LOSS INVESTIGATIONS INVOLVING HEATING ELEMENT FAILURES: FIRE, WATER AND PERSONAL INJURY

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ABSTRACT

Sheathed heating elements, or calrod heaters, are used in a variety of appliances and processes to heat a media (water, air, other fluids). Examples of appliances that utilize sheathed heating elements are water heaters (trough and residential), dishwashers, dry saunas, and RV refrigerator cooling units. The construction and use of various heating elements are reviewed with a focus on design features which may contribute to failures and safety features which should prevent catastrophic failures. This paper will expand on NFPA 921 (2014) Section 26.5.7 describing various heating element failures as the root cause of not only fires but also personal injury (e.g., burns, electrocution) and water losses. Common causes and failure modes of heating elements, from case studies and literature, are presented. A basic protocol for the thermal and materials characterization and laboratory examination and testing of heating elements and failures is provided.

BACKGROUND

Resistive heating elements are used in numerous residential appliances, manufacturing and chemical industries. Table 1 is a short list of devices and appliances that utilize one or more heating elements distinguishing between exposed and sheathed coiled resistive heating elements. The resistive heating elements in calrod[1] style heaters are surrounded by a cast or granular ceramic insulator inside a metal sheath.

Table 1 Applications of heating elements in residential setting

Sheathed or Calrod Style	**Exposed Heating Elements**
Water heater	Electric clothes dryer
Dishwasher	Curling iron
Dry sauna	Space heaters
RV refrigerator	Toaster
Fish tank heater	Electric blanket
Electric range top	Hair dryer
Oven cavity	Furnaces
Coffee cup heater	

Refrigerator ice maker	
Some plug in air fresheners	

Calrod style heaters are available in a variety of shapes, lengths and watt density; some construction features, however, are the same. This paper does not address the design of heaters for appliances but the failure modes and effects of resistive heating elements likely encountered by fire investigators and forensic engineers. Useful source material on the design of heating elements for appliances and process media includes various manufacturer's websites and the book *Integrating Electrical Heating Elements in Product Design*.[2,3]

Construction Features

A residential appliance heating element works with either 120 volt or 240 volt power. The design of calrod style heaters includes an electrical connection from a power cord or supply to a coiled length of resistive wire between two electrical terminals called cold pins. The resistance of the wire is based on its composition, diameter and length. Typical resistive wire alloys are Nichrome (Ni-Cr(Fe) per ASTM B344) or Kanthal (Fe-Cr-Al per ASTM B603). Coiled wires may be single-or dual-wrapped wire. The coiled wire is surrounded by an insulating material inside a metallic tube or sheath. Sheath materials can be ferrous (steel, cast iron, stainless steel, Incoloy, Inconel, etc.) or non-ferrous (aluminum, copper, titanium, quartz, etc.). The insulator serves to keep the wire centered in the sheath to prevent faulting. Due to the higher temperatures of the resistive wire during operation, the insulating material must be able to withstand temperatures on the order of 600°C and higher depending on the purpose and design of the heating element. Ceramics meet the temperature requirements for sheathed heating elements. The resistivity of the insulating ceramics must be elevated so that leakage current, and breakdown voltage to the outside sheathing meets standard IEC 335 *Safety Of Household And Similar Electrical Appliances*. The insulator, typically magnesium oxide (MgO), may be cast, granular or fine powder. Fused MgO is an indicator of insulator breakdown. Finally, the electrical connections and heater circuit has to be sealed. A silicon seal or other similar end plug acts as a spacer between the terminal end and the sheath. The plug end design parameters and materials will differ depending upon the use of the heating element, such as open air or water immersion elements. Figure 1 shows a schematic and photograph of a sheathed heating element electrical connection to the coil.

