

Full-Scale Validation Tests of a Forensic Methodology to Determine Smoke Alarm Response

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Introduction

Recent studies^{1,2,3} have demonstrated the utility of enhanced soot deposition around the openings of smoke alarm horns as an indication as to whether the device sounded during a fire. In these studies arrays of smoke alarm models and horn geometries were exposed to various sources of smoke and nuisance particulates and the resulting soot deposition patterns were evaluated. Phelan et al. developed inspection heuristics which optimize the predictive capacity of the observations in determining whether or not an alarm had sounded. However, much of the data used to develop and validate the inspection heuristics consisted of relatively controlled fire exposures. It was the objective of this study to expand upon the previous work and to validate the inspection heuristics developed by Phelan et al. for alarms exposed to full-scale enclosure fire scenarios allowed to proceed to flashover.

A test program comprised of six full-scale enclosure fires was conducted within a multi-room test enclosure using a variety of fuel sources and ignition scenarios. Pairs of smoke alarms consisting of an unpowered and a powered unit of two different models were installed in three of the four rooms of the enclosure. Test fires were permitted to reach flashover conditions within the room of origin and then extinguished shortly thereafter. A blind study was performed of the smoke alarm remains using the heuristics developed by Phelan et al.

Experimental Set Up

A series of full-scale fire tests were conducted within a 42 m² (450 ft²) apartment-style test enclosure [Mealy, 2006]. As shown in Figure 1, the test enclosure was comprised of four adjoining spaces. The living room was connected to the rest of the enclosure via a 2.44 m by 2.13 m (7ft) entryway, while the dining room was connected to both the kitchen and bedroom via 0.82 m (2.75 ft) by 2.13 m (7ft) open doorways. A 0.31 m (1 ft) soffit existed above the entryway and each of the doorways described.

