Journal of the National Academy of Forensic Engineers®

NATIONAL ACADEMY OF FORENSIC ENGINEERS

http://www.nafe.org

ISSN: 2379-3252

Vol. 35 No. 2 December 2018

Forensic Engineering Analysis of Fire Caused by Control Failure Due to Deviation from Patented Design

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Abstract

A fire in a multi-unit condominium complex occurred, causing the building to be a complete loss. The point of the fire's origin was traced to a recently drained hot tub's electric heater. Examination of an exemplar heater revealed that a key safety-related control feature was manufactured in a configuration inconsistent with its original patent drawings in a way that would have lessened its performance for what may have been cost of manufacturing considerations. This change also brought into question whether the control that was reportedly tested at Underwriters Laboratory was one designed to the patent specifications. The manufacturer has since discontinued use of the control for subsequent installations.

Keywords

Fire, hot tub fire, positive temperature coefficient heater, PTC, hot tub heater, over temperature shutoff control, NFPA 921, forensic engineering

Background

In October of 2010, a fire occurred in a condominium at a New England ski resort, resulting in a total loss of the subject and adjacent condominium units (**Figure 1**). This condominium included a four-person hot tub spa that was installed on the second-floor exterior porch of the 900-square-foot property. The hot tub spa was installed in 1997, and past service work included the installation of a new electric spa heater and circulating pump in 2003. The spa heater was again replaced in 2006.

The vacation property had not been used since the previous winter and was being prepared for the upcoming skiing season. Activities included cleaning and other property maintenance needed to make the condominium unit ready for winter renters. During nonuse periods, the hot tub spa was drained and covered with an insulated spa cover.

For what appears to be aesthetic purposes, the spa's electrical disconnect was installed 7 feet above the second-floor deck where the tub was located. This height was contrary to the National Electrical Code and the spa's manufacturer's installation instructions. Both documents require that this component of the tub's electrical system must be readily accessible; however, access to this spa's electrical disconnect required a step ladder.

Reportedly, during summertime periods of nonuse, the branch circuit breaker to the tub was shut off at the electrical panel that was not within line of site of the equipment. During the "opening" of the property for the upcoming rental season, many circuit breakers were closed to re-establish power to de-energized appliances. Possibly due to the 7-foot elevation of the tub's electrical disconnect

Figure 1
Location of fire indicated by arrow.

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Figure 2
Spa as seen. Fire patterns and other fire investigation techniques identified it as the origin of the building fire.

switch, the owner did not notice the position of the disconnect due to its inaccessibility — and the switch was left in the on position from the previous season. This allowed the empty spa's heater and controls to become electrically energized when the circuit breaker was closed, even though the spa had no water in it.

A fire occurred a few days after the property was opened by the owner, resulting in extensive damage to the property that required teardown and rebuilding of the condo and adjacent units.

Origin

Fire investigators determined that the fire originated from the hot tub spa located on the porch of the second floor (**Figure 2**). All other sources of the fire were eliminated both through visual examination, arc mapping, and fire pattern analysis. Part of the investigation included identifying parties that had access to or involvement with the condominium unit and spa including distributors, the manufacturer, ongoing maintenance repair technicians, as well as spare parts providers. Aside from the focus on the manufacturing and repair of the spa (and associated parts), the investigation also included recent carpentry work, because the second-floor porch where the spa was situated had recently been rebuilt. All parties were afforded the opportunity to conduct a fire scene examination. With winter weather conditions approaching — and in the interest of preserving the evidence from the fire scene — the spa and all electrical components were retained by the condominium owner's expert for later analysis.

Area of Origin within Hot Tub Control Cabinet

The construction of this 15-year-old spa was of a fiberglass tub shell and a cedar enclosure that housed the spa's circulating pumps, controller, and electric heater. Additionally, closed cell polyethylene foam was used on the underside of the spa shell.

Figure 3
Spa and evidence in forensic laboratory.

