Electrical Engineering

Introduction

Forensic electrical engineering is the practical application of electrical engineering knowledge to legal questions about electrical phenomena. Practical electrical engineering knowledge is obtained from experience in designing, installing, maintaining and repairing electrical devices, appliances, and equipment. Reports, demonstrations, depositions, and court testimony are used to explain electrical phenomena to insurers, attorneys, arbitrators, judges, and juries. The area of practice extends from software for computers to the generation and distribution of electrical power, which might be controlled by software, and to consumer products.

The electrical engineer explains how the electrical software, equipment, or device functions normally and why it malfunctioned, violated a copyright, or failed in this instance causing damage, financial loss, injury, or death. In some instances, the electrical engineer might be retained by a client to verify that electricity was not involved with the cause of a fire, damage, or injury. Quite frequently, electrical engineers must use mechanical, thermodynamic, and optical knowledge to answer questions since the generation, distribution, and utilization of electrical power involves mechanical components, which can produce heat and light.

History

The investigation of electrical phenomena began in Europe in the seventeenth century [1]. The first electrical investigators were called *electricians*. At the time electricity was believed to be fire, "fulmen fulminis" or fire of fire and lightning was fire from the sky, the wrath of God].[a] St Paul was struck by lightning in 33 AD while traveling to Damascus to suppress Christianity. On regaining his sight, St Paul was baptized and immediately began preaching Christian theology.[b] On July 2, 1505, lightning struck near a happy-go-lucky law student, Martin Luther. Fifteen days later, Martin Luther entered the Black Monastery in Erfurt, Germany [2]. Church bells often were inscribed with a Latin phrase, Fulgura frango, which when translated means, "I break up the lightning". A treatise on the subject by a medieval scholar titled "Proof that the ringing of bells during thunderstorms may be more dangerous than useful", found that over a 33-year period in Germany, a total of 386 lightning strikes on church towers killed 103 bell ringers [3, 4]. In 1767, a church in Venice storing 100 t of gunpowder was struck by lightning, 3000 people were killed and a large section of the city destroyed [5]. Benjamin Franklin perceived and proved that lightning is an electrical phenomenon. He devised the famous sentry box experiment in 1749, which clearly displayed the electrical nature of lightning [6]. When he reported his findings, the King of France, Louis XV, who was an electrical fanatic, had a sentry box built in 1752, and subsequently Franklin's experimental findings were verified in Europe [7, 8]. Benjamin Franklin made on-site inspections of churches, which were struck by lightning, [9] wrote newspaper articles requesting information about lightning damage.[c] and read articles about lightning damage to churches to determine the effectiveness of bell ringing [10].[d] Franklin found that bell ringing during a thunderstorm is a very dangerous occupation. If metal wire was used to ring the bells, the lightning would vaporize it but not damage anything along its path but killed the bell ringer. However, if rope was used to ring the bells, the lightning would cause severe damage to the steeple but probably not kill the bell ringer. This is where Franklin got the idea to attach metal wire to his rod. Franklin rods were opposed by church clergy on their structures because it seemed a sacrilegious act and an expression of no confidence in the mercy of God in striking a sacred structure. However, a Franklin rod was installed on a building in Venice (Campanile of San Marco) that had been struck and severely damaged by lightning nine times from 1388 to 1762. Since the installation of a Franklin rod in 1766, it has not been damaged by lightning [3, 4]. Franklin inspected buildings protected with a Franklin rod, which resulted in Franklin writing the first specifications or standards improving lightning rods [11].

Electrical engineering emerged as a discipline in 1864 when the Scottish physicist and mathematician James Clerk Maxwell summarized the basic laws of electricity in mathematical form and predicted that radiation of electromagnetic energy would occur in a form that later became known as *radio waves*.

The first practical application of electricity was the telegraph, invented by Samuel B. F. Morse in 1837.

However, there was not a great need for electrical engineers until the inventions of Alexander Graham Bell and Thomas A. Edison approximately 40 years later; Bell's telephone in 1876 and Edison's incandescent lamp in 1878 and the first central electric generating plant in New York in 1882. Overnight a large demand was created for men educated and trained to work with electricity [1]. During the 1890s, engineering schools all over the world added studies in electrical engineering, often as optional courses within the mechanical engineering field. Previously, the study of electricity was considered to be a subfield of physics. Academic departments of electrical engineering emerged around the turn of the century [12]. In 1883, Cornell University introduced the world's first course of study in electrical engineering and, in 1885, the University College, London, founded the first chair of electrical engineering in the United Kingdom [13]. The sudden explosion of the electrical industry generated a need for electrical experts to answer legal questions about electrical designs, patents, contracts, personal injury, and damage. The adversarial legal system permitted each party involved in litigation to retain their own electrical expert as opposed to other legal systems where the judge appoints the expert to assist with technical questions. In addition, the ability of attorneys in the United States to pursue litigation on a contingency basis and the subrogation laws of the United States increased the demand for forensic electrical engineers.

