Direct Current Electrical Hazards

from
A Complete Electrical Hazard Classification System and Its Application

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The need

- The shock effects of various forms of electricity have been studied for 120 years.
- More recent studies have focused on burn injury.
- Thresholds for electrical injury in the standards historically focused on 50/60 Hz shock for the protection of the public and the electrician/lineman.
- A more comprehensive electrical hazard classification system is needed to cover all electrical hazards found in research and industry.

Working towards a solution

- Over the past 10 years, the research community in the Department of Energy has been working towards a more comprehensive electrical hazard classification system, based on:
  - The known effects of electrical injury, and
  - Experience and accidents.

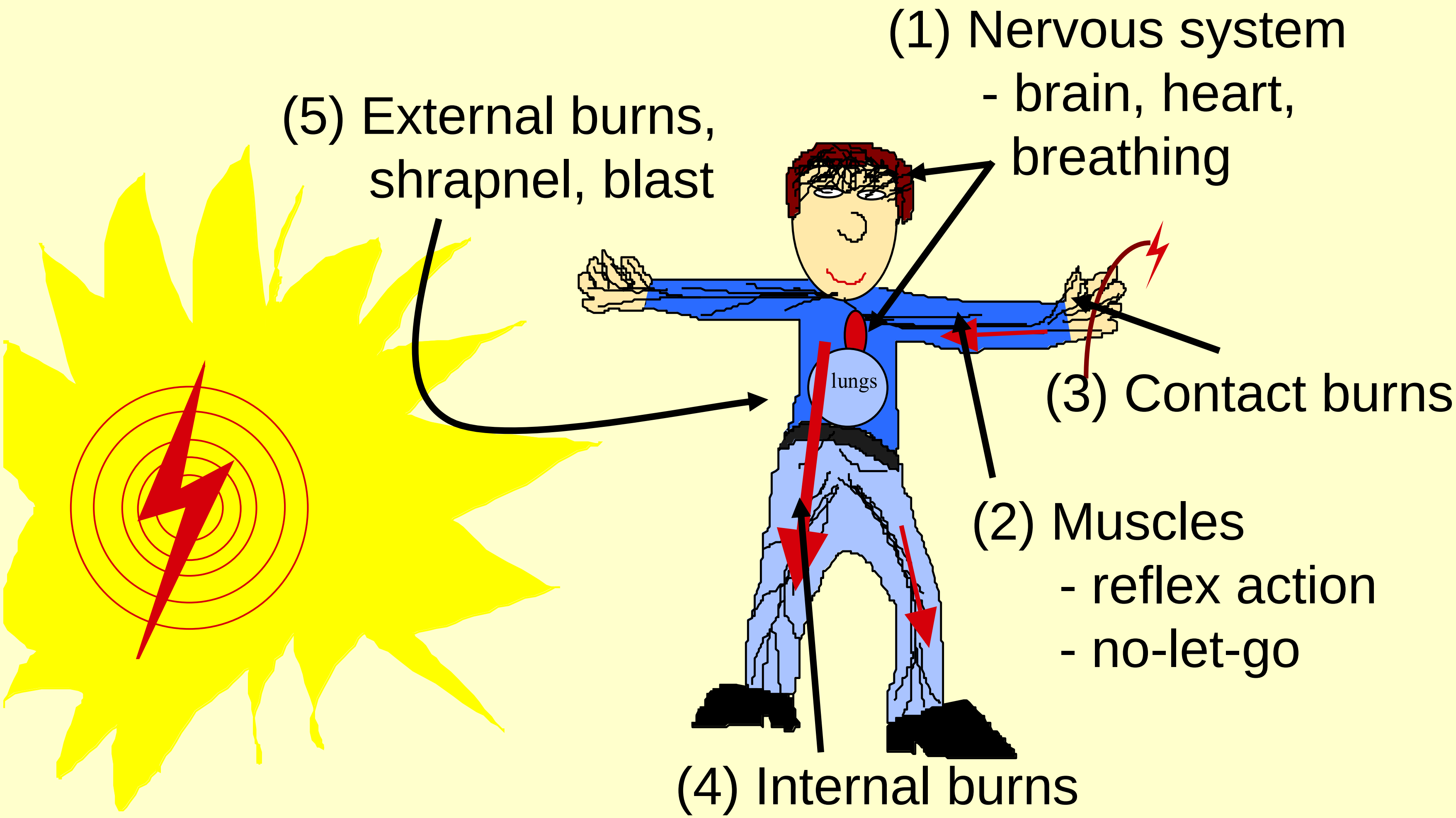
Outline

- Background
- A Complete System
- Application
- The Future

Background

- How can electricity hurt?
- What do the standards tell us?
- What is missing?

Classes of injury from electricity



Basic electrical waveforms

waveform - The shape of a parameter (such as voltage or current), when displayed as a function of time

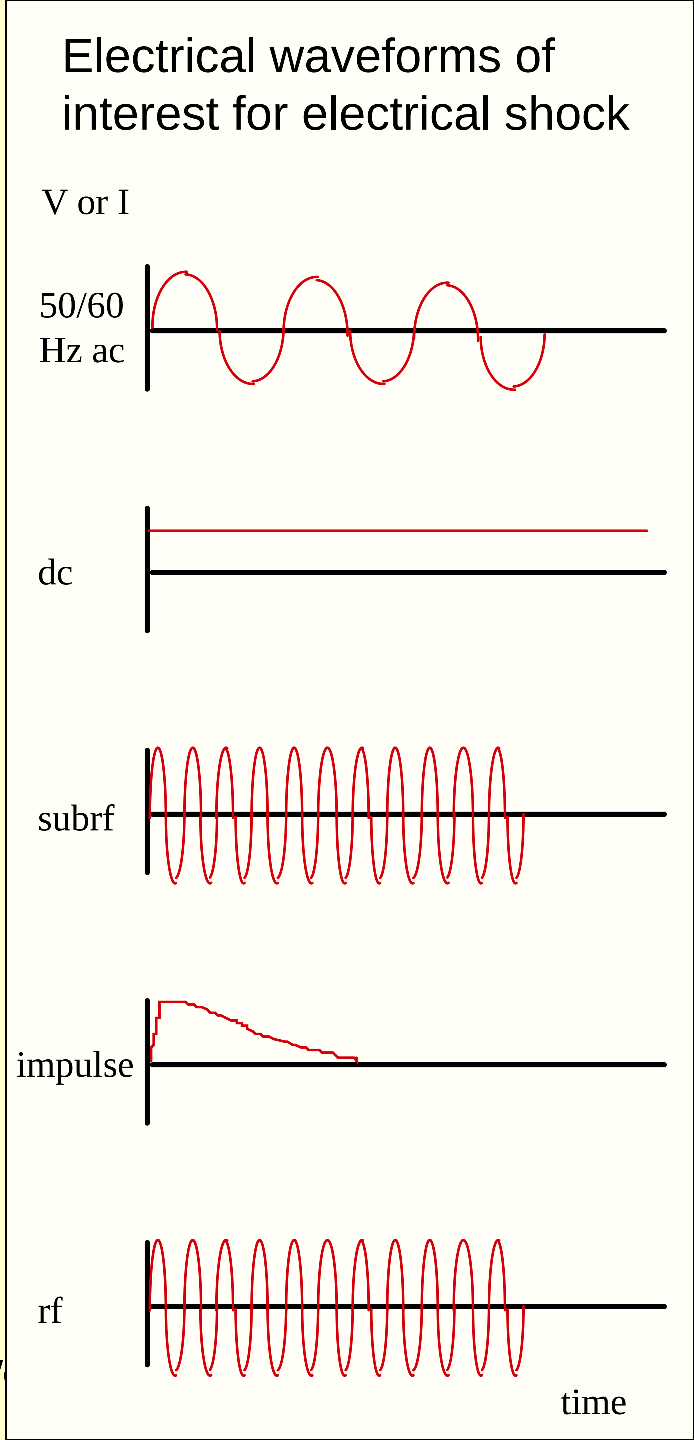
alternating current (ac) - A periodic current or voltage, the average value of which over a period is zero

