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Methodology and Tools for Forensic Engineering Analysis of Electrical Shocks

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Abstract

Forensic engineering analyses (FEA) of electrical shock incidents are challenging because many factors need to be considered to understand how and why the incident happened. The goal is to determine how and why the victim's body became part of an electrical circuit that caused the shock injury. To do this, the engineer needs to determine, if possible, all of the connected portions that combined to make the complete circuit at the time of the shock, including the energized and non-energized conductors. Then, failures (defects) of components and violations from standards by parties involved with manufacturing, installing, inspecting, operating, and servicing the electrical circuits/systems involved need to be determined and their relation to the cause (failure-modes) evaluated[1]. There will often be multiple circuits in the vicinity of the shock victim, some of which are pertinent to the shock and others that are not. These circuits need to be analyzed and non-pertinent circuits ruled out. When the pertinent circuit is determined, all the conductive elements and connections that form the (often three-dimensional) circuit should be identified. This includes service conductors, branch conductors, cords, portable devices, victims with their specific circumstances and conditions, their clothes, any moisture, tools, vehicles, and nearby materials, such as soil and vegetation. This paper outlines the scientific methodology and tools, logical decision analyses, and procedures for performing a shock analysis and provides specific examples based on actual investigations.

Keywords

Electrical shock injury, leakage current, resistance and impedance, insulation, stray voltage, electrophysiology, grounded conductor, grounding conductor, electrolyte, ground fault circuit interrupter

Background and Terms

This paper will focus on the forensic engineering investigations of electrical injuries involving an individual becoming part of an electrical circuit versus injuries due to flash, fire, or lightning. In the United States, there are approximately 1,000 deaths per year as a result of electrical injuries. Of these, approximately 400 are due to high-voltage electrical injuries, while lightning causes 50 to 300. There are also at least 30,000 shock incidents per year that are non-fatal. Each year, approximately 5% of all burn unit admissions in the United States occur as a result of electrical injuries. Approximately 20% of all electrical injuries occur in children. The incidence is highest in toddlers and adolescents. In adults, these injuries occur mostly in occupational settings and are the fourth-leading cause of workplace-related traumatic death, whereas, in children, electrical injuries occur most often at home[2]. This paper will focus on the electrical causes — not the pathology, diagnosis, therapy, or sequelae (except for a brief introduction to a diagnostic method that relates to how current flows in human tissue and informs the reader on one mechanism of shock injury). The general term "shock" is used in place of "electrocution," since shock injuries may or may not be fatal — the common implication is that an electrocution is a fatal shock injury.

Using the scientific method, a forensic analyst should strive to complete the following steps[3]:

1. Gather data on all the parties and circuits that need to be analyzed, including actions taken by parties, photographs, interviews, measurements, pertinent standards in effect that impact electrical safety, history of the circuits, documentation on their installation, any alterations, and injuries sustained. Gather this information as early in the

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investigation as possible because memories fade. The results from the data-gathering step will impact how scene and lab examination protocols are planned and performed.

2. Rule-in or rule-out circuits regarding causality, based upon scientific hypothesis testing.

3. Determine how and why any stray electrical current occurred and the path of the stray current that caused the electrical shock. Often multiple failures occur to cause the electrical hazard to be present. All of these necessary failures should be identified and their relation to the shock hazard discussed.

4. Evaluate if the results are consistent with the victim's condition and activities before and at the time of the accident.

5. Determine what human actions may have violated one or more standards that were causative to the electrical shock. An example of a party not meeting a standard is an electrician not installing a grounding and bonding conductor for a pool pump that is explicitly required in the installation manual and the electrical code requirements per the local inspector.

The following basic terms, which are often referred to without the adjective "electrical"[4], are important as they have precise meanings and are consistent with the terms of art used in the electrical codes, standards, and trades.

Electrical charge: An excess or deficiency of electrons in a body[5]. Charged particles can be electrons (sub-atomic) or ions (atomic)[6]. Charge has units of Coulombs.

Conductors and insulators: Conductors permit the passage of charge through them; insulators do not[6]. The passage or lack of passage of charge is not perfect in the sense of 100 or zero percent passage. All materials allow some (large to minute amounts of) passage of charge — this will be discussed further in the section on resistance and impedance. Many conductors are metallic wires, but uninsulated metal enclosures that can pass charge in an abnormal situation after an insulation breakdown occurs are also important conductors in a system that guards against shock injury.

Voltage: A measure of the electrical potential difference between two points[7]. Voltage has units of volts (V).

Electrical current: The current in a conductor is measured in amperes (A) and is a measure of the rate of motion of charge carriers in the conductor. Current is important in that it is related to conductor heating and determines the required size of the conductor, whereas voltage determines the insulation required for the conductor. The continuous current rating (ampacity) for a conductor depends on the temperature rise permitted for the conductor and its insulation because heat in a conductor is related to the square of the current in the conductor[7]. Direct current (DC) is a flow of charge in one direction only from a constant voltage source. Alternating current (AC) is charge flowing in alternating directions due to a voltage source that alternates from positive to negative voltage at a frequency of typically 50 or 60 cycles per second or hertz (Hz).

Electric circuit: An interconnection of electrical elements linked together in a closed path so that an electric current may flow continuously[8].

Electrical resistance and impedance: The resistance of a given circuit, measured in ohms (symbol Ω), is used to determine the current in a circuit for a given voltage difference across elements of the circuit[7]. Impedance consists of resistive, capacitive, and inductive components[8]. Appliance electrical insulation resistance is typically millions of ohms (MegΩ) and only allows minimal leakage current. For example, only 1.2 micro-amp (0.0000012A) flows through 100 MΩ (100,000,000 Ω) resistance when exposed to a voltage of 120V. Load resistances typically have much lower resistance, and the human body has a range of resistance of approximately 500 to many 1,000s of ohms, depending on the voltage, frequency, path of the current, time, and the condition or presence of the skin[9]. Tissues (such as blood, muscles, and nerves), moisture, and earth can also be conductors in a circuit path — and have their different impedances affect the flow of current[4,9,10].

Ground: The earth[4]. The earth is presumed to be at a potential of zero volts when it is not conducting current.

Grounded (or grounding): Connected (or connecting) to ground or a conductive body that extends the ground connection[4].

Grounded conductor: A system or circuit conductor (designed to carry current under normal operating conditions) that is intentionally grounded[4]. An example is a neutral conductor that can be at a potential greater than zero volts due to a voltage gradient while it carries current.

Grounding electrode (GE): A conducting object through which a direct connection to earth is established[4]. Common grounding electrodes include copper ground rods, metal water pipes, or building steel.

Grounding electrode conductor (GEC): A conductor used to connect the system grounded conductor or the equipment to a grounding electrode or to a point on the grounding electrode system[4].

Equipment grounding conductor (EGC): A conductive path(s) that is part of an effective ground-fault current path and connects normally non-current-carrying metal parts of equipment together and to the system grounded conductor or to the grounding electrode conductor or both[4].

Bonded (or bonding): Connected (or connecting) to establish electrical continuity or conductivity[4].

Main bonding jumper (MJB): The connection between the grounded circuit conductor and the equipment grounding conductor or the supply-side bonding jumper (or both) at the service[4].

Ungrounded: Not connected to ground or to a conductive body that extends the ground connection[4]. An example of an ungrounded conductor is one that is at full voltage for use in a device, such as 120VAC, 240VAC, 480VAC, and is often called a "hot" or "energized" conductor.

Ground fault: An unintentional, electrically conductive connection between an ungrounded conductor of an electrical circuit and the normally non-current-carrying conductors, metallic enclosures, metallic raceways, metallic equipment, or earth[4].

Load: The device designed to use electrical energy to perform a desired purpose.