Electrical litigation started with patent disputes and Lewis Howard Latimer was probably the first electrical engineer to testify in a patent dispute [14]. It is possible that there were earlier trials where someone was qualified in electrical engineering, but without an appeal that there is no documentation.

Education, Training, and Certification

There is presently no formal program for a Bachelor of Science degree in forensic electrical engineering. In the United States, the basic educational requirement for a forensic electrical engineer is normally a Bachelor of Science degree in electrical engineering from an accredited university. A few universities in the United States offer graduate courses in forensic engineering. The University of Iowa has a Biomedical Engineering Program. The University of Texas at Tyler has "Advanced Topics in Engineering (introduction to forensic engineering)". The University of Colorado at Denver offers "Failure Analysis and Condition Assessment in Civil and Mechanical Engineering". Purdue University's Weldon School offers a course to seniors and graduate students titled "Medical Device Accidents and their Engineering Analysis".

In addition, the individual should be a licensed professional engineer since state laws in the United States require engineers who work independently to be licensed. The requirements for licensing differ among the states.

In Canada, the engineering students normally take their professional engineering test in the senior year of their educational program.

Typically, engineers get involved with forensic work by joining a consulting firm, which specializes in forensic engineering, or associating with practicing forensic engineers. The senior members of the consulting firm or practitioners provide the training needed by the degreed and experienced engineer in the aspects of forensic engineering.

In 1997, the National Academy of Forensic Engineers (NAFE) appointed a committee, the Forensic Engineering Curriculum (FEC) Committee, and supplied funding to develop guidelines for university courses in forensic engineering. The FEC Committee determined that any forensic engineering degree program should begin at the masters degree level because of the specialized nature of forensic engineering.

Education and training for forensic electrical engineers is also available through various technical, legal, and forensic societies. The Institute of Electrical and Electronic Engineers (IEEE), conducts seminars and lectures on electrical equipment and the problems associated with the equipment. NAFE has seminars twice a year where technical papers are presented about forensic engineering investigations. The academy also publishes a journal of the papers that were presented at the seminars. Many of the presentations and published papers involve electrical engineering. The American Academy of Forensic Sciences (AAFS) has an engineering section. The engineering section of AAFS presents papers about forensic engineering investigations at their annual meeting each February. The AAFS has workshops at their annual meeting and sometimes the workshops involve some aspects of electrical engineering.

Certification in forensic electrical engineering in the United States is provided by NAFE through the Council of Engineering and Scientific Specialty Boards. Subsequently, members of NAFE can refer to themselves as a Board Certified Diplomate in forensic engineering by NAFE, program accredited by Council of Engineering and Scientific Specialty Boards (CESB). Another certification program is through the International Institute of Forensic Engineering Sciences, Inc., (IIFES). The IIFES maintains its certification program through the Forensic Specialties Accreditation Board. Forensic engineers who meet the requirements of IIFES are awarded a Certificate of Qualification as a Diplomate, IIFES. They are then entitled to represent themselves as being board certified by the IIFES.

Societies, CPD's and Sections

The largest forensic engineering society is NAFE. NAFE has approximately 400 members and 52 are degreed electrical engineers. NAFE is a chartered affinity group of the National Society of Professional Engineers of the United States and all members are licensed/registered professional engineers. All members of NAFE must provide forms each year reflecting that they have accumulated 100 continuing professional development (CPD) credits during the past 5 years.

The AAFS established an engineering sciences section in 1981. The AAFS engineering sciences section has approximately 170 members and 20 members are electrical engineers.

Casework

Electrical engineers are asked to answer legal questions about electrical phenomena from charged particles to the appliances in our homes and the electrical system that supplies them with power. The questions might be asked verbally or in written statements by a client to determine if further investigation or litigation should be pursued. Most of the casework involves civil litigation and the majority of the clients are insurance companies and their attorneys. The engineer is contacted by telephone, email, and fax machine by claim/loss adjusters, attorneys, public defenders, manufacturers, private investigators, military investigators, law enforcement, and individuals who are handling a matter involving financial loss, violations of law, or personal injury/death. The matter is discussed with the potential client and the engineer informs them if they can provide any assistance in the matter. The client usually requires a curriculum vita (CV) (resume) to check if the engineering education, training, and work experience would qualify them to be declared an expert witness in a court of law involving the matter. Rate sheets (charges for services) are almost always requested. If the client decides to retain the engineer, a contract should be signed between them, which details what service the engineer will provide to the client: inspection, investigation, testing, analysis, reports, and/or testimony.