direct current (dc) - Usually a constant, non-time varying current or voltage. It may be positive or negative.

Sub radiofrequency - Covers 1 Hz to 3 kHz, ac waveforms

impulse - A pulse that begins and ends within a short time period. Although the time duration may be short, in high power impulses the current, voltage, and power can be very large.

radiofrequency (rf) - A special term for high frequency (3 kHz to 300 GHz) ac signals.



Physiology of electrical injury severity of injury depends on:

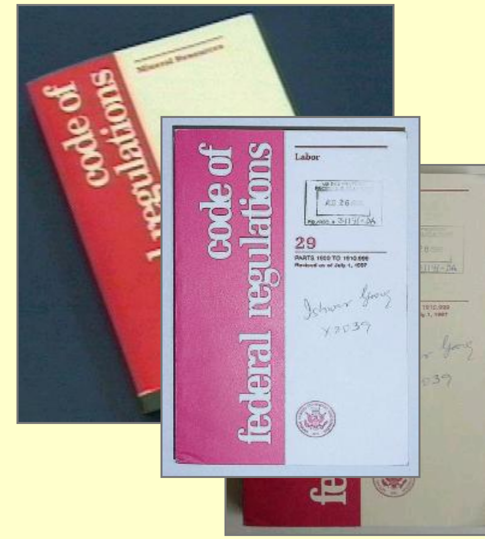
- **Voltage driving the current**
- **Current flowing through body**
- **Power through tools, conductors**
- **Energy dissipated**
- **Waveform of the current**
- **Duration of current flow through body**
- **Path of current through body**

Comparison of effects of waveforms

Form of electricity	threshold for fatality
60 Hz power	70 mA for 1 second - lethal
dc	300 mA for 1 second - lethal
Impulse shock	70 J delivered quickly
1 MHz rf	Amps for seconds, fatality from burn

National electrical standards

- OSHA - Code of Federal Regulations
- NEC (National Electrical Code) Standard for the safe installation of electrical wiring & equipment
- NFPA (National Fire Protection Association) 70E, Standard for Electrical Safety in the Workplace
- UL Standards



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Shock hazards covered by current standards

Hazard type	early research	standard
• 50/60 Hz ac	Dalziel, etc.	UL, NFPA
• DC	Dalziel	no
• Impulse	Geddes, etc.	no
• RF		IEEE C95
• Batteries		high current hazard not covered

Arc flash hazards covered by current standards

• 50/60 Hz ac utility/facility power	NESC, NFPA 70E, IEEE
• DC	no
• Capacitor	no
• Batteries	no

Note: research is currently underway for DC

The history of electrical hazard classification

thresholds	historical origin
50 V	ac fibrillation studies (1950s)
250 V	beginning of arc flash
600 V	classical division between LV/HV
0.25 J, 0.5 mA	reflex action studies, capacitors
5 mA	early ac shock studies, GFCI
10 J	DOE, chosen from early capacitor work
10 A	DOE, chosen for burn injury
500 V	skin breakdown threshold

Note: Thresholds are typically a function of several parameters
References Dalziel, Geddes, NFPA 70E, DOE, etc..

From the national codes

50 V rule was based on early ac fibrillation studies

250 V is a threshold for arc flash (with exceptions)

600 V is a classical division between LV and HV for the power distribution codes

5 mA rule was based on early ac fibrillation studies, GFCI is based on this

From early DOE documents

0.25 J, 0.5 mA lower end for reflex action for capacitors

10 J chosen to be an upper end for allowable capacitor shock

10 A chosen as a threshold for thermal burn

Limitation of current national codes for covering electrical hazards

- Focus on 50/60 Hz ac electric shock
- Does not account for High Voltage, Low Current
- Does not account for thermal burn hazard, Low Voltage, High Current
- RF shock standard often overlooked (ANSI/IEEE C95)
- Does not recognize all battery hazards
- Does not address impulse (capacitor) shocks
- Does not differentiate between ac and dc

Examples of electricity not covered by standards

- High voltage can be harmless
  - Electrostatic discharge (low energy)
  - Small photo detectors, mass spectrometers
- Low voltage can injure or kill
  - 18 V, 8000 A electroplating system
  - 5 V, 7000 A filament supply
- High impulse power and current can be harmless
  - 200 kW, 10 A carpet shock

Capacitor shocks

Below 100 V, capacitors are no more of a hazard than a battery. Skin resistance limits the current flow. The hazard for large capacitors below 100 V would be the same as a battery, a high current through jewelry or tools, possibly resulting in contact burns.

From 50 V to about 400 V a capacitor shock would have the same effect as a shock from any circuit (wall outlet or power supply). The skin resistance determines current, which can cause a reflex action or possibly cause fibrillation. However, the energy is limited and is important.

Above skin breakdown (>400 V) the energy in a high voltage capacitor is delivered very quickly (in ms) and the effects may be severe, depending on the energy stored. Moderate to severe reflex action occurs.