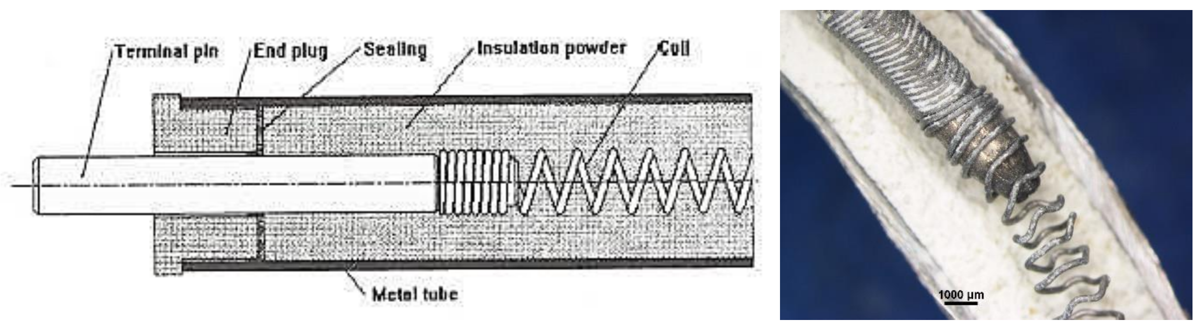

Figure 1 Cross section showing cold pin and coiled heating element of calrod style heater (Image on left from Ref. 3).

Sheathed heating elements are also found in industrial appliances and process industries and are typically referred to as process heaters, immersion or submersible heaters. Examples include tank heaters to maintain process solutions, such as electroplating and pickling baths, at an elevated process temperature. In chemical applications, the heater sheath material is selected to resist corrosion by the process media.

Some, but not all, sheathed appliance and process heaters have passive or active safety devices. Some process heaters have thermal cut off devices inside the heater circuit that will open if overheating occurs.

Sludge legs prevent the heater from sitting on or near the bottom of a tank where sludge could accumulate and cause overheating. If present, safety devices can be by-passed or fail to function.

Heating elements can cause fires—acting as an ignition source for a combustible solid during normal use, upset conditions or as a result of catastrophic failure. Based on its surface temperature, heating elements may be capable of igniting gases, vapors, mists and particulate or dust. Heating elements can also fail and cause property loss other than fire such as water released from electric water heaters. Electric resistance heaters are also energized devices and therefore can, under some conditions, result in electrical shock and electrocution. Burn injuries have also been attributed to the failure of a stove top heating element. Heating elements are the subject of some CPSC product recalls.

Not all heating element failures are a fire hazard or cause property damage; a heating element wire that locally opens the circuit and the heater then fails to function further is not a fire hazard. The internal fault is contained. If the failure is catastrophic but contained inside a vessel, that is also not combustible, such as a water tank, a release will not occur. Failures leading to fires, property damage and personal injury are likely to be encountered by private fire investigators and forensic engineers.

NFPA 921 *Guide for Fire and Explosion Investigations* identifies heaters including calrods as heat-producing devices. The basic construction, operation and failure mode of heating elements are generally described in chapter 26 Appliances and specifically under section 26.5.7 Heating Elements. Due to their materials of construction, heating elements typically survive exposure to an external fire. Heating elements are also part of an electrical circuit and are subject to arc mapping. Therefore, it is when a damaged heating element is found after a fire, the fire investigator needs to determine how the heater failed and if the heater or a failure of the heater was the cause of the fire.

Whether or not a fire, water loss or injury occurred, characterizing damage to the subject and exemplar calrod style heaters is typically occurs during a laboratory examination where the principles and practice of failure analysis apply.[4] The lab exam will typically include a non-destructive and destructive component and should include a close examination of the circuit involving the heating element and all electrical connections between the receptacle, power cord, safety device, cold pins and coiled resistive heating element.

Another consideration in the investigation of a fire loss is identifying and characterizing fuels in the area of the heater. Hypothesis testing in demonstrations with exemplar heaters are encouraged. For water loss investigations, root cause analyses should include whether the failure is related to installation (e.g., low liquid level) or manufacturing defect (e.g., at a connection).

AT THE LOSS SITE

If available, an investigation of field failures causing fires or water damage benefit from a site visit. In addition to photographic documentation and data gathering, the device or appliance and others like it should be identified and preserved. In other cases, only the failed heating element is made available for analysis to determine the cause of its failure. In both cases, basic age and use history are important.

When the site is available, as much of the circuit and subject appliance with the subject heating element should be documented in place then preserved for further study in the laboratory. Circuit tracing and arc mapping should be performed. The heating element may be custom built for the process; drawings and order documentation should be requested. Use history should include the age and last use of the subject heating element and problems, if any, during operation. Other heating elements, both in use and in storage or stock, should be collected as evidence for comparative analysis and/or incipient stage failures.

