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A COMPLETE ELECTRICAL HAZARD CLASSIFICATION SYSTEM AND ITS APPLICATION

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Abstract - The Standard for Electrical Safety in the Workplace, NFPA 70E, and relevant OSHA electrical safety standards evolved to address the hazards of 60-Hz power that are faced primarily by electricians, linemen, and others performing facility and utility work. This leaves a substantial gap in the management of electrical hazards in Research and Development (R&D) and specialized high voltage and high power equipment. Examples include lasers, accelerators, capacitor banks, electroplating systems, induction and dielectric heating systems, etc. Although all such systems are fed by 50/60 Hz alternating current (ac) power, we find substantial use of direct current (dc) electrical energy, and the use of capacitors, inductors, batteries, and radiofrequency (RF) power. The electrical hazards of these forms of electricity and their systems are different than for 50/60 Hz power.

Over the past 10 years there has been an effort to develop a method of classifying all of the electrical hazards found in all types of R&D and utilization equipment. Examples of the variation of these hazards from NFPA 70E include (a) high voltage can be harmless, if the available current is sufficiently low, (b) low voltage can be harmful if the available current/power is high, (c) high voltage capacitor hazards are unique and include severe reflex action, affects on the heart, and tissue damage, and (d) arc flash hazard analysis for dc and capacitor systems are not provided in existing standards.

This work has led to a comprehensive electrical hazard classification system that is based on various research conducted over the past 100 years, on analysis of such systems in R&D, and on decades of experience.

Initially, national electrical safety codes required the qualified worker only to know the source voltage to determine the shock hazard. Later, as arc flash hazards were understood, the fault current and clearing time were needed. These items are still insufficient to fully characterize all types of electrical hazards. The new comprehensive electrical hazard classification system uses a combination of voltage, shock current available, fault current available, power, energy, and waveform to classify all forms of electrical hazards.

Based on this electrical hazard classification system, many new tools have been developed, including (a) work controls for these hazards, (b) better selection of PPE for R&D work, (c) improved training, and (d) a new Severity Ranking Tool that is used to rank electrical accidents and incidents with various forms of electrical energy.

Index Terms — Electrical safety, electrical injury, electrical hazard classification, electrical safety standards

I. INTRODUCTION

Over the past century, since the beginning of the implementation of electricity into modern technology, the effects of electricity on the human body have been under study. Early studies focused on injury due to electric shock, later adding the injury due to arc flash. The initial primary focus in the early part of the 20th century was on protection of the public in the use of electricity. The results of the studies of electrical injury led to design standards in the United States (US) to protect the users of electrical equipment. Standards such as the National Electrical Code (NEC) [1] and those developed by Underwriters Laboratory (UL) strove to prevent fire and to protect the user against exposure to electric shock. Well known examples of design requirements to protect the user include the equipment grounding conductor (1960s) and the Ground Fault Circuit Interrupter (GFCI, 1970s). Both the NEC and UL were first created in the late 1800s, and were the key sources for electrical safety design standards in the United States.

The first focus on protection of the electrical worker was the development of safe work practices for transmission line workers, found in the National Electrical Safety Code (NESC) [2], first initiated in 1913 at the National Bureau of Standards. In the 1970s electrical safe work practices was broadened to cover facility type work, with the Occupational Safety and Health Act (OSHA) of 1970 and the creation of National Fire Protection Association (NFPA) Standard 70E (1979). The focus by NFPA 70E, Standard for Electrical Safety in the Workplace, was on the electrician or other facility electrical worker, dealing with 60 Hz, ac power.

The US national codes for electrical safe work practices evolved primarily for work on 60-Hz power transmission, distribution, and utilization equipment. They did not adequately address the unique electrical hazards found in R&D laboratories, and in some industries, including dc, RF, and capacitor hazards.

Dalziel, electrical engineering professor at the University of California in Berkeley, recognized in 1951 the need for electrical safety in experimental laboratories and included in his concern industrial, research, and instructional laboratories [3]. He mentioned that all laboratories need to comply with the "electrical safety code of the state", but went further to say that it was difficult, if not impossible to apply existing electrical safety codes to laboratories because of the unique electrical hazards. His suggestion was to "classify hazards and to study ways and means of reducing them." This was very progressive for his time, but was never acted upon by such research institutions in any major way.

In 1960 Dalziel took a sabbatical leave-of-absence and spent a year in nine countries of central and western Europe, followed by a month's service as a safety consultant at Los Alamos Scientific Laboratory, New Mexico (the institution of the authors of this paper), studying problems of electric shock and electrical safety [4]. Dalziel "deplored" the lack of electrical safety in both laboratories and schools of electrical engineering. This was nearly 50 years ago!

The first author of this paper wrote a more recent review of electrical hazards in the high-energy laboratory in 1991, based on his experience with electrical hazards while performing experimental research in Department of Energy (DOE) and University high-energy laboratories [5].

The DOE complex began to address some of the unique electrical hazards found in R&D laboratories with the release of the 1998 DOE Electrical Safety Handbook [6], a guidance document. These innovative methods of addressing high voltage/low current, low voltage/high current, and capacitor hazards were gradually implemented in the electrical safety programs at various DOE laboratories.

Since this release in 1998 much was learned on remaining weaknesses in electrical hazard classification for various forms of electricity. Over the subsequent 10 years, substantial effort was put forth in the DOE community to further develop a complete electrical hazard classification system that covers all injury mechanisms of all types of electrical hazards.

Although all electrical hazards are included in this comprehensive hazard classification system, the focus on background and explanation will be on the electrical shock hazard for all waveforms. Classification of arc flash hazards for dc, capacitors and batteries is based on the principles used in NFPA 70E and is not discussed in depth. Current research nationwide will add to the knowledge on dc arc flash in the coming years.

II. ELECTRICAL INJURY STUDIES

In order to provide a basis for electrical injury thresholds for all forms of electrical energy it is important to briefly review 110 years of study of electrical injury.

A. *Categories of Electrical Injury*

The types of injuries from electricity can be broadly divided into 5 major categories:

(1) immediate effects on the nervous system from shock currents, including life threatening effects on the heart, breathing, and brain

(2) stimulus of the muscles from current flowing through the body, including reflex action and being "frozen" to the circuit

(3) burns to the body from hot conductors caused by high currents flowing through metal conductors, does not necessarily involve a shock

(4) internal tissue damage from shock currents flowing through the body. Can range from mild cellular damage to major damage to organs and limbs

(5) external burns and other physical injury due to an arc, creating an arc flash (thermal energy) and/or an arc blast (including acoustic and kinetic energy), does not necessarily involve a shock

Early studies (beginning in 1899) focused on the injuries due to electrical shock, including categories 1, 2, and 4 above, since this was the most common cause of electrical injury and fatality. Study of the non shock burns, including categories 3 and 5 did not begin in earnest until much later (1970s) although the hazard had been recognized earlier by some.

An important point in discussing electrical injury is the assumption that shock initiates outside the body, i.e., from contact by skin. This paper and the thresholds discussed are NOT meant to cover electrical injury and thresholds from internally delivered electric shocks, such as can occur under medical procedures, and from internally placed electrical devices. For instance, the threshold of ventricular fibrillation from an externally delivered capacitor shock is on the order of 50 J. But internal defibrillators with electrodes placed in direct contact with cardiac tissue typically deliver 2 J to defibrillate. The purpose of the development of this comprehensive electrical hazard classification system is for worker protection when working on or near exposed electrical energy.

B. *Electrical Waveforms of Interest*

The type, or waveform, of electrical shocks can be divided into 5 major groups:

(1) power frequencies, including 50 and 60 Hz

(2) direct current, or dc, can have an ac component (ripple)

(3) sub radiofrequency, 1 Hz to 3 kHz

(4) radiofrequency, 3 kHz to 100 MHz

(5) impulse shock, such as a high voltage capacitor

Although the majority of historical studies of the effects of electric shock have been on 50 and 60 Hz power frequencies, there are adequate studies on all waveforms to propose thresholds for safety.