Once the hot tub spa became the focus of the cause, the wiring and components of the tub that had not been rendered unidentifiable by the fire were examined and analyzed. Major components of the spa were examined for evidence of heat generation, consumption, and arcing to identify any involvement in the fire (**Figure 3**).

After major components were identified within the mass of melted foam and fiberglass, X-ray and computed tomography (CT) scanning were performed to identify features not initially visible (**Figure 4**). Examination of the heater identified electrical activity consistent with a malfunction and arcing event.

Figure 4
After debris removed, spa heater located.

Heater Design

Overheating protection in hot tub spas is accomplished by a variety of control choices, including differential pressure switches that sense water flow through the heater vessel or by water-sensing probes. The basis of this control, however, was unique in that it did not verify the presence of water with a separate control BEFORE the heater electrical element was energized, instead relying upon a thermal sensing bulb and attached capillary tubing to REACT to overheating first, causing an "over-temperature shutoff switch" to open the heater circuit.

A second feature of the control — designed to prevent the sensing bulb from cooling and then allowing the over temperature shutoff switch to re-energize the circuit and start the overheating cycle again — was to use a positive temperature coefficient (PTC) heater. This heater, if configured in accordance with a patent referenced on the heater control's enclosure, was intended to be encircled by a number of turns of capillary tubing to heat the capillary tubing and its internal fluid. This appears to have been an intentional design feature to enhance heat transfer from the PTC heater to the capillary tubing and the over-temperature control switch (**Figure 5**).

Activation of the over-temperature switch removed power from the water heater and applied power to the PTC heater. This continuous heating of the PTC would keep the over-temperature shutoff switch in the activated position and prevent the water heater from being energized until power from the control circuit was removed. Overall, however, this control scheme was problematic in that it did not prevent the water heater from being energized when water was not present. Manufacturers of electric heating elements used in spas warn against dry firing elements (even instantaneously) because this causes damage to these elements. This heater control system only provided post-over temperature "lockout" protection. For convenience to the installer, the heater control was one self-contained unit.

Arcing Damage Found

Examination of the control unit identified that the heater vessel was damaged by arcing, which burned through the vessel over a length of approximately 3 inches (**Figure 6**). No other electrical activity was found on any wiring, spa control, or component. As such, the heater was identified as the point of origin of the fire within the spa. Examination of the heater identified that the heater element was melted and damaged as a result of uncontrolled electrical application. The end of the element coinciding with the arcing through the heater vessel was missing due to consumption.

