An Investigation of Enhanced Soot Deposition on Smoke Alarm Horns

A Thesis

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By

Patrick Phelan

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Approved:

Professor John P. Woycheese

Associate Professor, Center for Firesafety Studies

Professor Kathy A. Notarianni

Director, Center for Firesafety Studies

Dr. Daniel T. Gottuk

Senior Engineer, Hughes Associates Inc.

Abstract

Post-fire reconstruction often includes the analysis of smoke alarms. The determination of whether or not an alarm has sounded during a fire event is of great interest. Until recently, analysis of smoke alarms involved in fires has been limited to electrical diagnostics, which, at best, determined whether or not a smoke alarm was capable of alarm during the fire event. It has subsequently been proposed that evaluation of the soot deposition around a smoke alarm horn can be used to conclude whether a smoke alarm has sounded during a fire event.

In order to evaluate the effectiveness of using enhanced soot deposition patterns as an indication of smoke alarms sounding within a fire event, four test series were undertaken. First, a population of smoke alarms representative of the available market variety of horn configurations was selected. This population was subjected four test series. Test Series 1 consisted of UL/EN style experiments with fuel sources that included flaming polyurethane, smoldering polyurethane, flaming wood crib, and flaming turpentine pool. In Test Series 2, alarms were exposed to "nuisance" products from frying bacon, frying tortillas, burnt toast, frying breading, and airborne dust. Test Series 3 exposed the alarms to the following fire sources: smoldering cable, flaming cable, flaming boxes with paper, and flaming boxes with plastic cups. Test Series 4 included new, used, and pre-exposed smoke alarms that were exposed to two larger scale fires: a smoldering transitioning to flaming cabinet/wall assembly fire and a flaming couch section.

The results from all four series were used to generate a heuristic for use in evaluating alarms from fire events. These criteria were blindly tested against the population of alarms to develop a correlation between the criteria and the previously tested smoke alarms. The results support the evaluation of soot deposition on smoke alarms exposed to a fire event as a viable method to determine whether or not an alarm sounded, without false positive or negative identifications.

Keywords

soot deposition, smoke detector response, acoustic agglomeration, enhanced deposition

Acknowledgements

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Nomenclature

Agglomeration – The combination of soot particles into a larger mass through partial fusion within the flame and dispersion forces outside the flame

Diamond – Designation for the model of smoke alarm pictured in Figure 0.1

Disabled Alarm – A smoke alarm that was installed per manufacturer specifications, except that the battery was improperly installed to avoid powering the alarm to prevent alarm during an experiment

Enabled Alarm – A smoke alarm that was installed per manufacturer specifications to allow for proper performance during an experiment

Enhanced Acoustic Agglomeration – The increased rate of agglomeration of aerosols within a sonic field

External Face – Outermost face of the smoke alarm horn opening (see Figure 0.2)

False Negative – An alarm that has sounded, incorrectly identified as not having sounded

False Positive – An alarm that has not sounded, incorrectly identified as having sounded

FACI – Designation for the model of smoke alarm pictured in Figures 0.3-0.5

FBI – Designation for the model of smoke alarm pictured in Figures 0.6-0.8

FGBI– Designation for the model of smoke alarm pictured in Figures 0.9-0.10

FSBI– Designation for the model of smoke alarm pictured in Figures 0.11-0.13

Horn Chamber – Volume created between the smoke alarm horn disc and the smoke alarm horn opening in alarms with external horn openings (see Figure 0.14)

Identical Alarms – Smoke alarms of the same model with the same exposure history

Internal Face – Innermost face of the smoke alarm horn opening (see Figure 0.15)

New Alarm- An alarm not previously exposed to nuisance or fire sources purchased through a local retailer

Nuisance source – Origin of particulates, generated without fire that can activate a smoke alarm

Photo – Designation for the photoelectric model of smoke alarm pictured in Figure 0.16

Pre-exposed alarm – Smoke alarm that has been subjected to nuisance or fire sources

Radial Pattern – A pattern of soot that is deposited radially outward from the smoke alarm horn opening moving from higher to lower relative density of soot deposition (see Figure 0.17)

Ring Pattern - Continuous band of soot deposition around a smoke alarm horn opening (see Figure 0.18)

Smoke – The mixture of gases, vapors, particulates, and condensates generated during incomplete combustion

Smoke Alarm Cover – The external housing of a smoke alarm pictured in Figures 0.19 and 0.20.

Smoke Alarm Horn Disc – The metallic disc that forms the inside wall of the smoke alarm horn chamber. The disc vibrates, creating the sound in a smoke alarm horn (see Figure 0.21)

Smoke Alarm Horn Opening – The opening or openings in the smoke alarm cover through which the alarm tones escape and smoke moves in and out of the horn chamber. Figures 0.3-0.13 and 0.16 illustrate the variety of horn opening geometries studied

Smoke Condensate – Microdroplets of condensed organic vapors in smoke

Soot – Predominantly carbonaceous, solid agglomerate within smoke

Staining – Yellow or Orange discoloration of parts of a smoke alarm, typically the internal face of the smoke alarm cover, caused by smoldering sources

Used Alarm – Smoke alarm that has been *in situ* and has an unknown exposure history

Vertical Face – Sheer edges of a smoke alarm horn opening (see Figure 0.22)

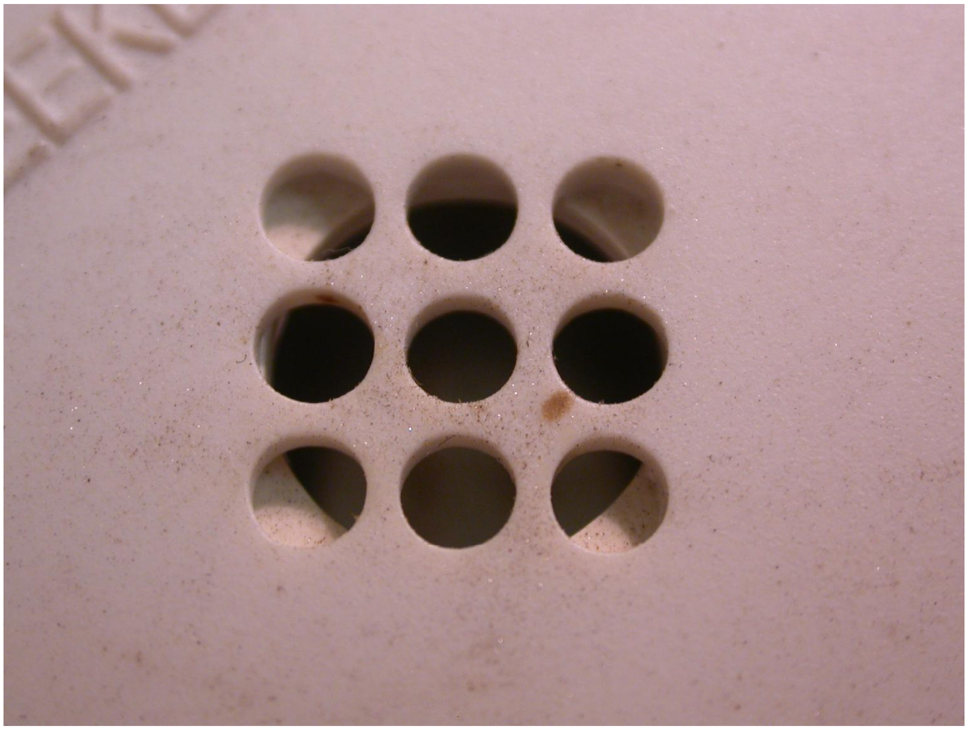

Figure 0.1 DIAMOND style smoke alarm horn opening.

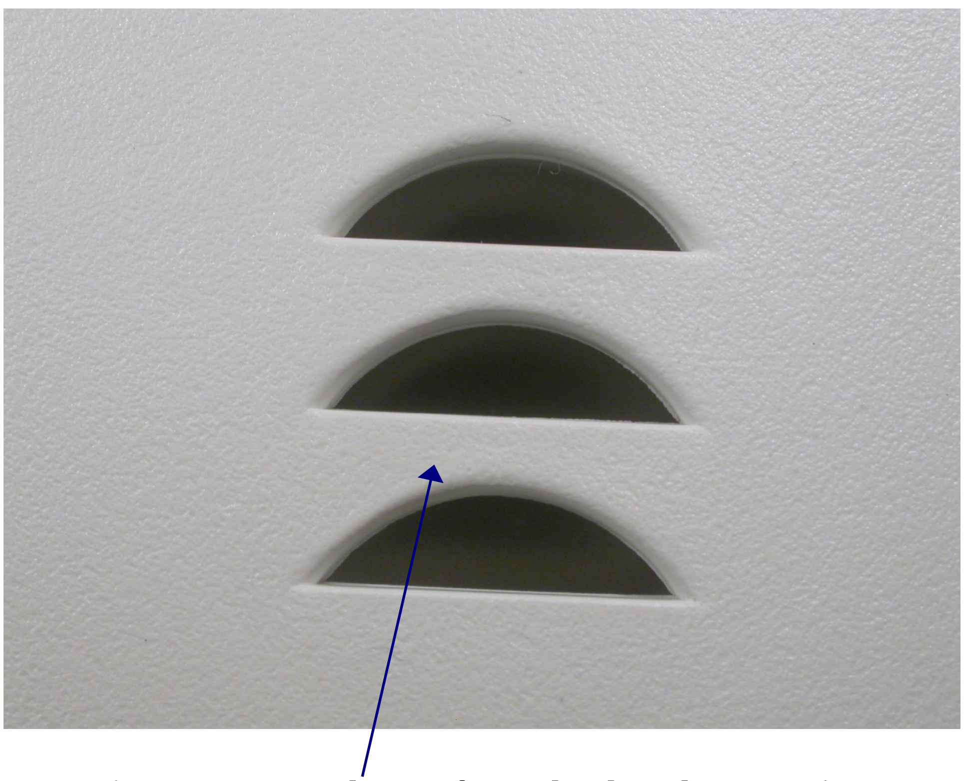

Figure 0.2 External Face of a smoke alarm horn opening.

Figure 0.3 FACI style alarm typical of those used in this study.

Figure 0.4 Exterior of FACI Smoke Alarm Horn Opening.

Figure 0.5 Interior of FACI Smoke Alarm Horn Opening.

Figure 0.6 FBI style alarm typical of those used in this study.

Figure 0.7 Exterior of FBI Smoke Alarm Horn Opening.

Figure 0.8 Interior of FBI Smoke Alarm Horn Opening.

Figure 0.9 FGBI style alarm typical of those used in this study.

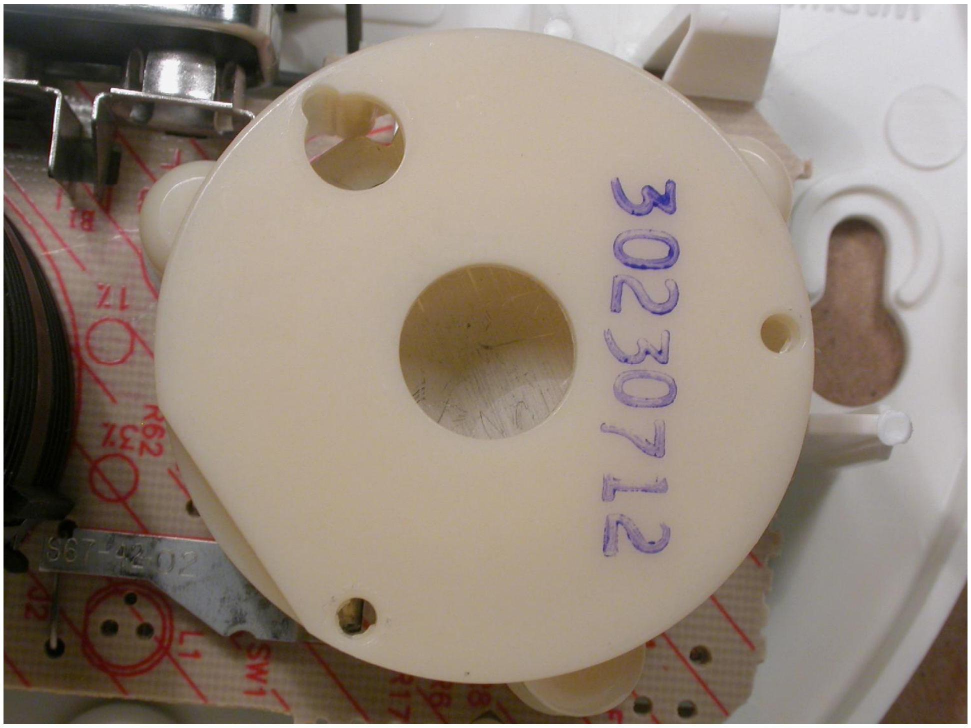

Figure 0.10 Exterior of FGBI Smoke Alarm Horn Opening.

Figure 0.11 FSBI style alarm typical of those used in this study.

Figure 0.12 Exterior of FSBI Smoke Alarm Horn Opening.

Figure 0.13 Interior of FSBI Smoke Alarm Horn Opening.

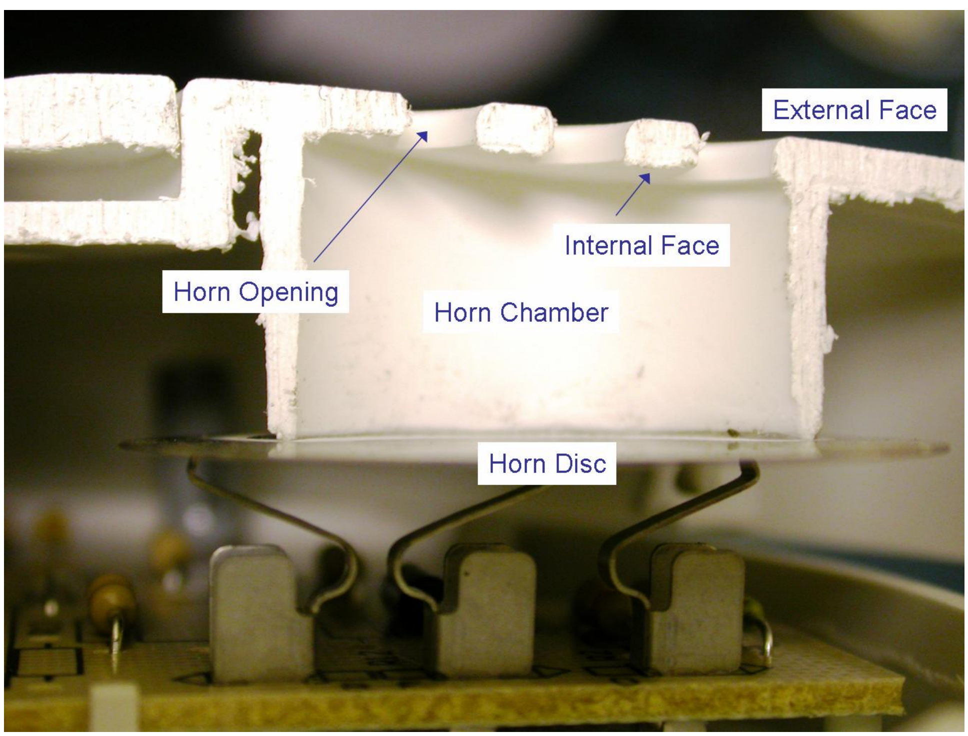

Figure 0.14 Cross-section of an FBI horn chamber.

Figure 0.15 Internal Face of a smoke alarm horn opening

Figure 0.16 PHOTO smoke alarm horn opening.

Figure 0.17 Radial Pattern on the exterior face of an FACI horn opening.

Figure 0.18 Ring Pattern.

Figure 0.19 Exterior of a Smoke Alarm Cover.

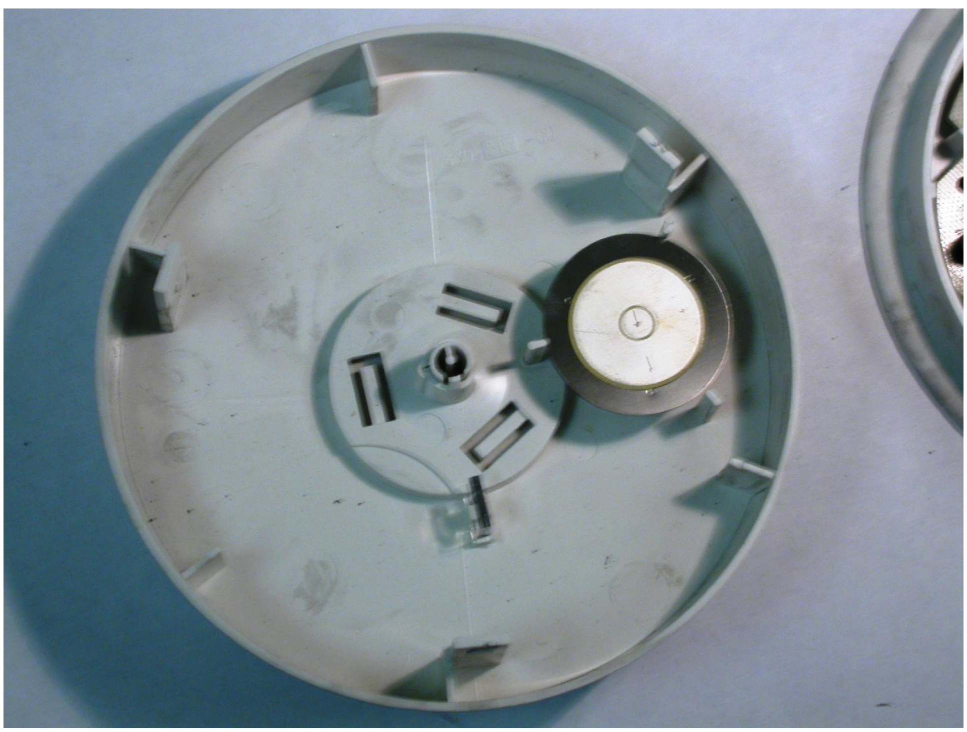

Figure 0.20 Internal cover of a smoke alarm.

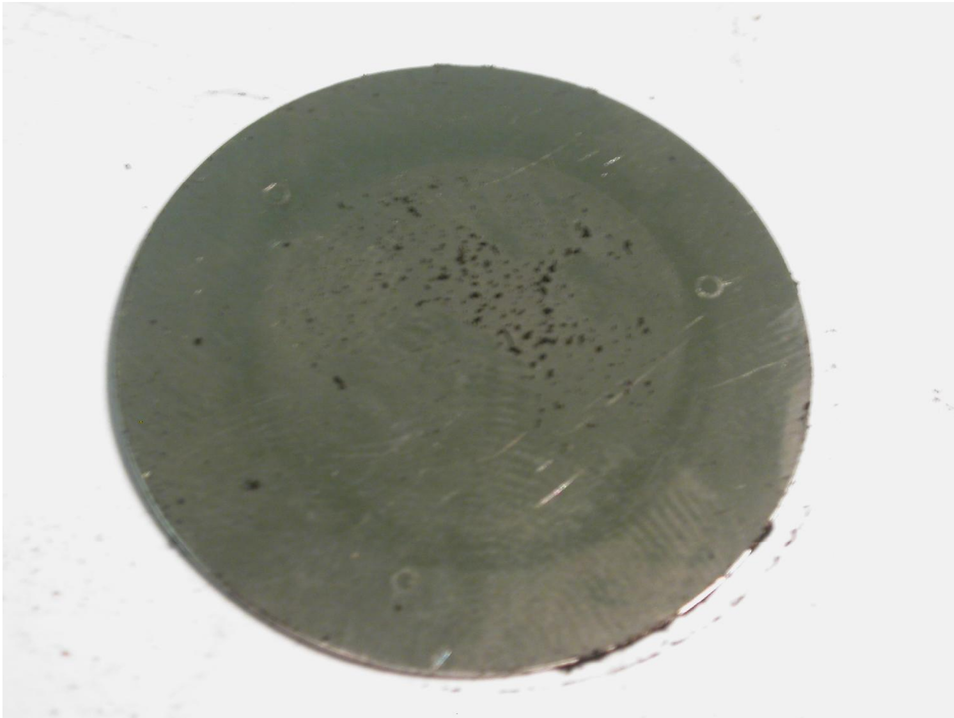

Figure 0.21 Smoke Alarm Horn Disc.

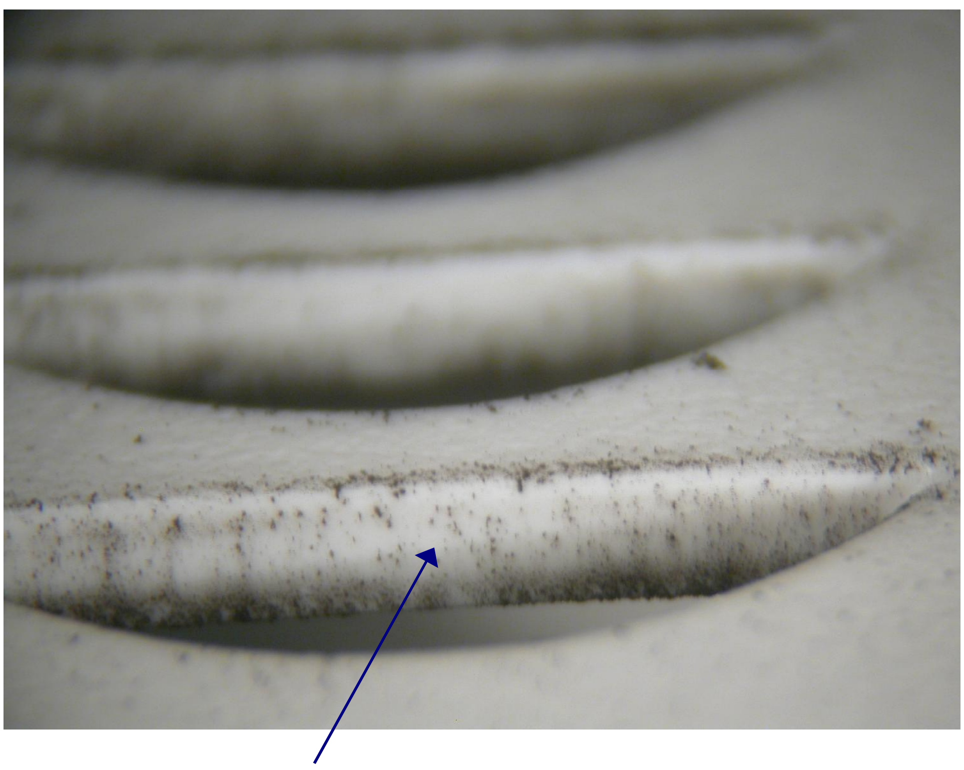

Figure 0.22 Vertical Face of FBI Smoke Alarm Horn Opening.

1 Introduction

1.1 Motivation

Establishing whether a smoke alarm has operated during a fire event is of great interest to the fire investigation community. Until recently, post-fire evaluation of a smoke alarm has been limited to an electrical evaluation, which can establish whether an alarm is still capable of alarm, but might or might not have a predictable relationship with the state of the device prior to and during the fire event.

Anecdotal reports have circulated within the experimental and investigative communities describing soot patterns developing on and around smoke alarm horns or horn openings [Rorck, 1993]. Recently, two studies have investigated the cause and applicability of these patterns [Worrell, et al. 2001 & 2003]. Worrell, et al., found that under some fire conditions, soot particulates can deposit in patterns around the smoke alarm horns of devices that sounded during a fire event. In both studies, the researchers conclude that the presence of enhanced soot deposition around the smoke alarm horn opening is a reliable indicator that an alarm sounded during a fire event. Worrell, et al., [Worrell, et al., 2001] indicates that enhanced soot deposition is not sufficiently reliable to determine that an alarm had *not* sounded during a fire event due to the absence of enhanced deposition. In the second study, Worrell, et al., [Worrell, et al., 2003] found that the generation of specific deposition patterns were reliable indicators of an alarm having sounded during a fire event; however, for fuel sources that result in enhanced soot deposition, the lack of enhanced soot deposition was sufficient to determine that an alarm had not sounded during the event.