For industrial applications, it is important to document and understand the process media and process controls. Process data should include the volume to be heated, chemical composition of solution, MSDS, conductivity, temperature, when last cleaned or maintained, etc. Process controls include timers, thermostats, and liquid level controllers. A sample of the process media should be collected. Environmental anomalies including brown-outs or lightning strike data should be gathered.

In one case, lightning was alleged to have caused a trough heater to fail electrically. It was shown however, that smaller gage, lower melting temperature conductors were more susceptible to damage from lightning strike than the heating element which exhibited extensive damage at the cold pin. Further, a paper by Miyazaki *et al* lists home electrical appliances damaged by lightning surges.[5] The paper does not list heater element appliances and devices in Table 1 as susceptible. In another case, users of immersion heaters observed 'smoking' from the cap outside the tank where the heater device was connected to a power cord. Loose connections were found inside the potting material that decomposed around the poor connections. One used, heater from the lot collected was energized, decomposed, and faulted progressing to flaming combustion. Poor wiring connections were identified as accounting for a large percentage of process heater problems in the field.[6]

LABORATORY EXAMINATION PROTOCOL

Heating elements recovered from losses range from intact to fractured or fragmented into one or more sections that may be straight or bent; the separated sections may be large or small. Penetrations in the sheath range from none, to locally damaged to damaged over a length of the heater with melted or missing metal sheath. The number of openings in the coiled heating wire range from one to many. Faults can occur at one or more location.

With the premise of not energizing or operating the subject heating element or device from a loss, a general protocol for the laboratory examination of failed sheathed heater elements should including the following steps:

1) Understand the operation of the device
2) Gross description of circuit and use or appliance
3) Photographic documentation including location and type of damage and discoloration
4) Examination of sheath surface for manufacturer information, rating and date stamp
5) Dimensional measurements
6) Electrical measurements at room ambient and other temperatures if thermostatically-controlled
7) Radiography and/or computed tomography (CT)
8) Cross-section sheath to expose connections and/or coiled heating element
9) Examination of damage using microscopy
10) Materials characterization by SEM and EDS of sheath, insulator and coiled heating element and any internal damage

Table 2 is a summary of data that should be collected during laboratory examination.

Table 2 Heating Element Materials Characterization, Electrical Measurements and Dimensional Analysis Data

Materials Characterization	Dimensional Analysis	Electrical Measurements
Outer jacket (if applicable)	Total length	Continuity
Sheath material	Outer diameter	Resistance at RT
Insulator	Sheath wall thickness	Resistance at 2nd temp.
Heating element	Diameter of coil	Hi-Pot
Mass of all pieces	Diameter of coil wire	
	Length of damage	

Radiography and/or computed tomography are the most useful non-destructive method that shows a heater's construction features; the presence, location and condition of safety devices; and, the condition of the embedded heating element wire and electrical connections. Radiography will also show if the heating element is off-center or near the sheath, the number of coils, coil regularity, and the number and location of openings in the wire. The density of fused MgO is different from surrounding granular MgO and is typically visible by x-ray or CT images. Figures 2 and 3 are photographs and x-ray images showing a single and multiple faults and melt locations in titanium sheathed process heater. The heater in Figure 3 was collected from the fire's area of origin. The heater in Figure 2 was found in a collection of discarded heaters from the same plant.

Figure 2 Localized breach in sheath of titanium sheathed process heater.

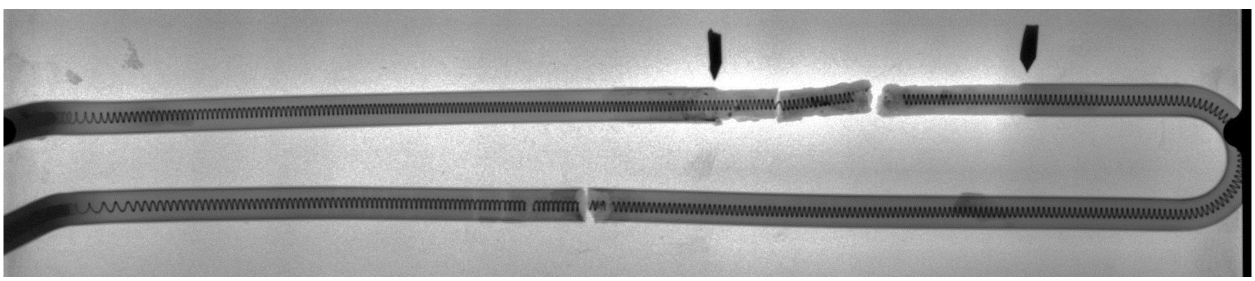

Figure 3 X-ray showing multiple physical and wire breaks in a titanium sheathed process heater.

