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Forensic Identification and Root Causes of Hot Socket Problems Found in Electrical Meters

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Abstract

Electric meters play a critical role in electric utility distribution systems, especially for residential customers. Because it occurs so infrequently, forensic engineers may not recognize a dangerous condition within these meters known as a "hot socket." This condition exists where the meter blades make insufficient electrical contact with the socket jaws. This paper reviews methods for forensically examining, diagnosing, and explaining the hot socket phenomenon while exploring smart meters' incident trends.

Keywords

Electrical utility distribution systems, hot sockets, smart meters, forensic engineering

Introduction

Electric meters play a critical role in electric utility distribution systems, especially for residential customers. Because it occurs so infrequently, forensic engineers may not be fully aware of a condition within these meters known as a "hot socket." This condition occurs where the meter blades make inadequate electrical contact with the meter's socket jaws[1]. This inadequate contact can be caused by many things, but the leading culprits are corrosion, vibration, metal fatigue, and mechanical assault. These poor connections can lead to high-resistance heating, fires, and risk of injury to individuals accessing these meters.

In this paper, the authors will review forensic engineering[2] methods for examining, diagnosing, and explaining the hot socket phenomenon while exploring incident trends involving smart meters. They will also provide recommended engineering guidelines to reduce the risk of spoliation while investigating meter box fires.

The professional standards on which the authors base this analysis include, but are not limited to, the National Fire Protection Association (NFPA) *Guide for Fire and Explosion Investigations* (NFPA 921)[3], the *Standard for Professional Qualifications for Fire Investigator* (NFPA 1033)[4], various related ASTM International forensic standards, and expert treatises in the field of fire and explosion investigations. The ASTM International publications form the foundation for the standards of care for the investigative and engineering fields, particularly those overseen by the ASTM Committees on Fire Testing (E05), Forensic Sciences (E30), and Forensic Engineering (E58).

Both NFPA 921 and NFPA 1033, which are approved American National Standards Institute (ANSI) standards, mandate that the science of fire investigation involves determining both the fire's origin and cause[5]. Making these determinations requires a "systematic approach" with the scientific method[6]. The basic concepts of the scientific method are: observe, hypothesize, test, and conclude using reliable and reproducible scientific principles and methodologies.

Residential Metered Electrical Power

Most homes in the United States have a 120/240V, single-phase, three-wire system for the meter center. Two of these wires, called "main service entrance conductors," are ungrounded and energized ("hot"); the third wire is the "neutral." If a voltmeter reading is taken between the two hot conductors (line to line), it will measure 240VAC. If a reading is taken between a hot conductor and the neutral (line to neutral), it will measure 120VAC.

Utility companies usually do not allow unmetered power, so virtually every residence has what is called a "service entrance." This entrance (for electrical power) contains a separate meter for measuring power consumption.

The device used to measure the power consumption is

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called a "watt-hour meter."

The watt-hour meter is typically supplied by the utility company; the property owner supplies the meter socket cabinet. The meter socket is the receptacle and structural support for the meter. Historically, utility companies provided both the meter and the meter "box" for the first 80 years or so of the power grid (~1890 to 1970). As they're known today, socket meters were first introduced in the late 1920s, but did not become popular until the post-WWII building boom, which began in the late 1940s. From 1970 to 1990, most utilities and state utility commissions transitioned ownership of the meter socket to the homeowner, including those already in place.

A homeowner today that is upgrading an electrical service or building a new residence has a contractor purchase and install the meter box; the utility company inspects the socket installation and installs an electric meter. The meter socket must be approved by Underwriters Laboratories (UL) and the local utility[7].

Within the socket are four clamps, commonly referred to as "jaws." On the back of the typical meter face are four matching prongs known as "blades." The jaws, which are similar to leaf springs, must have sufficient force between the blades and the surface of the jaws to maintain proper contact and minimize electrical resistance. The greater the gripping force of the jaws that come into contact with the meter blades, the lower the contact resistance.