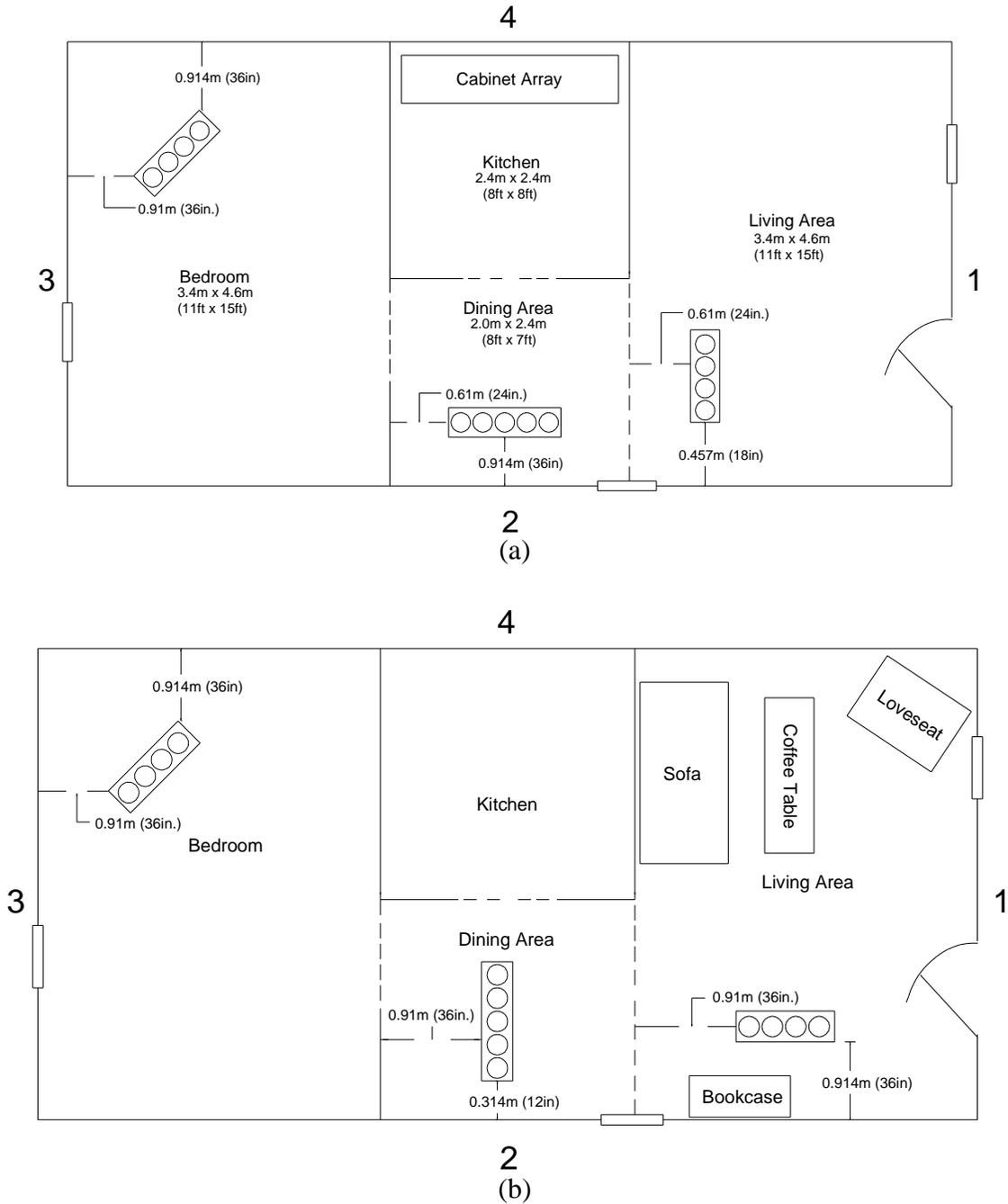


Figure 1: Plan view of enclosure for both wood cabinet fire tests (a) and upholstered sofa fire tests (b). Illustrations also provide smoke alarm cluster locations during both tests.

Fire sources included an elevated kitchen cabinet array, a floor-level kitchen cabinet array, and an upholstered sofa. Arrays of four wooden kitchen cabinets were used as the primary fuel load in the kitchen fire scenarios. A prescribed fuel load comprised of both cellulosic and plastic materials was installed in two of the four cabinets prior to testing. During elevated cabinet fire scenarios, the cabinet array was mounted 1.4 m (4.5 ft) above the floor of the enclosure, while in the floor level cabinet fire scenarios, the cabinet array was mounted 0.31 m (1 ft) above the floor of the

enclosure. Living room fire scenarios utilized an upholstered sofa comprised of wood framing, polyurethane foam cushioning, and cotton fabric upholstery. Photographs of each of the three fire scenarios are presented in Figure 2.



Figure 2: Photograph of elevated cabinet array (left), floor-level cabinet array (middle), and upholstered sofa (right) fire test setups.

Two ignition scenarios were used for the fire scenarios described above, an accidental ignition scenario and an accelerant-induced ignition scenario. The accidental ignition scenario utilized a 15 cm (6 in.) square methane sand-burner producing a fire size of approximately 10 kW. The burner was installed proximate to the primary fuel source (i.e., cabinet array or upholstered sofa) to provide direct flame impingement on the fuel. The accelerant-induced ignition scenario consisted of 1.75 L (0.46 gal.) of gasoline which was dispersed directly onto the primary fuel source and used to create a trail of fuel leading toward the exterior doorway. The test enclosure was initially unventilated during tests in which an accidental ignition scenario was used. These tests were manually ventilated after about a 30 or 60 minute vitiated burning period and permitted to grow to flashover conditions. Contrarily, when accelerant-induced ignition scenarios were utilized the exterior door to the enclosure remained open throughout the test.

Smoke alarm clusters were located in the living room, dining room, and bedroom during all tests as shown in Fig. 1. A total of thirteen smoke alarms were installed within the enclosure for each test. Clusters located in the living room and bedroom contained four ionization smoke alarms comprised of pairs of alarms from two manufacturers. Each pair of alarms consisted of one active (i.e., powered) and one inactive alarm (i.e., unpowered). The remaining cluster, located in the dining room, contained four ionization alarms and a single photoelectric alarm. Alarms were spaced 0.31 m (1 ft) on center at each location. Furthermore, all clusters were oriented with respect to fire source location such that each alarm in the cluster was exposed in a comparable manner. The alarms in this study provided two different horn types for evaluation. Each of these alarm styles and their corresponding horn configuration are presented in Figure 3. For the alarm design shown in Fig. 3a, the horn is mounted to the cover of the alarm such that the cover forms the top of the horn chamber. Figure 3b shows a design in which the horn is mounted to the base of the smoke alarm and is detached from, but below the openings in the cover. Smoke alarm activation (i.e., sounding) was recorded using a non-intrusive acoustic monitoring technique.