The effects of high voltage capacitor shocks

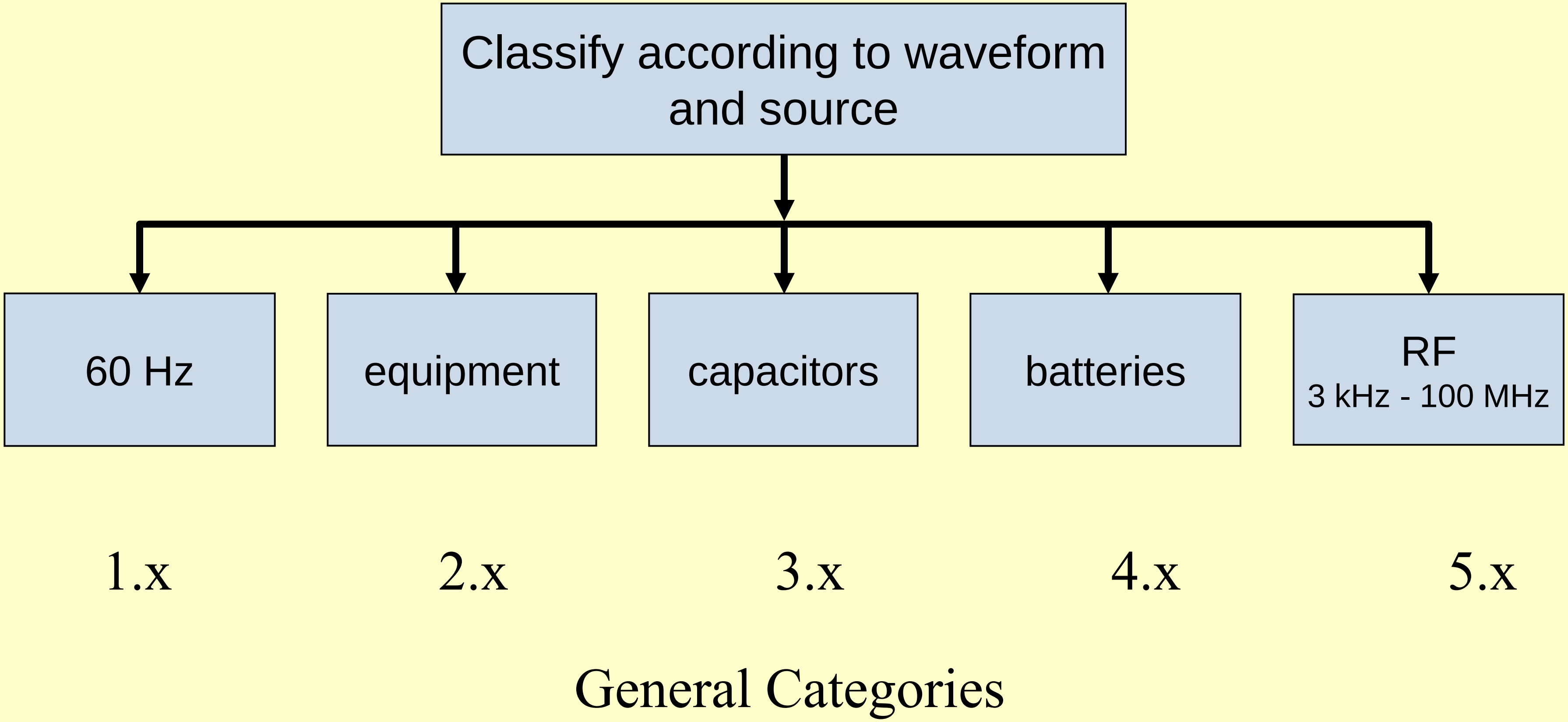
energy	example	result
0.01 J	carpet shock, photo detector	harmless
0.1 J	inside a small CRT (tv)	reflex action
1 J	a large color CRT (tv)	serious reflex action
10 J	in a microwave oven	hospitalization
100 J	a defibrillator	will stop/start the heart
1000 J	large laboratory laser	blows off chunks
10,000 J	capacitor bank	not survivable

Note: energy is delivered quickly (< 0.1 s)

A complete electrical hazard classification system

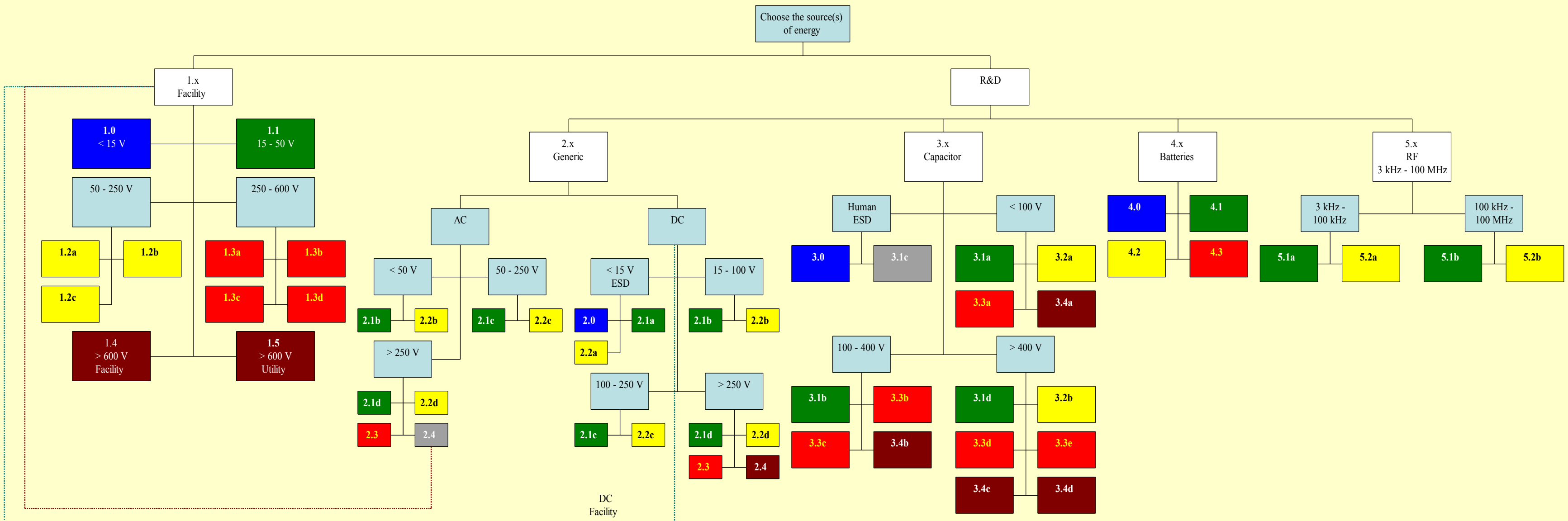
- Over the past 10 years, a more complete method to classify all electrical hazards has evolved to better manage electrical work in DOE R&D laboratories.
- These efforts can benefit industry as well as R&D laboratories
- This system is a graded approach that promotes more controls for higher hazards

Electrical Hazard Classification



Electrical hazard classification organizational table

1.x 2.x 3.x 4.x 5.x



60 Hz ac dc capacitors batteries RF

hazards - covers ALL electrical hazards

General features of new electrical hazard classification

x.0 = no hazard, no controls, no training (blue)