Stray voltage and stray (or leakage) current: Terms that will be used interchangeably and refer to undesired electrical potential and current flow that can cause a shock.

Figure 1 illustrates a ground fault in a load fed from a source transformer through a service circuit breaker[11]. Numbers, letters, and arrows were added to the IAEI diagram by this author. Normally, current flows to the load through the insulated energized conductors ("hot" and red arrows), flows through the load, and then flows safely back to the service/source through insulated grounded conductors (neutrals for 120VAC).

A correctly installed system keeps connections G1 and G2 as close to zero volts as possible as these are connected directly to earth ground. If there are separate EGC and grounded/neutral lugs, the main bonding jumper (MJB) connects the service EGC lug to the grounded/neutral lugs in the service panel to keep them at zero potential (G2). Problematically, a ground fault is shown where fault current flows, as shown by the purple arrows and lines, through the EGC, which is the conduit between the load and service enclosures, including bonding connections (A). Once this fault current reaches the area of the bonded service lug (G2), it can return to the source grounded connection at (G1) through three paths simultaneously:

1. Through the grounded conductor (neutral wire), as shown with the thick blue arrows (reference #1).
2. Through the bonded enclosures and conduit through bonding B connections, as shown with the thick green arrows (reference #2).
3. Through the earth ground loop as shown with the thick orange arrows (reference #3).

Normally, most fault current should flow through paths #1 and #2 as path #3 has the relatively high-impedance earth as part of the conductive path. The result of fault current flow through #1 and #2 is normally a short-duration

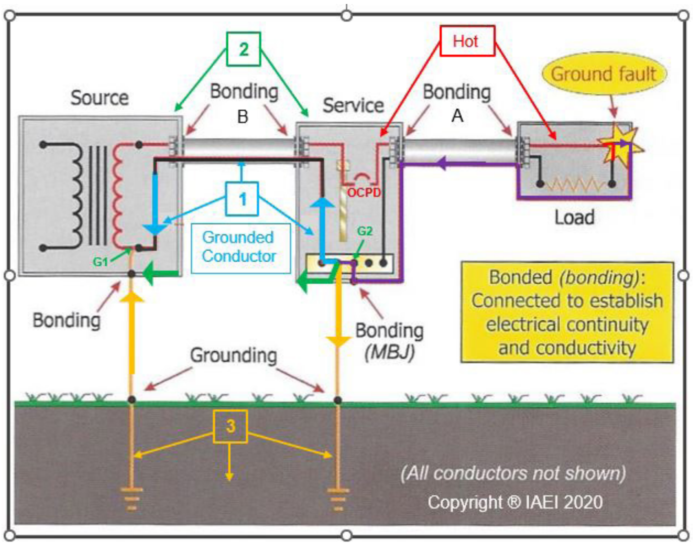

Figure 1
A ground fault and the resulting current paths[11].

overcurrent that trips an overcurrent device (OCPD), such as a fuse or circuit breaker so that no permanent damage occurs to the conductors or insulation systems — and the shock injury hazard is very short in duration. However, in a situation where there is no EGC between the service and the load and/or no bonding connections (A), the load enclosure may remain at 120VAC or a voltage substantially higher than a safe level. The load may or may not still be operating. The dangerous situation is further depicted as the shock hazard in **Figure 2**.

People Protection

The following devices and systems help protect users from shock hazards[4,12]:

- A proper grounding network (made from the grounding and bonding components discussed above) forms a reservoir of zero potential materials. This is designed to allow stray current to be passively diverted away from vulnerable persons and cause active devices to operate and further decrease the probability of a shock injury.

- An OCPD is an active device that deenergizes a circuit after it senses overcurrent, commonly at or more than 120% of the current rating of the device. Refer to the trip curve for a particular OCPD as the trip time varies with the percentage of overcurrent. The OCPD can protect the wiring from overheating as well as persons from becoming part of the circuit if the circuit is de-energized prior to a person contacting the damaged device.

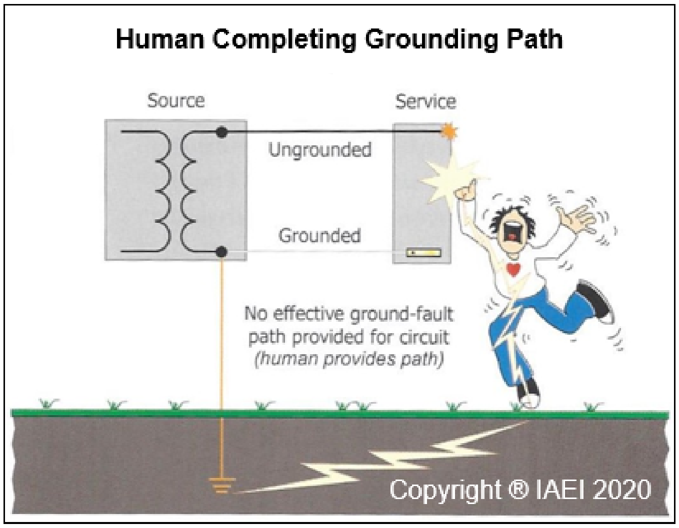

Figure 2
Shock through person in contact with an enclosure[11].

- A ground-fault circuit interrupter (GFCI or GFI) is an active device that measures the imbalance (leakage current) between the grounded and ungrounded conductors and will trip off if this imbalance reaches a nominal level of 5 milliamps (mA) or 0.005A.

- An arc-fault circuit interrupter (AFCI) or a residual current device (RCD) works in a similar way as a GFCI, but these devices trip at a nominal imbalance level of 30 mA (0.030 A) due to an abnormal current waveform.

- A double-insulated device has two independent insulation systems and no accessible grounded metal to become energized.

- A low-voltage device is one that operates at or less than 30VAC.

Normally, when electrical insulation is new and functioning well, its impedance can be thought of as infinitely high; however, it always has a finite quantity of impedance. When the insulation becomes degraded, its impedance can decrease to levels that may cause an electrical hazard.

Degradation due to surface contamination, moisture absorption, charring, dimensional and internal changes, and biological alterations may occur and cause the impedance to be reduced. Note the resistance drawn between the ungrounded and the EGC in **Figure 3**. This causes undesired current to flow. New plastic insulation for a 120VAC appliance cord may start out at an impedance of 100 MegΩ and only allow leakage current to ground of 1.2 microamps (0.0012 mA). If this impedance drops to 24 kiloohms (24 kΩ), the leakage current increases to 5 mA, which is the

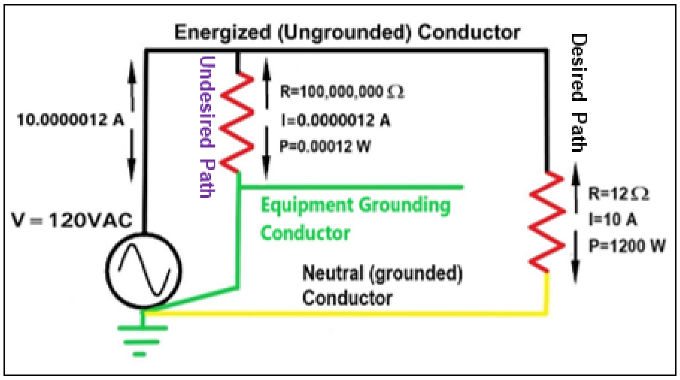

Figure 3
Schematic of current flowing through a desired path (black and yellow conductors) and an undesired path (green conductors).

leakage current level that should trip a GFCI. If there is no GFCI and the impedance drops to zero ohms, a person contacting the energized conductor will be the only impedance holding back the current from flowing. If a person contacts this energized conductor with no insulation, it is possible that the person may only add 500 to 1,000 Ω of impedance to this circuit, respectively, and the leakage current could reach 240 to 120 mA, which is above the level that can be fatal. The leakage current can normally be analyzed independently from the desired electrical current load (10A in this example) as seen in **Figure 3**.