These studies have established enhanced soot deposition as a forensic tool, a tool that is being applied in fire investigations and litigation without a clear set of conclusions or criteria for use and applicability. The results of these studies are correlated to a data set that is limited in scope, including only new smoke alarms with two horn configurations subjected to a limited number of fuel sources. To create an appropriate set of criteria, the variety of horn configurations and fuel sources must be expanded. It is also necessary to evaluate the effect of exposure histories representative of alarms *in situ* on enhanced soot deposition.

1.2 Problem Statement

The goal of this investigation was to develop methodology to evaluate soot deposition on a smoke alarm exposed to a fire. This investigation will establish a methodology by developing it from a data set that includes previously studied fuel sources and horn configurations. The study will expand upon the fuel sources previously studied, and evaluate the behavior of nuisance sources in comparison to the other fuel sources. The study will incorporate new alarms, alarms that have been *in situ*, and alarms previously exposed to nuisance sources. The tests will include multiple fuel locations relative to the alarms to allow for evaluation of distance and exposure time.

2 Background, Theory, and Literature

2.1 Smoke Alarms and Detection

Residential fire detection relies primarily upon smoke detection. This is most often accomplished with single station or multiple station smoke alarms. These smoke alarms utilize either light scattering or ionization principles of operation to measure the presence of smoke, or more accurately soot particulate or aerosol, and infer a fire condition. Photoelectric smoke alarms use an infrared beam sent across a sensing chamber. A sensor is placed at an angle from the beam (see Figure 2.1).

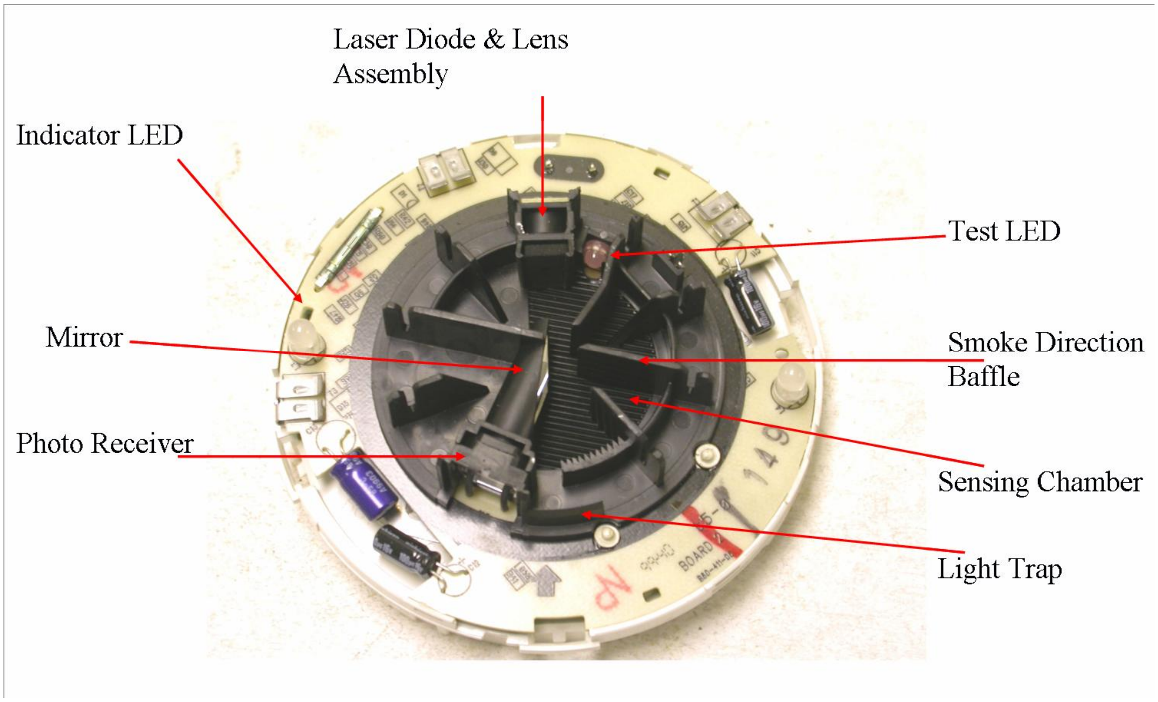

Figure 2.1 Anatomy of a photoelectric smoke detector.

Under quiescent conditions, the beam crosses the sensing chamber uninhibited and the sensor receives no light. As a fire develops, smoke and soot particulates are transported in increasing concentrations into the sensing chamber of the smoke alarm. The soot particulates scatter portions of the beam, some of which is incident upon the sensor. As the concentration of smoke within the chamber increases, more light is scattered and more is incident upon the sensor. Once the light incident upon the sensor exceeds the established threshold for the alarm, a signal is sent to the alarm horn and it sounds.

In an ionization smoke alarm, a source of radiation ionizes constituents of the air in the reference and measurement chambers (see Figure 2.2).

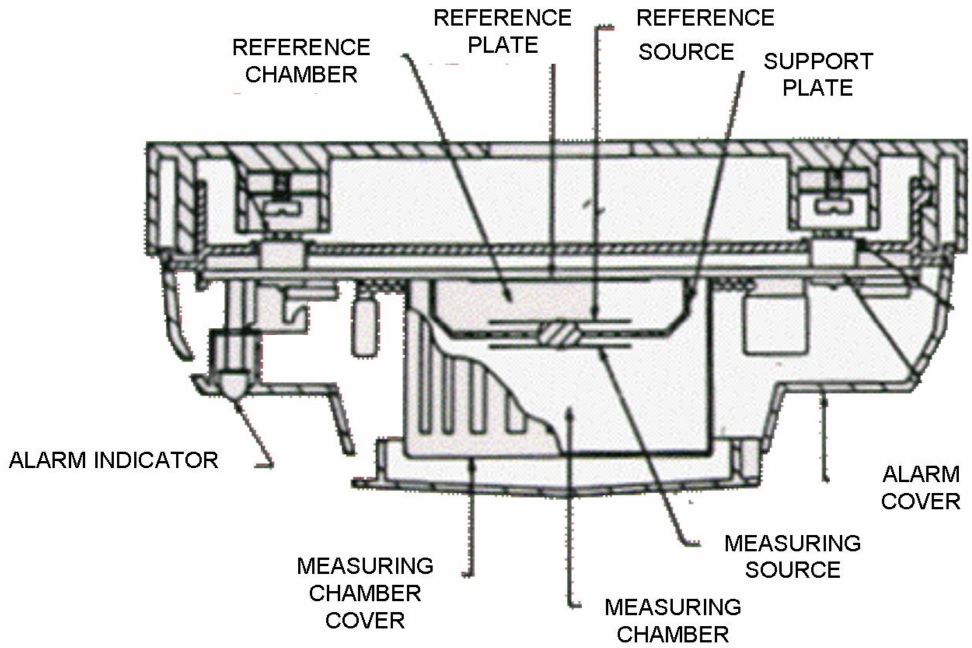

Figure 2.2 Ionization Smoke Detector Diagram.

The power source of a smoke alarm establishes a voltage differential between the reference and measurement chambers. This induces the movement of ionized particles within the chamber, generating an electrical current within the reference chamber and within the measurement chamber. Small charged particulates, such as those found in smoke, absorb some of the ionized particles, reducing the current the chambers. As a fire develops, more soot particles are transported into the ionization chamber, decreasing the current within the chamber. When the current is lowered to the established alarm threshold, a signal is sent to the horn and the alarm sounds.

As stated above, the ions within the ionization chamber establish a current within the measurement chamber. The soot particulate can be seen as a variable resistance and as such there is a changing voltage difference across the measurement chamber. This can be monitored by measuring the voltage difference between pins 13 and 16 on the Motorola chip on the smoke alarm board. Establishing an alarm state for an alarm in an experiment has been achieved by comparing the voltage to a threshold characteristic of the alarm type in use.

This threshold is established by monitoring the voltage difference until a representative alarm sounds. This technique established the alarm times of multiple devices sounding together. There are, however, issues inherent in the use of this technique: the alarm data taken is only an approximate time, and this time represents when an alarm should have sounded, but does not verify that an alarm did sound. Finally, this technique does not provide for monitoring an alarm sounding intermittently or determining a precise duration of alarm.

Smoke Alarms are required by NFPA 72, the Consumer Product Safety Commission and UL 217 to use the "temporal three" pattern. This pattern is required to attain 75 decibels at approximately 3 feet from the floor. The alarms in this study used a piezoelectric horn to generate the required pattern and volume. A metal disc is vibrates to create a complex sound.

The sound notifies occupants of a perceived fire condition; thus, it is the preferable indication of a functioning alarm. A technique for monitoring alarms via acoustic monitoring of horn activation was utilized in this study. The technique uses directional tubing and microphones to individually monitor each alarm and initiate a voltage step change when the alarm sounds. This method is further outlined in Section 5.2.

2.2 Soot Agglomeration

2.2.1 "Normal Agglomeration"

Incomplete combustion produces soot particulate and microdroplets of condensed organic vapor, both of which are capable of initiating sounding in the smoke alarms and of generating enhanced soot deposition that signifies the sounding of a smoke alarm. Soot particulates are primarily carbonaceous and are produced as monoparticle spheroids with an average diameter of 0.5 microns [Mulholland, 2004]. Within the flame region these spheroids can be partially fused to other particles; this agglomeration results in fewer, but larger particles. Outside of the flame, soot particles continue to agglomerate owing to dispersion forces resulting from turbulence and Brownian motion within the plume and upper layer. The condensed organic vapors or smoke condensate are subject to the same interactions outside the flame as soot particulates. When these droplets interact with each other they coalesce to form larger droplets.

2.2.2 Acoustic Agglomeration

It has been proven that a sonic field enhances the agglomeration rate of aerosols. Further research has shown that an increase in particle interaction produces an increase in final agglomerate size [Worrell, et al, 2001]. A sonic field creates pressure waves in the air within the field. These pressure waves increase the Brownian motion of any aerosols within the field, which yields larger agglomerates. When applied to a smoke alarm, it is thought that the soot deposited proximate to a smoke alarm horn will have longer fractal chains than the soot deposited elsewhere on the same face.

2.3 Pulsed Flow

The sonic field induced by a sounding alarm has another effect: The resultant pressure waves create "pulsed" flow in and out of the smoke alarm horn opening [Worrell, et. al., 2003]. This flow has been proven to increase turbulence and create eddies locally on the external face of the smoke alarm horn and, hypothetically, internally as well. These eddies and increased turbulence increases contact between the soot particulates and the local faces of the smoke alarm horn, which may be one cause of the increased soot deposition

2.4 Chladni Figures

Chladni established that, when a harmonic vibration is established on a substrate, free sand particles on its surface migrate to the vibrational nodes. It was then theorized that soot particles could act analogously to grains of sand and migrate to vibrational nodes established on sounding horn discs [Worrell, et al., 2001]. These Chladni figures would appear only on smoke alarm horn discs that sounded during a fire event.

2.5 Worrell et al studies

Recently, Worrell, et al. [Worrell, et al., 2001 & 2003], have studied both enhanced soot deposition and Chladni figures as indicative signatures of smoke alarm sounding during a fire. The first study included a number of alarms subjected to a house fire [Worrell, et al., 2001]. All of the alarms had internally mounted horn chambers with circular horn openings, identical to the FGBI style alarms in this study (see Figure 0.17). The alarms were mounted in pairs, with one capable and one incapable of alarm. Worrell, et al., concluded that the alarms did show evidence of enhanced soot deposition that could be directly linked to the alarm sounding, but no evidence of Chladni figures was reported.

The second study by Worrell, et al., [Worrell, et al., 2003], included two models of alarms that were subjected to UL/EN-style fire tests with the following fuel sources: heptane/toluene pool, flaming polyurethane, smoldering polyurethane, flaming wood, smoldering wood, flaming paper, smoldering paper, and smoldering cotton wicks. The first alarm model was identical to that used in the first house fire study. The second type of alarm contained a horn chamber mounted to the cover of the smoke alarm with half moon-shaped horn openings, identical to the FBI style alarms in this study (see Figure 0.15). The alarms were placed in pairs, with one enabled and one disabled. After evaluation, positive and negative determinations were made for alarms sounding for the heptane/toluene and flaming polyurethane sources. Classification that an alarm sounded was possible for some cases of the smoldering polyurethane, smoldering paper, smoldering wood, and smoldering cotton wick fires. The conclusions resulted from a comparison of the density of soot deposition "on the central horn opening to deposits adjacent to the rim." A positive identification also required uniform deposition of soot around the entire circumference of the horn opening.

A series of tests was to visualize the flow field around the smoke alarm horn was included in the second study. These experiments were conducted in a modified UL smoke box. A laser sheet was generated to visualize the soot particulates within the smoke. Video recordings were taken of sounding alarms, which verified the “pulsed flow” phenomena in the sounding alarms.

3 Experimental Plan

Four test series were developed to accomplish the objectives of this study. Test Series 1 included a series of Underwriter's Laboratory (UL) and EuropeanUL/EN-based experiments for comparison to and evaluation of previous test results. Test Series 2 exposed a representative population of alarms to "nuisance" sources to evaluate the behavior of the smoke alarms and depositions so exposed. Test Series 3 investigated a variety of previously untested fuel packages. Test Series 4 studied the behavior of alarms in larger scale fire scenarios and incorporated new and used alarms from Test Series 2.

3.1 Test Series 1 – EN/UL Style Fire Tests

Test Series 1 simulates the studies conducted by Worrell, et al., for comparison of results, and serve as baseline experiments and data for the remaining portions of the study. Four fire sources were used in this series: smoldering polyurethane (PU), flaming PU, flaming wood, and flaming turpentine. The procedures were based on the studies by Worrell, et al., and EN 54 Part 9 fire sensitivity tests.

3.2 Test Series 2 – Nuisance Behavior

Test Series 2 was included to determine the behavior of smoke alarms and depositions exposed to "nuisance" sources. Three groups of alarms were subjected to the following nuisance sources: frying bacon, frying tortillas, burnt toast, frying breading, and airborne dust. These were selected as representative of exposures in average households that may induce sounding of smoke alarms. They were also selected to produce a variety of aerosols, to establish any behavioral differences between the aerosols/sources and expand the exposure history of the alarms. An alarm's exposure history was important for inclusion in Test Series 4, and will be discussed further in relation to the goals of those experiments.

The experiments were concluded once the situation was deemed to be an unrealistic nuisance scenario. This threshold was subjective and was meant to weigh two factors. The first factor is the transition of the nuisance source from a benign cooking source to a source similar to an incipient fire. From the standpoint of a smoke alarm, these cooking events produce particulates similar to those from a fire. The airborne products are analogous to the products of incomplete combustion and arrive at the detector by a convective current. Defining the difference between nuisance source and incipient fire, from the perspective of alarm operation, is a measure of concentration. This leads to the second factor, a judgment of the airborne concentration within the context of a cooking event, which was established by the experimenter during the experiments.

3.3 Test Series 3 – Additional Source evaluation

One of the goals of this investigation was to expand the number of fuel sources to which alarms have been exposed to understand the limitations of enhanced soot deposition as a forensic technique. The previous studies in the literature [Worrell, et al., 2001 & 2003] primarily focused on UL/EN experiments, with one full-scale residential fire experiment. This series includes the following exposures: smoldering electrical cable, smoldering transitioning to flaming electrical cable, flaming boxes filled with paper, and flaming boxes filled with plastic cups. All of the exposures are realistically applicable to residential fires and have not been investigated previously with relation to enhanced soot deposition on smoke alarm horns.

3.4 Test Series 4 – Larger Scale Scenarios

Test Series 4 investigated a number of possible factors affecting soot deposition on smoke alarm horns, including smoke alarm and soot deposition behavior in relation to larger scale fire scenarios. The scenarios were conducted in a multi-room test arena and were modeled after real fires. Included in this series were smoldering-to-flaming transition of a cabinet-and-wall assembly and the flaming ignition of one-half of a couch. The multi-room configuration enabled placement of comparable alarms at varying distances from the source to evaluate the effect of distance from the source on the manifestation of soot patterns. Within this series, alarms exposed to nuisance sources during Test Series 2 were incorporated to determine the effects of nuisance exposure on the development of soot patterns. A small population of smoke alarms was collected from homes and had been *in situ* for varying amounts of time. These used alarms were placed into this series to evaluate the effect of unknown exposure histories on the development of soot patterns during the exposures.

4 Experimental Facilities

4.1 Basic Compartment Layout

The experimental facilities include a compartment constructed in the lab space at the headquarters of Hughes Associates, Inc., in Baltimore, Maryland. The total compartment, including the two smaller compartments and hallway, measures 33 feet by 33 feet by 10 feet in height. The space is constructed from standard stud and drywall with Plexiglas windows mounted variously around the exterior wall to allow for visual monitoring of experiments. The interior of the space is divided into 3 compartments and one hallway (see Figure 4.1).

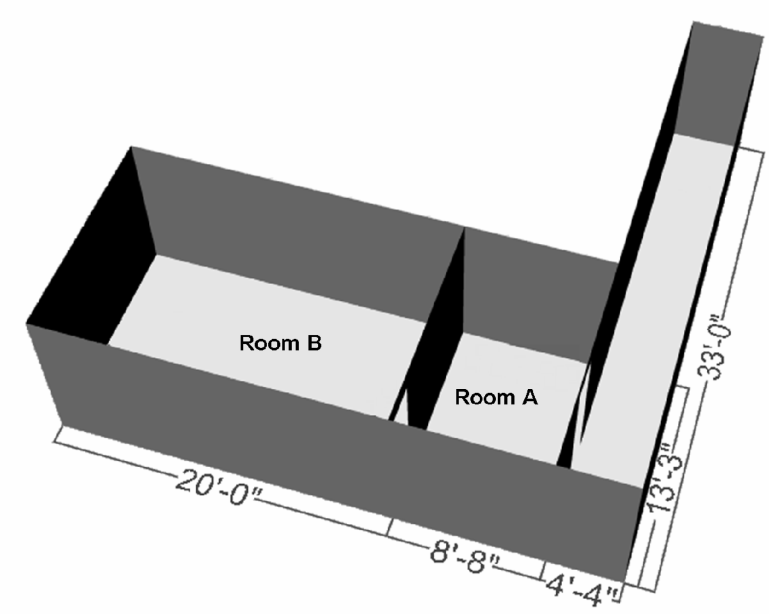

Figure 4.1 Basic compartment layout.

The interior walls are constructed of 3/8 inch drywall and steel studs nominally 18 inches on center. Exterior doorways are located at diagonal corners of the space in the hallway and medium sized compartment. The compartment ventilation is located approximately 10 feet from the end of the hallway, at the top right of Figure 4.1. A three-foot by three-foot vent is mounted in the ceiling. During all tests, the vents remained closed with the fan off until the experiment was terminated.

4.2 Test Series 1

The two smaller compartments and the hallway were utilized in different combinations for the various test series conducted. During Test Series 1 the smallest compartment, measuring 8 feet 8 inches by 13 feet 3 inches, and the hallway, measuring 4 feet 8 inches by 33 feet, were utilized. The doorway to the medium-sized compartment (Compartment A) was sealed with a sheet of 3/8 inch drywall for the duration of Test Series 1 and the door at the end of the hallway was closed while the experiments were in progress. This configuration is depicted in Figure 4.2, and includes an area of 267 square feet.

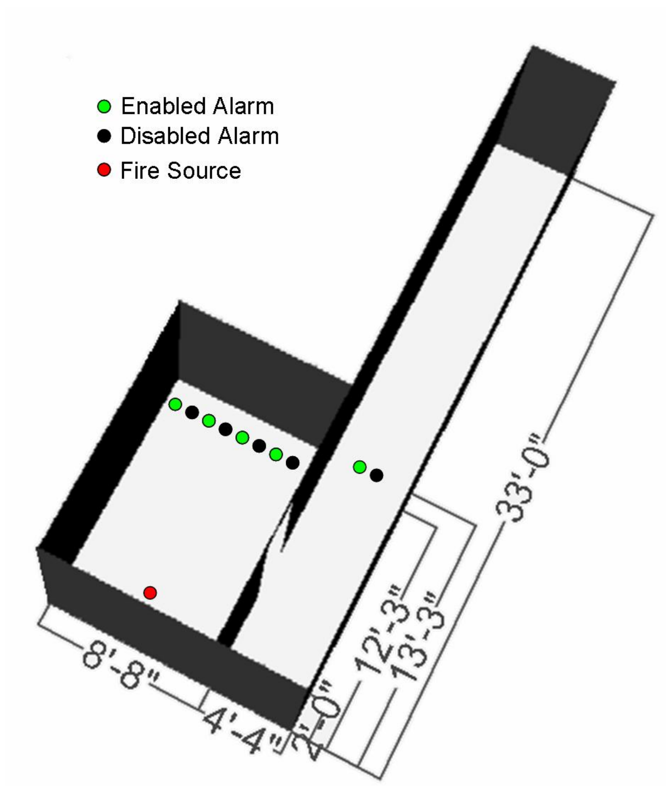

Figure 4.2 Test Series 1 compartment layout

4.3 Test Series 2

For the nuisance exposures of Test Series 2, the small compartment was used. The layout is pictured in Figure 4.2. The small compartment was chosen for its similarity to a residential kitchen. The room was isolated from Room B with a sheet of 3/8 inch drywall. During all of the cooking events, Room A was open to the hallway. Shown in Figure 4.3, the configuration is an area of 267 square feet.

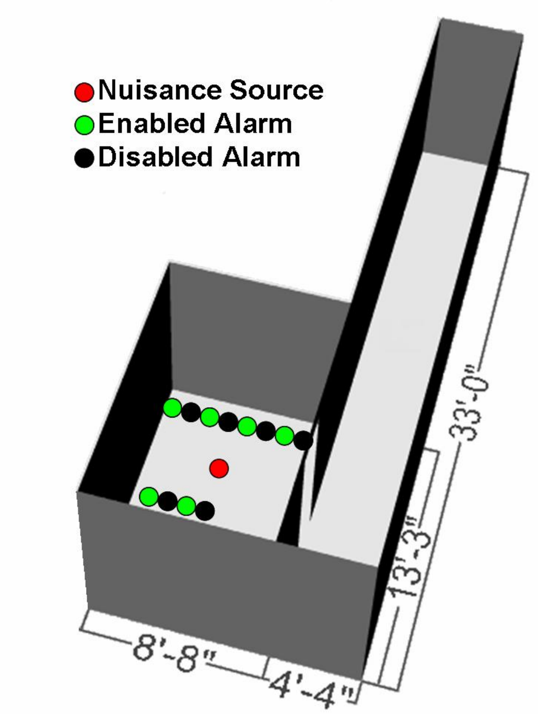

Figure 4.3 Test Series 2 compartment configuration.

During the airborne dust exposure, the doorway to the hallway was covered with a plastic sheet to contain the dust to the small compartment, reducing the area to approximately 113 square feet.

4.4 Test Series 3

Test Series 3 was conducted completely within the hallway. The hallway was isolated from Rooms B with sheets of 3/8" drywall (see Figure 4.3), and had an area of approximately 154 square feet.

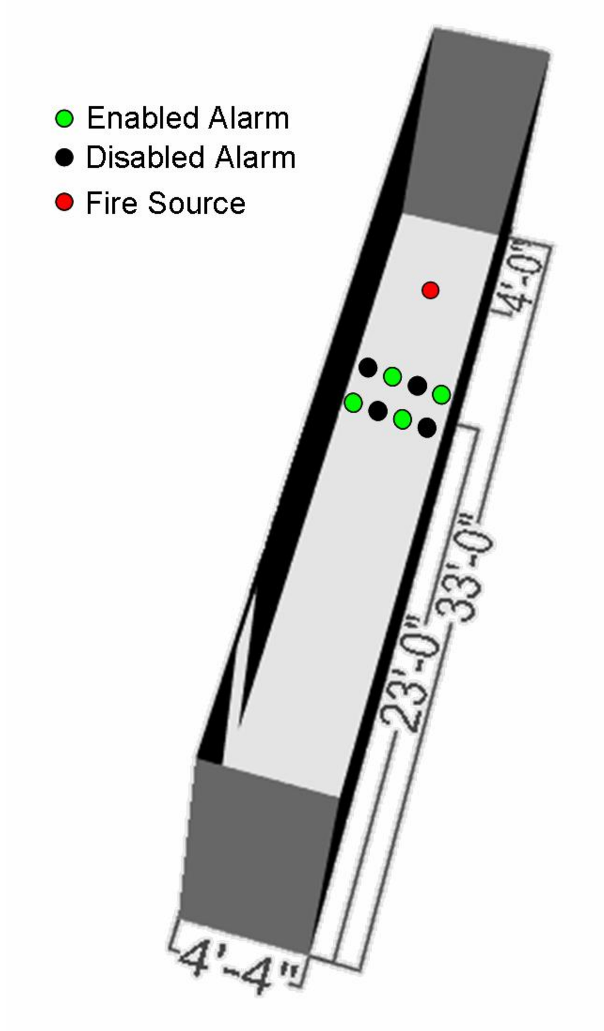

Figure 4.4 Test Series 3 compartment layout.