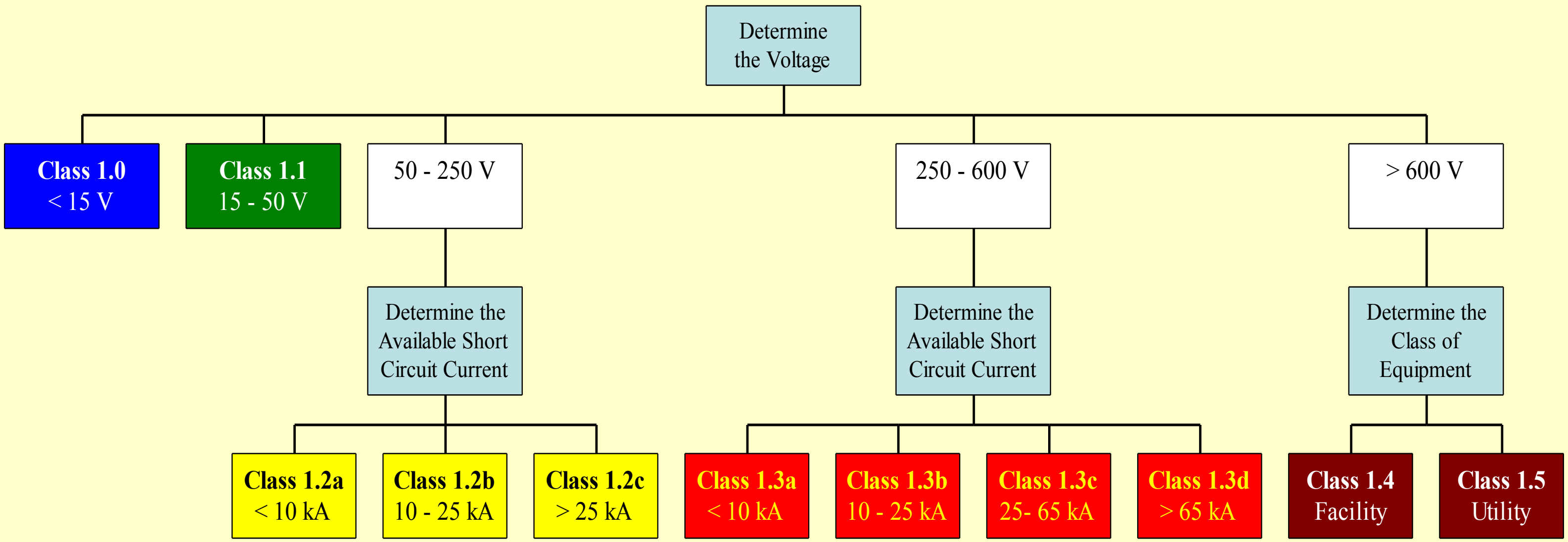
x.1 = minimum hazard, no injury, no controls, minimum training (green)

x.2 = can injure or kill, controls, some PPE (yellow)

x.3 = will injure or kill, controls, PPE (red)

x.4 = very serious, many controls, avoid work (maroon)