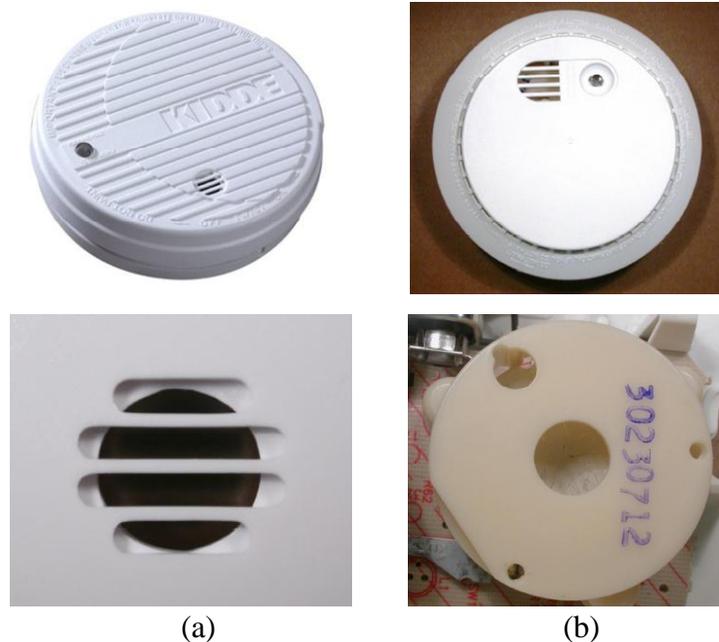


Figure 3: Photographs illustrating the general construction and alarm horn geometry for each of the alarms in the study.

Experimental Procedure

Each enclosure fire test began with the ignition of the initiating fire source (i.e., the burner or accelerant). For accidental ignition scenarios, the fire burned within the unventilated enclosure until quasi-steady state vitiated conditions were reached at which point the enclosure was manually ventilated via the exterior doorway. Fires initiated using an accelerant fire remained ventilated via the exterior doorway for the duration of the fire. All fires were permitted to grow to flashover conditions within the enclosure. The duration of post-flashover burning varied between tests, generally lasting approximately 1 – 2 minutes at which point the fire was manually extinguished via a hose line.

Following each enclosure fire test, the exposed alarms were removed, inspected, and photographed. Inspection and documentation primarily focused on whether enhanced smoke deposition occurred around the horn opening. Based upon the methodology outlined by Phelan et al., both macro- and microscopic inspection of the external, internal, and vertical surfaces of the horn opening were performed. Macroscopic inspection was performed with the naked eye while microscopic inspection was performed using a 10x – 90x microscope. Photographic documentation consisting of both macro- and microscopic images were collected for each alarm evaluated in this study.

Analytical Procedure

The following analytical procedure was followed during the blind study to evaluate the exposed alarms. A preliminary inspection of the alarm was conducted to

determine if sufficient soot deposition was present to make a determination as to activity of the alarm. If sufficient soot was present on the alarm to make such a determination, the inspection continued; if insufficient soot was present then the alarm was identified as an indeterminate case. Photographs illustrating this dichotomy are presented in Figure 4.



Figure 4: Photographs illustrating the different levels of soot deposited on alarms exposed to varying fire conditions.

Provided that sufficient soot deposition was identified a series of four observations were made via both macro- and microscopic inspection. Initially, a macroscopic examination of the external face of the alarm was conducted specifically examining the surface area proximate to the alarm horn opening. This was followed by a microscopic inspection of the external surfaces. A similar process was performed for both the vertical and internal surfaces of each of the horn openings. Finally, the density of soot deposition inside and outside the alarm horn chamber was evaluated for each of the alarms in which the horn was mounted to the cover of the alarm, thus forming a chamber between the horn opening and the piezoelectric sounder (Fig. 3a). See Figure 5 for a collection of photographs documenting enhanced soot deposition patterns around the horn openings.

Enhanced soot deposition on the external face of the horn opening is a potential indicator of an alarm sounding (Fig. 5a). Another indicator is enhanced deposition on the vertical surfaces of the horn opening into the sounding chamber (Fig. 5b). A third indicator is enhanced deposition on the internal face, which can particularly be characterized by a pattern of increased soot density fanning radially outward from the horn opening (Fig. 5c). Figure 5d shows the enhanced deposition and lack of deposition within the horn chambers relative to the underside of the alarm cover for smoke alarms that sounded and did not sound during the fire, respectively.