4.5 Test Series 4

Test Series 4 was designed to examine a larger scale fire event than prior test series and required the use of multiple compartments. Using Rooms A and B and the hallway, a multi-compartment geometry was created that is similar to many apartment and home settings. The configuration, an area approximately 550 square feet, is shown in Figure 4.5.

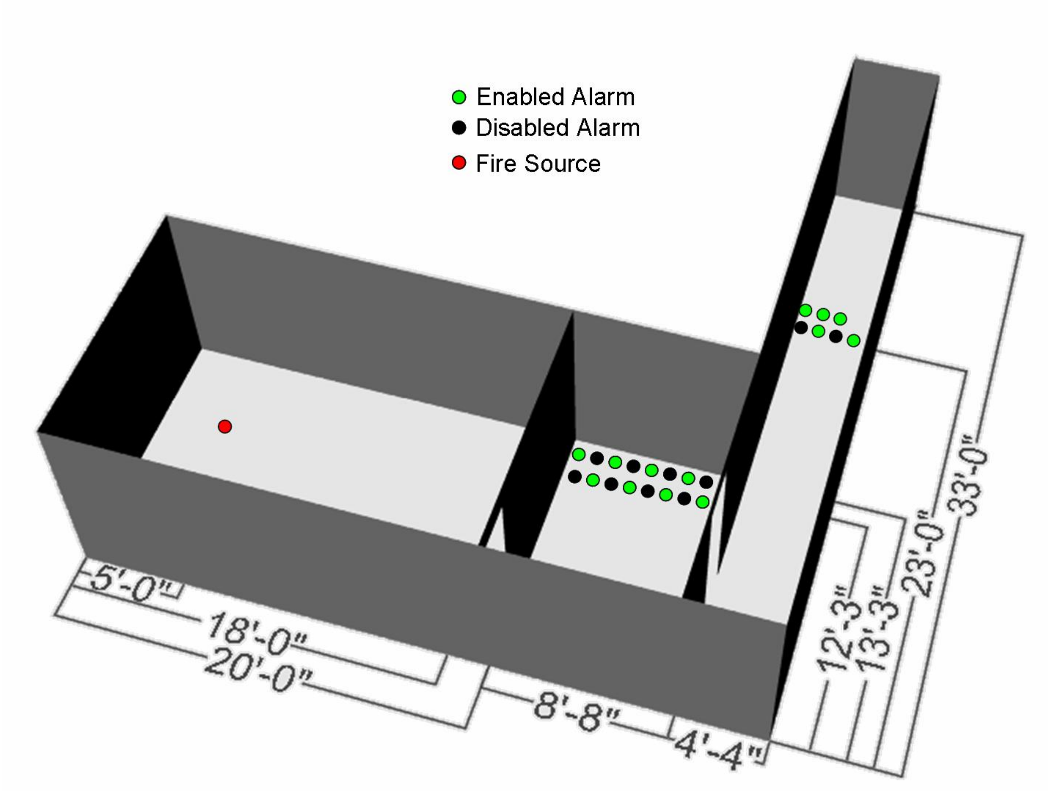

Figure 4.5 Test Series 4 compartment layout

5 Instrumentation and Data Collection

5.1 Pre-test Examination and Documentation

Prior to testing, all of the smoke alarms were examined and documented. Alarms were given a unique designation, which was permanently marked on the back of the alarm. Examples of each of the alarm types were examined and compared macroscopically and microscopically prior to testing to identify the differences in the alarms that might affect the manifestation of soot patterns. This included horn geometry, alarm surface textures, sound pressure level, etc. Comparisons between alarms of the same type were conducted to understand the variability of production and to ascertain whether the variability might affect the patterns. Photos were taken during these initial examinations to document the “new” state of the alarms and to serve as a post-test comparison. If new alarms of the same type were deemed sufficiently similar, the pre-test examination and documentation consisted only of a macroscopic external examination and documentation of the front back and horn opening. All of the used alarms were thoroughly examined and documented, including macro- and microscopic photographs.

5.2 Acoustic monitors

When studying the response and sounding of smoke alarms, alarm time is always important to document. However, with multiple alarms, the potential for simultaneous sounding makes it impossible to simply listen for the alarm tones. Therefore, many alarm studies have monitored a voltage difference between 2 pins on the chip on the alarm circuit board that compares the transient voltage from one of the plates within the ion chamber and a pin representing a reference voltage. Both the transient and reference voltages are specific to each type of alarm. The voltage difference is monitored using a data acquisition system. This method requires opening the alarms, removing the board, soldering wires to the pins, and replacing the boards. It is inherently intrusive and therefore undesirable. It is also necessary to equate the voltage difference to the actual sounding of the alarm. The results of this technique are indications of when an alarm should have sounded. There is no verification that the horn operated and the alarm sounded. In many studies, the behavior of the detection mechanism is more important than the notification. In this study however, the horn activity is of utmost importance. Therefore, it is necessary to know precisely when the horn sounded and of much lesser consequence how the detection mechanism was interpreting the sources. Ideally, the alarm horns would be monitored for when they sounded.

A technique developed by Kidde [Ratzlaff, 2003] enabled acoustic monitoring of the horn output via a non-intrusive method. The circuit diagram for the acoustic monitors is located within Appendix A. The concept utilizes a directional microphone to obtain the sound of the alarm horn in operation. A chip monitors the signal from the microphone and when the signal eclipses an established threshold the signal passes through to the data acquisition system. The sound threshold is established by sending the signal through a resistor series. In this way it is possible to tune the threshold to the specific experimental setup. With this technology, multiple alarms can be grouped in proximity and still be monitored individually for an audible signal. As can be seen in Figure 5.1, adjustable Loc-Line hose directs the alarm tone to the microphone positioned at the base of the hose.

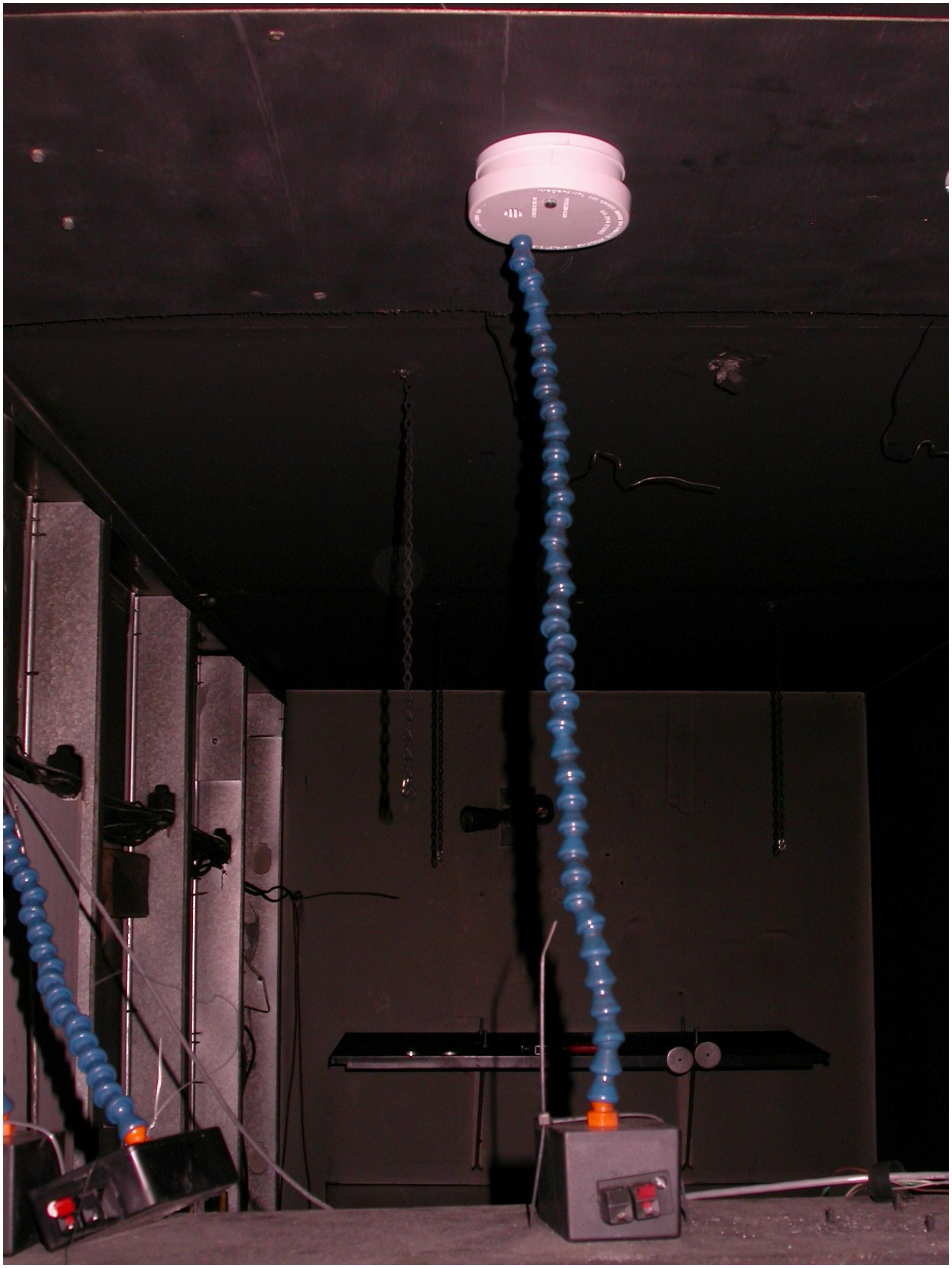

Figure 5.1 Acoustic Monitor.

Through experimentation it was determined that the line could be positioned up to three inches from the alarm horn opening and still register the sounding of the horn without interference of other nearby alarms. At greater than 1 1/2 inches from the horn opening it was estimated from the Worrell et al. results that the Loc-Line would not interfere with the pulsed flow phenomenon previously discussed

Figure 5.2 Loc-Line Hose oriented approximately 1 and 1/2 inches from the smoke alarm.

This technique precisely identifies the time the horn activates and deactivates, providing the exact duration of alarm sounding and enabling further investigation of the effects of alarm duration on enhanced soot deposition, including situations where the horns sounded intermittently during the test.

5.3 Data Acquisition

5.3.1 System

A Pentium computer running Microsoft Windows was used to run the Program Labtech Pro 10. In conjunction with Keithly Metrabyte Das-8 Exp 16 cards, this program allowed for the monitoring of analog signals. All of the instrumentation was monitored as analog signals. No processing was done in Labtech except changing the analog signal from the type K thermocouples into degrees Celsius. Measurements were recorded once per second for all of the monitored signals. Labtech generated a .prn data file, which was then imported into Microsoft Excel for data analysis.

5.3.2 Instrumentation

Instrumentation varied slightly within the four testing series, although certain instruments were present in every case. At each smoke alarm bank, temperature was measured with a Type-K thermocouple. Thermocouples (TC's) monitored air temperatures. Type-K, 24-gauge, bare-bead TC's measured the gas temperatures at the detectors. The TC's were positioned at the approximate height of the detectors, 8 cm (3 inches) below the ceiling. In addition, one TC was placed 1.5 m (5 feet) from the floor to measure the air temperature for tenability purposes.

Proximate to each bank, optical density was measured by Optical Density Meters (ODM's) mounted on the ceiling in the small compartment and in the hallway to monitor smoke development, as shown in Figures 5.3 through 5.5. The ODM's had a 1.5 m (five feet) path length and were positioned adjacent to each grouping of smoke detectors, such that the white light beam was 10 cm (4 in.) below the ceiling. The ODM consisted of a spotlight and a photocell consistent with the specifications in UL 217 [UL, 1999]. In addition, one ODM was placed in the center of compartment 1 at 1.5 m (5 feet) above the floor to measure the optical density at head height for tenability purposes.

Figure 5.3 Ceiling ODM in the small room.

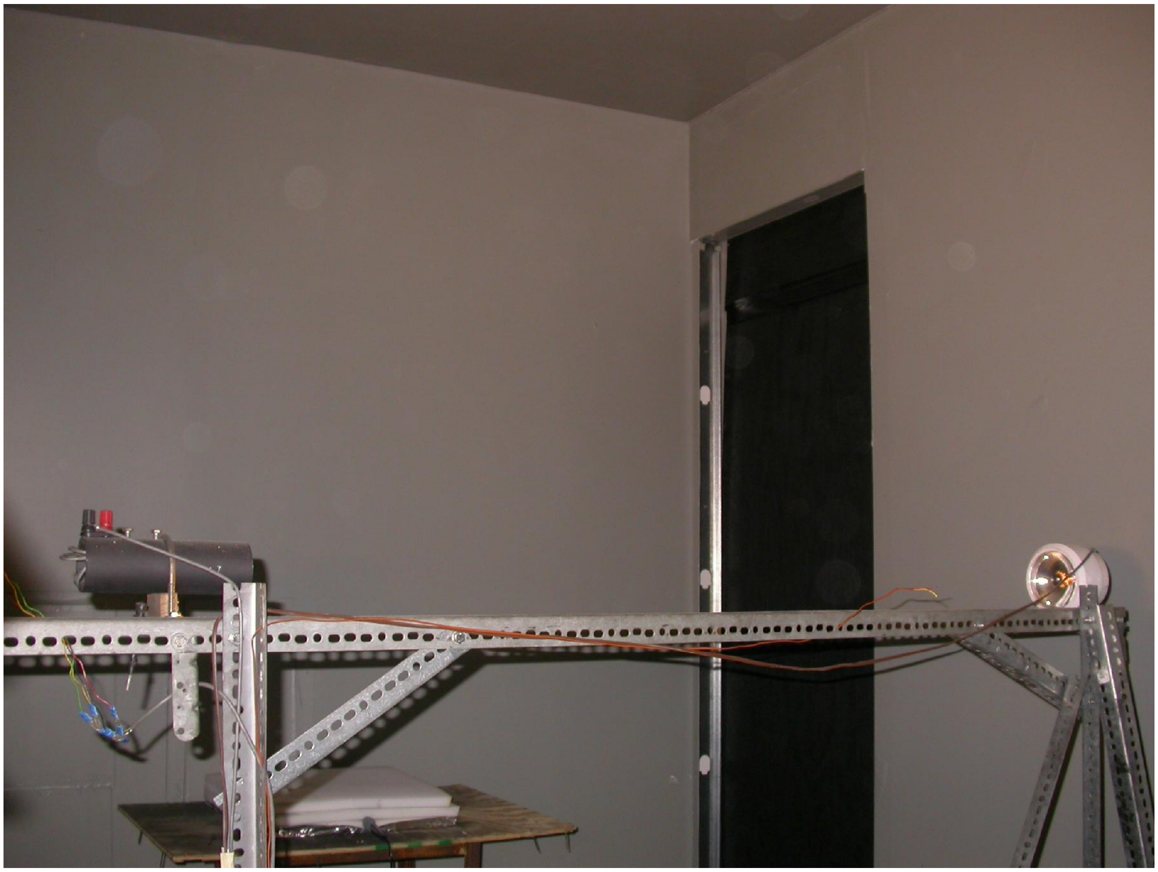

Figure 5.4 ODM at five feet high in Room A.

Figure 5.5 Hallway ODM at ceiling level.

When possible, carbon monoxide histories were generated at the same locations as the temperature and optical density histories. Using electrochemical cell CO sensors (Citicel, model 3E/F) and non-dispersive IR carbon monoxide gas analyzers (Horiba stack gas analyzer system model VIA-510) CO was measured. The Citicel had a range of 0 to 200 ppm carbon monoxide with an accuracy of 0.5 ppm. One of the carbon monoxide gas style analyzers has a range of 0 to 1000 ppm, which was not sufficient for the cabinet assembly fire. The other carbon monoxide gas analyzer has a range of 0 to 5000 ppm, which was sufficient for the couch fire.

6 Experimental Procedures

6.1 Test Series 1: EN/UL Style Test Fires

6.1.1 Alarm Selection and Placement

The smoke alarms selected for inclusion in Test Series 1 were all new alarms. One pair each of alarm types FSBI, FACI, FGBI, and FBI, pictured in Figures 0.3-0.13, were mounted in a line on the ceiling of the small compartment, two feet from the wall of the compartment opposite the fuel source, as pictured in Figure 4.2. The line of alarms began and ended 10 inches from the sidewalls of the compartment, and alarms were spaced 12 inches on center. Each pair of identical alarms was mounted next to the other in the line. In addition, one pair of FBI alarms was mounted in the hallway 15 feet from the fire source. The alarms were centered across the hallway, spaced 12 inches on center. All alarms banks were mounted on 3/8 inch plywood boards secured to the ceiling of the test facility. The manufacturer-supplied bases were attached to the plywood with wood screws and the alarms were locked into the prescribed bases (see Figures 6.1 and 6.2). For all of the tests, the convention established in previous studies of creating a control population of alarms for comparison was followed by utilizing identical pairs of alarms with one enabled and one disabled. Except for the used alarms (where it was impossible to have two identical alarms), alarms were always placed next to an identical alarm, as previously defined. One of each of these alarms was enabled through proper installation of the 9V battery and one was disabled through improper installation of the battery.

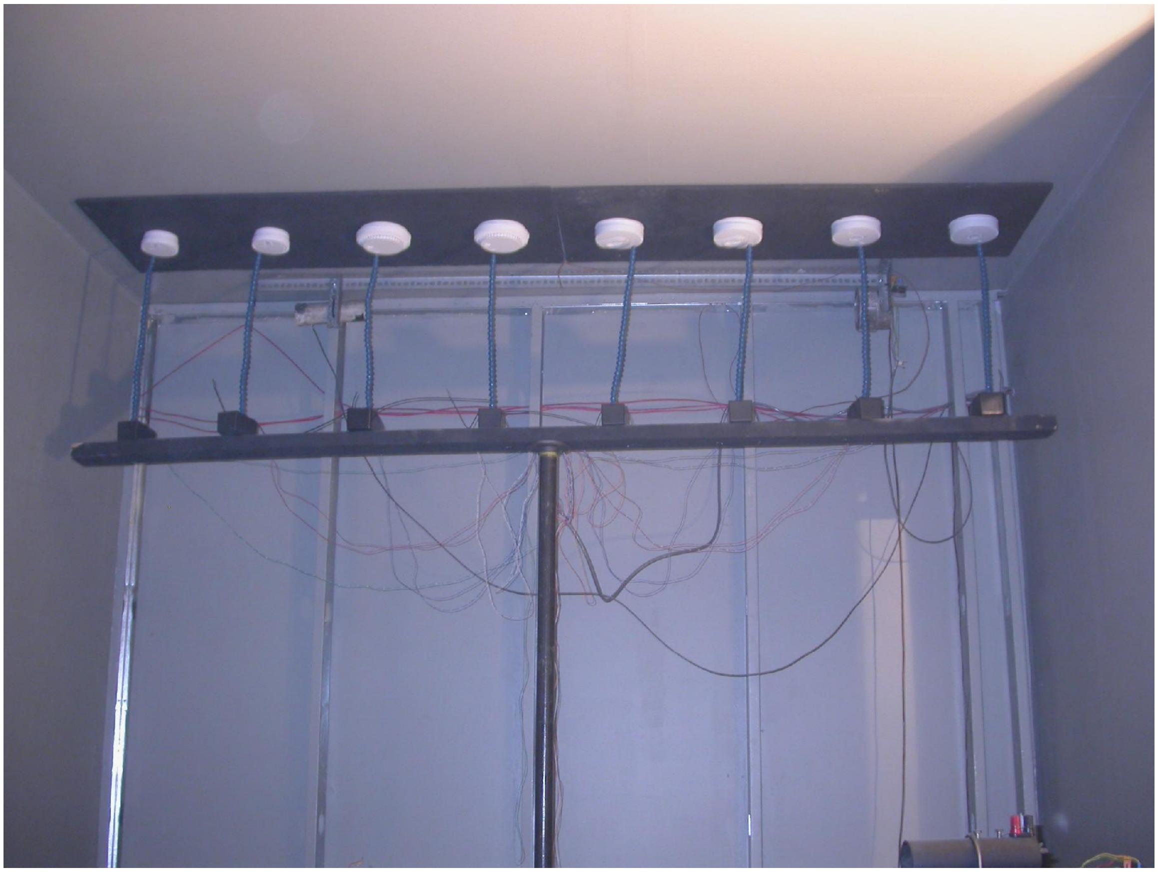

Figure 6.1 The alarm bank mounted in Room A Test Series 1. The bank consisted of four pairs of new alarms, enabled and disabled. One pair each of FBI, FGBI, FSBI, and FACI alarms.

Figure 6.2 The bank of alarms mounted in the hallway for Test Series 1. The bank consisted of one pair of new FBI alarms, one enabled and one disabled.

During Test Series 1, all alarms, whether enabled or disabled, were monitored with acoustic monitors. None of the alarms that had been disabled sounded, which verified both the disabling technique and the auditory isolation provided by the Line-Locs. During Test Series 2-4 it was necessary only to monitor the enabled alarms with the acoustic monitors.

6.1.2 Fuel Sources

Flaming Polyurethane:

Worrell , et al., utilized foam from a couch cushion. The 2-and-3/8-inch thick foam was cut to create a triangular prism with a base of 13 ½ inches and a height of 7 inches. The fuel package was set up with the base seven feet below the ceiling and was ignited at the tip using a butane lighter. The EN54 standard specifies three 19.7 inches by 19.7 inches by 0.8 inches non-fire-retardant polyurethane sheets with a density of approximately 1.25 lb/ft^3 [CEN, 1982]. The three sheets are laid atop one another on a sheet of aluminum foil. The package is lit at a corner using 5 cm^3 of methylated spirits in a 2 inch diameter bowl ignited by a flame or spark. The fuel package used in this test series was chosen to correspond with the EN54 tests. The material used was non-fire retardant foam of density approximately 1.25 lb/ft^3 in accordance with EN54. Three sheets measuring 20 inches by 20 inches by 3/4 inches thick were placed atop an aluminum foil sheet with the edges of the aluminum foil raised approximately 1/2 inch. This assembly was then placed in a 20.5 inches by 20.5 inches pan. The fuel was ignited by a butane lighter at one corner of one of the bottom sheets.

Smoldering Polyurethane:

Worrell, et al., used two 8-inch by 8-inch by 4-inch-thick sheets of polyurethane fastened together using a metal wire tie. The entire metal tip of a 30 W pen style soldering iron was inserted between the two sheets to initiate smoldering. There is no EN54 procedure for smoldering polyurethane. For the current study, the same foam was used as in the flaming tests. In Test 1.1 three sheets measuring 20 inches by 20 inches by 3/4 inch polyurethane were fastened together using a metal wire tie. The entire metal tip of a 30 W pen-style soldering iron was inserted between the bottom two sheets to initiate smoldering. During Test 1.1 no alarms sounded because the fuel was only consumed in a few inch radius around the pen tip, (see Figure 6.3), affecting an area approximately one-half of the 20 inch by 20 inch sheets.