The subrogation laws in the United States permit insurance companies to recoup the money they paid for fire damage from individuals, companies, or manufacturers for improper/defective installation, use, or manufacture of a product. Subsequently, most of the forensic electrical engineer's casework involves fire investigation. Electrical engineers who investigate the cause of fires must also have training in fire investigation. Fire investigation training is necessary because to determine the cause of a fire, the individual must be able to locate the origin of the fire (where it started). Examination of the electrical components, if any, at the point of fire origin will usually reveal if electricity was involved with the fire's cause. Training in fire investigation can be obtained through the International Association of Arson Investigators (IAAI). The IAAI holds annual fire investigation training seminars. It has state chapters throughout the United States and in other countries, which conduct fire investigation training seminars.

Electrical injury and electrocution cases are normally large loss matters exceeding several million dollars but there are very few of them compared to the number of fires.

Engineers evaluate electrical damage to determine if it is covered by an insurance policy or which policy (fire insurance, boilermaker, or umbrella). If the verbal statement of the engineer is not sufficient to answer the legal technical questions, then a written report might be requested from the engineer to pursue the matter further. Normally, the report would include the scope of work to be performed, details of the investigation, any testing, research, analysis, and conclusions. The analysis might include an evaluation of different versions of events in the matter and their affect on the cause of the damage or injury. The majority of the cases settle after a report is submitted. However, a few go on to depositions where the engineer is asked questions under oath by the attorneys involved in litigating the case. Before the deposition, the engineer must educate his client attorney about electricity and/or fire investigation. The client should understand how electricity caused the injury, damage, or fire and what laws, codes, or standards apply to the case and if any were violated by any parties involved. At the deposition, the engineer is asked for their CV by the deposing attorney and they are questioned under oath about the CV to evaluate their qualifications to testify about the matter at hand. They are asked details about their case file, investigation, testing, and analysis. Hypothetical questions are asked to evaluate potentially different conclusions. Sometimes, an estimate of the percentage of reliability of the conclusions is asked of the engineer.

Very few cases go to trial because of the cost of presenting a case in court. Some cases go to trial because the various parties have experts with drastically different opinions, personal grievances, or ask the court to determine how the case should be settled. Before trial, the engineer might be asked to submit a list of casework, authored articles, depositions, and trial testimony. At trial, the engineer is asked about their education, training, and professional work experience by attorneys and sometimes judges to determine if they are qualified to give expert witness testimony at the trial and on what areas/subjects they can testify about. The judge determines if the engineer qualifies as an expert witness. If qualified, the engineer answers technical questions posed by his client attorney, opposing attorneys, and rarely the judge and jury to aid the jury and court in their deliberations. During questioning by his client, the engineer must educate the judge and jury about electricity, fire investigation, computer software, or whatever is the subject of the litigation. The normal operation of the electrical device should be explained and also how it malfunctioned in this instance causing the financial loss, injury, or death. Next, the engineer is questioned by the opposing attorneys who attempt to find errors in the expert's testimony.

An example electrical injury case involved the loss of arms and a liability of \$10–15 million. An electrical engineer was contacted by an independent adjuster retained by a supermarket company to assist him or her with investigating the cause of the injury. Normally, property owners in the United States are liable for electrical damage or injury on their property and the injury occurred on supermarket property. A group of children had been playing behind a closed supermarket where a 13 kV switch was located near a loading dock (Figure 1). The engineer was asked to determine why the injury occurred; if the electrical equipment was properly installed, maintained, or manufactured and if not, what parties were at fault. At the injury location, the engineer saw that the switch did not have a fence or additional enclosure around it, as required by electrical standards [15]. This indicates that the switch was improperly installed by the supermarket's contractors. The observation opening on the front of the switch was missing a cover to keep water out, arrow 1 in Figure 1. The switch operating handle was in the closed position, arrow 1 in Figure 2. A key was broken off in a lock that was mechanically linked with the position of the switch, arrow 2 in Figure 2.