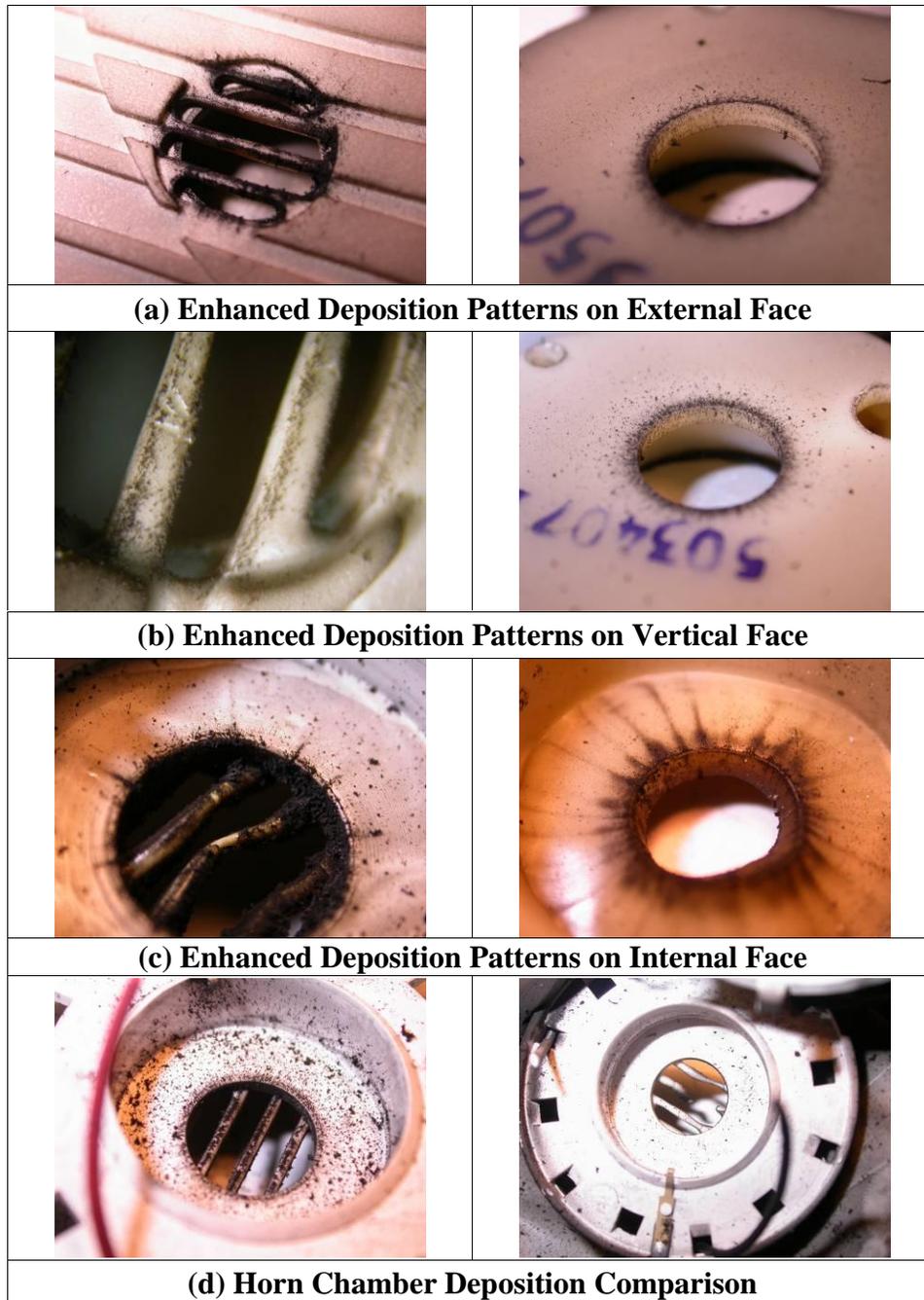


Figure 5: Photographs of observations obtained during examination of smoke alarms.