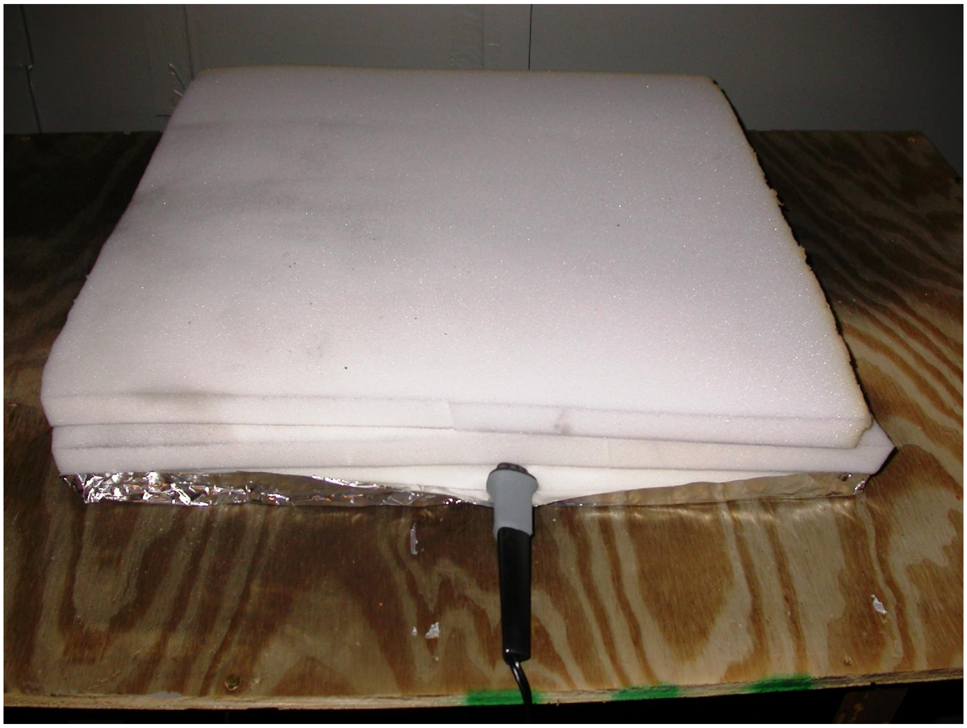

Figure 6.3 Original smoldering polyurethane source prior to Experiment 1.1.

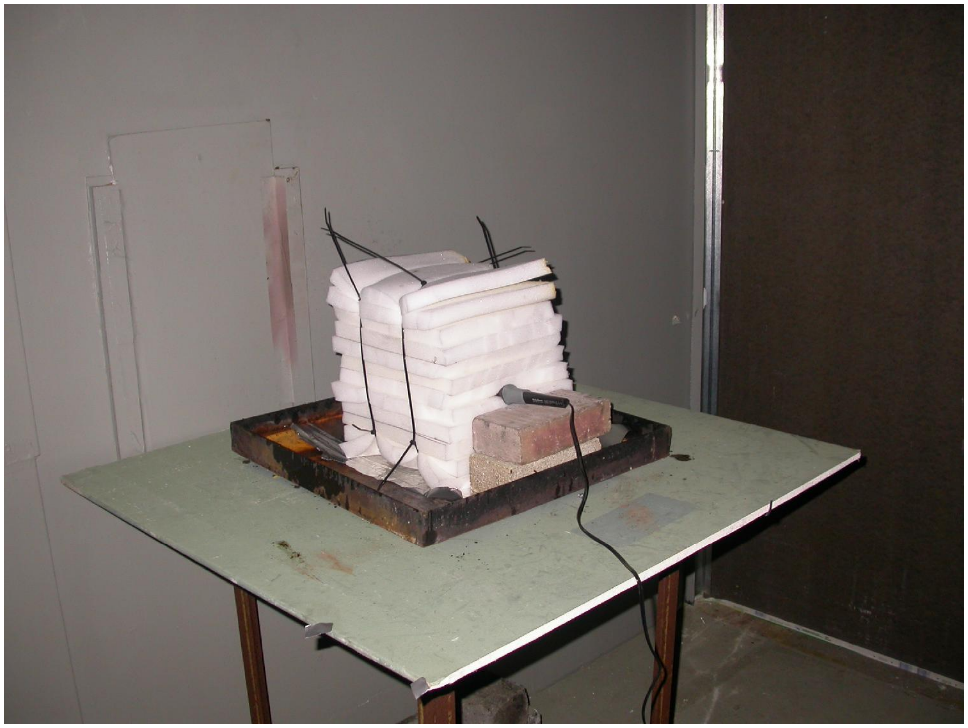

Figure 6.4 Reformatted polyurethane source before Experiment 1.2.

The area of the sheets was reduced by one-half and twice the number were used (see Figure 6.4). This supplied the same amount of fuel but allowed for a much greater portion to be consumed and activate alarms. Test 1.2 utilized six 10 inch by 10 inch by 3/4 inch sheets of the same polyurethane foam with the 30 W soldering iron tip placed between the third and fourth sheets from the bottom.

Flaming Wood

Worrell, et al., constructed a wood crib from 18 pieces of Douglas fir or pine. The crib consisted of three layers of six pieces, each 6 inches by 3/4 inch by 3/4 inch and was elevated on a ring stand such that the base was seven feet below the ceiling. The crib was ignited using a small amount of denatured alcohol in a 1-1/2-inch diameter container placed 3-1/2 inches below the crib. In comparison, the EN54 flaming wood fire utilizes 70 dried Beachwood sticks measuring 0.4 inches by 0.79 inches by 9.8 inches stacked in the crib arrangement shown in Figure 6.5 [CEN, 1982]. The crib is ignited at the center of the base surface using five cm^3 of methylated spirits, in a two-inch-diameter bowl, ignited by a flame or spark.

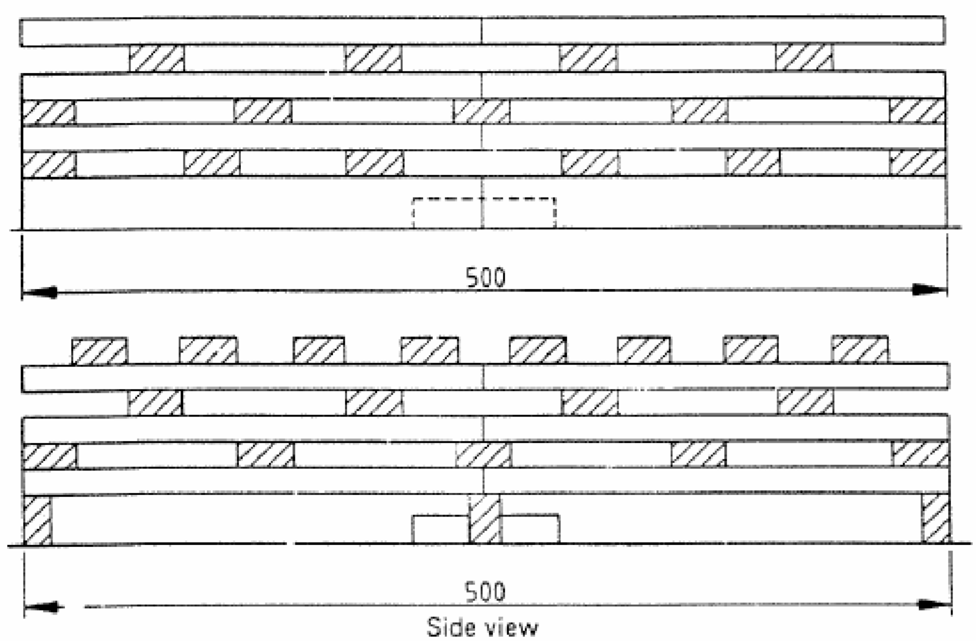

Figure 6.5 EN54 prescribed wood crib, figure from CEN, 1982.

The EN54 arrangement was utilized during Test 1.4, excepting that the ignition source was a 1/2 inch by 1/2 inch by 1/2 inch cup of methylated spirits lit with a butane lighter (see Figure 6.6).

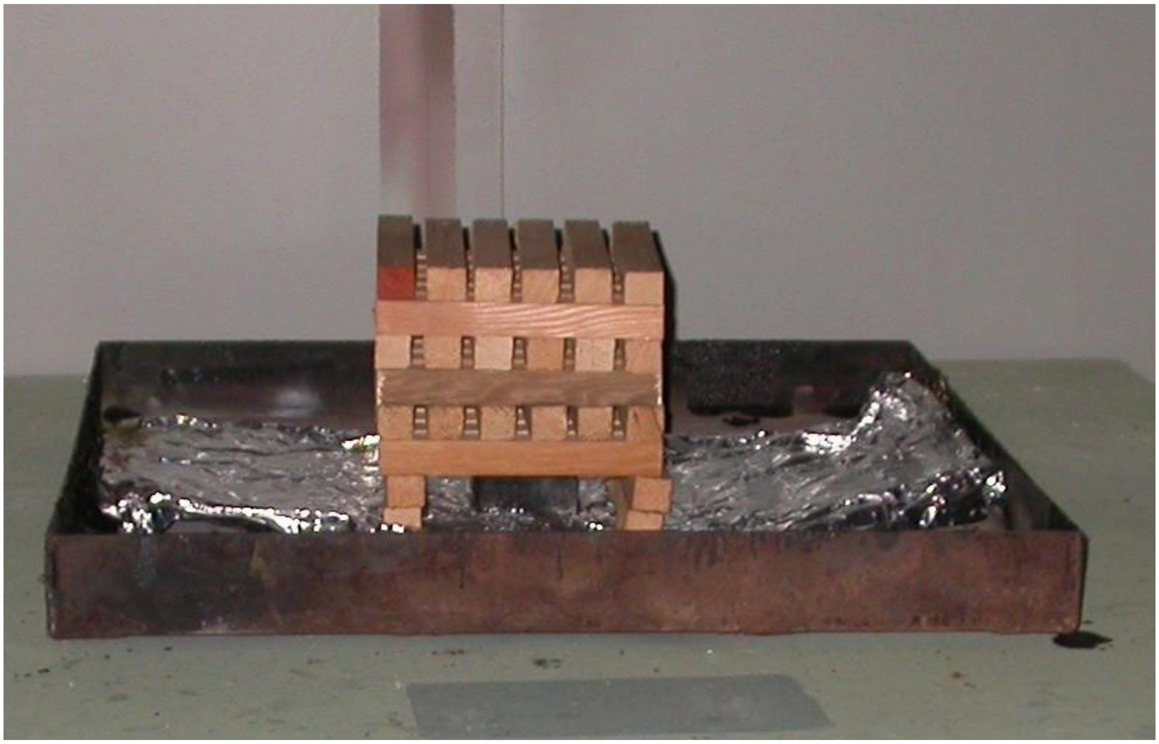

Figure 6.6 Wood Crib source prior to Experiment 1.4.

Flaming Turpentine:

For Test 1.6, a 6-inch by 6-inch by ¾-inch pool fire was ignited with a propane torch. The source was placed on a table seven feet from the ceiling towards two feet from the exterior wall of the small room (Compartment A) as with the other scenarios in Test Series 1.

6.2 Test Series 2: Nuisance Sources

6.2.1 Alarm Selection and Placement

Twenty four new alarms in Test Series 2 were exposed to nuisance sources: eight each of the FBI, FACI, FGBI, and FSBI style alarms. This provides for inclusion of enabled/disabled pairs of nuisance-exposed alarms in Test Series 4 while leaving pairs of each for the blind analysis. For this series, all alarms were enabled. The alarms were divided into two populations of 12, with the nuisance exposure series run, for each population. Eight alarms were mounted in the same positions as in Test Series 1, two feet from the wall, 12 inches on center, with the remaining four mounted symmetrically along the opposite wall, as shown in Figure 4.3 on page 4.3. The nuisance sources were placed in the center of the small room.

6.2.2 Sources

There is no prescribed methodology for exposing smoke alarms to nuisance sources, nor has a "typical" exposure level to nuisance sources been defined in literature. In running the experiments, 12-15 minutes of nuisance exposure yielded the pre-defined end of test conditions. During this exposure, the alarms were in alarm between 2 ½ and 13 minutes. Completing two complete cycles of cooking exposures meant each alarm had been exposed to multiple nuisance sources for approximately 120 minutes and had sounded during those exposures for about an hour. This exposure facilitated the first goal of this series, to understand whether nuisance sources behaved analogously to soot from fires relative to enhanced deposition. The time in alarm exceeded that necessary to manifest soot patterns during fire conditions, smoldering and flaming.

Frying Bacon

A small amount of vegetable oil was added to an eight-inch-diameter griddle until the surface was evenly coated. The oil was heated to boiling using a single burner, propane-fueled grill. Bacon was cooked on the griddle for 12-15 minutes. During this time, bacon was removed from the griddle before it burnt or was deemed inedible. (See Figure 6.7 for typical bacon) For each test, 2/3 to 3/4 of a pound of bacon was cooked, resulting in sounding of smoke alarms sounding for 10 to 12 minutes.

Figure 6.7 Typical end product of the frying bacon nuisance exposure tests in Test Series 2.

Frying Tortillas

A small amount of vegetable oil was added to an eight-inch-diameter griddle until the surface was evenly coated. The oil was then heated to boiling using a single burner camping style grill fueled with propane. Tortillas were added to the oil and both sides were cooked until they were brown. The tortillas were removed or flipped before they were burnt (see Figure 6.8). This procedure was continued for 12-15 minutes during which one package of approx. 10 tortillas was cooked. The smoke alarms sounded for a duration of 10 to 12 minutes.

Figure 6.8 Typical results of the frying tortillas nuisance exposures in Test Series 2.

Burnt Toast

Four slices of white bread were toasted at the darkest setting for three cycles in a Magic Chef (model number N-10 120 V AC 60 Hz 1500W) toaster. After three cycles, the bread was darkly toasted to slightly burnt. (See Figure 6.9 for exemplar toast.) The toast would start smoking slightly on the second cycle and the alarms would sound shortly thereafter. The toast was toasted for 12-15 minutes using approximately half a loaf of white bread. This placed the smoke alarms into alarm for a period between 10 and 12 minutes. At this time the aerosols in the room became such that it could no longer be fairly categorized as a nuisance situation.

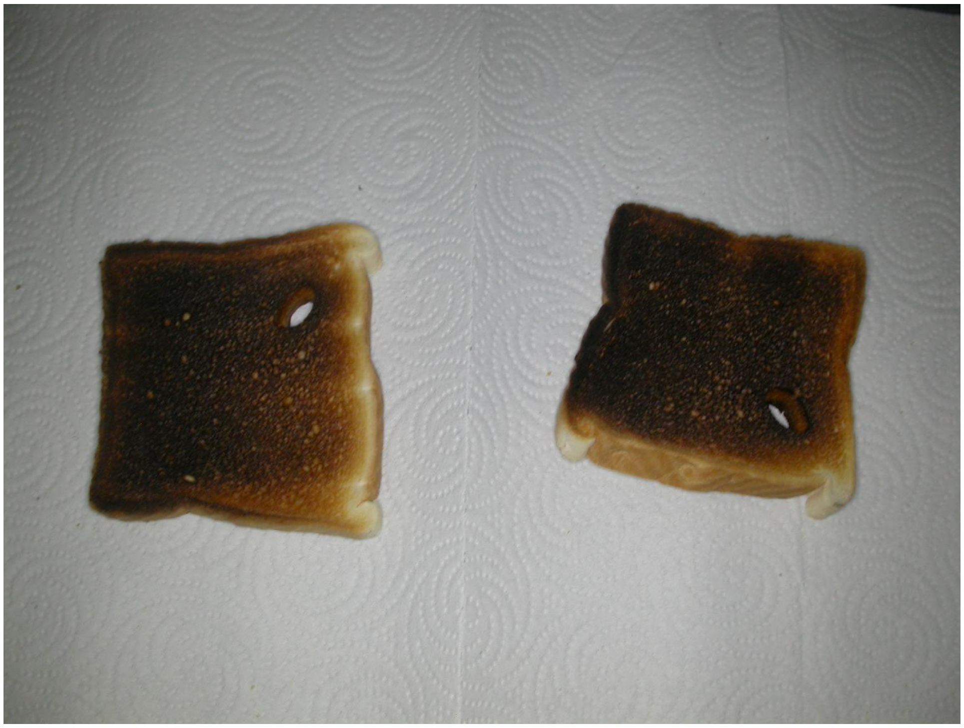

Figure 6.9 Typical of toast burnt in the nuisance exposure tests of Test Series 2.

Deep Frying Batter

A mixture of eggs, milk and flour was mixed until it was the consistency of batter suitable for chicken or fish. Vegetable oil was poured into an eight-inch-diameter griddle until it was approximately an inch deep and was heated with a single burner stove fueled by propane. Once the oil was bubbling, batter was poured into the oil and deep-fried until it was brown when it was removed. (See Figure 6.10 for exemplar batter.) Batter and oil was added as needed to continue frying batter for 12-15 minutes. At this time the alarms had sounded for 10-12 minutes and the conditions were no longer consistent with a nuisance event.

Figure 6.10 Typical end product of batter fried during the deep-fried batter nuisance exposures of Test Series 2.

Airborne Dust

For each test, approximately two kg of dust from household vacuum cleaners was placed into a 16 gallon 5.25 HP peak Rigid brand wet/dry shopvac. The filter was removed from the shopvac and the hose was placed on the discharge port. A ¼-inch wire mesh was fixed to the end of the hose, which was clamped to a stand in the center of Room A with the open end of the hose pointing vertically upwards, approximately seven feet below the ceiling. The shopvac was activated, dispersing dust within the room for approximately 25 minutes. Periodically, the shopvac was agitated to clear the mesh or ensure the dust within the shopvac was effectively transferred. After 25 minutes there was still some dust being circulated in the room by the turbulence created by the blowing vacuum, but there was a marked decrease in visible airborne dust from the peak concentration.

6.3 Test Series 3: Alternative Fire Sources

6.3.1 Alarm Selection and Placement

Test Series 3 was conducted entirely within the hallway; as such, all alarms were mounted therein. The alarms were mounted on 3/8-inch plywood at ceiling level approximately midway within the hallway. Each experiment included eight alarms, enabled/disabled pairs of new FBI, FGBI, FACI, and FSBI alarms. They were mounted as shown in Figure 6.11, two rows of four spaced 12 inches on center.

Figure 6.11 The bank of smoke alarms typical of the arrangement of alarms in the hallway for Test Series 3. The bank consisted of eight new alarms, one pair of enabled and disabled alarms each of new FBI, FGBI, FSBI, and FACI alarms.

6.3.2 Fuel sources

Smoldering Cable Bundle

As Seen in Figure 6.12, a bundle of cable consisting of 5 pieces, each one foot in length (Monroe Cable Co., LSTSGU-9, M24643/16-03UN XLPOLYO), surrounding one 500 W cartridge heater (Vulcan, TB507A) was used to create a smoldering source. The heater was energized using a variac set at 96 VAC (80% of 120 V max).

Figure 6.12 A Cable bundle typical of that used for smoldering and flaming cable fires for Test Series 3.

Smoldering Transitioning to Flaming Cable Bundle

A bundle of cable consisting of five pieces, each one foot in length (Monroe Cable Co., LSTSGU-9, M24643/16-03UN XLPOLYO), surrounding one 500 W cartridge heater (Vulcan, TB507A) was used to create a smoldering source. The heater was energized using a variac set at 96 VAC (80% of 120 V max). After three minutes of smoldering, flaming ignition was piloted with a butane lighter.

Flaming Cardboard Boxes

A total of four boxes measuring 10 inches by 10 inches by 4.5 inches were loosely filled with crumpled brown paper and positioned in two rows side by side with a one inch flue space between the rows. The boxes were oriented in each row so that the longer sides faced the opposite row across the flue space; See Figure 6.13. A butane lighter was used to ignite a bottom corner of a box in the flue space so that flames propagated up the flue space and involved both boxes.

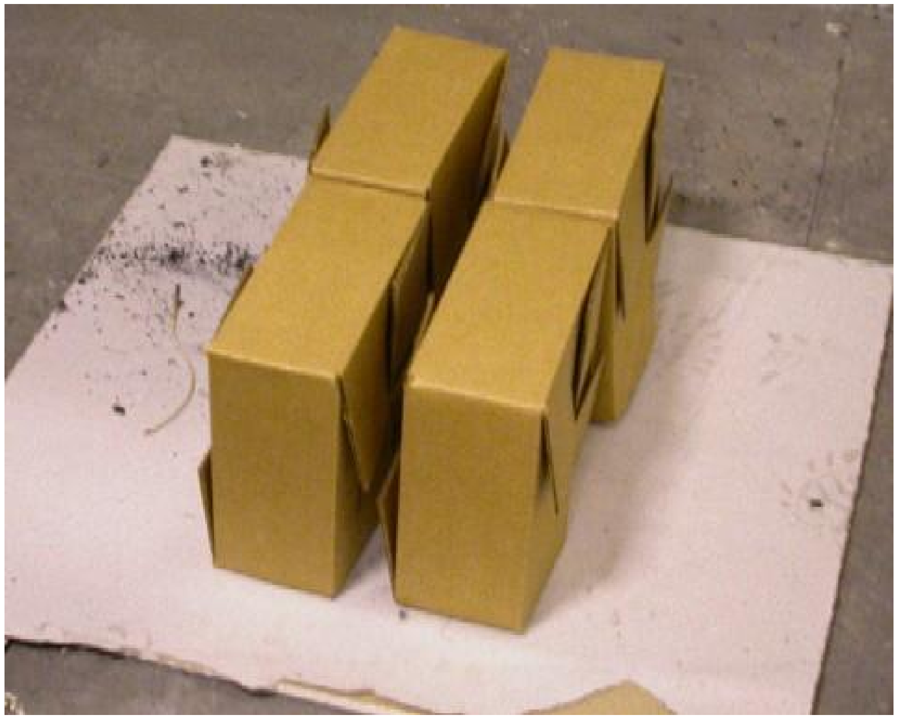

Figure 6.13 Arrangement of boxes for the boxes filled with paper experiment in Test Series 3. The boxes were ignited with a butane lighter in the central flue space.

Flaming Cardboard Box (plastic)

Two boxes measuring 10 inches by 10 inches by 4.5 inches were loosely filled with plastic cups and bubble wrap and positioned in two rows side by side with a one-inch flue space. The boxes were oriented end to end so that the longer sides faced the opposite box. A butane lighter was used to ignite a bottom corner of a box in the flue space so that flames propagated up the flue space and involved both boxes; See Figures 6.14 and 6.15

Figure 6.14 One of the boxes with cups and bubble wrap that was burned in the flaming box with cups test fire in Test Series 3.

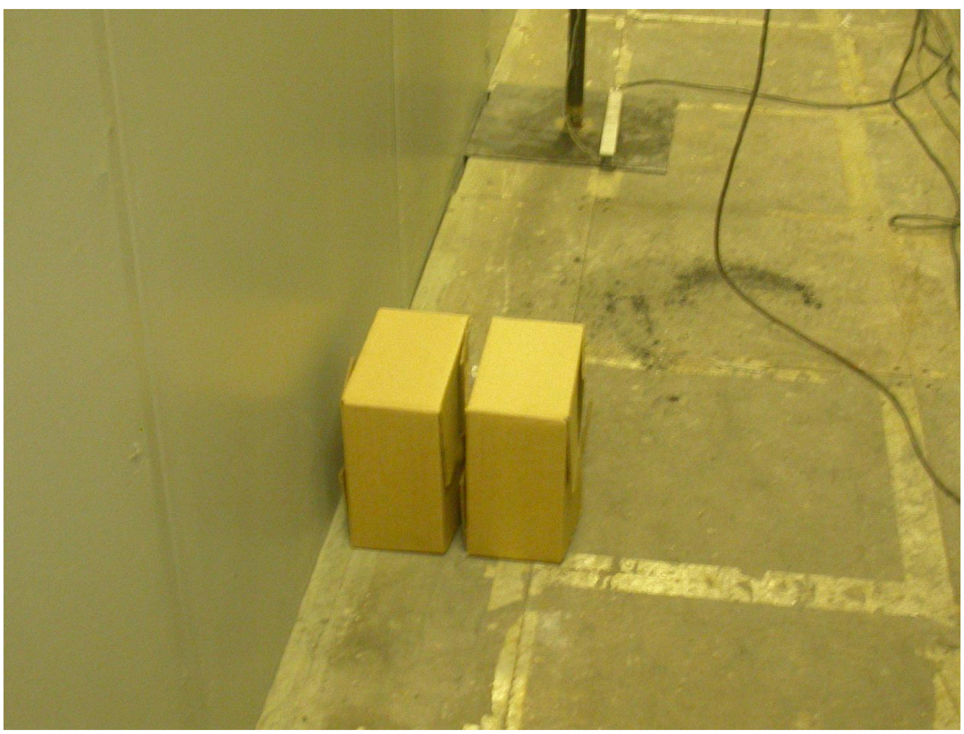

Figure 6.15 The arrangement of the boxes with cups used in Test Series 3. The boxes were ignited in the central flue space with a butane lighter.