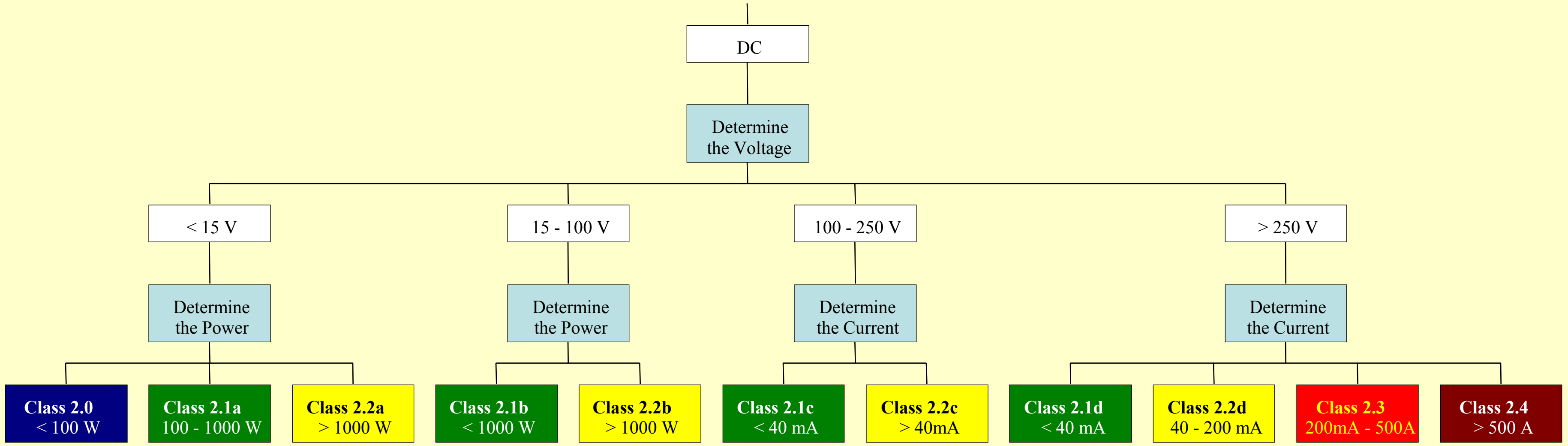
Hazard Classes 1.x: Facility



Note: for DC facility power refer to Classes 2.x: R&D DC

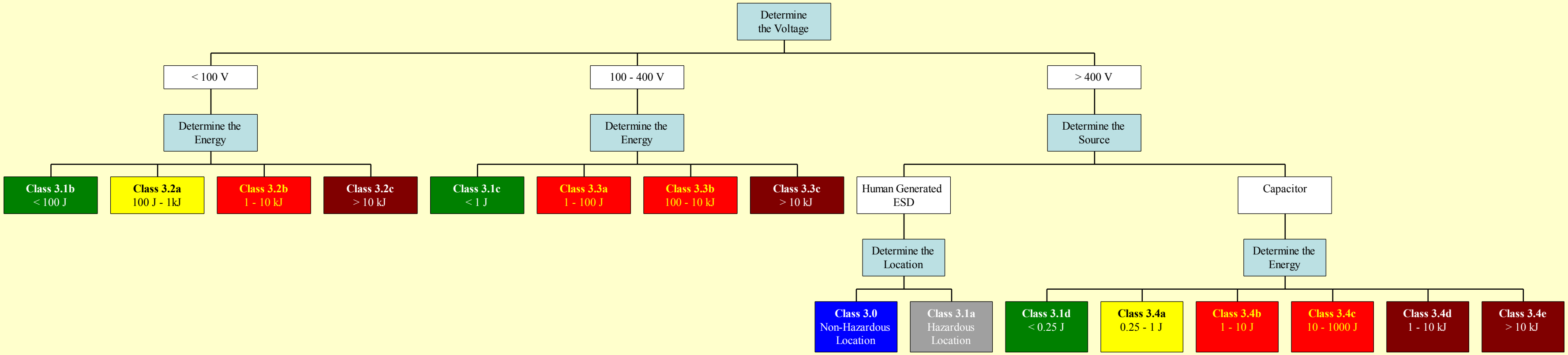
hazards - electrocution and arc flash

Hazard Classes 2.x: R&D - dc



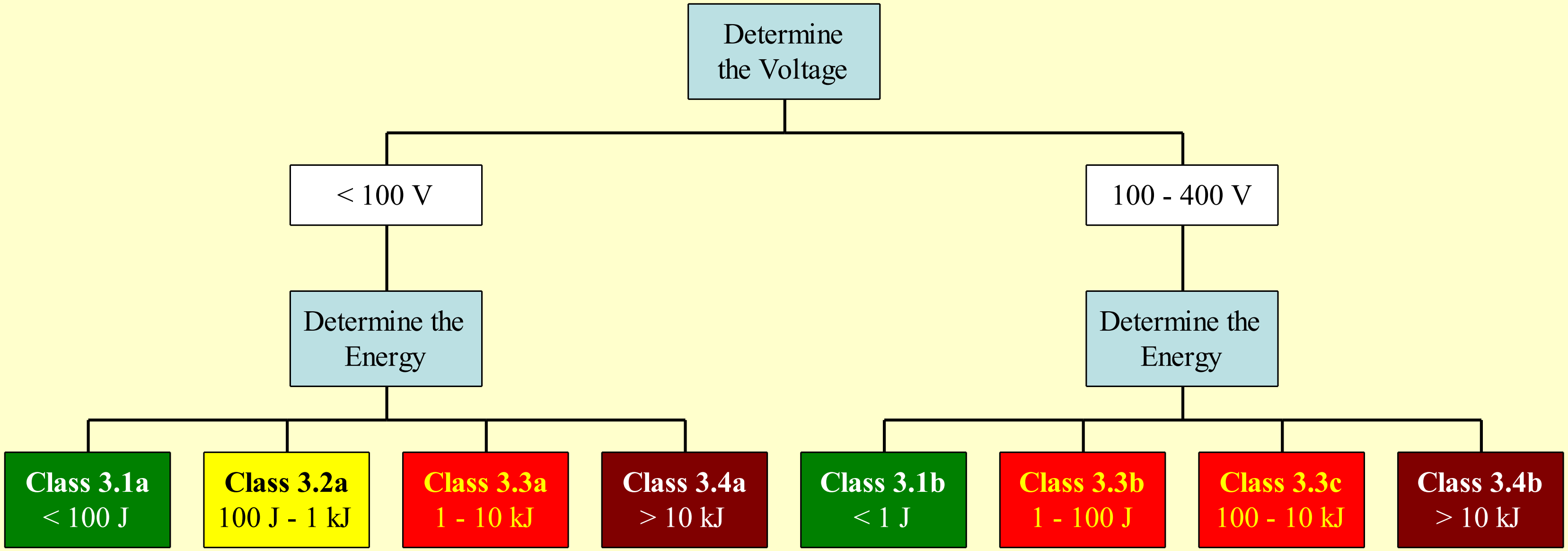
hazards - electrocution, high current, arc flash

Hazard Classes 3.x: Capacitors



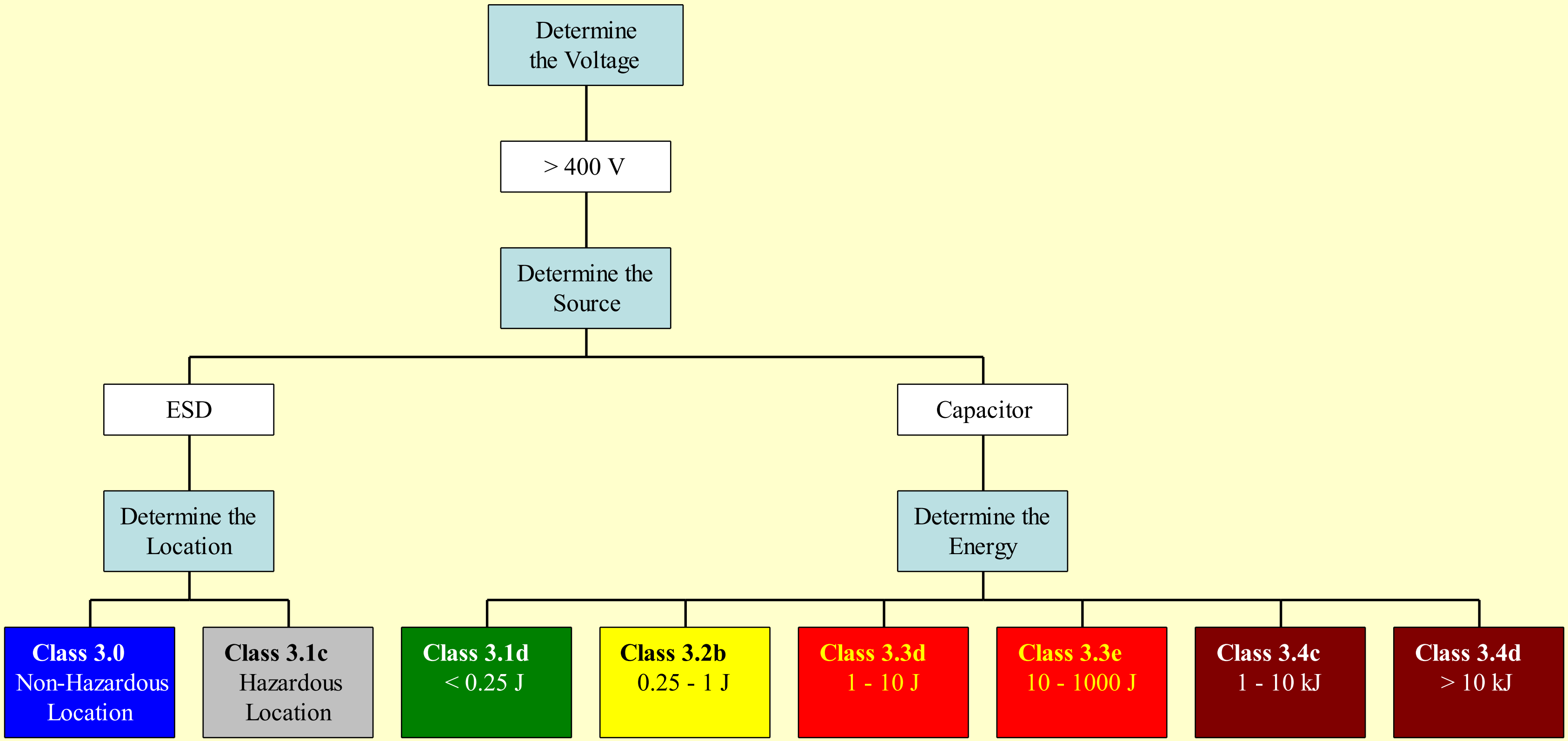
hazards - electrocution, high current, blast, magnetic force