C. *Electrical Shock Injury Studies and Results*

Although early studies on the effects of electrical shock and heart fibrillation began in the late 1800s, the research that led to our modern understanding of electrical shock and fibrillation took off in the 1930s and 1940s with the pioneers of Ferris [7], Dalziel [8-11], and in the 1950s, Kowenhoven [12]. Through extensive tests of perception and let-go thresholds for ac and dc on 100s of volunteers, and through extensive fibrillation studies on animals of different sizes and weights for fibrillation thresholds, an understanding of the effects of ac and dc currents on the human was established. Dalziel and others determined that susceptibility to heart fibrillation was due to current and duration. The longer the duration of the shock, the lower the current threshold. For a 3 second shock he determined that the threshold for ac fibrillation for 99.5 % of the population was 100 mA, and for dc about 450 mA. He proposed a 4.8 to 1 ratio for dc fibrillation levels as compared to 60 Hz ac. These early studies lead to the standards for leakage current on appliances [11]. This early work, plus others [13, 14] lead to the establishment of the 5 mA threshold for ac safety.

Good summaries on the early work on lethal electric shock were published by Lee [15] and Dalziel [16]. After 30 years of research an equation describing the ac threshold of fibrillation as a function of shock duration was finalized. Fibrillation shock threshold in rms mA = 120 divided by the square root of T, where T is duration in seconds.

Numerous studies by Dalziel and others contributed to the understanding of the effects of frequency and wave shape on the thresholds of fibrillation [10, 11, 16 – 20].

Numerous studies contributed to the understanding of the thresholds for dc shock [7-11, 17, 21, 22]. Thresholds were set at 4 to 5 mA for perception, and 300 to 500 mA for fibrillation. Numerous researchers stated that there was no let-go threshold for dc [7, 8].

Early researchers studied the effects of impulse shock on fibrillation [9, 23, 24]. This early work concluded that energy delivered by a capacitor shock was the relevant parameter, and that for most shocks it took over 100 J to cause ventricular fibrillation. However, if the impulse should occur during the vulnerable part of the cardiac cycle (the T wave) then lower energies could cause fibrillation. Conclusions led to a threshold of 25 to 50 J as the lowest probable threshold for any time of delivery.

Then, from the 1960s through the 1990s, extensive work for the development of external and internal capacitive discharge defibrillators resulted in substantial knowledge on the effects and injury due to capacitor shocks in the 10 to 500 J range [25-29]. One study found that there was no tissue injury to dogs for any capacitive discharge under 70 J [25]. Another study determined that capacitive discharges in the range of 24 to 250 J, properly delivered (with wide area electrodes), did not cause internal damage, discharges in the range of 250 J to 8 kJ resulted in internal organ and tissue damage, and discharges in the 2.4 kJ to 40 kJ range resulted in death due to internal damage [27]. This was normalized to a 150 lb person.

For the reader's interest, modern external defibrillators deliver 100 to 300 J from a capacitive shock with a shock voltage of 500 to 2000 V, and a shock current of 10 to 75 A, depending on design and settings. Internally implanted defibrillators, on the other hand, with electrodes against the heart, defibrillate with a 2 J, 180 V, 4 A capacitive pulse [29]. What a difference between externally delivered and internally delivered shocks.

One recent interesting study analyzed the reflex response threshold of electrostatic discharge shocks [30]. This study, plus others referenced above led to a threshold of 0.25 J as the beginning of a nuisance reflex action. Experience by many in R&D led to the conclusion that a high voltage capacitor shock above 1 J is not desirable. By 10 J the reflex action is so severe that the person will be injured from muscle contractions (refer to the 10 J accident described below).

D. *Electrical Burn Injury Studies and Results*

Extensive studies over the past 20 years have led to much improved understanding of external and internal burn injury from electric shock and arc flash [31-37]. This has led to the current advances in arc flash protection, which has been incorporated into NFPA 70E over the past 10 years.

E. *Summary of Studies*

The research from the 1930s to today have led to understanding of the effects of dc, 60 Hz ac, various frequencies, and impulse shocks. These thresholds will be used to explain the basis for existing thresholds found in current standards, and for the basis of those presented for dc and impulse shocks.

F. *Examples of Injury and Fatality Beyond 60 Hz*

There are extensive studies discussing the electrocutions in the home and to the electrical worker due to various voltages of 60 Hz power. Electrocutions due to dc and capacitor shock are rare. To provide some validation of the dc and capacitor thresholds presented below, some accidents examples will be briefly discussed.

It is difficult to find any examples of electrocutions from low voltage (less than 50 V rms) 60 Hz ac. There are known electrocutions while in a swimming pool due to contact of exposed conductors with the water. The swimmer is electrocuted from voltage gradients in the water, and is most likely electrocuted by only a few volts of potential difference across the body. In most cases electrocution was due to code violations and a failed insulation in a pool light or water pump, and lack of a GFCI led to the electrocution. The authors could find no examples of electrocutions in the work place from less than 50 V rms ac.

Roberts published an intriguing analysis of the potential for electrocution below 50 V [38]. In his analysis he showed that under the worst scenario of extreme wet conditions, large area contact, and worst-case path through the body that electrocution could occur at levels below 50 V ac or dc. However, there seem to be no fatality statistics to validate his analysis. In one study by a forensic pathologist 7 electrocutions at low voltage dc were described [39]. The workers were electrocuted form 30 to 45 V dc. However, all were welders in China working alone and in very hot and humid, closed environments. Five of the seven were at shipyards, inside of metallic, tight spaces. The authors of this study recognized that the workers were likely extremely sweaty, dehydrated, and possibly suffering from heat exhaustion. In all cases they died after prolonged exposure (many minutes to hours) to direct contact to the welding electrodes. There is no known case of a similar welding electrocution in the US. In the US, welding activities in shipyards and mines are covered by strict requirements for ventilation, temperature and humidity compensation and control, and PPE, as contained in OSHA 29 CFR 1915, Occupational Safety and Health Standards for Shipyard Employment, and 30 CFR, Mine Safety and Health, respectively. In is likely that the extreme, unsafe work conditions implied in the study were created by a lack of work control and safety standards and do not justify lowering shock thresholds in the US.

Dalziel conducted a fascinating review of capacitor shocks in 1953 [23]. Unfortunately, the authors do not know of any similar study done since then. However, Dalziel's study is very helpful for capacitor safety. Dalziel contacted persons in charge of high-voltage laboratories in Japan, countries of western Europe, and the US. He describes 14 serious high voltage accidents in R&D laboratories, resulting in only 1 fatality. However, description of the immediate injury sounds severe. All were high voltage (2 to 960 kV). He calculated capacitive energies deposited during the shock ranging from 9 to 25,000 J. The shocks included the following energies in J: 9, 15, 21, 24, 140, 264, 385, 400, 402, 429, 520, 720, 5,000, and 25,000. Interestingly the fatality occurred from the 24-J shock at about 1 kV. Apparently, it is possible to survive a high-energy capacitor shock. Long-term injury is unknown, however.

The first author has been in the field of Pulsed Power engineering for 34 years, and is aware of the serious high-voltage capacitor accidents in the US over the past 30 years. The author is aware of 3 fatalities at high-energy research laboratories during this period. Interestingly one was at a University graduate laboratory, one at a government research laboratory, and one at an industrial development laboratory. All involved capacitor shocks in the kJ range. The fatality at the University was to a graduate student, working alone on a research experiment using capacitor banks to heat confined plasmas. The other two were on high power R&D laser systems.

In addition to these three fatalities, the author is aware of about 6 other capacitor accidents resulting in serious injury. One was to a graduate student at a University on a high power laser, resulting in permanent neurological damage. A second was at a military research laboratory on a very large capacitor bank. The worker lost two fingers. A third was at the authors' institution in 1996. A graduate student contacted the 4-kV, 10-J capacitor in a standard household microwave oven while performing measurement tests. His heart did not go into fibrillation, but he was unconscious for several hours. He received first and minor second degree burns on his fingers, hands, upper back, and upper arm, where the current entered his body, and flashed across his back. The reflex action caused dislocation of both shoulders. One shoulder was so severely dislocated that he had to undergo surgery to repair it.

III. CURRENT ELECTRICAL SAFETY STANDARDS

In order to provide the basis for an expanded electrical hazard classification system, it is important to review what already exists in electrical safety standards.