When the meter is correctly plugged into its designated socket, the blades on the rear of the meter are inserted directly into the gripping jaws of the socket (**Figure 1**). The unit is locked in place by a retaining ring or by the meter socket cover, neither of which can be secured unless the blades are inserted into the jaws completely[8].

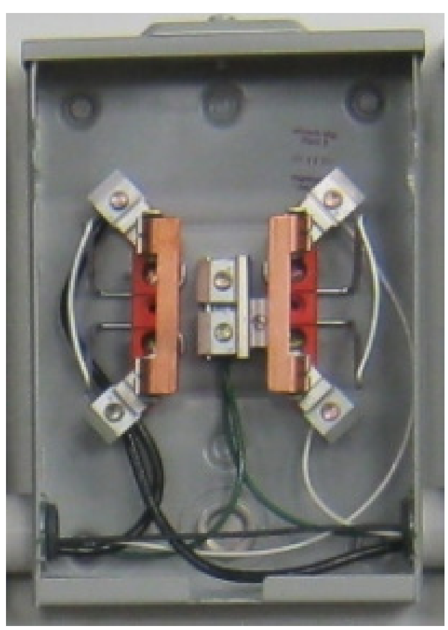
Loss Histories of Electrical Meter Center Fires

National fire statistics[9] show that electrically caused fires within residential meter centers are rare. For example, NFPA statistics on residential electrical fires in data from the National Fire Incident Reporting System (NFIRS) and the NFPA's annual fire department experience survey show that approximately 45,210 electrical fires occurred in home structures between 2010 and 2014 per year. Approximately 39,650 of these fires involved an electrical equipment malfunction as the leading factor contributing to the ignition (**Figure 2**). Of those 39,650 fires associated with electrical equipment malfunctions, the NFPA statistics show that, on average, 760 fires are involved with meters or meter boxes (1.9%). Consequently, even forensic experts who analyze electrical fires regularly may investigate very few fires originating in residential meter centers.

The Issue with "Hot Sockets"

The electrical components of the residential meter center should outlast the structures they serve under normal conditions. But there are conditions that can lead to their deformation, which, if left unchecked, can cause fires.

Overheating of electrical connections such as those in meter service panels are complex and can involve a



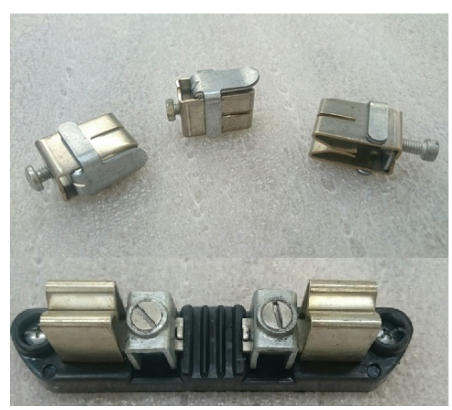


Figure 1
Typical meter socket base, meter socket, and jaws (left to right). Source: TESCO – The Eastern Specialty Company, Bristol, Pa; reprinted with permission.

Equipment Involved	Fires	%
Electrical distribution, lighting, and power transfer	22,510	57
Unclassified electrical wiring	7,880	20
Electrical receptacle or outlet	3,090	8
Electrical branch circuit	2,230	6
Panelboard, switchboard, or circuit breaker panel	1,180	3
Extension cord	1,180	3
Electrical service supply wires from utility	820	2
Electrical meter or meter box	*760*	2
Wiring from meter box to circuit breaker panel	590	1
Unclassified lamp or lighting	560	1
Electrical power service cables (utility)	560	1
Incandescence lighting fixture	530	1
Surge protector	460	1
Unclassified electrical cord or plug	390	1
Tabletop, floor or desk lamp	290	1
Detachable electrical power cord or plug	270	1
Permanently attached electrical power cord or plug	260	1
Wall switch	250	1
Fluorescent lighting fixture or ballast	220	1
Battery charger or rectifier	210	1
Other known electrical distribution or lighting equipment	780	2