Hazard Classes 3.x: Capacitors < 400 V



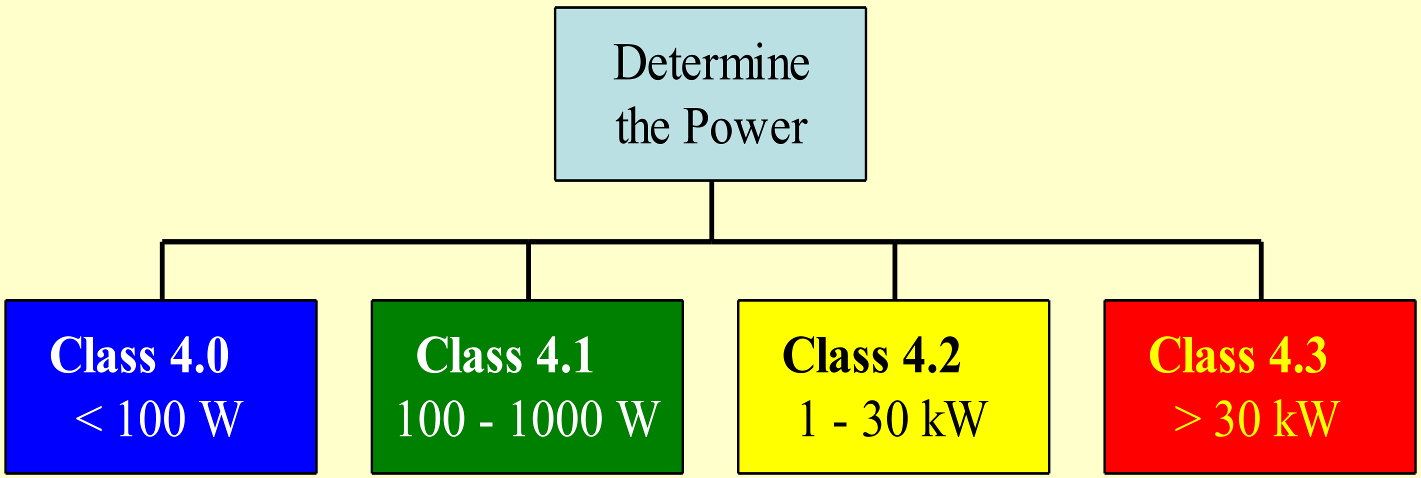
hazards - electrocution, high current

Hazard Classes 3.x: Capacitors > 400 V



hazards - electrocution, high current, blast, magnetic force

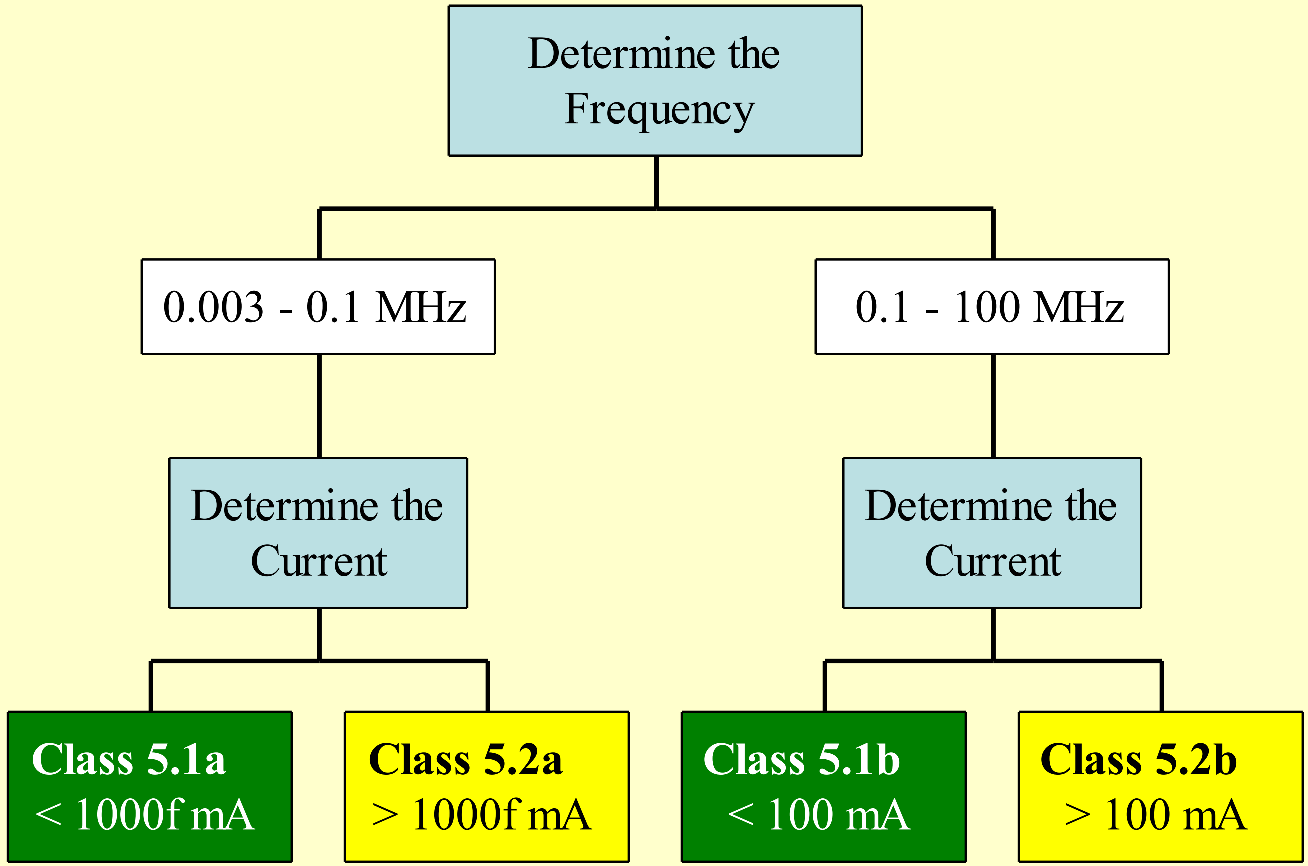
Hazard Classes 4.x: Batteries



Note: > 100 V also refer to Table 2.x: Generic to classify the shock hazard.