SEM/EDS is typically used to determine the composition of the sheath, the insulator and the coiled wire. Once the composition is known, the melting temperature of the sheath can be determined from literature.

As part of a fire investigation, exemplar heaters or appliances may be purchased for thermal characterization and for use in hypothesis generation and testing. In addition, an exemplar heater may have packaging labels, installation instructions, use and care instructions and warning tags. Exemplar heaters can be thermally characterized using thermal imaging and/or thermocouples. Temperature profiles should be performed in the same or similar process medium and/or temperature range under normal and upset conditions. In liquid-based process media, the temperature of the sheath will be lower as heat is transferred from the heater to the media. However, if evaporation occurs (e.g., stuck float, closed make-up water valve, leak in the tank, etc.), the process media may be lost or concentrated contributing to the failure of the heater. If the heater does not have thermal protection, it can overheat and fault. Other demonstrations could examine if metal splatter and/or hot pieces from a failed sheathed heater can ignite a nearby combustible material. Once a sheathed heater finishes faulting or is fragmented open, it will begin to cool. Therefore, the ability for the heater by itself or after failure to ignite nearby combustibles should be determined by measuring and understanding the operation of the heater, the failure mode and the type of nearby combustible materials.

FAILURE MODES

Failure modes of resistive heating element wires and calrod style heaters may be thermal, chemical, electrical, or mechanical, a combination of two of the listed modes and/or a manufacturing defect. Calrod heaters have a limited life based on usage and are capable of failing safe. Other calrod heaters fail prematurely and the investigator has to determine if the failure was inherent or precipitated. Common causes of calrod heater failure from numerous sources and field experience are summarized in Table 3.

Table 3 Common Causes of Calrod Heater Failures

Heater wire opens with parting arc with or without faulting to sheath
High temperature corrosion
Poor electrical connection
Wire deformation leading to locally increased temperatures
Localized or gross breach in sheath
Scaling, sludge, coking leading to locally increased temperatures
Loss of heat sink

Heater wires have limited life. Causes of heater wire failure are oxidation, high temperature corrosion, deformation leading to locally increased temperatures and changes in electrical properties.[3] Goodson *et al* published an article on fires caused by fractured resistance heating elements identifying modes of failure as 1) normal over time opening with a parting arc with or without welding to a grounded frame; and 2) improper installation leading to irregular coil length and increased wattage density.[7] Magnesium oxide becomes conductive with increasing temperatures which may occur as a result of localized heating or faulting. If faulted to the sheath through the insulator, part of the heater circuit can remain energized by-passing any thermostats or safety devices. From the exterior, oxidation, corrosion product, scaling, 'coking' and sludge on the sheath can lead to reduced heat transfer, localized over-heating and failure. Overheating, gross or localized, was identified as one of the most common causes of calrod heater failures.[8] From "Helping Heaters Live Longer", typical failures of heaters listed are: improper electrical installation; low liquid levels; build-up or scaling; chemical misapplication; physical damage and condensate entering the heater.[9] Another website lists premature failures due to corrosion or chemical destruction caused by unusual conditions such as excessively high solution temperatures, solution concentration, stray electrical currents, excessive sludge build-up, stagnant or turbulent flow of the solution.[10] Manufacturing defects include delamination between a sheath and heat sink (Ref. 8), poor electrical connections, ~~c~~ sheath resistance weld failures.

Calrod style heater failures can occur at different locations: at the electrical connection(s) between the power cord and cold pin; between the cold pin and wire; at one or more locations within the coil with or without faulting to the grounded or ungrounded sheath. Coil bunching leading to increase watt densities and temperatures and high resistance connections can occur between the cold pin and heater wire resulting in a failure. Two such failures are illustrated below—one resulted in a breach of the sheath. Figure 4 shows an overview photograph, close up and CT image of a heating element that faulted to the sheath at the cold pin location. A conductive path existed between the wire and sheath but the sheath was not penetrated. The black solid analyzed by SEM EDS was found to contain varying concentrations of iron (Fe) and chromium (Cr) from the heater wire. Figure 5 shows localized damage to a stove heating element. The heating element was dual wound and failed due to a high resistance connection at the cold pin connection. The failure resulted in melting and opening of the sheath indicative of the high temperature fault.