6.4 Test Series 4: Larger Scale Fires

6.4.1 Alarm selection and Placement

As discussed previously, Test Series 4 was designed as a multi-compartment experiment to allow the exploration of the effects of larger fire scenarios, varying distance between smoke alarms and the source, and different exposure histories. To explore these variables and also maintain a control set of alarms, 28 alarms were placed in each experiment. Of the 28 alarms, two new pairs of alarms were placed in Compartment B, four pairs of new alarms and four pairs of previously exposed alarms were placed in Compartment A, and two pairs of new alarms, two used alarms and two photoelectric alarms were place in the hallway. The alarms consisted of the following:

One new pair enabled/disabled FSBI in Compartment B

One new pair enabled/disabled FGBI in Compartment B

One new pair enabled/disabled FSBI in Compartment A

One new pair enabled/disabled FGBI in Compartment A

One new pair enabled/disabled FBI in Compartment A

One new pair enabled/disabled FACI in Compartment A

One nuisance exp pair enabled/disabled FSBI in Compartment A

One nuisance exp pair enabled/disabled FGBI in Compartment A

One nuisance exp pair enabled/disabled FBI in Compartment A

One nuisance exp pair enabled/disabled FACI in Compartment A

One new pair enabled/disabled FSBI in the hallway

One new pair enabled/disabled FSBI in the hallway

One used enabled FSBI in the hallway

One used enabled FSBI in the hallway

Two new previously exposed Photo in the hallway

The alarms were mounted as shown n Figures 6.16-6.18

Figure 6.16 Alarms mounted in the fire room for Test Series 4. The plastic Loc-Line hose was replaced for these alarms with 1 ¼" metal pipe due to the high temperatures expected at the detectors. The bank consists of two pairs of new alarms enabled and disabled.

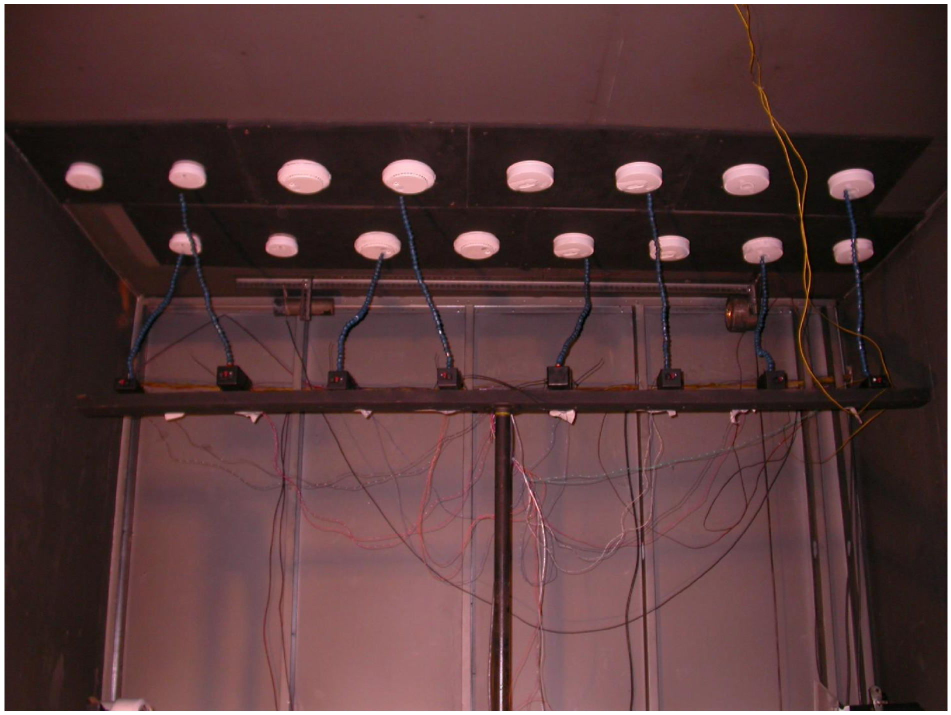

Figure 6.17 The alarm bank mounted in Room A for Test series 4. The bank consists of one row of new alarm pairs enabled and disabled and one row of alarms previously exposed in Test Series 2 enabled and disabled.

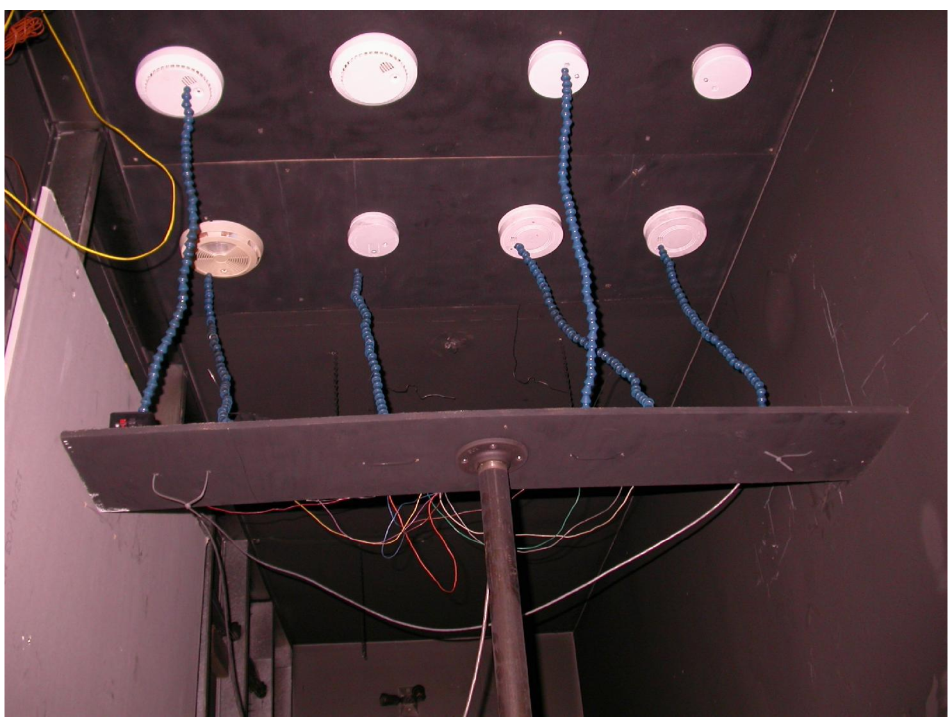

Figure 6.18 The bank of alarms in the hallway for Test Series 4. The bank consists of 2 pairs of new alarms enabled and disabled, two used alarms enabled, and two enabled photo alarms.

The alarms mounted in Compartment B were ceiling mounted on 3/8-inch plywood near the doorway, 10 feet from the fire source. The 16 alarms in Compartment A were ceiling mounted on 3/8” plywood in two lines of eight. All of the new alarms were mounted as described in Test Series 1, in a line two feet from the wall spaced 12 inches on center (see Section 6.1.1 on page 22). The line began six inches from the wall shared with Compartment B. Another line of eight nuisance-exposed alarms was mounted 12 inches closer to the center of the room. These alarms were also mounted 12 inches on center but the line was placed such that each alarm was centered on the 12 inch space between the alarms adjacent in the line of new alarms. The alarms in the hallway were mounted as described in Test Series 3. They were mounted as shown in Figure 6.18, two rows of four spaced 12 inches on center at the doorway between Compartment B and the hallway, 45 feet from the fire source (see Section 4.5 on Page 4.4).

6.4.2 Fuel Sources

Cabinet Assembly

A cabinet assembly with flue space was constructed from 3/8 inch drywall and a pressboard cabinet. A drywall sheet was cut down to a three feet square section. The pressboard cabinet was mounted onto the drywall sheet using drywall screws and was centered on the drywall sheet with the bottom of the cabinet flush with one edge of the drywall sheet. Two-inch drywall screws affixed the cabinet to the drywall. The experiment was intended to mimic an installed floor cabinet. Two screws were added approximately 6 inches up from the bottom center of the cabinet. These screws were run through the flue space and spaced two inches apart horizontally to provide a place to sit the cartridge heater within the flue space. The shelves were installed within the cabinet at 1/3 and 2/3 the interior height. The cartridge heater was inserted into the flue space such that it rested upon the spacer screws and was energized with 120 V A/C to begin the smoldering phase. A pre-test picture of the cabinet assembly can be found in Figure 6.19.

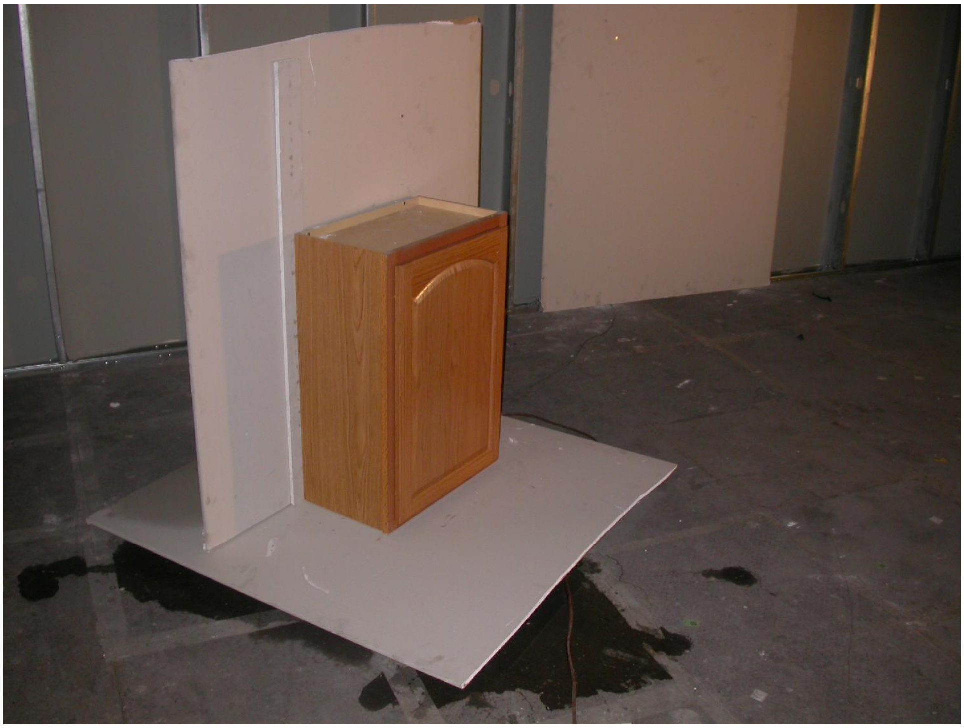

Figure 6.19 Pre-test Cabinet Assembly burned in Test 4.1. A 500W cartridge heater was placed six inches from the floor between the dry-wall and the cabinet back. The assembly smoldered, finally transitioning to flames

Couch

A wood framed "sleeper" couch covered with a fabric was acquired for the final test. The armrests were padded with layers of cotton batting, and the backrest contained some polyurethane padding. The couch was cut in half using a sawzall and the sleeper mattress was removed. The couch was ignited at the lower back corner with a butane lighter. A pre-test picture of the couch can be found below in Figure 6.20.

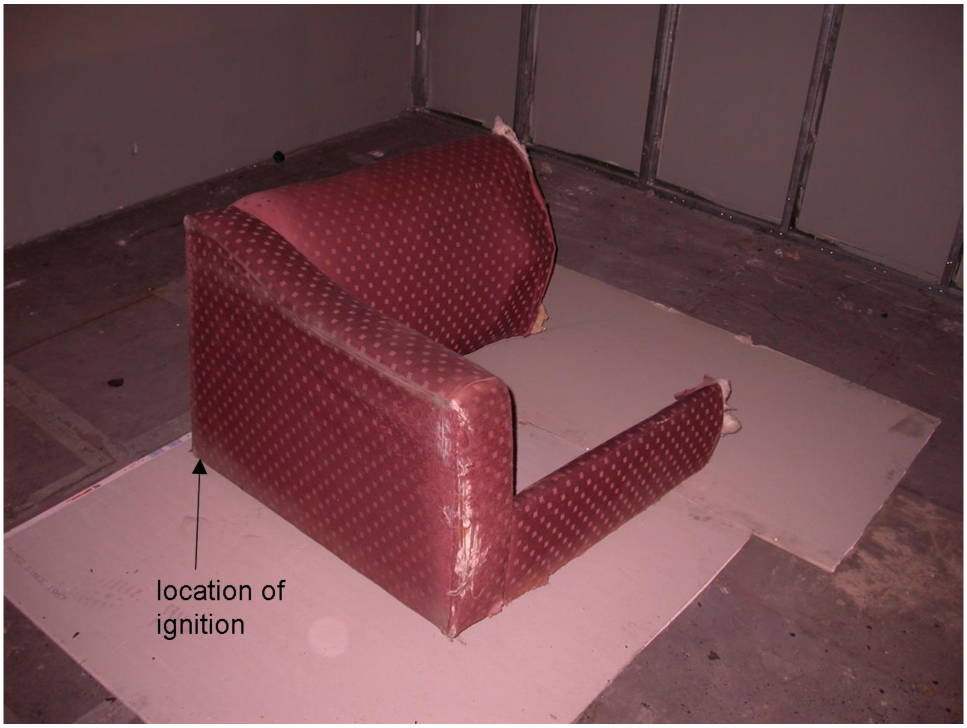

Figure 6.20 This figure shows the couch section used in Experiment 4.2, pre-test. The couch was ignited with a butane lighter in the location labeled. Most of the couch was consumed before it was extinguished.

7 Results

Table 7.1 contains a test matrix including all of the experiments run through the four test series. The table contains the test id, fuel source and mode, number of alarms that sounded during the experiment, number of alarms that did not sound, and the duration of the source.

Table 7.1 Test Matrix for the four test series

Test ID	Source	Compartments Utilized	Number of Alarms that Sounded	Number of Alarms that did not sound	Source Duration (min)
1.2	smoldering polyurethane	A & B	0	10	51
1.2	smoldering polyurethane	A & B	5	5	42
1.3	flaming polyurethane	A & B	5	5	5.5
1.4	flaming wood crib	A & B	5	5	17.5
1.5	smoldering polyurethane	A & B	5	5	8
1.6	flaming turpentine	A & B	5	5	8
1.7	flaming polyurethane	A & B	5	5	12
2.1	frying bacon	A	11	1	15
2.2	frying tortillas	A	12	0	12
2.3	burning toast	A	12	0	15
2.4	deep-frying batter	A	11	1	15
2.5	frying bacon	A	12	0	15
2.6	frying tortillas	A	12	0	12
2.7	burning toast	A	und	und	15
2.8	deep-frying batter	A	12	0	15
2.9	frying bacon	A	12	0	12
2.10	frying tortillas	A	12	0	15
2.11	burning toast	A	12	0	15
2.12	deep-frying batter	A	12	0	15
2.13	frying bacon	A	12	0	15
2.14	frying tortillas	A	12	0	12
2.15	burning toast	A	12	0	12
2.16	deep-frying batter	A	11	1	15
2.17	Airborne Dust	A	1	11	25
2.18	Airborne Dust	A	0	12	25
3.1	Smoldering Cable	HW	3	5	59
3.2	Smoldering Cable	HW	3	5	42
3.3	Flaming Box with Cups	HW	4	4	15
3.4	Flaming Box with Paper	HW	4	4	6
3.5	Smoldering Cable	HW	4	4	20
3.6	Smoldering/Flaming Cable	HW	4	4	18
4.1	Smoldering/Flaming Cabinet Assembly	A, B, HW	16	12	119
4.2	Flaming Couch	A, B, HW	16	12	7

1- "A" and "B" denote the smaller and larger rooms, respectively, as shown in Figure 4.5. "HW" indicates that the hallway was used for the test.

7.1 Test Series 1: EN/UL Style Fires

7.1.1 Experiment 1.1: Smoldering Polyurethane Exposure

As outlined in Section 6.1, Test 1.1 exposed 10 new alarms, five enabled and five disabled, to sheets of polyurethane heated with a pen-style soldering iron to smoldering in Test Series 1 compartment layout, see Figure 4.2. The source smoldered for 51 minutes, during which no alarms sounded. Figure 7.1 shows the extent to which the polyurethane was consumed during Test 1.1. There was no temperature increase noted during the experiment, a peak optical density of approximately 1 m^{-1} was reached, a peak of 30 ppm CO was measured at ceiling level in the fire room, and a peak of approximately 20 ppm CO was measured at five feet in the fire room and the ceiling level in the hallway. The lack of alarm activations was cause to revisit the smoldering polyurethane technique as outlined in Sections 6.1 and 6.2.

Figure 7.1 This figure shows a smoldering polyurethane source from Experiment 1.1 post-test. No alarms sounded when exposed to this source.

7.1.2 Experiment 1.2: Smoldering Polyurethane Exposure

The fuel source for Experiment 1.2 was slightly modified from Experiment 1.1, as outlined in Section 6.1.2. Experiment 1.2 exposed 10 new alarms, five enabled and five disabled, to polyurethane sheets heated to smoldering with a pen style soldering iron. The source smoldered for 42 minutes. During the test the five enabled alarms sounded from 1 to 130 seconds. Figure 7.2 shows the remains of the polyurethane post-test. There was a temperature rise of approximately 2 ºC at the ceiling level in the fire room during the experiment, a peak optical density of approximately 1 m^{-1} was reached, and a peak of 56 ppm CO was measured at the ceiling level in the fire room and hallway, and a maximum of 30 ppm CO was measured at five feet in the fire room. Table 7.2 summarizes the relevant alarm activity and the corresponding environmental data for the experiment.

Figure 7.2 Smoldering polyurethane source from Experiment 1.2 post-test. This reformatted source caused all 5 of the enabled alarms to sound.

Table 7.2 Alarm Summary for Experiment 1.2

Location	Type	Alarm Time (min:s)	OD @ Alarm (m^{-1})	CO @ Alarm (ppm)	Cessation Time (min:s)	OD @ Cessation (m^{-1})	Sounding Duration (min:s)
fire room	FBI	28:59	0.19	56	29:00	0.19	0:01
fire room	FACI	29:14	0.21	56	30:18	0.84	1:04
fire room	FGBI	29:17	0.21	56	30:50	0.86	1:33
fire room	FSBI	28:53	0.19	56	31:03	0.86	2:10
hallway	FBI	29:34	0.08	56	29:44	0.22	0:10

7.1.3 Experiment 1.3: Flaming Polyurethane Exposure

As outlined in Section 6.3, Experiment 1.3 exposed 10 new alarms, five enabled and five disabled, to polyurethane sheets ignited with a butane lighter. The source burned for 5-1/2 minutes. During this time, the five enabled alarms sounded for a duration of 12 -½ to 21 minutes. A maximum temperature of 118 ºC at ceiling level in the fire room was recorded during the experiment. A peak optical density of 0.9 m^{-1} and 56 ppm CO were reached. At five feet in the fire room, peaks of 40ºC, 25 ppm CO, and 0.7 m^{-1} were measured. At ceiling level in the hallway there were maximums of 80 degrees Celsius, 56 ppm CO, and 0.5 m^{-1} optical density. Table 7.3 summarizes the relevant alarm activity and the corresponding environmental data for the experiment.

Table 7.3 Alarm Summary for Experiment 1.3

Location	Type	Alarm Time(min:s)	OD @ Alarm (m^{-1})	CO @ Alarm (ppm)	Cessation Time (min:s)	OD @ Cessation (m^{-1})	Sounding Duration (min:s)
fire room	FBI	0:49	0.06	2	21:48	0.12	20:59
fire room	FACI	0:45	0.05	2	21:47	0.12	21:02
fire room	FGBI	1:55	0.60	35	21:44	0.12	19:49
fire room	FSBI	0:49	0.09	2	22:38	0.10	12:39
hallway	FBI	1:24	0.06	23	19:58	0.07	18:34

7.1.4 Experiment 1.4: Flaming Wood Crib Exposure

As outlined in Section 6.4, Experiment 1.4 exposed 10 new alarms, five enabled and five disabled, to a flaming wood crib fire ignited by a small amount methylated spirits. The source burned for 14-¾ minutes and the five enabled alarms sounded for approximately 17-½ minutes. The maximum temperature at ceiling level in the fire room was 67ºC . Peaks in optical density of 0.9 m^{-1} and 60 ppm CO were reached. At five feet in the fire room peaks of 32ºC, 55 ppm CO, and 0.6 m^{-1} optical density were recorded. At ceiling level in the hallway the maximum values were 48 ºC, 60 ppm CO, and 0.3 m^{-1} optical density. Table 7.4 summarizes the relevant alarm activity and the corresponding environmental data for the experiment.

Table 7.4 Alarm Summary for Experiment 1.4

Location	Type	Alarm Time (min:s)	OD @ Alarm (m^{-1})	CO @ Alarm (ppm)	Cessation Time(min:s)	OD @ Cessation (m^{-1})	Sounding Duration (min:s)
fire room	FBI	1:12	0.05	24	1126	0.07	17:34
fire room	FACI	1:08	0.04	19	1126	0.07	17:38
fire room	FGBI	1:16	0.06	29	1129	0.06	17:33
fire room	FSBI	0:58	0.01	11	1138	0.07	18:00
hallway	FBI	1:24	0.02	4	1132	0.06	17:52

7.1.5 Experiment 1.5: Smoldering Polyurethane Exposure

Experiment 1.5 exposed 10 new alarms, 5 enabled and 5 disabled, to sheets of polyurethane heated to smoldering with a pen style soldering iron. The source burned for approximately 37 minutes, and the five enabled alarms sounded for between five and nine minutes. There was a temperature rise of 3 ºC at the ceiling level in the fire room during the experiment. Peaks in optical density of 0.9 m^{-1} and 60 ppm CO were reached. At five feet high in the fire room, no increase above ambient temperature was measured while maximum values 40 ppm CO and 0.6 m^{-1} optical density were measured. At ceiling level in the hallway there was a negligible temperature increase and peaks of 60 ppm CO and 0.2 m^{-1} optical density were reached. Table 7.5 summarizes the relevant alarm activity and the corresponding environmental data for the experiment.

Table 7.5 Alarm Summary for Experiment 1.5

Location	Type	Alarm Time(min:s)	OD @ Alarm (m^{-1})	CO @ Alarm(ppm)	Cessation Time (min:s)	OD @ Cessation (m^{-1})	Sounding Duration (min:s)
fire room	FBI	32:15	0.73	60	36:26	0.50	4:11
fire room	FACI	29:44	0.41	56	37:15	0.52	7:31
fire room	FGBI	31:30	0.72	58	40:13	0.38	8:43
fire room	FSBI	30:38	0.72	57	37:00	0.46	5:32
hallway	FBI	32:13	0.43	57	40:21	0.27	8:08

7.1.6 Experiment 1.6: Flaming Turpentine Pool Exposure

Experiment 1.6 exposed 10 new alarms, five enabled and five disabled, to a turpentine pool ignited with a butane lighter. The CO concentration was not monitored during this test to avoid soot and thermal damage of the CO sensors. The source burned for approximately eight minutes and the 5 enabled alarms sounded for 6-1/2 to 11 minutes. A maximum temperature of 90ºC at ceiling level in the fire room during the experiment and the optical density meter was saturated. At five feet high in the fire room, the temperature reached 48ºC and the optical density reached 1.0 m^{-1}. At ceiling level in the hallway, a peak of 64ºC was measured and the optical density meter was saturated. Table 7.6 summarizes the relevant alarm activity and the corresponding environmental data for the experiment.