If the conductor insulation inside an enclosure fails, the conductor contacts an accessible metal surface, and energizes the metal surface, the current path to ground can be through a person during a shock event, as shown in **Figure 2**[11].

How Electricity Affects the Human Body

Figure 4 shows how the body responds to increasing AC current[7]. The data shows the non-injurious perception at 1.0 mA through serious cardiac arrhythmia at 60 mA and other more serious conditions as the current increases. There are some differences between the effects on males versus females. Based upon this data, the trip levels for GFCIs were set at 5 mA, above the perception threshold and below the let-go currents (both considered safe levels).

The results of studies by Charles Dalziel in **Figure 5** show the different effects of electricity on the human body (men and women) for DC and AC[9]. It was found that, on average, the human body can tolerate DC current at a higher level than AC current, and males can tolerate higher currents than females.

Figure 6 shows valuable relationships between imbalance trip current verses shock duration for a typical GFCI, electrocution threshold, let-go thresholds for adults, and body resistances for 120VAC shock scenarios[13]. Highlights of red, yellow, and blue were added by this author for clarification and perspective. The black curves show the approximate GFCI performances for zero load and an imbalance with a load of 15A. There are also data points shown. Note that the vertical axis represents shock current, and the horizontal axis shows shock duration or trip time in log scales. From the graph, note the following:

- GFCIs have short trip times at high-current imbalances and longer trip times at low-current imbalances, but all are generally well under 0.1 second.
- All GFCIs trips shown are at an imbalance current of 4 mA and above. Below 3 mA, the GFCI will not trip.
- The yellow region represents the region where a GFCI will trip to safely deenergize a circuit.
- The maximum current of 240 mA level corresponds to a minimum body resistance of 500 Ω at 120VAC; other current levels are shown for the corresponding body resistances.
- The red line shows the locus of points for electrocution for adults, which corresponds to severe injury or death.
- The region where a GFCI will trip is outside the threshold for electrocution for adults.
- The blue line represents the let-go threshold for men, which can be inside the trip region; however, the trip time for this let-go phenomena will be less than 0.1 seconds.

Table 3.3 Thresholds for effects of commercial electrical power

Response	Threshold current*
Perception	1.0 mA (M)
	0.5 mA (F)
Let-go	16 mA (M)
	11 mA (F)
Cardiac Arrhythmia	60 mA
Ventricular fibrillation	100 mA
Disruption of skeletal muscle membranes	1500 mA [20]

Notes:
** Assumes current path in the upper extremity.*
(M) Males, (F) Females

Figure 4
Thresholds for effects of commercial electrical power.

	Direct Current (mA)		60-HZ Current (mA rms)	
Effect	**Men**	**Women**	**Men**	**Women**
No sensation on hand	1	0.6	0.4	0.3
Slight tingling. Perception threshold	5.2	3.5	1.1	0.7
Shock — not painful and muscular control not lost	9	6	1.8	1.2
Painful shock — painful but muscular control not lost	62	41	9	6
Painful shock — let-go threshold	76	51	16.0	10.5
Painful and severe shock — muscular contractions, breathing difficult	90	60	23	15

* From Dalziel, IEEE Trans. Bio. Med. Eng. 1956. 5:44-62.

Figure 5
Thesholds for effects of DC and AC for men and women.

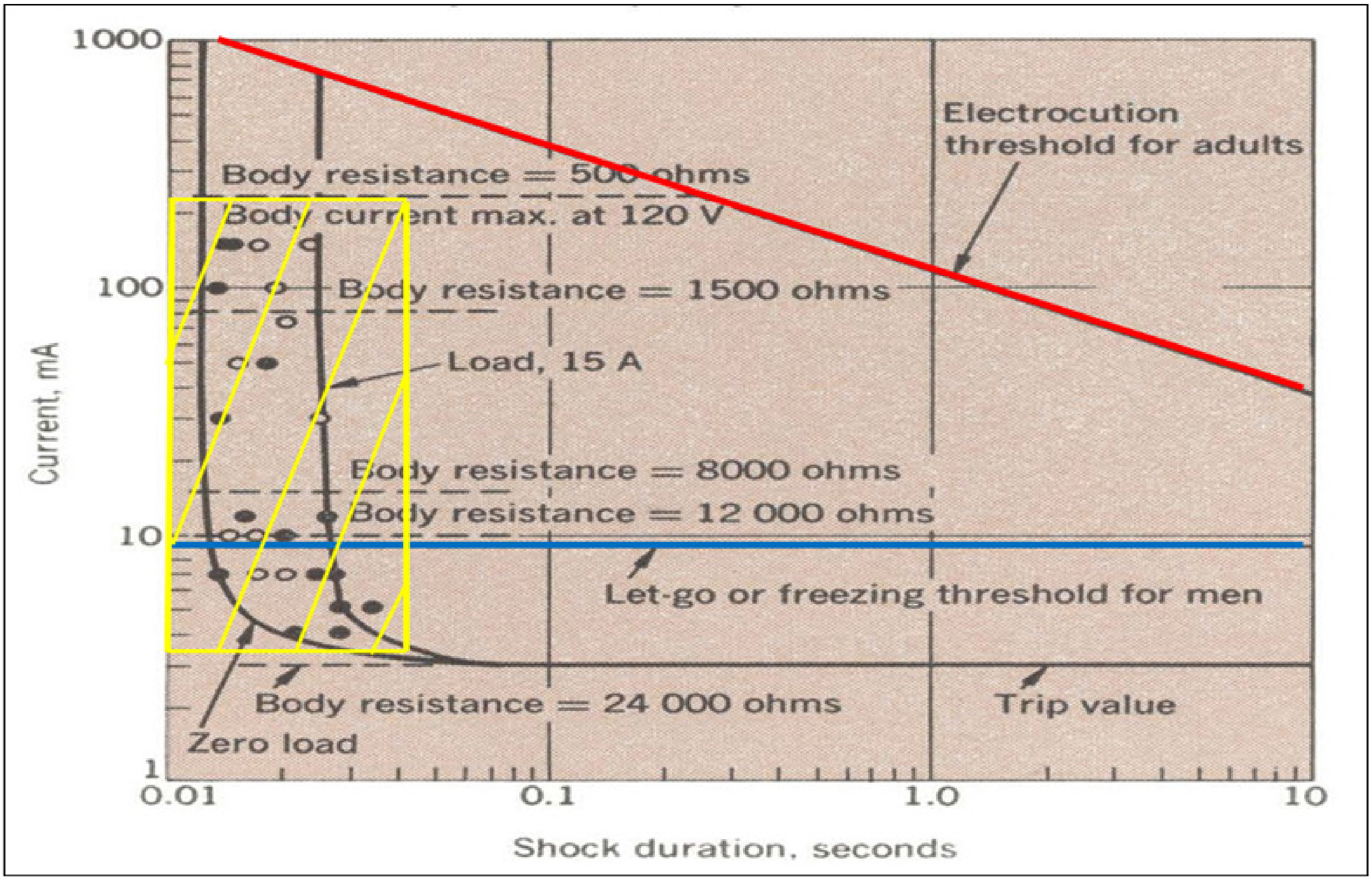

Figure 6
Imbalance trip current vs. shock duration for a typical GFCI, electrocution threshold, let-go thresholds for adults[13]. Colored lines were added by the author.

