# Evaluation of "Alternate Equipotential Bonding Means" to Reduce Voltage Gradients In Pool Areas

*Final Report*

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## FOREWORD

A common approach to reduce the voltage gradients in a pool area is by using a single buried #8 AWG copper conductor following the perimeter surface around the pool. This is identified as an alternate means of perimeter equipotential bonding for permanently installed swimming pools and spas according to 680.26(B)(2)(b) of the 2011 edition of NFPA 70®, National Electrical Code® (NEC®).

This arrangement is intended to provide a 60 Hz ac voltage gradient protection to prevent injury or death, but questions exist on its effectiveness. This includes defining nominal "safe" levels based on differentiating between conditions that are tolerable (i.e., benign or an irritant) versus dangerous, and evaluating nominal performance of the conductor with respect to these levels.

This project provides information that clarifies the effectiveness of “alternate equipotential bonding means” for swimming pools and similar installations. A specific focus is provided on the impact on voltage gradients from the use of a single #8 AWG copper ring installed according to the requirements of 680.26(B)(2)(b) of the NEC.

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The content, opinions and conclusions contained in this report are solely those of the author.

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REPORT

# Evaluation of "Alternate Equipotential Bonding Means" to Reduce Voltage Gradients in Pool Areas

## Final Report

_Submitted to_

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## Executive Summary

An electrically safe environment in and around swimming pools can be established by creating an equipotential system. The objective of an equipotential system is to create an area where there is no significant voltage difference between objects that can be touched simultaneously thus eliminating the hazard of an electric shock. An equipotential system is created by intentionally connecting all conducting objects together electrically, a practice that is known as 'equipotential bonding'.

As described in Article 680.26(B)(2) in the National Electric Code (NEC), bonding to the perimeter surface around swimming pools may be provided via a grounding grid, which is a buried mesh constructed of metal, that is connected to the swimming pool deck and other conducting objects in the pool area. The 2008 version of the code adopted an alternative bonding method. For this "Alternate Means" option the minimum requirement is to provide bonding to the perimeter surface via a single 8 AWG solid copper wire that is installed 18 to 24 inches from the swimming pool walls and secured within or under the perimeter surface 4 to 6 inches below the subgrade. The effectiveness of the "Single Conductor" option in reducing voltage gradients in swimming pool areas to safe levels is in question and there has been a petition to remove this "Single Conductor" option from the NEC and instead make an equipotential grid mandatory for perimeter bonding. This petition has been rejected by the Code-Making Panel 17 (CMP-17) on the grounds that there is no sufficient evidence that voltage levels encountered if the "Single Conductor" option is employed are unsafe.

The Fire Protection Research Foundation (FPRF) contracted EnerNex to review the pertinent literature to document the current knowledge on the subject of bonding methods in swimming pool areas and also to identify gaps in knowledge. Additionally, EnerNex conducted two field trips as part of this project – one field trip to the EPRI swimming pool test facility in Lenox, Massachusetts where EPRI conducted a hands-on workshop during which various equipotential methods were tested and another field trip to a residential swimming pool in Alabama where EnerNex investigated a pool owner complaint about nuisance shocks.

The main findings of our effort to illuminate the issue are summarized briefly below.

- Previous experimental investigations did not qualify (or did not convincingly qualify) measured deck-to-water voltage levels for the "Single Conductor" option with regards to being "safe" or "unsafe". Instead, these studies focused on a comparative analysis of the equipotential bonding effectiveness of each option.
- Data from testing done recently by the Electric Power Research Institute (EPRI) appears to be the most pertinent data available. The data are sufficient to estimate body current in order to assess the effectiveness of the "Single Conductor" option levels for the tested scenarios, but we did not find documentation that presents the results of such an analysis. Also, the existing data would likely not be sufficient for drawing general conclusions because (1) the experiments were only conducted on a single swimming pool structure and (2) the range of fault current levels and NEVs generated for these experiments was somewhat limited.
- Acquiring additional experimental data combined with a complete analysis of the data and computer simulations would likely result in a solid conclusion with regard to the effectiveness of the "Single Conductor" option. The additional testing, analysis, and simulations should account for different swimming pool and deck types.
- Experimental investigations conducted by EPRI and NEETRAC show conclusively that the "Copper Grid" option is significantly more effective in equalizing the potential difference in the pool area than the "Single Conductor" option.

- The EPRI experiments showed that deck-to-water voltages during a 2,700 volt line-to-ground fault ranged between 40 and 90 V if the "Single Conductor" option was employed. For the same fault scenario, the deck-to-water voltage was in the order of a few volts if the "Copper Grid" option was employed.
- Preliminary results from EPRI testing seemed to indicate that there may be some intermediate methods (between the "Single Conductor" and the "Copper Grid" options) that may provide sufficient protection under all conditions but more testing is required to determine this.
- Preliminary results from EPRI testing seemed to indicate that there is some potentially hazardous voltage gradient at the edge of the copper grid if the grid does not extend to the outside edge of the deck. These preliminary results warrant further research in the form of additional testing, data analysis, and computer simulations.
- Detailed records of actual shock cases that are publicly available are very limited. A contributing factor to this scarcity of information is likely the lack of public reporting requirements for such incidents. In addition, for those cases documented, detailed data on the design of the equipotential option being used are nonexistent.
- Actual occurrences of the "Single Conductor" option not providing adequate protection have not been observed in the field. Factors that would explain this observation include (1) non-occurrence of these events, (2) lack of detailed records (see previous item), (3) limited number of installations using the "Single Conductor" option, or (4) limited number of primary faults in the vicinity of swimming pools. It is not clear which of these factors apply. Imposing nation-wide reporting requirements would illuminate this issue.
- It is not clear what voltage levels can be considered safe for people wearing certain medical equipment (such as pacemakers).
- Data relating specific voltage "shock" levels to the effects on the human body is readily available but was done many years ago. The belief is that the data is still good and as such no further research is needed.
- We argue that the method for determining body impedances described in IEC Standard 60479-1 is the preferred method and appears to be adequate.
- We argue that the method for determining shock current thresholds described in IEC Standard 60479-1 is the preferred method and appears to be adequate.

Additional information and detailed recommendation for "next steps" are provided in the subsequent paragraphs, which are categorized into four sections (1) Effectiveness of Bonding Methods, (2) Electrical Shock Incidents in Swimming Pool Areas, (3) Electrical Characteristics of the Human Body, and (4) Effects of Current Flow through the Human Body.

## Effectiveness of Bonding Methods

**Question:** What are the results of previous investigations on the effectiveness of equipotential methods?

**Relevance:** NEC requirements need to recommend bonding methods that adequately protect from injuries due to electric shocks in pool areas. Results from previous studies on the effectiveness of bonding methods would be helpful to identify adequate bonding methods.

**Conclusions and Recommendations:** The most complete experimental investigation of the effectiveness of bonding methods for swimming pools was conducted by the Electric Power Research Institute (EPRI) on their swimming pool test structure in Lenox, Massachusetts. Most of the testing was conducted on concrete deck sections, but some testing was also conducted on a section with brick pavers. EPRI documented their findings in their report "Guidebook for Evaluating Elevated Neutral-to-Earth and Contact Voltages in Distribution Systems, Part 1: Swimming Pools, Water Bodies, and Other Wet Areas" published in December 2010 [1]. In August 2011, the author of this report attended a hands-on two-day workshop at the EPRI test facility in Lenox where additional experiments were conducted on the swimming pool test structure. Further tests with 4 kV arc faults were conducted by EPRI on September19, 2011. There is a wealth of information that can be gleaned from the EPRI experiments, part of it is document in Section 6.2 of this report, but it is important to point out that the analysis of the EPRI data as presented in the EPRI report is primarily comparative in nature, that is, the equipotential bonding performances of various methods were compared with each other. The EPRI report does not use the data to estimate body currents and compare the results with shock hazard current levels. Consequently, the EPRI report does not contain a conclusion regarding whether the measured voltage levels for a given scenario are acceptable or not.

In order to illuminate the open questions, in particular (1) what is the absolute effectiveness of the "Single Conductor" option, (2) what body current levels can be expected during worst-case conditions, and (3) what is the variability of these current levels with pool type, deck type, environment, etc., we suggest a three-step approach that combines experimental results with results from computer simulations. This approach could also be employed to shed light on the issue of a potentially dangerous voltage gradient at the outside edge of the copper grid (item 5 above) and to explore the suitability of other equipotential bonding options that are currently not employed widely, such as the use of multiple ring conductors.

Step 1) **Conduct experiments on a test swimming pool**; preferably one with a concrete deck because, as unpublished EPRI data have shown, the measured deck-to-water voltages are more consistent and predictable for the concrete deck scenario than they are for the brick paver scenario. The measured parameters should include the deck-to-water voltage, but also other parameters, such as any measurable impedances in the current path, soil resistivity, voltages at other locations, currents, etc. The experiments should be conducted during steady-state Neutral-to-Earth Voltage (NEV) conditions and temporary fault conditions. These experiments would be similar to experiments already conducted by EPRI, but would include additional scenarios and more measured parameters.

Step 2) **Simulate the experimental setting** of the experiments conducted in the previous step in a **detailed computer model**. The computer model should account for all parameters that may have an effect on the deck-to-neutral voltage. The goal would be to recreate the experimentally determined deck-to-water voltages in a computer simulation by using all measured parameters as input to the simulation and make reasonable assumption about the parameters that could not be measured. If successful, this will result in a computer model that is verified with experimental data and therefore accurate for modeling scenarios that resemble the scenarios from the experiments.

Step 3) **Use the computer model** developed and verified in the previous step for **scenarios that were not tested in the Step-1 experiments** because they were difficult/expensive to create experimentally, such as, different pool types, different pool decks, very high (but still realistic) fault currents, different soil resistivities, etc.

EnerNex discussed the approach laid out above with Doug Dorr of EPRI and we agreed that this would be a promising undertaking for reaching solid conclusions that would give grounds for changes or reaffirmation of the equipotential methods currently listed in the NEC. Additionally, the effectiveness of equipotential methods currently not listed in the NEC could be assessed conclusively, which potentially opens the door for adopting (1) equipotential methods that are proven to be safe AND cost efficient and (2) equipotential methods that are practical options (for instance, retrofitting an existing pool with adequate protection from shocks). Mitigation options other than providing an equipotential should also be investigated experimentally and through computer simulations (for instance, reduction of the shock hazard by changing a conducting concrete deck surface to a surface that is electrically insulated, such as a wood surface).

**<u>Electrical Shock Incidents in Swimming Pool Areas</u>**

**Question:** What do we know about electrical shock incidents that have occurred in the past?

**Relevance:** This is important because knowledge about electrical shock incidence in swimming pool areas, in particular the ones that resulted in injuries and fatalities, will give insight regarding the adequacy of the employed equipotential methods. Changes to the NEC would be required if the existence of such incidence can be identified; no changes to the NEC would be necessary if such incidences can be ruled out positively.

**Conclusion and Recommendations:** The findings of our literature search are inconclusive due to the shortage of reported swimming pool incidence that resulted in injuries/death and, for the ones that were reported in newspaper articles, literature, and on the Internet, the lack of detailed information regarding the circumstances (employed equipotential method, NEC compliance, etc.) that led to the incidence. There is anecdotal evidence that the bonding employed on many swimming pools does not sufficiently protects from shocks resulting in tingling sensations (nuisance shocks) – one of such nuisance shock incidents was investigated by EnerNex at a residential swimming pool in Alabama. However, to our knowledge, there are no statistical data available that would allow the quantification of these types of complaints and it is unclear if nuisance shocks can be eliminated by employing the "Copper Grid" option instead of the "Single Conductor" option.

It is not clear if the lack of sufficient documentation of actual high-voltage electrical shock incidents that occurred on NEC compliant pools and were traceable to improper pool bonding is attributable to the non-occurrence of such incidents, or if such incidences did occur, but were not reported with sufficient details to allow conclusions regarding the effectiveness of the equipotential bonding (or not reported at all).

The results of the utility survey recently conducted by EPRI are expected to yield some insight on shock incidents in swimming pool areas. However, one difficult-to-overcome problem is the lack of detailed information related to swimming pool incidence that resulted in injuries/death. It would be beneficial if any swimming pool incidence that results in injury/death would trigger a thorough investigation that documents the circumstances that led to the incidence and that the results would be publicly available (or at least available to independent research organizations). The preliminary results of the EPRI survey indicate that only one U.S. state in which a responding utility was located in has any kind of public reporting requirement for swimming pool incidences. Other states in which non-responding utilities are located in, may have reporting requirements, but it appears that the absence of widespread reporting requirements is at the heart of the problem. Imposing nationwide public reporting requirements for electric shock incidents that occurred in swimming pool areas and that resulted in injuries would shed some light on the adequateness of the NEC bonding methods. It is important to note that utilities will not be able to provide data on all swimming pool incidents that actually occurred, regardless of reporting requirements, because utilities are often not involved in swimming pool incidents. This adds an additional difficulty to resolving the issue of obtaining complete and accurate data on swimming pool incidents. However, we do think that reporting requirements are a step in the right direction because it would at least provide some information on the number of pool incidents, even though that number would likely be an underestimation.

**Electrical Characteristics of the Human Body**

**Question:** What do we know about the electrical characteristics of the human body?

**Relevance:** This is important because the magnitude of the current flow during an electrical shock depends on the electrical impedance of the current path through the body and consequently the body impedance is a key parameter for determining safety thresholds.

**Conclusion and Recommendations:** In many studies, a body is simply represented by a 1,000 Ω resistance (for dry condition) or a 500 Ω body resistance (for wet conditions). Other studies use a more discriminating approach by selecting the body impedance based on the points of contact (e.g., hand-to-hand, hand-to-foot, etc.). Currently, no generally accepted values for body impedances exist and consequently results of studies that assess shock hazards to persons are often inconsistent. The underlying problems for the lack of standardized values are twofold: (1) experimental data on the impedance of the body when exposed to high voltages are scarce and (2) the impedance of the current path through the body is hard to define due to a large number of variables. Additional research would improve the accuracy of impedance estimates, but we argue in the report (see Section 7.1) that there are many obstacles to overcome and it is questionable if the value obtained from the research would justify the effort. Instead, we propose, based on our review of the experimental data, to either simply select a conservative value of 500 Ω for the body impedance, or adopting a more sophisticated method for the selection of the body impedance. Such a method is described in the IEC Standard 60479-1. The IEC selection process is, in our opinion, convincing because it is based on literature and accounts for the body impedance dependence on key parameters, such as the shock voltage level, the surface area of contact, and environmental conditions (dry, water wet and saltwater wet). Additionally, the statistical variation of body impedance within the population is accounted for by specifying impedance values for the $5^{th}$, $50^{th}$, and $95^{th}$ percentile of the population. The body impedances specified in the IEC apply to the hand-to-hand current path. Body impedances for other current paths may be obtained by employing correction factors; for instance, a conservative estimate for the hand-to-foot impedance would be to reduce the hand-to-hand impedance by 30%.

**Effects of Current Flow through the Human Body**

**Question:** What do we know about the effect of current flow through the human body?

**Relevance:** This is important because the current magnitude/duration as well as the current path through the body determines the injury a shock victim receives. Studies that investigate safety from electrical shocks require a benchmark to assess the effectiveness of safety strategies.

**Conclusion and Recommendations:** Current thresholds based on Dalziel’s research are widely used in the industry today for quantifying shock hazards. Dalziel and Lee [2] derived the so-called “electrocution equation” from electrocution data documented by Lee [3]. This equation can be employed to estimate current thresholds for ventricular fibrillations. The fourth edition of the IEC standard 60479-1 "Effects of Current on Human Beings and Livestock, Part-I: General Aspects," published in 2005 [4] defines various physiological effects of electrical shocks and specifies current thresholds for each of these effects. The shock duration is accounted for in the selection process. The current thresholds specified in the IEC standard were selected for a current path from the left hand to foot – the thresholds for ventricular fibrillation for other current paths can be obtained by multiplying the left hand-to-foot threshold with a heart current factor, which is specified in the IEC standard for numerous current paths. The IEC states that the current thresholds were selected conservatively and are therefore applicable to all persons of normal physiological conditions, including children.

There is a fair amount of experimental data available in the pertinent literature on the effects of currents on the human body. The data are somewhat dated (much of the data was acquired in the 1930s and later from experiments conducted by Dalziel), but we do not see any reason to question the validity of these data, which forms the basis for the current thresholds used today. However, the method to quantify the shock hazard by using only the magnitude of the current oversimplifies the problem and is sometimes non-conservative (in particular for long exposure times). In reality, shock effects depend on many variables, the key variables being the shock duration and the current path through the body. The selection process for shock current thresholds described in the IEC standard 60479-1 accounts for these two key variables and is therefore, in our opinion, the preferred method.

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# 1 Introduction

Electrical safety is important in the swimming pool/aquatic environment. An electrically safe environment in and around swimming pools can be established by creating an equipotential system. The objective of an equipotential system is to create an area where there is no significant voltage difference between objects that can be touched simultaneously thus ensuring there is no hazardous body current. These objects include concrete decking, ladders, handrails, light fixtures, and pool pumps. An equipotential system is created by intentionally connecting all these objects together electrically, a practice that is known as 'equipotential bonding'. Providing an equipotential to metallic objects can be done simply and effectively by electrically connecting these objects together via a metal wire that is attached to these objects using a connection method that conforms to code. On the other hand, equalizing the potentials of conducting non-metallic surfaces, such as concrete or brick paver decks around swimming pools, nearby objects, and the swimming pool water is more challenging if the deck is not constructed with internal metallic bonding, such as structural reinforcing steel. Essentially, the outside of the non-metallic conductive pool deck is on earth potential, while the bonded objects near the pool and the water are on neutral potential. A potential difference between the neutral and the surrounding earth will result in a voltage gradient that spans from the pool water to the outside part of the deck section. A person that bridges the gap between the "water potential" and the "deck potential" (for instance, a person in the swimming pool touching the deck or a person outside the pool standing on the deck and touching the water) is in danger of receiving an electric shock if the neutral-to-earth voltage is large. Equipotential bonding of the deck, other objects near the swimming pool, and the water is needed to minimize the potential difference sufficiently so that a shock hazard is eliminated.

Article 680.26(B)(2) in the National Electric Code (NEC) NFPA 70-2011 requires bonding to the swimming pool deck if the swimming pool deck has a conductive surface, such as a concrete decks and brick paver decks. NEC defines the perimeter surface as the surface that extends three feet horizontally beyond the inside wall of the pool. The code requires that bonding to the perimeter surface shall be provided by either one of the following bonding methods:

- **Structural Reinforcing Steel**, which shall be bonded together by steel tie wires or equivalent bonding means.
- **Alternate Means**, which shall comply to the following requirements:
    - At least one minimum 8 AWG solid copper conductor shall be provided.
    - The conductors shall follow the contour of the perimeter surface.
    - Only listed splices shall be permitted.
    - Installed at a minimum of 18 inches and at a maximum of 24 inches from the inside walls of the pool.
    - Secured within or under the perimeter surface 4 inches to 6 inches below the subgrade.

Two implementations of the "Alternate Means" option are listed here:

1) A **single 8 AWG solid copper conductor** that follows the contour of the perimeter surface and is installed 18 inches to 24 inches from the inside walls of the pool. This implementation is the minimum-requirement "Alternate Means" option and is referred to in this report as the **"Single Conductor"** option.
2) A **Copper Conductor Grid** constructed of a minimum 8 AWG bare solid copper conductors bonded together at each point of crossing that follows the contour of the perimeter and is installed from the pool wall out to a minimum of 18 inches from the pool wall. The copper conductor grid also

conforms to the requirements listed in the "Alternate Means" option. This option is referred to in this report as the **"Copper Grid"** option.

The only "Alternate Means" option permitted in the 2005 version of the NEC code was a copper grid that extends a minimum of 3 feet horizontally from the inside wall of the pool and that has a 12 inch by 12 inch rectangular grid pattern, which complies to the "Cooper Grid" option described above. The 2008 and 2011 versions of the NEC code include the "Single Conductor" option as an economic alternative to the "Copper Grid" option. There has been some controversy related to the effectiveness of the "Single Conductor" option in reducing voltage gradients in swimming pool areas to safe levels. Notable studies on this subject were conducted previously by the Electric Power Research Institute (EPRI) and the National Electric Energy Test Research & Application Center (NEETRAC). In these studies the effectiveness of the "Single Conductor" option and the "Copper Grid" option were compared. A brief summary of the experiments conducted and the findings by EPRI and NEETRAC is provided below:

1) In 2008 EPRI constructed a swimming pool at Lenox, MA test facility to evaluate the NEC "Copper Grid" and "Single Conductor" options and also to assess other implementation of the "Alternate Means" option. The conclusion of their experiment based on different NEV and fault scenarios was that the "Copper Grid" option was more effective than the "Single Conductor" option and other options. For the "Copper Grid" option the voltages stayed at less than one volt for every condition, including high-current faults, and never exceeded a tenth of a volt for the steady-state neutral-to-earth-voltage tests. On the other hand, the voltages were in the order of tens of volts during fault conditions if only the "Single Conductor" option was employed. [1]
2) In 2008, NEETRAC conducted tests at a residential pool in Buford, Georgia in 2008 to compare the equipotential bonding effectiveness of the "Copper Grid" option with the effectiveness of the "Single Conductor" option. Based on their experimental results they concluded that the "Copper Grid" option was more effective in mitigating the voltages than the "Single Conductor" option. The "Copper Grid" option reduced the water-deck voltage to values that were 70% to 93% lower than the voltages measured when the "Single Conductor" option was employed. Step voltages were reduced to values that were 57% to 97% lower than the voltages measured when the "Single Conductor" option was employed [5].

Based on the experiments and analysis conducted by NEETRAC, an amendment in the code to require a "Copper Grid" was proposed. Code-Making Panel 17 (CMP-17) rejected the proposed changes on the basis of insufficient evidence of the inadequacy of the "Single Conductor option. Specifically, they noted that for the NEETRAC tests where bonding was provided by the "Single Conductor" option, none of the measured voltages were flagged as "unsafe". Also, the code officials questioned the general applicability of the NEETRAC results because the experiments were conducted at only one swimming pool in Georgia, thereby implying that the results would be different for different swimming pools/pool types and perhaps different for different localities [6].

The objective of his study is to clarify the issue by documenting the information that is known and identify knowledge gaps based on information from the pertinent literature, and previous and ongoing research on this subject. Of particular interest is providing answers to the following three key questions:

1) What are the voltage levels persons in swimming pool areas are exposed to if the "Single Conductor" option is employed?
2) What is the voltage threshold that results in "unsafe" body currents?
3) Have persons been injured by electrical shocks in swimming pool areas where the pool was in compliance with NEC requirements?

## 2 Swimming Pool Types

There are three basic swimming pool types that are commonly used today, i.e., (1) above-ground pools, (2) portable pools, and (3) in-ground pools.

**Above-ground swimming pools** are constructed on or above the ground and are capable of holding water to a maximum depth of 1.0m (42 in.); they are also pools with nonmetallic, molded polymeric walls or inflatable fabric walls regardless of dimension [7]. Above-ground pools comprise two types: (1) soft-sided pools and (2) hard-sided pools. The soft-sided pools are constructed from rubber or latex. Hard-sided pools are constructed using metals and fiberglass, which makes them more durable and expensive [8]. Hard-sided pools often have an elevated wooden deck constructed around them. Above-ground pools are usually less expensive than in-ground pools and are typically easier to install. However, their lifetime is typically shorter than the lifetime of in-ground pools. Often above-ground pools are viewed as aesthetically less appealing than in-ground type pools.

**Portable swimming pools** are small pools that can be taken to any location, filled/drained easily, and conveniently stored when not in use. They are typically made of inflatable plastic.

This study focuses on electrical safety for **in-ground swimming pool structures**. In-ground swimming pools are swimming pools that are constructed in the ground or partially in the ground, capable of holding water in a depth greater than 1.0 m (42 in.), and all pools installed inside of a building, regardless of water depth [7]. Discussed below are the some of the commonly shell types used in-ground pools:

- **Poured concrete pools** involve the pouring of concrete into wooden frames for its construction [8]. Poured concrete pneumatically applied or sprayed concrete or concrete block with painted or plastered coatings are considered conductive materials due to water permeability and porosity [9] [10]. Rebar is reinforcing steel that is used for structural support of concrete swimming pool structures. It is installed in a grid pattern under the concrete pour. Some swimming pool structures employ 'bare' rebar, which acts as an equipotential grid but is subjected to rust and corrosion. Other swimming pool structures employ rebar that is encapsulated in a non-conductive compound, such as epoxy, to protect it from deterioration. This type of rebar is electrically insulated and does not function as an equipotential grid.
  Poured concrete pools are highly customizable giving the customer many option regarding the pool layouts. However, the installation of this type is difficult and time consuming.
- **Fiberglass pools** are made from fiberglass-reinforced plastic, which are molded into a basin shape [9]. Fiberglass is an insulator and consequently cannot be used for establishing an equipotential system. Fiberglass pools have lower maintenance costs as compared to the vinyl type and are usually installed by professional swimming pool installers using pre-made shells [8].
- **Vinyl-liner in-ground pools** are the most commonly used type of in-ground pools. For this type, soil is dug out, a frame is constructed for the pool structure, and sand is placed at the bottom. The walls constructed out of metal, wood or plastic are covered with a vinyl liner. The vinyl liner is a thin insulator; the wall material may or may not be an insulator. These pools are relatively inexpensive compared to poured concrete and fiberglass pools. However, the vinyl lining needs to be replaced every few years [8].
- **Gunite Pools** are installed by creating a 'steel reinforcing rod framework' called 'rebar rods' [8]. This framework of steel rods is built within the space dug out for the pool. The framework is then sprayed with a heavy gunite (which is a mixture of cement & sand mixed with water) coating, smoothened and left for a week, after which the plaster is added to give it a smooth finish. These pools are designed as per requirement and last longer than other types.