Figure 1 Figure showing the front doors on the high-voltage disconnect switch. Arrow 1 indicates the missing cover over the observation window of the switch. Arrow 2 indicates a lock with a key broken off in it, which is shown in more detail in Figure 2. Arrow 3 indicates holes in the fuse compartment door, which is shown in more detail in Figure 3

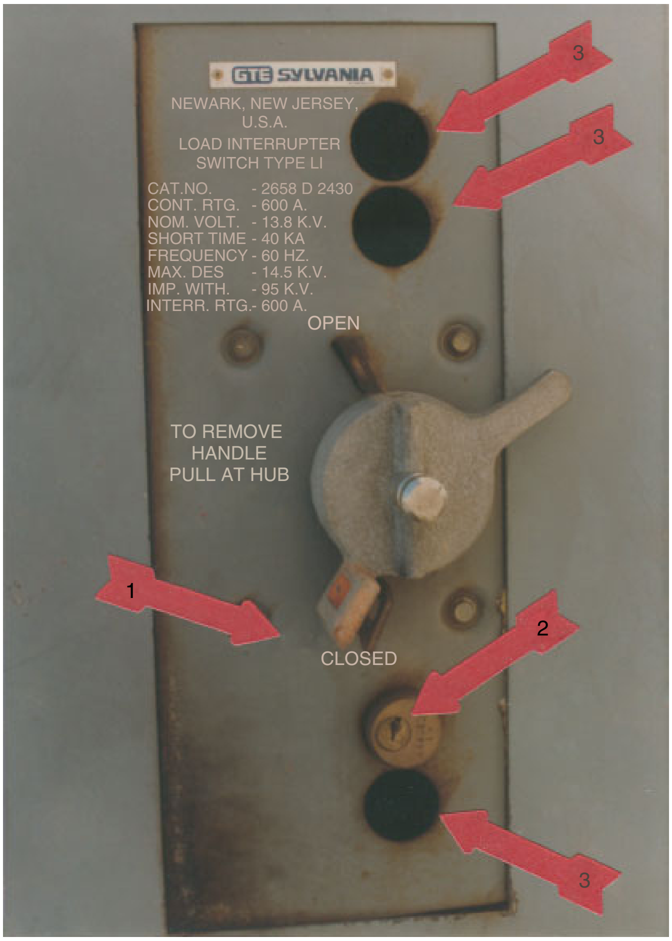

Figure 2 Figure showing the operating handle of the switch. Arrow 1 indicates that the switch is in the closed position. Arrow 2 indicates the broken key in the lock. Arrow 3 indicates unsealed openings

Normally, the key can only be removed from the lock when the switch is in the open position. When the switch is open, the key is removed from the lock and utilized to unlock another lock, which is securing the lower door of the switch where fuses are located. Additional unsealed openings were found around the switch handle, arrow 3 in Figure 2. The switch's lower fuse compartment door had holes in it where a lock that was controlled by the broken key should have been located, arrow 3 in Figures 1 and 3. This indicates that the switch was not properly maintained by the supermarket. Subsequently, the fuse compartment of the switch could be opened and entered while the switch was energized with 13 kV. Evidence of burning, arcing, and melted metal was found at the top of the left fuse holder in the fuse compartment (Figure 4). This is where the child's right hand made contact with 13 kV. Fingerprints in metal were found on the left side of the fuse compartment opening (Figure 5). This is where the electrical current exited the boy's left hand. The electrical current flowed from the top of the fuse holder through the boy's arms to the side of the switch, which is grounded as required by electrical codes. This injury was caused by the improper design, installation, and maintenance of the high-voltage disconnect switch, which violated electrical codes and standards. It was not designed for outdoor use. The openings in its enclosure permitted water and debris to enter into the switch. A single-door design covering the fuse compartment

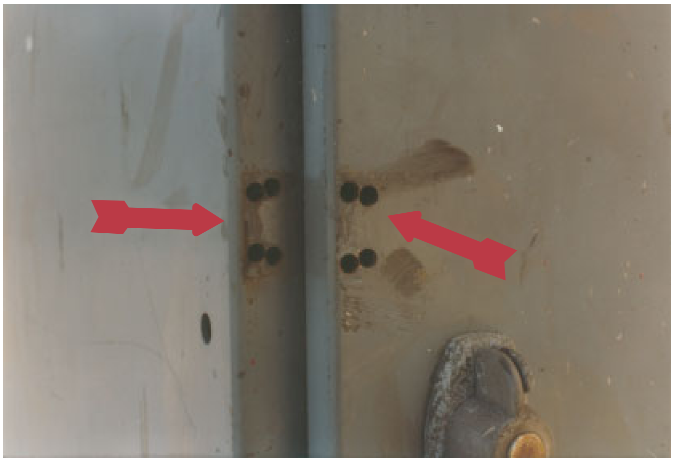

Figure 3 Close-up figure showing the holes in the door of the fuse compartment and frame of the switch, as indicated by the arrows in the Figure