While it is interesting to know the effect of current on the human body, the exact value of the current at the time of the shock may not be known. There may be methods available to approximate the current for some shock scenarios, one of which will be discussed later in this paper. What is often more readily available is the voltage for the ungrounded conductors that often can stay constant for a given current draw. If the shock current exceeds the available current, the voltage may drop — this may need to be factored into the analysis. For all further discussions in this paper, it is assumed that the voltage stays constant during a shock incident[13].

Conditions for obtaining experimental data for human exposure to voltage included intact skin, wet hands and feet, low current densities, and maximum current while still allowing the test subject to let go. In addition, Dalziel reported that the lowest fatal shock voltage known was at 46V. Some examples of standards that refer to safe voltages are Underwriters Laboratory (UL) 1310 (Class II Power units) that mentions 30VAC and 60VDC as safe and UL 1838, "Low Voltage Landscape Lighting Systems," which refers to 15VAC and 30VDC as safe.

Factors in the severity of a shock include:

1) Current available

2) Voltage source
    a) Amplitude (at start of and during shock)
    b) Waveform (AC or DC)
    c) Frequency of voltage source

3) Impedance/resistance
    a) Skin impedance/resistance
        i) Intact or open
        ii) Surface area of contact
        iii) Function of voltage (the higher the voltage, the lower the impedance)
    b) Body structures impedance/resistance
    c) Path of current through the body and whether this path includes the heart
    d) Remainder of current path outside the body

4) Current exposure time

When current flows through a metal conductor and then to the human body, the mode of conduction often changes from electronic (the flow of electrons) to ionic (the flow of ions). At the metal to skin contact point, the current flow undergoes an electrochemical reaction from electronic to ionic current flow that can generate rapid heating. The reaction rate is dependent on the voltage drop at this contact and can generate toxic chemical byproducts. All current flow through liquids is ionic in nature. By itself, saline solution has only resistive impedance; however, other tissues can have resistive and capacitive impedances that influence the magnitude and path of current flow through the tissues. **Figure 7** illustrates these concepts[7].

Three main injury mechanisms for shocks include:

1. Arcing due to a dialectric breakdown in the current path — consists of ionized current flow through superheated air, which is highly conductive. Often, a bright flash of light is observed. There are approximately 300V required for a minimum gap to initiate the arc. After the arc is established, the arc continues with lower voltage across the gap. A metal to skin contact at 10 kilovolts (kV) can vaporize skin at 1,000ºC and cause 10 to 20 A to flow through the body[7].

2. Pure resistive or Joule heating — proportional to the square of the voltage for a given impedance[7].

3. Electroporation due to cell membranes rupturing — the cells break open like soap bubbles with a pin. If the cell membranes rupture, the cells then most likely die. The cells function as capacitors with their impedance being an inverse function with frequency[7].

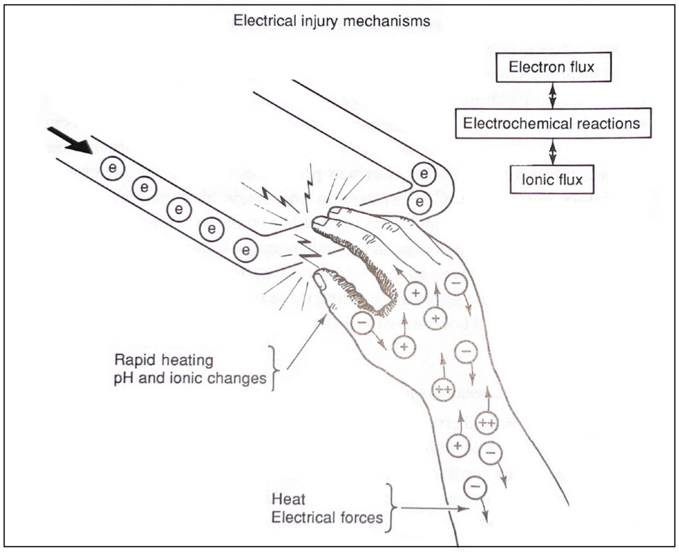

Figure 7
Effects of electrochemical conversion at the body surface during an electrical shock.

Electrical Impedance Spectroscopy

A diagnosis method called electrical impedance spectroscopy (EIS) evaluates the viability of burn tissue by measuring the capacitive impedance of tissue cells. It also gives insights as to how current flows in tissues due to resistive and capacitive (reactive) impedances. Measurements of the real and reactive impedances are made during a frequency sweep to determine if the cells have been ruptured.

Figure 8 shows a healthy tissue impedance plot (red

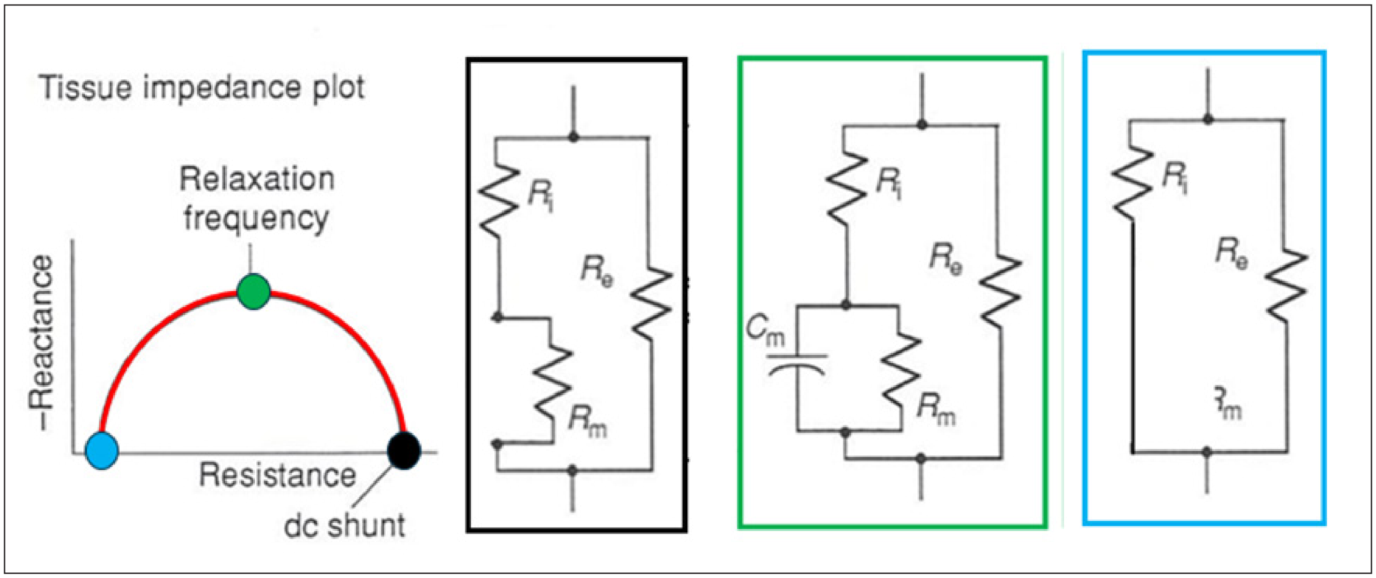

Figure 8
Healthy tissue impedance EIS plot.

curve) and its equivalent circuits in the colored boxes[7]. Lee's diagram was rearranged by this author for clarification and illustration of the frequency sweep concept, and colored highlights were added. As the frequency of the voltage changes from zero Hz (black) to the relaxation frequency (green) and then to a maximum frequency (blue), the plot would follow a circular curve, indicating if the cell walls were intact and acting like capacitors. From this diagram, it is seen that cells can conduct more current at higher frequencies because the impedances are lower at higher frequencies.