- **Shotcrete pools** are created from a variation of concrete and gunite. The main difference from concrete is that shotcrete is sprayed. The spray application is similar to gunite however it differs because the water is premixed with the cement and sand in the mixer prior to arriving at the jobsite. Shotcrete is sprayed on with a pressurized hose in order to form the walls and floor. If the shotcrete happens to crack or decompose in any way, it must be repaired by a pool professional, specializing in shotcrete applications and renovations [11].

# 3 Sources for Electric Shocks in Swimming Pool Areas

This section provides a description of common sources of electric shocks occurring in swimming pool areas.

## 3.1 Elevated Neutral-to-Earth Voltage

Elevated Neutral-to-Earth Voltage (NEV) in distribution systems has long been a concern for reasons of power quality, and because of its ability to create unacceptably high step-and-touch potentials in publicly and privately accessible locations. NEVs are caused by unsymmetrical networks, unbalanced loads, harmonics, and the common practice of grounding the neutral conductor at multiple points throughout the power system. Conventional NEV analysis on three-phase systems focuses on the residual neutral return due to the unbalance on the system and loading at the fundamental frequency.

Non-linear loads in distribution systems generate harmonics, which can contribute to the neutral-conductor voltage. Triplen harmonics (especially the third) are of particular concern because they add arithmetically in the neutral conductor (as opposed to non-triplen harmonics, which completely cancel in the neutral if the system is perfectly balanced). Harmonic distortion levels can be excessive for systems that have resonances at the same frequencies of the harmonics produced by the non-linear loads. This situation may be encountered in three-phase wye grounded distribution systems with distributed power-factor-correction capacitor banks [1] because the capacitance of the capacitor banks may lower the resonance frequencies close to 180 Hz, that is, the third harmonic, which, as mentioned above, adds arithmetically in the neutral and many non-linear load produce third harmonics.

Harmonics can be particularly troublesome in the vicinity of substation [12]. In [13], the authors discuss a case of elevated NEV measurements at a swine farm where the animals experienced shock sensations from the metal water spouts. Closer analysis revealed the triplen harmonics in the neutral current, at the nearby substation (located about 200 m from the farm), as the main cause. The authors showed that without the triplen current harmonics, the NEV waveform would not have exceeded the 4 V threshold recommended by the United States Department of Agriculture Handbook #696.

Studies show increased NEV levels at buses on multi-grounded distribution systems. In [14] neutral-to-earth voltage measurements taken on the primary side of a distribution transformer at a bus located at the end of a multi-grounded feeder revealed potential difference between the neutral point and the local ground of 31 V. This high neutral voltage was caused by the flow of the harmonic currents in the neutral conductor due to both linear load unbalance and the non-linear characteristics of electrical equipment throughout the feeder. According to measurements, the largest harmonic components of the neutral voltage were the 2nd, 3rd, 4th, and 5th harmonics.

In multiple neutral earth system both neutral and earth are connected together [15]. In addition, the earthing is bonded together with gas/water pipes in order to improve overall earthing in a household system. Properly grounded and bonded electrical systems offer safety, are beneficial for the correct operation of the electrical system, and maintain power quality/harmonics when fault occurs [15]. In properly grounded and bonded systems, fault current is diverted safely to ground. On the other hand, if a low-impedance ground cannot be established and/or equipment is insufficiently bonded (i.e., the contact impedance is high due to, for instance, a loose bonding connection), there may be a significant potential difference in the system, in particular during faults, which may cause an electrical shock to people in contact with the grounded/bonded equipment (e.g., the enclosure of the pool pump or a metal pool ladder). Fault types are (1) reverse polarity, (2) neutral failure, (3) earthing failure, (4) high-impedance faults, and (5) burn-out in direct burial cables. [15].

### 3.2 Line Faults

Faults on distribution lines usually occur if there is a conducting path between an energized phase conductor and another phase conductor (line-to-line fault), ground (line-to-ground fault), or the neutral conductor (line-to-neutral fault). The conducting path can be established by a low-impedance connection, such as a metallic object, which results in a bolted fault or a high-impedance connection. An example for a high-impedance connection is an arc fault, where current is flowing through the air. Fault current flowing to ground will elevate the electrical potential near the fault current injection point which may be transferred to nearby swimming pools via conduction.

In general, there are two types of faults – permanent faults and temporary faults. The latter are usually cleared within a few cycles. Temporary faults constitute between 50% and 90% of all faults on overhead distribution systems; regional variation is one factor that influences the percentage value. Faults on underground systems are almost always permanent [16].

An EPRI study conducted in the 1980s characterized distribution faults based on data obtained from 13 utilities monitoring 50 feeders [17]. The study showed that lightning, tree contact, and equipment failure were the three major causes for permanent faults on distribution lines – the three causes constituted about 55% of all faults. About 40% of all faults in this study occurred during adverse weather (rain, snow, and ice). Seventy-five percent of all faults involved the transfer of electrical potential to ground. Most faults on distribution lines are single-phase faults (not surprisingly because distribution lines are predominantly single phase) [16].

Various studies determined fault rates on overhead distribution lines and found annual fault rates ranging between 70 and 99 faults per 100 miles of line for the Northeastern US, Virginia, the Southeastern US, and South Carolina, but also much higher annual fault rates of 317 faults per 100 miles of line for Florida [16]. Apparently, fault rates are much higher in areas with high lightning activity. Areas with relatively low lightning activities have generally lower fault rates – for instance, the annual fault rate in England was determined to be 35 faults per 100 miles of line [18].

### 3.3 Faulted Equipment

Electric shocks can be due to faulty equipment or wiring problems. Commonly faulted equipment in pool areas are the electric motors used in swimming pool pumps. Faulted equipment/wiring problems typically result in a short circuit between the hot wire and ground/neutral.
Failing insulation may also result in faults – insulation degrades over time due to exposure to environmental conditions. Exposure to environmental conditions widens already existing small openings in cable insulations, porcelain insulators used in overhead lines crack, and polymer insulators can become covered with contaminants. As a result, they allow electrical tracking across the insulated path, creating high-impedance faults and thus a potential for a contact voltage condition [19].

### 3.4 Inadvertent Energization

Accidental energization occurs if a de-energized circuit is inadvertently re-energized (1) due to reconnection to its normal source or (2) by contact with an energized circuit.

### 3.5 Magnetic Field Coupling From Nearby Energized Conductors

Magnetic field coupling is the transfer of energy between a current-carrying conductor and nearby conductors due to a time-varying magnetic field that is created by time-varying current in the energized conductor. The magnetically induced current in each nearby conductor will be slightly different since it depends on the relative location of each individual conductor to the energized conductor. If the conductors are in parallel, the induced current is proportional to the inducing current. While currents from magnetic field induction in a loop are typically larger than currents caused by electric field induction in similar configurations, the magnetically induced currents are impeded by the impedance of the body. This does not mean magnetically induced currents are not dangerous. Both electric and magnetic field induced currents can be fatal in given situations [20].

### 3.6 Electric Field Coupling From Nearby Energized Conductors

Electric field coupling is the transfer of energy between an energized conductor and the nearby conductors due to a time-varying electric field that is created by moving charge in the energized conductor. For electric field induction under normal conditions, the induced voltage in the nearby sink conductor depends on the operation voltage and the relative location to the energized source conductors. The induced voltages result in current flow if the sink conductor is grounded. If a person gets in series with the sink conductor and ground, approximately the magnitudes of the current flowing in the sink conductor and the current flowing through the person will be very similar because the impedance of the driving voltage source is considerably larger than the impedance of the worker (assuming a typical body impedance of 1000 Ω or less).

### 3.7 Galvanic Corrosion

Galvanic corrosion is an electrochemical process that takes place when two different metals come into contact with an electrolyte. The conductive medium could be an impure water or soil moisture, which results in a flow of direct current (DC) electricity [21]. The current always flows away from the anodic metal (anode) to the cathodic metal (cathode) through the electrolyte. In the process, the anode is always corroded while cathode is not corroded. The current flow is a result of the different electrode potentials of the two different metals and the ion migration from the anode to the cathode, which is facilitated by the electrolyte. Galvanic corrosion can also occur on a single metal due to an inhomogenous metal surface or a so-called concentration cell. Concentration cell corrosion occurs when two or more areas of a metal surface are in contact with different concentration of the same electrolyte. When the electrical current leaves the anode to enter the electrolyte, small iron particles are dissolved into a solution causing pitting at the anode. When the current enters the cathode, molecular hydrogen gas forms on the surface of the cathode protecting it from corrosion.

For a piece of pipe or a long pipeline buried in the ground, the moisture in the soil acts as the electrolyte [21]. The anode and the cathode areas are both on the same pipe structure, and the pipe itself provides the return circuit. The different physical conditions in the soil environment create two factors that affect the rate of galvanic corrosion: (1) low resistance or high electrolyte conductivity and (2) the chemical components which comprise the corrosion cell created as a result of various physical conditions of the soil. Thus, the rate of corrosion in salt-polluted soils is found to be greater as compared to the pipe backfilled with high resistant sand or gravel. When a piece of steel pipe is buried in the ground, the solution potential of the steel is observed to be approximately one-half volt and in a piece of buried galvanized steel pipe, it is over one volt.

We did not find documentation in the pertinent literature of galvanic corrosion in the context of swimming pool shocks. However, it appears that dc voltage due to galvanic corrosion exist in some swimming pool areas, as indicated by our case study of a nuisance shock incident at a residential swimming pool in Alabama (see Section 5.2). At this pool, EnerNex measured a dc voltage of approximately 1 V between the pool water and remote ground. After excluding all other sources for the dc voltage, we attributed the presence of the dc voltage to galvanic corrosion, possibly facilitated or augmented by the saltwater in the swimming pool (the saltwater, or salt-polluted soils around the swimming pool acting as an electrolyte). However, the voltage we measured between the deck of the swimming pool and the water did not have a significant dc component and consequently, for this particular incident, the dc voltage was apparently not a contributor for the nuisance shocks.

# 4 Electricity and the Human Body

Any voltage imposed on a person results in current flow through that person. The magnitude of this current flow depends on (1) the magnitude of the voltage and (2) the electrical impedance of the current path through the body – according to Ohm's law, the current magnitude is proportional to the applied voltage and inverse proportional to the impedance of the current path. The body current is one of the two critical electrical parameters for determining the effect an electrical shock has on the human body (the other important parameter is the duration of the electrical shock) and is therefore important for determining safety thresholds. Safety thresholds are often specified in terms of the voltage a person is exposed to. The voltage level that, if exceeded, causes harm to a person can be estimated from the body impedance and the current thresholds.

This section addresses the current flow through the human body. We reviewed the literature to find answers to the following three questions:

1) What is an accurate representation of the electrical impedance of the human body – in particular in a wet environment, such as swimming pool areas?
2) What is the effect of electrical current flow through the human body?
3) What are safety limits for voltages a person can be exposed to?

## 4.1 Electrical Characteristics of the Human Body

**The body is a resistor (more or less)…**

Traditionally, electrical studies use a simple resistor to represent the current path through the human body. This representation is accurate if the current is only composed of a single frequency, which is often the case, and if the impedance does not change during the shock event, which is typically not the case. For example, fault currents that cause electrical shocks are mostly composed of power-frequency components (50 or 60 Hz) and an electrical circuit in which the human body is represented as a resistor would be appropriate. However, the impedance of the skin does change if the shock current is substantial as high shock currents cause skin to break down, which changes the skin's electrical characteristics.

**but frequency is important**

An electrical shock caused by, for instance, a lightning strike requires a more complex electrical representation of the human body because a current surge due to a lightning strike is composed of a frequency spectrum ranging from quasi DC to up to 1 MHz, or so. Consequences are that inductive and capacitive characteristics[1] of the human body need to be accounted for and other effects become important, such as the tendency of currents with higher frequencies to flow closer to the surface of the body/object they are traversing. This effect is known as the "skin effect". The skin depth is a measure of the skin effect – it is the distance from the surface (in the case of the human body, the skin) at which the electrical current is 37% lower (or, more accurately, lower by a factor of 1/e, where 'e' is Euler's constant) than the current flowing at the surface. For example, the skin depths for a 10 kHz current flowing through an object is 0.76 mm, which means that if a current of 100 A current would flow on the surface, a current of only 37 A would flow at a depth of 0.76 mm, and even lower currents would flow at deeper depths. Even at power frequency current, the skin effect is significant – the skin depth for 60 Hz is approximately 1 cm. A third harmonic current (180 Hz), which is often present in elevated Neutral-to-Earth voltages (see Section 3.1), has a skin depth of about 6 mm. Note that the current path through the human body is

[1] The IEC standard states that the impedance of the human body is mostly resistive, but has also a small capacitive component.

important if damaging effects of electrical shocks to internal organs, in particular the heart, are assessed. For the remainder of this section, we focus on the electrical representation of the human body in response to power-frequency currents, but it is important to keep in mind that (1) the power-frequency impedance changes with frequency and (2) the current path through the human body changes with frequency.

The total impedance of the body can be viewed as being composed of two impedances- internal body impedance and skin impedance. The **internal impedance** is mostly resistive and its resistance value mainly depends on the current path and to a lesser extent on the contact surface area. The **skin impedance** offers the greatest opposition to the current flow and it also varies widely over the body surface [22]. The skin impedance is much more complex to characterize than the internal impedance because it shows nonlinear behavior with respect to voltage and shock duration. This is due to the fact that skin exposed to extended duration of high currents changes its electrical properties over time. The skin can be viewed as a network of resistances and capacitances and varies with the values of touch voltage, frequency, duration of current flow, surface area of contact, pressure of contact, the degree of moisture in/on the skin, temperature, and type of skin [4]. For lower touch voltages the skin impedance is high and shows much variability. On the other hand, higher touch voltages have lower skin impedances and the skin impedance becomes negligible once the voltage is high enough to cause the skin to break down. Skin breakdown becomes significant at touch voltages between 450 V and 1,000 V [23]. Similar to the impedance of a capacitor, the skin impedance is lower for higher frequencies [4] and consequently this is an indication that the capacitive characteristics of the skin impedance are significant[1]. Reily [24] specifies the capacitance of the skin to be in the range of 0.02 to 0.06 $\mu F/cm^2$. The total impedance for a given current path is calculated by adding the internal impedance for all the body parts the current traverses to the skin impedance of the surface areas of contact.

### *4.1.1 Body Impedances from IEC 60479-1*

The fourth edition of the IEC standard 60479-1 "Effects of Current on Human Beings and Livestock, Part-I: General Aspects," published in 2005 [4] includes a comprehensive treatment of the body impedance for different conditions. The body impedance values are based on experimental data from low-voltage experiments conducted on living persons and on data from high-voltage experiments conducted on corpses.

**Internal Impedance**

Figure 1 shows the internal impedance of the body for different parts expressed as a percentage of the path from hand to foot (data from Reily [24] and IEC 60479-1 [4]). For instance, for the current paths "hand-to-hand" and "hand-to-foot", the bulk of the impedance is in the arms and legs. As mentioned above, the internal impedance does not vary much with contact surface area, but the skin impedance does.

The IEC standard specifies the total body impedance for a range of touch voltages for different scenarios – large surface area of contact (10,000 $mm^2$), medium surface area of contact (1,000 $mm^2$) and small surface area of contact (100 $mm^2$)in dry, water-wet[2] and saltwater-wet[3] conditions [4]. For **large surface contact**

[1] A capacitor's impedance is lower for higher frequencies.

[2] The IEC standard defines water-wet conditions as the condition where the skin of a surface area of contact is exposed for 1 minute to water of public water supplies (average resistivity φ= 3,500 Ωcm, pH = 7 to 9).

[3] The IEC standard defines saltwater-wet conditions as the condition where the skin of a surface area of contact is exposed for 1 minute to a 3% solution of NaCl in waters (average resistivity φ= 30 Ωcm, pH = 7 to 9).

**area** (10,000 mm$^2$), total impedances were determined experimentally or derived for touch voltages ranging from 25 Vac to 1000 Vac.

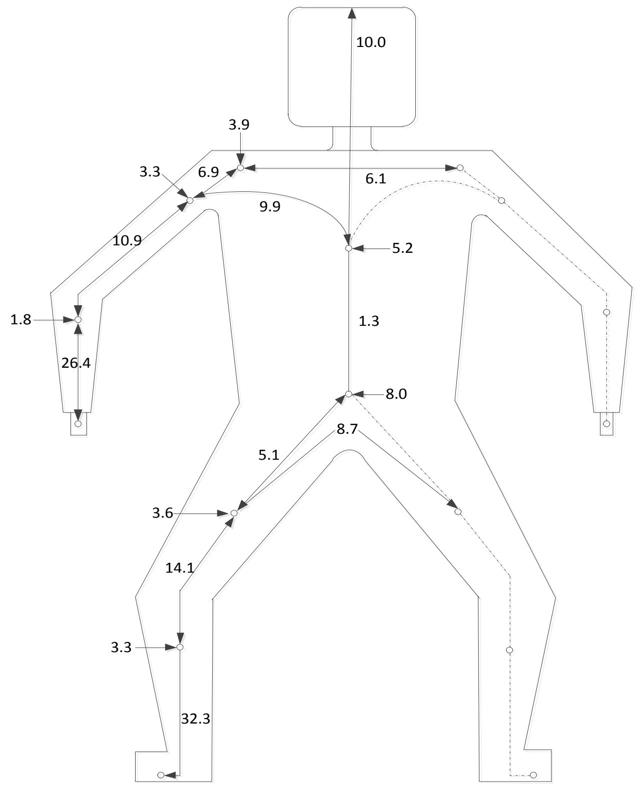


**Figure 1: Internal impedances of the human body. The impedances are normalized percentage values with respect to the total hand-to-foot impedance. Data adopted from Reily [24] and IEC 60479-1 [4].**

The impedances for **touch voltages from above 25 Vac to 200 Vac** are based on experimental data. The IEC standard does not explicitly state the source of these data but, based on the description of the experiments in the IEC standard, it appears that the data is from experiments conducted by Biegelmeier, which were published in 1979[1] [25]. The impedance measurements for this voltage range described in the IEC standard were conducted on living human beings and are summarized below:

- The body impedances in the experiments conducted with living human were the measured total **hand-to-hand impedance**.
- Body impedances for **dry conditions** were measured on **100 living persons** at 25 Vac (50 Hz) using electrodes with **large surface areas** (brass cylinders with effective sizes of the contact areas of 8,200 mm$^2$). These measurements were made 100 ms after applying the voltage.
- Body impedances for **dry, water-wet, and saltwater-wet conditions** were measured on **10 living persons** using electrodes with a **medium surface area** (rings with effective sizes of the contact

[1] Hammam and Baishiki [29] describe Biegelmeier's experiments and the description matches the description of the experiments from which the IEC data are from.

areas of 1,250 mm$^2$) and a **small surface area** (squares with effective sizes of the contact areas of 100 mm$^2$). The maximum duration of the currents was 25 ms.

- Body impedances for dry, water-wet, and saltwater-wet conditions were measured on **one living person** using touch voltages **up to 200 V**. The larger touch voltages were limited to a duration of 30 ms. In addition to the **large-surface- area** and **medium-surface**-**area** electrodes described above, two other electrode types with **small surface areas** were employed: (1) a circular electrode with an effective surface area of 10 mm$^2$ and (2) a circular electrode with an effective surface area of 1 mm$^2$. The measurements were made 20 ms after applying the voltage.

The IEC standard bases impedances for touch voltages above 200 V on a different set of data, which were published by Freiberger [26] in 1934. Freiberger measured impedances on a large number of corpses for a hand-to-hand current path and a hand-to-foot current path. The electrodes had a large surface area (about 9,000 mm$^2$). The touch voltages ranged from 25 V to 5,000 V in dry conditions. Measurements were made 3 s after applying the voltage. Note that the impedance values measured on the corpses for voltages up to 220 V had to be adjusted to match the impedance of living persons – apparently this adjustment was necessary because of the lower temperature of corpses compared to living persons resulted in higher skin impedances. Missing data were filled in by using calculations and assumptions based on the known data. For instance, deviation factors for the 5$^{th}$, 50$^{th}$, and 95$^{th}$ percentiles of the population were calculated from statistical significant experimental data such as the low-voltage experiments conducted on 100 living persons and applied to data with smaller sample values, such as the higher-voltage experiments conducted on only a single person.

In this section, we present graphs based on the hand-to-hand body impedances specified in the IEC standard selected for scenarios that resemble scenarios in swimming pool areas, that is, the body impedance for large surface areas of contact (e.g., a person immersed in water), small surface areas of contact (e.g., a person holding a skimmer), water-wet conditions (e.g., fresh water pools), and saltwater-wet conditions (e.g., saltwater pools). Impedance graphs for additional scenarios, including medium surface area of contact and DC, are in Appendix B.

We plotted the IEC impedances versus hand-to-hand contact voltage for 5$^{th}$, 50$^{th}$, and 95$^{th}$ percentiles of the population on semi-logarithmic scale (Figure 2 through Figure 5). For example, the 95$^{th}$ percentile graph in Figure 2 shows that for a large surface area and water wet conditions 95% of the population have a body impedance of at least 2,000 Ω if the hand-to-hand voltage is 200 Vac. It is apparent from the figures that (1) larger surface areas of contact result in smaller impedances and (2) the impedance values for saltwater-wet conditions are lower than the respective impedances for water-wet conditions (and much lower than the respective impedances for dry conditions). Interestingly, large surface areas of contact and high voltage have an equalizing effect for the impedances for different conditions, that is, the body impedance are fairly similar for dry, water-wet, and saltwater wet conditions for (1) large surface areas of contacts and (2) voltages of 200 V and above. Note also that the lowest impedance value is 575 Ω, which is the impedance value for the 5$^{th}$ percentile of the population for large surface areas of contact during saltwater wet conditions and a contact voltage of 700 V and above.

An often expressed concern is that the body impedance is lowered if the skin is punctured or otherwise broken and consequently lower values should be used if this is the case. This is true if low-voltage body impedances are used for a person with punctured skin – the selected low-voltage impedance will possibly be not low enough. However, the skin condition (broken or intact) does not impact the IEC values for high-voltage body impedances because the current flow resulting from high voltages will break down the skin, anyway, thereby making the skin impedance negligible.

When evaluating the shock hazard in swimming pool areas, the hand-to-hand impedance is not always the impedance of interest. For instance, the hand-to-foot impedance is important to assess the shock hazard for a person standing on the swimming pool deck and skimming the water with a conductive pool skimmer. Experimental data (see Table 1 in Section 4.1.2) shows that the hand-to-feet impedance of a person is generally lower than the hand-to-hand impedance of the same person. The IEC standard suggests that hand-to-foot impedances are approximately 10% to 30% lower than corresponding hand-to-hand impedances. Based on the information given in the IEC, it appears that the 500 Ω value often used to represent the body impedance of persons in swimming pool areas is a reasonable and conservative value.