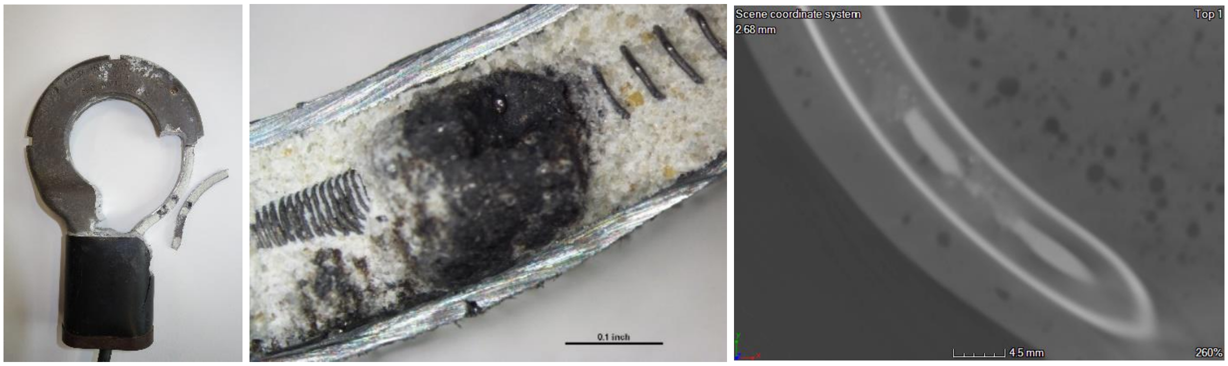

Figure 4 Thermostatically controlled immersion heater failure at cold pin with a conductive path to the sheath

Figure 5 Failure of stove top heating element at cold pin

A heater element that fails under water or other liquid process media will likely not have sufficient energy to ignite combustibles (e.g., the plastic tank) unless the process media is lost but can become a shock hazard if faulted to the sheath and not properly grounded. While not a fire hazard, an electric water heater calrod heating element failure can lead to the release of water either through an opening created in the sheath or a melt opening through the screw-plug base (Fig. 6). More often, a failed water heater calrod does not result in the release of water but a service call and a replacement heating element. Multiple occurrences of a water heater element failure are likely related to installation. ‘Dry firing’ refers to deformation damage sustained by electric water heater elements when they operate in the absence of or low water level. The loss of the heat sink can result in overheating until failure. If not installation related and the calrod’s sheath is found open along the seam, the sheath weld seam should be examined to determine if the weld failed first allowing water to intrude and cause the heating element to fail.

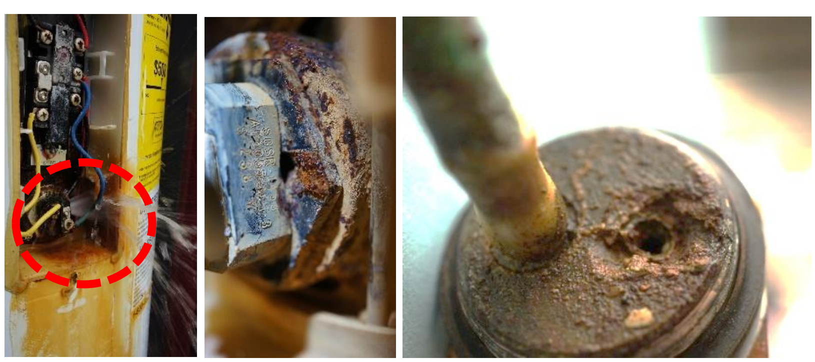
Figure 6 Failure of water heater element leading to breach in screw plug and release of water.

CASE STUDIES

Three field failures are described illustrating causes of and factors contributing to calrod style heater failures.

Fire inside Printed Circuit Board Washer. A business that manufacturers printed circuit boards (PCB) utilized an appliance that resembled a stand-alone modified-dishwasher to wash and rinse production PCBs of residual flux after soldering. A fire occurred after hours; the washer was the fire's origin. A J-shaped Incalloy 840 immersion heater was found in the debris at the lower left of the appliance where the water tank was located. The sheath had two areas of localized damage. It was determined lightning struck a pole and transformer near the plant resulting in a power surge that interrupted the operation of the washer and the heating element remained energized ultimately igniting the washer's plastic water tank ~~then~~ then faulting. Had the heater failed during normal operation, it likely would not have resulted in ignition. The appliance and its calrod heater are shown together in Figure 7.