Figure 9 shows four plots, ranging from healthy (largest plot), partially damaged, and severely damaged, tissue (smallest plot)[7]. Colored dots and a dotted line were added to illustrate the change of the relaxation frequency impedances in healthy and damaged tissue. The resistive and reactive impedances for the zero, relaxation, and maximum frequencies all decrease with increasing tissue damage. Lee was able to correlate the quantities of these impedances to the probabilities of tissue necrosis toward the goal of identifying and removing this damage during the minimum number of surgical procedures. From this diagram, it is seen how damaged tissue can carry more current than healthy tissue as the impedance is lowered when the tissue is damaged.

Methods and Tools

Effective methods and tools for analyzing shock incidents include the following:

- Keep safety first to make sure another shock injury does not occur. Utilize safety methods, such as lockout/tagout (LOTO), to deenergize circuits and wear appropriate personal protective equipment (PPE) during analysis[14,15].

- Perform as much non-destructive data taking and analysis while the circuit is deenergized.

- Take additional precautions when energizing equipment that may be shorted to ground without tripping a protective device, and announce these precautions to all in the area. Be aware that energizing circuits may be destructive in nature.

- Use the appropriate meter in the appropriate manner for checking electrical parameters, and be aware of the limitations of the measurement devices. Read and understand the operation manuals for all meters and equipment used. In one case, an electrician attempted to measure ground continuity by obtaining a zero-voltage measurement between two exposed metal surfaces. If there was a continuous ground, there would be no voltage between the two exposed metal surfaces; however, just because there is no voltage does not mean that there is continuity. The electrician concluded that there was ground continuity, but this turned out to be erroneous. This error contributed to the potential for a future shock injury. In this case, a resistance measurement would have been the correct method to measure ground continuity.

- Measure insulation resistance when appropriate. A 12VDC powered multimeter can measure low resistances well but may not measure a more realistic resistance when the device is powered. Using a megger at 500 or 1,000VDC to non-destructively check the resistance of a device may be a more realistic value of the insulation resistance at the full operating voltage. Refer to the UL standard for the device hipot testing requirement and the operation manual for the megger used[16].

- The analyst may use safety devices such as a GFCI, AFCI, or RCD during measurements while full voltage is applied to a circuit under evaluation to both assist in evaluating the level of leakage current present and to protect the persons performing the tests.

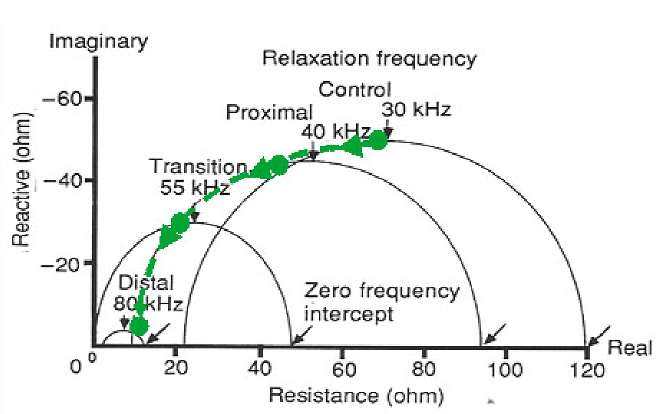

Figure 9
Comparison of healthy to damaged tissue impedance frequency plots for an EIS evaluation.

Different Shock Scenarios

Shock current paths and the impedances involved can vary between incidents requiring all possible paths to be evaluated individually. Certain shock paths are simpler with fewer impedances in series with the victim's body (i.e., if a victim's two wet hands had grasped two metallic surfaces involved with the current path). In this case, the voltage between the metal surfaces can be measured. In parallel with the voltage reading, the current through a known impedance can be measured. This may inform the investigator as to the possible current through the victim, if the impedance is similar to the victim's impedance and if all other impedances in the circuit have remained constant since the shock incident. If the victim's hands were wet or their skin impedance were compromised, an impedance of 1,000 Ω may be in the range of the impedance of the victim's body. This current reading would then also take into account other (often hidden) impedances in the complete path in series with the victim. It also helps determine if the total impedance present was low enough to allow a dangerous current to flow through the victim's body, given the available voltage source. An example of a more complex path with additional impedances may be a person swimming in a pool and not touching any metal surfaces. Current flows through the pool water, and an electric field exists. Early testing by Dalziel with dogs was done with this shock path to determine when the dogs would exhibit loss of muscle control[13].

To simulate the type of shock path with a person having body parts immersed in water but not touching any metal, a simple lab test was performed. This test setup is shown in **Figure 10**. Various 120VAC voltage sources were placed into a plastic pan with a grounded copper pipe on the other side of the pan, approximately 14 inches (in.) apart. The voltage source and pipe were covered with tap water. Wires were placed into the water with the bare ends being 11 in. apart as shown by the yellow and white squares.

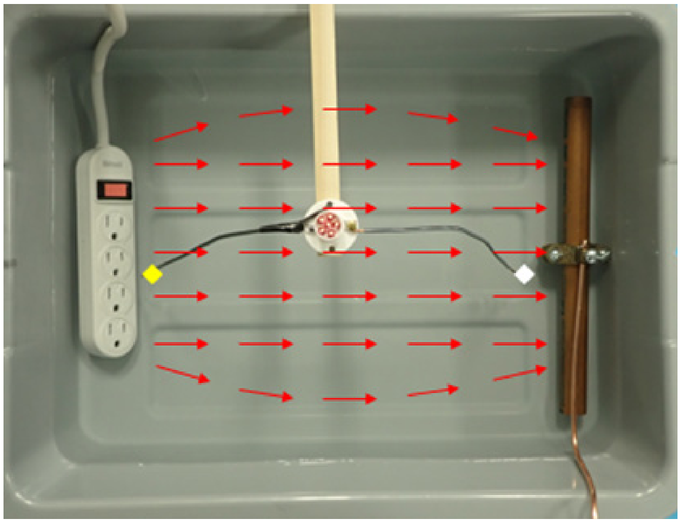

Figure 10
Test arrangement to measure voltage
drop in water due to an electric field.

Voltage readings were taken between the ends of the wires. Red arrows were drawn onto this test setup figure to indicate an instantaneous electric field from an alternating current voltage source to a grounded metal object. The yellow diamond is an inch and a half from the power strip. The white diamond is an inch and a half from the grounded copper tube. Current measurements were not made, but it is expected that additional electrolytes in the water, such as salt, would decrease the overall impedance of the circuit and increase the current flow through the 1.5 in. of water on either of the two gaps between the ends of the wires and the metallic conductors as shown by the white arrows. The gap on the left is seen between the yellow square and the ungrounded conductors inside the RPT, and the gap on the right is seen between the white square and the grounding clamp.

The following devices were placed into the water for testing in the same position:

- A relocatable power tap (RPT) or power strip with plastic enclosure or case with EGC. This allows for three current paths: ungrounded conductor to EGC, ungrounded conductor to grounded conductor, and ungrounded conductor to grounded copper pipe.
- An RPT with a metal case with EGC. This allows for four current paths: ungrounded conductor to EGC on inside of RPT, ungrounded conductor to EGC on exterior of RPT, ungrounded conductor to grounded conductor, and ungrounded conductor to grounded copper pipe.
- A double-insulated hair dryer with a plastic case and no EGC. This allows for two current paths: ungrounded conductor to grounded conductor, and ungrounded conductor to grounded copper pipe.
- An RPT with a metal case with no internal EGC (to simulate it being plugged into a cheater plug with no ground connection to the receptacle). This allows for three current paths: ungrounded conductor to EGC, ungrounded conductor to grounded, and ungrounded conductor to grounded copper pipe.
- An RPT with a plastic case (with EGC) and

cord plugged into the RPT with only the bare un-grounded wire exposed. This allows for three current paths, ungrounded conductor to EGC, ungrounded conductor to grounded conductor, and ungrounded conductor to grounded copper pipe.