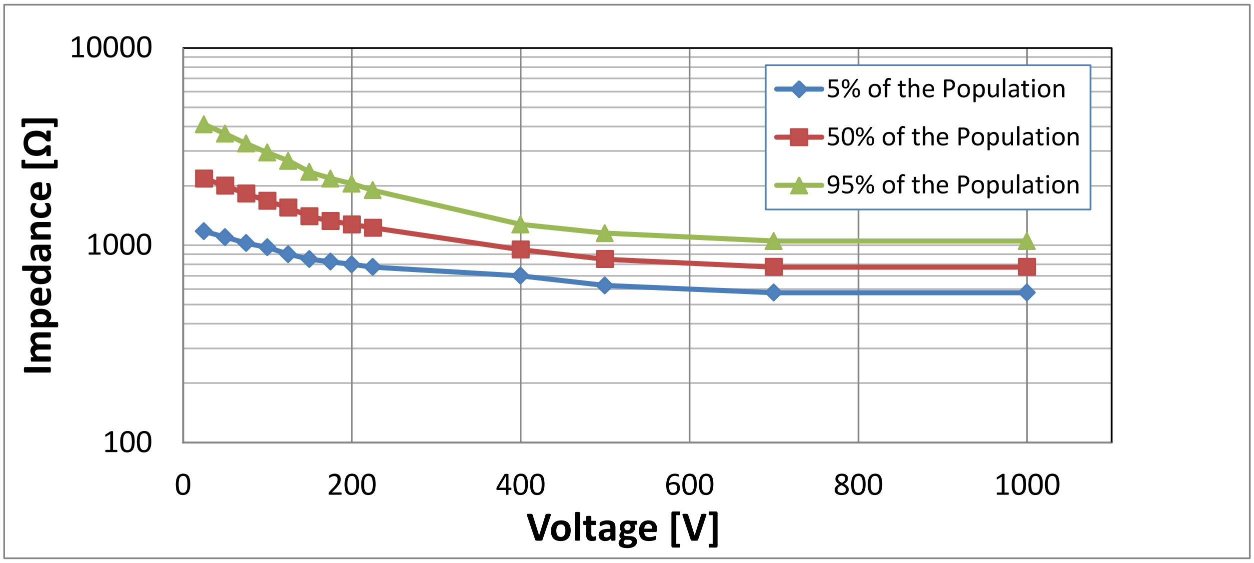


**Figure 2: Total body impedances $Z_T$ for a hand-to hand current path, ac 50/60 Hz, large surface areas of contact, water-wet conditions.**

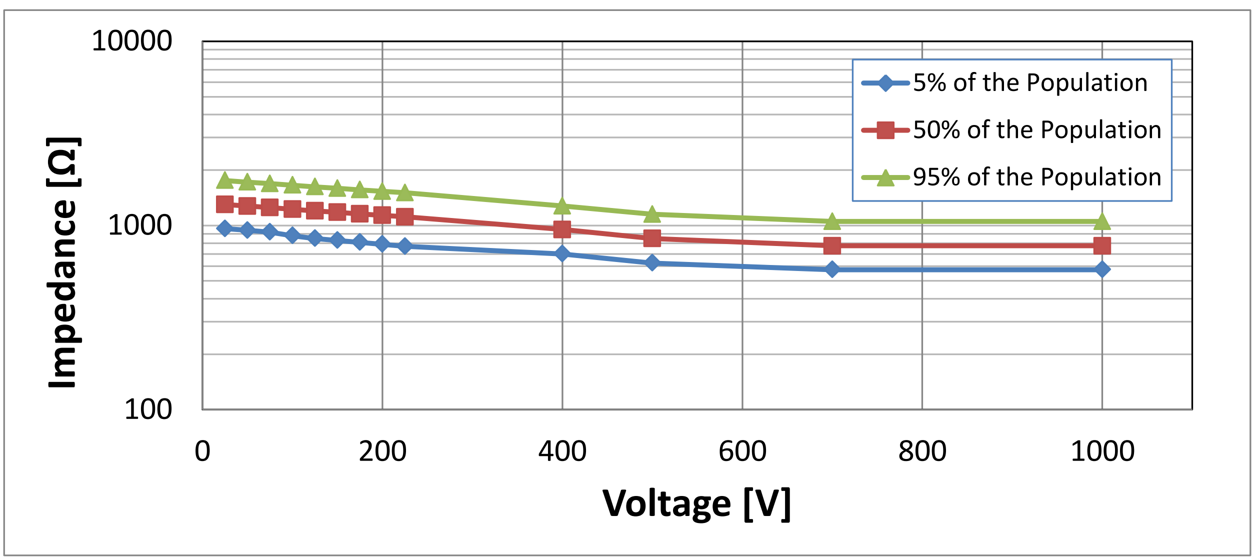


**Figure 3: Total body impedances $Z_T$ for a hand-to hand current path, ac 50/60 Hz, large surface areas of contact, saltwater-wet conditions.**

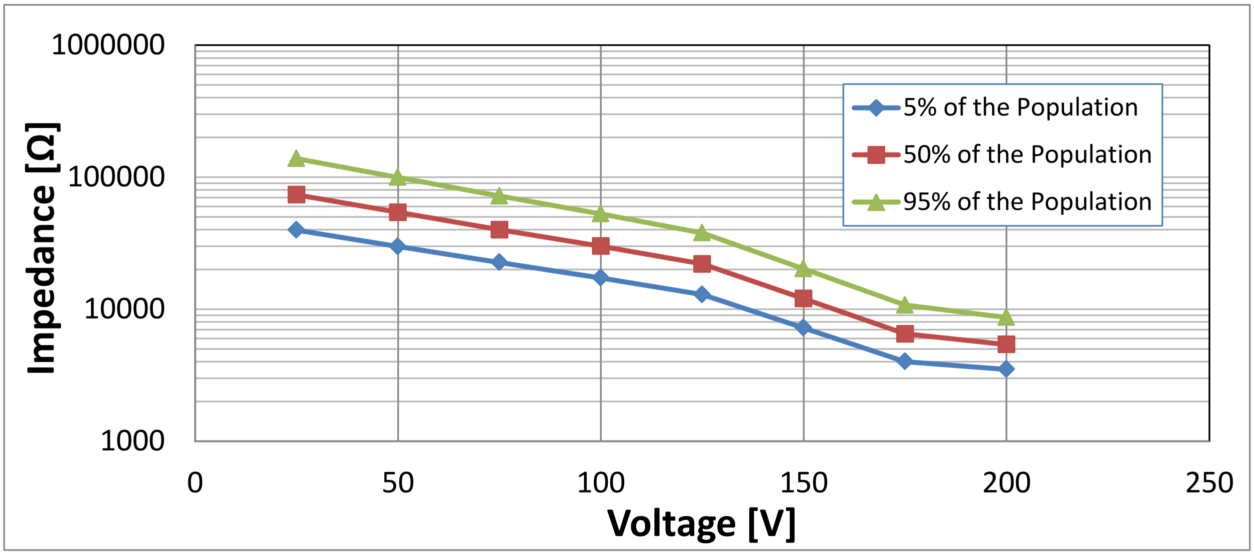


**Figure 4: Total body impedances $Z_T$ for a hand-to hand current path, ac 50/60 Hz, small surface areas of contact, water-wet conditions.**

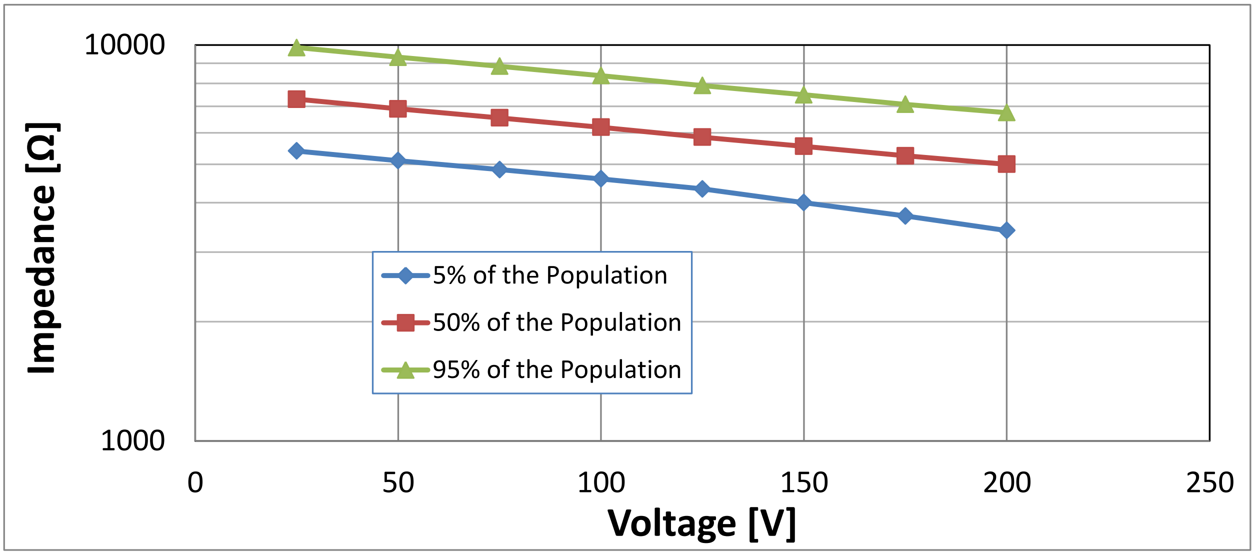


**Figure 5: Total body impedances $Z_T$ for a hand-to hand current path, ac 50/60 Hz, small surface areas of contact, saltwater-wet conditions.**

#### *4.1.2 Body Impedances from Other Studies*

IEEE Std. 80-2000 [27] gives recommended values for body impedance which are based on research conducted by Dalziel et al. [28] [29] [2], Geddes and Baker [30], Geiges [31], Kiselev [32], and Osypka [33]. According to these studies, the internal body impedance is approximately 300 Ω and the total body impedance, including the impedance of the skin, ranges from 500 Ω to 3,000 Ω. For example, Dalziel and Massogilia [34] determined experimentally that the hand-to-hand body impedance for saltwater wet conditions is 2,330 Ω and the hand-to-feet body impedance for saltwater wet conditions is 1,130 Ω. Based on Dalziel's and Massogilia's research, IEEE Std. 80-2000 uses 1,000 Ω for hand-to-hand and hand-to-feet body impedances, which is stated to be a conservatively low value that neglects hand and foot contact impedances and the impedance of gloves/shoes. Dalziel [28] states that often a comparably low impedance of 500 Ω is used as a conservative value for the body impedance between major extremities to estimate shock currents during industrial accidents, but does not mention the research this impedance value is based on.

Burke and Untiedt [35] experimentally determined hand-to-hand impedances for full-hand contact with solid metal objects and maximum pressure to minimize contact impedance. They measured impedances of 172 kΩ, 10 kΩ, and 5 kΩ for dry-skin conditions, water-wet skin conditions, and saltwater-wet skin conditions, respectively. Based on these results, Burke and Untiedt suggest that a 1,000 Ω resistance is "fairly conservative in most situations".

Whitaker [36] experimentally determined the body impedances of 47 children of ages ranging from 3 years to 15 years and 40 adults using a 12 Vdc battery. The average dry/wet impedance for adults was determined to be 4,838/865 Ω. The average dry/wet impedance for children was generally higher than the corresponding impedance of adults and determined to be 6,046/1,443 Ω.

Table 1 summarizes the findings of the aforementioned references for ac impedances under different skin contact conditions.

**Table 1: Human impedance values under different skin contact conditions and environment**

| Type of Skin-contact | Contact Condition | Source | Body Impedance | Comment |
|---|---|---|---|---|
| Hand-hand and Hand-foot | Not specified | IEEE Std. 80-2000 [27] | 1,000 Ω | - |
| Hand-foot | Saltwater wet | Dalziel and Massogilia [34] | 1,130 Ω | - |
| Hand-hand | Saltwater wet | Dalziel and Massogilia [34] | 2,330 Ω | |
| Hand-foot | Water wet | Hammam and Baishik 1983 [22] | 1,000 Ω | Impedance measured with 11 Vac voltage source |
| Hand-hand | Water wet | Hammam and Baishik 1983 [22] | 1,300 Ω | |
| Hand-foot | Dry | Hammam and Baishik 1983 [22] | 3,000 Ω | |
| Hand-Hand | Dry | Hammam and Baishik 1983 [22] | 5,000 Ω | |
| Hand-Hand | Dry | Burke and Untiedt [35] | 172,000 Ω | Impedance measured for full-hand contact with solid metal objects and maximum pressure. |
| Hand-Hand | Water wet | Burke and Untiedt [35] | 10,000 Ω | |
| Hand-Hand | Saltwater wet | Burke and Untiedt [35] | 5,000 Ω | |

## 4.2 Current Thresholds

The effect electric current has on the human body depends on (1) the magnitude of the current, (2) the duration of the current flow (3) the frequency of the current, and (4) the current path through the body. The current path is largely determined by the point of entry and point of exit of the current. For instance, current flowing from one hand to the other hand or from hand to foot are likely to traverse the heart and are therefore much more likely to be fatal than currents flowing from one foot to the other foot. The current path from hand to foot is considered to be one of the most dangerous path for shock currents [37], although a current path from the chest to a hand may be even more likely to be fatal as an even greater fraction of the total current will flow through the heart. Effects of current flow through the body range from a slight tingling sensation to death. Death due to excessive current flow in the body is often caused by the current causing an uncoordinated contraction of cardiac muscles (ventricular fibrillation). Ventricular fibrillation can occur for currents of 100 mA flowing through the chest, although much smaller currents can be fatal if the current has a direct pathway to the heart, for instance, via a cardiac catheter.

In this section, we review thresholds for current magnitudes that are commonly used to quantify shock hazards.

### *4.2.1 Current Thresholds from IEC 60479-1*

The fourth edition of the IEC standard 60479-1 "Effects of Current on Human Beings and Livestock, Part-I: General Aspects," published in 2005 [4] defines various physiological effects of electrical shocks and specifies current thresholds for each of these effects. The current thresholds specified in the IEC standard accounts for the shock duration and the current path through the body. Note that other commonly used current thresholds (e.g., the current thresholds specified in Table 3) are almost exclusively based on the current magnitude (the exceptions are the current thresholds for ventricular fibrillation where two shock durations are considered).

The data used to determine the IEC current thresholds are mainly based on experiments with animals and on information available from clinical observation – only very limited data are available from experiments with living human beings and the experiments that yielded these data only involved electrical shocks of short duration (and presumably low current magnitudes). The IEC states that the current thresholds were selected conservatively[1] and are therefore applicable to all persons of normal physiological conditions, including children. Note that the hazard assessment in the IEC does not account for other harmful effects of electrical shocks that are not directly related to the physiological effects of current flow through the human body, such as falls, heat, fire, etc..

The IEC defines the four general categories, categories A-1 through A-4, for effects of electrical shocks on humans:

- **AC-1:** A person perceives current flow through his/her body as a **tingling sensation**. This current does not cause any harmful effect on a person.
- **AC-2:** A person has a **"startled" reaction** and/or **involuntary muscular contractions** as a result of current flow through the body. This current does not cause any harmful effect on a person.
- **AC-3:** A person has **strong involuntary muscular contractions** as a result of current flow through the body. This current may cause difficulty in breathing, reversible disturbances of heart function, and immobilization, but no organic damage is expected.

[1] This is likely due to the fact that the lethal current thresholds were determined from experiments with animals and are therefore not exactly applicable to humans.

- **AC-4:** A person may experience **patho-physiological effects** as a result of current flow through the body. These effects include cardiac arrest, breathing arrest, and burns (or other cellular damage). The probability of ventricular fibrillation increases with the magnitude of the shock current and the shock exposure time. The likelihood of ventricular fibrillation is captured in the following sub-categories
    - **AC-4.1:** Probability of ventricular fibrillation is up to 5%
    - **AC-4.2:** Probability of ventricular fibrillation is up to 50%
    - **AC-4.3:** Probability of ventricular fibrillation is above 50%

The IEC standard takes the duration of the shock into account by making the selection of the current thresholds depend on the shock duration. The hazard for a given shock current and exposure time can be determined from Figure 6. These thresholds are applicable for scenarios were the current flows between the left hand and the foot.

As discussed previously, the ventricular fibrillation hazard depends significantly on the current path to the body. The IEC standard accounts for that by introducing a heart-current factor. This factor can be used to calculate current thresholds for ventricular fibrillation for current paths other than left hand-to-foot. The left hand-to-foot current threshold is used as a reference – thresholds for other current paths can be calculated by dividing the reference threshold by the heart-current factor. For instance, the heart-current factor for a hand-to-hand current path is 0.4, which means that a 100 mA current flowing from the left hand to the foot has the same probability of causing ventricular fibrillation as a current of 250 mA (100 mA divided by 0.4) flowing from the left hand to the right hand.

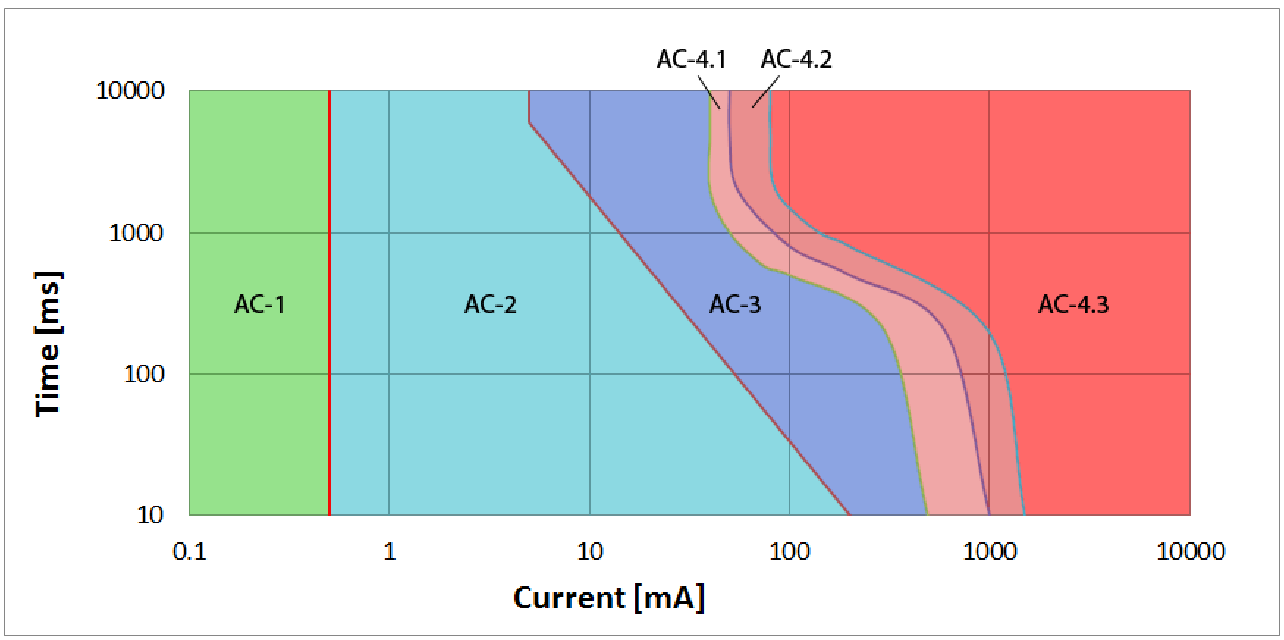


**Figure 6: IEC time/current zones for shock effects categories AC-1 through AC-4. The shock duration is on the vertical axis and the ac current magnitude is on the horizontal axis. The graph applies to currents with frequencies ranging from 15 Hz to 100 Hz.**

**Table 2: Current paths (defined by the entry/exit point of current and heart-current factors.**

| Current Path | | Heart-Current Factor |
|---|---|---|
| Left Hand | Left Foot, Right Foot or Both Feet | 1.0 |
| Both Hands | Both Feet | 1.0 |
| Left Hand | Right Hand | 0.4 |
| Right Hand | Left Foot, Right Foot, or Both Feet | 0.8 |
| Back | Right Hand | 0.3 |
| Back | Left Hand | 0.7 |
| Chest | Right Hand | 1.3 |
| Chest | Left Hand | 1.5 |
| Seat | Left Hand, Right Hand or Both Hands | 0.7 |
| Left Foot | Right Foot | 0.04 |

Of particular interest is the **let-go threshold** because a person unable to break the current path may be exposed to the shock current "indefinitely" potentially resulting in severe burn injuries and death (even if the current is below the "ventricular fibrillation" threshold). The let-go threshold depends on several parameters, such as the contact area, the shape and size of the energized equipment, and the physiological characteristics of the shock victim. According to the IEC, current magnitudes below about 5 mA are below the let-go threshold for the entire population and current magnitudes below about 10 mA are below the let-go threshold for the adult male population. Figure 7 gives the percentage of adult males, adult females, and children that are not able to "break the circuit" for a given let-go threshold. The percentile rank is the percentage of the population that cannot "let go" if the applicable current threshold is exceeded. For instance, for a shock current of 6 mA, 25% of the population of children, 5% of the adult female population, and 0% of the adult male population would not be able to break the circuit.

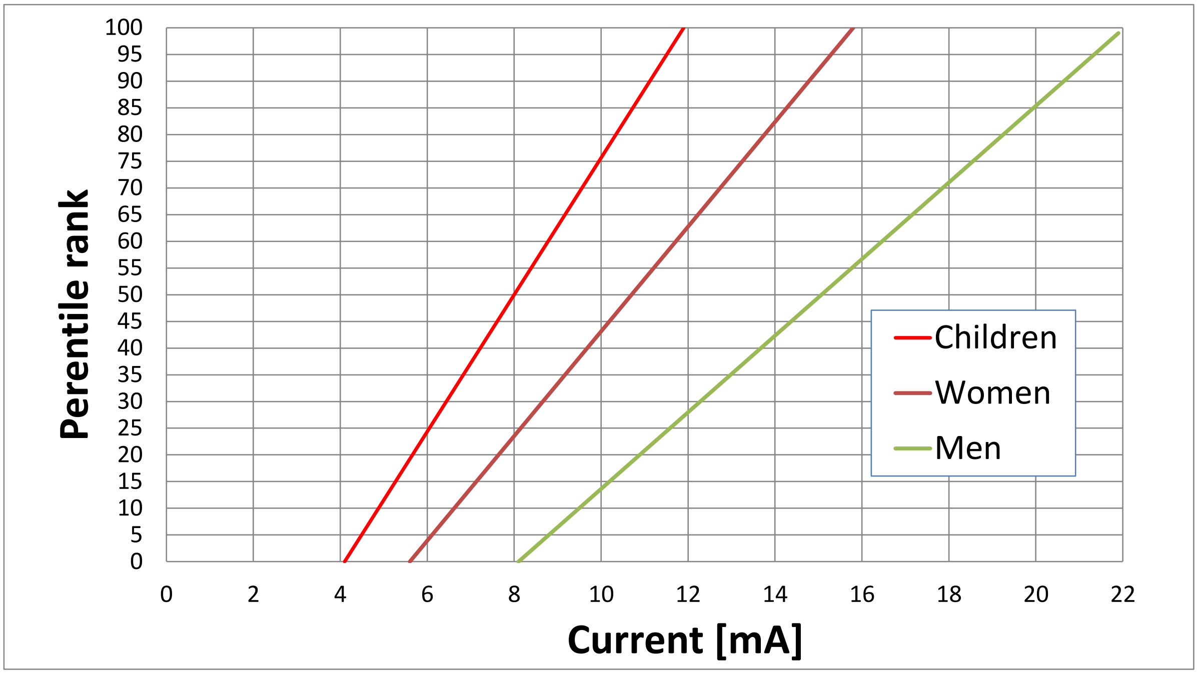


**Figure 7: IEC let-go current thresholds for ac currents (60 Hz) vs. the percentile rank of the population for men (based on experimental data from 134 adult males), females (based on experimental data from 28 women), and children (based on Dalziel's estimates).**

The IEC standard specifies the effects of current density and duration of current flow on the human skin by classifying four zones.

**Zone 0:** below 10 mA/mm$^2$, no changes to the skin. However, prolonged current flow (several seconds) may result in the skin below the electrode assuming a greyish white color with a coarse surface.

**Zone 1:** 10 mA mm$^2$ to 20 mA/mm$^2$, a reddening of the skin occurs with a wave like swelling of whitish color along the edges if the electrode.

**Zone 2:** 20 mA/ mm$^2$ to 50 mA/mm$^2$, a brownish color develops below the electrode extending into the skin. Prolonged current flow results in blisters of the skin around the electrode.

**Zone 3:** Above 50 mA/ mm$^2$, carbonization of the skin is observed.

Note that the current densities specified above give only rough estimates of the ranges. The exact thresholds depend on the shock duration – the IEC standards provides a figure from which the current density thresholds for a particular zone can be obtained based on the shock duration.

### *4.2.2 Current Thresholds from Other Studies*

Many studies use current thresholds based on Dalziel's research. The current thresholds listed in Table 3 were published by Dalziel in 1956 [38] and are widely used in the industry today for quantifying shock hazards. Dalziel based the non-lethal thresholds on shock experiments conducted on humans – let-go thresholds are determined from experiments with 134 male adult humans and 28 female adult humans [39], and perception thresholds are determined from experiments with 167 male adult humans [28] and Thompson's experiments on 40 men and women [40]. The lethal thresholds (ventricular fibrillation possible/certain) are based on experiments conducted on sheeps, calves, pigs, and dogs, whose chest dimensions, body weights, heart weights, and heart rates are comparable to humans. Note the current thresholds specified in Table 3 do not account for the shock duration (except for the ventricular fibrillation thresholds for which two shock durations are considered) and consequently the IEC methodology described previously is expected to be more accurate in most scenarios. Note also that none of Dalziel's experiments were conducted on children. Instead, it was assumed that the thresholds for children are half of the thresholds for adult male.

Dalziel and Lee [2] derived the so-called "electrocution equation" from electrocution data documented by Lee [3]. The electrocutions occurred in England and Wales during the years 1962-1963 [3]. One-hundred-sixty-six of the electrocutions occurred on voltages less than 250 volts 50 Hz, 30 percent were females, and 26 percent were persons under 20 years of age. This equation specifies the current threshold $I_{fib}$ at which ventricular fibrillation can occur. The actual average weight of the electrocution victims was estimated to be less than 70 kg, but, for conservatism, Dalziel and Lee propose to use this equation for adults of 50 kg of weight. The empirically derived electrocution equation is given below and is applicable for shock durations ranging from 8.3 ms to 5 s.

$$I_{fib} = \frac{0.116 \ to \ 0.185}{\sqrt{t}} \tag{1}$$

where $I_{fib}$ is the current threshold in Ampere at which ventricular fibrillation is possible and t is the shock duration in seconds. IEEE 80-2000 [27] adopts Equation (1) with a value of 0.157 in the numerator and for adults with 70 kg body weight. Dalziel and Lee extrapolated the data, which was only obtained from adults, to derive an electrocution equation that is applicable to children:

$$I_{fib,children} = \frac{0.052 \ to \ 0.069}{\sqrt{t}} \tag{2}$$

Whitaker of Underwriters' Laboratories (UL) established 5mA as the maximum uninterrupted 60 Hz ac current as the safe let- go current for a 2-year old child by extrapolating the ventricular fibrillation data on animal body, having the body and heart weight proportional to that of a 2 year old child [22]. This value is still used by UL as the maximum continuous safe current for the general population.