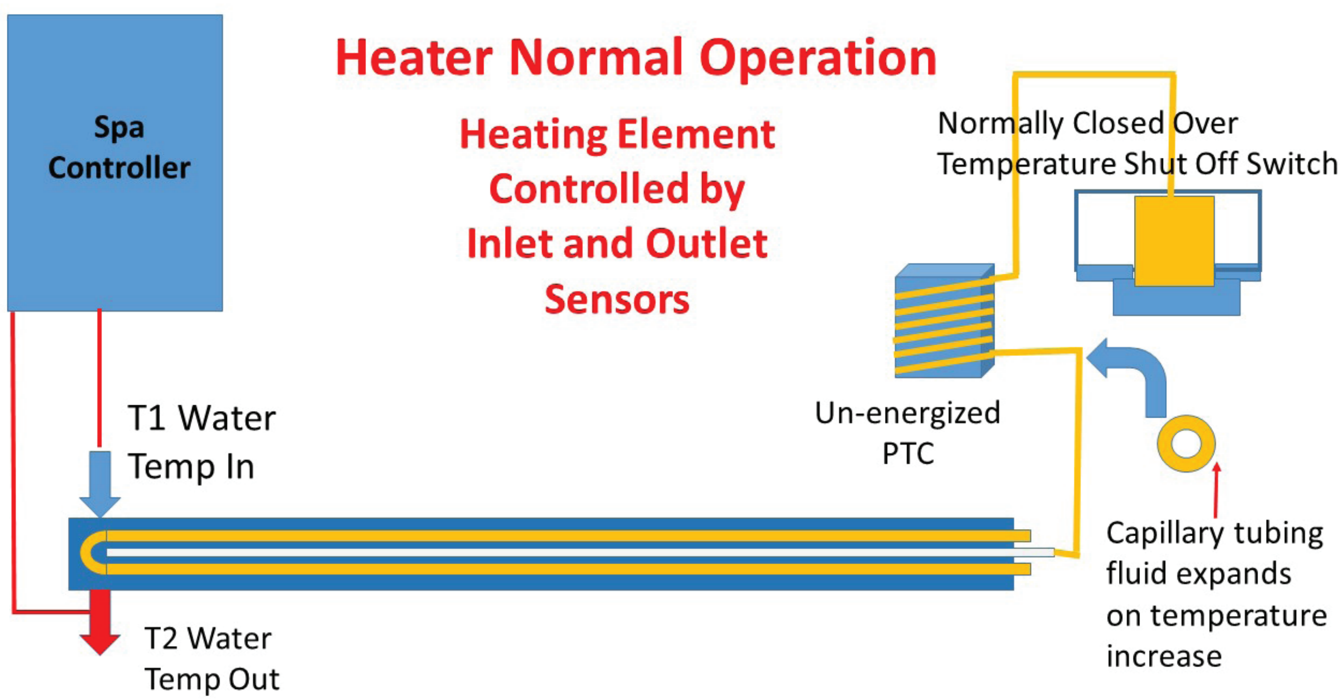

Figure 5
Drawing showing orientation of heater, sensing bulb and over-temperature shutoff switch.

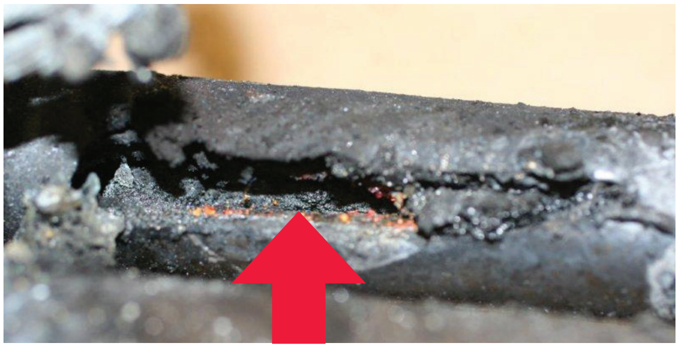

Figure 6
Arcing damage found to heater vessel.

Understanding Subject Component's Manufacturing

The first step in forensic failure analysis is understanding how a component suspected of failing normally works as well as its manufacturing features. Past experience with similar equipment can be drawn upon as well as available manufacturer's instructions and drawings. Some of this information may be unavailable or considered proprietary, causing the forensic investigator to seek other means of understanding the machine's design. However, additional information of an unfamiliar machine design can be obtained by examination, testing, and disassembly of an exemplar component as well as patent documentation.

Review of Patent

The patent (with images) for the subject heater was identified, and the features of the patented design were compared to the subject heater as well as a recently purchased exemplar heater (**Figure 7**). In comparison to the patent's Detailed Description of the Preferred Embodiment of the design, a major deviation on the subject and exemplar heaters was identified. The patent design of the overheating protection circuit and controls featured a heat generating positive temperature coefficient PTC heater that was designed to be encircled with capillary tubing, leading to the over-temperature shutoff switch.

This design would keep the over-temperature shutoff switch in the open position and prevent the heater from being energized until power was removed to prevent continuous OFF-ON cycling of the heater. Additionally, the patent design documentation was quite specific in that it directed that the PTC heater be encircled by a specific number of turns of capillary tubing, to provide a thermal coupling (as shown in **Figure 8**).