Figure 2
Breakdown of 39,670 U.S. residential fires involving electrical equipment failures or malfunctions as a leading factor contributing to the ignition (2010 to 2014 averages); Source: Campbell, R. 2017. Electrical Fires. Research, Data and Analytics Division. Quincy, Mass., National Fire Protection Association.

number of variables. Some of the reported conditions contributing to hot sockets include, but are not limited to, the:

- Introduction of moisture into the electric meter enclosure.
- Localized resistive heating in electrical connections.
- Corrosion of the electrical meter socket jaws.
- Improper insertion of electrical meters into the meter sockets.
- Vibration.
- Deep electrical cycling.
- Unbalanced electrical loads.
- Tampering of or electrical power theft[10].
- Failure of the initial installer of the meter base enclosure to apply sufficient torque to the screws holding down the electrical cables to the meter mount (NFPA 70, 2017, Section 110.14(D) requires proper torque at cable terminations).

The failure of the electrical meter center components through localized heating of the jaws of the meter socket is well-documented in forensic engineering literature[11]. The engineering sciences behind localized heating of the electrical meter center connections can be complex in nature[12]. Many inter- and intra-related problems include copper oxide formation, increased contact resistance connection, creep and relaxation, vibration, electric arc erosion, and arcing through char.

- Typical conditions that result from localized heating associated with hot socket cases include, but are not limited to, pitted and discolored meter blades.
- Melted plastic around one or more of the meter stabs (typically the plastic around one stab is where the deformation starts).
- Pitted and discolored socket jaws.
- Loss of spring tension in the socket jaws[13].

Figures 3, 4, and **5** show typical jaw and blade damages that can lead to hot socket conditions and blade abnormalities.

Removing and reinserting the electric meter into the jaws, particularly those with overheated connections, can also lessen the spring tension. The reasons for the removal of an electric meter from its sockets can vary, such as: termination of electric service to a customer, routine service, or calibration of meters due to tampering of electric service of theft[14]. Each provides an opportunity for the damage needed to create a hot socket.

Studies by The Eastern Specialty Company (TESCO) have shown that the normal insertion force for an electric meter to its jaws can be as high as 50 lb. If an electric meter is removed and re-inserted into its socket eight times, the insertion force can drop to approximately 15 lb[15]. Several additional removals and insertions of the electric meter can drop the force to approximately 5 lb[16] or less. If the compromised electric meter connection is subject to localized heating at 700°F (370°C) for 5 minutes, this results in the potential for a hot socket condition.

The hot socket condition can also extend to the cables connecting the electric meter to the jaws of the socket through the jaw screws or when the electric meter blades do not make a good electrical contact with the jaws. This condition occurs due to the jaw blades spreading, corrosion, insulating effect within the meter socket, or the failure to tighten the bolted terminal connections of the jaws properly.

Under-torqueing the main electrical service entrance cables and the load cable connections to the meter centers is also an underlying issue associated when terminals attached to the jaws are not tightened sufficiently to ensure a sound connection. This also applies to the torque standard for the terminals connected to both the supply and load cables affixed to the meter socket. Although there is no set standard, the typical maximum temperature rating of a connector is 158°F (70°C)[17].

This torquing problem was recently addressed in the 2017 Edition of the *National Electrical Code* (NFPA 70, 2017)[18]. If conductors are not properly torqued (tightened), a high-resistance connection can occur. These connections can lead to arcing, which, in turn, increases the heating effect. This increased heating can lead to a short circuit or ground fault, fire, or arc flash.

