Identifying Thresholds for Observational Indicators of Enhanced Sonic Deposition on Smoke Alarms in Forensic Investigations

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Abstract. The activation status of a smoke alarm in a fire becomes a central question in forensic fire investigations when there are injuries or deaths. Forensic techniques have been developed to answer this question through the evaluation of the presence of enhanced soot deposition on specific locations of a smoke alarm. Testing was conducted to evaluate the thresholds where these observational indicators may be obscured or destroyed. Fifty-four smoke alarms were exposed to simulated fire conditions to create enhanced soot deposition observational indicators. A series of post exposure tests were conducted to determine the threshold(s) of thermal damage to determine when those indicators begin to be obscured. All powered smoke alarms presented observational indicators in locations like those identified in previous research, as well as four additional locations for this smoke alarm geometry. Enhanced soot deposition indicators were found to persist in most cases when the alarm was exposed to high temperatures (up to 325°C to 450°C), when the alarms were exposed to high temperatures and dropped to a floor surface, and when the alarm was exposed to carpet contamination.

Keywords: Sonic deposition, Acoustic agglomeration, Smoke alarm, Smoke detector, Soot deposition, Fire investigation

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1. Background

Since the early 1970’s, millions of people have come to rely upon the residential smoke alarm as their primary fire safety resource. Both 9-V battery and 120-V AC powered, alarms have been installed in most homes and residential occupancies. These devices have served as early warning to fires resulting in thousands of lives saved over the past 50 years in the United States [1]. The National Fire Protection Association (NFPA) indicates that smoke alarms were present in approximately 74% of the reported home fires in 2014–2018 [1].

The NFPA reports that almost three out of five home fire deaths were caused by fires in properties with no smoke alarms or smoke alarms that failed to operate [1]. When someone is injured or killed during a fire incident, it is often of great importance to know whether a particular smoke alarm operated during a fire event. Forensic fire investigation techniques have been developed to examine this question [2–9]. The techniques developed have primarily focused on the visible observation of enhanced soot deposition (ESD) on various locations of the smoke alarm.

1.1. Enhanced Soot Deposition (ESD) on Smoke Alarms

NFPA 921 defines smoke as the “airborne solid and liquid particulates and gases evolved when a material undergoes pyrolysis or combustion, together with a quantity of air that is entrained or otherwise mixed into the mass.” [8] During incomplete combustion, soot particulates are produced that can enter a smoke alarm and initiate an alarm. When this occurs a sonic field from the activated horn produces pressure waves, which increase the brownian motion and acoustic excitation of any aerosols within the field, causing larger agglomerates (soot particles binding together) [3]. The resultant pressure waves from the pulsed flow in and out of the smoke alarm horn opening have been proven to increase turbulence and create eddies locally on the external face of smoke alarms and internal faces of the horn enclosures [3–6]. This creates localized areas of ESD along the exterior cover (ec), interior cover (ic), the vertical faces of the cover opening (ecv, icv), exterior and interior areas of the horn enclosure (eh, ih), and vertical faces of the horn enclosure (ehv), and the disc themselves (Figs. 3–4) [2–9].

The first series of testing that confirmed these observational indicators was studied by Worrell et al., which examined the physics of the pulsed flow phenomena in sounding alarms [3, 4]. These studies concluded that “the presence of locally enhanced deposition and soot agglomerates on the main central opening of the plastic horn enclosure was a strong indicator the detector sounded” [3]. Kennedy et al. further studied this phenomenon, supporting that the “presence of soot agglomeration is a strong indicator that a particular smoke alarm activated in a fire,” and that the “absence of soot agglomeration products on a fire exposed smoke alarm is evidence that the alarm did not sound, providing that the atmosphere to which the smoke alarm was exposed to was sufficiently sooty” [5]. In addition to supporting Worrell’s work, a single test was conducted to determine whether elevated temperatures would affect the persistence of ESD. This test
determined that ESD can persist when exposed to 433°F (223°C) for 30 min. In 2019, research was conducted to determine what temperatures would result in thermally-induced failures of smoke alarms, which found that sound signals decreased at component temperatures of 56°C and total failure to sound at 144°C [6].

Phelan et al. [7, 8] confirmed the findings of previous studies and added metrics for evaluation. A hierarchy of observations were identified to include a rank order for ESD locations for positive identification of alarm activation and positive indication that the alarm did not sound (Fig. 1) [7, 8]. Phelan noted that the central horn enclosure opening would have soot deposited in a larger band surrounding the opening on the order of approximately 0.5 mm in thickness. A decision tree or heuristic based on the observational indicators was created and tested for reliability and validity [8]. The heuristic was shown to be both reliable and valid in a blind study resulting in no false-positives or false-negatives. NFPA 921 has identified that this is the correct methodology for evaluating smoke alarms to determine sounding or not sounding [9]. The heuristic begins by asking two simple questions prior to evaluating the smoke alarm: Is there insufficient deposition of combustion products; and is thermal damage to the alarm enough to alter observational indicators? If the answer is yes to either question the heuristic directs the analyst to an indeterminate conclusion, otherwise the alarm is evaluated. The results of the blind study using the decision tree “clearly validate the utility and accuracy of the heuristics developed by Phelan et al.” [8].