A. *Standards Covering Shock Hazards*

The primary US codes and standards that set thresholds to protect workers against electric shock are OSHA, NFPA 70E, NESC, and UL.

1) *Occupational Safety and Health Standards*

In the Code of Federal Regulations (CFR) OSHA Part 1910, Occupational Safety and Health Standards is found the rules for electrical safe work practices under Subpart S, 1910.331 – 333. From 1910.332, Training, 1910.332(b)(3)(ii), "Qualified persons shall, at a minimum, be trained in and familiar with.........The skills and techniques necessary to determine the nominal voltage of exposed live parts.....". The only threshold for shock safety that OSHA provides is 50 V rms, and so the training requirements include the ability to determine the voltage. These OSHA standards were written with 60 Hz ac in mind, and not capacitors, batteries, RF, or even dc. But, OSHA does state that this is a minimum requirement. Clearly, to use a comprehensive electrical classification a qualified worker must be able to determine all of the information to properly assess the electrical hazard.

In OSHA 1910.333, Selection and use of work practices, is the only shock threshold, 1910.333(a)(1), "Live parts that operate at less than 50 volts to ground need not be deenergized if there will be no increased exposure to electrical burns or to explosion due to electric arcs." This section opens the door for consideration of the thermal burn, or arcing effects, but does not give any thresholds. From 1910.399, Definitions applicable to this subpart, the definition for *Voltage (of a circuit)*, "The greatest root-mean-square (rms) (effective) difference of potential between any two conductors of the circuit concerned. Also, the definition for *Voltage, nominal*, "A nominal value assigned to a circuit or system for the purpose of conveniently designating its voltage class (as 120/240 volts, 480/277 volts, 600 volts". It seems as if the 50 V rule was written with 60 Hz, ac in mind. The 50 V rule could not be applied universally to all waveforms as other codes and standards would disagree. For example, IEEE/ANSI C95.1, for RF shock states that a safe voltage for MHz frequencies is considered to be 120 V rms.

The "50 V" rule is also found in OSHA 1910.269, Electric Power Generation, Transmission, and Distribution, Appendix B – Working on Exposed Energized Parts.

2) *NFPA 70E, Standard for Electrical Safety in the Workplace [40]*

In Chapter 1, Safety-Related Work Practices, of NFPA 70E, the 50 V rule is used 25 times. Some examples include training requirements for persons permitted to work within the Limited Approach Boundary "....operating at 50 volts or more....", 110.6(D)(1)(b); hazard identification ".....identify a hazard/risk evaluation procedure.....operating at 50 volts or more......", 110.7(F); and, achieving an electrically safe work condition, ".......operating at 50 volts or more lockout/tagout devices shall be applied.........", 110.8(B). An important section is in Article 130, Work Involving Electrical Hazards, 130.1, Justification for Work, part (3) Less than 50 Volts, "Energized electrical conductors and circuit parts that operate at less than 50 volts to ground shall not be required to be deenergized...........", but proceeds to allow the possibility of exposure to burns or explosion for under 50 V. Again, NFPA 70E has opened the door to managing low voltage thermal burn hazards.

Table 130.2 (C) Approach Boundaries....... for Shock Protection, lists the Approach Boundaries for Nominal System Voltage Ranges, in phase to phase rms as "Not specified".

Voltage definitions in NFPA 70E are identical to those in OSHA 1910.399 above, and were clearly written for 60 Hz ac systems.

3) *National Electrical Safety Code [2]*

Section 44, Additional Rules for Supply Employees, Section 441 A 2, Precautions for Approach-Voltages from 51 V to 300 V, "Employees shall not contact exposed energized parts operating at 51 V to 300 V........."

4) *Underwriters Laboratories Inc.*

Many of the UL standards deal with protection of the public under all conditions of knowledge and use, such as non qualified persons, wet environments, no work control, etc. To the authors' knowledge there are no UL standards that address shock thresholds for safe work practices. However, several do address protection against shock for design requirements. An example is UL 1244 – Electronic Test Equipment, which lists the voltage which must be made inaccessible through design.

These voltages are anything above 30 V rms and 60 V dc. Similar voltages can be found in UL 696 – Electric Toys, and others.

The design standard for GFCIs (UL 943) states that the device will interrupt a ground fault greater than 6 mA, but not less than 4 mA. The average of 5 mA is often used to describe the threshold of a GFCI.

5) International Electrotechnical Commission

An important resource for the development of design and safe work practice standards are the Technical Specifications (TS) TS 60479 (5 total) published by the International Electrotechnical Commission (IEC). These 5 specifications, under the numbers TS 60479-x, are based on the extensive research conducted over the past century on the effects of electric shock on humans and animals. Here we will briefly summarize elements of two of these specifications, TS 60479-1, 4th edition, 2005, "Effects of current on human beings and livestock – Part 1: General Aspects" [41]; and TS 60479-2, 3rd edition, 2007, "Effects of current on human beings and livestock – Part 2: Special aspects" [42]. Part 1, General Aspects, presents the electrical impedance of the human body, the effects of sinusoidal alternating current in the range of 15 Hz to 100 Hz, and the effects of direct current. Some of the topics presented in Part 2 include the effects of alternating current with frequencies above 100 Hz, effects of special waveforms of current, effects of electric current through the immersed human body, and effects of unidirectional single impulse currents of short duration. These two technical specifications are excellent summaries of the body of knowledge for the effects of dc, 15 Hz to 100 Hz ac, 100 Hz and above ac, and impulse shocks.

Three important points are made in the introduction of these Technical Specifications. First, these specifications are not meant to set electrical safety requirements, but are technical specifications providing basic guidance on the effects of shock current on humans, for the USE in the establishment of electrical safety requirements.

Second, based on the evidence available, the values are so conservative that the specification applies to persons of normal physiological conditions including children, regardless of age and weight.

Third, despite being conservative there are other conditions such as work conditions, probability of faults, probability of contact with live parts, technical feasibilities, and economics that have to be considered carefully when establishing safety requirements. What this means is that there are unusual or extreme circumstances that could result in injury or fatality despite any developed standard. Examples would be a worker immersed in water, working with open wounds, working in extreme temperature or humidity conditions, or with a serious heart condition. In such cases the 50 V rule would not be sufficient to prevent fibrillation, or a 30 V rule, or a 20 V rule!

It is important when establishing safety standards to consider not only possible injury based on theoretical, predicted, or extrapolated limits, but also on accident and injury statistics. For instance, the 50 V ac rule benefited from statistics gathered from decades of review of 1000s of electrocutions. If the only known electrocutions at lower voltages were persons immersed in water, or workers in extreme and unacceptable working conditions, it might not be justifiable to lower current ac thresholds. If there is no known case of a worker being "frozen" to, or electrocuted by a dc circuit under 100 V dc or 40 mA dc shock current, then there is not sufficient justification to arbitrarily set dc thresholds to be the same as 50/60 Hz ac.

There is not sufficient space here to discuss these IEC Technical Specifications in detail, but some important points, useful for this discussion are provided.

The thresholds for ac (15 to 100 Hz) perception, reaction, let-go, and fibrillation are quite conservative, in general lower than those established by Dalziel. The threshold for perception and reaction generally begin about 0.5 mA. The threshold for no-let for 0.05 % of the population (that is 99.95 % can let go at this number) range from 5 mA for children to 9 mA for men. Thus, it would seem that the 5 mA rule discussed below is an appropriate threshold for 60 Hz ac. Indeed, this TS states that "a value of 5 mA covers the entire population." The threshold for the beginning of the possibility for fibrillation ranges from about 40 mA for a 5 s shock to 500 mA for a 100 ms shock. This accounts for the worst-case path through the body, left hand through both feet.

The IEC TS states for dc, "Unlike ac there is no definable threshold of immobilization or let-go for dc. Only making and breaking of current lead to painful and cramp-like contractions of the muscles". The threshold for perception and reaction for dc is stated to be about 2 mA. There is not a let-go threshold for dc. The fibrillation threshold, for worst-case path through the body ranges from 150 mA for a 5 s shock to 500 mA for a 100 ms shock. This value for very brief shocks is actually the same as for ac, since the heart can not tell the difference between ac and dc for very short times. Vulnerability occurs when the brief shock occurs during the T wave portion of the cardiac cycle.