Forensic engineers are responsible for being aware of potential product liability issues and to report them to their clients, interested parties, and, when appropriate, to the U.S. Consumer Product Safety Commission (CPSC). Electric meter centers exist that have inherent manufacturing weaknesses. One example occurred in 2009: the CPSC in cooperation with the Milbank Manufacturing Company

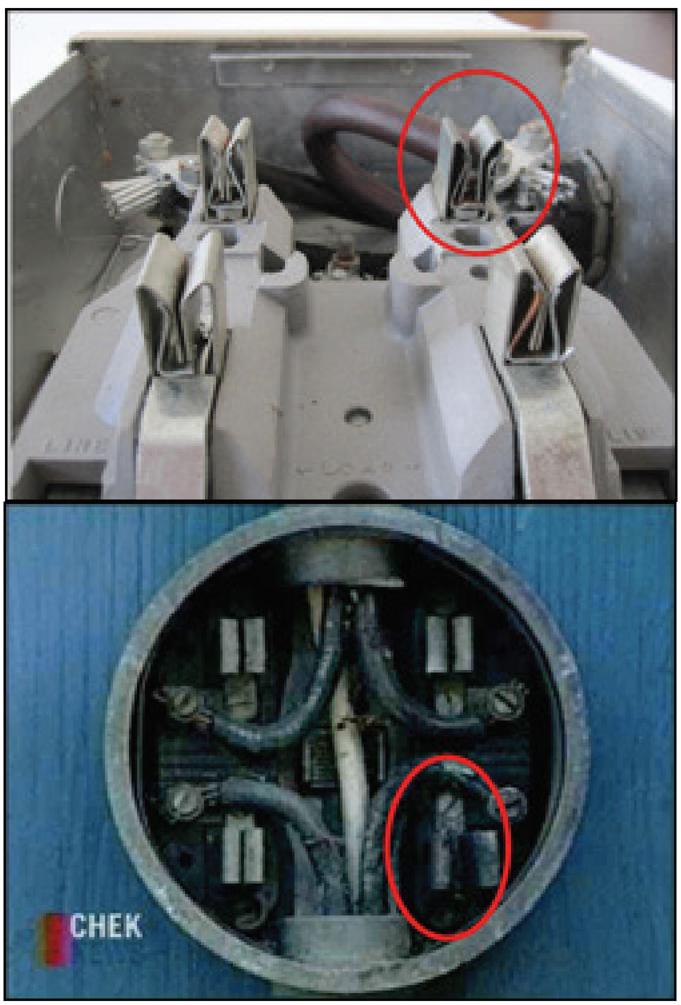


Figure 3
Typical trademark damage features for hot socket conditions showing pitted and discolored jaw sockets. Source: Lawton & Schamber (2017).