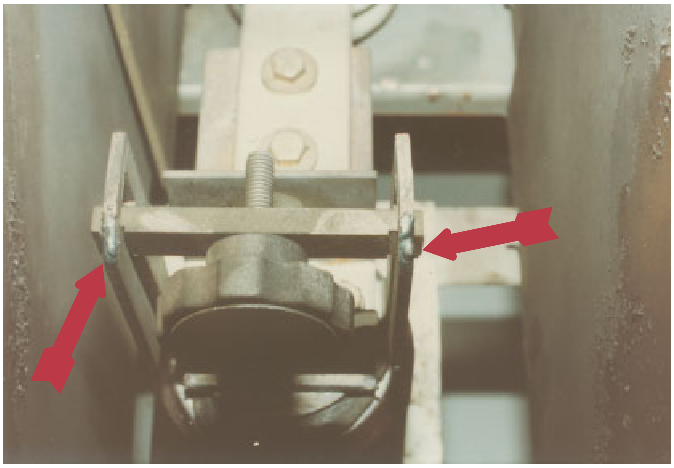

Figure 4 Close-up figure showing the melted metal at the top of the fuse holder, as indicated by the arrows in the Figure

and switch operating handle would have eliminated the problem with the missing interlock lock on the fuse compartment door. The fuse compartment is required to be secured from entry when the switch is closed. The switch was designed for installation in a locked electrical room. However, it was incorrectly listed in a utility company's book of acceptable switches for the location. A scheduled maintenance program would have detected the switch's deficiencies and corrected them. This case settled out of court without depositions or reports. The engineer educated the supermarket attorneys verbally and with printed documents about the improper installation, design, and maintenance of the switch and the codes/standards that were violated. The education and documents enabled the supermarket attorneys to bring their contractors and the utility company to the bargaining table and share in the liability for the injury.

An example of a fire case involves a severe residential fire with a large property loss. A fire investigator brought a box of items from the fire's area of origin to this engineer's office. The fire investigator asked the engineer to inspect and photograph the items to determine if they were involved with the

Figure 5 Figure showing fingerprints in metal, as indicated by the arrows in the Figure

Figure 6 Figure showing the bottom of the steam generating tank

cause of a fire. He also emailed photographs of the fire scene and his fire determination report to the engineer. Among the items was a severely heat-damaged steam generating tank (Figure 6). The steam generating tank was X-rayed (Figure 7). The X-ray showed that the sheath (exterior enclosure) of the unit's heating element was open (arrow 1 in Figure 7) and a thermal over-temperature device had blown apart (arrow 2 in Figure 7). In addition, the nichrome wire inside the heating element was separated and disintegrated in many locations (Figure 8). The nichrome wire is the device that generates heat inside the

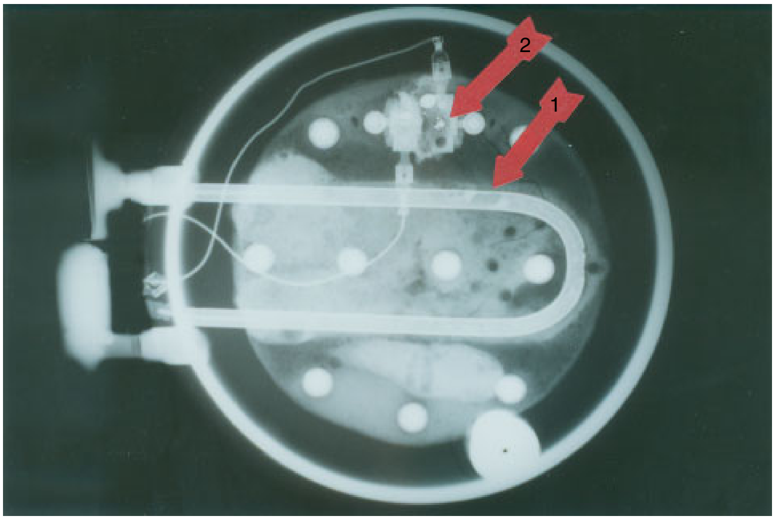

Figure 7 Figure showing an X-ray of the steam generating tank. Arrow 1 indicates an opening in the sheath of the heating element. Arrow 2 indicates a thermal control device