hazards - high current, chemical, hydrogen, arc flash

Hazard Classes 5.x: RF 3 kHz - 100 MHz



hazards - rf shock and burn, EM fields

f is frequency in MHz

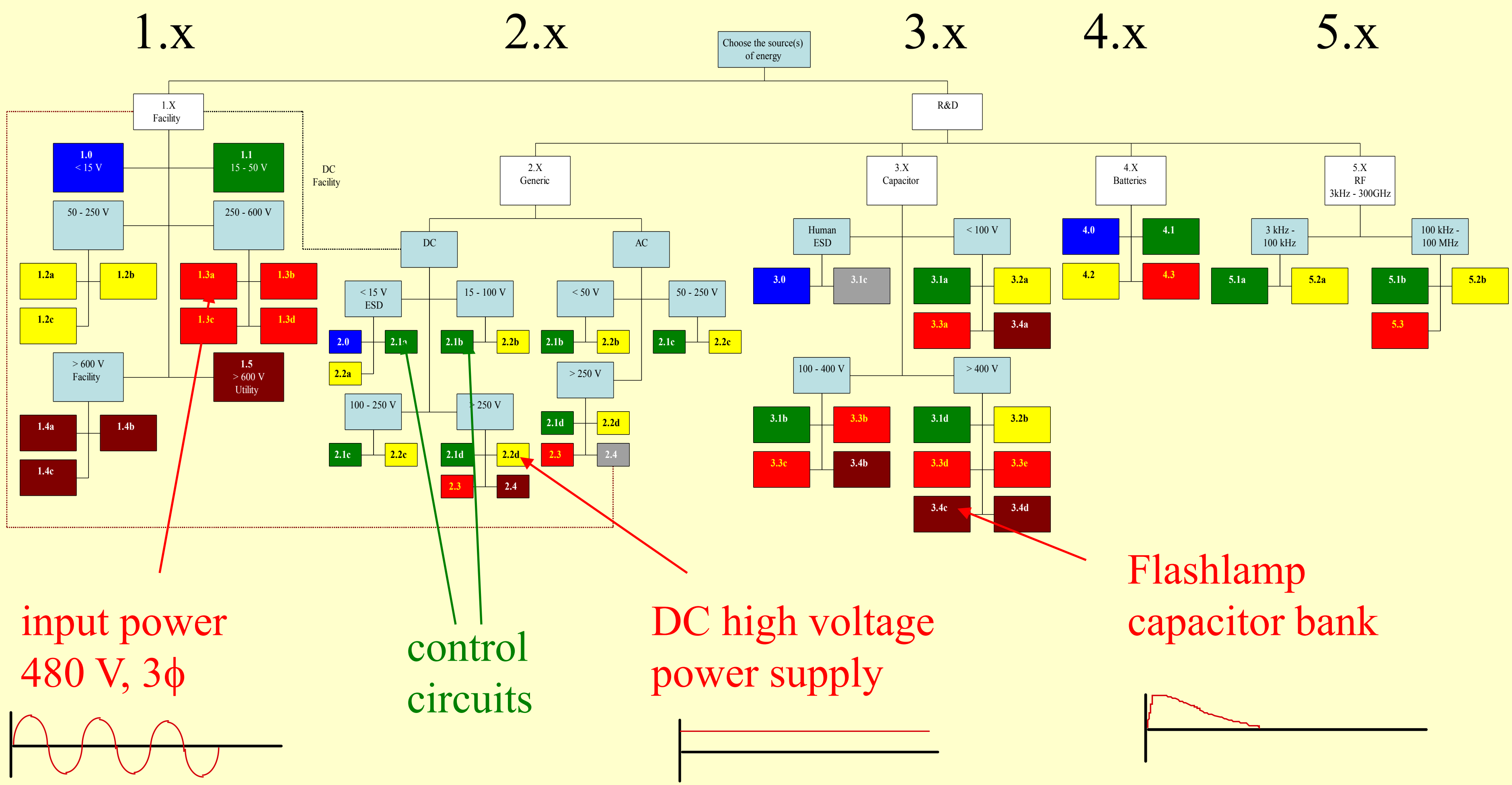
Applications in R&D and industry

- This comprehensive electrical hazard classification has been tried at several large DOE laboratories.
- This approach is valuable in recognizing all electrical hazards and developing the correct controls (both are OSHA and 70E requirements)

General controls for electrical hazard classes

	NRTL or AHJ equipment approval	work control for work on	training for work on
X.0 (blue)	no	no	no
X.1 (green)	no	maybe	minimal or none
X.2 (yellow)	yes	yes	yes
X.3 (red)	yes	yes	yes
X.4 (maroon)	yes	yes	yes

Hazard classification of a large laboratory laser



The Future

- Currently, guidance for comprehensive electrical hazard classification is found only in safety documents at DOE labs.
- For the future, we need to look towards national consensus standards.
- Examples:
  - Shock approach boundaries for DC
  - Arc flash calculations and boundaries for DC, capacitors, batteries

Shock approach boundaries for 60 Hz from NFPA 70E

Table 130.2(C) Approach Boundaries to Live Parts for Shock Protection. (All dimensions are distance from live part to employee.)

(1)	(2)	(3)	(4)	(5)
	Limited Approach Boundary[1]		Restricted Approach Boundary[1]; Includes Inadvertent Movement Adder	
Nominal System Voltage Range, Phase to Phase	Exposed Movable Conductor	Exposed Fixed Circuit Part		Prohibited Approach Boundary[1]
Less than 50	Not specified	Not specified	Not specified	Not specified
50 to 300	3.05 m (10 ft 0 in.)	1.07 m (3 ft 6 in.)	Avoid contact	Avoid contact
301 to 750	3.05 m (10 ft 0 in.)	1.07 m (3 ft 6 in.)	304.8 mm (1 ft 0 in.)	25.4 mm (0 ft 1 in.)
751 to 15 kV	3.05 m (10 ft 0 in.)	1.53 m (5 ft 0 in.)	660.4 mm (2 ft 2 in.)	177.8 mm (0 ft 7 in.)
15.1 kV to 36 kV	3.05 m (10 ft 0 in.)	1.83 m (6 ft 0 in.)	787.4 mm (2 ft 7 in.)	254 mm (0 ft 10 in.)
36.1 kV to 46 kV	3.05 m (10 ft 0 in.)	2.44 m (8 ft 0 in.)	838.2 mm (2 ft 9 in.)	431.8 mm (1 ft 5 in.)
46.1 kV to 72.5 kV	3.05 m (10 ft 0 in.)	2.44 m (8 ft 0 in.)	965.2 mm (3 ft 2 in.)	635 mm (2 ft 1 in.)
72.6 kV to 121 kV	3.25 m (10 ft 8 in.)	2.44 m (8 ft 0 in.)	991 mm (3 ft 3 in.)	812.8 mm (2 ft 8 in.)
138 kV to 145 kV	3.36 m (11 ft 0 in.)	3.05 m (10 ft 0 in.)	1.093 m (3 ft 7 in.)	939.8 mm (3 ft 1 in.)
161 kV to 169 kV	3.56 m (11 ft 8 in.)	3.56 m (11 ft 8 in.)	1.22 m (4 ft 0 in.)	1.07 m (3 ft 6 in.)
230 kV to 242 kV	3.97 m (13 ft 0 in.)	3.97 m (13 ft 0 in.)	1.6 m (5 ft 3 in.)	1.45 m (4 ft 9 in.)
345 kV to 362 kV	4.68 m (15 ft 4 in.)	4.68 m (15 ft 4 in.)	2.59 m (8 ft 6 in.)	2.44 m (8 ft 0 in.)
500 kV to 550 kV	5.8 m (19 ft 0 in.)	5.8 m (19 ft 0 in.)	3.43 m (11 ft 3 in.)	3.28 m (10 ft 9 in.)
765 kV to 800 kV	7.24 m (23 ft 9 in.)	7.24 m (23 ft 9 in.)	4.55 m (14 ft 11 in.)	4.4 m (14 ft 5 in.)