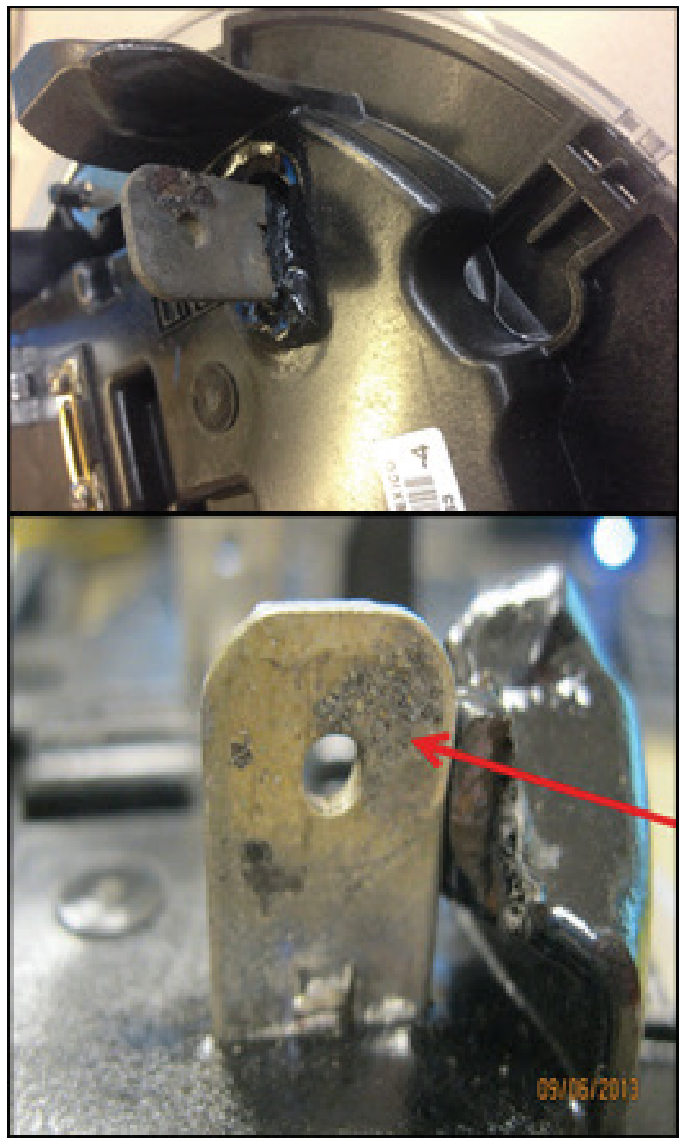


Figure 4
Typical trademark damage features for hot socket conditions showing signs of incipient jaw-to-blade arcing. Source: Lawton & Schamber (2017).

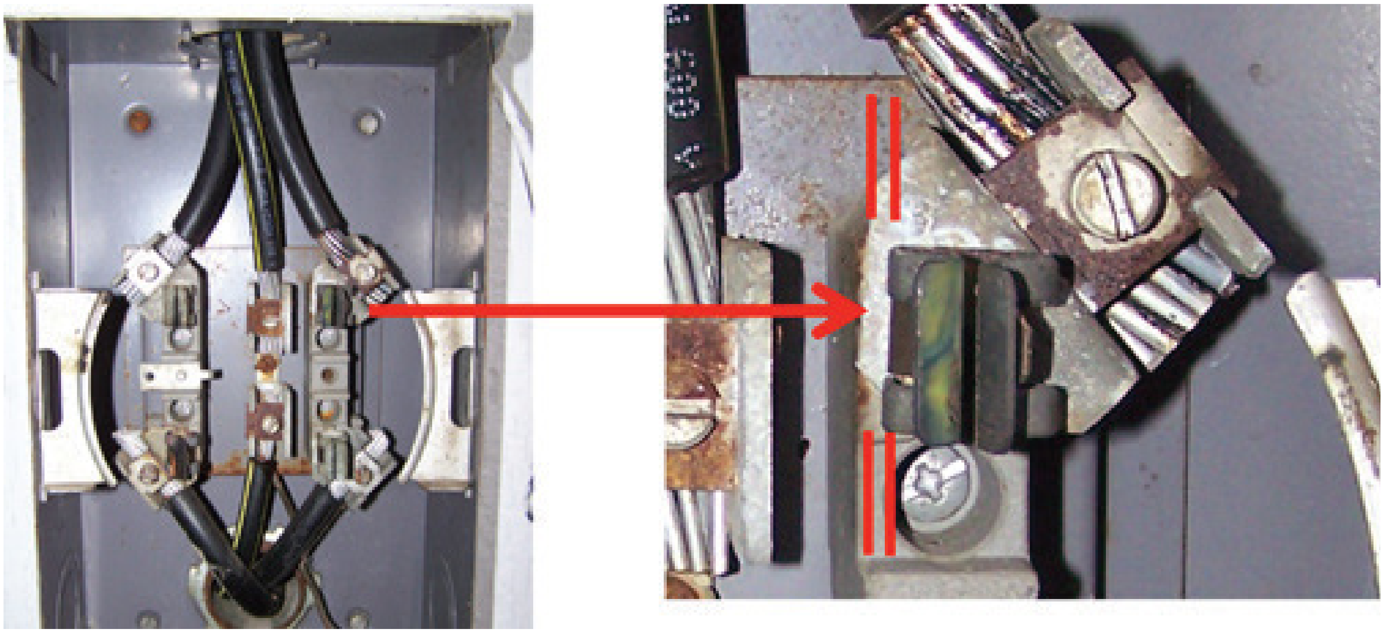


Figure 5
Example of a deformed jaw that results in evidence of localized heating and discoloration due to a poor electrical connection. Source: Lawton & Schamber (2017).