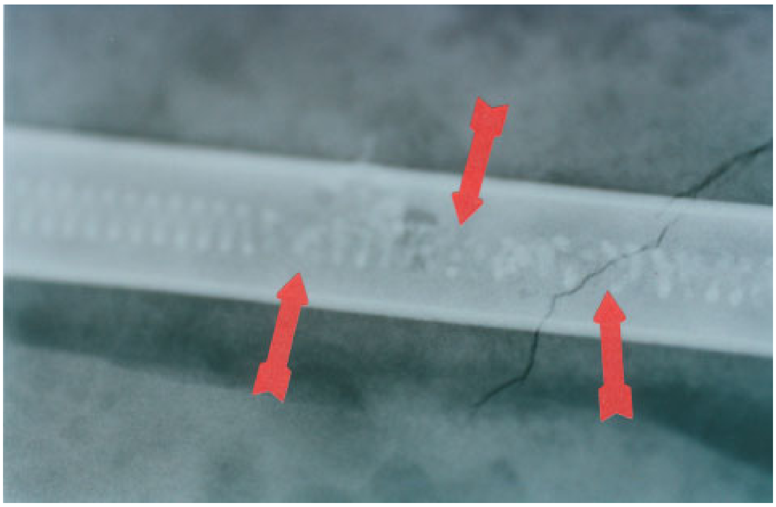

Figure 8 Close-up figure showing the nichrome wire inside the heating element, as indicated by the arrows in the Figure

heating element when electric current passes through it. Nichrome wire is a nickel-base alloy, containing chromium and iron. Nichrome wire has a melting point of 1020–1452°C depending upon the chemical composition of the alloy [16]. The fire temperatures in a residential building normally do not exceed 800°C. Subsequently, the disintegration of the nichrome wire inside the heating element indicates that the heating element malfunctioned and caused the fire. The engineer verbally reported his conclusions about the inspection and X-rays to the fire investigator and the insurance company that retained him. An exemplar steam generating tank by the same manufacturer was purchased, inspected, and tested by the engineer. The exemplar was found to be defective in design and manufacture. An engineering report was requested and submitted with photographs and X-rays. The report stated that the subject steam generating tank was defective in design, manufacture, and caused the fire. The manufacturer retained experts with different opinions even after examining the evidence, X-rays, and exemplar. As a result, the engineer was deposed by the manufacturer's attorneys and he educated them about the appliance's defects. The case settled after the deposition.

Another case involved a large residential building that sustained fire damage while \$500 000 worth of renovations was being performed. An electrical engineer was retained to investigate the origin and cause of a fire along with a fire investigator and mechanical engineer for subrogation purposes. The building had experienced electrical problems and the fire was discovered just after the building's new fireplace was lit for the first time. The fire originated within the walls of the building where electrical wiring was located. The origin was in the concealed space above the new fireplace. Electrical wiring was located there to supply electrical power to an outlet on the right side of the fireplace. The wiring was solid copper and evidence of melting was found <2 cm apart on two wires (Figure 9). Melted copper between two electrical wires quite frequently indicates that the two wires short-circuited together. When copper wiring short circuits, it generates temperatures exceeding 1200°C with sufficient energy to ignite most common combustibles. However, the evidence of melting is normally at the same location along the length of the wire. Microscopic inspection of the melted areas found that they were bite marks (Figures 10 and 11). Subsequently, an animal bit the wiring and produced the short circuit, which ignited the building. The fire was the result of the renovation contractor leaving openings to the interior of the walls unsecured during construction after electrical power was supplied to the building. The engineer determined the origin and cause of the fire and the party at fault, the renovation contractor. However, no litigation followed because the building owner had signed a contract with the renovator that eliminated their liability for damages that occurred during the renovation.

Another example of an electrical injury case involves an electrical explosion in an electrical distribution room that caused electrical injury and severe property damage (Figure 12). The engineer was asked by a law firm to inspect the scene of the explosion, evidence retained from the scene and research documents to determine the cause of the explosion and the parties at fault for causing the personal injuries of workers. The oil within a 5000-V oil circuit breaker had exploded and ruptured its tank (Figure 13). The explosion occurred when the oil circuit breaker was closed after maintenance was performed on it. The maintenance personnel were only permitted 30 min to work on the circuit breaker. Their maintenance consisted of draining the oil out of the bottom of circuit breaker and pumping new oil in. However, proper maintenance on this type of oil circuit breaker requires a minimum of two