For impulse shocks, TS 60479-2 gives examples of a 0.5 J shock as "painful", and a 50 J shock as "potentially lethal".

6) Summary of Shock Standards

In summary, US national codes and standards use 50 V rms ac as the threshold for safe work practices, and 5 mA as the threshold for design limiting shock currents to a user. The IEC TS 60479-1 supports the 5 mA threshold. To limit shock currents at 50 V to the lowest IEC threshold of 40 mA would require a minimum total body resistance of 1250 ohms. From this TS, the average total body impedance for a large area contact for dry, wet, and salt-water wet conditions is 2500 ohms, 2000 ohms, and 1300 ohms, respectively. Thus, the IEC TS supports the 50 V rule, but just marginally for the large area, salt water contact for the threshold of fibrillation. TS 60479-2 discusses the body impedance for immersion in water, and it is true that the 50 V rule would be inadequate. The TS states that a mere few volts could cause fibrillation in a full body immersion case. Thus, safe work practices should limit electrical work in extreme environments, and not lower thresholds to try and allow or anticipate such extreme and unacceptable work conditions.

Also, consider the UL 30 V rule for the design of instruments, toys, and other devices that the public uses. The 30 V rule for exposure to the public is meant to prevent discomfort, injury and possible electrocution in all conditions to the unqualified public. The 50 V rule in OSHA and NFPA 70E is meant for qualified worker protection, in a controlled work environment.

B. *Standards Covering Arc Flash Hazards*

To adequately discuss the history, development of standards, and needs for additional thresholds for arc flash hazards would require another paper of this length, and must be left for future discussion. Basically, the development of safe work practices for managing the arc flash hazards for 60 Hz ac systems has matured over the past 10 years. The standards are primarily found in NFPA 70E [40] and in IEEE 1584 [43]. They focus on managing the arc flash hazards for 60 Hz ac systems. Areas of future growth include accounting for and managing other injury mechanisms found in the arc blast, and in developing methods for arc flash analysis of dc, capacitor and battery systems. Research is currently underway nationwide which will add to our body of knowledge in the area. The few arc flash thresholds used in this comprehensive electrical hazard classification system for dc, capacitors and batteries are based on the concepts of available arc energy from NFPA 70E and IEEE 1584.

C. *DOE Electrical Safety Handbook* [6]

The DOE Electrical Safety Handbook was developed in the 1990s to provide guidance for consistent electrical safety across the DOE complex. In the version published in 1998, two new chapters were added with a focus on the unique electrical hazards and requirements in the R&D laboratory. In the 1998 edition three new concepts were introduced to better manage unique electrical hazards in laboratories.

1) *The "5 mA" rule, high voltage/low current*

This rule stated that an electrical source that could not provide over 5 mA of shock current, regardless of voltage, was NOT an electrical shock hazard. In R&D (and in other commercial and industrial applications) there are numerous small high voltage power supplies that can supply a "carpet shock" type of stimulus, but do not have sufficient current or energy to cause any type of injury. This rule was based on the results of the substantial electrical injury studies over the past century. The 5 mA threshold that was chosen (also seen in the GFCI standard) was based on results for 60-Hz ac safety. It was universally applied to all waveforms in this first implementation.

Examples of equipment with high voltage, very low shock currents include radiation detection circuits, small photo detectors, mass spectrometers, and in general, any instrument that uses a high voltage electric field to accelerate charged particles. Typical voltages are in the 1 to 5 kV, and typically the currents (electron or ion) are in the 10s to 100s of μA range. Although mild shocks from such equipment are well known in the laboratory, there is no known injury from such shocks.

As an example, at Los Alamos National Laboratory there are over 10,000 such pieces of equipment. With over 200,000 workers in the 60 year history of research at LANL, there is no known injury from electrical shock on such instruments, although there have been many minor carpet like shocks.

This rule was innovative, as the national standards, which were generally based on exposure to 60 Hz power systems with ample shock currents available, implied that all voltages over 50 V rms were hazardous.

There are two cautions that must be noted, however. Often such equipment is dc, and any output capacitor must be analyzed separately, as a shock hazard. The new hazard classification methods account for this issue. Second, there can be a carpet shock type reflex action, often just from surprise. Care must be taken that such a reflex does not endanger the worker through a fall, or sudden movement. However, this caution is no different than managing natural electrostatic discharge, such as carpet shock, in a low humidity environment.

2) *The "10 A" rule, low voltage, high current*

This rule states that an electrical source can be a hazard even at low voltages, if there is sufficient current available to heat metal tools or jewelry through resistive or "joule" heating. Examples include rings and watches across battery terminals and tools across low voltage, high current dc systems such as electroplating, welding, or electromagnet systems.

The hazard is not electrical shock, but thermal bums to the hands due to rapidly heated metal. This is classed as the "thermal burn" injury mechanism #3 in section II-A above.

The "10 A" rule in the 1998 DOE Electrical Safety Handbook stated that any exposed electrical conductors capable of delivering a continuous current in excess of 10 A, regardless of voltage, must be treated as hazardous, and exposure to the worker must be prevented, or treated as energized electrical work.

This was innovative at the time, as the existing national codes and standards treated all systems below 50 V as safe. The current NFPA 70E, however, does recognize potential hazards from low voltage, as mentioned earlier. However, no thresholds for thermal burn injury are given in either OSHA or NFPA 70E.

3) *The "10 J" rule, capacitors*

No national electrical safe work practice standard had ever included thresholds for protection against high voltage capacitor shock, although the hazard was well known and often discussed in the literature.

The 1998 DOE Electrical Safety Handbook established 10 J as a threshold for capacitor shock. Although this is below the energy required to cause ventricular fibrillation, a 10 J shock from a high voltage capacitor will definitely cause substantial reflex action. This rule was implemented as a threshold at most DOE research laboratories across the country (one lab lowered the number to 5 J). Experience and study since 1998 have shown that this threshold may be too high for injury prevention, and has resulted in an improved classification system for capacitor thresholds.

4) *Application of the DOE Electrical Safety Handbook Thresholds over a 10 year period*

All three above rules have been implemented in various forms at over 15 research laboratories, representing approximately 10,000 R&D electrical workers, and have been in use for 10 years. They have worked quite well, and there has been no known injury that would indicate these rules were inadequate, with the exception of the capacitor threshold. The example was discussed in Section II-F above.

IV. WHAT IS MISSING?

The US standards for setting the thresholds for electrical hazards have focused on 60 Hz ac electric shock and arc flash hazards. There are, however, many more forms of electrical energy, and other mechanisms of injury. With over a century of research there is significant information to help fill this gap. Missing thresholds in electrical safe work practice codes lead to a need to account for:

- a lower current limit, where there is not a shock hazard below a certain current, regardless of high voltage
- thermal burn hazards, high current or high power can be a hazard, regardless of low voltage
- effects of frequency (IEEE/ANSI C95.1)
- dc thresholds, are higher than for 60 Hz ac
- capacitor thresholds, a graded approach, as a function of energy
- battery hazards, including thermal, shock, etc.
- arc flash hazards for dc, capacitors, and battery banks

V. A COMPLETE ELECTRICAL HAZARD CLASSIFICATION SYSTEM

The following description of a comprehensive electrical hazard classification system is an overview. In this short paper it is not possible to present the full details of this system. For instance, the reader does not have the user tools to understand and determine the parameter values necessary to determine the hazard classes. There are substantial user notes that go with the charts shown in the presentation. Contact the authors for more detailed information.

A. *Electrical Parameters Determining Injury*

Predicting potential injury, and thus determining thresholds for exposure depend on many factors, including: voltage; current; power; energy; waveform and frequency; duration of the shock; contact points and path through the body; environmental circumstances (such as humidity or moisture); and, size, weight, gender, and physical condition of the person.

The electrical parameters are usually known. Thus, they are used to establish thresholds for safe work practices. They include voltage, current, power, energy available, and waveform.