of Kansas City, Missouri[19]. The recall stated that certain electric meter sockets in a single meter center may short while energized due to an incorrect bridge, which was attached to the meter jaws. If a manufacturing defect exists, all metal parts of the electric meter could create an electric shock hazard. Burns could occur to personnel if the cover is off, and the meter socket is energized. Fortunately, of the three incidents reported to the CPSC of the unit shorting, none caused an injury.

Forensic Engineering Analysis of Hot Socket Cases

A forensic engineer should address a wide range of areas as part of regular field service, inspections, and failure investigations of electrical meter centers. Following are recommended areas of inspecting electric meter centers and associated equipment, and, if possible, the subject electric meter:

- Gaps in the electric meter socket jaws.
- Unique or inconsistent discoloration in any of the jaw blades.
- Signs of melted or deformed plastic on the meter base.
- Pitting of either the meter blades or socket jaws.
- Loss of tension in the meter socket jaws.
- Condition of the cable insulation and connections to meter jaws.
- Overall condition of the box, socket, electric meter, how they attach to each other and to the building.
- Signs of tampering.
- Signs of corrosion.
- Signs of water or debris inside of the electric meter can or box.

Once a potential hot socket or related condition is discovered by the forensic engineer during an investigation, a higher level of professional responsibility is triggered. This responsibility includes notice to the responsible agencies of the potentially unsafe conditions, the client, and other interested parties[20]. This is not necessarily true. The forensic investigation may discover a not properly torqued cable connection.

When there are signs of damaged jaws or electric meter blades, the engineer should not conduct any field repairs. Forensic investigations do not involve repairs. This repair is the responsibility of the property owner. These conditions, along with other indicators, should be documented per guidelines outlined in the appropriate NFPA and ASTM standards. In cases where the entire electric meter center should be secured as evidence, the forensic engineer has a responsibility to immediately notify the client, property owner and occupant, and other interested parties. Again, this paper deals with forensic investigations, not repairs. To do a forensic investigation implies that the forensic engineer was called to investigate the electric meter. The electric meter was removed in order to do the investigation, or meter tampering was suspected.

The forensic engineer should be careful around energized electric meter centers. This applies to working with all energized electrical equipment. For example, measurement of voltages with non-commercial metering equipment may cause hazardous or life-threatening arc flash conditions. These events are of grave concern when handling energized electrical equipment and circuits. Individuals exposed to arc flash conditions can be seriously injured or killed, particularly if they are not wearing appropriate personal protective equipment.

Emerging Areas of Hot Sockets Involving Smart Meters

Since the late 1980s, the standard baseline electromechanical meters and electronic meters have been steadily replaced with a new generation of electronic solid-state meters known as "smart meters," defined as meters with two-way communication capability. Deployment of them began in North America in 2007. Loss histories suggest that the new smart meters should be designed with hot socket detection components in mind.

Over the past two or three years, smart meter manufacturers have started designing meters to withstand hot sockets. Improvements include placing temperature sensors closer to the meter blades (instead of only on the metrology boards), specifying heat-resistant components within the meter itself, increasing the mass of plastic at the meter base to better insulate the inside of the meter. Historically, meter bases used glass and phenolic and then moved to thermoplastics. One smart meter maker is now using high-temperature base plate plastic.