There is limited guidance and research on objectively answering the first two questions, specifically the thermal damage question. The most important question for reliability of the heuristic is what threshold(s) exist to identify when an alarm has experienced too much thermal damage to alter the observational indicators. Mealy and Gottuk identified that “too much thermal damage to obscure observational indicators” would consist of “melt/flow of the plastic in the vicinity of the horn chamber”, and “extensive thermal deformation observed in the immediate

![Figure 1. Smoke alarm geometry-reference dots and labeling before testing.](image-url)
vicinity of the horn chamber” [8]. The outer covers and bases of modern smoke alarms are constructed of thermoplastics. They are capable of melting and deforming at elevated temperatures. UL 217 Sect. 62.2 sets the maximum temperature to which smoke alarm thermoplastic components must maintain their shapes at 90°C (194°F) [11]. Previous testing disclosed an initial softening temperatures of smoke alarm cover at 93°C (199°F), initial softening of the plastic horn compartment at 121°C (250°F), and smoke sensing chamber plastic components at 177°C (351°F) [5].

Havey et al. conducted a study to evaluate the influence that a variety of handling procedures post-fire of the smoke alarm may have on the evidentiary value [10]. Their work first exposed sixty alarms to smoke from a variety of fuels burning (i.e. smoldering wood, flaming toluene-heptane, smoldering polyurethane foam, and flaming polyurethane “PU” foam). These alarms were then subjected to a variety of post-test handling actions (e.g. running water, canned smoke, standing water, pushing the test button) to determine if any of these actions influenced the evidentiary value of the ESD. Their conclusions of what post-test action influenced the ESD were influenced by what fuel had been used in creating the ESD. This is partially due to their finding that smoke from smoldering wood and smoldering PU foam fueled fire “deposited a sticky resin type of soot on the horn openings,” while the flaming PU foam and flaming pool fire “deposited a light soot on the horn openings” [10]. Their study concluded that the sticky resin type soot from the smoldering fires was more difficult to remove with a post-test action than was the lighter soot. The authors employed an objective evaluation system that ranked the degree to which soot was removed from the alarm horns: 0 (no soot removed), 1 (some soot removed), and 2 (all soot removed) based on visual inspection.

In this study a series of tests were performed to investigate thermal damage thresholds for observational indicators of ESD. The tests were designed to simulate common forms of damage sustained in fire events. Smoke alarms were preconditioned by the same methods used by Havey, et al. [10], and then subjected to physical and thermal effects to determine when observational indicators were obscured.

2. Experiments

Thirty-six (36) powered and eighteen (18) non-powered smoke alarms were conditioned using methods similar to Havey et al. [10]. Alarms were exposed to sooty environments for at least 20 min: six powered and six unpowered in smoldering (smoldering PU foam ~ 20 min exposure); 24 powered and five unpowered in smoldering transitioning to flaming (smoldering PU foam followed by flaming PU foam additional ~ 10 min exposure); and flaming only (kerosene pool fire ~ 20 min exposure). All smoke alarms used were ionization types powered by a 9-V battery. All smoke alarms tested were of similar construction with a separate horn enclosure detached from the exterior cover with the same dimensions. The horn for this smoke alarm geometry is a small diameter stainless steel disc that is
mounted into a thermoplastic compartment, known as the horn enclosure. The sounder for this alarm was a piezo-electric type that produced frequencies up to 3000–4000 Hz with a volume of ~ 85 dB at 10 feet.

The conditioned alarms were documented and evaluated to answer the first threshold question: is there sufficient soot deposition. Macroscopic images were taken with an Olympus TG6 and microscopic images were captured using an Ash Inspex III Digital Imaging System which included digital measurements of soot disposition. The alarms were individually labeled as Powered (P) or Non-Powered (NP) followed by a sequential number. A template was used to add five dots on the top surface of the horn enclosure, used as a reference for deformation of the horn enclosure (Fig. 1). Post conditioning, 100% of the powered smoke alarms self-actuated and exhibited all observational ESD indicators identified in previous studies [2–5, 8, 10], and no observational indicators were observed in non-powered alarms, consistent with other research (Fig. 2).

2.1. Thermal Damage Test

A bench scale muffle furnace was used to expose components of the smoke alarm cover, PCB, and horn to elevated temperatures. The two thresholds identified by Mealy [8] evaluated by this series of tests were the deformation and discoloration of ESD-witnessing components. Alarm orientation was identified as critical to deformation effects, therefore, each component was subjected to heating in one of three orientations: face-down (simulating ceiling mount), face up (simulating heating post-drop), and horizontal (simulating wall mount). The thermal insult was progressively increased (10°C/min) from 20°C until visible ESD indicators were obscured. Individual components were tested to fully monitor deformation and discoloration effects (Fig. 3).

Figure 2. Experimental setup–pre-conditioning tests: smoldering and flaming tests.
2.2. Thermally Induced Drop Test

In this test, alarms were subjected to heat until the alarm fell from its mount. The remains of the alarms were then collected and evaluated for ESD identifier persistence. The thresholds of damage evaluated by this test were deformation due to dropping from installation height and obscuration of effects by damage and contamination. Smoke alarms were ceiling-mounted with manufacturer-included mounting brackets at a height of 2.44 m in the center of a 3.7 m by 3.7 m room (Fig. 3). Thermal insult was provided by a propane radiant heater perpendicular to the ceiling, clear of the drop path. A Gardon heat flux gauge configured for radiant and convective collection was used to calibrate the distance between the heater and the alarms to expose them to 20 kW/m². Flooring evaluated was carpeting with padding, and plywood sheeting to simulate wood flooring. Orientation of components and distance from center were recorded (Fig. 3).