The circumstantial parameters, with a few exceptions, are usually not known, or not under consistent control of the worker. They include contact points, path through the body, duration of a shock, environmental conditions, and physical condition of the person. Thresholds are typically established to be conservative and account for variation in condition and person. For example, most shock thresholds, including thresholds for perception, reflex reaction, no-let-go, and fibrillation, are usually chosen such that 99.5 % of the population would fall above the threshold, regardless of duration of the shock, or path through the body.

Certain work conditions, such as a high temperature and/or high humidity environment may require more stringent safe work practices. The 50 V rule, or even a 30 V rule would not apply if the worker was immersed in water, for example.

As discussed above, current standards use voltage, current, energy, and waveform/frequency to define thresholds for safe work practices. The complete electrical hazard classification system presented here uses voltage, current, power, energy, and waveform/frequency to set thresholds, based on existing knowledge and standards.

B. *Organization of System – Super Categories*

The comprehensive electrical hazard classification system presented here starts by dividing electrical sources and energy into 5 "super" or general categories, based on source and waveform (refer to the charts in the accompanying presention):

Category 1 – 60 Hz power
Category 2 – 0 Hz to 3 kHz, includes dc and sub RF
Category 3 – Capacitors
Category 4 – Batteries
Category 5 – RF from 3 kHz to 100 MHz

The selection of this General Category depends on source and waveform. The first number, X, in a hazard class designation, X.x gives the General Category.

C. *54 Electrical Hazard Classes*

Each of the 5 General Categories are then broken into a number of Hazard "Classes", depending on voltage, shock current available, short circuit current available, waveform, energy stored, short circuit power, and/or frequency.

To properly classify electrical energy the worker must be qualified, and have the ability to determine the necessary information. Current OSHA and NFPA standards state that the qualified worker must "be able to determine the nominal voltage". This is an example of how the standards were written with a focus on 60 Hz shock hazards. To properly use this hazard classification system the qualified worker must be able to determine more than just "nominal voltage".

With very few exceptions every type and source of electrical energy can be placed into one or more of the 54 Hazard Classes. The classes are color coded to represent the level of hazard using 5 colors. Colors are not necessary, however, as the second number, x, in the Class designation also gives the hazard ranking. The 5 ranks are:

Classes X.0 – Blue – no electrical hazard
Classes X.1 – Green – minimal electrical hazard
Classes X.2 – Yellow – can injure or kill
Classes X.3 – Red – Serious hazard
Classes X.4 and X.5 – Extreme

This graded approach is very useful to identify hazardous electrical systems, and to develop design and work controls.

This system does cover most of the direct injury mechanisms that could occur from the exposure to electrical energy, including the 5 Groups discussed in Section II-A above covering shock, thermal and arc flash injury. This system, however, does not cover all secondary hazards created by electricity, including initiation of fire, non ionizing radiation (electric, magnetic, and RF fields), and ionizing radiation (X-rays can be created from high voltage circuits in vacuum). Those secondary hazards are not usually covered by electrical safety processes, but by other methods and standards.

D. *Classes 1.x – 60 Hz Power*

Category 1, containing classes 1.x, includes all 60 Hz power from transmission and distribution, to facility power distribution, and into power cords and utilization equipment that use 60 Hz power directly. This could be broadened to cover 50 Hz power as well, as there is no difference in the shock hazards between 50 and 60 Hz. The primary hazards in this Category are shock and arc flash. This Category of electrical energy is the one that results in the majority of the accidents and fatalities in the home, public and workplace, and is the one covered by existing national codes and standards (OSHA, NEC and NFPA 70E).

Hazard Classes 1.x are based on the 2004 NFPA 70E, and some minor changes in classes 1. 2 and 1.3 may occur upon incorporation of the 2009 NFPA 70E.

Four voltage thresholds are used in the Category, 15, 50, 250, and 600 V. The 15-V threshold is not found in current standards, but was chosen by the developers as a dividing line between very low hazard, and low hazard. Although this may sound vague, the logic is that, although 50 V has been universally chosen as the threshold for electrical hazard for workers for 60 Hz ac in the US, lower voltages can be hazardous under extreme work conditions, such as very high humidity, or flooded conditions. Thus, under extreme conditions extra caution may be needed. This is true for all thresholds, but does not justify lowering thresholds based on decades of standards work.

The 50 V rms threshold between Classes 1.1 and 1.2 is from NFPA 70E and other US standards. The primary hazard in Class 1.2 is electric shock, unless sufficient short circuit current is available to create an arc flash hazard (see 2009 NFPA 70E 130.3, Exception #1).

The 250 V rms threshold between Classes 1.2 and 1.3 is used to indicate a substantial increase in the possibility of arc flash and is in line with NFPA 70E and IEEE 1584.

The 600-V threshold between Classes 1.3 and 1.4/1.5 is the classical 600 V division used throughout US electrical standards. Class 1.4 is for facility electrical hazards over 600 V, and is covered by NFPA 70E, whereas Class 1.5 is for utility electrical hazards over 600 V and is covered by the NESC.

The subclasses in Classes 1.2 and 1.3 (e.g., 1.2a, 1.2b, and 1.2c) were based on the footnotes in the 2004 NFPA 70E and were created to remind the worker to analyze the arc flash hazard and determine the short circuit current.

E. *Classes 2.x – Equipment AC and DC*

Category 2 contains all uses of electricity from dc (0 Hz) to 3 kHz, that are NOT 50/60 Hz power, and are NOT capacitors or batteries.

Circuits using ac between 1 Hz and 3 kHz are not common, but can be found in some specialized equipment. In general, thresholds for electric shock are the same as for 60 Hz ac power.

There are many uses of dc throughout the home, industry, and R&D laboratories. In general, the public and homeowner are not exposed to dc electrical hazards (such as in a microwave oven), but there are many opportunities to work on or near dc electrical hazards in laboratories and industry. Thus, the dc portion of this system is quite valuable. It is important to discuss the basis for the thresholds chosen. The dc for batteries is covered in Category 4.

There are three voltage thresholds, 15, 100, and 250 V. The 15-V threshold, similar to the reasons given above for ac, was chosen as a threshold for very low voltage. There is no electric shock hazard below 15 V. The 100 V dc value was chosen as the threshold for worker safety, similar to the 50 V rms ac threshold. The extensive research performed over the past century supports this threshold as a safe value and was summarized in Section II above.

The 250-V threshold was chosen as a threshold for sustaining an arc flash, similar to the 250 V rms ac value in NFPA 70E.

The threshold for dangerous shock currents was chosen as 40 mA, analogous to the 5 mA rule for 60 Hz ac. Again, a 40 mA limit for allowable dc shock is conservative based on the extensive research conducted over the past century, and summarized above. Since there is no let-go threshold for dc, and since the fibrillation values for dc are in the 300 mA range, a dc shock threshold of 40 mA is conservative.

Below 15 V dc, electrical sources are non hazardous for available short circuit power less than 1000 W (Classes 2.0 and 2.1a). For short circuit powers over 1000 W, the electrical hazard is high current through tools and jewelry resulting in thermal burn (Class 2.2a). Examples of dc power supplies in Class 2.2a include welders and electroplating systems.

From 15 to 100 V sources are again non hazardous for available short circuit power less than 1000 W (Classes 2.1b). For short circuit powers over 1000 W, the electrical hazard is thermal burn (Class 2.2b). Examples include welders and electromagnet systems.

For voltages from 100 to 250 V dc, the important electrical parameter for safety changes from power (the hazard was thermal burn) to available shock current (the hazard is dc electric shock). Below 40 mA, there is no shock hazard (Class 2.1c), and above 40 mA there is a dc shock hazard (Class 2.2c).

For dc voltages above 250 V, three current thresholds were established: 40 mA, 200 mA, and 500 A. What may confuse the reader is that the focus on injury changes for higher currents. For less than 40 mA there is no shock hazard or arc flash hazard (Class 2.1d). From 40 to 200 mA (Class 2.2d) there is a dc shock hazard resulting in possible injury due to a reflex action when first contacting and letting go of the circuit, and possible tissue damage at the higher end, for long exposure. Class 2.3 (red) covers the range from 200 mA to 500 A. In addition to the reflex action in Class 2.2d, there are two new hazards to be considered. First, the range now incorporates dc induced ventricular fibrillation (around 300 to 500 mA for sufficient time), and the beginnings of potential dc arc flash hazards.