One innovative design for early detection of hot socket conditions is the use of a specialized field detector embedded within the meter that makes use of the smart meter's two-way communication capacity "to send an alarm back to the utility." Since arcing emits broadband energy in the form of radio waves sometimes referred to as "pink noise," the intensity of this falls off with increasing frequency. Sensors couple through the air with the nearfield electric and magnetic fields, which induce a detectable signal. Advantages of this approach include no direct connection, and the communication method is resistant to interference from other radio frequency emitting devices such as cell phones and power lines.

Analytical Tools

NFPA 921 outlines a range of tools and analytical approaches for the investigator's use in analyzing the cause of the failure of a component or system involved in a fire or explosion. These tools can assist in organizing information and help an investigator comply with the scientific method. Such tools suggested by NPPA 921's Chapter 22 on "Failure Analysis and Analytical Tools" include, but are not limited to, timelines (pt. 22.2), systems analysis (pt. 22.3), mathematical modeling (pt. 22.4), fire testing (pt. 22.5), and specialized data collection (22.6).

These approaches include the use of timelines (pt. 22.2.1), which NFPA 921 considers "a graphic or narrative representation of events related to the fire incident, arranged in chronological order." A timeline can show event relationships, gaps, or inconsistencies of data — and is a logical approach to complex cases. Shown previously in Table 1 is the representational timeline for this case as suggested by NFPA 921.

• Identified by NFPA 921, Failure Mode and Effects Analysis (FMEA) is an appropriate technique for identifying the basic sources and consequences of failure within electric meter centers. Factors used when applying FMEA can include the component, failure mode and frequency, direct effect, potential hazard, and corrective actions. The results of the FMEA assists in identifying the item (or action) being analyzed.

• Basic fault (failure) or error that created the hazard.

• The consequence of the failure.

An action is said to have "foreseeable consequences" if it can be reasonably assumed that it will cause a certain direct effect or harm based upon a reasonable person's actions. The benefit of these analytical tools as recommended by NFPA 921 is that they can assist in organizing information and help the forensic engineer comply with the scientific method.

Responsibilities of the Forensic Engineering Expert

The expert treatise, Kirk's Fire Investigation, makes clear that the fire scene is often the most important piece of evidence in forensic analysis and reconstruction, particularly when the fire could result in criminal or civil litigation. Therefore, a major concern of fire investigators is the preservation of evidence before it is submitted for examination and analysis. Failure to prevent spoliation can result in the damaging disallowance of testimony, sanctions, or other civil or criminal remedies[21].

Both NFPA 921 (pt. 12.3.5.1) and ASTM E860 caution that spoliation may occur during fire scene processing, particularly when the movement or the alteration of debris impairs the ability of other interested parties to obtain the same evidentiary value from the evidence as did any prior investigator. The act of spoliation is also a violation of professional standards of conduct for the forensic fire investigation and engineering fields. These standards include NFPA 921, NFPA 1033, and various related ASTM International forensic standards.

Forensic engineers, fire investigators, insurance claims personnel, and attorneys must be well informed on their responsibilities to alert interested parties, collect, and preserve evidence, and share the appropriate information. They are routinely taught at continuing education seminars and in textbooks to correct methods for avoiding spoliation[22]. They are instructed that breaches of professional conduct in the documentation, collection, analysis, and preservation of evidence may undermine their legal case, whether it be civil or criminal (NFPA 921, pt. 11.3.5.3). Remedies for spoliation may include monetary sanctions, application of evidentiary inferences, exclusion of evidence and expert testimony, dismissal of the claim or defense, tort actions for the intentional or negligent destruction of evidence, and potential prosecution under criminal statutes relating the obstruction of justice (NFPA 921, pt. 12.3.5.3).

The cited reference[23] by Dean entitled "Legal Issues Involved in Failure Analysis" sets forth clear guidance to investigators, particularly engineers.