Most studies on quantifying shock hazards to people were performed for DC and power-frequency currents. Quantifying the shock hazard to people due to impulse currents, such as currents due to direct or indirect lightning strikes, is significantly more complex. High-frequency effects, such as the skin effect (i.e., the tendency of high-frequency currents to flow near the surface resulting in a non-uniform current path), need to be considered and injuries to people will depend significantly on the frequency-content of the impulse current. The hazard of impulse currents is reviewed in Dalziel [41] and lightning injuries and death are reviewed in Golde and Lee [42], Cooper [43], and Golde [44]. To our knowledge, there are no generally accepted thresholds or equations that would allow an easy quantification of the impulse current shock hazard. However, in general, impulse currents are considered to be less hazardous than power-frequency currents of the same magnitude because (1) the current path of a significant fraction of the impulse current is near the body surface due to the skin effect, which reduces current flowing through vital organs, such as the heart, and (2) the duration of impulse currents is typical less than the duration of power-frequency fault currents and consequently the energy content of impulse currents is less than the energy content of power-frequency currents with the same magnitude.

**Table 3: Effects of 60 Hz electric current on the human body.**

| Effect | Current Threshold for Men (mA, RMS) | Current Threshold for Women (mA, RMS) |
|---|---|---|
| Perception Threshold (Slight Tingling) | 1.1 | 0.7 |
| Painful Shock | 9.0 | 6.0 |
| Let-Go Threshold | 16.0 | 10.5 |
| Painful & Severe Shock, Muscle Contract, Breathing Difficult | 23.0 | 15.0 |
| Ventricular Fibrillation Possible, Short Exposure (0.03 Seconds) | 1000 | 1000 |
| Ventricular Fibrillation Possible, Long Exposure (3 Seconds) | 100 | 100 |
| Certain Death from Ventricular Fibrillation, Short Exposure (0.03 Seconds) | 2750 | 2750 |
| Certain Death from Ventricular Fibrillation, Long Exposure (3 Seconds) | 275 | 275 |

### 4.3 Safe Voltage Limits

Often safety thresholds are specified in terms of voltage (even though the current flowing through the body is generally believed to causes the harm). Possibly, this is because many sources of electricity resemble an ideal voltage source[1] more than they resemble an ideal current source[2], that is, a change of the load impedance will affect the current flowing through the impedance more than it does affect the voltage (this is known as a "stiff" voltage source). In reality, ideal sources do not exist and the source of electricity for the shock must be represented as a non-ideal voltage source (i.e., a voltage source with a Thevenin impedance in series) or, equivalently, as a non-ideal current source (i.e., a current source with a Norton impedance in parallel). Many studies simply ignore these intricacies and assume that if the load impedance is increased by, for instance, 50%, the current through the load will be decreased by 50%, which is never the case in reality (this would only be true if the shock current were to be supplied by an ideal voltage source, which, as mentioned above, does not exist in the real world). Consequently, it is, in our opinion, not appropriate to specify safety thresholds on voltage levels alone. Instead, it is necessary to also specify the load impedance for which the voltage was measured[3].

To further support our reasoning by illustrating the sensitivity of the measured voltage on the load impedance, we give the following example. We measured voltages between the concrete deck and the pool water at the EPRI test swimming pool in Lenox, Massachusetts for the same elevated Neutral-to-Earth voltage scenario with three different meters. One meter without load resistance measured 15 Vac, another meter with a 3,000 Ω load resistance measured 9 Vac, and a third meter with a 500 Ω load resistor measured 3 Vac. The current flowing through the 3,000 Ω load was calculated to be 3 mA (9 V divided by 3,000 Ω) and the effect would be that the shock victim would perceive the current, but would neither be hurt nor harmed. On the other hand, the current flowing through the 500 Ω load was calculated to be 6 mA (3 V divided by 500 Ω) and the effect would be that the shock victim, if female, would receive a painful shock (see Table 3). In other words, using voltage as a safety threshold resulted in an incorrect conclusion, that is, the effect of the higher voltage (9 V) is less severe than the effect of the lower voltage (3 V). This is important to keep in mind when using the voltage thresholds suggested in the literature, which are documented below.

Another concern with high-impedance voltage measurements is that they are affected by capacitive-coupled voltages [19]. Capacitive-coupled voltages are voltages that are induced from nearby voltages sources, such as power lines, lighting ballasts, or unshielded power cords. Voltage readings that are high because of a large contribution of capacitive-coupled voltages invoke the impression that there is a significant shock hazard when there is none because this type of voltage does not have a strong source that can drive significant current through a high impedance, such as the impedance of the human body. Capacitive-coupled voltage collapse to near-zero if they are measured with a meter that has a load resistor

[1] For an ideal voltage source, the voltage is constant and the current flowing through a load is inverse-proportional to the applied load impedance (the smaller the impedance, the larger the current)
[2] For an ideal current source, the current is constant and the voltage across the. load is proportional to the applied load impedance (the larger the impedance, the larger the voltage)
[3] Of course, the current magnitude also depends on the load impedance, but, in our view, this is of less importance as the current magnitude is the parameter that determines the shock effect. For instance, a body current of 10 mA will likely cause a painful shock – a conclusion that is irrespective of the voltage and the impedance that caused the 10-mA current flow.

with a value that is in the range of typical body impedances. Consequently, a meter with a load resistor mitigates the issue of "false" readings due to capacitive-coupled voltages.

In a paper published in 2009, Dorr [45] summarizes safe voltage levels specified in pertinent standards and codes. Table 4 below is based on this summary. These voltage levels should be viewed as conservative levels imposed for regulatory purposes and do not necessarily reflect causality. Some non-regulatory information on fibrillation voltage thresholds is included in IEEE Std. 902 [46]: ***"Voltage levels as low as 50 V with low skin impedance and current flowing through the chest area can cause fibrillation, which can result in death."***

**Table 4: Summary of Published Voltage Levels of Concern for Humans**

| Voltage Level | Concern | Reference |
|---|---|---|
| 50 Vac | Shock hazard when working with power electronics equipment | NEC [7]: Per article 110.27(A) for power electronics equipment *"except as elsewhere required or permitted by this code live parts of electrical equipment operating at 50V or more shall be guarded against accidental enclosures or by any of the means"* |
| 15 Vac | Shock hazard during relamping in the swimming pool or spa area | NEC [7]: Per article 680.23(A)(3) for swimming pool and spas *"A GFCI shall be installed in the branch circuit supplying luminaries (fixtures) operating at more than low voltage contact limit such that there is no shock hazard during relamping."* |
| 30 Vac or 60 Vdc | Shock hazard associated with power electronics equipment | NFPA 70E [47]: Per article 340.5(3) for electrical hazards associated with power electronics equipment *"A voltage of 30 V rms, or 60V dc, is considered safe except when the skin is broken the internal body impedance can be as low as 500 ohms so fatalities can occur."* |
| 51- 300 Vac | Shock Hazard when working with energized parts or conductor | NESC [48]: Per standards for energized conductor or parts *"Employees shall not contact exposed energized parts operating at 51 V to 300V, unless the provisions of Rule 441A1 are met."* |
| 50 Vac | Shock Hazard when working with live parts of electrical equipment | OSHA Rule (29 CFR Part 1910) [49]: The std. states that *"Except as required or permitted elsewhere in this subpart, live parts of electrical equipment operating at 50 V or more shall be guarded against electrical contact by approved cabinets or enclosures or by any of the means stated in (A)-(D)."* |

### 4.4 Which Parameters are Important for Quantifying Shock Effects (revisiting what we think we know)

In the previous sections and throughout the pertinent literature it is stated that the likelihood of an electrical shock resulting in ventricular fibrillation depends on two electrical parameters, that is, (1) the magnitude of the shock current and (2) the duration of the exposure time to the shock, and one non-electrical parameter, that is, the body weight (e.g., [2]). There is no doubt that there is a strong dependency of the shock effects on these parameters, which has been observed and confirmed in many experiments. However, we think it is possible that certain shock effects may have additional dependencies and it would be worth reexamining the issue. Specifically, some scientists support the view that shock effects are related to energy [22]. If this view is true, then the voltage drop inside the body would also be a key parameter as energy is the time integral of current multiplied with voltage. For example, a current of let's say 50 mA flowing through a body impedance of 500 Ω for one second will result in a certain amount of energy dissipated in the body impedance. The same current flowing through a 1,000 Ω body impedance will result in twice the amount of energy dissipated in the body impedance because the body impedance/voltage drop/energy is doubled.

### 4.5 Increased Vulnerability to Electric Shocks

It is important to point out that the safety thresholds for electric shocks discussed in the previous sections are mostly applicable for healthy persons and not necessarily applicable for people with an increased vulnerability to electric shocks, such as ailing people. Of particular concern is the validity of the ventricular fibrillation threshold because (1) ventricular fibrillation can be fatal and (2) conditions that are expected to lower the ventricular fibrillation thresholds, such as heart conditions and wearing a pacemaker, are fairly common. We did not perform an in-depths investigation regarding appropriate safety thresholds for vulnerable persons– the study performed here is an engineering study and this issue is primarily of medical nature, but we do give some general observations/discussion points on the possible effect of pacemakers on the shock hazard in the following paragraphs.

Pacemakers are small devices powered by batteries that are used to deliver artificial electroshock signals to the heart in order to regulate the heartbeat. A pacemaker is usually inserted beneath the person's skin on his or her chest. A wire is threaded from the device through a vein to the heart. When the pacemaker releases an electrical shock, the wire transfers the shock to the heart, causing it to beat. There are different types of pacemakers available – some continuously stimulate the heart to beat and others only stimulate a heartbeat if the natural heart rhythm gets too slow or becomes otherwise abnormal [50].

In our view, a pacemaker can have the following effects:

1) The electric shock current may cause the pacemaker to fail. It is very difficult to determine currents at which pacemakers fails due to the rapidly evolving pacemaker technology.
2) The metal of the pacemaker may distort the electromagnetic field in the body causing a larger portion of the body current to flow near the heart. In other words, the pacemaker may "attract" shock current and direct it towards the heart in a similar manner as a lightning rod attracts lightning. This effect would increase the likelihood of ventricular fibrillation.
3) The pacemaker lead may facilitate a low-impedance path from the external electrical source to the heart causing large current to flow to the heart. In other words, the body impedance is "bypassed" and the heart is exposed to the full shock current. This effect would increase the likelihood of ventricular fibrillation substantially.
4) The pacemaker may react on the abnormal heart rate caused by an electric shock and stabilize it thereby preventing ventricular fibrillation. However, this is speculative and we did not find any evidence in the pertinent literature to substantiate our hypothesis.

# 5 Electrical Shock Incidents

In this section, we present the results of our literature search on electrical shock incidents in swimming pool areas. We sorted our findings into two categories – (1) Section 5.1 discusses electric shock incidents in which a person was severely injured or that resulted in a fatality and (2) Section 5.2 discusses electric shock incidents in which a person experienced a tingling sensation but did not sustain any injury.

## 5.1 Severe/fatal injuries caused by electric shocks in pool areas

The U.S. Consumer Product Safety Commission (CPSC) reports that there have been around 60 deaths and nearly 50 serious injuries reported over the past 13 years involving electrical hazards in and around the swimming pools [51]. We conducted a literature search on severe/fatal incidents in pool areas and found eleven incidents, which are listed below. Reportedly, ten of these incidents were caused by incorrect installations, that is, (1) faulty/exposed/frayed wiring, (2) lack of ground, (3) oversized fused, (4) lack of GFCI protection, (5) lack of bonding, and (6) structurally unsound pools. The cause of one of the eleven incidents, which resulted in two fatalities, was not revealed. We did not find an incident that resulted in severe/fatal injuries in which the pool installation was compliant with the NEC.

1) In May 2002, a 14-year-old girl, was electrocuted when **wiring problems with the underwater lights** charged the water with electricity. A 16-year-old boy trying to save the young girl was also seriously shocked when he jumped in the pool. Another teenager used a fiberglass shepherd hook (a non-conductive device) to pull both of them from the water. [51] [52]
2) A 29-year-old man, was electrocuted in his parents' pool in mid-May. Family members found the victim in waist-deep water and were shocked by the electrical current when they tried to pull him out of the pool. A breaker was turned off to halt the flow of electricity, but medics were unable to resuscitate the victim. Investigators attributed the accident to **faulty wiring in an underwater light fixture** [53].
3) An 11-year old girl received a fatal shock when she was lying down on a concrete pool deck and touched the junction box supplying the swimming pool lighting fixture. The reason for the incident was found to be a defective splice in an adjacent junction box. Although part of the wiring was in a rigid conduit, the wiring from the source consisted of a 12 AWG type UF direct burial cable without a ground wire. The **conduit supplying the lighting fixture was not metallically grounded and the circuit was overprotected by a 30A fuse**. The deck box and its system were energized at 122 V, which caused a current of 8 A to flow to the ground [54].
4) Two boys, 16 and 17 years of age, were diving for coins in a private swimming pool near the drain. A **defect developed in the wire supplying the circulating pump**. Both succumbed to death due to electric field in the vicinity of the pool drain. The cause of death seems to be due to loss of muscular control which caused an asphyxial death [54].
5) A 21-year old girl was swimming in the deep end of a recently remodeled swimming pool when her **foot touched an underwater light. She received an electrical shock and her body went limp**. The girl's brother tried to help her and received a shock, too. However, the girl could not be saved and she died. [55].
6) A 28-year old man received an intense electric shock while swimming in a residential swimming pool. The man was in the vicinity of a submerged 400W lighting fixture. He was immediately rescued and laid down on the concrete walkway. Unfortunately, he was placed in the vicinity of the electrified deck box and, as he was being massaged, his body made momentary contact with the deck box causing him additional shocks. The person was previously suffering from spinal fusion

and the additional shocks caused a recurrence of the back trouble. The cause of the accident was reportedly a **short circuit occurring in the conduit supplying the lighting fixture. The conduit was not metallically grounded and the light switch interrupted the grounded conductor.** Subsequently, the conduit was energized at 113.5 V causing a current of 11.5 A to flow to the ground. The voltage between the submerged lighting fixture and the pool drain was found to be 99V [54].

7) An electric shock caused a lifeguard in the Kansas City area to freeze to her stand; unable to move or call for help. The shock was cause by a construction company that was in the process of digging trenches adjacent to the pool when a **track hoe operator ran the vehicle's boom into a 12.47 kV overhead utility power line.** This incident charged the earth adjacent to the pool, which was constructed of large quantities of reinforced steel and contained conductive ionic water thereby acting as a ground plane. This resulted in a voltage gradient from the utility line, through the track hoe, to the pool ground plane. The lifeguard stand located in a direct path between the gradient and the pool ground plane experienced electric shock when **a touch potential developed between the two stainless steel (conductive) arms of her stand**. An investigation after the accident revealed that only one of the two metal arms of the lifeguard's stand was bonded to the pool grounding grid; the other arm was floating (i.e., not bonded and grounded). Apparently, the potential difference between the two metal arms of the stand resulted in a current through the lifeguard's body that exceeded the let-go threshold and as a result incapacitated the lifeguard's movement. Simultaneously, the track hoe operator noticed that his co-worker, in the pit below the track hoe, also appeared to be experiencing electrical shock. He was shaking as his hands were touching the earth on the side of the pit. Upon seeing his co-worker in this condition, the track hoe operator lowered his boom. Pool patrons heard an arc when the boom broke contact with the energized utility line, freeing both the lifeguard and the co-worker [10].
8) A 13-year old girl was fatally injured while she was swimming in a swimming pool of an apartment complex. Five other girls playing in the pool started screaming as the electrical shocks began to sting them. The other girls were pulled out of the pool in time. The accident was caused by a **frayed wire touching a conduit.** Also, the circuit breakers were not up-to-date. [55]**.**
9) A 13-year old boy, was fatally injured in a plastic pool as a result of electrocution caused by the **collapse of the pool resulting in a short circuit in the motor pump** [54].
10) An 8-year old girl who had been swimming at a neighbor's pool in South Texas was fatally injured by the shock she received from touching an **exposed electrical wire connected to an improperly wired washing machine**. The girl was standing in a pool of water at the time. [56] [57].
11) Three men located in a pond of an amusement park suffered electrical shocks. Two of the three men were fatally injured. Apparently, one man was located in the pool and received a shock and the other two men were trying to rescue him. The two men who were trying to help the third were injured fatally. The **exact details of the incident have not been revealed** [58].

## 5.2 Incidents involving nuisance shocks

There is anecdotal evidence of nuisance shocks occurring in swimming pool areas – one of such nuisance shock incidents was investigated by EnerNex at a residential swimming pool in Alabama. The owner of a residential swimming pool complained about a tingling sensation when touching the water from the pool deck. The swimming pool has a fiberglass shell, a concrete pool deck, and was filled with saltwater. Donny Cook, who is the Chief Electrical Inspector at Shelby County Development Services in Alabama and also part of the panel of this project, and the EnerNex team conducted a site visit to investigate this issue. An interview with the pool owner revealed that the tingling sensation was not always perceptible throughout the day and more likely to occur during the evening hours. The EnerNex team measured the integrity of the bonding of the metallic equipment in the swimming pool area and found the bonding to be intact. The equipotential method used for the concrete deck could not be determined.

EnerNex measured the voltage between the pool water and remote earth (50 feet from the pool) using a Fluke 123 meter. The results of the measurements are shown in Table 5. Note that a large portion of the total measured voltage was DC. In an attempt to find the source of the DC voltage, the galvanic protection of a nearby buried gas line was temporarily turned off. This did not cause a change in the measured voltage between the water and remote earth and, consequently, the galvanic protection of the gas line was ruled out as a possible source for the DC voltage. Instead, we suspect that the DC voltage was due to galvanic corrosion (see Section 3.7).

**Table 5: Measured water-to-remote-earth voltages at a residential swimming pool in Alabama.**

| Parameter | Value |
|---|---|
| $V_{dc}$ | 0.78 V |
| $V_{ac}$ (rms) | 0.6 V |
| Voltage combined $V_{dc}$ and $V_{ac}$ | 1.06 V |
| Peak to Peak Voltage | 2.5 V |

Additionally, EnerNex measured the voltages between (1) the water and the outside area of the concrete deck, (2) the water and the center of the concrete deck, and (3) the water and the inside area (that is, close to the water) of the concrete deck. The measured voltages are displayed in Table 6. The measurements showed that voltage was mainly AC. Note that the voltage between the water and the inside area of the pool deck is the voltage that would be "applied" to a person standing on the pool deck and reaching into the water or contacting a metallic pool ladder.

**Table 6: Measured deck-to-water voltages at a residential swimming pool in Alabama.**

| Measurement Location | $V_{ac}$ | $V_{dc}$ |
|---|---|---|
| Voltage between water and outside area of the concrete deck | 0.78 V | 10 mV |
| Voltage between water and center of the concrete deck | 0.7 V | 17-20 mV |
| Voltage between water and inside area of the concrete deck | 0.6 V | 6 mV |

EnerNex also conducted measurements of the water-to-remote-earth voltage at the swimming pool of the next-door neighbor and measured similar voltage levels, that is, voltages around 1 V with a large DC portion. Interestingly, the next-door neighbor or any of the users of his pool reportedly never experienced tingling sensations. A notable difference between the two pools is that the next-door neighbor's pool is a freshwater pool with a vinyl liner and the pool where tingling sensations were experienced is a saltwater pool with a fiberglass shell.

Our interpretation of the information obtained during the site visit is that the nuisance shocks were caused by slightly elevated NEVs. We speculate that during the day, the NEV is not large enough to result in perceptible current. On the other hand, in the evening hours, during peak load conditions, the NEV is likely higher and the perception threshold of the current is likely exceeded resulting in nuisance shocks for the swimming pool users. The fact that nuisance shocks occurred on a saltwater pool and not at the neighbor's freshwater pool may be an indication that saltwater pools are more susceptible to nuisance shocks because (1) the higher conductivity of saltwater, (2) the higher sensitivity of skin in contact with saltwater, (3) the lower saltwater wet body impedance compared to the water wet body impedance (see Section 4.1), or (4) a combination of the first three possibilities. The measured water-to-remote-earth AC voltage is similar to the voltage measured between the water and the deck. This is some indication that the concrete deck is not sufficiently bonded and perhaps floating. We do not view the voltages resulting in tingling sensations as a safety hazard. However, we think that the fact that the AC voltage measured between the water and remote earth and the voltage measured between the water and the concrete deck are similar is disconcerting as this suggests that other events that result in much higher elevated ground potentials, such as faults of electric equipment, faults on the utility system, and lightning strikes, may cause deck-to-water voltage levels that are high enough to result in hazardous shock currents.

A possible mitigation measure would be to retrofit the concrete deck with equipotential bonding, for instance by installing "cut rings" similar to the ones installed in the EPRI swimming pool test structure (see Section 6.2).

Another cases of nuisance occurred in Marlboro, NJ. Four people including a child, a lifeguard and a man with pacemaker experienced low-voltage electric shocks in a community pool [59]. None of them required any emergency care nor were they injured. The cause of the electric shock was not positively identified although it was suspected that a nearby transformer belonging to Jersey Central Power & Light is "leaking stray voltage" into the Greenbriar Housing Development pool. The local utility, Jersey Central Power & Light, is currently investigation the issue.

## 5.3 EPRI Survey

EPRI recently conducted a utility survey on shock incidences in swimming pool areas. Some preliminary results of the survey were reported to EnerNex by Douglas Dorr of EPRI in an email communication on September 22, 2011:

- Responses were received from all four quadrants of the U.S. (nothing from Canada) and all quadrants had at least 6 respondents.
- On the question of reporting pool shocks, only one state in the U.S. appears to have any kind of public reporting requirements. As a caveat, there could be a few other states where a public report is required, and they may have not participated in the survey.
- On the question of reporting pool shocks, those that do not have a public reporting requirement have various methods of documentation ranging from: Investigating, but not formally documenting the findings, to just internal documentation and maintaining of a file with the results of the investigation, to reporting the results of the findings back to just the pool owner.
- 26% or (Six out of 23) respondents to the question about wet area (pool and spa) shocks were aware of shock events that were above 15Vac.
- 23% (Five out of 22) respondents were aware of more serious concerns associated with a shock event such as reported difficulty with exiting the water, a fall or other minor injury, a serious injury, or a fatality.

100% of the 23 respondents to the questions about primary and or secondary faults agree that the neutral and all of the items bonded to the grounding system can see a "localized" increase in voltage during a power system fault. Results from tests conducted on the EPRI swimming pool test structure in Lenox, MS substantiate this issue.

# 6 Protection from Hazardous Voltages in Swimming Pool Areas

An electrically safe environment in swimming pool areas can be provided by limiting voltage gradients during any conditions (for instance, steady-state Neutral-to-Earth Voltages and temporary electrical faults) to levels that are considered to be safe. This can be achieved by establishing an equipotential zone. Equipotential zones are established by electrically connecting all equipment that can carry an electrical potential, that is, equipment such as concrete decking, metal ladders, metal handrails, light fixtures, pumps, and any other equipment made out of conducting material. The method of intentionally connecting conducting objects together electrically is also called 'bonding' or 'equipotential bonding'. Establishing an equipotential zone between metallic equipment is trivial – a wire of sufficient size (typically an 8 AWG copper wire) electrically connected with an approved bonding means to all metallic equipment will suffice. However, establishing an equipotential zone if non-metallic conductors are involved can be more challenging. Specifically, providing sufficient bonding to a swimming pool deck composed of concrete or other poorly conducting material is a non-trivial task that can involve substantial costs to the swimming pool owner. The essence of the problem is that concrete is a good enough conductor so that a sufficiently high voltage imposed on the concrete will result in a potentially hazardous voltage gradient along the concrete and a poor enough conductor so that simply connecting the concrete at one location to the other bonded equipment will not suffice to remove the voltage gradient. On the other hand, decks made of insulating or very poorly conducting materials, such as wood, are usually considered to be electrically safe, as their high resistance inhibits any significant flow of current.

In this section we document the swimming pool bonding requirements for conductive decks as described in Article 680.26 from the 2011 edition of the National Electrical Code® (NEC®). Additionally, we review experimental investigations of the effectiveness of the equipotential bonding of swimming pool decks including, but not limited to, the equipotential bonding methods described in the NEC.