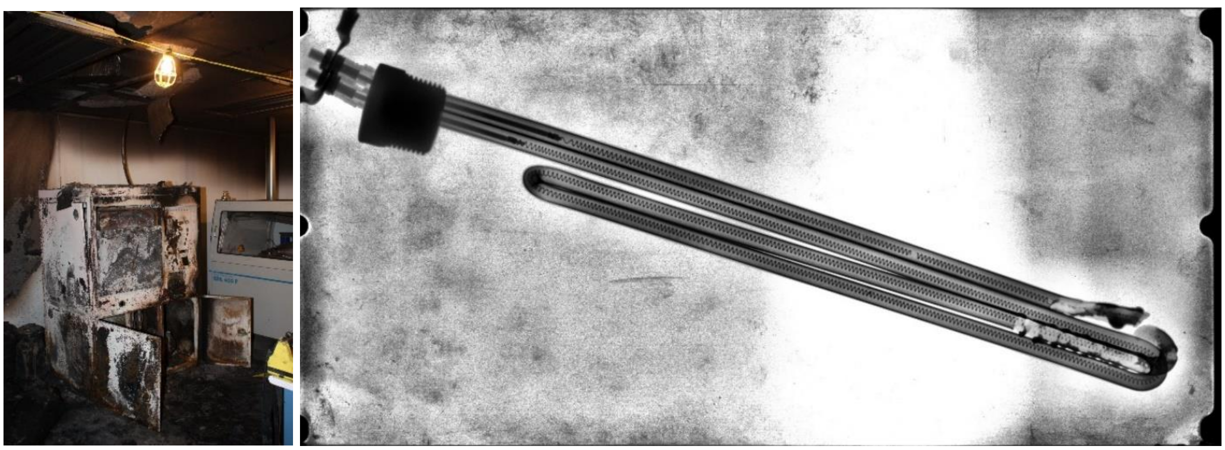

Figure 7 Overview of washer appliance and failed immersion heater

Dry Sauna Fire. A fire occurred inside a sports complex men's locker room dry sauna. The sauna heater had three-vertically oriented calrod heaters inside a steel box/housing. The sauna heater was on a timer circuit. Two elements were found electrically damaged and in multiple pieces (Fig. 8); at least one piece of the calrod heater and some solidified melt were found outside the heater housing. Fuels in the immediate area at the bottom of the sauna heater were the sauna floor wood slat boards and low density light-weight environmental debris accumulated under the boards. Alternate ignition scenarios involving an operating sauna heater were considered and demonstrations were performed to evaluate whether newspaper draped over the wood frame surrounding the heater could ignite.