- A RPT with a metal case with no internal EGC and the metal case energized. This allows for only one current path, the ungrounded conductor to the grounded copper pipe.

The first three devices (1, 2, and 3) with no defects were placed into the water. These voltage drop readings in the water are shown as the blue bars on the graph in **Figure 11**. The red line in this graph is at 30VAC, which is the AC voltage generally deemed safe. The other three devices with defects (4, 5, and 6) were placed into the water; these voltage drop readings in the water can be seen as the red bars on the graph.

This test illustrates that, especially for defective devices and applications, a dangerous shock at a dangerous voltage is possible even if a person is not touching one or more metal surfaces. Many of the results in this chart (red-colored bars) are near and above the maximum safe level of voltages discussed earlier. A takeaway from this test is that there is a greater chance of a dangerous shock if certain defects are present. This is especially true for those that allow an energized conductor to be closer to a person than when the defect is not present and if there is a lack of an EGC. A proper EGC can act to collect stray current because it is often near the energized conductors. If the EGC encloses the energized conductor or it is between a person and the energized conductor — even more personal protection is afforded to a person outside the enclosure.

Standards

A standard is defined as "a model accepted as correct by custom, consent, or authority or a criterion for measuring acceptability, quality, or accuracy'[1]. Some common standards for various parties involved (including electricians, forensic engineers, and other experts) are used to judge the actions of the party involved prior to, during, and/or after an electrical shock incident. The pertinent standard is the document that was in effect at the time of the party's involvement, including, but not limited to:

- Manuals, labels, and instructions provided by the manufacturer and used by installers, inspectors, operators, servicers, etc.
- Written company policies for various companies involved, such as utilities, manufacturers, etc.
- Construction and performance standards such as the NEC and International Electrical, Mechanical, and Building Codes (IEC, IMC, IBC), written by standard bodies and used by architects, designers, installers, inspectors, etc.

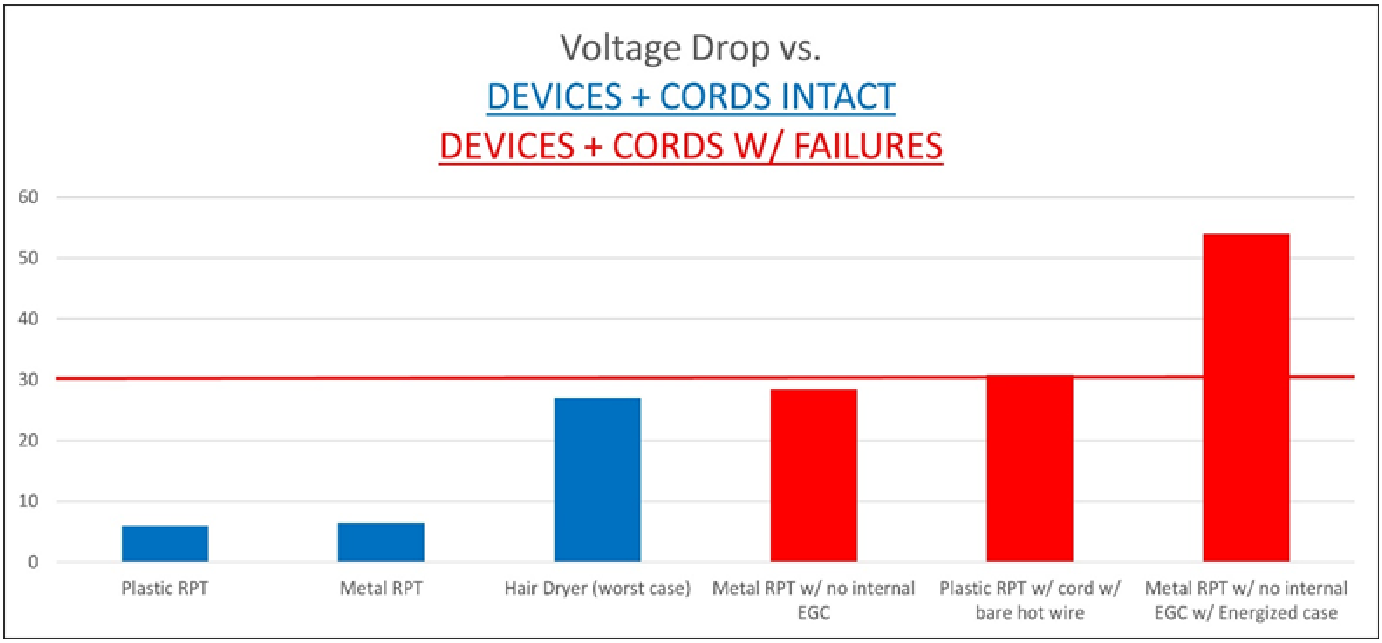

Figure 11
Voltage measurements in water due to an electrical field.

- National Electric Safety Code (NESC), written by the Institute of Electrical and Electronics Engineers (IEEE) for utilities and subcontractors to design, construct, inspect, and service electrical distribution and transmission equipment.

- National Fire Protection Association (NFPA) 70E, Standard for Electrical Safety in the Workplace used by safety and maintenance personnel, manufacturers, installers, inspectors, servicers, etc.

- Independent testing agencies such as UL, Canadian Standards Association (CSA), and Intertek (ETL), for manufacturers, installers, inspectors, etc.

- Standards-writing bodies such as American National Standards Institute (ANSI), American Society of Materials (ASM), for manufacturers, installers, inspectors, etc.

- Decisions by local authorities having jurisdiction (AHJs).

- Federal, state, and local codes that draw upon other standards with alterations as decided upon by federal, state, and local legislators and AHJs.

- Associations for specific industries for designers, manufacturers, installers, inspectors, servicers, etc. One example is the Association for the Advancement of Medical Instrumentation (AAMI) medical device standards.

- Trade association training programs and texts for trades workers, such as electricians.

- Textbooks for a particular discipline for use in applying basic principles to solving specific problems.

One pertinent example is for determining whether an electrical device was properly grounded and bonded during installation. The installation manual may give specific instructions on how to ground and bond the device. If not, the question of whether installation meets "Code" can be determined by consulting the local AHJ to determine if they have adopted the same version of the NEC (possibly with alterations) as the state or if they have different alterations of a local variety. Again, the standard to be used in judging the installation is what was in effect at the time of installation.

Case Study

The author's firm along with another firm were hired to investigate a tragic incident on behalf of the estate of a man who was a guest at a residential pool party who was fatally electrocuted while jumping a fence after exiting the pool to get a ball. The homeowner's insurance carrier also hired a forensic engineer. The death certificate stated the cause of death was anoxic encephalopathy due to cardiac arrest due to ventricular fibrillation due to electrocution. In other words, electrocution caused his heart to go into an abnormal rhythm, which led to cardiac arrest and then to brain death due to lack of oxygen.

The layout of the pool is shown in **Figure 12** (a Google Earth image from before the incident). The electrical system for the pool is fed by the circuits in the pool house, and there is a chain link fence that surrounds the pool and deck. Electrical circuits in the immediate vicinity of the pool include in-pool lights, a string of lights hung on the fence that was powered from an extension cord, a light pole approximately 23 in. west of the chain link fence, and a receptacle on the southern corner of the fence.

The initial basic facts given prior to the scene visit were as follows. The man exited the pool to retrieve a ball and was in the process of climbing over a metal fence when he stopped moving and lost consciousness. The fence had always been next to the pool — since no one ever received

Figure 12
Pool layout.

a shock from the fence, it was mentioned by a member of the investigation group that it may be difficult or impossible to determine how this fence became energized. In the initial discussion, the author made a special point to not form presumptions, but to search for the source of the unwanted voltage and the ground path back to the source and let the scientific method determine the conclusions.