Subject Artifact Examination

In examining the artifacts that survived the fire, what became apparent was that the PTC heater, which was crucial to the over-temperature protection features of the heater's

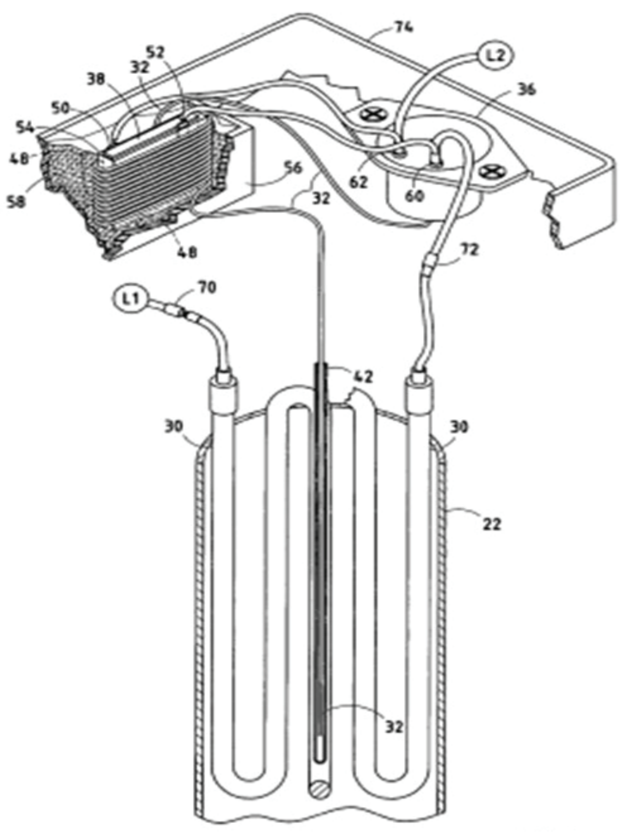

Figure 7
Drawing from heater patent filing.

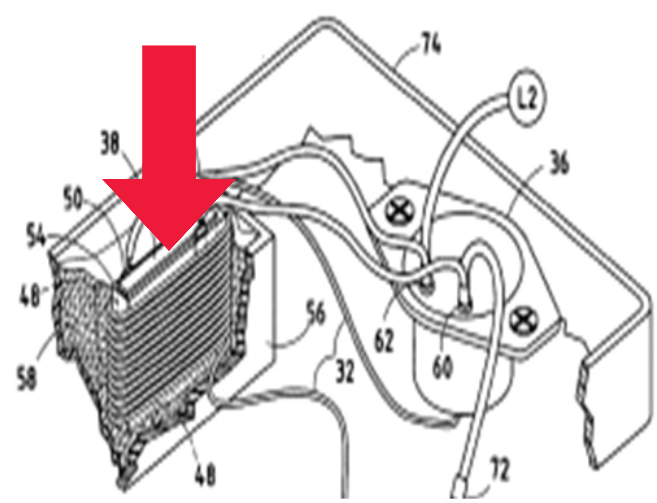

Figure 8
Number of turns as described in patent drawing.
Item 38 is the PTC with capillary tubing
wrapped around it (see red arrow).

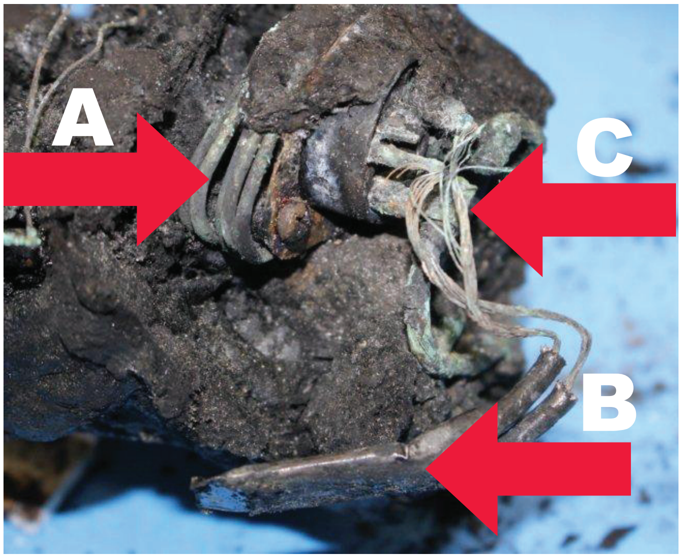

Figure 9
Over-temperature protection components of the heater as seen in fire debris: A – capillary tubing, B – PTC heater, C- Over-temperature shutoff switch.

patented design, was not encircled by capillary tubing in the manner shown in the patent documentation (**Figure 9**). Speculation was generated regarding whether this was the result of the fire. This led to further nondestructive tests, including X-ray and CT scanning examinations of the suspect components.