2.3. Thermal Damage and Carpet Exposure Test

A series of tests were conducted to simulate a smoke alarm falling from its mount and resting on top of a section of carpet. These tests were conducted by first exposing the alarms to sufficiently high temperatures (> 300°C) in a furnace to replicate softening of the plastic with minor discoloration, and then the alarms were placed on top of a section of carpet in the furnace to replicate a smoke alarm falling onto the carpet after being heated. The carpet used was medium thickness polypropylene pile with latex backing and no underlay. Four powered
and four non-powered smoke alarms were increased to a temperature of approximately 315°C (from 20°C, 10°C/min) and then the horn enclosure was flipped over and exposed to a piece of carpet (Fig. 3).

2.4. Evaluation Methods
A similar evaluation system to Havey et al. [10] was employed within this study to evaluate change(s) to the initial observation. Each indicator location was documented after the alarms were conditioned and then again after the thermal tests, both powered and non-powered. A numerical ranking system (0–2) was employed to identify changes or obscuration at these locations. A zero (0) was assigned for no change to the observation, a one (1) for some loss to the observation, and a two (2) for those observations that could no longer be evaluated or obscured due to the extent of deformation or discoloration.

3. Observations and Results
Each alarm was examined post-test to identify the changes to observational ESD indicators in the locations identified in previous studies [8]. These locations are as follows, with location identification indicators used throughout the rest of this paper: external cover grillwork (ec), external cover vertical faces (ecv), interior cover grillwork (ic), interior cover vertical faces (icv), horn enclosure exterior (eh), horn enclosure exterior vertical faces (ehv), and horn enclosure internal (ih) (Figs. 4, 5, Table 2).

Figure 4. Location of ESD Indicators found on cover and horn enclosure.
Additionally, four previously unreported observational ESD indicators were identified (Figs. 6, 7, 8, 9, 10, Table 2). ESD was found located where the horn enclosure rests on top of the external frame of the smoke alarm (he). ESD was identified along the bottom of the disc as a thin band around the circumference of the disc (ud) when exposed to smoldering. ESD was also identified along the underside (ude) and top of the disc edge (tde). These newly discovered indicators are incorporated into this study and evaluated for post-testing persistence. Table 1

Figure 5. Location of ESD Indicators found on horn enclosure and disc.

Figure 6. Comparison of powered (P-right) and non-powered (NP-left) smoke alarms exposed to flaming kerosene fuel source—ESD Indicator between horn and smoke alarm internal cover (he) is present on the powered (right) but not the non-powered (left).
displays ESD indicators of every conditioned smoke alarm pre-test, including the four newly identified indicators.

The non-sounding (Non-Powered) alarms did not have any ESD observational indicators present in any of the tests (Table 2). All the sounding (Powered) alarms had ESD indicators present (Table 2, Figs. 6, 7, 8, 9, 10). The most obvious locations of ESD were the vertical faces of the cover ($icv$, $ecv$), center horn opening ($eh$, $ih$), vertical faces of the horn opening ($ehv$), and metal disc ($ude$, $tde$, $ud$). Several of the NP smoke alarms did have deposition of soot observed, however, none had soot present in significant density or in patterns identifiable with the published work. The soot deposition in the NP alarms was more sporadic and driven by gravitational forces, not by acoustic agglomeration. The ESD patterns, both the presence of soot and density, were able to reliably be evaluated and confirm
the use of the standard methodology for accurately concluding whether an alarm sounded or not.

The smoldering polyurethane foam generated smoke that left a sticky resin with a brownish-orange discoloration (Fig. 11). The flaming polyurethane foam and kerosene pool fire would produce a light and dry soot deposition that was black (Fig. 12). Thus, the ESD patterns for alarms exposed to a smoldering fuel source had a light-brown or orange color while the ESD patterns for alarms exposed to a flaming kerosene fuel source had a black color (Figs. 11, 12).

The ESD extended from the openings of the exterior cover (eh) grillwork between 0.1 and 0.8 mm. The center hole of the horn enclosure (eh, ih) consistently had the most significant ESD pattern extending between 0.2 and 1.5 mm away from the opening. The other, smaller holes in the horn enclosure, also had ESD extending between 0.05 and 0.7 mm away from the opening. The underside of the disc (ud) had an ESD pattern extending between 1 and 3.5 mm from the
disc edge. Near the edge of the disc, both on the underside and top of the disc (ude, tde), there was an ESD pattern that extended 0.15 to 0.5 mm from the edge.

Consistent with other research in this area, no ESD observational indicators were identified for the NP smoke alarms, including the newer observational indicators identified for this geometry. All ESD observational indicators that had been identified in previous studies [2–5, 8, 10] were identified on 100% of the powered smoke alarms. The four new observational indicators (Table 2) were found on all the smoke alarms (100%) that were conditioned with a smoldering source. The identification of a thin band wrapping around the circumference of the underside of the disc (ud) was never identified (0%) on powered smoke alarms exposed to a flaming kerosene fuel source. ESD was also found in 5 out of 6 (83.3%) powered smoke alarms along the top edge of the disc (tde) of those alarms exposed to a flaming kerosene fuel source.

3.1. Results of Thermal Damage Tests

Tests were conducted to determine the temperature at which different components began to deform and discolor, as well as the influence elevated temperatures had on the ESD patterns. The external cover, horn, and disc were all evaluated through the thermal damage tests.