The police department had done interviews of the pool party attendees; these interviews yielded valuable details as to what happened as the man exited the pool and attempted to get over the fence. They also included the details that when he became stuck with one leg on either side of the fence, slid down the side of the fence, one person said his hands were stuck grabbing the fence, and another said he grabbed onto the light pole and received a shock from the pole. There was a short video of the pool party taken before the shock incident that showed the string lights operating. There were no thunderstorms in the area on the day of the incident.

There was an initial non-destructive scene exam, and the premises was surveyed as to the electrical system in the home and the visible items in the vicinity of the pool. The author found many potential electrical problems with the pool electrical systems, such as a lack of GFCIs, lack of grounding, multiple corroded conduits and exposed wires, rodent damage, etc. However, it was unknown which were causal to the injury.

The author found a hole in the lawn where there were individual visibly exposed wires (with colored insulation) as 7 in. of the underground conduit had disintegrated due to corrosion as seen in the white ellipse in **Figure 13**. Plus, there were many unanswered questions about the detailed actions of the man and other site anomalies, which caused the team to only do a non-destructive brief broad survey of the electrical characteristics over a large physical area.

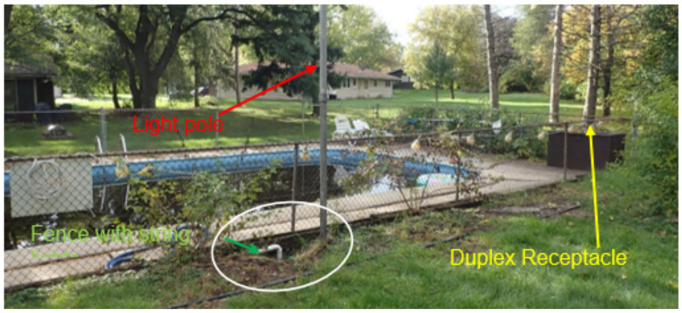

Figure 13
Pool layout and hole in lawn (see white ellipse).

There were many circuits and structures underground that could have been involved with the shock scenario. Since the forensic engineers were not allowed to energize any circuits at the pool, they could not detect stray voltage or current.

Figure 14 shows the state of the electrical pool controls inside the pool house that had a doorway, but no door. Damage found included corroded enclosures, corroded and disintegrated conduits (one is shown inside the yellow rectangles), multiple cords, and rodent damage. The individual visibly exposed wires (with colored insulation) in the yellow rectangle in **Figure 14** were similar to the wires that were visible in the hole in the lawn in the white ellipse in **Figure 13**.

Since one of the team's major investigation goals for the second scene exam was to determine what conductive materials were contacted by any of the extremities or body part — and to then determine the voltages of each of these body contact points — the author was interested in any recent electrical work, repairs, or problems, the motions of the man, the reasons for these motions, and what witnesses observed during these motions, what devices were energized and/or operating at the time of the shock, and why there was a hole in the lawn. Another goal was to discover pertinent information by examination of above-ground circuits and structures with a minimum excavation of any underground circuits and structures, such as feeders, lights, or grounding and bonding conductors.

After some discussion, it was thought by some that the team should use discretion and not ask questions early in the investigation because certain people could become

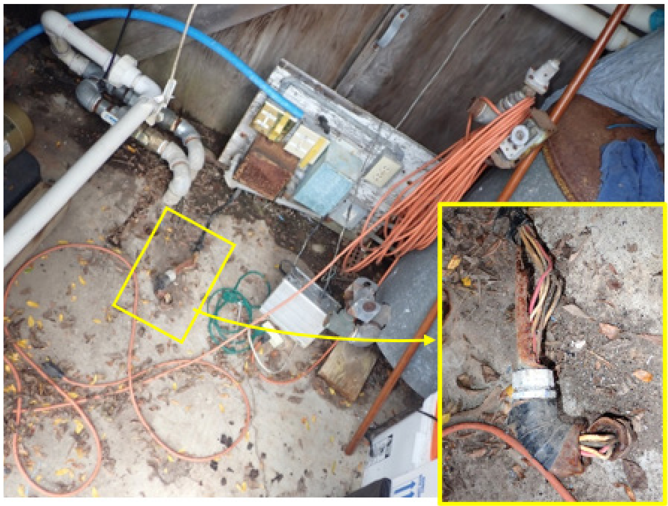

Figure 14
Pool house electrical controls.

upset, and there might not be answers forthcoming. Nonetheless, a list of 25 questions was drawn up and submitted to the homeowners. To the forensic engineering team's surprise, answers to most of the questions were forthcoming. The author learned the history of the home, that there were no recent changes or previous problems or shocks, that all lights were turned on and operating, the receptacle was not used, the man had climbed the fence near the light pole, the reason for the hole in the lawn, and that the city inspector turned off circuit breakers in the basement after the incident.

The homeowners were aware that there had been a pool pipe leak that had eroded the ground and caused the hole in the lawn. The leak had been recently repaired, and the hole in the lawn not been filled in. This information greatly allowed the author to focus the investigation on the area of the fence and light pole, even though other circuits were documented and tested as well. Prior to the second scene exam, the author also asked for permission to excavate, as little as necessary. After some initial pushback, the team was given approval to excavate with discretion.

During the second scene exam, the team was able to energize the pool circuits and measure a stray voltage of 102VAC from the light pole to the fence. To characterize the remaining circuit, a resistor of impedance of 1,000 Ω (in the ballpark of a wet body experiencing an electric shock) was wired in series with a multimeter to measure the current through the resistance. A current of 102 mA flowed through the 1,000-Ω resistor connected to the light pole and fence, indicating that the total impedance of the circuit was only 1,000 Ω, and the impedance of the underground portions of the circuit was negligible. No other electrical anomalies were found in the general area of the fence and light pole. After the measurements were taken, the local area was minimally excavated, underground circuits documented, the light pole cut down, and the wires internal to the light pole were examined.

Figure 15 illustrates two photos that show a portion of the internal wiring for the light pole that had splices with electrical tape for insulation. It was found that a bare copper wire had worn through the tape (as seen in the yellow circles), and the copper wire was able to touch the inside of the light pole to energize the metallic light pole with 102VAC.

After the voltage between and current through the light pole and the fence was measured, the power to the light pole was turned off, and a test was performed to determine if an EGC was present, would the circuit breaker trip or the fault clear. A #12 AWG copper wire was affixed to the light pole and the grounding electrode conductor at the pool house. When the power was reapplied to the light pole, a brief current of 11.4A AC was recorded. The circuit breaker did not trip, but the fault cleared itself; the light pole was found to be not energized after this test. The author's conclusions included:

1. The causes of the electrocution in this incident were both of the following conditions occurring simultaneously:
    a. A failure in the electrical system of the light

Figure 15
Internal wiring for the light pole with a bare copper wire protruding through a worn hole in electrical tape.

pole circuits such that stray voltage and current occur, resulting in the light pole becoming energized. This failure was a lack of insulation on the electrical conductors such that an energized copper wire came into contact with the inside of the metallic light pole, allowing stray voltage and current to enter the light pole.
b. A failure in the electrical system of the light pole circuits caused the energized light pole to persist and not be terminated immediately. This failure was the absence of an intact and continuous underground conduit, acting as an EGC, which would have allowed the fault current to flow and cause the circuit breaker to trip or the fault to open, thereby deenergizing the light pole.

2. The electrocution occurred when portions of the victim's wet body simultaneously touched the energized light pole and the chain link fence. When this occurred, a closed circuit was formed such that the energized light pole caused electrical current to flow through his body to ground — this electrical current caused the electrocution. Based on the information available, one hand touched the light pole, and one hand, his torso, and legs touched the chain link fence.