CT Scanning Examination

CT scanning and other means of evidence examination confirmed that the PTC heater was not encircled by the capillary tubing in the manner shown in the patent documents (**Figure 10**). Additionally, in the exemplar heater purchased, the same configuration (as the subject heater) confirmed that the capillary tubing merely passed by the PTC heater in its path between the thermal sensing bulb within the heater vessel and the over-temperature shutoff switch. The deviation from the design shown in the patent resulted in a reduction in surface area between the capillary tubing and PTC heater, which would serve to diminish heat transfer between these two components and reduce control performance and effectiveness.

Exemplar Heater Examination

In the examination of the exemplar heater, the PTC heater was a "standalone" component not encircled with capillary tubing — contrary to patent documentation (**Figure 11**).

The securing of the PTC within the control box was not affixed and was free to move within the enclosure. Furthermore, contact with the capillary tubing, if any, was minimal — with only one segment of the capillary tubing (less than an inch long) being in direct contact with the heater. This comparatively reduced surface area between the PTC heater and capillary tubing would likely cause a proportionately different change in reaction time and performance. The author opined that this deviation between the patent design and the production components may have been a cost-driven manufacturing alteration.

Underwriters Laboratory Testing

The heater received the UL symbol for approval per UL 1563[1] and 1261[2]. Recommendations were made to attorneys in the case to obtain the actual prototype heaters and UL test reports to determine if the UL test configuration was the same as the subject heater, though the case

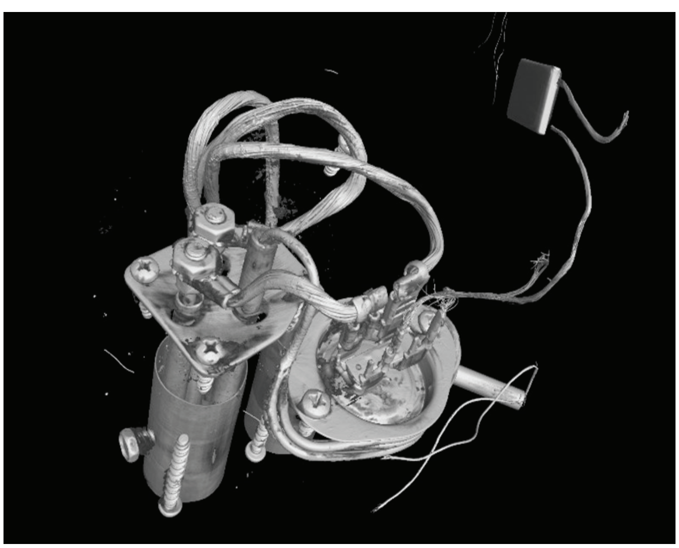

Figure 10
CT scan showing PTC heater and capillary tubing.