Note: For Flash Protection Boundary, see 130.3(A).
[1]See definition in Article 100 and text in 130.2(D)(2) and Annex C for elaboration.

70 E Shock Boundaries were Developed for 60 Hz Power

- Voltage is phase to phase
- Voltage is rms
- Moveable conductors refers to transmission line conductors
- Gaps in voltages were driven by common transmission line ranges
- Was based on all early work by Dalziel for 60 Hz shock ONLY

70E Shock Boundaries were never written for DC

- The research clearly shows that the fatal shock thresholds for dc are 4 times greater than ac (the k factor)
- Research clearly shows that there is NOT a no-let-go threshold for dc
- Thresholds were proposed by Dalziel and others, were never used in U.S. codes, but are in the International Standards

The 50 V rule

- For decades, many safety professionals and auditors have claimed that the 50 V rule applies to dc, per OSHA and 70E.
- There is absolutely no basis for this assumption.
- It occurred because of the glaring gap in U.S. standards, they do NOT address dc.
- ALL of the research for 120 years clearly indicates that dc has much HIGHER thresholds for injury than ac.
- The International standards (IEC) are far ahead of the U.S. standards in this area.

IEC Technical Standards

- Far ahead of U.S. standards for waveforms other than power frequencies.
- Clearly give thresholds based on 100 years of research for dc and impulse shocks.

Recent dc shock examples

- LANL - October 2008
  - 120 V dc, bare hands, standing in water
  - Barely perceptible
  - Predicted shock current
    - I = V/R = 120/500 = 24 mA
  - No injury, multiple shocks
- LANL - March 2009
  - 3570 V dc, punctured skin
  - Entrance wounds
    - Holes in two fingers on left hand
    - Two 2nd degree burns on stomach
  - Predicted shock current
    - I = V/R = 3500/150 = 20 A, source was limited to 1 A
  - Stunned, not a let-go threshold, no permanent injury

Current Use of DC in the laboratory

- We extensively use listed dc power supplies with exposed terminals up to 80 V dc, e.g., Kepco, etc.
- There are no known shocks or injuries from dc below 100 V.

Proposed shock boundaries for DC, based on NFPA 70E

(1)	(2)	(3)	(4)	(5)
Nominal DC Voltage Conductor to Ground	Limited Approach Boundary		Restricted Approach Boundary, Includes Inadvertent Movement Adder	Prohibited Approach Boundary
	Exposed Movable Conductor	Exposed Fixed Circuit Part		
< 100	Not specified	Not specified	Not specified	Not specified
100 Š 300	3.05 m (10Õ0Ó)	1.07 m (3Õ6Ó)	Avoid contact	Avoid contact
301 Š 750	3.05 m (10Õ0Ó)	1.07 m (3Õ6Ó)	304 mm (1Õ0Ó)	25 mm (0Õ1Ó)
751 Š 15 kV	3.05 m (10Õ0Ó)	1.53 m (5Õ0Ó)	660 mm (2Õ2Ó)	178 mm (0Õ7Ó)
15 kV Š 45 kV	3.05 m (10Õ0Ó)	2.5 m (8Õ0Ó)	0.8 m (2Õ9Ó)	0.44 m (1Õ5Ó)
45 kV Š 75 kV	3.05 m (10Õ0Ó)	2.5 m (8Õ0Ó)	1 m (3Õ2Ó)	0.65 m (2Õ1Ó)
75 kV Š 150 kV	3.4 m (10Õ8Ó)	3 m (10Õ0Ó)	1.2 m (4Õ0Ó)	1 m (3Õ2ÓÓ)
150 kV Š 250 kV	4 m (11Õ8Ó)	4 m (11Õ8Ó)	1.6 m (5Õ3Ó)	1.5 m (5Õ0Ó)
250 kV Š 500 kV	6 m (20Õ0Ó)	6 m (20Õ0Ó)	3.5 m (11Õ6Ó)	3.3 m (10Õ10Ó)
500 kV Š 800 kV	8 m (26Õ0Ó)	8 m (26Õ0Ó)	5 m (16Õ5Ó)	5 m (16Õ5Ó)

Suggestions for DC Boundary Table

- Break up 751 - 15,000 V to
  - 751 - 3,000 V
  - 3000 - 15,000 V
- Get input from R&D workers for best voltage divisions
- Consider eliminating the "moveable" conductor column

To succeed in a DC NFPA 70E proposal

- Must argue the 100 V threshold from extensive research literature, and IEC standards.
- Review accident and injury statistics.
- Show that the conversion from rms, phase to phase, to dc to ground is valid.

Examples of calculated energies and arc flash boundaries for various capacitors

Type	Voltage	Energy	Arc Flash Boundary
Cathode Ray Tube	40,000 V	0.1 J	0.1 mm
High Pot Tester	60,000 V	0.1 J	0.1 mm
Microwave Oven	4,000 V	10 J	0.7 cm
High Power Laser	10,000 V	1000 J	7 cm
X-ray Source	100,000 V	10 J	0.7 cm
Energy storage Cap	60,000 V	200 kJ	1 m
Capacitor Bank	60,000 V	1 MJ	2 m

Notes: The arc flash boundary for the ac input power must be calculated separately, most of these are well within the Prohibited Approach Boundary

Summary

- National Codes and Standards adequately cover the electrical hazards of 60 Hz power
- There is a need for better definition and control of DC, RF, and impulse electrical hazards
- A comprehensive electrical hazard classification system has been evolving at DOE laboratories

Conclusions

- The principles of protection of the worker against 60 Hz shock and arc flash hazards can be applied to other forms of electricity.
- Future code development will clarify the hazards and controls for:
  - DC
  - Capacitors
  - Batteries
  - RF systems

We welcome your thoughts and suggestions

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