## 6.1 Equipotential Bonding Requirements per NEC 2011, Article 680.26

Article 680.26(B)(2) in the National Electric Code (NEC) NFPA 70-2011 requires bonding to the swimming pool deck if the swimming pool deck has a conductive surface, such as a concrete decks and brick paver decks. NEC defines the perimeter surface as the surface that extends 3 feet horizontally beyond the inside wall of the pool. The code requires that bonding to the perimeter surface shall be provided by either one of the following bonding methods:

- **Structural Reinforcing Steel**, which shall be bonded together by steel tie wires or equivalent bonding means.
- A **Copper Conductor Grid**, (referred to in the remainder of this report as the **equipotential grid**), which shall comply to the following requirements:
    - Constructed of minimum 8 AWG bare solid copper conductors bonded together at each point of crossing.
    - Conform to the contour of the pool.
    - Be arranged in 12 inches by 12 inches network of conductors in a uniformly spaced perpendicular pattern with a tolerance of 4 inches.
    - Be secured within or under the pool no more than 6 inches from the outer contour of the pool shell.
- A **Copper Conductor** (referred to in the code as the **"Single Conductor"** option), which shall comply to the following requirements:

- At least one minimum 8 AWG solid copper conductor shall be provided.
- The conductors shall follow the contour of the perimeter surface.
- Only listed splices shall be permitted.
- Installed at a minimum of 18 inches and at a maximum of 24 inches from the inside walls of the pool.
- Installed at a minimum of 4 inches and at a maximum of 6 inches below the subgrade.

## 6.2 EPRI Testing of Equipotential Methods

To our knowledge, the most complete experimental investigation of the effectiveness of bonding methods for swimming pools was conducted by the Electric Power Research Institute (EPRI) on their swimming pool test structure in Lenox, Massachusetts. In this section, we describe the EPRI test structure, the experiments, and present results published previously in the EPRI report "Guidebook for Evaluating Elevated Neutral-to Earth and Contact Voltage in distribution Systems, Part-1: Swimming Pools, Water Bodies, and other Wet Areas" [1] and also unpublished results.

### *6.2.1 Description of the EPRI Swimming Pool Test Structure*

The EPRI swimming pool test structure shown in Figure 8 is a 12 foot by 24 foot rectangular in-ground swimming pool located in the EPRI outdoor test facility in Lenox, Massachusetts. The test structure has a shell consisting of fiberglass walls with a poured concrete bottom (see Figure 9) and a vinyl lining material between the water and the shell and a bare #8 copper bonding ring conductor (aka the "green" ring) around the pool circumference, 6 inches from the water's edge and up to 30 inches below grade that is electrically connected to all conductive objects in the pool area as required by the NEC. A six-foot wide deck was built around the pool.

EPRI conducted a number of experiments to test the effectiveness of various bonding methods in reducing the electrical potential difference between the pool deck and the water. The bonding methods included the "Copper Grid" option and the "Single Conductor" option. For the testing, five differently built pool deck sections are available – four concrete sections and one section with brick pavers. One of the concrete sections had a 6 inch by 6 inch steel mesh embedded in the concrete, which extends from the water's edge to the outside 6 foot edge of the deck. Another concrete section had 12 inch by 12 inch copper equipotential grid embedded in the concrete, which extends from the water's edge three foot outward. This bonding method was in compliance with the NEC "Alternate Means" requirement and is referred to in this report as the "Copper Grid" option. The third concrete section is an experimental section that was used in an unsuccessful attempt to retrofit the deck with a copper equipotential grid. The fourth concrete section and the brick paver section are left electrically floating. Later, three "cut rings" were installed in the fourth concrete sections, that is, trenches were cut a few inches deep into the concrete, a bonding wire was laid inside the trenches, and the trenches were sealed with concrete pour. The cut rings were installed 12 inches, 24 inches, and 36 inches from the water's edge[1].

[1] Cut rings may be a possible retrofit options for decks that do not have any (or insufficient) bonding as they can be installed in existing decks, although the "scars" left on concrete deck (i.e., the sealed trenches) may inhibit the aesthetic appeal of the pool deck. Installing cut rings in existing pool decks with stone pavers should be less problematic than installing them in concrete decks as the stone pavers can be replaced relatively easily.

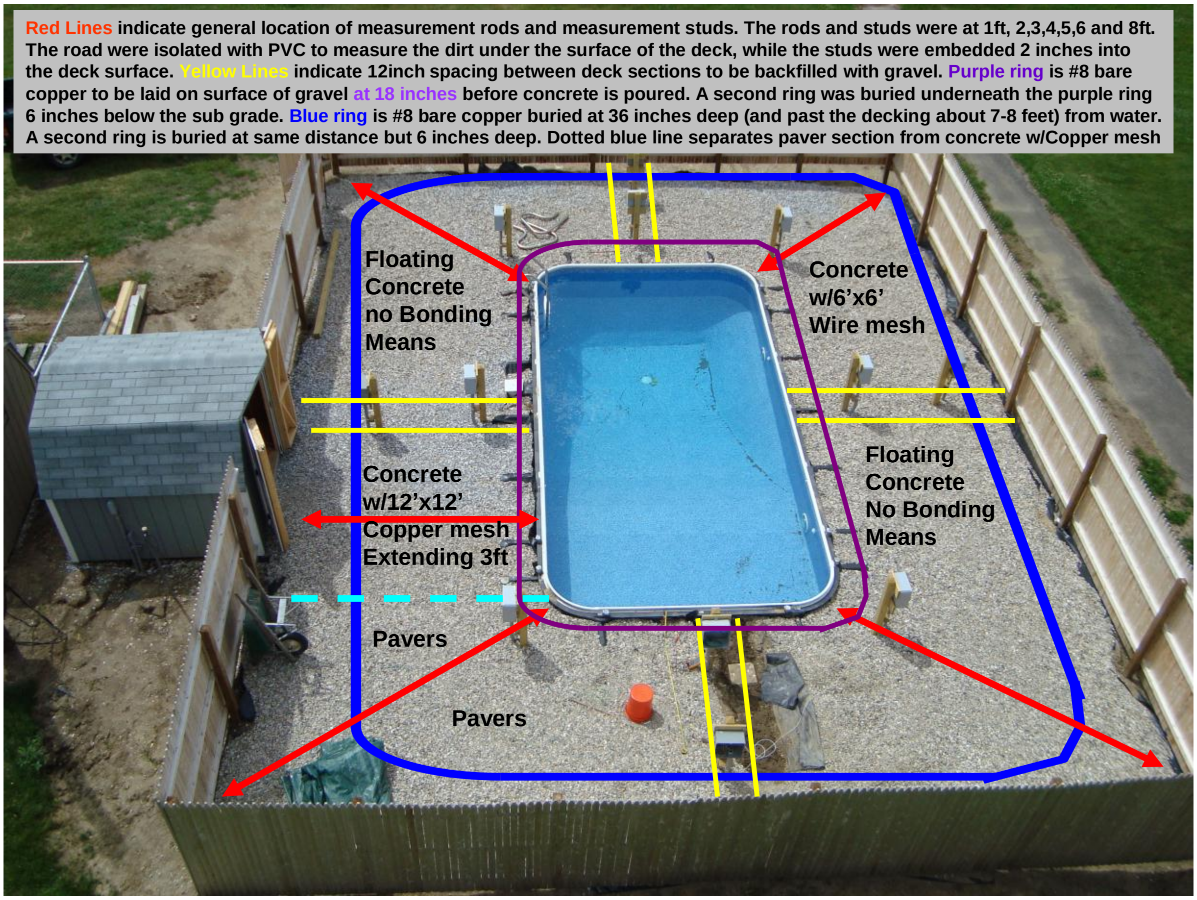


**Figure 8: EPRI Swimming Pool Test Structure with different bonding means (photograph courtesy of EPRI).**

**Figure 9: Construction of the EPRI Swimming Pool Test structure (photograph courtesy of EPRI).**

Additional to the permanent wire meshes that are embedded in some of the deck sections, a number of ring conductors all consisting of #8 bare copper were available to provide bonding to each of the deck sections. These ring conductors could be switched ‘on’ and ‘off’ individually thereby enabling testing of their individual performance and also testing of the performance of any combination of them. The locations of the available ring conductors are listed below:

a) Ring conductor 18 inches from the water’s edge and embedded in the concrete (aka the “yellow” ring). This ring conductor is in compliance with the “Alternate Means” option described in the NEC.
b) Ring conductor 18 inches from the water’s edge and 6 inches below grade (aka the “black” ring). This ring conductor is in compliance with the “Alternate Means” option described in the NEC.
c) Supplemental Mitigation Ring 1: One Cut Groove with number 8 bare copper at 12 inches
d) Supplemental Mitigation Ring 2: One Cut Groove with number 8 bare copper at 24 inches
e) Supplemental Mitigation Ring 3: One Cut Groove with number 8 bare copper at 36 inches
f) Supplemental Mitigation Ring 4: One number 8 bare copper ring at 8 feet – buried 6 inches deep
g) Supplemental Mitigation Ring 5: One number 8 bare copper ring at 8 feet – buried 36 inches deep

#### *6.2.2 Description of EPRI Experiments and Key Findings*

EPRI conducted a number of tests to assess the effectiveness of various bonding methods in reducing the potential difference between the pool deck and the pool water during elevated Neutral-to-Earth Voltages (NEVs). The elevated NEVs were created (1) by using an actual overhead distribution line and injecting current into the neutral conductor, which results in a voltage drop and (2) with a Variac[1]. Additionally, a series of primary and secondary fault tests were conducted to simulate scenarios in which the bonding must protect from fault voltages, which are typically much higher than NEVs. The primary fault was faulting the overhead line (1) to various ground rods located within 100 feet of the pool (high-impedance fault scenario) and (2) to the system neutral (low impedance fault scenario). The secondary fault was faulting the 120 V phase conductor to various bonded metal parts, such as the “green” ring conductor, which is connected to the pool light ground wire. The key findings documented in the EPRI report “Guidebook for Evaluating Elevated Neutral-to-Earth and Contact Voltages in Distribution Systems, Part 1: Swimming Pools, Water Bodies, and Other Wet Areas” published in December 2010 [1] are listed below:

1. **Unacceptably high deck-to-water voltages** can build up on **electrically floating concrete deck sections** during fault conditions. Any of the tested **equipotential methods** (“Single Conductor” option, “Copper Grid” option, steel equipotential grid, multiple ring conductors), substantially **reduce these voltages**.
2. The **“Copper Grid” option** was significantly more efficient in reducing the potential difference between the pool deck and the pool water than any combination of the ring conductors. For instance, during any of the 2,700 volt-to-ground faults, the voltage between the water and the deck section with the equipotential grid underneath **never exceeded one volt**.
3. The **“Single Conductor” option reduced the deck-to-water voltage substantially** compared to the voltage measured on the electrically floating deck, although the equipotential grid performance in reducing the voltage was superior. For instance, for the scenario in which the deck was bonded by

[1] EPRIs initial testing showed that the line-created NEVs and the NEVs of the same magnitude created by the Variac produced essentially identical results and, consequently, the Variac, which was more convenient to use, was employed for most of the tests.

a single ring conductor 18 inches out from the water's edge and 6 inches below the grade (compliant with the "Alternate Means" option in NEC 680.26 and referred to in this report as the "Single Conductor" option), the deck-to-water voltages during a 2,700 volt line-to-ground fault were measured to be between 40 V and 90 V[1].

4. Installing **additional ring conductors** in close proximity to the "Single Conductor" option resulted in **additional reduction of the voltages**.

In August 2011, the author of this report attended a hands-on two-day EPRI workshop where additional experiments were conducted on the swimming pool test structure. During the tests, line NEVs were created for different load conditions (simulated by a resistive load elements connected line to neutral on the distribution line) and for different lengths of the neutral conductor (simulated by a rheostat, which adds a resistance to the neutral path to mimic the resistance of a longer line). NEVs were also created by a Variac. Initially, Deck-to-water voltages were measured with three different measurement configurations – (1) a voltmeter without a load resistor, (2) a voltmeter with a 500 Ω load resistor, and (3) a voltmeter with a 3,000 Ω load resistor. Only a 500 Ω load resistor was used for later measurements. The preliminary findings from these tests are summarized below:

5. Earlier results that **an equipotential grid performs better in providing equipotential bonding than the "Single Conductor" option were confirmed**. The 6 inch by 6 inch steel mesh and the 12 inch by 12 inch copper equipotential grid performed similarly well in reducing the deck-to-water voltages at distance of up to three feet from the water's edge.
6. For the deck section with the "Copper Grid" option, we measured a **significant voltage gradient** between the following **two areas**: (1) the deck section that does not have the grid underneath (i.e., three feet and more from the water's edge) and (2) the area within the three-feet perimeter (that is, the pool water and the three-feet deck section with the grid underneath).
   This is a concern because a pool can be constructed in compliance with the NEC, which requires only bonding of the perimeter surface which extends three feet from the water's edge, but a person is still in danger of receiving an electrical shock if this person is located outside the perimeter surface and electrically bridges the gap to the water. This may occur, for instance, if a person is standing outside perimeter surface and is holding a skimmer in his hand that "connects" to the pool water, if a person steps from outside the perimeter surface into the perimeter surface (step voltage), or if a person lies on the deck and is in simultaneous contact with the two areas. This is an issue that should be investigated further. The effectiveness of mitigation options, such as (1) extending the equipotential grid across the whole deck area (expensive) or (2) employing an equipotential ring around the outside edge of the deck (simple, inexpensive, and possibly "good enough") should be investigated.
7. The application of **load resistance** across the meter test leads has a **significant impact on the measured voltage**. Deck-to-neutral voltages measured without load resistance were up to five times larger than deck-to-neutral voltages for the same scenario measured with a 500 Ω load resistance. The 500 Ω load resistor is a suitable approximation for simulating humans standing on wet concrete and holding a metal pool strainer as well as scenarios with partial body immersions and arms (or torso) on the deck.
8. The **equipotential performance of any single cut-ring was similar or better than the performance of the "Single Conductor" option**. Additional improvement of the equipotential performance was

[1] Reportedly, the variation was due to different fault current magnitudes during the 2,700 V faults.

achieved by employing **multiple cut rings**. This indicates that cut ring, in particular multiple cut rings, are an effective means to retrofit an existing swimming pool deck with equipotential bonding.

Further tests with 4 kV (line to line voltage or 2.7 kV line to ground voltage) arc faults were conducted by EPRI on September19, 2011. The preliminary findings as reported by Doug Dorr of EPRI in an email communication with EnerNex on September 22, 2011 are listed below:

9. The **“Copper Grid” option** limited the deck-to-water voltages to **below 3 V** for all fault tests (but only out to the three-foot mark where the copper stops). Beyond that point the voltages get much higher
10. The **“Single Conductor” option** that is installed 18 inches from the water’s edge and **embedded in the concrete** (aka the “yellow” ring) was ten or more times less effective than the “Copper Grid” option. This comparison is based on voltage measurements conducted at a one-foot distance from the water’s edge.
11. The **“Single Conductor” option** that is installed 18 inches from the water’s edge and **6 inches below grade** (aka the “black” ring) was twenty or more times less effective than the “Copper Grid” option and only about half as effective as the “yellow” ring. This comparison is based on voltage measurements conducted at a one-foot distance from the water’s edge.
12. **All three options were effective in reducing the hundreds of volts** that would exist on an electrically floating deck during the simulated fault conditions to significantly lower levels, but the only option that appears to keep the voltages under “arbitrarily safe levels” of a few volts was the “Copper Grid” option. An analysis whether or not the voltage levels for the other bonding options can be considered “safe” was not performed.

Figure 10 shows a histogram based on EPRI data [60]. The data are averaged voltages measured at the EPRI Lenox test facility for five swimming pool bonding configurations at two locations – 1 foot from the water’s edge and 3 foot from the water’s edge. The data are shown relative to the average deck-to-water voltage for the surface of the floating concrete section. For example, the black column shows that the voltage measured on a concrete deck that employs the “black” ring “Single Conductor” option is 20% to 40% of the voltage that a “floating” concrete deck would have during a fault. Some of the variation (e.g., 20-40% for the “black” ring configuration) is due to the fact that the voltages were measured at two different locations (1 foot and 3 foot distances from the water’s edge) and the relative voltage reduction depends somewhat on the distance from the water’s edge. Reportedly, the relative voltage reduction also depends on the magnitude of the fault voltage.

Figure 11 shows an example of two measurements captured during a 4 kV distribution system fault [60]. The green trace shows the voltage measured on a deck section that is bonded with the NEC “Copper Grid” option. The black trace shows voltage measured on a deck section that is bonded with the NEC “Single Conductor” option. These measurements were taken at a one foot distance from the water’s edge. In general, voltages measured for the “Single Conductor” option varied widely and were dependent on the amount of fault current, the number of grounded points between the fault and the energized pool water, and the distribution voltage. EPRI intentionally grounded the neutral of the circuit multiple times before it reached the water to effectively reduce the “Single Conductor” voltages and insure that the input channels to the measurement equipment would not be damaged.

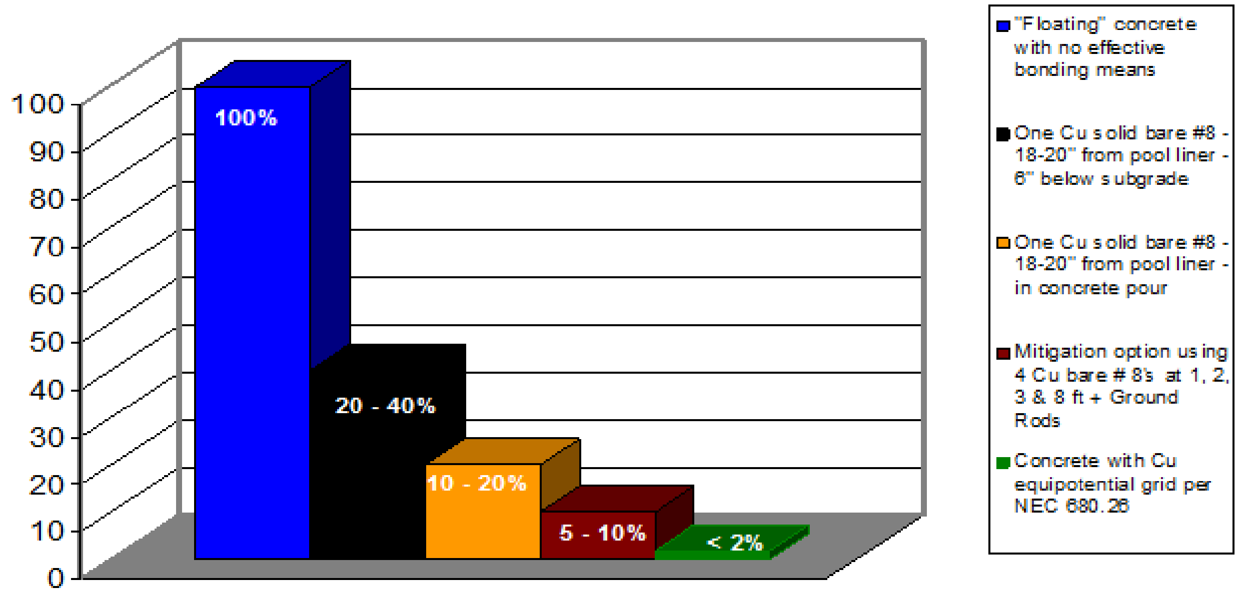


**Figure 10: Relative comparison of equipotential voltages between pool decking and water during AC faults. Each column shows average values from a number of voltage measurements. The ranges over which the voltages varied for each configuration are indicated in each column. Courtesy of EPRI [60].**

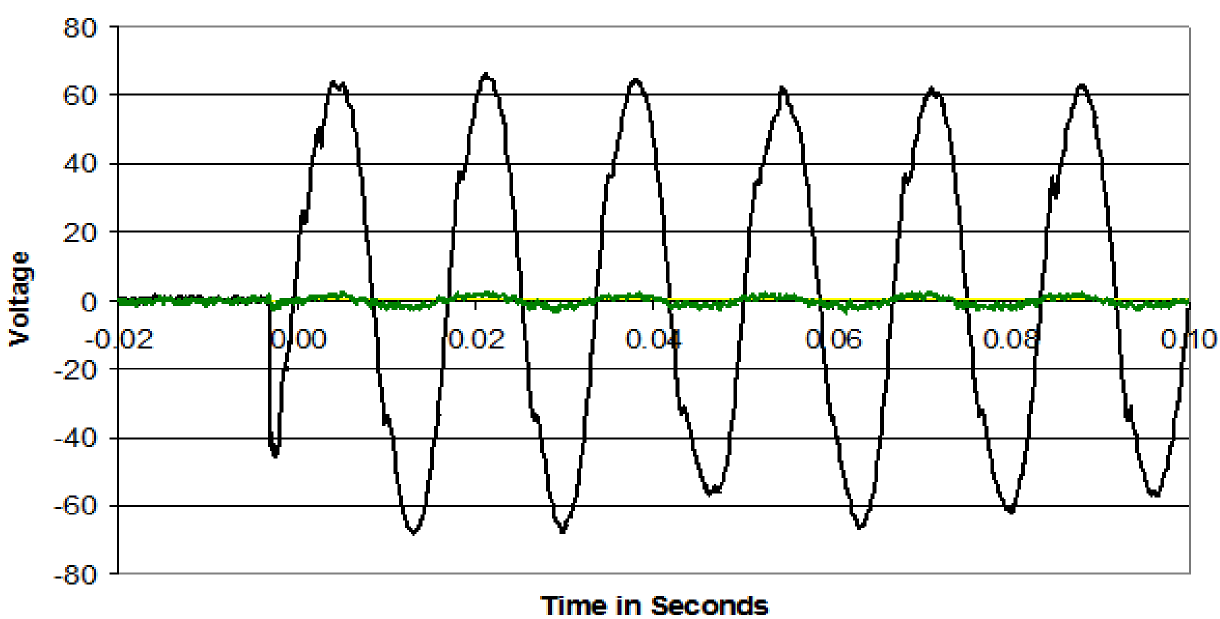


**Figure 11: Oscilloscope traces showing (1) the voltage during a fault measured on a deck bonded with the NEC "Single Conductor" option and (2) the voltage during a fault measured on a deck bonded with the NEC "Equipotential Grid" option. The unit of the voltage axis is 'Volt'. Courtesy of EPRI [60].**

## 6.3 NEETRAC Testing of Equipotential Methods

In 2008, the National Electric Energy Test Research & Application Center (NEETRAC) conducted tests at a swimming pool to compare the equipotential bonding effectiveness of the equipotential grid with the effectiveness of the "Single Conductor" option. The following sections describe the experiment and results as reported in the NEETRAC document "Evaluation of Ground Ring vs. Equipotential Mat at a Swimming Pool in Buford, Georgia" [5].

### *6.3.1 Description of the NEETRAC Experimental Setup*

NEETRAC tested equipotential bonding methods on a residential swimming pool in Buford, Georgia. The dimensions of the rectangular test swimming pool are 14 foot by 31 foot. The pool shell consists of fiberglass material with a fibercrete lip, which secured the coping stones around the pool. The deck surface is made of stone pavers that are sitting on fine sand and crusher run. The only conducting part in contact with the pool water is the underwater light fixture.

Initially, the "Single Conductor" option described in NEC Article 680.26(B)(2) was employed. An 8 AWG solid copper wire was buried around the pool at a depth of approximately 6 inches deep and 24 inches from the water's edge. After burying the ring, the soil was covered, compacted, and pavers were installed. A number of experiments were conducted for this experimental configuration

Following the ground ring measurements, the "Single Conductor" option was removed and the "Copper Grid" option was installed. This bonding method is referred to in this report as the "Copper Grid" option. The equipotential copper bonding grid completely encircled the perimeter of the pool and was bonded to all conducting equipment via UL listed split bolts. Another set of experiments was conducted for this experimental configuration.