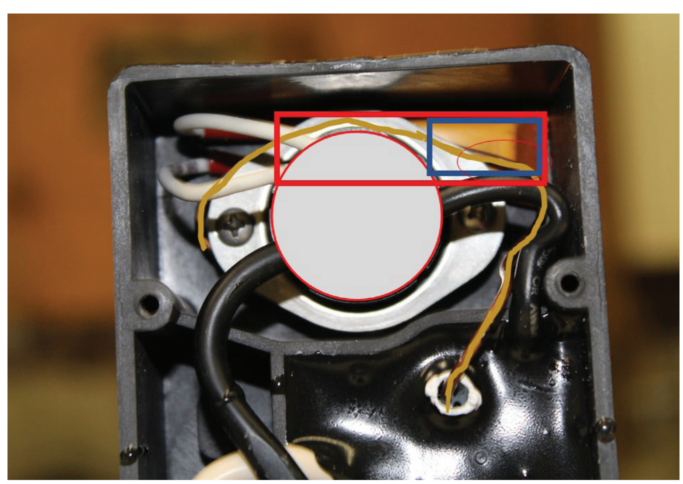

Figure 11
Examining exemplar heater to locate placement of PTC and other components. Blue rectangle shows placement of PTC behind switch. Yellow line depicts capillary tubing NOT encircled around PTC.

settled before this occurred.

Testing the Hypothesis

Exemplar testing of an identical heater was performed by applying thermocouples to the heater barrel and thermal sensing bulb in a test duplicating the conditions of the heater from the fire.

As opposed to a lockout condition of the over-temperature switch occurring as intended, cyclic heating and cooling resulted, allowing the heating element to be continuously and repeatedly exposed to heating and cooling cycles. The resulting temperatures (in the exemplar testing) were higher than what would have been experienced during normal operation (**Figure 12**). Nevertheless, this repeated short cycling of the over-temperature shutoff switch would induce accelerated operational cycles, leading to more rapid switch failure and potential overheating and arc welding of the contacts. Additionally, the continuous heating and cooling could have the effect of inducing heater element damage and thermal sensing bulb leakage, which would make this position of the heater incapable of transmitting an increased internal pressure due to increased temperature within the heater.

Failure of the sensing bulb, which is attached to the capillary tubing, would then prevent increases in capillary tubing fluid pressure from being transmitted to the