And finally, for dc systems that are above 250 V and can have a short circuit current over 500 A (Class 2.4, maroon), an arc flash analysis must be performed. Such high power dc systems (over 125 kW) are rare. At Los Alamos National Laboratory, out of 10,000s of R&D dc power supplies, there are only two or three such dc power supplies used for large electromagnet systems on linear accelerators. There are high power dc systems in industry including electrical railways and large metal smelting systems.

F. *Classes 3.x – Capacitors*

The methods presented for the assessment and classification of capacitor hazards is quite innovative, and is based on the research on impulse shock hazards over the past century, as well as 50 years of experience at research laboratories around the world. This material was developed and reviewed by over 15 experts in high voltage, energy storage, and pulsed power systems. Also, many known capacitor accidents in R&D were reviewed.

The only common uses of capacitors in 60 Hz power systems are power factor correction capacitors in the utility system, and motor starter capacitors for single-phase motors. But capacitors are extensively used in dc power supplies, as a rectifier filter, to supply special wave shapes, or in pulse conditioning. High-energy capacitors are also used extensively to store electrical energy at a dc state, and then release it quickly as a pulse. This field of pulsed-power engineering is used throughout research and industry.

Capacitor hazards are divided into three major groups by voltage. The two voltage thresholds are 100 and 400 V. The 100-V threshold was chosen to be in agreement with the 100-V threshold for dc electrical hazards. The thought at the time was a focus on dc capacitors. Any capacitor in an ac 60 Hz power system would be operating at 60 Hz ac, and during operation General Category 1, 60 Hz power should be used for electrical safety analysis. If the ac system is tumed off and locked out, then the ac capacitor could have a residual dc charge at a voltage somewhere between the negative and positive peaks of the ac waveform. At this point (the ac source is off and locked out) the ac capacitor could be treated as a dc capacitor hazard.

A capacitor contains a finite amount of energy, such as 10 J in a microwave oven capacitor. Thus, contact with a capacitor results in discharge of this energy through the person. In contrast, the power system is essentially infinite in energy, limited only by the action of over current protection, in case of a fault condition, or by letting go of the circuit, in case of a shock.

Capacitors, on the other hand, will deliver their energy into a short circuit, or shock condition, until the energy is exhausted, or close to zero.

The 400-V threshold was chosen to be close to the skin breakdown voltage level. This is important, as below skin breakdown levels the resistance of skin dominates in the rate of delivery (current) of an electric shock, but above skin breakdown only internal body resistance limits shock current. For capacitors this means that for a capacitor shock below skin breakdown levels (chosen to be 400 V here), the capacitor energy will be delivered in seconds to minutes (the RC time constant), as a typical resistance can range from 1000s of ohms for wet skin, to 100s of kilo-ohms for dry skin. But for a capacitor shock above the skin breakdown level, the capacitor energy can be delivered in milliseconds. This results in a substantial reflex action, possible fibrillation, and increased injury at the contact points.

Below 100 V, the capacitor hazard is similar to a battery hazard, that is high power dissipated through jewelry or tools. The rate-of-discharge of a battery during an electric shock is determined by the resistance of the victim, and the internal resistance of the battery. Discharge of a battery into a metallic conductor, such as a ring, is limited by the intemal resistance of the battery, which will be in ohms. A capacitor, on the other hand, has negligible intemal resistance, and discharge into a conductive short circuit, such as a tool or jewelry, will be very rapid. For this reason, rate of discharge will be very high. For batteries the rate of discharge, determined by short circuit current or power, is a good measure of the hazard, as the power determines resistive heating of the short circuit. For a capacitor, however, the total short circuit resistance will be in milliohms, and the power will be huge. For instance, a typical carpet shock at a 600 ns pulse produces a 10 A pulse at 20,00 V resulting in a 200 kW shock. These numbers are very misleading, as they sound scary. In reality, a 20,000 V, 10 A, 200 kW electrostatic discharge from a typical carpet shock is harmless to a person because it only delivers about 10 mJ of energy.

For the above reasons, available energy in the capacitor was chosen as the primary measure of the hazard, both for low voltage and for high voltage capacitor shocks. This is consistent with the results of decades of research on the effects of impulse shock.

Below 100 V capacitor hazards are divided into 4 energy ranges, < 100 J, between 100 and 1000 J, between 1 and 10 kJ, and over 10 kJ. A capacitor in Class 3.1a shorting into a person's ring would hardly warm the ring (less than 100 J, the energy used by a 100 W light bulb in 1 s). In Class 3.2a a person could receive a bum from 100s of J rapidly heating a piece of jewelry. In Class 3.3a 1000s of J will result in a short circuit current of several kA and will heat substantial metal. The fast impulse in the kA range will create magnetic forces on the conductors resulting in mechanical motion. And finally, any short circuit of a capacitor bank in Class 3.4a will result in massive conductor melting and mechanical motion. As far as an electrical shock hazard there is none below 100 V. The capacitor is no different in a shock that a dc source. The intemal body resistance limits currents to below fibrillation thresholds as discussed above. For example, contact with a 10 kJ capacitor at 80 V dc would be no different that contact with a dc power supply at 80 V. The current would be limited by skin resistance and would be in mA range. The worker would feel a sensation and would let go (there is not a let go threshold for dc), resulting in only a fraction of the 10 kJ being delivered to the worker.

For the range between 100 and 400 V capacitors were divided into four groups by energy. Keep in mind that above 100 V a capacitor shock is now above the dc shock safety threshold. For less than 1 J (Class 3.1b), however, such a shock could not cause fibrillation. In Class 3.3b, from 1 to 100 J, a capacitor shock delivers the energy in many seconds. Fibrillation is unlikely (less than 100 J delivered slowly) so this Class could have been ranked at a lower level (Class 3.2a, or yellow), but was conservatively rated. Class 3.3c is clearly a potential fibrillation hazard as well as a substantial short circuit hazard, as is Class 3.4b.

The classification of the hazards of high voltage capacitors benefited greatly from the studies of impulse shock and from the development of various forms of the defibrillator. This group is divided into two subgroups, shock from electrostatic discharge (ESD, e.g., carpet shock) and from a discrete capacitor. Having a category for ESD (Class 3.0, blue) helps to properly classify harmless shocks. Some equipment can deliver low-level ESD shocks that are also harmless. A perfect example is a shock felt by raking one's hand across the glass surface of a Cathode Ray Tube (CRT) television in a dry environment. Consideration for an ESD discharge in a hazardous location was actually included as Class 3.1c. The color gray was chosen to stand out against the other colors. The problem is no longer injury from electric shock, but from explosion or ignition and must be dealt with by further analysis and control.

The rest of the high voltage group is ranked in a graded manner, using 5 breakpoints. A high voltage capacitor shock of less than 0.25 J can cause a reflex action, but will not cause injury (Class 3.1d). A high voltage capacitor shock from 0.25 to 1 J (Class 3.2b) will cause a significant reflex action, possibly causing injury from the reaction. Contact with this category, although not potentially lethal, should be avoided. Contact with a high voltage capacitor from 1 to 10 J (Class 3.3d) is also not lethal, but based on known shock incidents, and subsequent injury, this level was chosen to be ranked higher (red). The range from 10 to 1000 J (Class 3.3e) includes possible death due to ventricular fibrillation, as well as damage to nerve pathways and other tissue damage. Above 1 kJ (Classes 3.4c and 3.4d) injury and fatality can occur from fibrillation, massive tissue damage, significant entrance/exit wounds, and other secondary mechanisms. A short circuit of a capacitor or capacitor bank in these two highest Classes can also cause injury from the arc blast type effect, including acoustic shock wave, magnetic forces on conductors, and shrapnel.