Covers from powered and non-powered alarms conditioned with smoldering PU foam, flaming kerosene and PU foam were evaluated in the muffle furnace. Deformation began at 160°C (± 5°C), followed by yellow/brown discoloration at 260°C (± 15°C). All structural form is lost at 290°C (± 10°C) and discolored to a dark brown/black at 335°C (± 15°C) (Figs. 15, 16). As long as the cover deformation does not cover the ESD location, the observational indicator persist until ~ 350°C (Figs. 13, 14). Table 2 summarizes the findings for changes to initial observations. Gravity had a greater influence on obscuring the initial observation at the grillwork for the horizontal orientation at lower temperatures, which influenced the

| Test | (1) ec & ecv | (2) ic & icv | (3) eh & ehv | (4) ih | (5) he* | (6) ude* | (7) ude* | (8) tde* |
|------|-------------|-------------|-------------|-------|--------|---------|---------|---------|
| NP S (N = 6) | 0% | 0% | 0% | 0% | 0% | 0% | 0% | 0% |
| NP B (N = 6) | 0% | 0% | 0% | 0% | 0% | 0% | 0% | 0% |
| NP F (N = 6) | 0% | 0% | 0% | 0% | 0% | 0% | 0% | 0% |
| P S (N = 6) | 100% | 100% | 100% | 100% | 100% | 100% | 100% | 100% |
| P B (N = 19) | 100% | 100% | 100% | 100% | 100% | 100% | 100% | 100% |
| P F (N = 6) | 100% | 100% | 100% | 100% | 100% | 0% | 100% | 83.3% |

ec = exterior cover, ecv = exterior cover vertical face, ic = interior cover, icv = interior cover vertical faces, eh = exterior horn, ehv = exterior horn vertical faces, ih = internal horn, he = between horn and smoke alarm internal cover, ud = underside of disc, ude = under disc edge, tde = top disc edge, S smoldering experiments, F flaming experiments, B both exposures smoldering then flaming experiments

*ESD observational indicators identified in this study

Table 1

Enhanced Soot Deposition (ESD) Observational Indicators Results
average change to the initial observations. No changes were identified to the initial observation at temperatures up to 250°C ($NP = 0.0$, $P = 0.0$), discoloration and deformation begins to influence the initial observations at approximately 300°C ($NP = 1.17$, $P = 1.07$), and complete loss of initial observations were found to occur at 350°C ($NP = 2.0$, $P = 2.0$).

Printed circuit boards containing the disc and horn enclosures were exposed to elevated temperatures in the muffle furnace. Seven tests (two non-powered, seven powered) were conducted for each studied orientation: face-down, face-up, and horizontal. At 120°C ($±5^\circ$C) the first signs of deformation appear with significant deformation occurring at 155°C ($±5^\circ$C). Between 175°C and 200°C horn enclosures on PCBs mounted face-down (ceiling orientation) would deform and dislodge from the PCB onto the furnace floor. Color change transitions from white and off-white, to light brown between 250°C and 325°C, progressing to black between 325°C and 375°C (Figs. 15, 16, 17). ESD visual patterns persisted in face-

### Table 2

Results of Changes to Initial Observations for Smoke Alarm Cover

| Orientation | Test | Change to initial observations |
|-------------|------|--------------------------------|
|             |      | 250°C | 300°C | 350°C | 250°C | 300°C | 350°C |
| Face up     | NP 1 | 0     | 1     | 2     | 0     | 1     | 2     |
|             | NP 4 | 0     | 1     | 2     | 0     | 1     | 2     |
| Horizontal  | NP 2 | 0     | 1     | 2     | 0     | 1     | 2     |
|             | NP 12| 0     | 2     | 2     | 0     | 2     | 2     |
| Face down   | NP 3 | 0     | 1     | 2     | 0     | 1     | 2     |
|             | NP 7 | 0     | 1     | 2     | 0     | 1     | 2     |
| NP Avg      |      | 0.0   | 1.17  | 2.0   | 0.0   | 1.17  | 2.0   |
| Face up     | P 1  | 0     | 1     | 2     | 0     | 1     | 2     |
|             | P 2  | 0     | 1     | 2     | 0     | 1     | 2     |
|             | P 16 | 0     | 1     | 2     | 0     | 1     | 2     |
|             | P 23 | 0     | 1     | 2     | 0     | 1     | 2     |
|             | P 26 | 0     | 1     | 2     | 0     | 1     | 2     |
| Horizontal  | P 7  | 0     | 1     | 2     | 0     | 1     | 2     |
|             | P 17 | 0     | 2     | 2     | 0     | 2     | 2     |
|             | P 20 | 0     | 2     | 2     | 0     | 2     | 2     |
|             | P 24 | 0     | 1     | 2     | 0     | 1     | 2     |
|             | P 27 | 0     | 1     | 2     | 0     | 1     | 2     |
| Face down   | P 3  | 0     | 1     | 2     | 0     | 1     | 2     |
|             | P 4  | 0     | 1     | 2     | 0     | 1     | 2     |
|             | P 22 | 0     | 1     | 2     | 0     | 1     | 2     |
|             | P 25 | 0     | 1     | 2     | 0     | 1     | 2     |
|             | P 28 | 0     | 0     | 2     | 0     | 0     | 2     |
| PAvg        |      | 0.0   | 1.07  | 2.0   | 0.0   | 1.07  | 2.0   |

0 is no change to the observation, 1 for some loss to the observation, and 2 is for those observations that could no longer be evaluated or obscured due to the extent of deformation or discoloration.
up horn enclosures until the color change conceals the ESD indicator, though a texture difference remains. Horizontally-mounted horn enclosures would deform to obscure the smaller holes though ESD indicators persisted on the large center hole. Table 3 summarizes the findings of changes to initial observations for the

![Figure 11. Comparison of powered (P) and non-powered (NP) smoke alarm horn (eh, ehv, ih) exposed to a smoldering PU foam (S) source.](image)