### *6.3.2 Description of the NEETRAC Experimental Procedure*

The tests were performed on the $6^{th}$ of July 2008. During the tests, the sky was partly cloudy and mild. The soil was wet due to previous rain. The test procedure as described in the NEETRAC report [5] is quoted here:

> ***"The neutral to earth and resulting water-deck voltages at the swimming pool were expected to be small and therefore, a customized test procedure to raise the voltage gradients around the pool was designed and carried out. … The pool equipment including the light were isolated at the switch panel by opening the disconnect switch and physically isolating the ground wire from the ground bus. A 120 volt, 10 amperes variac was then connected between the equipment ground by the panels and a current return ground rod located approximately 160 feet from the pool. A Fluke ammeter was connected in the circuit to measure the test current. Another reference rod was driven to measure the ground potential rise (GPR) of the pool and connected ground approximately 125 feet from the pool in perpendicular direction to the current return rod. The test consisted of passing a current between the pool ground and the current return rod and measuring water-deck voltages along eight radial directions ... the voltages were measured at 0.5', 1', 2', 3' and 4' distances from the edge of the water. The location of the last measurement was at 3.5' distance from the water …"***

### *6.3.3 Conclusion of the NEETRAC Experiments*

The conclusions from the NEETRAC report [5] are quoted here:

> ***"There are several sources of touch and step voltages that can exist around a swimming pool. Some of these sources such as neutral-to-earth voltages or stray voltages are due to normal operation of the power system. Typically less than 10 volts, these voltages result from the load current returning to its source through a multigrounded neutral system. Higher voltages may also exist if the secondary neutral is corroded or, in an extreme case, is open. Another source that can cause high voltages around the pool area is a high impedance fault in an underground cable circuit. This type of fault is characterized by lower current and higher voltage and can remain undetected for a long time. Although the probability is extremely small, a phase-ground fault on the primary cable can bring high voltages in the swimming pool areas. These voltages are significantly high but usually are of short duration. The data of this investigation proves unequivocally that an equipotential copper bonding grid around a swimming pool can and will effectively mitigate the voltages described above and provide adequate protection to the swimmer and person walking on the deck. The alternate means (ground ring) described in 680.26(B)(2)(b) of the 2008 NEC may not provide adequate protection to the swimmer and person walking on the deck. The test data is supportive of the University of Wisconsin, Midwest Rural Energy Council, American Society of Agricultural and Biological Engineers, and the University of Minnesota's test data for equipotential bonding grids in dairy barns and Article 547 of the NEC"***

#### *6.3.4 NEETRAC Petition for Changes to the NEC*

NEETRAC issued a request for a Tentative Interim Amendment (TIA Log No. 936) to NEC Article 680.26. NEETRAC's substantiations for the proposed changes to the code are quoted here:

1. ***Comment 17-92, no substantiation or adequate test data was submitted to support a single conductor for perimeter surfaces outlined in 680.26(B)(2)(b). After requesting the pertinent test data from NFPA the only available test data for pools was from comment 17-98. This data only supported the new 2008, Section 680.26(C) not 680.26(B)(2)(b). The code change was proposed and implemented solely based on OPINION, not from actual test data, even though substantial test data for equipotential bonding grids was available for dairies.***
2. ***Testing has now been conducted by A Research Center of the Georgia Institute of Technology, National Electric Energy Test Research & Application Center (NEETRAC) that unequivocally proves an equipotential bonding grid is required and a single wire will NOT always provide adequate protection!***
3. ***The requirements in 680.26(B)(1)(b) conflicts with the requirements of 680.26(B)(2)(b). Code sections within an Article that conflict with one another will lead to misinterpretation and improper application of the applicable wiring method which ultimately will endanger the public. Rewording "Alternate Means" (single wire reference) from the 2008 Edition and replacing it with the 2005, 680.26(C)(3) Alternate Means, will remedy this error by installing a copper conductor grid.***
4. ***680.26(B)(1)(b)(2) requires the grid to contour to the pool and deck; however in the same instance 680.26(B)(2) requires the perimeter surface to extend 3' out, not to the complete contour of the deck. The result of this conflict will be***

***misapplication, increased cost for pool construction and danger to the public. Equipotential bonding grids are established by definition under 547.2 and 547.10 "Equipotential Plane, an area where wire mesh or other conductive elements are embedded in or placed under concrete, bonded to all metal structures and fixed non-electrical equipment that may become energized, and connected to the electrical grounding system to prevent a difference in voltage from developing within the plane". The equipotential bonding grid for dairies and agricultural buildings are based on solid testing documentation from the American Society of Agricultural and Biological Engineers (ASABE). Their self-help guide for Equipotential Planes for Stray Voltage Reduction requires a grid system, not a single conductor. It further identifies that 8 AWG copper is considered the minimum conductor size (see attached PDF). Further studies and data are available from the American Society of Agricultural Engineers (ASAE), 1998 International meeting revisiting the requirements of equipotential planes. One of the major issues outlined in this TIA is that we afford more protection for dairy cows than we do for humans in pool environments. Humans and dairy cows carry approximately the same resistance in body mass.***

5. ***The proposed TIA intends to correct a circumstance where changes to 680.26(C), 2005 Edition were implemented without adequate technical (safety) justification to support the single conductor over a copper grid. In addition, it provides clarification regarding the grid and contour of the deck requirements.***

***Emergency Nature: Test data from NEETRAC refutes a single copper conductor application for decks, pavers, unpaved surfaces and supports an equipotential plane or copper grid system, as originally outlined in the 2005 Edition of the NEC. Supporting documentation from utilities in Georgia and Mississippi referencing stray-current problems on pool decks, along with conclusive testing conducted by NEETRAC, confirms the need for rewording a single conductor alternate means outlined in 680.26(B)(2)(b)(1), and replacing it with the copper conductor grid identified in 680.26(B)(1)(b). The test data from NEETRAC proves unequivocally that an equipotential copper bonding grid (ground mat) around a swimming pool can and will effectively mitigate the voltages over an alternate means (ground ring) described in 680.26(B)(2)(b)(1) of the 2008 NEC. A ground ring will work only when there is no evidence of stray current, but cannot protect the public where conditions of multiple grounded neutral systems and stray-current conditions prevail, which may happen at anytime. In addition the test data supports the studies for equipotential bonding grids in dairy barns and agricultural areas as referenced in Article 547 NEC. An order to provide minimum safety standards for the public in pool environments; I am compelled to respectfully submit this TIA.***

Code-Making Panel 17 (CMP-17) rejected the proposed changes stating that the NEETRAC report did not give enough argument as to why the "Single Conductor" option is inadequate. Specifically, they noted that for the NEETRAC tests where bonding was provided by the "Single Conductor" option, none of the measured voltages were flagged as "unsafe". Also, the code officials questioned the general applicability of the NEETRAC results because the experiments were conducted at only one swimming pool in Georgia [6].

#### *6.3.5 EnerNex Comment on NEETRAC Conclusions and Petition*

In our opinion, the NEETRAC study had the following major shortcomings:

1) The NEETRAC report does not discuss which voltage levels should be considered as hazardous. Consequently, the conclusion that the NEETRAC data ***"proves unequivocally that an equipotential copper bonding grid around a swimming pool can and will effectively mitigate the voltages described above and provide adequate protection to the swimmer and person walking on the deck."*** and the conclusion that the "Single Conductor" option ***"will work only when there is no evidence of stray current, but cannot protect the public where conditions of multiple grounded neutral systems and stray-current conditions prevail, which may happen at anytime."*** are, in our opinion, not sound conclusions. Note that our argument is in line with the argument of CMP-17, which rejected the NEETRAC petition based on their criticism that the NEETRAC study does not identify the "Single Conductor" option as unsafe.
2) The effectiveness of the bonding methods were assessed by using a Variac and applying a voltage of approximately 95 V. While this scenario might be appropriate to test the effectiveness of the bonding methods in protecting from NEVs, it is not appropriate to test the effectiveness of the bonding methods in providing protection during primary or secondary fault conditions. For these scenarios, much higher voltages are possible (and likely) as shown in the EPRI experiments [1]. Consequently, the NEETRAC statement that the NEETRAC data "proves unequivocally that an equipotential copper bonding grid around a swimming pool can and will effectively mitigate the voltages described above and provide adequate protection to the swimmer and person walking on the deck." is not appropriate.
3) The NEETRAC report does not specify if a load resistor was used when measuring the deck-to-water voltage. Note that voltages measured without load resistors are typically much higher than voltages measured with a load resistor and consequently overestimate the voltages a person is exposed to. However, the relative results or ratios would still be valid (e.g., a result such as "equipotential method A reduced the deck-to-water voltage by 50% compared to equipotential method B" would be independent of the load resistor).

We agree with the following points in the NEETRAC petition:

1) There appears to be no experimental evidence that the "Single Conductor" option does provide adequate protection under all realistic conditions.
2) There is some inconsistency in the code in that the requirement for the equipotential grid is to cover the whole equipotential surface, which stretches out 36 inches from the water's edge while the "Alternate Means" option only requires a minimum distance of 18 inches from the water's edge thereby effectively reducing the equipotential zone to an area that stretches out 18 inches from the water's edge.

CMP-17 questioned the applicability of the NEETRAC results because they are only from one swimming pool in Georgia [6]. We are unclear on the rationale of CMP-17 regarding this criticism. This criticism implies that the results were perceived as not to be generally applicable and may vary for different swimming pools and different pool types. Perhaps there is also the notion that the code officials expect variability for different localities (e.g., due to different electrical characteristics of the soil). It is our opinion that the variability of the deck-to-water voltage is expected to be minimal (1) for other swimming pools with the same deck type (the NEETRAC experiments were conducted on a stone paver pool deck) and (2) for different localities. On the other hand, in our opinion, significant variability of deck-to-water voltage is expected for swimming pools with different types of decks (e.g., concrete decks) as the electrical characteristics of the deck material are a crucial parameter for the voltage gradient along the deck.

In our view, the main conclusion from the NEETRAC experiments is that the equipotential grid is superior to the "Single Conductor" option in providing equipotential bonding to pool decks. This conclusion is in line with the EPRI findings [1]. However, we think that further research is required to determine (1) what deck-to-water voltage levels can be considered safe, (2) what deck-to-water voltage levels can be expected for each bonding method under feasible worst-case scenarios, and (3) what deck-to-water voltage levels can be expected for each swimming pool type and deck type.

# 7 Conclusions, Knowledge Gaps, and Recommendations for Future Research

We reviewed the information related to personal safety in swimming pool areas that is currently available in the pertinent literature and identified a number of knowledge gaps. We discuss these knowledge gaps, categorized into four categories, in the subsequent sections and give recommendations on how to fill in these gaps:

## 7.1 Electrical Characteristics of the Human Body

### *7.1.1 Why is this important?*

Any voltage imposed on a person will result in current flow through that person. The magnitude of this current flow depends on the electrical impedance of the current path through the body – according to Ohm's law, the lower the impedance of the current path, the higher the magnitude of the body current. The body current is one of the two critical parameters for determining the effect an electrical shock has on the human body (the other important parameter is the duration of the electrical shock) and is therefore important for determining safety thresholds.

### *7.1.2 What do we know?*

In many studies, a body is simply represented by a 1,000 Ω resistance (for dry condition) or a 500 Ω body resistance (for wet conditions). Other studies use a more discriminating approach by selecting the body impedance based on the points of contact[1] (e.g., hand-to-hand, hand-to-foot, etc.). The impedance can vary considerably for different points of contact and there are no generally agreed upon values for these impedances. The IEC methods does account for the effect of the point of contacts on the body impedance.

The body impedance is composed of the skin impedance and the internal impedance of the body. Typically, the skin impedance is much higher than the internal impedance and, consequently, the body impedance is substantially reduced if the skin is punctured or otherwise broken. Also, the body impedance may change during the shock event if the shock current is high enough to break down the skin. That is, at the onset of the shock the skin is intact and the body impedance is higher. If the current is high enough and flows long enough, the skin may break down and the body impedance will be much lower.

Other external impedances add to the body impedance. For instance, the contact impedance between the skin and an energized object can be substantial, in particular if the pressure between the skin and the object is low. Even if maximum pressure is assumed, there is some research that suggests that commonly assumed values for the body impedance should be increased by a few thousand Ohms [35].

### *7.1.3 What is missing?*

There are currently no generally accepted values for body impedances and consequently results of studies that assess shock hazards to persons are often inconsistent. The underlying problems for the lack of standardized values are twofold: (1) experimental data on body impedances are hard to come by for obvious reasons[2] and (2) the impedance of the current path through the body is hard to define due to a large number of variables, which vary from person to person and are also dependent on the circumstances of the particular shock scenario. The variables are listed below:

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[1] The contact points are the points on the body across which a voltage difference exists, that is, the location where current enters the body and the location at which current flows out of the body.

[2] The body resistance can be determined by applying a defined voltage to a person and measuring the resulting current. However, in order to account for effects such as breakdown of the skin, the applied voltage has to be rather large, so that it would injure the person. Obviously, this is not a practical option.

- Characteristics of the person (mainly height, weight, and gender)
- Characteristic and condition of the skin (thick or thin, punctured or intact)
- Pressure and surface area between the skin and the energized object, and between the skin and ground (this changes the contact impedance)
- Clothing and shoes (for shock assessment in swimming pool areas it is a conservative assumption that the energized object and the ground are in contact with bare skin)
- Magnitude of the shock current (large currents will cause the skin to break down)

#### *7.1.4 Conclusion*

In principal, the problem can be addressed in two ways:

1) **Additional research** on electrical characteristics on the human body would improve the accuracy of body impedance assumptions and, consequently, would improve the validity of results from a shock analysis. In principal, experimental data can be obtained from experiments with humans, but this is obviously not a feasible (and ethical) option if high currents are involved. Using medical cadavers may be an option for characterizing the electrical characteristics of the human body, but there are also ethical concerns and it is not clear if the electrical characteristics of cadavers are similar to the electrical characteristics of a living body. The ethical barriers are lower for data obtained from experiments with animals, but, even if there would not be any moral concerns, it is unlikely that the results would be accurate as the characteristics of the human skin would likely not be captured correctly in these experiments. Experiments with test dummy's or sophisticated computer simulations that represent the electrical characteristics of the human body may be an option, but there will always be some degree of uncertainty if the results that would come out of this effort cannot be verified experimentally. Last not least, due to the large number of variables involved, the body impedance can only be defined in a statistical manner and therefore additional research would have to be carried out on a statistical significant sample size, which further complicates the issue. In summary, there are many obstacles to overcome in order to improve upon our current knowledge of the body impedance. We do not see sufficient value to undertake this task and instead suggest using body impedances that are (1) conservative (2) account for the key variables, and (3) are based on sound experimental data. We think that the methodology outlined in the IEC Standard 60479-1 fits this description, as argued in the next paragraph.
2) It is important to use **generally accepted values for the body impedance** for different scenarios (dry/wet, male/female/child, hand-to-hand, hand-to-feet, etc.). These values would not necessarily have to be exact (this would be difficult to achieve, partly because of the statistical nature of the body impedance value) – the primary goals would be (1) to select conservative values that are based on sound experimental data and (2) to achieve consistency so that results from research studies become comparable, which is currently not the case if the studies use different assumptions for the body impedance.
   Based on the experimental data we reviewed in our literature search, we conclude that a value of 500 Ω for the body impedance is a reasonable and conservative value. A more sophisticated approach for selecting the body impedance is described in the IEC Standard 60479-1. The IEC selection process is, in our opinion, convincing because it is based on experimental data and accounts for the body impedance dependence on key parameters, such as the shock voltage level, the surface area of contact, and environmental conditions (dry, water wet and saltwater wet). Additionally, the statistical variation of body impedance within the population is accounted for by specifying impedance values for the $5^{th}$, $50^{th}$, and $95^{th}$ percentile of the population. The body

impedances specified in the IEC apply to the hand-to-hand current path. Body impedances for other current paths may be obtained by employing correction factors; for instance, a conservative estimate for the hand-to-foot impedance would be to reduce the hand-to-hand impedance by 30%.

## 7.2 Effects of Current Flow through the Human Body

### *7.2.1 Why is this important?*

The current magnitude/duration as well as the current path through the body determines the injury due to an electrical shock. Studies that investigate safety from electrical shocks require a benchmark to assess the effectiveness of safety strategies.

### *7.2.2 What do we know?*

Current thresholds based on Dalziel's research are widely used in the industry today for quantifying shock hazards. Dalziel based the non-lethal thresholds on shock experiments conducted on humans –let-go thresholds are determined from experiments with 134 male adult humans and 28 female adult humans [39], and perception thresholds are determined from Dalziel's experiments with 167 male adult humans [28] and Thompson's experiments on 40 men and women [40]. The lethal thresholds (ventricular fibrillation possible/certain) are based on experiments conducted on sheeps, calves, pigs, and dogs, whose chest dimensions, body weights, heart weights, and heart rates are comparable to humans. None of Dalziel's experiments were conducted on children. Instead, it was assumed that the thresholds for children are half of the thresholds for adult male. Dalziel and Lee [2] derived the so-called "electrocution equation" from electrocution data documented by Lee [3]. This equation can be employed to estimate current thresholds for ventricular fibrillations.

The fourth edition of the IEC standard 60479-1 "Effects of Current on Human Beings and Livestock, Part-I: General Aspects," published in 2005 [4] defines various physiological effects of electrical shocks and specifies current thresholds for each of these effects. The shock duration is accounted for in the selection process. The current thresholds specified in the IEC standard were selected for a current path from the left hand to foot – the thresholds for ventricular fibrillation for other current paths can be obtained by multiplying the left hand-to-foot threshold with a heart current factor, which is specified for each current path. The data used to determine the IEC current thresholds are mainly based on experiments with animals and on information available from clinical observation – only very limited data are available from experiments with living human beings and the experiments that yielded these data only involved electrical shocks of short duration (and presumably low current magnitudes). The IEC states that the current thresholds were selected conservatively and are therefore applicable to all persons of normal physiological conditions, including children.

### *7.2.3 What is missing?*

The method to base the effect of current flow through the human body on a single value for the current magnitude oversimplifies the issue. In reality, the effect depends on many variables. Below is a list of the key variables that are often not accounted for in studies that assess shock hazards to humans:

- **Current path through the body:** Fatalities due to electrical shock are primarily caused by ventricular fibrillation, that is, electrical current flowing through the heart and causing an uncoordinated contraction of cardiac muscles. Consequently, the path of the current through the body needs to be considered when assessing the potential for body currents to be fatal. For instance, a hand-to-hand current path likely results in a substantial fraction of the current flowing

through the heart. On the other hand, the heart current would be very low for a foot-to-foot current path through the human body (but may be substantial for the foot-to-foot path for animals).
Furthermore, the current path depends on the electrical characteristics of the body, which vary with gender, body weight, and height.

- **Susceptibility of persons to shock injuries and fatalities:** There is a fair amount of variation between the susceptibility of persons to electrical shocks. This variation applies to the whole range of current; some people are able to sense much lower currents than other people and current with magnitudes that cause ventricular fibrillation in one person may not cause any harm in another person.
- **Pacemakers and other objects:** Pacemakers and other engineered objects that may be inside the body, such as implants, may have at least two effects that potentially increase the shock hazard. (1) These objects can alter the current path because of their electrical characteristics. For instance, the low impedance of the metal used in pacemakers may "attract" current so that a larger fraction of the current flows through the heart. (2) Current flowing through these objects may cause damage to them. This can be fatal if the object is a pacemaker.
- **Exposure time:** The effect of shock current depends significantly on the exposure time. The current thresholds suggested in the literature to determine fatal body current do account for the exposure time somewhat by giving two different current thresholds (2,750 A and 275 A) based on two different exposure times (30 milliseconds and 3 seconds). In reality, the exposure time is determined by either the system protection (how long does it take for a fuse/relay to trip) or by the duration of the contact with the energized equipment (how long does it take to let go of the energized equipment). However, the system protection may not trip if it is not properly designed, fails, or if the fault current is too low to cause it to trip (high-impedance fault). Also, a person exposed to a shock may not be able to break the current path if the let-go threshold is exceeded. Consequently, any current above the let-go threshold has the potential to cause severe burn injuries, and death (even if the current is below the "ventricular fibrillation" threshold).
- **Frequency and waveshape of the current:** Safety thresholds are based on the assumption that the current flowing through the body is a pure sinusoid with power frequency (50 Hz or 60 Hz). This is not always the case.
  **Harmonic distortion** may cause the presence of higher frequency terms in the body current. Triplen harmonic currents (harmonics that are multiples of three of the fundamental) are of particular concern as they do not cancel in the neutral conductor[1] and instead sum arithmetically, which may cause significant Neutral-to-Earth harmonic voltages. The third harmonic is typically the triplen harmonic that is most prevalent in distribution systems.
  **Arc fault currents** are often treated as power-frequency sinusoidal currents, which is not entirely accurate. In reality, arc currents are 'turned-off' at low currents and 'turned-off' if the arc fault current exceeds a threshold. This mechanism causes a non-sinusoidal waveshape.
  **Current surges** are often produced by switching operations and lightning events. Current surges are non-periodic and have frequency contents and magnitudes that are much higher than the power-frequency and steady-state current magnitude, respectively.
  Most studies on quantifying shock hazards to people were performed for DC and sinusoidal power-frequency currents. Quantifying shock hazards associated with higher-frequency currents, in

[1] Under balanced conditions, the fundamental and non-triplen do cancel in the neutral.

particular current surges is significantly more complex because high-frequency effects, such as the skin effect (i.e., the tendency of high-frequency currents to flow near the surface resulting in a non-uniform current path), need to be considered and injuries to people will depend significantly on the frequency-content, which is difficult to define[1]. However, in general, high-frequency currents are considered to be less hazardous than power-frequency currents of the same magnitude because (1) the current path of a significant fraction of the impulse current is near the body surface due to the skin effect, which reduces current flowing through vital organs, such as the heart, and (2) the duration of impulse currents is typical less than the duration of power-frequency fault currents and consequently the energy content of impulse currents is less than the energy content of power-frequency currents with the same magnitude. On the other hand, the effectiveness of bonding in protecting from high-frequency currents may be inhibited because there will be a voltage drop across the inductive component of the bonding impedance, which is proportional to the frequency of the current flowing through that impedance.

#### *7.2.4 Conclusion*

There is a fair amount of experimental data available in the pertinent literature on the effects of currents on the human body. The data are somewhat dated (much of the data was acquired in the 1930s from experiments conducted by Dalziel), but we do not see any reason to question the validity of these data, which forms the basis for the current thresholds used today. However, the method to quantify the shock hazard by using only the magnitude of the current oversimplifies the problem and is sometimes non-conservative (in particular for long exposure times). In reality, shock effects depend on many variables, the key variables being the shock duration and the current path through the body. The selection process for shock current thresholds described in the IEC standard 60479-1 accounts for these two key variables and is therefore the preferred method.

### 7.3 Electrical Shock Incidents in Swimming Pool Areas

#### *7.3.1 Why is this important?*

It is important to know about electrical shock incidence in swimming pool areas, in particular the ones that resulted in injuries and fatalities, to gain an understanding regarding the necessity of equipotential bonding methods and the adequacy of the equipotential options currently suggested in the NEC. Identifying (or ruling out) the existence of shock incidence that resulted in injuries/death in swimming pools that were built in compliance with the NEC is of particular interest. Changes to the NEC would be required if the existence of such incidence can be identified; no changes to the NEC would be necessary if such incidences can be ruled out positively.

The issue of real-world evidence for (or against) the effectiveness of a particular equipotential method in providing safe conditions was brought up in the discussion resulting from the recent petition of equipotential grid advocates to remove the "Single Conductor" option from the NEC code. The "Single Conductor" option proponents based their case largely on the lack of sufficient documentation of actual high-voltage electrical shock incidents that occurred on NEC compliant pools and were traceable to improper pool bonding. Code Making Panel 17 rejected the petition to remove the "alternate mean" option. [61]

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[1] For instance, lightning surges are not composed of a single frequency, but rather a frequency spectrum, which is different for different lightning events.

#### *7.3.2 What do we know?*

The findings of our literature search on electric shock incidents in swimming pool areas are summarized below:

- We did not find any evidence for the occurrence of severe/fatal injuries at swimming pools that were built in compliance with the NEC.
- In general, the information of the reviewed incidents was sparse and was insufficient to illuminate important pool-safety related questions, such as (1) the effectiveness of an equipotential grid vs. the "Single Conductor" option, (2) any effect of different pool configurations on pool safety, such as concrete/wood deck, metal/fiberglass pools, salt/fresh water pools, etc..
- A common complaint from pool owners/users is a tingling sensation when (1) a person in is in the water and contacts a conductive part outside the swimming pool or (2) a person is outside the water and comes in contact with the pool water by, for instance, reaching into the water.

EPRI recently conducted a utility survey on shock incidences in swimming pool areas. Some preliminary results of the survey were reported to EnerNex by Doug Dorr of EPRI in an email communication on September 22, 2011:

- Responses were received from all four quadrants of the U.S. (nothing from Canada) and all quadrants had at least 6 respondents.
- On the question of reporting pool shocks, only one state in the U.S. appears to have any kind of public reporting requirements. As a caveat, there could be a few other states where a public report is required, and they may have not participated in the survey.
- On the question of reporting pool shocks, those that do not have a public reporting requirement have various methods of documentation ranging from: Investigating, but not formally documenting the findings, to just internal documentation and maintaining of a file with the results of the investigation, to reporting the results of the findings back to just the pool owner.
- 26% or (Six out of 23) respondents to the question about wet area (pool and spa) shocks were aware of shock events that were above 15 Vac.
- 23% (Five out of 22) respondents were aware of more serious concerns associated with a shock event such as reported difficulty with exiting the water, a fall or other minor injury, a serious injury, or a fatality.
- 100% of the 23 respondents to the questions about primary and or secondary faults agree that the neutral and all of the items bonded to the grounding system can see a "localized" increase in voltage during a power system fault. Results from tests conducted on the EPRI swimming pool test structure in Lenox, MS substantiate this issue.

#### *7.3.3 What is missing?*

The findings of our literature search are inconclusive due to the shortage of reported swimming pool incidence that resulted in injuries/death and, for the ones that were reported in newspaper articles, literature, and on the Internet, the lack of detailed information regarding the circumstances (employed equipotential method, NEC compliance, etc.) that led to the incidence. On the other hand, there is anecdotal evidence that swimming pools built in accordance with NEC requirements do not sufficiently protects from shocks resulting in tingling sensations (nuisance shocks) – one of such nuisance shock incidents was investigated by EnerNex at a residential swimming pool in Alabama. However, to our knowledge, there are no statistical data available that would allow the quantification of these types of complaints and it is unclear if nuisance shocks can be eliminated by employing the "Copper Grid" option instead of the "Single Conductor" option.

#### *7.3.4 Conclusion*

It is not clear if the lack of sufficient documentation of actual high-voltage electrical shock incidents that occurred on NEC compliant pools and were traceable to improper pool bonding is attributable to the non-occurrence of such incidents, or if such incidences did occur, but were not reported with sufficient details to allow conclusions regarding the effectiveness of the equipotential bonding (or not reported at all).