In addition to photographic documentation of the observations made during the inspection of each alarm, the presence/absence of enhanced soot deposition patterns on the various alarm faces were tabulated. Though single indicators of enhanced deposition can provide a determination of sounding or non-sounding for alarms in fires, Phelan et al. demonstrated that the correlation of multiple independent observations can lead to increased accuracy and more robust alarm activation determination. Phelan successfully developed both sounding and non-sounding alarm inspection heuristics that provided 100

percent correct determinations. A decision tree which combines both of the heuristics developed by Phelan et al. is presented in Figure 6.

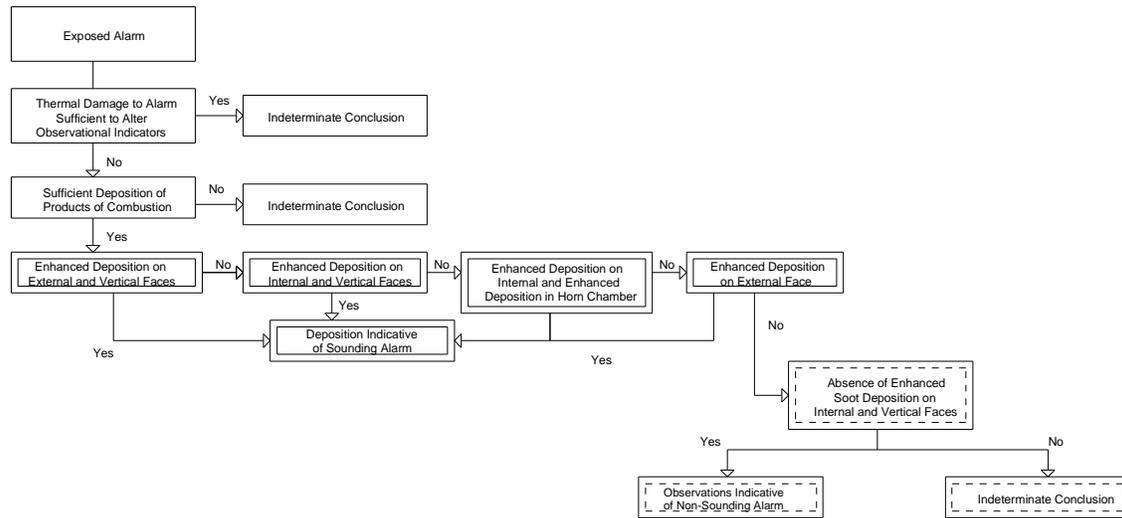


Figure 6: Decision tree developed based upon Phelan et al. heuristics. Decisions enclosed within double-solid line boxes are those associated with the Sounding heuristic while decisions enclosed in single-solid, single-hatched line boxes are those associated with the Non-Sounding heuristic.

The observational data collected in this study were used with the Phelan et al. heuristics to develop alarm activity determinations for each of the alarms evaluated. Upon inspection of an exposed alarm a decision as to whether or not the alarm had sufficient deposition of products of combustion was made. Provided that sufficient deposition was present the data collected for the alarm was first applied to the Sounding heuristic to determine whether or not a positive determination could be established. As shown in Figure 6 a positive determination was established if soot deposition patterns were identified via microscopic inspection of the external face or any combination of the external/vertical, internal/vertical, or internal/horn chamber comparison evaluations. If the data set did not provide a positive determination (i.e., sounding) it was then applied to the Non-Sounding heuristic. It is important to note that a negative determination using the Sounding heuristic is not sufficient to make a non-sounding determination for an alarm being evaluated. In order to make such a determination it was necessary to apply the same data set to the Non-Sounding heuristic. If a positive determination could be developed using this heuristic, then the alarm being evaluated was determined to have not sounded. A positive determination using the Non-Sounding heuristic was established if sufficient soot deposition on the alarm was initially identified but there was a lack of enhanced soot deposition both internally and on the vertical faces of the alarm opening. If a positive determination could not be established using either of the heuristics then the activity of the alarm being evaluated was indeterminate. An indeterminate alarm evaluation was the result of an insufficient data set either due to the thermal degradation of the alarm surfaces being investigated or due to the smoke conditions to which the alarm was exposed not producing sufficient soot deposition on the alarm surfaces.