![Figure 12. Comparison of powered (P) and non-powered (NP) smoke alarm horn (eh, ehv, ih) exposed to a flaming kerosene pool fire (F) source.](image)

up horn enclosures until the color change conceals the ESD indicator, though a texture difference remains. Horizontally-mounted horn enclosures would deform to obscure the smaller holes though ESD indicators persisted on the large center hole. Table 3 summarizes the findings of changes to initial observations for the
horn enclosures exposed to thermal damage. No changes were identified to the initial observation at temperatures up to 300°C ($\bar{NP} = 0.0$, $\bar{P} = 0.0$), discoloration and deformation begins to influence the initial observations at approximately 350°C ($\bar{NP} = 1.0$, $\bar{P} = 1.0$), and complete loss of initial observations were found to occur at 400°C ($\bar{NP} = 2.0$, $\bar{P} = 2.0$). In all cases the strongest influence upon the non-metal components was orientation to gravity.

The discs were removed and independently evaluated. All ESD indicators noted prior to heating persisted. In alarms exposed to smoldering PU foam, the ring had darkened along the underside of the disc ($ud$) for the entire circumference, as well as the top and underside edge of the disc ($tde$, $ude$). When exposed to higher temperatures the effect intensified until reaching temperatures between 450°C and 500°C where the indicator began to crack (Figs. 18, 19). Higher temperatures cause further discoloration and cracking of the pattern, obscuring the indicator (Fig. 19). Table 4 summarizes the changes to the initial observations for the smoke alarm disc. No changes were identified to the initial observation at temperatures up to 350°C ($\bar{NP} = 0.0$, $\bar{P} = 0.0$), discoloration begins to influence the initial observations at approximately 450°C with the most influence occurring to the horizontal orientation where plastic adhered to the top disc edge most commonly.

Figure 13. Elevated temperature tests of smoke alarm cover.
Figure 14. Elevated temperature tests of smoke alarm cover with ESD indicators.

Figure 15. Elevated temperature tests of smoke alarm horn conditioned with a smoldering PU foam source that transitioned to flaming—mounted facing upwards.
and complete loss of initial observations were found to occur at 550°C. (\( \overline{NP} = 2.0, \overline{P} = 2.0 \)).

**Figure 16.** Elevated temperature tests of smoke alarm horn conditioned with a smoldering PU foam source that transitioned to flaming—mounted vertically to reflect smoke alarm mounted to a wall.

**Figure 17.** Elevated temperature tests of smoke alarm horn conditioned with a flaming kerosene pool fire source—mounted facing upwards.

(ud: \( \overline{NP} = 1.0, \overline{P} = 1.2 \); ude: \( \overline{NP} = 1.0, \overline{P} = 1.33 \), tde: \( \overline{NP} = 1.33, \overline{P} = 1.53 \)), and complete loss of initial observations were found to occur at 550°C (\( \overline{NP} = 2.0, \overline{P} = 2.0 \)).
3.2. Results of Thermally Induced Drop Tests

Eight powered and eight non-powered pre-conditioned alarms were mounted to a ceiling and exposed to radiant heat. The alarms were re-evaluated after dropping for ESD persistence, using the same metrics used by Havey et al. [10]. Each indicator for each alarm is noted in Table 5 (Fig. 20).

Table 5 summarizes the changes found to the initial observations. No changes were identified to the initial observation on the non-powered smoke alarms to the exterior horn, exterior horn vertical face, interior horn, underside of the disc, and underside and top side of the disc edge ($N_P = 0.0$). Influencing the statistics was a single non-powered smoke alarm cover which was thermally damaged beyond evaluation. Thermal damage to one powered smoke alarm obscured all observations. If the complete destruction of an alarm did not occur, there were locations that survived the thermal insult and drop test. In all cases, orientation to gravity

| Orientation  | Test | Change to initial observations |
|--------------|------|-------------------------------|
| Face up      | NP 1 | 0 1 2                         |
|              | NP 4 | 0 1 2                         |
| Horizontal   | NP 2 | 0 1 2                         |
|              | NP 12| 0 1 2                         |
| Face down    | NP 3 | 0 1 2                         |
|              | NP 7 | 0 1 2                         |
| NP Avg       | 0.0  | 1.0 2                         |
| Face up      | P 1  | 0 1 2                         |
|              | P 2  | 0 1 2                         |
|              | P 16 | 0 1 2                         |
|              | P 23 | 0 1 2                         |
|              | P 26 | 0 1 2                         |
| Horizontal   | P 7  | 0 1 2                         |
|              | P 17 | 0 1 2                         |
|              | P 20 | 0 1 2                         |
|              | P 24 | 0 1 2                         |
|              | P 27 | 0 1 2                         |
| Face down    | P 3  | 0 1 2                         |
|              | P 4  | 0 1 2                         |
|              | P 22 | 0 1 2                         |
|              | P 25 | 0 1 2                         |
|              | P 28 | 0 1 2                         |
| P Avg        | 0.0  | 1.0 2                         |

0 is no change to the observation, 1 for some loss to the observation, and 2 is for those observations that could no longer be evaluated or obscured due to the extent of deformation or discoloration

