distance from arc to person (mm)

Simplified Incident Energy Calculation

$$I_a = 0.6 I_{bf}$$

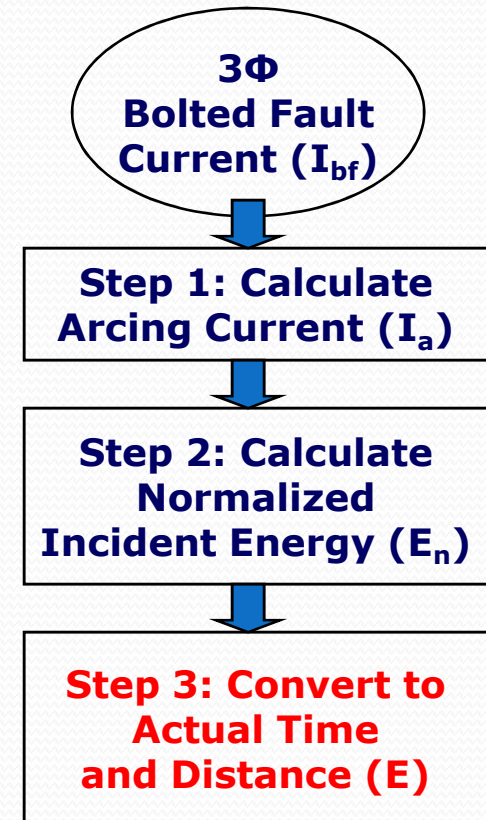
$$E_n = 0.43 I_a$$

$$E = 1.5 E_n (t/0.2) (610/457)^{1.641}$$

Combining Equations Gives:

$$E = 3.11 (I_{bf}) (t)$$

480V



Similar Equations Developed for Other Cases

System Voltages 600 V and Below

$$E = 4.14 (I_{bf}) (t)$$

System Voltage Over 1,000 V

$$E = 5.1 (I_{bf}) (t)$$

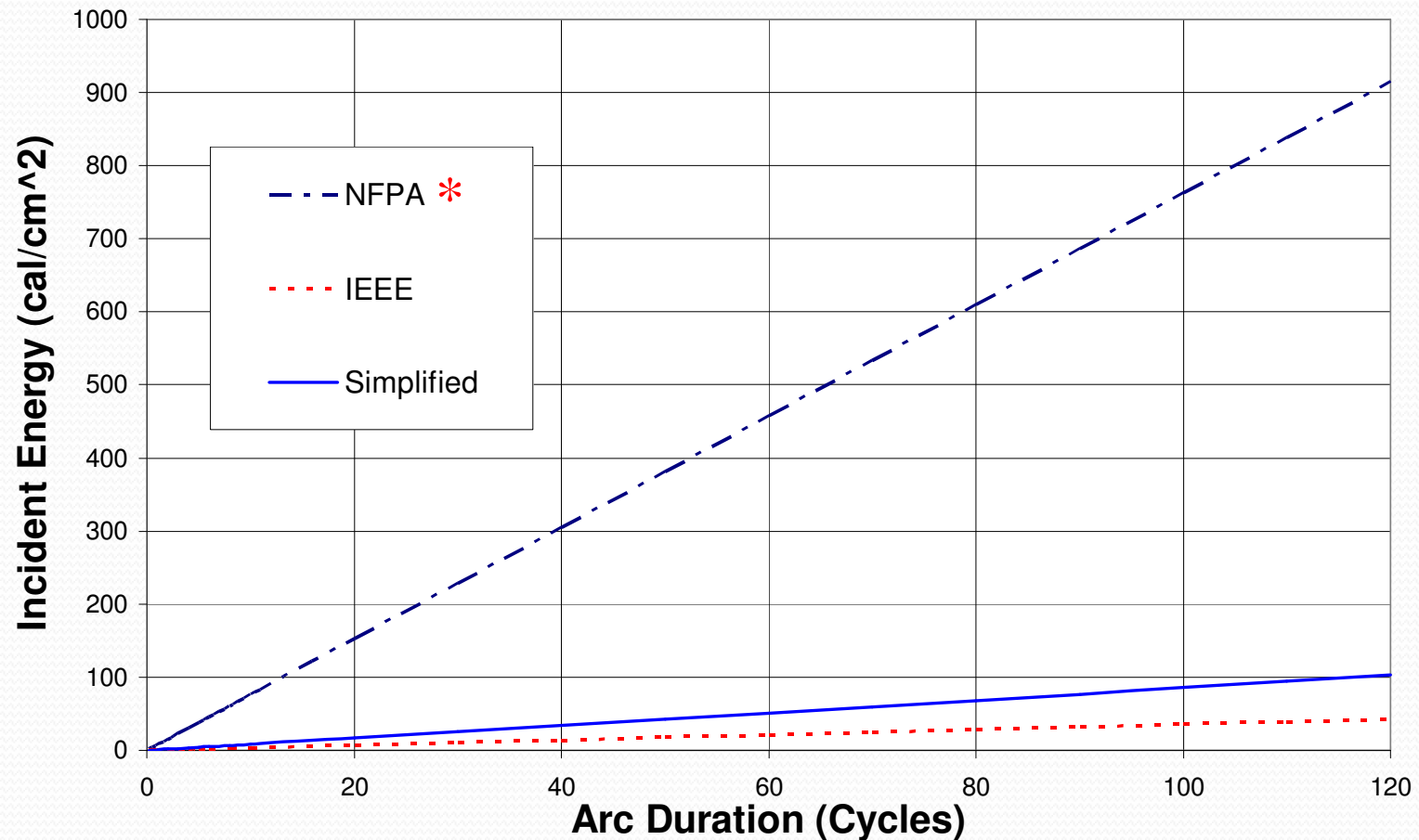
The Simplified Approach is as easy as ~~3-4-5~~

[3, 4, 5] x [kA] x [Time Duration]

**For 480V, 600V and Above 1,000V
at 18" Working Distance**

Results

Incident Energy vs. Arc Duration (12 kV Bus)



Lee Method is used to predict the open-air incident energy levels in cases where working voltages fall outside of the range of The NFPA 70E Standard.