Results & Discussion

A total of six fires were set, consisting of three unventilated and three ventilated enclosure fire tests. Of the six enclosure fires, four reached flashover conditions within the room of origin. Consequently, the conditions to which the alarm evaluated in this study were exposed varied significantly. In three of the enclosure fires with accelerant ignition scenarios, the alarms were exposed to rapid fire growth resulting in relatively short duration, severe thermal exposure and sooty conditions. The remaining three fire tests conducted with accidental ignition scenarios resulted in prolonged exposure of the alarms to moderate thermal and smoke conditions. As a result of the different types of fire conditions to which the alarms were exposed, the post-test condition of the alarms varied from severe (i.e., complete melting and detachment from the ceiling) to relatively moderate (i.e., thermally discolored with no evidence of physical deformation). Photographs illustrating the variety of damage to the alarms being evaluated are presented in Figure 7.



Figure 7: Photographs illustrating the range of post-test alarm conditions evaluated in study.

A total of seventy-six alarms were evaluated in this study, forty (53%) active (i.e., powered) and thirty-six (47%) inactive (i.e., unpowered). The inequality of powered/unpowered alarms is due to the inclusion of a single, powered photoelectric alarm in each of the six fire tests. Of the seventy-six alarms evaluated, twenty-one (28%) were found to be indeterminate due to a complete lack of observational data resulting from the thermal deterioration of the alarm during the fire exposure. The observational data from the remaining fifty-five alarms was then applied to the heuristics shown in Figure 6. During this evaluation twenty-two (29%) alarms were positively identified as having alarmed during the fire exposure, twenty-five (33%) alarms were positively identified as having not sounded, and eight (11%) alarms did not have sufficient observational data to make a determination using the heuristic thus were concluded to be indeterminate cases.

Of the twenty-nine alarms resulting in indeterminate evaluations, eighteen were active (i.e., powered) and eleven were inactive (i.e., unpowered). Consequently, there were a total of twenty-two active alarms and twenty-five inactive alarms which were evaluated, resulting in forty-seven alarms that had sufficient data sets to make accurate alarm activity determinations. All were correctly identified using the observational data with the Phelan et al. heuristics. There were no false-positive or false-negative determinations for the alarms evaluated in this study.

Further analysis of the observational data resulted in the development of an observational hierarchy based upon the utility of the observations in making a determination regarding the positive identification of an alarm that sounded. Of the twenty-two alarms identified as having sounded, twenty of the alarms were identified as having enhanced soot deposition on the internal surfaces of the alarm. A total of eighteen of the twenty-two sounding alarms were found to have enhanced soot deposition on the vertical faces of the alarm horn opening and fifteen of the twenty-two alarms had enhanced soot deposition on the external surfaces of the alarm. The aforementioned data indicates that when examining alarms using the Sounding heuristic, observations having the most utility are those on the interior of the alarm, followed by the vertical surfaces, and then the external surfaces. A similar hierarchy was found to exist in the work of Phelan et al.

Conclusions

The inspection heuristics developed by Phelan et al. are based upon the systematic evaluation of a large population of alarms comprised of a variety of horn geometries and fire/smoke exposures. Much of the data collected by Phelan et al. is based upon relatively controlled fire exposures. The results of this study expand upon the Phelan et al. alarm population to included data from full-scale enclosure fire scenarios. These fire scenarios resulted in varying degrees of thermal exposures and smoke conditions. The results of the blind study conducted clearly demonstrate the utility and accuracy of the heuristics developed by Phelan et al. When used in combination with the observational data collected in these tests, the heuristics positively identified alarm activity for all potential candidates for evaluation. A total of forty-seven alarms were accurately identified as having either sounded or not sounded during exposures to enclosure fire conditions. Based upon these results and those of the previous study¹ it is apparent that the heuristics developed by Phelan et al. provides a valid methodology for evaluating soot deposition around smoke alarm horn openings as an indication as to whether or not the device sounded during a fire.

References

- 1 – Phelan, P., “An Investigation of Enhanced Soot Deposition on Smoke Alarm Horns,” Master of Science Thesis, Worcester Polytechnic Institute, Worcester, MA, 250p., 2005.
- 2 – Worrell, C.L., Roby, R.J., Streit, L., and Torero, J.L., “Enhanced Soot Deposition, Acoustic Agglomeration, and Chladni Figures in Smoke Detectors,” *Fire Technology*, 37:4, pp. 343-362, 2001.
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