### Table 3

| Orientation | Test | (3) $eh$ & $ehv$ | (4) $ih$ |
|-------------|------|-----------------|----------|
|              | 300°C | 350°C | 400°C | 300°C | 350°C | 400°C |
| Face up      | NP 1  | 0     | 1    | 2     | 0     | 1    | 2     |
|              | NP 4  | 0     | 1    | 2     | 0     | 1    | 2     |
| Horizontal   | NP 2  | 0     | 1    | 2     | 0     | 1    | 2     |
|              | NP 12 | 0     | 1    | 2     | 0     | 1    | 2     |
| Face down    | NP 3  | 0     | 1    | 2     | 0     | 1    | 2     |
|              | NP 7  | 0     | 1    | 2     | 0     | 1    | 2     |
| NP Avg       | 0.0   | 1.0   | 2.0  | 0.0   | 1.0   | 2.0   |
| Face up      | P 1   | 0     | 1    | 2     | 0     | 1    | 2     |
|              | P 2   | 0     | 1    | 2     | 0     | 1    | 2     |
|              | P 16  | 0     | 1    | 2     | 0     | 1    | 2     |
|              | P 23  | 0     | 1    | 2     | 0     | 1    | 2     |
|              | P 26  | 0     | 1    | 2     | 0     | 1    | 2     |
| Horizontal   | P 7   | 0     | 1    | 2     | 0     | 1    | 2     |
|              | P 17  | 0     | 1    | 2     | 0     | 1    | 2     |
|              | P 20  | 0     | 1    | 2     | 0     | 1    | 2     |
|              | P 24  | 0     | 1    | 2     | 0     | 1    | 2     |
|              | P 27  | 0     | 1    | 2     | 0     | 1    | 2     |
| Face down    | P 3   | 0     | 1    | 2     | 0     | 1    | 2     |
|              | P 4   | 0     | 1    | 2     | 0     | 1    | 2     |
|              | P 22  | 0     | 1    | 2     | 0     | 1    | 2     |
|              | P 25  | 0     | 1    | 2     | 0     | 1    | 2     |
|              | P 28  | 0     | 1    | 2     | 0     | 1    | 2     |
| P Avg        | 0.0   | 1.0   | 2.0  | 0.0   | 1.0   | 2.0   |

3.2. Results of Thermally Induced Drop Tests

Eight powered and eight non-powered pre-conditioned alarms were mounted to a ceiling and exposed to radiant heat. The alarms were re-evaluated after dropping for ESD persistence, using the same metrics used by Havey et al. [10]. Each indicator for each alarm is noted in Table 5 (Fig. 20).

Table 5 summarizes the changes found to the initial observations. No changes were identified to the initial observation on the non-powered smoke alarms to the exterior horn, exterior horn vertical face, interior horn, underside of the disc, and underside and top side of the disc edge ($N_P = 0.0$). Influencing the statistics was a single non-powered smoke alarm cover which was thermally damaged beyond evaluation. Thermal damage to one powered smoke alarm obscured all observations. If the complete destruction of an alarm did not occur, there were locations that survived the thermal insult and drop test. In all cases, orientation to gravity
had the largest effect on the survivability of indicators sites. Gravity influenced the
direction of flow for deformation effects as well as the severity of post-impact
deformation.

Figure 18. Elevated temperature tests of smoke alarm disc conditioned with a smoldering PU foam source that transitioned to flaming: underside of the disc after conditioning without heating compared to underside of disc when heated to 315°C.

Figure 19. Thermal tests of smoke alarm disc conditioned with a smoldering PU foam source that transitioned to flaming.
It is important to note observations from the drop tests, to clarify the nature of damage to the PCB, horn, and other components to the alarm. The exterior cover of the smoke alarm would begin to deform with the greatest deformation happening in the vicinity of the battery holder (Fig. 21). This effect was constant regardless of how the alarm was rotated in relation to the heat source. The battery would drop free of the alarm prior to the alarm dropping in 100% of the cases. The non-powered smoke alarms had batteries inserted that were drained of any power. When the alarm fell, it rarely fell as a single component with horn and sensing unit staying connected to the PCB in 60% of the cases. When alarm components impacted the floor, they did not cease motion upon impact, instead deflecting in random directions. This effect was not significantly reduced when landing on carpet versus wood flooring. Alarms maintained enough elasticity post-fall to continue deforming with the influence of gravity. Tables 6, 7 include orientation of the horn/sensor and distanced from the point of impact.

| Orientation | Test | Change to initial observations |
|-------------|------|--------------------------------|
|             | 350°C | 450°C | 550°C | 350°C | 450°C | 550°C | 350°C | 450°C | 550°C |
| Face up     | NP 1  | 0     | 1     | 2     | 0     | 1     | 2     | 0     | 1     | 2     |
|             | NP 4  | 0     | 1     | 2     | 0     | 1     | 2     | 0     | 1     | 2     |
| Horizontal  | NP 2  | 0     | 1     | 2     | 0     | 1     | 2     | 0     | 2     | 2     |
|             | NP 12 | 0     | 1     | 2     | 0     | 1     | 2     | 0     | 2     | 2     |
| Face down   | NP 3  | 0     | 1     | 2     | 0     | 1     | 2     | 0     | 1     | 2     |
|             | NP 7  | 0     | 1     | 2     | 0     | 1     | 2     | 0     | 1     | 2     |
| NP Avg      | 0.0   | 1.0   | 2.0   | 0.0   | 1.33  | 2.0   | 0.0   | 1.33  | 2.0   |
| Face up     | P 1   | 0     | 1     | 2     | 0     | 1     | 2     | 0     | 1     | 2     |
|             | P 2   | 0     | 1     | 2     | 0     | 1     | 2     | 0     | 1     | 2     |
|             | P 16  | 0     | 1     | 2     | 0     | 1     | 2     | 0     | 2     | 2     |
|             | P 33  | 0     | 1     | 2     | 0     | 1     | 2     | 0     | 1     | 2     |
|             | P 34  | 0     | 1     | 2     | 0     | 1     | 2     | 0     | 1     | 2     |
| Horizontal  | P 7   | 0     | 1     | 2     | 0     | 2     | 2     | 0     | 2     | 2     |
|             | P 17  | 0     | 2     | 2     | 0     | 2     | 2     | 0     | 2     | 2     |
|             | P 29  | 0     | 2     | 2     | 0     | 2     | 2     | 0     | 2     | 2     |
|             | P 30  | 0     | 2     | 2     | 0     | 2     | 2     | 0     | 2     | 2     |
|             | P 31  | 0     | 1     | 2     | 0     | 2     | 2     | 0     | 2     | 2     |
| Face down   | P 3   | 0     | 1     | 2     | 0     | 1     | 2     | 0     | 1     | 2     |
|             | P 4   | 0     | 1     | 2     | 0     | 1     | 2     | 0     | 2     | 2     |
|             | P 18  | 0     | 1     | 2     | 0     | 1     | 2     | 0     | 2     | 2     |
|             | P 21  | 0     | 1     | 2     | 0     | 1     | 2     | 0     | 1     | 2     |
|             | P 36  | 0     | 1     | 2     | 0     | 1     | 2     | 0     | 1     | 2     |
| P Avg       | 0.0   | 1.2   | 2.0   | 0.0   | 1.33  | 2.0   | 0.0   | 1.53  | 2.0   |