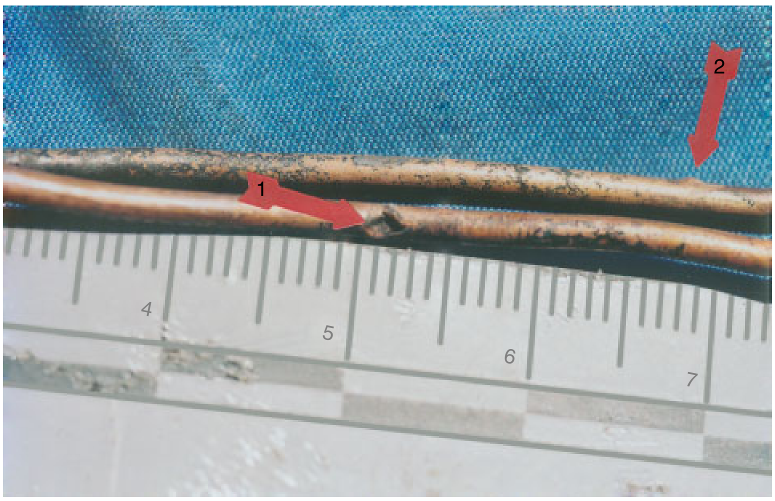

Figure 9 Figure showing copper wires with melted areas. Arrow 1 indicates a melted area shown in more detail in Figure 10. Arrow 2 indicates a melted area shown in more detail in Figure 11

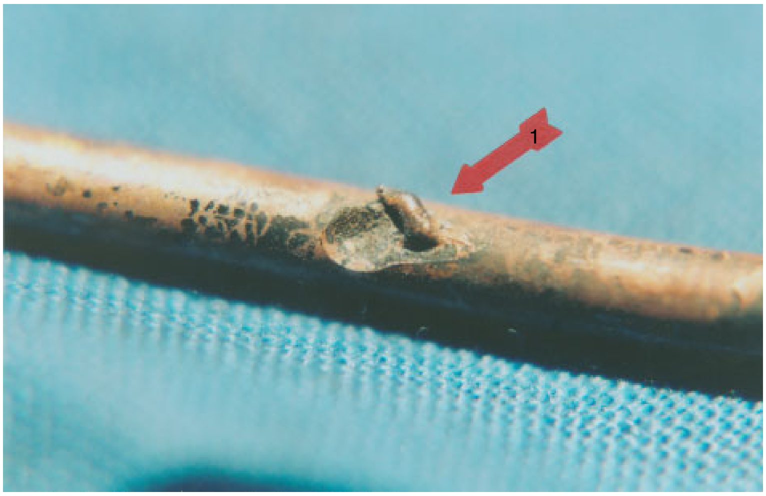

Figure 10 Close-up figure showing the melted area indicated by arrow 1 in Figure 9

Figure 11 Close-up figure showing the melted area indicated by arrow 2 in Figure 9

men working 4 h. The oil should have been put back into the tank from the top of the tank after its interior was cleaned, inspected, and mechanically tested. Furthermore, the electrical distribution room should have been cleared of personnel before the circuit breaker was closed after maintenance. Consequentially, the property damage was caused by bad maintenance. The personnel injuries were the result of not following proper electrical protocol in closing the switch after maintenance without clearing the area of all unnecessary personnel. The engineer reported his conclusions to his attorney client who did not request a formal written report. Litigation against the maintenance people was started and during the discovery process the engineer was deposed by the maintenance attorneys. The engineer educated the maintenance attorneys while testifying about their own electrical protocol, which required the injury area to be cleared of all unnecessary personnel (the injured workers) before a high-voltage switch is closed after maintenance. After the deposition, the case settled out of court.