Table 7.6 Alarm Summary for Experiment 1.6

Location	Type	Alarm Time (min:s)	OD @ Alarm(m^{-1})	CO @ Alarm (ppm)	Cessation Time(min:s)	OD @ Cessation(m^{-1})	Sounding Duration (min:s)
fire room	FBI	0:23	0.12	Nm	11:52	0.29	11:29
fire room	FACI	0:26	0.12	Nm	14:29	0.20	14:03
fire room	FGBI*	0:58	0.29	Nm	7:48	1.04	6:32
fire room	FSBI	0:21	0.11	Nm	18:20	0.10	17:59
Hallway	FBI	0:52	0.11	Nm	7:38	0.90	6:46

nm = not monitored, * sounded erratically

The FGBI style alarm, denoted in the table with the *, in the fire room sounded erratically throughout the test. Only the first activation and deactivation were reported in the table. The alarm sounded four times in addition to those listed in the table. The total duration of these soundings was 42 seconds, for a total sounding duration of 6 minutes 32 seconds as listed in the table. There were periods of 20 seconds to 1 minute where the alarm did not sound. The erratic behavior lowered the total alarm time drastically in comparison to the other alarms in the test. It did not however, preclude the generation of enhanced soot deposition patterns.

7.1.7 Experiment 1.7: Flaming Polyurethane Exposure

Experiment 1.7 exposed 10 new alarms, five enabled and five disabled, to sheets of polyurethane ignited with a butane lighter. The source burned for approximately 12 minutes and the 5 enabled alarms sounded for 5 to 9 minutes. Temperature profiles were not recorded for this test. Experiment 1.7 was run identically to the previous flaming polyurethane test, Experiment 1.3. At the ceiling level in the fire room the optical density reached 1.0 m^{-1}. 72 ppm CO was reached at ceiling level in the hallway. At five feet high in the fire room, peaks of 40 ppm CO, and 0.4 m^{-1} optical density were reached. At ceiling level in the hallway peaks of 45 ppm CO, and 0.4 m^{-1} optical density were measured. Table 7.7 summarizes the relevant alarm activity and the corresponding environmental data for the experiment.

Table 7.7 Alarm Summary for Experiment 1.7

Location	Type	Alarm Time (min:s)	OD @ Alarm (m^{-1})	CO @ Alarm (ppm)	Cessation Time(min:s)	OD @ Cessation(m^{-1})	Sounding Duration (min:s)
fire room	FBI	2:27	0.10	nm	20:57	0.12	18:30
fire room	FACI	1:59	0.06	nm	22:07	0.19	20:08
fire room	FGBI	1:47	0.03	nm	22:13	0.18	20:26
fire room	FSBI	1:41	0.03	nm	21:49	0.14	18:38
hallway	FBI	2:30	0.01	5	20:43	0.05	18:13
hallway	FBI	2:33	0.01	5	20:51	0.05	18:18
hallway	Photo	1:51	0.02	7	20:58	0.05	18:07
hallway	Photo	3:59	0.09	15	20:41	0.05	16:42

nm = not monitored

7.2 Test Series 2: Nuisance Source Exposures

7.2.1 Experiment 2.1: Frying Bacon Nuisance Exposure

Experiment 2.1 exposed 12 new enabled alarms to products from frying bacon in a skillet on a gas burner . There was a negligible rise in temperature in the compartment during the experiment. A maximum of 15 ppm CO was measured. The peak optical density was 0.05 m^{-1} , with optical densities at alarm ranging from 0.005 to 0.015 m^{-1}. Bacon was cooked for approximately 15 minutes and the alarms sounded for an average of 8 minutes. Table 7.8 summarizes the alarm activity for Experiment 2.1.

Table 7.8 Alarm summary for Experiment 2.1: Frying Bacon Nuisance Exposure

Type	Alarm Time (min:s)	OD @ Alarm (m-1)	Sounding Duration (min:s)
FBI	11:58	0.005	10:02
FBI	15:51	0.015	4:33
FACI	15:14	0.015	9:32
FACI	15:20	0.015	7:20
FGBI	dna	dna	0
FGBI	16:28	0.015	0:25
FSBI	15:44	0.015	5:39
FSBI	15:41	0.015	5:13
FACI	11:51	0.005	10:57
FACI	12:04	0.005	9:55
FSBI	12:05	0.005	10:22
FSBI	12:00	0.005	12:51

dna = did not alarm

7.2.2 Experiment 2.2: Frying Tortillas Nuisance Exposure

Experiment 2.2 exposed the alarms from Experiment 2.1 to tortillas fried in a skillet on a gas burner. There was a negligible rise in temperature in the compartment during the experiment, and a maximum of 11 ppm CO was measured. The peak optical density reached was 0.1 m^{-1}, while the optical density at alarm ranged from 0.003 to 0.08 m^{-1}. Tortillas were fried for approximately 12 minutes, and the alarms sounded for an average of 7-1/2 minutes. Table 7.9 summarizes the alarm activity for Experiment 2.2.

Table 7.9 Alarm Summary for Experiment 2.2: Frying Tortillas Nuisance Exposure

Type	Alarm Time (min:s)	OD @ Alarm (m-1)	Sounding Duration (min:s)
FBI	3:42	0.003	6:50
FBI	4:22	0.030	6:28
FACI	4:16	0.030	6:42
FACI	4:19	0.030	10:40
FGBI	4:47	0.080	5:19
FGBI	4:42	0.080	6:14
FSBI	4:15	0.030	6:59
FSBI	4:01	0.010	7:17
FACI	3:40	0.003	6:50
FACI	3:42	0.003	6:50
FSBI	3:40	0.003	7:40
FSBI	3:30	0.003	8:35

7.2.3 Experiment 2.3: Burning Toast Nuisance Exposure

Experiment 2.3 exposed the alarms from Experiments 2.1 and 2.2 to burned toast. There was a negligible rise in temperature in the compartment during the experiment and a maximum of two ppm CO. The maximum optical density reached was 0.1 m^{-1}, while the optical density at alarm ranged from 0.08 to 0.1 m^{-1}. Toast was burned for approximately 15 minutes and the alarms sounded for an average of 13 minutes. Table 7.10 summarizes the alarm activity for Experiment 2.3.

Table 7.10 Alarm Summary for Experiment 2.3: Burning Toast Nuisance Exposure

Type	Alarm Time (min:s)	OD @ Alarm (m-1)	Sounding Duration (min:s)
FBI	8:58	0.100	15:30
FBI	13:24	0.090	6:29
FACI	9:16	0.120	15:29
FACI	9:13	0.080	14:37
FGBI	14:11	0.090	3:41
FGBI	13:31	0.080	6:55
FSBI	13:03	0.080	7:20
FSBI	8:32	0.100	18:17
FACI	7:57	0.110	16:51
FACI	8:58	0.08	15:29
FSBI	8:59	0.080	15:48
FSBI	8:54	0.080	18:37

7.2.4 Experiment 2.4: Deep-Frying Batter Nuisance Exposure

Experiment 2.4 exposed the alarms from Experiments 2.1-2.3 to frying batter as outlined in Section 6.2 on page 6.8. There was a negligible rise in temperature in the compartment during the experiment and a maximum of 10 ppm CO. The maximum optical density reached was 0.02 m^{-1}. Batter was fried for approximately 15 minutes and the alarms sounded for an average of 4 minutes. Table 7.11 summarizes the alarm activity for Experiment 2.4.

Table 7.11 Alarm Summary for Experiment 2.4: Deep-Frying Batter Nuisance Exposure

Type	Alarm Time (min:s)	OD @ Alarm (m^{-1})	Sounding Duration (min:s)
FBI	8:03	0.004	3:44
FBI	9:20	0.004	0:13
FACI	9:15	0.004	2:17
FACI	9:13	0.004	1:38
FGBI	dna	dna	0
FGBI	17:50	0.05	1:27
FSBI	8:40	0.004	3:37
FSBI	8:13	0.004	7:42
FACI	7:55	0.004	4:23
FACI	8:10	0.004	3:55
FSBI	8:50	0.004	9:12
FSBI	3:22	0.004	12:18

dna = did not alarm

7.2.5 Experiment 2.5: Frying Bacon Nuisance Exposure

Experiment 2.5 exposed the alarms from Experiments 2.1-2.4 to frying bacon in a skillet on a gas burner . There was a negligible rise in temperature in the compartment during the experiment and a maximum of 14 ppm CO. The maximum optical density reached was 0.1 m^{-1} with optical densities at alarm ranging from 0.001 to 0.03. Bacon was cooked for approximately 12 minutes and the alarms sounded for an average of 8 minutes. Table 7.12 summarizes the alarm activity for Experiment 2.5.

Table 7.12 Alarm summary for Experiment 2.5: Frying Bacon Nuisance Exposure.

Type	Alarm Time (min:s)	OD @ Alarm (m^{-1})	Sounding Duration (min:s)
FBI	3:35	0.00	9:06
FBI	5:20	0.03	7:13
FACI	4:44	0.02	7:50
FACI	4:46	0.02	7:42
FGBI	5:23	0.03	6:46
FGBI	5:13	0.03	7:18
FSBI	4:21	0.02	8:09
FSBI	3:28	0.02	8:32
FACI	3:35	0.01	9:08
FACI	3:40	0.02	9:01
FSBI	3:37	0.01	9:03
FSBI	3:28	0.01	9:20

7.2.6 Experiment 2.6: Frying Tortillas Nuisance Exposure

Experiment 2.6 exposed the alarms from Experiments 2.1-2.5 to tortillas fried in a skillet on a gas burner There was a negligible rise in temperature in the compartment during the experiment and a maximum of 15 ppm CO. The maximum optical density reached was 0.06 m^{-1}, while the optical density at alarm ranged from too low to measure to 0.02 m^{-1}. Tortillas were fried for approximately 12 minutes and the alarms sounded for an average of 9 minutes. Table 7.13 summarizes the alarm activity for Experiment 2.6.

Table 7.13 Alarm summary for Experiment 2.6: Frying Tortillas Nuisance Exposure

Type	Alarm Time (min:s)	OD @ Alarm (m^{-1})	Sounding Duration (min:s)
FBI	4:55	0.00	9:14
FBI	5:52	0.02	8:14
FACI	5:20	0.01	8:44
FACI	5:22	0.01	8:44
FGBI	5:56	0.02	7:11
FGBI	5:31	0.02	8:34
FSBI	5:23	0.01	8:45
FSBI	5:13	0.01	8:53
FACI	4:44	0.00	9:13
FACI	4:55	0.00	9:14
FSBI	4:34	0.00	9:36
FSBI	4:28	0.00	9:45

7.2.7 Experiment 2.7: Burning Toast Nuisance Exposure

Experiment 2.7 exposed the alarms from Experiments 2.1-2.6 to toast burned as outlined in Section 6.2 on page 6.8. There was a negligible rise in temperature in the compartment during the experiment and a maximum of three ppm CO. The maximum optical density reached was 0.15 m^{-1}. Toast was burned for approximately 12 minutes and the alarms sounded for an average of 2 1/2 minutes. Table 7.14 summarizes the alarm activity for Experiment 2.7.

Table 7.14 Alarm summary for Experiment 2.7: Burning Toast Nuisance Exposure

Type	Alarm Time (min:s)	OD @ Alarm (m^{-1})	Sounding Duration (min:s)
FBI	10:29	0.13	2:06
FBI	15:28	0.13	1:12
FACI	10:47	0.13	2:19
FACI	10:39	0.13	1:43
FGBI	16:22	0.13	0:05
FGBI	16:10	0.13	1:36
FSBI	15:32	0.13	1:20
FSBI	10:32	0.13	4:08
FACI	6:58	0.13	2:29
FACI	10:32	0.13	1:53
FSBI	10:46	0.13	3:19
FSBI	6:22	0.13	6:19

7.2.8 Experiment 2.8: Deep-Frying Batter Nuisance Exposure

Experiment 2.8 exposed the alarms from Experiments 2.1-2.7 to frying batter as outlined in Section 6.2 on page 6.8. There was less than a one degree rise in temperature in the compartment during the experiment and a maximum of 10 ppm CO. The maximum optical density reached was 0.02 m^{-1}. Batter was fried for approximately 15 minutes. The alarm activity data is not available for this experiment.

7.2.9 Experiment 2.9: Frying Bacon Nuisance Exposure

Experiment 2.9 exposed 12 new enabled alarms, all enabled, to frying bacon in a skillet on a gas burner outlined in Section 6.2 on page 6.8. Experiment 2.9 was the first set of experiments with the second set of 12 new alarms. There was a negligible rise in temperature in the compartment during the experiment and a maximum of 12 ppm CO. The maximum optical density reached was 0.1 m^{-1} with optical densities at alarm ranging from 0.005 to 0.07. Bacon was cooked for approximately 15 minutes and the alarms sounded for an average of 7-1/2 minutes. Table 7.15 summarizes the alarm activity for Experiment 2.9.

Table 7.15 Alarm summary for Experiment 2.9: Frying Bacon Nuisance Exposure

Type	Alarm Time (min:s)	OD @ Alarm (m-1)	Sounding Duration (min:s)
FBI	4:24	0.020	10:46
FBI	5:14	0.070	9:54
FACI	5:12	0.070	10:04
FACI	4:21	0.070	10:57
FGBI	4:49	0.020	6:01
FGBI	6:55	0.020	6:57
FSBI	4:18	0.060	10:52
FSBI	4:21	0.020	14:49
FGBI	4:43	0.020	9:57
FGBI	4:26	0.020	10:44
FBI	4:19	0.020	9:57
FBI	3:52	0.005	11:16

7.2.10 Experiment 2.10: Frying Tortillas Nuisance Exposure

Experiment 2.10 exposed the alarms from Experiment 2.9 to tortillas fried in a skillet on a gas burner as outlined in Section 6.2 on page 6.8. There was a negligible rise in temperature in the compartment during the experiment and a maximum of 16 ppm CO. The maximum optical density reached was 0.1 m^{-1}, while the optical density at alarm ranged from 0.02 to 0.04 m^{-1}. Tortillas were fried for approximately 12 minutes and the alarms sounded for an average of 7 -/2 minutes. Table 7.16 summarizes the alarm activity for Experiment 2.10.

Table 7.16 Alarm summary for Experiment 2.10: Frying Tortillas Nuisance Exposure

Type	Alarm Time (min:s)	OD @ Alarm (m-1)	Sounding Duration (min:s)
FBI	6:05	0.020	9:18
FBI	7:54	0.040	6:20
FACI	6:09	0.020	8:24
FACI	6:14	0.020	8:19
FGBI	6:17	0.020	8:13
FGBI	8:00	0.040	3:58
FSBI	5:37	0.020	8:47
FSBI	5:39	0.020	8:35
FGBI	6:16	0.020	7:23
FGBI	5:07	0.020	9:16
FBI	5:10	0.020	7:08
FBI	5:01	0.020	9:14

7.2.11 Experiment 2.11: Burning Toast Nuisance Exposure

Experiment 2.11 exposed the alarms from Experiments 2.9 and 2.10 to toast burned as outlined in Section 6.2 page 6.8. There was a negligible rise in temperature in the compartment during the experiment and a maximum of 2 ppm CO was measured. The maximum optical density reached was 0.16 m^{-1}. Toast were burned for approximately 15 minutes and the alarms sounded for an average of 6-1/2 minutes. Table 7.17 summarizes the alarm activity for Experiment 2.11.

Table 7.17 Alarm summary for Experiment 2.11: Burning Toast Nuisance Exposure

Type	Alarm Time (min:s)	OD @ Alarm (m-1)	Sounding Duration (min:s)
FBI	6:32	0.160	9:18
FBI	11:21	0.160	0:05
FACI	6:48	0.160	6:31
FACI	6:45	0.160	8:18
FGBI	7:39	0.160	2:21
FGBI	13:58	0.160	5
FSBI	6:53	0.160	9:07
FSBI	6:44	0.160	8:35
FGBI	6:12	0.160	8:40
FGBI	6:35	0.160	9:13
FBI	6:24	0.160	5:17
FBI	6:35	0.160	8:17

7.2.12 Experiment 2.12: Deep-Frying Batter Nuisance Exposure

Experiment 2.12 exposed the alarms from Experiments 2.9-2.11 to frying batter as outlined in Section 6.2 page 6.8. There was negligible rise in temperature in the compartment during the experiment and a maximum of 10 ppm CO was measured. The maximum optical density reached was 0.02 m^{-1}. Batter was fried for approximately 15 minutes and the alarms sounded for an average of 7-1/2 minutes. Table 7.18 summarizes the alarm activity for Experiment 2.12.

Table 7.18 Alarm summary for Experiment 2.12: Deep-Frying Batter Nuisance Exposure

Type	Alarm Time (min:s)	OD @ Alarm (m-1)	Sounding Duration (min:s)
FBI	4:11	0.050	12:03
FBI	6:12	0.050	7:05
FACI	5:56	0.050	10:19
FACI	4:17	0.050	13:17
FGBI	6:25	0.050	9:18
FGBI	9:57	0.050	0:15
FSBI	4:12	0.050	12:02
FSBI	4:38	0.050	11:34
FGBI	5:45	0.050	9:59
FGBI	4:11	0.050	12:03
FBI	4:49	0.050	10:35
FBI	4:45	0.050	10:43

7.2.13 Experiment 2.13: Frying Bacon Nuisance Exposure

Experiment 2.13 exposed the alarms from Experiments 2.9-2.12 to frying bacon in a skillet on a gas burner . There was a negligible rise in temperature in the compartment during the experiment and a maximum of 10 ppm CO was measured. The maximum optical density reached was 0.12 m^{-1} with optical densities at alarm ranging from 0.01 to 0.07. Bacon was cooked for approximately 12 minutes and the alarms sounded for an average of 8-1/2 minutes. Table 7.19 summarizes the alarm activity for Experiment 2.13.

Table 7.19 Alarm summary for Experiment 2.13: Frying Bacon Nuisance Exposure

Type	Alarm Time (min:s)	OD @ Alarm (m-1)	Sounding Duration (min:s)
FBI	5:00	0.010	9:32
FBI	6:35	0.070	6:10
FACI	5:49	0.030	8:34
FACI	5:02	0.010	9:57
FGBI	6:04	0.060	7:30
FGBI	6:10	0.060	5:28
FSBI	5:07	0.010	9:19
FSBI	5:07	0.010	9:24
FGBI	5:35	0.030	7:38
FGBI	5:02	0.010	9:30
FBI	5:15	0.010	7:07
FBI	5:02	0.010	8:27

7.2.14 Experiment 2.14 Frying Tortillas Nuisance Exposure

Experiment 2.14 exposed the alarms from Experiments 2.9-2.14 to tortillas fried in a skillet on a gas burner outlined in Section 6.2 on page 6.8. There was a negligible rise in temperature in the compartment during the experiment and a maximum of 10 ppm CO was measured. The maximum optical density reached was 0.07 m^{-1}, while the optical density at alarm ranged from 0.02 to 0.04 m^{-1}. Tortillas were fried for approximately 12 minutes and the alarms sounded for an average of 8-1/2 minutes. Table 7.20 summarizes the alarm activity for Experiment 2.14.

Table 7.20 Alarm summary for Experiment 2.14: Frying Tortillas Nuisance Exposure

Type	Alarm Time (min:s)	OD @ Alarm (m-1)	Sounding Duration (min:s)
FBI	6:08	0.020	9:42
FBI	9:53	0.040	157
FACI	7:27	0.040	7:48
FACI	6:06	0.040	10:08
FGBI	7:47	0.040	6:37
FGBI	11:12	0.040	3:35
FSBI	6:14	0.040	16:14
FSBI	6:17	0.040	9:35
FGBI	6:48	0.040	8:09
FGBI	6:16	0.040	9:34
FBI	6:45	0.040	7:45
FBI	6:10	0.040	8:24

7.2.15 Experiment 2.15: Burning Toast Nuisance Exposure

Experiment 2.15 exposed the alarms from Experiments 2.9-2.14 to toast burned as outlined in Section 6.2 on page 6.8. There was a negligible rise in temperature in the compartment during the experiment and a maximum of 2 ppm CO was measured. The maximum optical density reached was 0.15 m^{-1} where all of the alarms sounded. Toast was toasted for approximately 12 minutes and the alarms sounded for an average of 7-1/2 minutes. Table 7.21 summarizes the alarm activity for Experiment 2.15.

Table 7.21 Alarm summary for Experiment 2.15: Burning Toast Nuisance Exposure

Type	Alarm Time (min:s)	OD @ Alarm (m-1)	Sounding Duration (min:s)
FBI	6:37	0.150	14:38
FBI	19:24	0.150	0:15
FACI	7:21	0.150	6:43
FACI	6:56	0.150	14:28
FGBI	7:13	0.150	13:57
FGBI	7:13	0.150	13:57
FSBI	7:13	0.150	14:28
FSBI	7:13	0.150	14:06
FGBI	6:38	0.150	9:16
FGBI	6:37	0.150	14:14
FBI	6:36	0.150	7:57
FBI	6:48	0.150	9:20

7.2.16 Experiment 2.16: Deep-Frying Batter Nuisance Exposure

Experiment 2.16 exposed the alarms from Experiments 2.9-2.15 to frying batter as outlined in Section 6.2. There was a negligible rise in temperature in the compartment during the experiment and a maximum of 10 ppm CO was measured. The maximum optical density reached was 0.02 m^{-1}. Batter was fried for approximately 15 minutes and the alarms sounded for an average of 4 minutes. Table 7.22 summarizes the alarm activity for Experiment 2.15.

Table 7.22 Alarm summary for Experiment 2.15: Frying Bacon Nuisance Exposure

Type	Alarm Time (min:s)	OD @ Alarm (m-1)	Sounding Duration (min:s)
FBI	5:21	0.020	7:43
FBI	dna	dna	0
FACI	6:09	0.020	2:48
FACI	5:22	0.020	5:31
FGBI	6:48	0.020	1:05
FGBI	7:28	0.020	0:05
FSBI	5:23	0.020	7:49
FSBI	5:28	0.020	7:26
FGBI	6:09	0.020	1:42
FGBI	5:21	0.020	7:31
FBI	5:46	0.020	3:07
FBI	5:49	0.020	3:26

dna = did not alarm

7.2.17 Experiments 2.17 and 2.18: Airborne Dust Nuisance Exposures

The procedure for experiments 2.17 and 2.18 was outlined in Section 6.2. During Experiment 2.17 the 12 alarms from Experiments 2.9-2.16 were exposed to airborne dust. During Experiment 2.18 the 12 alarms from Experiments 2.1-2.8 were exposed to airborne dust. The environmental data was similar to other nuisance sources studied, but only one alarm sounded for one set of temporal three tones. The goal of the dust exposure was mainly to deposit dust on the alarms to allow for evaluation of how those depositions might or might not affect soot deposition during a real fire event. It was therefore not necessary that the alarms sound during the experiment.

7.3 Test Series 3: Alternative Fuel Source Exposures

7.3.1 Experiment 3.1: Smoldering Electrical Cable Exposure

As outlined in Section 6.3, Experiment 3.1 exposed 8 new alarms, four enabled and four disabled, to smoldering electrical cable heated by a 500 W cartridge heater in the hallway. The source smoldered for 59 minutes, during which time three of the four enabled alarms sounded for 1 to 2395 seconds. There was a negligible temperature rise at ceiling level in the hallway during the experiment where a peak optical density of 1 m^{-1} optical density was reached. Table 7.23 summarizes the relevant alarm activity and the corresponding environmental data for the experiment.

Table 7.23 Alarm summary of Experiment 3.1: Smoldering Electrical Cable

Location	Type	Alarm Time (min:s)	OD @ Alarm(m^{-1})	Cessation Time (min:s)	OD @ Cessation(m^{-1})	Sounding Duration (min:s)
hallway	FBI	63:38	1	63:39	1	0:01
hallway	FACI	18:03	0	61:18	1	43:15
hallway	FGBI	dna	dna	dna	dna	dna
hallway	FSBI	60:35	1	3799	1	0:05

dna = did not alarm

Only one of the smoke alarms in Experiment 3.1 sounded consistently. The enabled FSBI alarm sounded 5 times intermittently. Table 7.23 includes only the first occasion on which it sounded, for a total of 5 seconds throughout the test, while the enabled FBI alarm sounded only once for a total of 1 second.