0 is no change to the observation, 1 for some loss to the observation, and 2 is for those observations that could no longer be evaluated or obscured due to the extent of deformation or discoloration.
3.3. Results of Thermal Damage and Exposure to Carpet Tests

Four powered and four non-powered preconditioned alarms were exposed to temperatures above 300°C and then were placed face-down on carpet that had been heated to 200°C. In all powered alarm cases, the ESD indicators persisted through damage and exposure to melting into the flooring (Figs. 22, 23). In a single non-powered case, the horn had melted sufficiently to bond the horn to the carpet thereby obscuring the center hole location. Table 8 is a summary of these findings. No changes were identified to the initial observation of ESD to any of the powered smoke alarms when exposed to carpet ($\bar{F} = 0.0$). The only major influence was found when the carpet adhered to the horn enclosure in one of the non-powered smoke alarm tests, which influenced the initial observations for the horn only.

**Table 5**

Results of Changes to Initial Observations for Thermally Induced Drop Tests

| Test | (1) ec & ecv | (2) ic & icv | (3) eh & ehv | (4) ih | (5) he* | (6) ud* | (7) ude* | (8) tde* |
|------|-------------|-------------|-------------|------|------|------|------|------|
| NP 8 | 0           | 0           | 0           | 0    | 2    | 0    | 0    | 0    |
| NP 9 | 0           | 0           | 0           | 0    | 2    | 0    | 0    | 0    |
| NP 10| 1           | 1           | 0           | 0    | 2    | 0    | 0    | 0    |
| NP 11| 0           | 0           | 0           | 0    | 0    | 0    | 0    | 0    |
| NP 13| 0           | 0           | 0           | 0    | 0    | 0    | 0    | 0    |
| NP 14| 0           | 0           | 0           | 0    | 0    | 0    | 0    | 0    |
| NP 15| 0           | 0           | 0           | 0    | 0    | 0    | 0    | 0    |
| NP 16| 2           | 2           | 0           | 0    | 0    | 0    | 0    | 0    |
| NP Avg| 0.375       | 0.375       | 0           | 0    | 0.75 | 0    | 0    | 0    |
| P 8  | 0           | 0           | 0           | 0    | 0    | 0    | 0    | 0    |
| P 9  | 1           | 0           | 0           | 0    | 0    | 0    | 0    | 0    |
| P 10 | 0           | 0           | 0           | 0    | 1    | 1    | 0    | 0    |
| P 11 | 0           | 0           | 0           | 0    | 0    | 0    | 0    | 0    |
| P 12 | 0           | 0           | 0           | 0    | 0    | 0    | 0    | 0    |
| P 13 | 2           | 2           | 2           | 2    | 2    | 2    | 2    | 2    |
| P 14 | 0           | 0           | 0           | 0    | 2    | 0    | 0    | 0    |
| P 15 | 0           | 0           | 0           | 0    | 0    | 0    | 0    | 0    |
| P Avg| 0.5         | 0.25        | 0.25        | 0.25 | 0.5  | 0.375| 0.375| 0.25 |

*ESD observational indicators identified in this study

0 is no change to the observation, 1 for some loss to the observation, and 2 is for those observations that could no longer be evaluated or obscured due to the extent of deformation or discoloration

ec = exterior cover, ecv = exterior cover vertical face, ic = interior cover, icv = interior cover vertical faces, eh = exterior horn, ehv = exterior horn vertical faces, ih = internal horn, he = between horn and smoke alarm internal cover, ud = underside of disc, ude = under disc edge, tde = top disc edge

3.3. Results of Thermal Damage and Exposure to Carpet Tests

Four powered and four non-powered preconditioned alarms were exposed to temperatures above 300°C and then were placed face-down on carpet that had been heated to the 200°C. In all powered alarm cases, the ESD indicators persisted through damage and exposure to melting into the flooring (Figs. 22, 23). In a single non-powered case, the horn had melted sufficiently to bond the horn to the carpet thereby obscuring the center hole location. Table 8 is a summary of these findings. No changes were identified to the initial observation of ESD to any of the powered smoke alarms when exposed to carpet ($\bar{F} = 0.0$). The only major influence was found when the carpet adhered to the horn enclosure in one of the non-powered smoke alarm tests, which influenced the initial observations for the horn only.
Figure 20. Three examples of smoke alarms after thermally induced drop tests (left column) horn enclosure after conditioning, (center column) smoke alarm condition after thermally induced drop test, (right three columns) persistence of ESD indicators.