3. The abnormalities and damage to the light pole conduit and wire in the hole in the lawn and the conduit in the pool house, detailed in this report, were conditions of disrepair and lack of maintenance of the pool electrical system that were visible to the homeowner.

4. The abnormalities and damage posed hazards to persons in the yard in the vicinity of the pool house and west edge of the pool:
a. Physical protection of the individual wires had been lost due to the missing metallic conduit in the pool house and in the hole in the ground on the west edge of the pool. Any damage to the individual wire insulation would have allowed voltage and current leakage into materials or persons in the vicinity of these wires.
b. The path for stray voltage and current to return to the grounding network, which performs a critical safety function, had been lost due to the conduit being missing, disintegrated, or corroded.

5. The lack of a conduit and the exposed wires in the hole in the ground near the light pole and fence existed prior to the electrocution, had been caused by a leak of pool water, and should have been repaired by a licensed electrician to the NEC in effect at the time.

6. If repairs and maintenance had been performed by a licensed electrician and the circuit brought up to the NEC, an EGC would have been installed. A proper intact and continuous EGC could have been accomplished by a properly installed metallic conduit, a ground wire, or both.

7. This electrocution would not have occurred if there had been a proper and continuous EGC for the pool light. Having proper EGCs would have caused the circuit breaker to trip or a fault to open if a ground fault to an exposed metal surface in the vicinity of the pool had occurred (such as at the light pole). This was borne out by the test that was run when an EGC was installed, and the light pole energized with the result being that the fault cleared itself without the circuit breaker tripping. Not having an EGC meant that the circuit breaker would not trip, or the ground fault would not be opened, leaving an extremely dangerous condition to persist.

8. The conditions of disrepair and lack of maintenance inside the pool house, lack of GFCIs for the pool pump, pool receptacle, and string lights and the use of the string lights too close to the pool should have been noticed and repaired as they were safety hazards that could have been a cause of an injury.

9. The danger of electrocution from the short circuit inside the light pole would have been eliminated by a proper intact and continuous EGC for the light pole. The discontinuity in the conduit (light pole EGC) was visible to the homeowner.

10. On the date of loss, the local township and the state statutes required the light pole to be grounded per [redacted], following NEC 2017 and all editions of NEC from 1947 to 2017. The State statues required all repairs to the light pole to have proper grounding to the State Electrical Code in effect at the time of the repair.

11. The measured current of 102 mA AC through the 1,000-Ω resistor indicates that the total impedance

in the remaining portions of the completed circuit, necessary for current to flow, were negligible. The electrocution is consistent with a current at or near 102 mA AC.

12. It is the author's opinion that the electrocution would have been prevented had the electrical system and structures around the pool been properly maintained and repaired.

For clarity's sake, **Figure 16** shows two diagrams of the pertinent pool circuit components. The left-hand diagram shows the circuits as they should have existed under prevailing codes and standards such that a short circuit to the light pole could be carried to ground by continuously connected conduits as EGCs. The right-hand diagram shows the pool circuits as they were in the incident where the conduits were not continuous, eliminating this as a current path and creating the causal hazard.

The case was settled at mediation.

Overview

To summarize:

1. Keep safety first.

2. Strive to determine the truth as to what occurred and why regarding the incident.

3. Be proactive as to what is needed for a thorough investigation, not only reactive to information already available.

4. Perform non-destructive testing first; then consider destructive testing after notification of all interested parties.

5. Analyze applying the scientific principles and engineering methodologies.
   a. Develop incident scenarios based upon the supplied data/information, reports, photos, examinations, statements, depos.
   b. Limit the forensic engineering analysis to the expertise of the engineer.
   c. Gather data (detailed and thorough as often alterations have been made to make the scene safer).
   d. Analyze data (evaluate data with respect to protection schemes present and defeated, patterns, circuits, time lines, consistency of injuries to shock possibilities, etc.).
   e. Synthesize all possible hypotheses and the corresponding postulates.
   f. Verify and validate (V&V) the hypotheses to determine the scenario and cause(s) of the incident.
   g. Select the final (highest probability) hypothesis.

6. Develop conclusions as to whether certain standards were or were not met by the parties involved.

Conclusions

The scientific method can be used to identify the (often three-dimensional) complete circuit of current flow

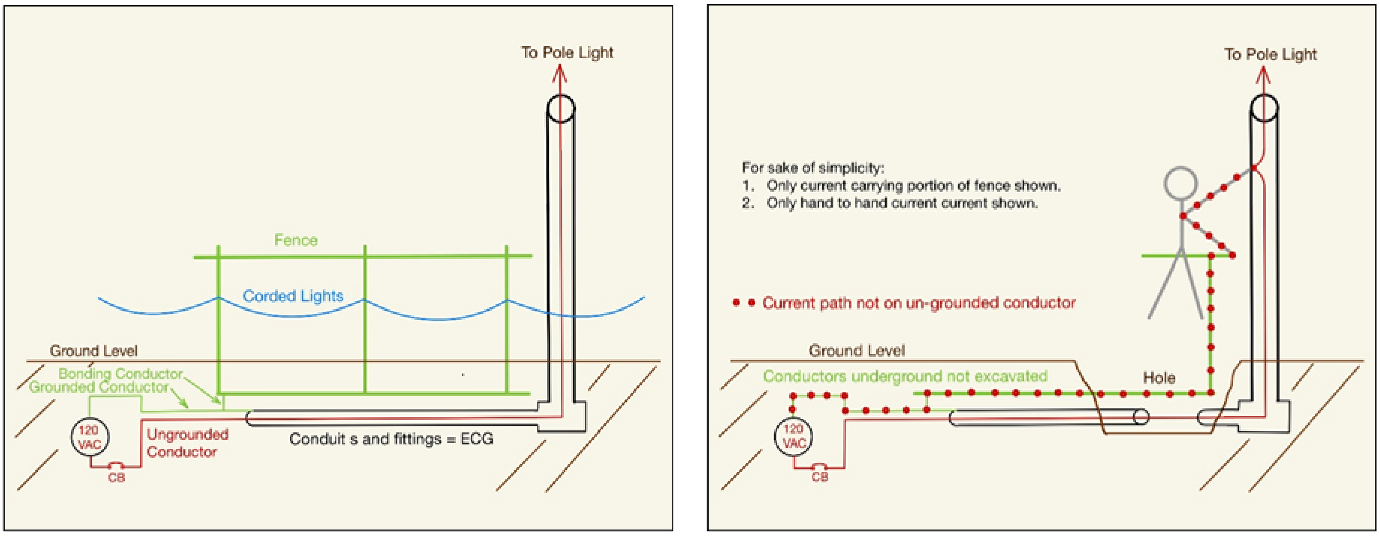

Figure 16
Two diagrams — reasonably safe circuits on the left; hazardous circuits on the right.

through the body of a shock victim. This paper lays out the fundamentals of shock analyses addressing the basics and vernacular of electrical faults, the effects of electricity on the human body, and the various ways electrical energy flows and causes tissue damage. Furthermore, it discusses the need to identify the pertinent standards (material to the cause of the shock incident) that were in effect and not met by specific parties.

This forensic engineering analysis can be challenging as equipment is often altered after the incident, conditions (e.g., the presence of moisture) may have changed since the incident, witnesses may be injured, killed, or have psychological trauma, memories fade quickly, and there are often other multiple circuits in the general or immediate area of the shock incident that need to be ruled out. Purposeful and proactive planning should be done as early as possible with the investigation team to gather the maximum amount of data as early as possible that can inform how the examinations are carried out. To maximize efficiencies, protocols can be written, distributed, and discussed amongst all interested parties to accomplish the goals of the investigation utilizing the site and lab resources and time available.

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