The results of the utility survey recently conducted by EPRI are expected to yield some insight on shock incidents in swimming pool areas. However, one difficult-to-overcome problem is the lack of detailed information related to swimming pool incidence that resulted in injuries/death. It would be beneficial if any swimming pool incidence that results in injury/death would trigger a thorough investigation that documents the circumstances that led to the incidence and that the results would be publicly available (or at least available to independent research organizations). The preliminary results of the EPRI survey indicate that only one U.S. state in which a responding utility was located in has any kind of public reporting requirement for swimming pool incidences. Other states in which non-responding utilities are located in, may have reporting requirements, but it appears that the absence of widespread reporting requirements is at the heart of the problem. Imposing nationwide public reporting requirements for electric shock incidents that occurred in swimming pool areas and that resulted in injuries would shed some light on the adequateness of the NEC bonding methods. It is important to note that utilities will not be able to provide data on all swimming pool incidents that actually occurred, regardless of reporting requirements, because utilities are often not involved in swimming pool incidents. This adds an additional difficulty to resolving the issue of obtaining complete and accurate data on swimming pool incidents. However, we do think that reporting requirements are a step in the right direction because it would at least provide some information on the number of pool incidents, even though that number would likely be an underestimation.

### 7.4 Effectiveness of bonding methods

#### *7.4.1 Why is this important?*

NEC requirements need to recommend bonding methods that adequately protect from injuries due to electric shocks in pool areas.

#### *7.4.2 What do we know?*

The most complete experimental investigation of the effectiveness of bonding methods for swimming pools was conducted by the Electric Power Research Institute (EPRI) on their swimming pool test structure in Lenox, Massachusetts. The test structure is swimming pool with a poured concrete shell and a six-foot wide pool deck. The deck was composed of different sections to test a variety of equipotential methods; most of the testing was conducted on concrete deck sections, but some testing was also conducted on a section with brick pavers. The EPRI findings are summarized below. Additional details on the EPRI experiments can be found in Section 6.2 of this report and in the EPRI report "Guidebook for Evaluating Elevated Neutral-to Earth and Contact Voltage in distribution Systems, Part-1: Swimming Pools, Water Bodies, and other Wet Areas" [1].

1. **Unacceptably high deck-to-water voltages** can build up on **electrically floating concrete deck sections** during fault conditions. Any of the tested **equipotential methods** ("Single Conductor"

option, "Copper Grid" option, steel equipotential grid, multiple ring conductors), substantially **reduce these voltages**.

2. The **"Copper Grid" option** was significantly more efficient in reducing the potential difference between the pool deck and the pool water than any combination of the ring conductors. For instance, during any of the 2,700 volt-to-ground faults, the voltage between the water and the deck section with the equipotential grid underneath **never exceeded one volt**.
3. The **"Single Conductor" option reduced the deck-to-water voltage substantially** compared to the voltage measured on the electrically floating deck, although the equipotential grid performance in reducing the voltage was superior. For instance, for the scenario in which the deck was bonded by a single ring conductor 18 inches out from the water's edge and 6 inches below the grade (compliant with the "Alternate Means" option in NEC 680.26 and referred to in this report as the "Single Conductor" option), the deck-to-water voltages during a 2,700 volt line-to-ground fault were measured to be between 40 V and 90 V[1].
4. Installing **additional ring conductors** in close proximity to the "Single Conductor" option resulted in **additional reduction of the voltages**.

In August 2011, the author of this report attended a hands-on two-day workshop at the EPRI test facility in Lenox where additional experiments were conducted on the swimming pool test structure. Preliminary findings from these experiments are summarized below:

5. Earlier results that **an equipotential grid performs better in providing equipotential bonding than the "Single Conductor" option were confirmed**. The 6 inch by 6 inch steel mesh and the 12 inch by 12 inch copper equipotential grid performed similarly well in reducing the deck-to-water voltages at distance of up to three feet from the water's edge.
6. For the deck section with the "Copper Grid" option, we measured a **significant voltage gradient** between the following **two areas**: (1) the deck section that does not have the grid underneath (i.e., three feet and more from the water's edge) and (2) the area within the three-feet perimeter (that is, the pool water and the three-feet deck section with the grid underneath).
This is a concern because a pool can be constructed in compliance with the NEC, which requires only bonding of the perimeter surface which extends three feet from the water's edge, but a person is still in danger of receiving an electrical shock if this person is located outside the perimeter surface and electrically bridges the gap to the water. This may occur, for instance, if a person is standing outside perimeter surface and is holding a skimmer in his hand that "connects" to the pool water, if a person steps from outside the perimeter surface into the perimeter surface (step voltage), or if a person lies on the deck and is in simultaneous contact with the two areas.
This is an issue that should be investigated further. The effectiveness of mitigation options, such as (1) extending the equipotential grid across the whole deck area (expensive) or (2) employing an equipotential ring around the outside edge of the deck (simple, inexpensive, and possibly "good enough") should be investigated.
7. The application of **load resistance** across the meter test leads has a **significant impact on the measured voltage**. Deck-to-neutral voltages measured without load resistance were up to five times larger than deck-to-neutral voltages for the same scenario measured with a 500 Ω load resistance. The 500 Ω load resistor is a suitable approximation for simulating humans standing on

[1] Reportedly, the variation was due to different fault current magnitudes during the 2,700 V faults.

wet concrete and holding a metal pool strainer as well as scenarios with partial body immersions and arms (or torso) on the deck.

8. The **equipotential performance of any single cut-ring was similar or better than the performance of the "Single Conductor" option**. Additional improvement of the equipotential performance was achieved by employing **multiple cut rings**. This indicates that cut ring, in particular multiple cut rings, are an effective means to retrofit an existing swimming pool deck with equipotential bonding.

Further tests with 4 kV arc faults were conducted by EPRI on September19, 2011. The preliminary findings as reported by Doug Dorr of EPRI in an email communication with EnerNex on September 22, 2011 are listed below:

9. The **"Copper Grid" option** limited the deck-to-water voltages to **below 3 V** for all fault tests (but only out to the three-foot mark where the copper stops). Beyond that point the voltages get much higher
10. The **"Single Conductor" option** that is installed 18 inches from the water's edge and **embedded in the concrete** (aka the "yellow" ring) was ten or more times less effective than the "Copper Grid" option. This comparison is based on voltage measurements conducted at a one-foot distance from the water's edge.
11. The **"Single Conductor" option** that is installed 18 inches from the water's edge and **6 inches below grade** (aka the "black" ring) was twenty or more times less effective than the "Copper Grid" option and only about half as effective as the "yellow" ring. This comparison is based on voltage measurements conducted at a one-foot distance from the water's edge.
12. **All three options were effective in reducing the hundreds of volts** that would exist on an electrically floating deck during the simulated fault conditions to significantly lower levels, but the only option that appears to keep the voltages under "arbitrarily safe levels" of a few volts was the "Copper Grid" option. An analysis whether or not the voltage levels for the other bonding options can be considered "safe" was not performed.

The National Electric Energy Test Research & Application Center (NEETRAC) tested equipotential bonding methods on a residential swimming pool in Buford, Georgia. The pool shell consists of fiberglass material with a fibercrete lip, which secured the coping stones around the pool. The deck surface is made of stone pavers that are sitting on fine sand and crusher run. The only conducting part in contact with the pool water is the underwater light fixture. NEETRAC tested compared the effectiveness equipotential grid In our view, the main conclusion from the NEETRAC experiments is that the equipotential grid is superior to the "Single Conductor" option in providing equipotential bonding to pool decks. This conclusion is in line with the EPRI findings [1].

NEETRAC conducted tests in which the equipotential bonding effectiveness of the "Copper Grid" option is compared with the effectiveness of the "Single Conductor" option. Based on their experimental results they concluded that the "Copper Grid" option was more effective in mitigating the voltages than the "Single Conductor" option. The "Copper Grid" option reduced the water-deck voltage to values that were 70% to 93% lower than the voltages measured when the "Single Conductor" option was employed. Step voltages were reduced to values that were 57% to 97% lower than the voltages measured when the "Single Conductor" option was employed [5].

#### *7.4.3 What is missing?*

The results from the EPRI experiments are a central piece of today's knowledge about the effectiveness of bonding methods. However, as of today, the EPRI findings have not been adopted in standards and codes that impose requirement to ensure safety in swimming pool areas. It is our opinion that part of the reason for the sluggish adoption of EPRI's experimental findings into standards and codes is that one has to be careful to jump to conclusion and to impose general requirements based on somewhat limited experimental data from a single swimming pool test structure, in particular if some of the requirements have significant economic implications[1]. In our view, the NEETRAC petition for code changes discussed in Section 6.3.5 of this report suffered from these type of issues and was therefore somewhat flawed (and ultimately unsuccessful in realizing changes to the code).

We think that in order to make a convincing argument for a standard/code change, the following questions need to be answered:

1) What is the threshold at which deck-to-water voltage levels must be considered unsafe?
2) What are the deck-to-water voltage levels that can be expected for each bonding method under feasible worst-case scenarios?
3) To which extend do the deck-to-water voltage levels vary with swimming pool type, deck type, environment, etc.?

To answer question 1), the electrical characteristics of the human body and the effect of electrical current flow through the human body must be understood better. The knowledge gaps related to these issues are discussed in Section 7.1 and Section 7.2 of this report. The following section gives our suggested approach for answering questions 2) and 3).

#### *7.4.4 Conclusion*

There is a wealth of information that can be gleaned from the EPRI experiments, but it is important to point out that the analysis of the EPRI data as presented in the EPRI report is primarily comparative in nature, that is, the equipotential bonding performances of various methods were compared with each other. The EPRI report does not use the data to estimate body currents and compare the results with shock hazard current levels. Consequently, the EPRI report does not contain a conclusion regarding whether the measured voltage levels for a given scenario are acceptable or not.

In order to illuminate the open questions, in particular (1) what is the absolute effectiveness of the "Single Conductor" option, (2) what body current levels can be expected during worst-case conditions, and (3) what is the variability of these current levels with pool type, deck type, environment, etc., we suggest a three-step approach that combines experimental results with results from computer simulations. This approach could also be employed to shed light on the issue of a potential dangerous voltage gradient at the outside edge of the copper grid (item 5 above) and to explore the suitability of other equipotential bonding options that are currently not employed widely, such as the use of multiple ring conductors.

Step 1) **Conduct experiments on a test swimming pool**; preferably one with a concrete deck because, as unpublished EPRI data have shown, the measured deck-to-water voltages are more consistent and predictable for the concrete deck scenario than they are for the brick paver scenario. The measured parameters should include the deck-to-water voltage, but also other parameters, such as any measurable impedances in the current path, soil resistivity, voltages at other locations, currents, etc. The experiments should be conducted during steady-state NEV conditions and temporary fault conditions. These experiments would be similar to

[1] For instance, EPRI identified the equipotential grid as the preferred method to bond the pool deck. However, an equipotential grid is not an economical option for existing pools and, even for new pool constructions, it is usually the most expensive bonding option.

experiments already conducted by EPRI, but would include additional scenarios and more measured parameters.

Step 2) **Simulate the experimental setting** of the experiments conducted in the previous step in a **detailed computer model**. The computer model should account for all parameters that may have an effect on the deck-to-neutral voltage. The goal would be to recreate the experimentally determined deck-to-water voltages in a computer simulation by using all measured parameters as input to the simulation and make reasonable assumption about the parameters that could not be measured. If successful, this will result in a computer model that is verified with experimental data and therefore accurate for modeling scenarios that resemble the scenarios from the experiments.

Step 3) **Use the computer model** developed and verified in the previous step for **scenarios that were not tested in the Step-1 experiments** because they were difficult/expensive to create experimentally, such as, different pool types, different pool decks, very high (but still realistic) fault currents, different soil resistivities, etc. The goal of this effort would be to capture the different electrical characteristics of the changed scenario in the simulation. For instance, what changes if the experiments are conducted on a swimming pool with a vinyl liner instead of a swimming pool with a concrete shell? Some insight could be gained by conducting additional experiments on other swimming pools (without recreating the whole experiment). For instance, the question above could be answered by measuring the impedance from the water to the bonded metal on a swimming pool with vinyl liner and incorporating the measured value into the circuit simulated in the computer model.

EnerNex discussed the approach suggested above with Doug Dorr of EPRI and we agreed that this would be a promising approach for developing firm conclusions regarding the effectiveness of the equipotential methods currently listed in the NEC in providing safety from electrical shocks in swimming pool areas. Additionally, the effectiveness of equipotential methods currently not listed in the NEC could be assessed conclusively, which potentially opens the door for adopting (1) equipotential methods that are proven to be safe AND cost efficient and (2) equipotential methods that are practical options (for instance, retrofitting an existing pool with adequate protection from shocks). Mitigation options other than providing and equipotential should also be investigated experimentally and through computer simulations (for instance, reduction of the shock hazard by changing a conducting concrete deck surface to a surface that is electrically insulated, such as a wood surface).

## 8 Works Cited

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## *Appendix A NEC Requirements*

This section lists the 2011 NEC® code requirements for swimming pool areas that are pertinent to this project [7].

The article 680 provides information on the installation and equipment requirements necessary to prevent severe shock to human beings in and around swimming pools, spas and similar installations.

> ***680.1 Scope:***
>
> ***The provisions of this article apply to the construction and installation of electrical wiring for, and equipment in or adjacent to all swimming pools, wading, therapeutic and decorative pools, fountains, hot tubs spas and hydromassage bathtubs, whether permanently installed or storable and to metallic auxiliary equipment such as pumps, filters, and similar equipment.***
>
> ***680.5 Grounding :***
>
> ***Electrical equipment shall be grounded in accordance with parts V,VI, and VII of article 250 and connected by wiring methods of chapter3, except as modified by this article. The following equipment shall be grounded:***
>
> - ***Through-wall lighting assemblies and underwater luminaries, other than those low-voltage lighting products listed for the application without a grounding conductor.***
> ***All electrical equipment located within 1.5 m (5 ft) of the inside wall of the specified body of water***
> - ***All electrical equipment associated with the recirculating system of the specified body of water***
> - ***Junction boxes***
> - ***Transformer and power supply enclosures***
> ***Ground-fault circuit interrupters***
> ***Panelboards that are not part of the service equipment and that supply any electrical equipment associated with the specified body of water."***
>
> ***680.7 Cord-and-Plug-Connected Equipment :***
>
> ***Fixed or stationary equipment, other than underwater luminaries, for a permanently installed pool shall be permitted to be connected with a flexible cord and plug to facilitate the removal or disconnection or repair.***
>
> ***Length- For other than storable pools, the flexible cord shall not exceed 900 mm (3 ft.) in length.***
>
> ***Equipment Grounding- The flexible cord shall have a copper equipment grounding conductor sized in accordance with 250.122 but not smaller than 12 AWG. The cord shall terminate in grounding –type attachment plug.***

***Construction- The equipment grounding conductors shall be connected to a fixed metal part of the assembly. The removable part shall be mounted on or bonded to the fixed metal part.***

***680.9 Underground wiring location :***

***Underground wiring shall not be permitted under pool or within the area extending 1.5 m (5 ft.) horizontally from the inside wall of the pool unless this wiring is necessary to supply pool equipment permitted by this article. Where space limitations prevent wiring from being routed a distance 1.5 m (5 ft.) or more from the pool, such wiring shall be permitted where installed in complete raceway systems of rigid metal conduit, intermediate metal conduit, or a nonmetallic raceway system. All metal conduit shall be corrosion resistance and suitable for the location. The minimum cover depth shall be as given in Table 680.10.***

***680.21 Motors:***

***680.21(C) GFCI Protection:***

***Outlets supplying pump motors connected to single-phase, 120V through 240V branch circuits, rated for 15 or 20A, whether by receptacle or by direct connection, shall be provided with a ground-fault circuit protection for personnel.***

***680.22 Lighting, Receptacles, and Equipment***

***Receptacles:***

***680.22(A)(4) GFCI Protection:***

***All 15 and 20 ampere, single-phase, 125-volt receptacles located within 6.0 m (20 ft.) of the inside walls of a pool shall be protected by a ground-fault circuit interrupter.***

***Luminaries, Lighting Outlets, and Ceiling-Suspended (Paddle Fans)***

***680.22(B)(4) GFCI Protection in adjacent areas:***

***Luminaries, lighting outlets, and ceiling-suspended (paddle) fans installed in the area extending between 1.5 m (5 ft.) and 3.0 m (10 ft.) horizontally from the inside walls of a pool shall be protected by a ground-fault circuit interrupter unless installed not less than 1.5 m (5 ft.) above the maximum water level and rigidly attached to the structure to or enclosing the pool.***

***680.23 Underwater Luminaries :***

***General***

***680.23(A)(2) Transformers and Power Supplies:***

***Transformers and power supplies used for the supply of underwater luminaries, together with the transformer or power supply enclosure, shall be listed for swimming pool and spa use. The transformer or power supply shall incorporate either a transformer of the isolated winding type, with an ungrounded secondary that has a grounded metal barrier between the primary and secondary windings, or one that incorporates an approved system of double insulation between the primary and secondary windings.***

***680.23(A)(3) GFCI protection, relamping:***

***A ground-fault circuit interrupter be installed in the branch circuit supplying luminaries operating at more than the low voltage contact limit such that there is no shock hazard during relamping. The installation of the ground-fault circuit interrupter shall be such that there is no shock hazard with any likely fault –condition combination that involves a person in a conductive path from any ungrounded part of the branch circuit or the luminaire to ground.***

***680.23(A)(4) Voltage limitation:***

***No luminaire shall be installed for operation on supply circuits over 150 V between conductors.***

***Wet –Niche Luminaries.***

***680.23(B)(3) Equipment grounding provisions for cords:***

***Other than listed low voltages lighting systems not requiring grounding wet-niche luminaries that are supplied by a flexible cord or cable shall have all exposed non-current –carrying metal parts grounded by an insulated copper equipment grounding conductor that is an integral part of the cod or cable. This grounding conductor shall be connected to a grounding terminal in the supply junction box, transformer enclosure, or other enclosure. The grounding conductor shall not be smaller than the supply conductors and not smaller than 16 AWG.***

***680.23(B)(5) Luminaire Bonding:***

***The luminaire shall be bonded to, and secured to the following shell by a positive locking device that ensures a low-resistance contact and requires a tool to remove the luminaire from the forming shell. Bonding shall not be required for luminaires that are listed for the application and have no non-current-carrying metal parts.***

***Branch-Circuit Wiring***

***680.23(F)(2)Equipment Grounding:***

***Other than listed low voltage luminaries not requiring grounding , all through-wall lighting assemblies, wet-niche, dry-niche or no-niche luminaries shall be connected to an insulated copper equipment grounding conductor installed with the circuit conductors. The equipment grounding conductor shall be installed without joint or splice except as permitted in (F)(2)(a) and F(2)(b). The equipment grounding conductor shall be sized in accordance with table 250.122 but shall not be smaller than 12 AWG.***

***Exception: An equipment grounding conductor between the wiring chamber of the secondary winding of a transformer and a junction box shall be seized in accordance with the overcurrent device in this circuit.***

***680.23(F)(2)(a)- If more than one underwater luminaire is supplied by the same branch circuit, the equipment grounding conductor, installed between the junction boxes, transformer enclosures, or other enclosures in the supply shall be permitted to be terminated on grounding terminals.***

***680.23(F)(2)(b)- If the underwater luminaire is supplied from a transformer, ground-fault circuit interrupter, clock operated switch, or a manual snap switch that is located between the panelboard and a junction box connected to the conduit that extends directly to the underwater luminaire, the equipment grounding conductor shall be permitted to terminate on grounding terminals on the transformer, ground fault circuit interrupter, clock-operated switch enclosure, or an outlet box used to enclose snap switch.***

***680.24 Junction Boxes and Electrical Enclosures for Transformers or Ground Fault-Circuit Interrupters***

***Installation***

***680.24(2)(F) Grounding:***

***The equipment grounding conductor terminal of a junction box, transformer enclosure, or other enclosure in the supply circuit to a wet-niche or no-niche luminaire and the field-wiring chamber of a dry-niche luminaire shall be connected to the equipment grounding terminal of the panelboard. The terminal shall be directly connected to the panelboard enclosure.***

***680.25 Feeders.***

***680.25(B) Grounding:***

***An equipment grounding conductor shall be installed with the feeder conductors between the grounding terminal of the pool equipment panelboard and grounding terminal of the applicable service equipment or source of a separately derived system. For other than (1) existing feeders covered in 680.25(A), exception or (2) feeders to separate buildings that do not utilize an insulated equipment grounding conductor in accordance with 680.25(B)(2), this equipment grounding conductor shall be insulated.***

***680.26 Equipotential Bonding***

***Performance.***

***The equipotential bonding required by this section shall be installed to reduce voltage gradients in the pool area.***

***Bonded Parts.***

***The parts specified in 680.26(B)(1) through B(7) shall be bonded together using solid copper conductors, insulated covered, or bare, not smaller than 8 AWG or with rigid metal conduit of brass or other identified corrosion-resistant metal. Connections to bonded parts shall be made in accordance with 250.8. An 8 AWG or larger solid copper bonding conductor provided to reduce voltage gradients in the pool area shall not be required to be extended or attached to remote panelboards, service equipment, or electrodes.***

***Conductive Pool Shells.***

***Bonding to conductive pool shells shall be provided as specified in 680.26(B)(1)(a) or (B)(1)(b). Poured concrete, pneumatically applied or sprayed concrete and concrete block with painted or plastered coatings shall be considered conductive materials due to water permeability and porosity. Vinyl liners and fiberglass composite shells shall be considered to be nonconductive materials.***

***Structural reinforcing steel. Unencapsulated structural reinforcing shall be bonded together by steel tie wires or the equivalent. Where structural reinforcing steel is encapsulated in a nonconductive compound, a copper conductor grid shall be installed in accordance with 680.26(B)(1)(b).***

***Copper Conductor Grid. A copper conductor grid shall be provided and comply with (b)(1) through (b)(4).***

***Be constructed of 8 AWG bare solid copper conductors bonded to each other at all points of crossing. The bonding shall be in accordance with 250.8 or other approved means.***

***Conform to the contour of the pool.***

***Be arranged in a 300-mm (12-in.) by 300-mm (12-in.) network of conductors in a uniformly spaced perpendicular grid pattern with a tolerance of 100 mm(4 in.)***

***Be secured within or under the pool no more than 150 mm (6 in.) from the outer contour of the pool shell.***

***Perimeter Surfaces:***

***The perimeter surface shall extend for 1 m (3 ft.) horizontally beyond the inside walls of the pool and shall include unpaved surfaces, as well as poured concrete surfaces and other types of paving. Perimeter surfaces less than 1 m (3 ft.) separated by a permanent wall or building 1.5 m(3 ft.) in height or more shall require equipotential bonding on the pool side of the permanent wall or building. Bonding to perimeter surfaces shall be provided as specified in 680.26(B)(2)(a) or (2)(b) and shall be attached to the pool reinforcing steel or copper conductor grid at a minimum of four (4) points uniformly spaced around the perimeter of the pool. For nonconductive pool shell, bonding at four points shall not be required.***

***Structural Reinforcing steel. Structural reinforcing steel shall be bonded in accordance with 680.26(B)(1)(a).***

*Alternate Means. Where structural steel reinforcing steel is not available or is encapsulated in a nonconductive compound, a copper conductor(s) shall be utilized where the following requirements are met:*

*At least one minimum 8 AWG bare solid copper conductor shall be provided.*

*The conductors shall follow the contour of the perimeter surface.*

*Only listed splices shall be permitted.*

*The required conductor shall be 450 mm to 600 mm (18 in.to 24 in.) from the inside walls of the pool.*

*The required conductor shall be secured within or under the perimeter surface 100 mm to 150 mm (4 in. to 6 in.) below the subgrade.*

*Metallic Components:*

*All metallic parts of the pool structure, including reinforcing metal not addressed in 680.26(B)(1)(a), shall be bonded. Where reinforcing steel is encapsulated with a nonconductive compound, the reinforcing steel shall not be required to be bonded.*

*Underwater lighting.*

*All metal forming shells and mounting brackets of no-niche luminaires shall be bonded.*

*Exception: Listed low voltage lighting systems with non-metallic forming shells shall not require bonding.*

*Metal Fittings*

*All metal fittings within or attached to the pool structure shall be bonded. Isolated parts that are not over 100 mm (4 in.) in any dimension and do not penetrate into the pool structure more than 25 mm (1 in.) shall not require bonding.*

*Electrical Equipment:*

*Metal Parts of electrical equipment associated with the pool water circulating system, including pump motors and metal parts of pool equipment associated with pool covers, including electric motors, shall be bonded.*

*Exception: Metal parts of listed equipment incorporating an approved system of double insulation shall not be bonded.*

*Double-insulated water pump motors: Where a double-insulated water pump motor is installed under the provisions of this rule, a solid 8 AWG copper conductor is sufficient length to make a bonding connection to replacement motor shall be extended from the bonding grid to an accessible point in the vicinity of the pool pump motor. Where there is no connection between the swimming pool bonding grid and the equipment grounding shall be connected to the equipment grounding conductor of the motor circuit.*

*Pool Water Heaters. For pool water heaters rated at more than 50 A and having specific instructions regarding bonding and grounding, only those parts designated*