There can be missed opportunities during the preliminary and follow-up investigations of meter center fires. It is important that forensic engineers be cognizant that evidence in hot socket fires are often fleeting, and the engineer may not get a second chance to later document, preserve, and collect critical evidence.

When confronted with potential hot socket cases, the forensic engineer should:

- Per NFPA 921 (NFPA 921, pt. 12.3.5) and ASTM E860 (ASTM E860, pt. 5.2, et seq.), recognize, secure, preserve essential evidence, and notify interested parties.

- Perform non-destructive and destructive testing of the meter, meter center, jaws, and associated equipment to document the hot socket condition as well as any signs of tampering or vandalism.

- With destructive testing of the jaws, determine whether there is still sufficient jaw tension to preclude a hot socket from being the cause. Here, it is important to recognize that the fire itself could have dramatically reduced the jaw tension.

- Look for signs of pitting on the jaw and the blade, which is usually a result of prolonged meter arcing (a series of intermittent events that occurred in ever increasing durations over a prolonged period).

- Conduct scanning electron microscopy and, where possible, x-ray computed tomography, and focused ion beam of the electrical equipment.

- Determine the difference between arcing and melting of components.

- Inspect neighboring meters and meter centers to determine if there existed similar conditions.

- Notify other interested parties of their existence and, if necessary, file the appropriate disclosures to the U.S. Consumer Product Safety Commission if potential product defects were found.

Summary and Conclusions

Hot sockets start with a loss of tension in at least one of the meter socket jaws. This loss of tension can be from a variety of sources. These may start as early as improper installation or even "tight sockets." Loss of tension is one factor necessary to create the initial micro-arcing conditions. Sockets with repeated electric meter exchanges observed to have higher incidence of hot socket issues, and "booting" a meter may loosen a meter's jaws even more. Hot socket repair kits are not available that contain all the tools and parts for servicing meters[24].

Vibration appears to be the most common catalyst for the micro-arcing that creates the initial heat in a "hot socket." The meter must be energized, but current is not a significant factor in how quickly or dramatically a hot socket occurs. The effects of vibration and weakened jaws can reinforce each other.

Electric meter manufacturers have been working on the design of their meters to better withstand a hot socket. These new electric meters have better baseline performance than even the older electromechanical meters, though the heat from a hot socket will eventually consume even the most robust meter.

When replacing an electric meter, the installer should conduct tension inspection tests for all the jaws. A non-invasive check that the minimum safe holding force or greater is present in all socket jaws should be performed[25]. Advanced forensic engineering testing equipment is also available to evaluate the health of the meter socket.

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5. NFPA 921, 2021 Edition, Ch. 3.3.76 defines fire investigation as "The process of determining the origin, cause, and development of a fire or explosion."

   NFPA 921, 2021 Edition, Ch. 3.3.140 defines a fire's origin as "The general location where a fire or explosion began."

   NFPA 921, 2021 Edition, Ch. 3.3.71 defines a fire's cause as "The circumstances, conditions, or agencies that brought about or resulted in the fire or explosion incident, damage to property resulting from the fire or explosion incident, or bodily injury or loss of life resulting from the fire or explosion incident."

6. NFPA 921, 2021 Edition, Ch. 3.3.167 defines the Scientific Method as "The systematic pursuit of knowledge involving the recognition and definition of a problem; the collection of data through observation and experimentation; analysis of the data; the formulation, evaluation and testing of hypotheses; and, when possible, the selection of a final hypothesis."

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17. Hattangadi, A.A. 2000. Electrical Fires and Failures: A Prevention and Troubleshooting Guide. McGraw-Hill Companies, p. 128.

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20. NFPA 921 (2021, pt. 3.3.123) defines an interested party as: Any person, entity, or organization, including their representatives, with statutory obligations or whose legal rights or interests may be affected by the investigation of a specific incident.

21. Burnette, G. E. 2012. Spoliation of Evidence. Tallahassee, FL: Guy E. Burnette, Jr, P.A.

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