7.3.2 Experiment 3.2: Smoldering Electrical Cable Exposure

As outlined in Section 6.3, Experiment 3.2 exposed 8 new alarms, four enabled and four disabled, to smoldering electrical cable heated by a 500 W cartridge heater in the hallway. The source smoldered for 42 minutes; during this time, the 4 enabled alarms sounded for 13 to 20 minutes. There was a negligible temperature rise at ceiling level in the hallway during the experiment where a peak optical density of 1 m^{-1} was reached. Table 7.24 below, summarizes the relevant alarm activity and the corresponding environmental data for the experiment.

Table 7.24 Alarm summary of Experiment 3.2: Smoldering Electrical Cable

Location	Type	Alarm Time(min:s)	OD @ Alarm(m^{-1})	Cessation Time(min:s)	OD @ Cessation(m^{-1})	Sounding Duration (min:s)
HW	FBI	dna	dna	dna	dna	dna
HW	FACI	und	und	und	und	und
HW	FGBI	27:40	1	48:13	1	20:33
HW	FSBI	27:24	1	41:55	1	12:56

dna = did not alarm, und = undetermined

The FSBI enabled alarm sounded erratically throughout the experiment, only the first period is shown in the table above. The FACI alarm did sound during the test but exact times are not available. During test preparation but after verification of the acoustic monitors the Loc-Line hose for this alarm was inadvertently shifted four to six inches away from the horn opening. The problem was discovered when it was the first alarm to sound, but the output did not register on the DAQ monitor. The remaining enabled alarms sounded and registered with the DAQ and the Loc-Line displacement was identified post-test.

7.3.3 Experiment 3.3: Flaming Box with Cups Exposure

As outlined in Section 6.3, Experiment 3.3 exposed 8 alarms, 4 enabled and 4 disabled, to 2 boxes filled with plastic cups and bubble wrap ignited with a butane lighter. The source burned for 15 minutes. During this time, the 4 enabled alarms sounded for 15 minutes. The optical density meter was saturated during the test because of the extreme soot production from the source. Table 7.25 summarizes the relevant alarm activity and the corresponding environmental data for the experiment.

Table 7.25 Alarm summary of Experiment 3.3: Flaming Box with Cups

Location	Type	Alarm Time (min:s)	OD @ Alarm(m^{-1})	Cessation Time (min:s)	OD @ Cessation(m^{-1})	Sounding Duration (min:s)
Hallway	FBI	1:09	0.03	15:54	0.2	14:45
Hallway	FACI	1:00	0.03	15:58	0.2	14:58
Hallway	FGBI	1:04	0.03	16:07	0.2	15:03
Hallway	FSBI	0:57	0.03	16:23	0.2	15:26

7.3.4 Experiment 3.4: Flaming Boxes with Paper Exposure

As outlined in Section 6.3, Experiment 3.4 exposed 8 alarms, 4 enabled and 4 disabled to four boxes filled with paper and ignited with a butane lighter. The source flamed for six minutes; during this time, the 4 enabled alarms sounded for 7-1/2to 9 minutes. There was a negligible temperature rise at ceiling level in the hallway during the experiment where a peak optical density of 1 m^{-1} was reached. Table 7.26 summarizes the relevant alarm activity and the corresponding environmental data for the experiment.

Table 7.26 Alarm summary of Experiment 3.4: Flaming Boxes with paper

Location	Type	Alarm Time (min:s)	OD @ Alarm(m^{-1})	Cessation Time (min:s)	OD @ Cessation(m^{-1})	Sounding Duration (min:s)
HW	FBI	2:03	0.04	9:41	1	7:38
HW	FACI	1:52	0.04	10:01	1	8:09
HW	FGBI	1:53	0.04	11:16	1	9:11
HW	FSBI	1:54	0.04	10:03	1	8:09

7.3.5 Experiment 3.5: Smoldering Electrical Cable Source

As outlined in Section 6.3, Experiment 3.5 exposed 8 new alarms, 4 enabled and 4 disabled, to smoldering electrical cable heated by a 500 W cartridge heater in the hallway. The desire was for the cables to transition from smoldering to flaming. This did not occur; instead the cable smoldered for 20 minutes and was extinguished. During that time, the 4 enabled alarms sounded for 3 to 8 minutes. There was a negligible temperature rise at ceiling level in the hallway during the experiment. A peak optical density of 1 m^{-1} was reached. Table 7.27 summarizes the relevant alarm activity and the corresponding environmental data for the experiment.

Table 7.27 Alarm summary of Experiment 3.5: Smoldering Electrical Cable

Location	Type	Alarm Time(min:s)	OD @ Alarm(m^{-1})	Cessation Time(min:s)	OD @ Cessation(m^{-1})	Sounding Duration (min:s)
HW	FBI	12:13	0.8	20:02	1	7:49
HW	FACI	15:38	1	20:31	1	4:53
HW	FGBI	16:21	1	20:31	1	2:47
HW	FSBI	12:14	0.8	20:20	1	8:06

7.3.6 Experiment 3.6: Smoldering to Flaming Electrical Cable Source

As outlined in Section 6.3, Experiment 3.6 exposed the 8 alarms from Experiment 3.5 to electrical cable heated to smoldering by a 500W cartridge heater and then piloted to flaming ignition with a butane lighter. The source smoldered for 3minutes; during this time, none of the enabled alarms sounded. After flaming ignition was piloted, flames persisted for approximately 15 minutes and the 4 enabled alarms sounded for 13 to 15 minutes. A peak optical density of 1 m^{-1} was reached at ceiling level in the hallway. Table 7.28 summarizes the relevant alarm activity and the corresponding environmental data for the experiment.

Table 7.28 Alarm summary of Experiment 3.6

Location	Type	Alarm Time(min:s)	OD @ Alarm(m^{-1})	Cessation Time(min:s)	OD @ Cessation(m^{-1})	Sounding Duration (min:s)
HW	enabled	9:31	0.002	23:26	0.002	13:55
HW	enabled	9:09	0.002	23:48	0.001	14:39
HW	enabled	10:48	0.002	23:48	0.001	13:00
HW	enabled	9:35	0.002	23:42	0.001	14:07

7.4 Test Series 4: Larger Scale Fire Exposures

7.4.1 Experiment 4.1: Smoldering to Flaming Cabinet Assembly Exposure

As outlined in Section 6.4, Experiment 4.1 exposed 28 alarms, 16 enabled and 12 disabled to a cabinet assembly, which began smoldering and transitioned to flaming. The fire was initiated by a 500 W cartridge heater located between the cabinet back and the mock-wall assembly. The source burned for 119 minutes; during this time, the 16 enabled alarms sounded for 25 to 115 minutes. The alarms sounded at optical densities ranging from 0.02 to 0.3 m^{-1}. The remains of the cabinet assembly are pictured in Figure 7.3. A maximum temperature of 78ºC was measured at the ceiling level in the fire room during the experiment. A peak optical density of approx 1.2 m^{-1} was reached, and a peak of 400 ppm CO at five feet high in Room A was measured. Table 7.29summarizes the relevant alarm activity and the corresponding environmental data for the experiment.

Figure 7.3 Cabinet assembly post-test.

Table 7.29 Alarm summary of Experiment 4.1

Location	Type	Alarm Time (min:s)	OD @ Alarm (m^{-1})	Cessation Time (min:s)	OD @ Cessation (m^{-1})	Sounding Duration (min:s)
Room B*	FGBI	7:59	nm	123:06	nm	115:07
Room B*	FSBI	~8:15	nm	und	nm	und
Room A	FSBI	14:40	0.072	119:33	0.01	104:53
Room A	FSBI	14:09	0.061	119:26	0.01	105:17
Room A	FGBI	93:01	0.331	118:41	0.022	25:40
Room A	FGBI	81:04	0.169	84:34	0.166	31:14
Room A	FACI	16:12	0.069	120:40	0.027	104:28
Room A	FACI	14:50	0.073	121:56	0.022	107:06
Room A	FBI	8:57	0.169	118:24	0.04	25:28
Room A	FBI	16:02	0.122	118:26	0.031	98:31
Hallway	Used	15:34	0.102	113:54	0.175	98:20
Hallway	Used	15:26	0.052	117:31	0.054	102:05
Hallway	FGBI	15:47	0.111	117:31	0.054	101:44
Hallway	FSBI	13:51	0.052	115:58	0.117	102:07
Hallway	Photo	12:00	0.027	119:18	0.02	107:18
Hallway	Photo	11:43	0.022	119:27	0.022	107:44

nm = not measured und = undetermined *Fire Room

The FSBI alarm in the fire room (Room B) was heard to alarm second, shortly after the FGBI alarm in the same room. The alarm state was inspected and verified audibly and visually, through confirmation of the blinking LED. The alarm sounding was not registered by the DAQ, as the acoustic monitor was discovered post-test to be unplugged. The approximate time of alarm is recorded from observation but the cessation time and duration of sounding were undetermined.

7.4.2 Experiment 4.2: Flaming Couch Exposure

As outlined in Section 6.4, Experiment 4.2 exposed 28 alarms, 16 enabled and 12 disabled, to one-half of a couch ignited with a butane lighter. The source burned for 7 minutes before it was extinguished: Figures 6.18 and 7.4 show the couch pre- and post-fire respectively. During this time, the 16 enabled alarms sounded for periods ranging from 13 to 25 minutes at optical densities ranging from 0.00 to 0.01. The highest temperature at ceiling level in the fire room was measured to be 212ºC. The optical density meters at ceiling level were saturated at the peak smoke density. Table 7.30 summarizes the relevant alarm activity and the corresponding environmental data for the experiment.

Figure 7.4 Couch post-test.

Table 7.30 Alarm summary of Experiment 4.2

Location	Type	Alarm Time (min:s)	OD @ Alarm (m^{-1})	Cessation Time (min:s)	OD @ Cessation (m^{-1})	Sounding Duration (min:s)
Room B	FGBI	1:16	nm	27:09	nm	25:14
Room B	FSBI	1:24	nm	26:51	nm	25:27
Room A	FSBI	2:51	0.04	25:40	0.26	22:49
Room A	FSBI	5:34	0.06	25:00	0.32	19:26
Room A	FGBI	2:55	0.10	27:43	0.19	24:48
Room A	FGBI	2:38	0.05	25:48	0.25	23:10
Room A	FACI	2:42	0.05	28:09	0.18	24:44
Room A	FACI	2:21	0.07	25:57	0.24	23:36
Room A	FBI	2:32	0.03	25:49	0.25	23:17
Room A	FBI	2:22	0.07	25:47	0.24	23:25
Hallway	Used	2:27	0.03	30:52	0.13	27:21
Hallway	Used	3:32	0.14	22:15	0.37	13:44
Hallway	FGBI	2:37	0.10	24:34	0.3	21:31
Hallway	FSBI	2:34	0.10	23:33	0.25	20:59
Hallway	Photo	4:47	0.01	25:06	0.15	17:09

nm – not monitored *Fire Room

7.5 Initial Observations

Preliminary observations and documentation of the alarms were made as soon after the test as feasible. The alarms were examined with the naked eye (macroscopically) and under magnification from 10-90 times (microscopically). All portions of the alarms were examined and documented, with special care and interest paid to the external, vertical, and internal faces of the horn openings. Areas of enhanced soot deposition were examined, as were the levels of soot deposited proximate to and further away from the horn openings. At a minimum the following series of photographs were taken and observations were made:

- Backside photo showing the alarm id
- Front face macro of the entire alarm
- Close-up of the exterior horn opening(s), where the opening(s) fill the entire field of view
- Interior face of the alarm cover/overall with alarm cover open
- Close-up of the interior horn openings, where the openings(s) fill the entire field of view

The following photos were taken when appropriate, which was the vast majority of cases

- Microscopic views of the exterior face
- Microscopic views of the interior face
- Views of the vertical face
- Microscopic views of the vertical face

After the bulk of the testing had been concluded; the preliminary observations allowed for an initial analysis. It was determined that enhanced soot deposition occurred on the internal, external, and vertical faces of the smoke alarm horn openings. The enhanced deposition of carbonaceous soot appeared macroscopically as deposits in two qualitative patterns: a ring or band pattern that appeared as a solid band of soot deposited in approximately equal density, as described by Worrell, et al., (see Figure 7.5), and a pattern that begins at a higher density and moves to a lower density moving radially away from the horn opening (see Figures 7.6 and 7.7).

Figure 7.5 An example of an enhanced soot deposition pattern with ring-like characteristics on the interior face of a FSBI smoke alarm horn opening. This enhanced soot deposition pattern occurred in an alarm that sounded during exposure to a flaming polyurethane source.

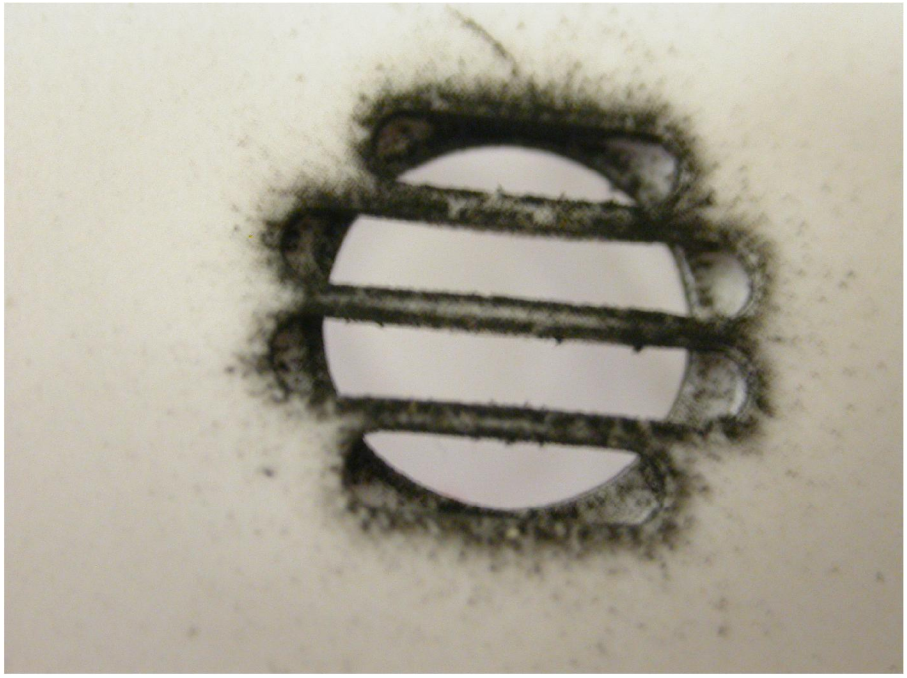

Figure 7.6 An example of an enhanced soot deposition pattern with radial characteristics on the external face of an FSBI horn opening. This occurred on an alarm that sounded during exposure to a flaming polyurethane source.

Figure 7.7 An example of enhanced soot deposition with radial characteristics on the external face of an FGBI smoke alarm horn opening. This pattern is indicative of an alarm which sounded during exposure to the flaming couch fire of Experiment 4.2.

Patterns that appear to have more radial characteristics include examples that were not uniformly deposited around the entire circumference of the smoke alarm horn opening, as seen in Figure 7.8.

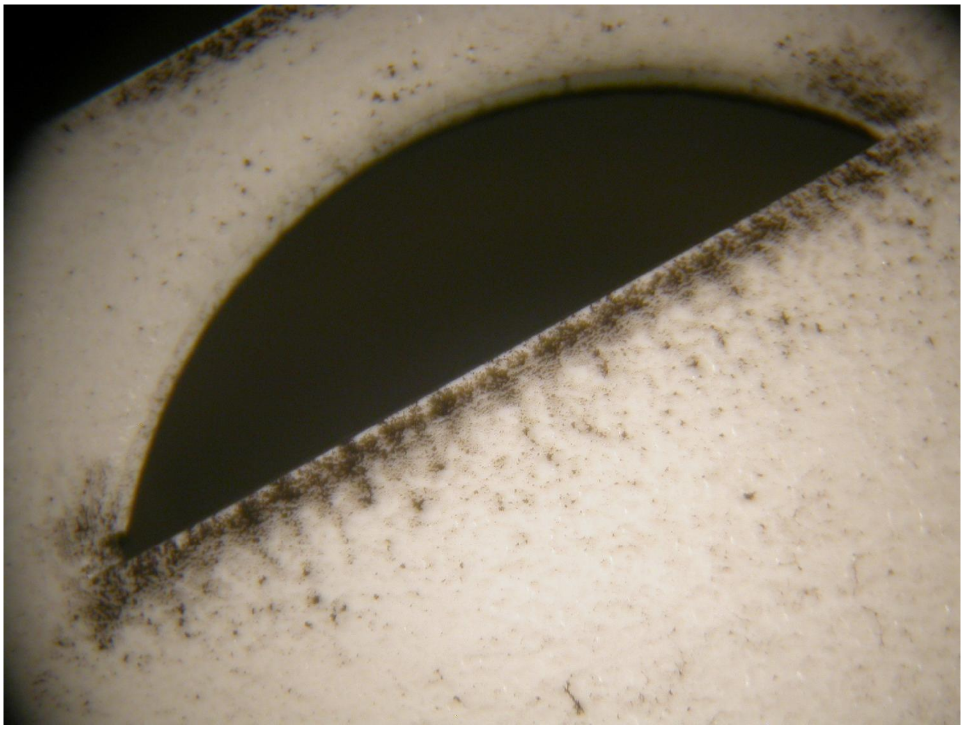

Figure 7.8 This figure shows enhanced soot deposition that occurred on the external face of an FBI alarm horn when it sounded during exposure to a flaming polyurethane source. This pattern of enhanced soot deposition is not uniform around the entire horn opening, but displays the radial characteristics.

Enhanced depositions from smoldering sources did not display either ring or radial characteristics. The hydrocarbon microdroplets from smoldering sources deposited as tarry spots ranging from yellow to brown in color. The enhanced deposition during sounding under exposure to smoldering sources were seldom uniform or symmetric. Most alarms exposed to smoldering fires displayed light yellow staining of the interior surface of the alarm cover. This light staining of the alarm cover was not indicative of sounding, only of exposure to a smoldering fire. However, the tarry spots of enhanced deposition only appeared around the smoke alarm horns, on the internal, external and vertical faces of the openings, on alarms that sounded (see Figure 7.9). That fact, combined with the distinctive appearance of the tarry enhanced depositions, facilitates their identification.

Figure 7.9 An example of a "Tarry" pattern on the external face of an FSBI style horn opening. This is indicative of a smoke alarm that sounded during exposure to a smoldering polyurethane source.

7.5.1 Initial Documented Observations

After the initial alarm evaluation, a number of observations were made and documented. The numbers in parentheses are the percentage of total devices with the characteristic and the percentage of devices that alarmed with the characteristic. (Numbers greater than 100% for the second value signify observations that were seen in alarms that sounded and in alarms that did not sound. This lead to percentages greater than 100 when based upon the number of alarms that sounded):

7.5.1.1 Patterns of Enhanced Soot Deposition

1. Macroscopically observable enhanced soot deposition with ring characteristics
    a. Present (23%, 40%)
    b. Higher density than surrounding soot deposition (20%, 34%)
2. Microscopically observable external enhanced soot deposition ring characteristics
    a. Higher density than surrounding soot deposition (25%, 43%)

   b. Tarry deposition (5%, 9%)

   c. Carbonaceous deposition (24%, 41%)

3. Macroscopically observable external enhanced soot deposition with radial characteristics

   a. Present (16%, 28%)

   b. Higher density than surrounding soot deposition (28%, 28%)

4. Microscopically, 10-90x magnification, observable external enhanced soot deposition with radial characteristics

   a. Present (25%, 43%)

   b. Higher density than surrounding soot deposition (24%, 41%)

   c. Tarry deposition (2%, 4%)

   d. Carbonaceous deposition (25%, 44%)

5. Macroscopically observable internal enhanced soot deposition with ring characteristics

   a. Present (20%, 35%)

   b. Higher density than surrounding soot deposition (20%, 34%)

6. Microscopically, 10-90x magnification, observable internal enhanced deposition with ring characteristics

   a. Higher density than surrounding soot deposition (23%, 39%)

   b. Tarry deposition (5%, 8%)

   c. Carbonaceous deposition (21%, 36%)

7. Macroscopically observable internal enhanced soot deposition with radial characteristics, higher density than surrounding soot deposition (18%, 32%)

8. Microscopically observable internal enhanced soot deposition with radial characteristics

   a. Higher density than surrounding soot deposition (23%, 39%)

   b. Tarry deposition (5%, 8%)

   c. Carbonaceous deposition (24%, 41%)

9. Macroscopically observable soot on the vertical face

a. Present (43%, 73%)

b. Present as enhanced soot deposition (17%, 29%)

10. Microscopically, 10-90x magnification, observable soot on the vertical face

    a. Present (79%, 139%)

    b. Present as enhanced soot deposition (23%, 39%)

11. Observed deposition on the vertical face

    a. Tarry deposition (8%, 13%)

    b. Carbonaceous deposition (60%, 102%)

7.5.1.2 Additional Observations

1. Observable staining on the internal face of the alarm cover (10%, 18%)
2. Macroscopically observable soot on alarm battery terminals (14%, 25%)
3. Microscopically observable soot on alarm battery terminals (26%, 45%)
4. Macroscopically observable soot on battery terminals (11%, 19%)
5. Macroscopically observable soot on battery terminals (23%, 40%)
6. Macroscopically observable soot on battery body (31%, 53%)
7. Macroscopically observable soot on battery body (76%, 131%)
8. Macroscopically observable pattern of the battery arms on the body of the battery (13%, 22%)
9. Microscopically observable pattern of the battery arms on the body of the battery (13%, 23%)
10. Observable deposition on the horn disc

    a. Present (30%, 51%)

    b. Tarry Deposition (9%, 15%)

    c. Carbonaceous Deposition (24%, 41%)

11. Macroscopically observable ring scratched into the surface of the horn disc

    a. Present (24%, 41%)

    b. Incomplete ring (22%, 38%)

c. Complete ring (2%, 3%)

12. Observable soot on the exterior cover of the alarm indicating the direction of smoke flow past or through the alarm (25%, 44%)

13. Observable soot on the interior of the alarm indicating the direction of smoke flow past or through the alarm (17%, 29%)

14. Observable deformation of the exterior alarm cover (3%, 5%)

7.5.1.3 Conclusions Based on Observations

Sufficient observable evidence to support a:

Positive determination of sounding (34%, 59%)

Negative determination of sounding (34%, 81% based on the number of alarms that did not sound)

Insufficient observable evidence to support a determination (32% of total alarms)

The additional observations included soot deposition on battery terminals, staining of smoke alarm covers, markings on metal horn discs, and the bulk flow of smoke across an alarm. These observations did not prove to be useful in identifying alarms that had sounded as enhanced soot deposition. Discussion of these observations is provided in Appendix C.

7.5.2 Enhanced Soot Deposition

7.5.2.1 Worrell, et al., Discussion

Worrell, et al. reported the appearance of macroscopically observable enhanced soot deposition at a lower rate than microscopically observable enhanced soot deposition. Of 24 alarms sounding during exposure to flaming polyurethane fires, 13 displayed macroscopically observable enhanced soot deposition but 17 alarms were positively determined to have sounded when microscopic observations were considered. The following excerpt describes the method for microscopic determination of whether an alarm with an internally mounted circular horn opening (a horn configuration identical to the FGBI alarms in this study, see Figure 0.17) sounded or not [Worrell, et al., 2003].

> "For horn configuration #1[FGBI in this study], the microscopic determination of whether the detector sounded during the test was based on the comparison of soot deposits primarily on the central horn opening to the deposits adjacent to the rim. If soot deposition on the rim was denser than deposition adjacent to the rim, the detector was determined to have sounded. In addition, an abundance of soot particles on the rim that were clearly larger compared to those adjacent to the rim was taken as an indication that the horn sounded. Determination that the detector sounded required that enhanced soot deposition and agglomerates were distributed uniformly around the entire circumference of the circular horn opening. On the other hand, if the density of soot deposition on the rim of the horn opening was similar to the deposition adjacent to the rim, the detector was determined not to have sounded. If the detector did not have sufficient soot deposition on the horn to facilitate such a comparison, the detector was declared 'undetermined.' That is, it was unknown whether the detector sounded or not."