Figure 21. Smoke alarm battery location a overview of battery holder location, b battery holder extended, c battery removed from holder.
4. Conclusions

A total of 54 smoke alarms were tested in this study. All powered and non-powered smoke alarms presented ESD indicators as identified in previous work. Four additional locations of ESD indicators were identified in this study for this specific smoke alarm geometry, including between the horn enclosure and the internal base, the underside of the disc, and the top and underside edge of the disc. The nature of the tests was to examine thresholds of damage to smoke alarms that would destroy or obscure observational ESD indicators.

An upper temperature threshold was determined for thermal damage to ESD indicator locations. ESD indicators on powered alarms persisted through deformation and discoloration until $\sim 335^\circ$C to $350^\circ$C, when discoloration was severe enough to obscure the ESD pattern. This result was the same independent of orientation to gravity, with ceiling, wall, and face-up alarms all showing persistent

| Alarm number | Orientation at end of test (horn/sensor) | Dist. from centerline (PCB) | Battery distance |
|--------------|-----------------------------------------|-----------------------------|-----------------|
| P8           | Face up                                 | 38 cm (15")                | 102 cm (40")    |
| P9           | Face up                                 | 0 cm (0")                  | 25 cm (10")     |
| P10          | Face down                               | 10 cm (4")                 | 38 cm (15")     |
| P11          | Face up                                 | 61 cm (24")                | 112 cm (44")    |
| P12          | Face down                               | 20 cm (8")                 | 46 cm (18")     |
| P13          | Face up                                 | 30 cm (12")                | 84 cm (33")     |
| P14          | Face down                               | 0 cm (0")                  | 53 cm (21")     |
| P15          | Face down                               | 10 cm (4")                 | 91 cm (36")     |

| Alarm number | Orientation at end of test (horn/sensor) | Distance from centerline (PCB) | Battery distance |
|--------------|-----------------------------------------|-------------------------------|-----------------|
| NP7          | Face up                                 | 43 cm (17")                  | 104 cm (41")    |
| NP8          | Face down                               | 10 cm (4")                   | 3 cm (1")       |
| NP9          | Face up                                 | 8 cm (3")                    | 114 cm (45")    |
| NP10         | Face up                                 | 10 cm (4")                   | 102 cm (40")    |
| NP11         | Face down                               | 0 cm (0")                    | 86 cm (34")     |
| NP13         | Face up                                 | 94 cm (37")                  | 25 cm (10")     |
| NP14         | Face down                               | 20 cm (8")                   | 25 cm (10")     |
| NP15         | Face up                                 | 25 cm (10")                  | 122 cm (48")    |
| NP16         | Face down                               | 10 cm (4")                   | 46 cm (18")     |
Figure 22. Smoke alarm horn conditioned with a non-powered (NP) smoke alarm with a smoldering PU foam fire source thermally damaged and exposure to carpet (top row) horn enclosure and PCB thermally damaged, (bottom row) exposure to carpet showing lack of ESD or obscuration of indicator locations.

Figure 23. Smoke alarm horn conditioned with a powered (P) smoke alarm with a smoldering PU foam fire source thermally damaged and exposure to carpet (top row) pre-conditioned horn, thermally damaged, and exposure to carpet, (middle and bottom row) ESD persistence at various indicator locations.
ESD indicators. ESD indicators on the disc, first noted in this study, persisted until exposed to temperatures greater than 450°C.

Findings from the drop tests showed that the threshold to damage was limited to situations where material melted or flowed over an indicator site, or that discoloration obscured the indicator. In every case, those indicators not directly damaged by flow obscuration or discoloration persisted past the drop.

Findings from the heated carpet tests show that while carpet may impact the shape of the thermal deformation, unless the component with ESD observations bonds to the carpet, ESD indicators persist.

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Table 8
Enhanced Soot Deposition (ESD) Observational Indicators Results After carpet Tests

| Test | (3) eh & ehv | (4) ih | (5) he* | (6) ud* | (7) ude* | (8) tde* |
|------|--------------|--------|---------|---------|---------|---------|
| NP 5 | 0            | 0      | 0       | 0       | 0       | 0       |
| NP 6 | 0            | 0      | 0       | 0       | 0       | 0       |
| NP 17| 2            | 2      | 2       | 0       | 0       | 0       |
| NP 18| 0            | 0      | 0       | 0       | 0       | 0       |
| NP Avg| 0.25       | 0.25   | 0.25    | 0       | 0       | 0       |
| P 5  | 0            | 0      | 0       | 0       | 0       | 0       |
| P 6  | 0            | 0      | 0       | 0       | 0       | 0       |
| P 32 | 0            | 0      | 0       | 0       | 0       | 0       |
| P 35 | 0            | 0      | 0       | 0       | 0       | 0       |
| P Avg| 0            | 0      | 0       | 0       | 0       | 0       |

ec = exterior cover, ecv = exterior cover vertical face, eh = exterior horn, ehv = exterior horn vertical faces, ih = internal horn, he = between horn and smoke alarm internal cover, ud = underside of disc, ude = under disc edge, tde = top disc edge

*ESD observational indicators identified in this study

0 is no change to the observation, 1 for some loss to the observation, and 2 is for those observations that could no longer be evaluated or obscured due to the extent of deformation or discoloration
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