***to be bonded shall be bonded and only those parts designated to be grounded shall be grounded.***

***Fixed Metal Parts***

***All fixed metal parts shall be bonded including, but not limited to, metal-sheathed cables and raceways, metal piping, metal awnings, metal fences, and metal door and window frames.***

***Exception No.1: Those separated from the pool by a permanent barrier that prevents contact by a person shall not be required to be bonded.***

***Exception No.2: Those greater than 1.5 m (5 ft.) horizontally of the inside walls of the pool shall not be required to be bonded.***

***Exception No.3: Those greater than 3.7 m (12 ft.) measured vertically above the maximum level of the pool, or as measured vertically above any observation stands, towers, or platforms, or any diving structures, shall not be required to be bonded.***

***Pool water:***

***An intentional bond of a minimum conductive surface area of 5800 mm$^2$ (9 in.$^2$) shall be installed in contact with the pool water. This bond shall be permitted to consist of parts that are required to e bonded in 680.26(B).***

Article 680.26 for bonding gives the reference of article 250.8. The article states as follows:

***250.8 Connection of grounding and Bonding Equipment:***

***Permitted method.***

***Equipment grounding conductors, grounding electrode conductors and bonding jumpers shall be connected by one of the following means:***

***Listed pressure connectors***

***Terminal bars***

***Pressure connectors listed as grounding and bonding equipment***

***Exothermic welding process***

***Machine screw-type fasteners that engage not less than two threads or are secured with a nut***

***Thread – forming machine screws that engage not less than two threads in the enclosure***

***Connections that are part of a listed assembly***

***Other listed items***

***Not permitted methods:***

***Connection devices or fittings that depend solely on solder shall not be used.***

## *Appendix B Body Impedance from IEC 60479-1*

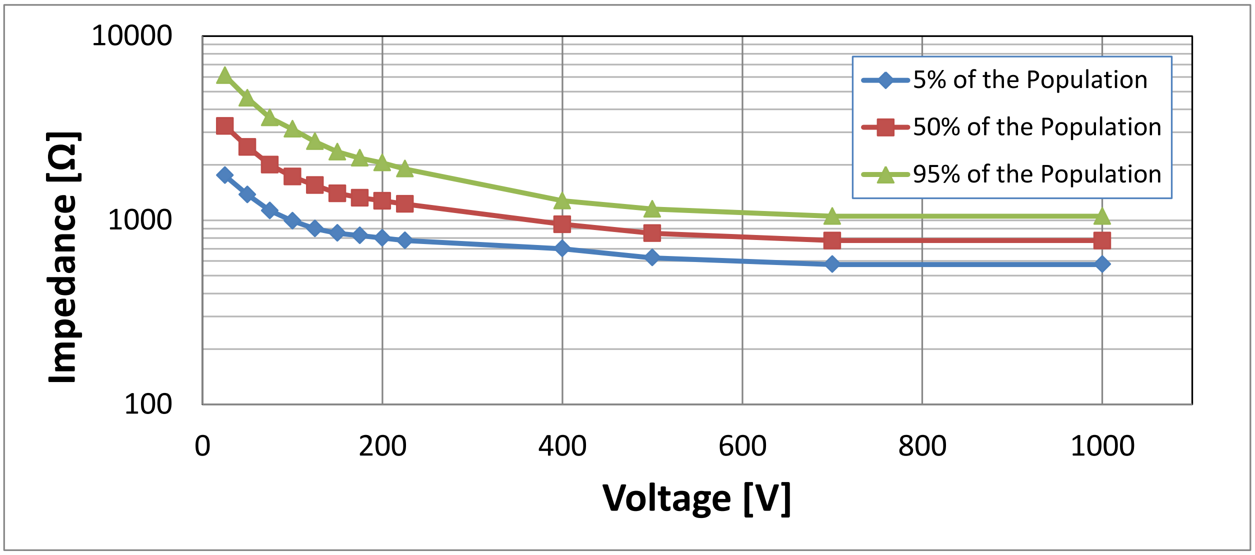


**Figure 12: Total body impedances $Z_T$ for a hand-to hand current path, ac 50/60 Hz, large surface areas of contact, dry conditions.**

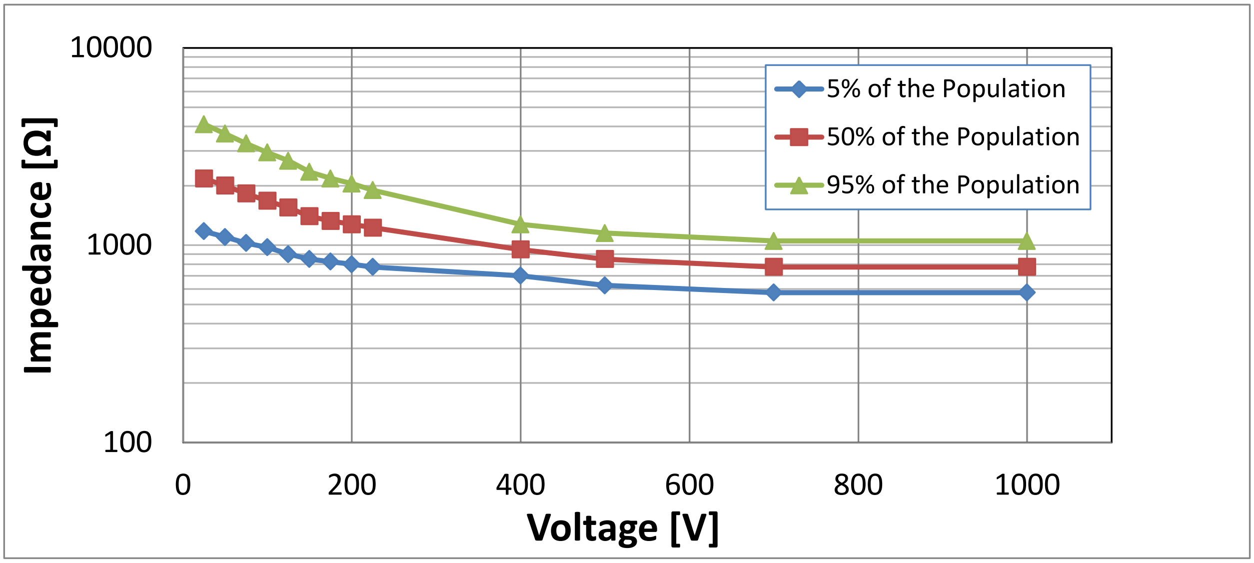


**Figure 13: Total body impedances $Z_T$ for a hand-to hand current path, ac 50/60 Hz, large surface areas of contact, water-wet conditions.**

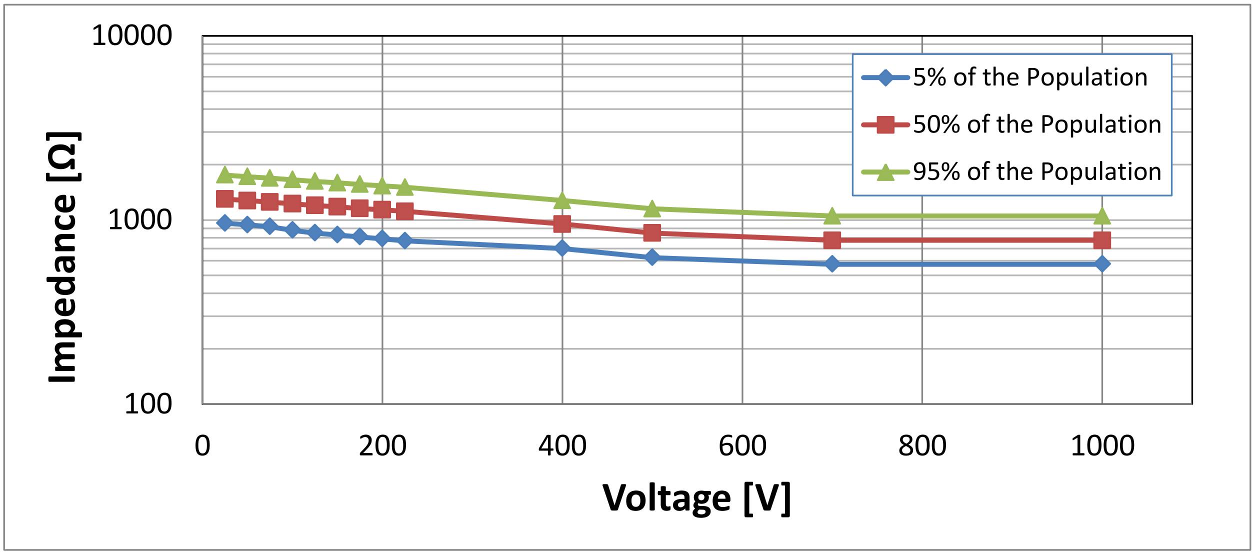


**Figure 14: Total body impedances $Z_T$ for a hand-to hand current path, ac 50/60 Hz, large surface areas of contact, saltwater-wet conditions.**

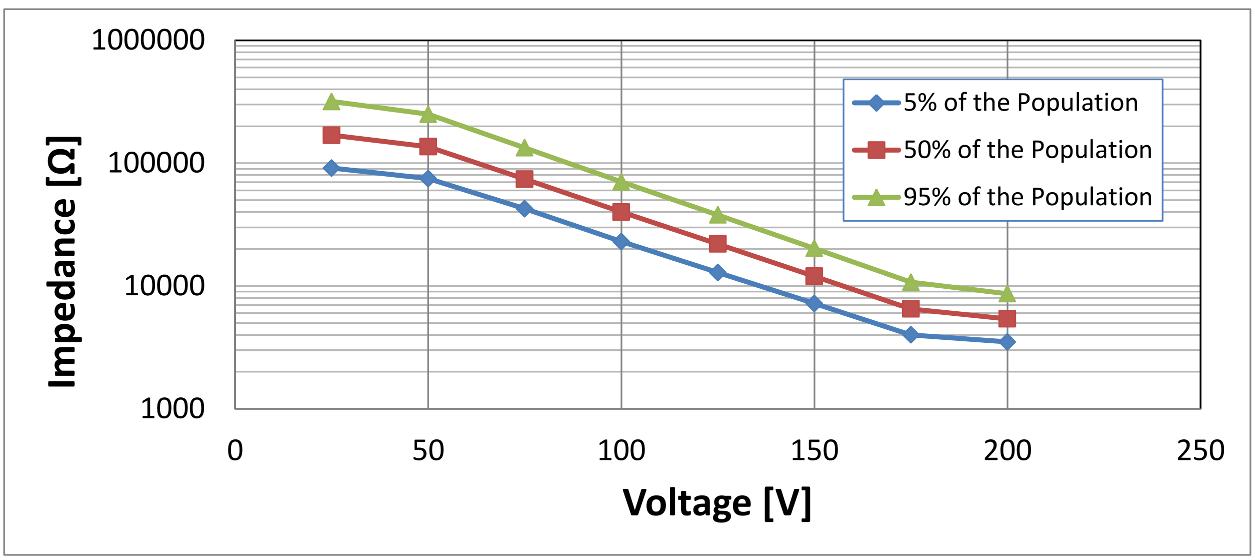


**Figure 15: Total body impedances $Z_T$ for a hand-to hand current path, ac 50/60 Hz, medium surface areas of contact, dry conditions.**

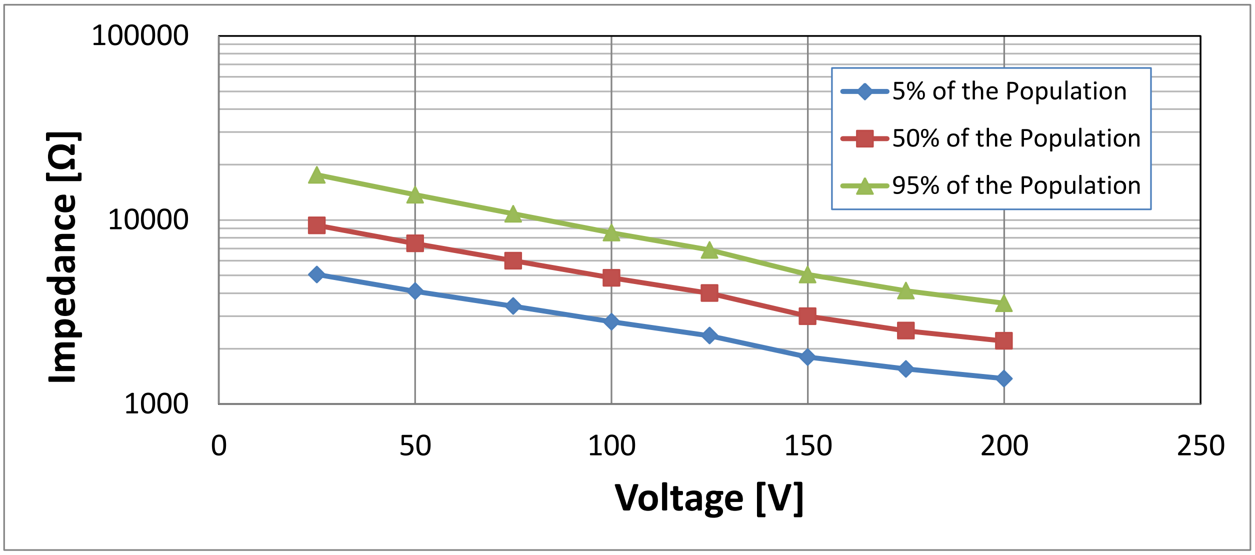


**Figure 16: Total body impedances $Z_T$ for a hand-to hand current path, ac 50/60 Hz, medium surface areas of contact, water-wet conditions.**

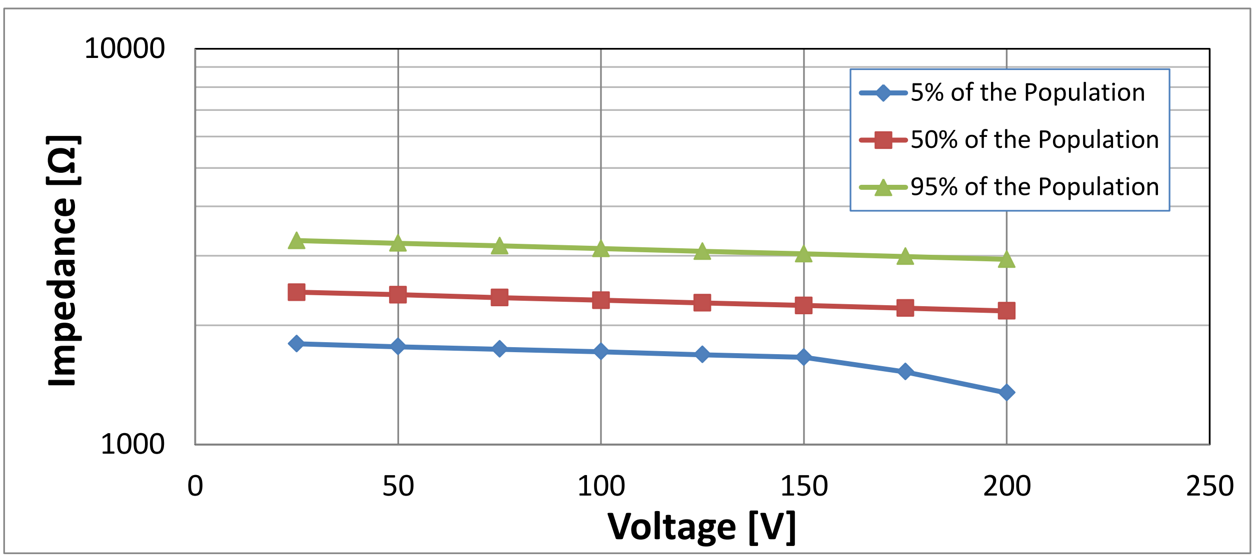


**Figure 17: Total body impedances $Z_T$ for a hand-to hand current path, ac 50/60 Hz, medium surface areas of contact, saltwater-wet conditions.**

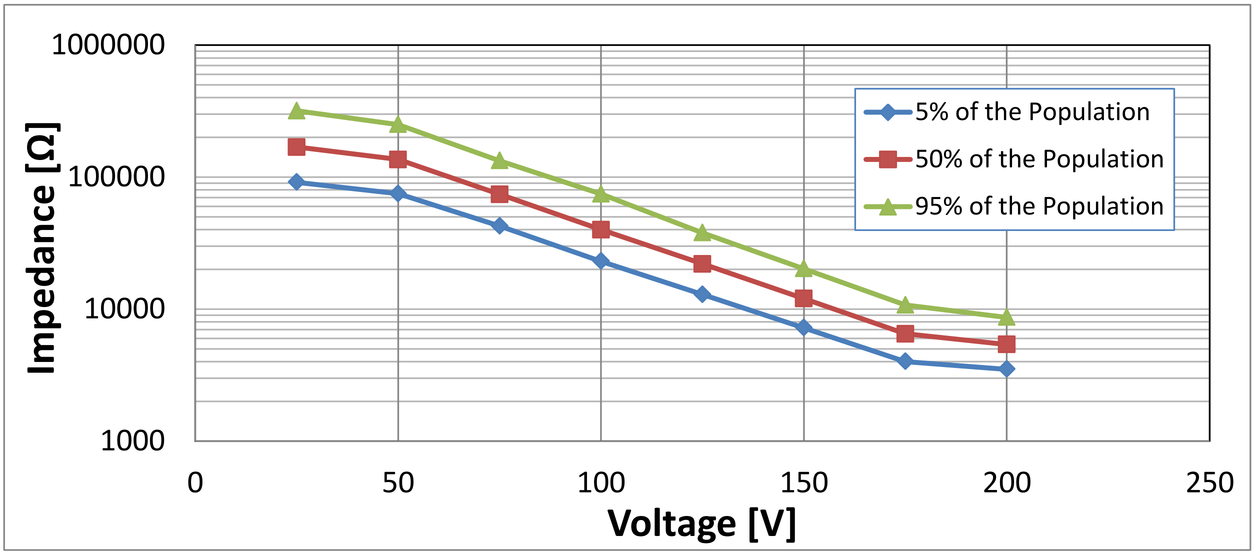


**Figure 18: Total body impedances $Z_T$ for a hand-to hand current path, ac 50/60 Hz, small surface areas of contact, dry conditions.**

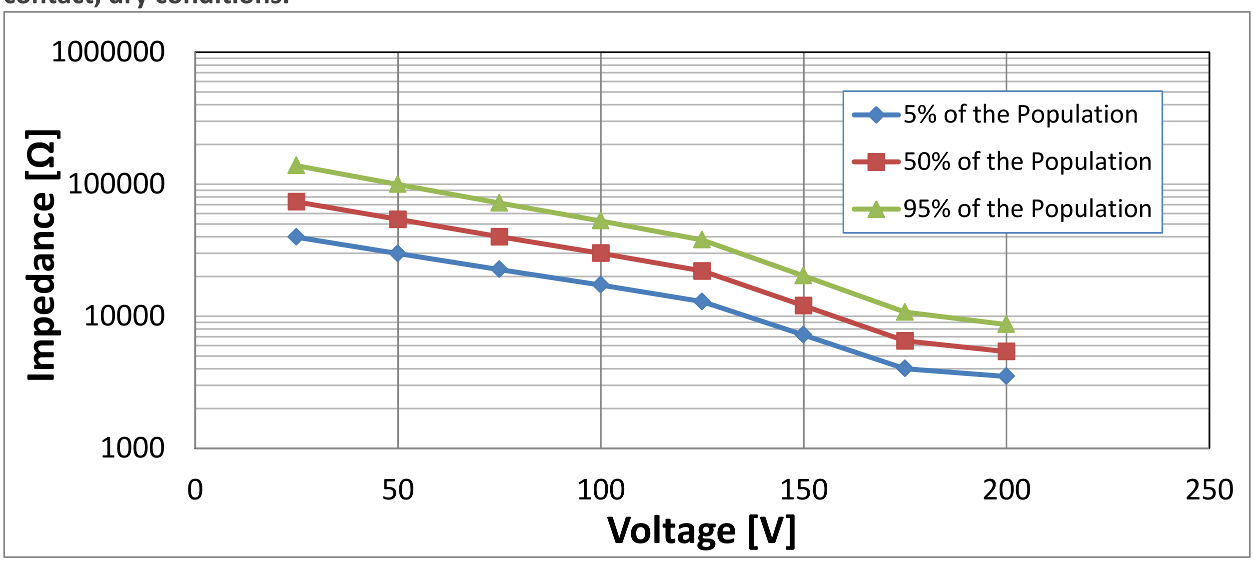


**Figure 19: Total body impedances $Z_T$ for a hand-to hand current path, ac 50/60 Hz, small surface areas of contact, water-wet conditions.**

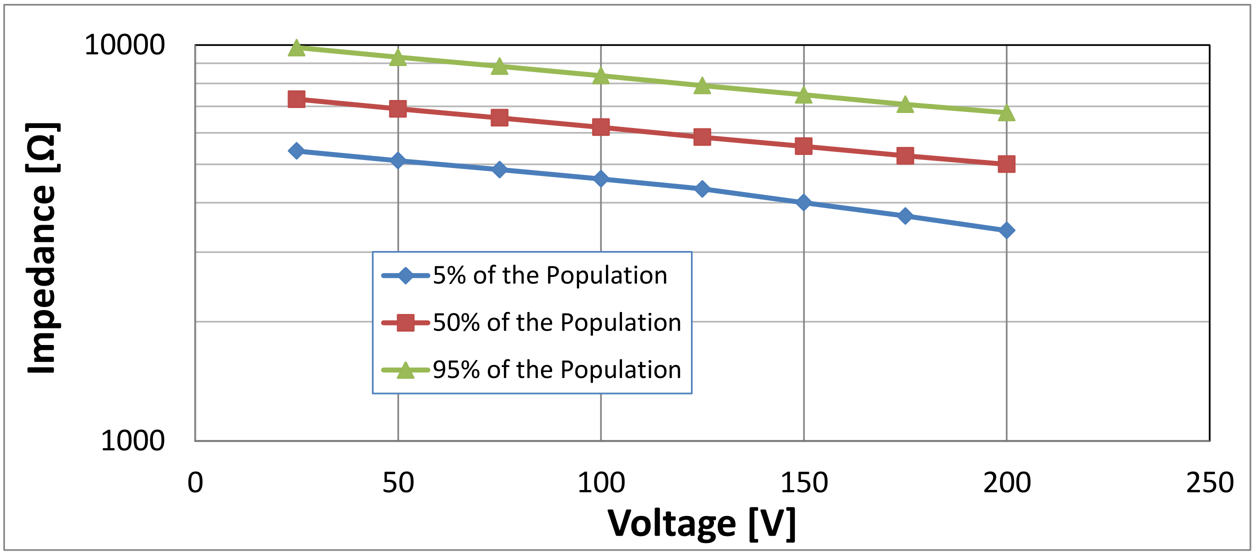


**Figure 20: Total body impedances $Z_T$ for a hand-to hand current path, ac 50/60 Hz, small surface areas of contact, saltwater-wet conditions.**

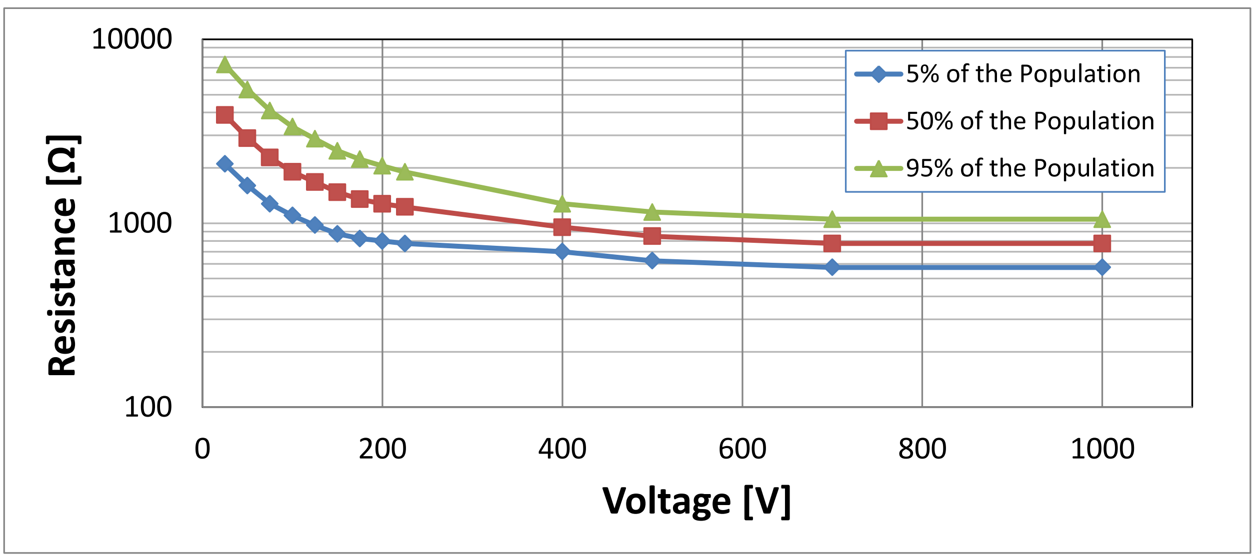


**Figure 21: Total body impedances $Z_T$ for a hand-to hand current path, dc, small surface areas of contact, dry conditions.**