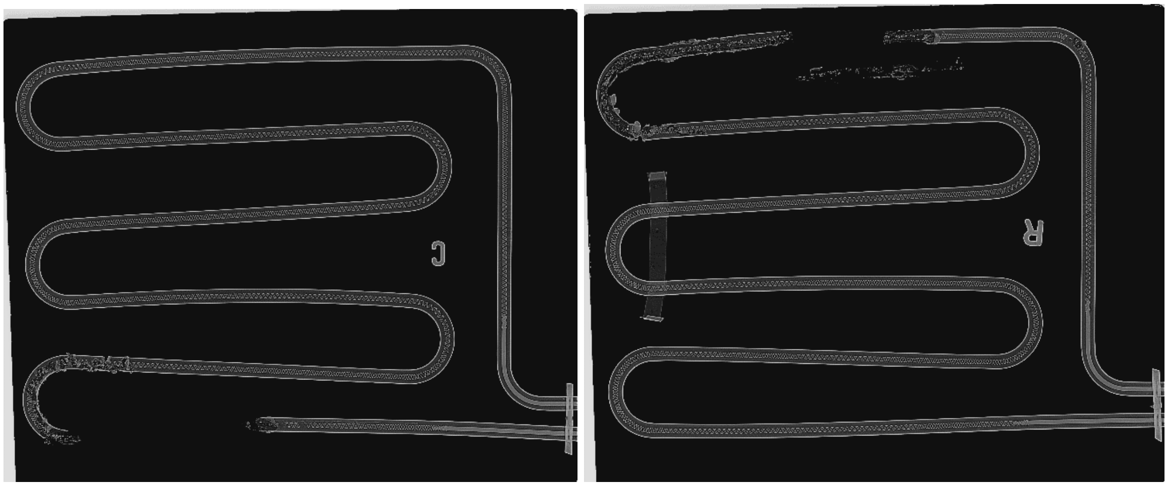

Figure 8 Xray images of dry sauna heater elements

Water Losses from Electric Water Heater Failure. Electric water heaters have one or more calrod style heating elements. In one case, the electric water heater in the entrance of a seasonal home in Michigan was found releasing water from the top screw-in heating element location. There was melting in the metal screw flange around the connection to the coil. The leak rate was characterized and the heating elements removed. In another case, a water leak led to dry firing of the water heater element (Fig. 9). As a result of dry firing, the exterior sheath was damaged and allowed water into the insulator and creating a conduit for water out of the water heater unit through the interior of the sheathing and out near the exterior electrical connections. The element was a rated for 120V, 2000 Watts.

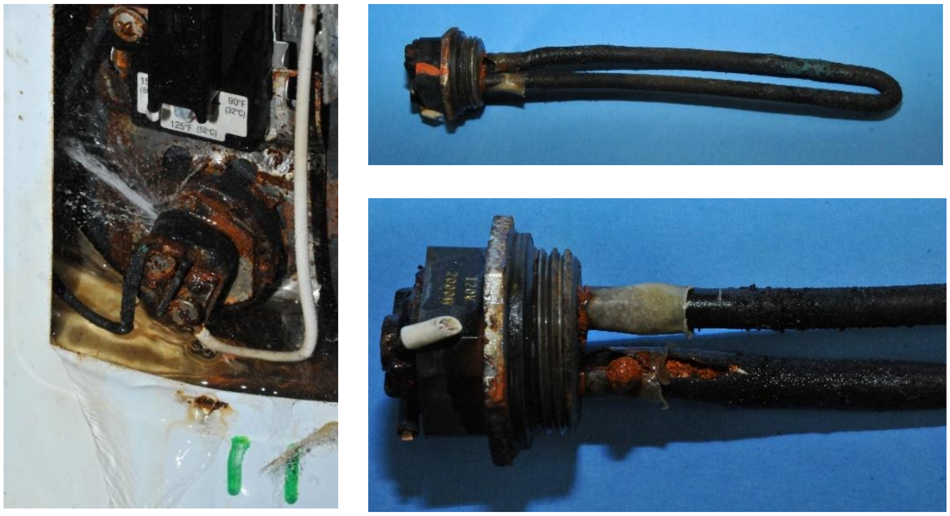

Figure 9. Dry fire leading to water loss

CONCLUSION

The private or fire investigators and forensic engineers encounter heating elements in the field that can act as ignition sources, cause property damage and personal injury. Site investigations are beneficial; the subject appliance and its heating element should be preserved for examination in the laboratory. If damaged, the investigator has to determine how the heater failed and if its failure caused the loss. At fire losses, nearby and first materials ignited have to be identified. For water losses, the forensic engineer needs to determine why the heater failure and if there are manufacturing or installation contributing factors.

ABOUT THE AUTHORS

Goodson Engineering's Michael Shuttlesworth is a mechanical engineer with 6 years experience in the forensic and failure analysis industry. Mr. Shuttlesworth has a BSME from Oklahoma Christian University. Mr. Shuttlesworth oversees the mechanical and electrical failure analysis instrumentation and equipment at Goodson Engineering.

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FMRL's Elizabeth Buc is a chemist, metallurgist and fire investigator with 20 years experience in the industry.

ENDNOTES

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[11] Calrod™ is a trademark of GE but is now commonly used to describe a steel sheathed heating element.
[2]www.Tempco.com/process heaters.
[3] Hegbom, T. (1997). *Integrating electrical heating elements in appliance design*. New York: Marcel Dekker.

[4] Technical Council on Forensic Engineering (American Society of Civil Engineers). (1989). Guidelines for failure investigation. New York, N.Y: American Society of Civil Engineers.
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[8] Murray, S. J., Loud, J. D., and Caligiuri, R. D.; Proc. International Appliance Tech. Conference, 2006.
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[10] www.process-technology.com M-08-02, Revision Date 00-05/29/08