*

Safety by Design Future Challenges

Electrical Safety Training

Qualifying Workers

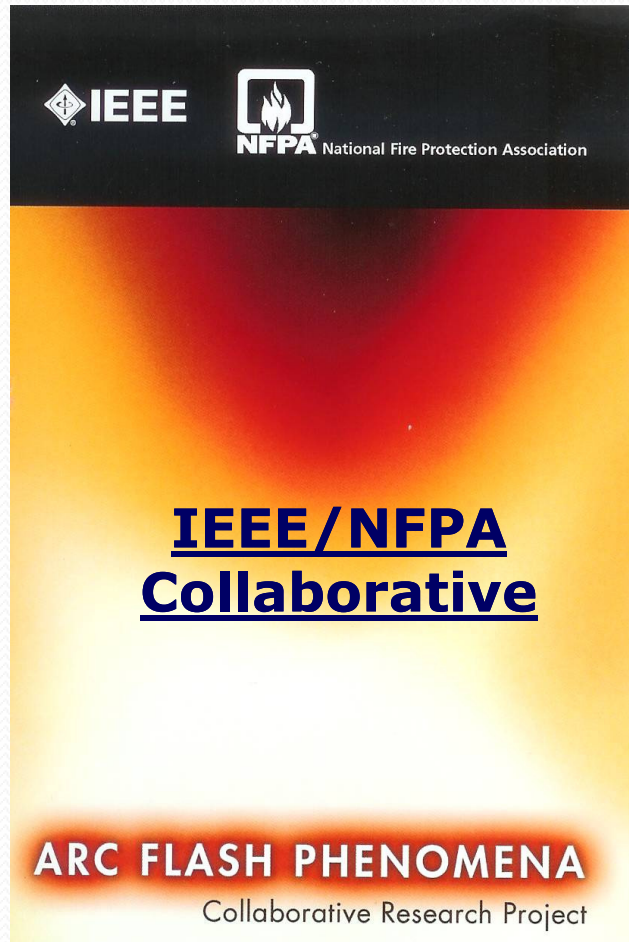
- ◆ **Assessing Effectiveness of Training Materials**
- ◆ **Establishing Competency in Hazard Awareness Evaluation**

Research and Testing

**"TWO" PRONG
ATTACK !!**

Research Projects

Industrial & Low
Voltage



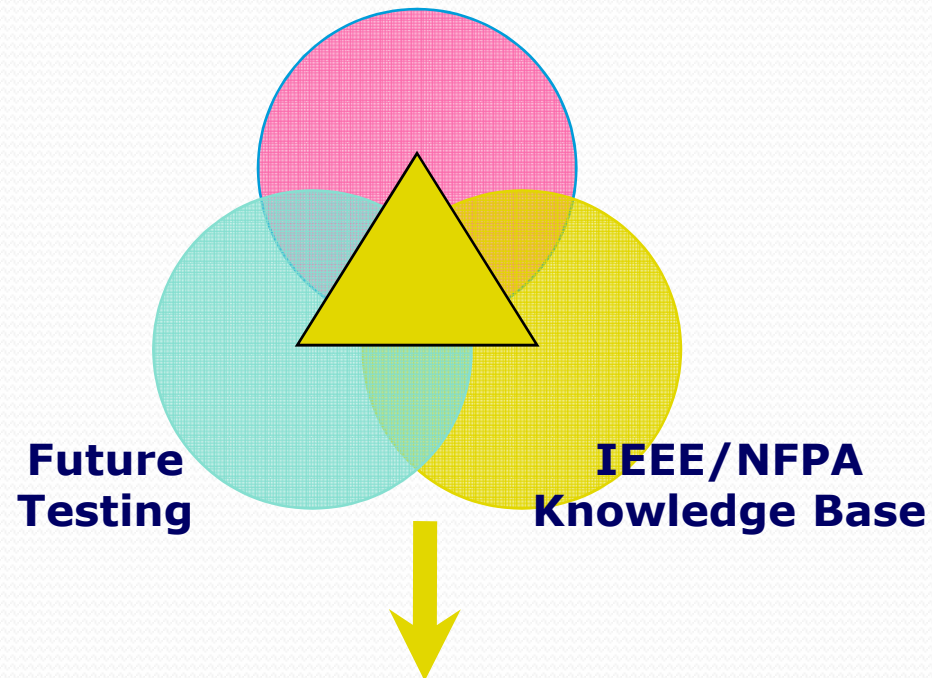
Utility & Medium
Voltage



EPRI Distribution
Arc Flash

Future Work

**Mitigating Arc
Flash Hazards**



**Improved Standards
Improved Safety Awareness**

Contact Information

Dr. P.K. Sen, PE

psen@mines.edu

Dr. Ravel F. Ammerman

rammerma@mines.edu



Thank You