Figure 12 Figure showing where an explosion occurred in an electrical room

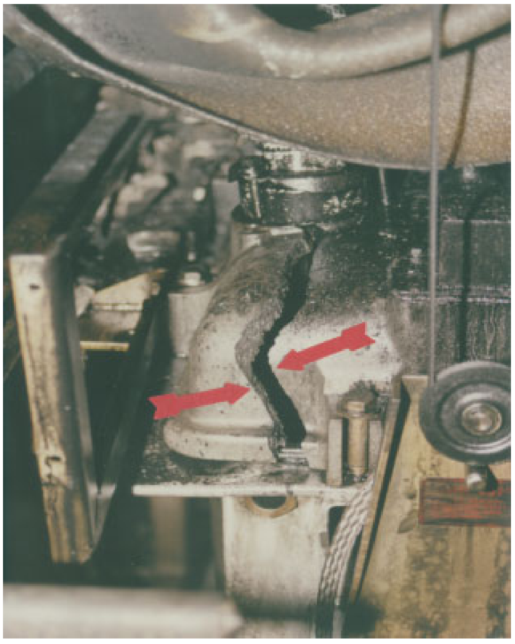

Figure 13 Figure showing where the tank of the circuit breaker ruptured

The last example involves a severe fire in a commercial building with a large property loss. The fire originated in an electrical distribution panel in a room of one of the commercial businesses in the building. An electrical engineer was retained by the insurance company who provided liability coverage to the tenant of the commercial business where the fire originated. The engineer was asked to determine the origin, cause, and parties at fault for the fire damage. The owner of the building had filed a million-dollar complaint against the tenant. Most of the contents of the fire building had been removed prior to this engineer's arrival at the fire scene except for the main circuit breaker, which protected the electrical conductors (wires) located within metal conduits (pipes) that feed electrical power to distribution panel previously located in the area of the fire's origin. The burn pattern in the area of fire origin indicated that the fire started in the ceiling area above the distribution panel where a conduit containing the service conductors feeding the panel was located. The service conductors were fused to the bottom inside of the conduit that was in contact with the structural wood components of the ceiling.

Figure 14 Figure showing the exterior of the circuit breaker

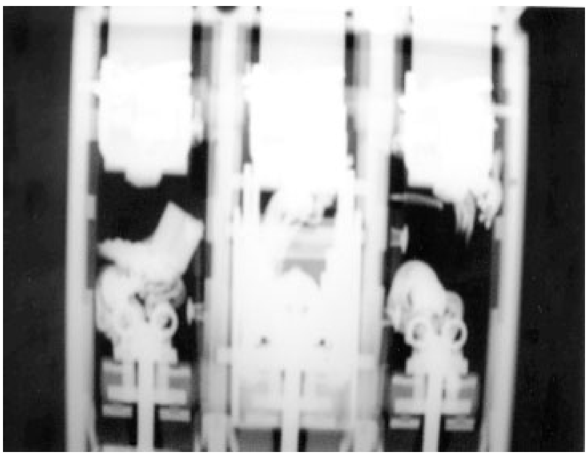

Figure 15 Figure showing the X-ray of the circuit breaker

The conductors were separated from the conduit to perform tests on the circuit. The tests indicated that the conductors had short-circuited to the interior of the conduit all the way back to the main circuit breaker. The main circuit breaker's operating handle was found in the closed position even though the conductors were not energized. Tests found no voltage present on the load terminals of the circuit breaker. Therefore, the local utility company was contacted to shut off power to the building so that the main circuit breaker could be removed from the main panelboard for further testing. The main circuit breaker had three phases and was rated at 200 A. No evidence of fire damage or overheating was found on the exterior of the circuit breaker (Figure 14). Preliminary tests of the circuit breaker indicated that two of the phases (circuits) inside the circuit breaker were open even when its operating handle was in the closed position. The circuit breaker was X-rayed. The X-ray showed that internal components of two phases of the circuit breaker had separated and melted (Figure 15). The engineer reported the results of the inspection, testing and X-rays to the insurance company adjuster. A report was requested with Figures and X-rays. The manufacturer of the defective circuit breaker was put on notice of the financial loss. Subsequently, the circuit breaker was disassembled with representatives of its manufacturer present. The

Figure 16 Figure showing the interior of the circuit breaker after disassembly

Figure 17 Figure showing the internal components of an exemplar circuit breaker

internal examination of the circuit breaker confirmed what the X-rays showed (Figure 16). An exemplar circuit breaker was disassembled to compare internal components. The components that melted and separated in the other circuit breaker were much lighter in color (Figure 17). The difference in color indicates that the separated components had overheated. The circuit breaker should have opened before its components melted and separated. A circuit breaker is "a device designed to open and close a circuit by nonautomatic means and to open the circuit automatically on a predetermined overcurrent without damage to itself when properly applied within its rating". The circuit breaker "is provided to open the circuit if the current reaches a value that will cause an excessive or dangerous temperature in conductors or conductor insulation" [17]. The purpose of the main circuit breaker is to open and disconnect electrical power from an electrical distribution panel and the circuit feeding it before the malfunction produces sufficient heat to ignite a fire in a building. Consequentially, the fire was caused by a defective main circuit breaker. The engineer answered the technical questions about the origin, cause, and party at fault for the fire damage, the circuit breaker manufacturer. The case was settled after disassembly of the circuit breaker with representatives of the circuit breaker manufacturer present, engineers, and attorneys.

End Notes

[a.] Revelations 8: 3–5 and http://www.energycite.com/ben%20franklin.htm.

[b.] Acts of the Apostles 8 : 1–3; 9 : 1–30; 22 : 3–21; 26 : 9–23; Galatians 1 : 12–15.

[c.] Franklin, B. Request for information on lightning, Pennsylvania Gazette, June 1753.

[d.] Effect of lightning on Captain Waddel's Compass, and on the Dutch Church in New York, from James Bowdoin to Benjamin Franklin, Boston, 2 March 1752.

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