G. *Classes 4.x – Batteries and Battery Banks*

The primary electrical hazard of a battery to the worker is high current through jewelry and tools. With this in mind, the parameter used to classify battery electrical hazards (below 100 V dc) is the short circuit power available. For instance, the short circuit power available from Size AA, C, D, and cell phone batteries is typically in the 10s of W, placing them in class 4.0. Lantern size and small UPS size batteries tend to have short circuit currents in the 100s of W, placing them in class 4.1. A car battery can have a short circuit current of 1000 A, and a short circuit power on the order of 10 kW, and is a substantial high current hazard to the public and any worker. A car battery is in Class 4.2. An important note that accompanies the full classification system is that if the single battery, or battery bank system voltage exceeds 100 V dc, then Category 2 must be used to asses the dc shock hazard. In other words, there are rare batteries that could be in Battery Class 4.1 (no hazard) for a high current hazard, but in dc Class 2.2c (a shock hazard) due to shock voltages available. This classification system for batteries does NOT account for chemical battery hazards such as acid, hydrogen, lead, and lithium. They could be added at a later time.

H. *Classes 5.x – Radiofrequency (3 kHz to 100 MHz)*

The hazard classification for electric shocks in the RF range of 3 kHz to 100 MHz are based on 1999 IEEE/ANSI C95, and may need to be updated to the 2005 edition. Basically, the classes are based on frequency and available shock current, which determines the thresholds between allowed (Classes 5.1) and not allowed (Classes 5.2).

VI. APPLICATIONS

Many elements of this new electrical hazard classification system have been under review and use over the past 3 years at several DOE R&D laboratories, including Los Alamos National Laboratory, Argonne National Laboratory, Sandia National Laboratory, and others. The value of this new electrical hazard classification system can be shown through examples.

A. *Differentiation Between Hazardous and Non-Hazardous Electricity*

A challenge in the laboratory with many forms of electrical energy is the differentiation between hazardous electrical energy (that which can injure or kill), and nonhazardous electrical energy (that which will not injure or kill). Clearly, one can experience electrical shock (carpet shock) and burns (shorting a small battery in one's pocket) and not be seriously injured. Thresholds are required in the workplace to establish reasonable boundaries. Clearly, fatalities must be prevented. What level of injury is acceptable? And how much can one count on work control and worker qualification to protect the worker during exposure? The answers to these questions are often quite subjective.

This new comprehensive electrical hazard classification system has greatly aided the worker and safety manager at DOE laboratories in properly classifying electrical hazards. In general, if the electrical energy falls in Classes X.0 or X.1 (blue or green), there is no electrical hazard. Of course, qualified persons must assess the hazard class, as there are always borderline cases, or unusual work conditions that may warrant additional control. For instance, one would not want to apply the 50 V ac or 100 V dc rules, while working immersed in water. And, electrical energy in Classes X.2 and above (yellow, red and maroon) are hazardous and must be treated as hazardous electrical energy and managed using requirements such as NFPA 70E, Chapter 1.

B. *Controls for Electrical Hazard Classes*

There are many controls for working on or near exposed electrical sources. Just a few are: shock PPE, arc flash PPE, insulated tools, no jewelry, hearing protection, etc. Without adequate hazard classification it is easy to choose the wrong, or inadequate controls. In the actual implementation at DOE laboratories of the comprehensive electrical hazard system presented there are accompanying controls tables that list appropriate controls for each of the 54 hazard classes. These are especially unique and innovative, for example, in Category 3, Capacitors. There is not sufficient space in this paper to share these controls.

C. *Examples of Using Electrical Hazard Classification on Complex Systems*

A complete electrical hazard analysis of a complex electrical system will find that there are many classes of electrical energy, some hazardous and some not. In a complex system, there may be 6 to 10 Classes present. Examples include induction furnaces, high power lasers, linear accelerators, electron microscopes, etc. For example, the input to a large 100 kW induction furnace is 480 V three phase, with shock and arc flash hazards (Class 1.3). The qualified electrician is the right worker to troubleshoot and repair this end of the machine. The output, however, is high power RF, with high voltages, and capacitors (Classes 2.x, 3.x, and 5.x). It is likely to be the specially trained engineer or technician that works on this end of the system. The training, PPE and procedures are different, depending on the hazard.

D. *An Electrical Incident Severity Ranking Tool*

Within the DOE complex there are 17 national laboratories and a dozen other facilities with around 1000 facility and utility electrical workers and over 10,000 R&D electrical workers. At these laboratories every conceivable form of electricity and electrical hazard can be found. There are systems that generate PW pulses (that is a Petawatt), systems that generate 40 MA currents, and multi MV systems, and so on. Although the DOE complex has made great strides in electrical safety over the decades, there are still electrical incidents and accidents, both in the facility and R&D areas. Due to the unique nature of the electrical hazards, and variations in electrical safety programs from site to site, in the past there was considerable variation in the analysis, reporting, and corrective actions of electrical incidents across the complex. In some cases electrical events were being over reported, but in some cases they had been under reported.

In parallel with the development of this comprehensive electrical hazard classification system, a tool was developed known as the "Electrical Severity Measurement Tool". This tool uses this electrical hazard classification system, approach boundaries from NFPA 70E, and injury to the worker as parameters to assess the severity of an electrical incident or accident. This tool is now in widespread use across the complex and has been successful in improving consistent analysis and reporting of events, and in improving electrical safety!

VII. CONCLUSIONS

This paper has presented a comprehensive electrical hazard classification system that has been under development in the DOE R&D community over the past 10 years. This system incorporates existing electrical safety standards, as well as covering areas of injury and types of electrical hazards not previously covered by such standards. The classification system is based on the substantial international research conducted over the past 110 years on the injuries from electrical hazards.

Future papers will provide more details on the basis, development, and application of this system. For the future we need to look towards proposing new material for US national standards to cover all electrical hazards.

VIII. ACKNOWLEDGEMENTS

This material presented has been under development at a series of Electrical Safety Workshops held in the DOE complex from 2004 to 2008. Over the past 5 years, the number of knowledgeable scientists, engineers, and safety professionals that have contributed to this development of new methods of electrical hazard classification is well over 50 individuals. Any attempt to list individual names would surely leave someone out. But, in general, these contributors came from Argonne National Laboratory, Brookhaven National Laboratory, Lawrence Berkeley National Laboratory, Lawrence Livermore National Laboratory, Los Alamos National Laboratory, Oak Ridge National Laboratory, Pacific Northwest National Laboratory, Sandia National Laboratory, and others. Without their participation this progress would not be possible.

IX. REFERENCES

[1] NFPA 70, 2008 *National Electrical Code*, Quincy, MA: National Fire Protection Association.

[2] ANSI/IEEE C2-2007, *National Electrical Safety Code*, New York, NY: IEEE.

[3] C. F. Dalziel, "Obtaining Safety in Experimental Electrical Laboratories", *Electrical Engineering*, Vol. 70, pp 99-103, Feb 1951.

[4] C. F. Dalziel, "Improvements in Electrical Safety", *Transactions of the American Institute of Electrical Engineers, Part I (Communications and Electronics)*, Vol. 81, pp 121-127, May 1962.

[5] L. B. Gordon, "Electrical Hazards in the High Energy Laboratory", *IEEE Transactions on Education"*, Vol. 34, No. 3, pp 231-242, August 1991.

[6] DOE-HDBK-1092-98, *DOE Handbook – Electrical Safety*, ,U.S. Department of Energy, Washington, D.C., 1998.

[7] L. P. Ferris, B. G. King, P. W. Spence, and H. B. Williams, "Effect of Electric Shock of the Heart", *Electrical Engineering*, Vol. 55, pp 498-515, May 1936.

[8] C. F. Dalziel and J. B. Lagen, "Effects of Electric Current on Man", *Electrical Engineering,* Vol. 60, pp 63-66, Feb 1941.

[9] C. F. Dalziel, "Dangerous Electric Currents", *Electrical Engineering,* Vol. 65, pp 579-585, Aug/Sept 1946.

[10] C. F. Dalziel, "Perception of Electric Currents", *Electrical Engineering,* Vol. 69, pp 794-800, Sept 1950.

[11] C. F. Dalziel, "The Threshold of Perception Currents", *Electrical Engineering,* Vol. 73, pp 625-630, July 1954.