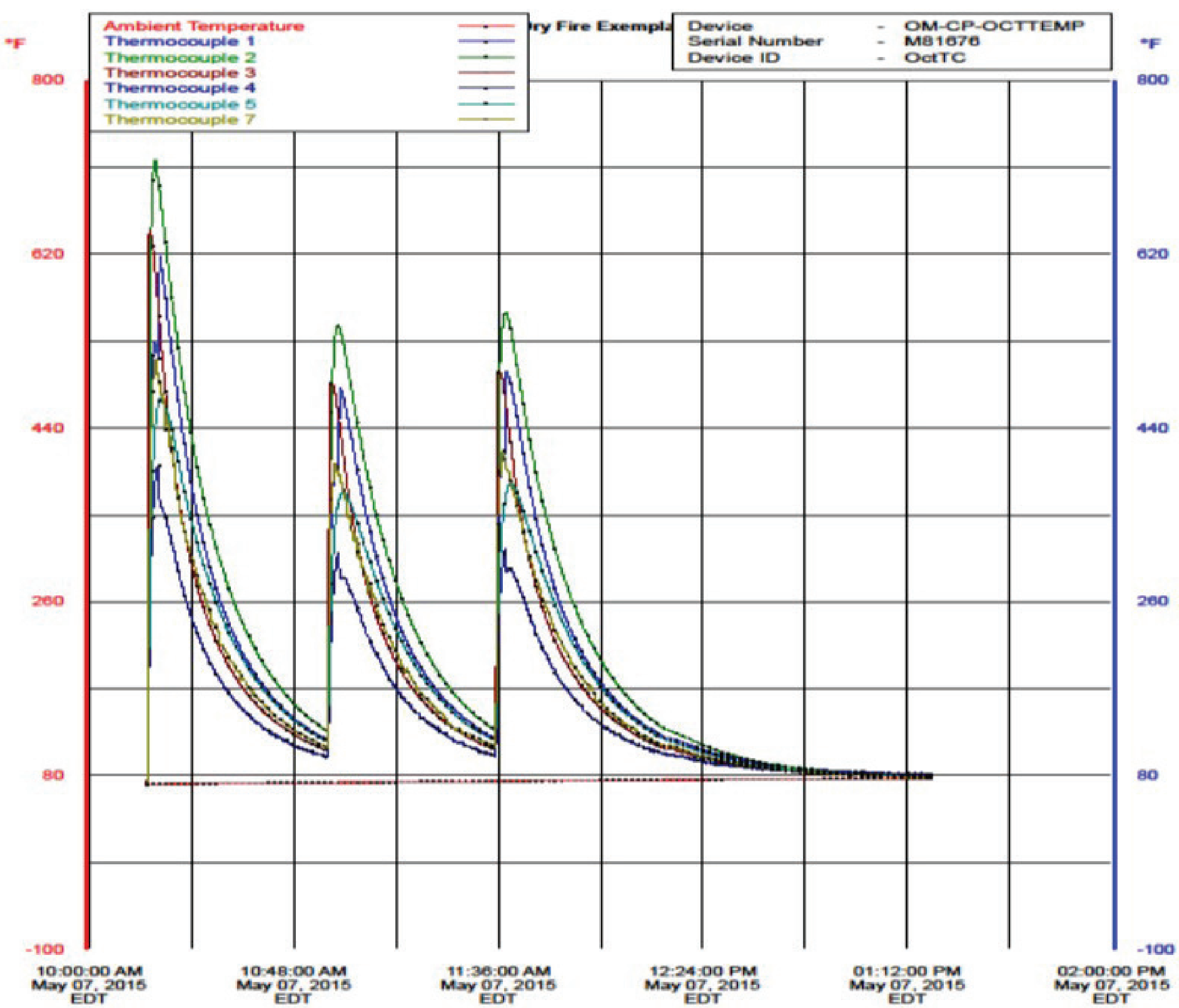

Figure 12
Temperature data logging of heater in operation.

Figure 13
Heater arcing due to overheating damage.
https://youtu.be/KJ8sIBma22o

over-temperature shutoff switch, allowing a continuously energized heater element to occur.

Exemplar testing of an unsubmerged heater element resulted in arcing, flames, and molten steel, all of which would be easily capable of igniting combustibles within the control cabinets, such as the wooden cabinetry and instruction manual typically left in this area of the spa (**Figure 13**).

Conclusion

This fire investigation exemplifies the analysis of the larger "macro" view of the fire scene in identifying the area of origin within the building to the "micro" view of the fire occurring not only within the appliance but also within the appliance's controls. The joint cooperation of the fire investigator and supporting engineer together identified the origin and cause of the fire by further refining the fire's point of origin within the appliance and then investigating component design and manufactured characteristics to determine the cause.

Despite a lack of manufacturer-provided documentation, including manufacturing drawings (which were requested but not received), the patented design of the heater was identified by using exemplar controls and components as well as the control's patent descriptions and images. This information was then compared to the actual manufacturing configuration of the recovered subject heater as well as an exemplar unit. It was also noted that the use of this heater design was discontinued by the manufacturer.

Once the patented design as well as the "as-built" design (actual conditions of how the control was manufactured) were established, testing of an exemplar heater was able to fairly and accurately represent a condition of failure consistent with the fire patterns and conditions of the heater components involved in the fire. It was also noted that this heater was listed by UL. Recommendations were given to attorneys in the case to obtain the heater's design drawings and reports from UL testing to determine the configuration of the heater that was tested. However, after depositions of experts and investigators, the case settled, and detailed testing conditions from the UL testing were not produced.

Based upon the investigation it is the author's opinion that had the heater been built consistent to the patent, with the capillary tubing "wrapped" around the PTC heater, the control would have been more responsive to low water conditions and performed more reliably. The choice of the manufacturer to deviate from the patent design defeated the intended interaction of the heat-generating PTC component and capillary thermal sensing element, which was a key element of the patent, and which led to the fire. The reason for the design change is unknown, however the simplification of the design was likely less labor-intensive to manufacture and as such likely less expensive. As such, regardless as to why the design specified in the patent differed from how the control was actually built, the final design was one conducive to heater element overheating and failure.

Acknowledgements

Victor DaCosta, Electrical Fire Investigator
Tom Zarek

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