[12] W. B. Kouwenhoven, G. G. Knickerbocker, R. W. Chesnut, W. R. Milnor, and D. J. Sass, "A-C Shocks of Varying Parameters Affecting the Heart", *Transactions of the American Institute of Electrical Engineers – Part 1 (Communication and Electronics),* Vol. 78, No. 42, pp 163-167, May 1959.

[13] R. S. Banks and T. Vinh, "An Assessment of the 5-mA, 6-Hz Contact Current Safety Level", *IEEE Transactions on Power Apparatus and Systems*, Vol. PAS-103, No. 12, Dec 1984.

[14] J. C. Keesey and F. S. Letcher, "Minimum Thresholds for Physiological Responses to Flow of Alternating Electric Current Through the Human Body at Power-Transmission Frequencies", Naval Medical Research Institute, Bethesda, Maryland, September 3, 1969, Project MR005.08-0030B, Report No. 1.

[15] W. R. Lee, "Death from electric shock", *Proc. IEE*, Vol. 113, No. 1, pp 144-148, Jan 1966.

[16] C. F. Dalziel, "Reevaluation of Lethal Electric Currents", *IEEE Trans. on Industry and General Applications,* Vol. IGA-4, No. 5, pp 467-476, Sept/Oct 1968.

[17] C. F. Dalziel, J. B. Lagen, and J. L. Thurston, "Electric Shock", *Transactions of the American Institute of Electrical Engineers,* Vol. 60, pp 1073 – 1297.

[18] C. F. Dalziel, "Effect of Wave Form on Let-Go Currents", *Electrical Engineering,* Vol. 62, No. 12, pp 739-744, Dec 1943.

[19] C. F. Dalziel, E. Ogden, and C. E. Abbott, "Effect of Frequency on Let-Go Currents", *Electrical Engineering,* Vol. 62, No. 12, pp 745-750, Dec 1943.

[20] J. Weirich, St. Hohnloser, and H. Antoni, "Factors determining the susceptibility of the isolated guinea pig heart to ventricular fibrillation induced by sinusoidal

alternating current at frequencies from 1 to 1000 Hz", *Basic Research in Cardiology,* Vol. 78, pp 604-616, 1983.

[21] A. L. Angelis, W. R. Lee, and S. Zoledziowski, "Experimental Investigation of the Effects of Direct Current Electric Shock on Respiration", *British J. of Industrial Medicine,* Vol. 22, No. 3, pp 210 – 216, 1965.

[22] S. Hohnloser, J. Weirich, and H. Antoni, "Influence of direct current on the electrical activity of the heart and on its susceptibility to ventricular fibrillation", *Basic Research in Cardiology,* Vol. 77, pp 237-249, 1982

[23] C. F. Dalziel, "A Study of the Hazards of Impulse Currents", *Power Apparatus and Systems,* Vol. 8, pp 1032-1043, Oct 1953.

[24] W. B. Kouwenhoven and W. R. Milnor, "Electric Defibrillation", *Trans. of the American Institute of Electrical Engineers,* Vol. 74, pp 561-567, Aug 1955.

[25] G. T. Smith, R. Beeuwkes, Z. M. Tomkiewicz, T. Abe, and B. Lown, "Pathological Changes in Skin and Skeletal Muscle Following Alternating Current and Capacitor Discharge", *The American Journal of Pathology,* Vol. 47, No. 1, pp 1-17, July 1965.

[26] L. A. Geddes and W. A. Tacker, "Engineering and Physiological Considerations of Direct Capacitor-Discharge Ventricular Defibrillation", *Medical and Biological Engineering,* Vol. 9, pp 185-199, 1971.

[27] C. F. Babbs, W. A. Tacker, J. F. VanVleet, F. D. Bourland, and L. A. Geddes, "Therapeutic indices for transchest defibrillator shocks: Effective, damaging, and lethal electrical doses", *American Heart Journal,* Vol. 99, No. 6, pp 734-738, June 1980.

[28] F. M. Charbonnier, "External Defibrillators and Emergency External Pacemakers", *Proc. of the IEEE,*, Vol. 84, No. 3, pp 487-499, Mar 1996.

[29] G. Tomassoni, K. H. Newby, M. M. Kearney, M. J. Brandon, H. Barold, and A. Natale, "Testing Different Biphasic Waveforms and Capacitances: Effect on Atrial Defibrillation Threshold and Pain Perception", *JACC,* Vol. 28, No. 3, pp 695-699, Sept 1996.

[30] Y. Liu, Z. Wu, and S. Liu, "Threshold of Perception for Capacitor Discharge on the Human Body", *Proceedings of the 1997 International Symposium on Electromagnetic Compatibility,* pp 340-343, IEEE.

[31] R. C. Lee, "Physical Mechanisms of Tissue Injury in Electrical Trauma", *IEEE Trans. on Education,* Vol. 34, No. 3, pp 223-230, Aug 1991.

[32] R. C. Lee, E. G. Cravalho, and J. F. Burke, *Electrical Trauma- the pathophysiology, manifestations, and clinical management,* Cambridge, Great Britain: Cambridge University Press, 1992.

[33] R. C. Lee, "Injury by Electrical Forces: Pathophysiology, Manifestations, and Therapy", *Current Problems in Surgery,* Vol. 34, No. 9, pp 679-764, Sept 1997.

[34] M. Capelli-Schellpfeffer, "Correlation Between Electrical Accident Parameters and Injury", *IEEE Industry Applications Magazine,* Vol. 4, No. 2, pp 25-41, Mar/Apr 1998.

[35] R. C. Lee, D. Zhang, and J. Hannig, "Biophysical Injury Mechanisms in Electrical Shock Trauma", *Annual Review of Biomedical Engineering,* Vol. 2, pp 477-509, 2000.

[36] R. C. Lee, "Electrical Injury: Mechanisms, Manifestations, and Therapy", *IEEE Trans. on Dielectrics and Electrical Insulation,* Vol. 10, No. 5, pp 810-829, Oct. 2003.

[37] R. Lee, "Cell Injury by Electric Forces", *Annals of the New York Academy of Science,* Vol. 1066, pp 85-91, 2005.

[38] D. Roberts, "50 Volt Shock Hazard Threshold", *Proceedings of the 2008 IEEE IAS Electrical Safety Workshop,* 2008, pp 80-85.

[39] Z. Peng and C. Shikui, "Study on electrocution death by low-voltage", *Forensic Science International,* Vol. 76, pp 115-119, 1995.

[40] NFPA 70E, 2009 *Standard for Electrical Safety in the Workplace*, Quincy, MA: National Fire Protection Association.

[41] IEC TS 60479-1, Effects of current on human beings and livestock – Part 1: General aspects, 4th edition, July 2005, International Electrotechnical Commission, Geneva, Switzerland.

[42] IEC TS 60479-2, Effects of current on human beings and livestock – Part 1: Special aspects, 3rd edition, May 2007, International Electrotechnical Commission, Geneva, Switzerland.

[43] IEEE 1584-2002, *IEEE Guide for Performing Arc-Flash Hazard Calculations*, New York, NY: IEEE.

X. VITAE

Lloyd B. Gordon graduated from Texas Tech University in 1981 with a PhD in Electrical Engineering. He started his research career at Lawrence Livermore National Laboratory (DOE), conducting research in topics of pulsed power engineering, plasma physics and dielectric engineering from 1981 to 1986. From 1986 to 1991 he was in the Department of Electrical Engineering at Auburn University, and from 1991 to 1998 was in the Department of Electrical Engineering at the University of Texas at Arlington. Since 1998 he has been at Los Alamos National Laboratory (DOE). Dr. Gordon has 25 years of experience in experimental high-energy research, 34 years of experience as an educator and trainer, and has focused his efforts on R&D electrical safety over the past 15 years. He has lectured to and trained over 50,000 scientists and engineers throughout the DOE and DOD complex over the past 20 years in R&D Electrical Safety. Dr. Gordon is currently the Chief Electrical Safety Officer at Los Alamos National Laboratory, chairs the ISA committee on Electrical Safety Standards for High Power R&D Systems, is chair emeritus for the DOE's Energy Facility Contractors Operating Group (EFCOG), and manages the DOE/EFCOG Center of Excellence for Electrical Safety. He may be contacted through the Center website at http://www.lanl.gov/safety/electrical/.

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