Additionally, Worrell, et al., described the determination of patterns on or around the half moon-shaped horn openings as follows'.

> "For Horn configuration #2, the microscopic determination as to whether the detector sounded was based on a comparison of soot deposits on the inside surfaces of the three moon-shaped slotted openings of the detector lid. To determine whether the horn sounded or did not sound, the methodology described above for horn configuration #1 was followed."

The definition for determination that an alarm has sounded requires the enhanced deposition to be uniform about the entire circumference of the circular opening of the FGBI style horns, with the "same" evaluation applicable to the "moon" style horn openings. This suggests that the enhanced soot deposition needs to be uniform about the entire circumference of the moon-shaped opening to determine that the alarm has sounded. However, photos of alarms of the moon-shaped style with asymmetric depositions are used as examples of those that have sounded (see Figure 18 in [Worrell, et al., 2003]; a similar pattern is pictured within this text in Figure 7.10 do not correspond with this assertion.)

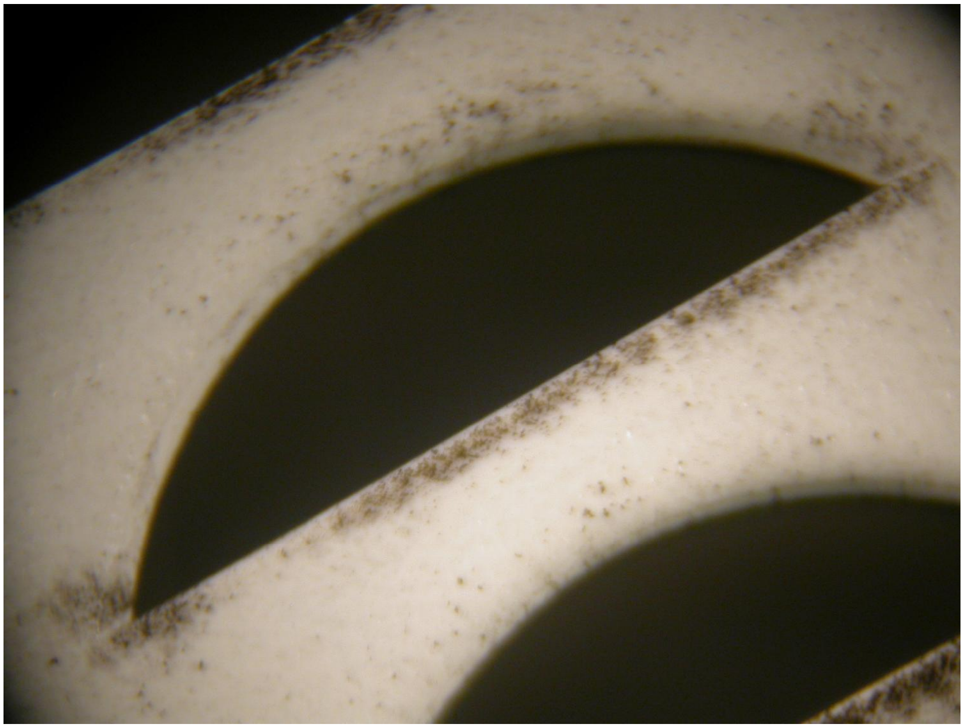

Figure 7.10 This is enhanced soot deposition occurring in an FBI alarm sounding during exposure to flaming polyurethane. The corners of the enhanced deposition on this alarm is not uniform about the entire circumference, but was found to be comparable to Figure 18 in [Worrell, et al., 2003] and indicative of alarm sounding.

7.5.2.2 Observed Enhanced Soot Deposition

To clarify the patterns of enhanced soot deposition observed in this study, soot deposition with ring characteristics describes concentrated soot deposition proximate to the horn opening in a band of similar density. This solid ring pattern was often observed macroscopically.

When observed microscopically, the macroscopically solid ring of soot deposition was found to have a gradual decrease in density moving away radially away from the horn opening. The soot agglomerates also appeared to be aligned radially outward from the horn opening. Similar observations were made [Worrell, et al., 2003] to describe the macroscopic observations of the depositions found on the alarms that sounded owing to exposure to hydrocarbon pool fires. Worrell, et al., noted soot agglomerates directed radially from the alarm horn opening.

The enhanced soot deposition observed on alarms that sounded during exposure to carbonaceous soot often was found to have both ring and radial characteristics. The deposition was not always symmetric or uniformly distributed about the entire circumference of the horn opening. In numerous alarms that sounded, the enhanced deposition was concentrated around corners, faces, or other areas of constricted flow on the horn openings. The tarry enhanced depositions found on alarms exposed to smoldering sources were found to be especially non-uniform and were frequently deposited around only portions of the horn opening. Figures 7.11-7.12 picture alarms that sounded during exposure to flaming sources but that display patterns that are non-uniform over the circumference of the horn opening.

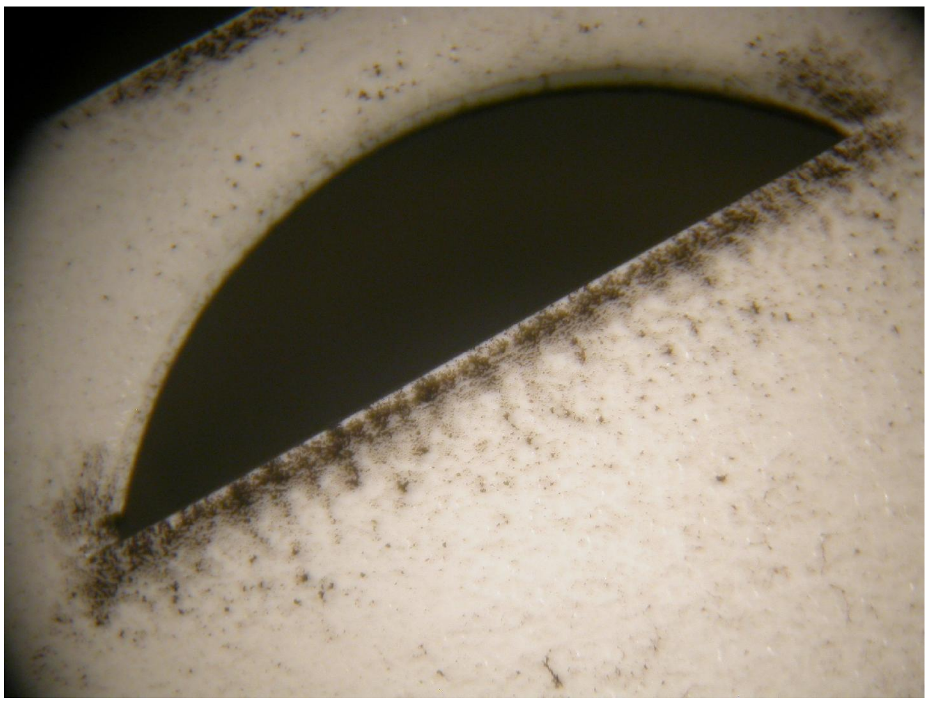

Figure 7.11 An example of enhanced soot deposition pattern on the external face of an FBI horn opening in an alarm that sounding during exposure to a flaming polyurethane test fire. The enhanced deposition is especially concentrated on the corners and flat portions of the moon-shaped openings and not around the entire opening.

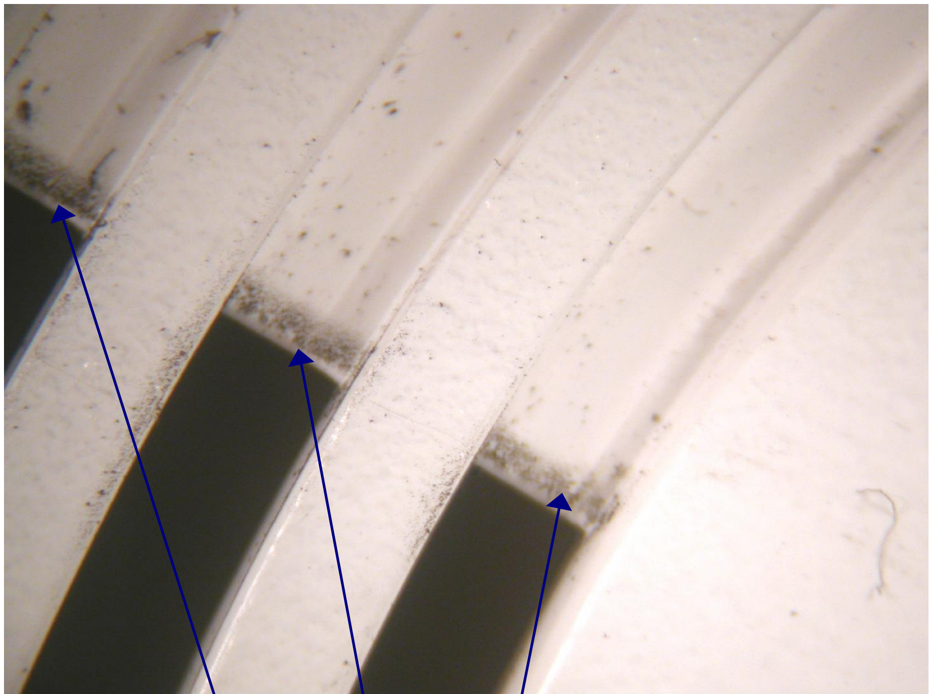

Figure 7.12 Enhanced soot deposition on the external face of a PHOTO horn opening occurring in an alarm sounding during exposure to a flaming polyurethane fire. The enhanced deposition is concentrated on the side edges of the horn opening.

Enhanced soot deposition that decreases in density progressively moving away from the opening, ending in a density approximating the ambient soot deposition on the adjacent face, was described as having radial characteristics, see Figure 7.13.

Figure 7.13 Enhanced soot deposition on the exterior of a used alarm that sounded 45 feet away from the flaming couch fire. The density of the deposition gradually decreases from almost 100% of the area covered directly adjacent to the horn opening to deposition comparable to the ambient soot deposition on the horn. This change along with the radial direction of the soot agglomerates are what is meant by radial characteristics of enhanced deposition.

The enhanced soot deposition was most often uniform about the opening in the FGBI alarms, but less often so in the other horn openings. The uniformity of the enhanced depositions were likely to mirror the symmetry of the horn opening; i.e., it was likely, with circular openings, that the deposition will be found encircling the opening for carbonaceous depositions. With moon and slat-shaped openings it was likely that depositions would be symmetric about an axis of symmetry of the opening, although symmetry was not necessary for positive identification of alarm sounding. The enhanced deposition were especially likely to be found at points of constricted flow, for example, at the corners of the moon-shaped openings (see Figure 7.11), or the rounded or pointed corners/edges of the slat type openings (see Figure 7.12). This likely results from increased turbulence induced by the constriction in the flow that exacerbate the eddies formed by the acoustically induced pulsed flow.

Soot is also deposited on alarms by the bulk flow of smoke into and around the alarm. This flow leads to the possibility of deposition on or around the horn openings by this bulk flow of gases. Deposition of soot agglomerates by bulk smoke flow by and into the horn openings differs from enhanced soot deposition in two ways. First, the soot agglomerates deposited by bulk flow of smoke are of smaller size than the agglomerates affected by an acoustic field [Worrell, et al., 2001]. The soot agglomerates deposited by bulk flow of smoke on or around the horn opening are of similar size to those deposited on the bulk of the alarm cover. There is no obvious difference in the sizes of the agglomerates local to the horn opening and farther out on the alarm cover. Second, the soot agglomerates deposited by bulk flow of smoke are directed in one direction across the horn openings and not radially outward from the horn opening. Therefore, enhanced soot depositions found in both corners of an opening, but not uniformly about the entire circumference of the horn opening, as in Figures 7.10-7.12, were caused by the sounding horn.

Images of enhanced soot depositions that were identified macroscopically and microscopically were analyzed to measure the radial widths of the enhanced soot depositions from the edge of highest density adjacent to the horn opening to the edge of the deposition, which was judged to be the last agglomerate involved in the deposition of larger size than the soot agglomerates ambiently deposited on the same surface. See Figure 7.14 for an example of the edges of a deposit.

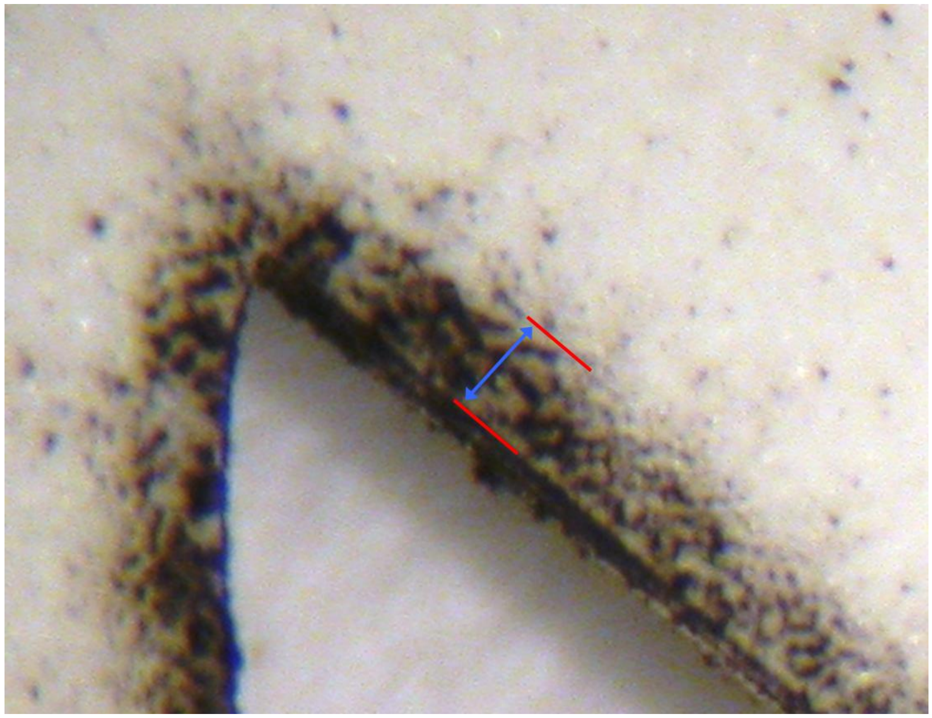

Figure 7.14 An example of the measurement of the radial width of an enhanced soot deposition on the internal face resulting from a flaming polyurethane exposure. The radial width is conservatively measured to the extent of soot agglomerates obviously larger than the ambient agglomerate size. The radial width, measured perpendicular to the horn opening edge, or radially, between the two red lines is 0.433 mm.

The dimensions of deposits were measured perpendicular to the edge of the adjacent horn opening, or radially from the horn opening. The lower density edge was judged conservatively in an attempt to determine a lower bound of the radial widths observed. The example in Figure 7.14 was measured between the two red lines, perpendicular to the horn opening's edge, and found to be 0.433 mm. Enhanced soot depositions in this study were observed to be 0.4 mm or greater for alarms that sounded. This was true of both tarry and carbonaceous depositions.

7.5.2.3 Potentially Misleading Depositions

The first examinations of alarms subjected to high carbonaceous soot yield sources gave the first hint of soot depositions that might complicate the utility of enhanced soot deposition as a technique to identify alarms that sounded. In some case, alarm configurations with horn openings integral to the exterior body of the alarm, when subjected to sooty fire sources such as the flaming polyurethane and flaming turpentine; had a uniform ring of deposition around the entire horn opening. These deposits (see Figure 7.15) would apparently qualify as a pattern as defined by previous studies [Worrell, 2003].

Figure 7.15 Potentially misleading deposition on the internal face of an FBI style horn opening. This is representative of an alarm that did not sound during exposure to a flaming polyurethane source.

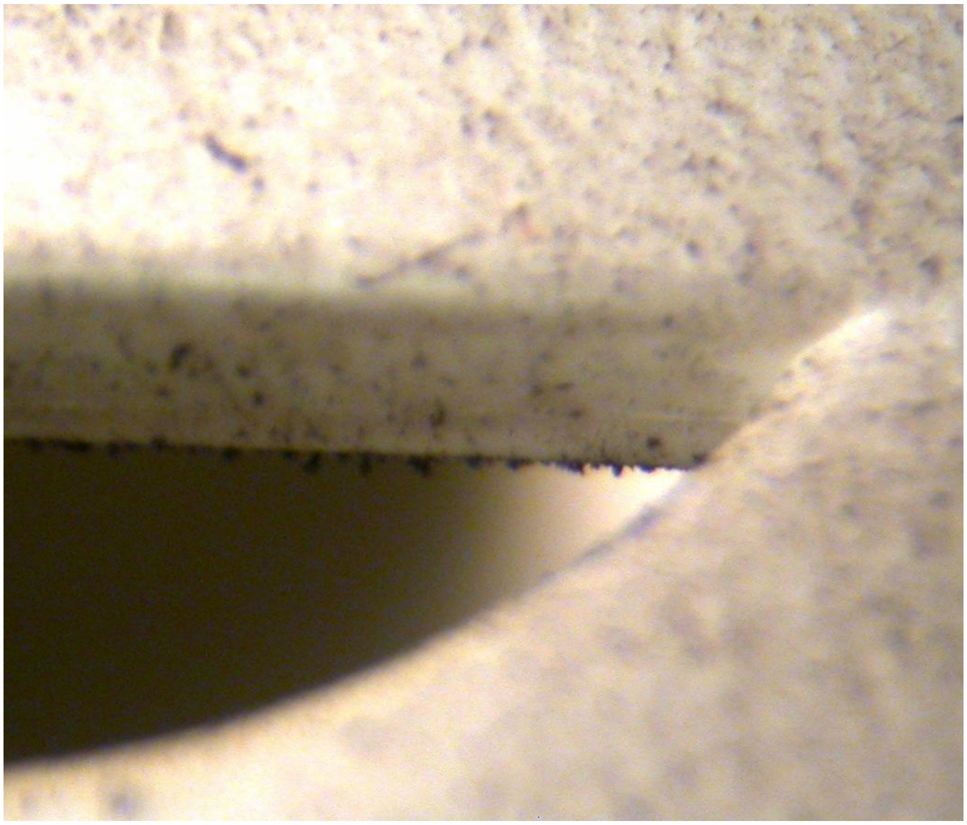

Figure 7.16 Vertical face of the alarm pictured in Figure 7.15. This alarm did not sound but displayed potentially misleading depositions. There is no pattern on the vertical face and the deposition on the internal face can bee seen hanging into the horn opening.

As can be seen in Figure 7.15, the deposition appears as a light ring around the inside edge of the horn opening. The soot deposition is uniform and symmetric and is apparently higher density than the deposition farther from the horn openings but within the horn chamber. Figure 7.16 shows the vertical face of the same alarm and illustrates the deposition hanging into the horn opening and the absence of a vertical face pattern. The soot ring is present on the corner between the internal and vertical faces of the horn opening. Figure 7.17 is an illustration of misleading depositions on an FBI horn chamber cross-section.

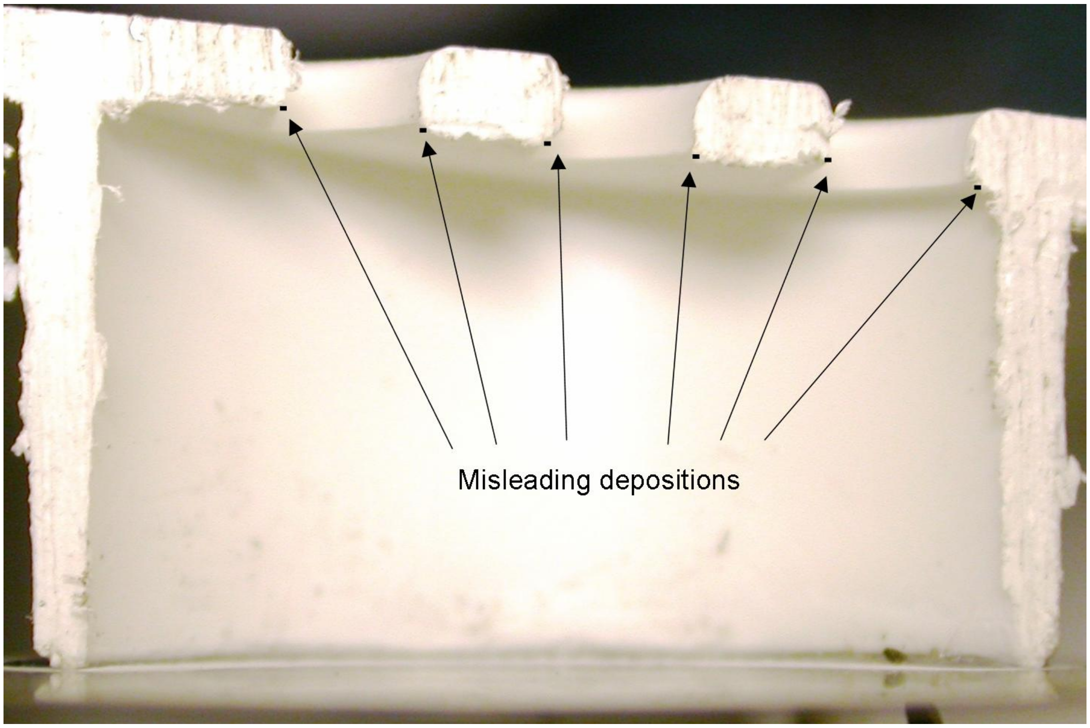

Figure 7.17 This is a cross-section of an FBI horn chamber with an illustration of misleading depositions on the corners between the internal and vertical faces of the smoke alarm horn opening. The markings in the figure are roughly proportional to the actual width of the misleading depositions. Note the extension of the deposits into the horn opening and the positioning of the deposition more on the corner than either of the sheer faces.

The depositions can be seen looking at either the internal face or the vertical face, but do not extend very far onto either of the surfaces. Image analysis of the misleading depositions was completed, in a similar manner to the measurements of the enhanced soot depositions to determine their widths. The misleading depositions were measured perpendicular to the horn opening across the width of the agglomerate ring including the portion that hangs into the smoke alarm horn opening. A sample measurement on the misleading deposition in Figure 7.15 is found in Figure 7.18.

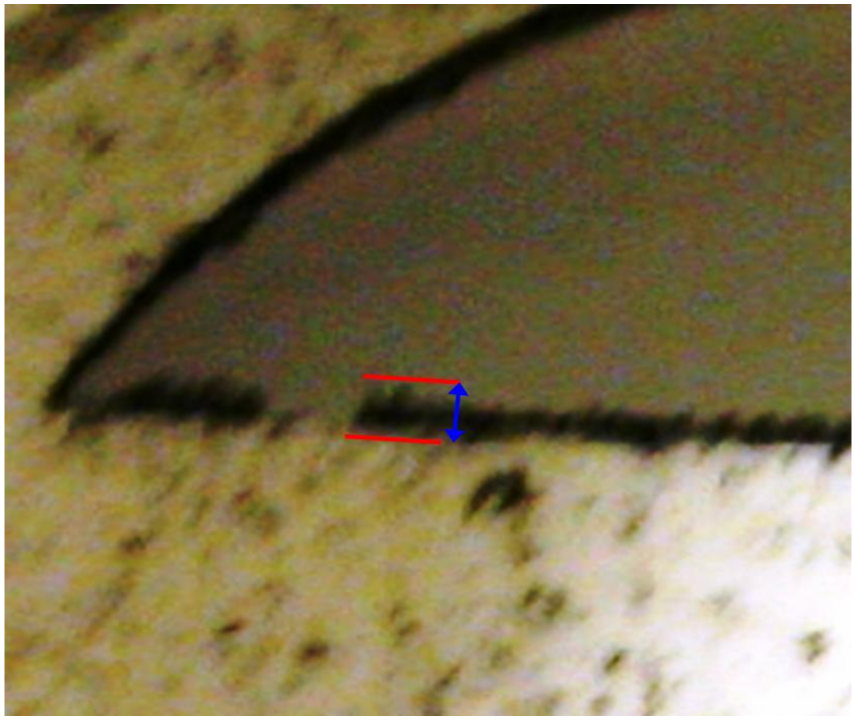

Figure 7.18 This is an example of the measurement of the width of a misleading deposition. The dimension was measured from the one edge of the agglomerate ring to the other, red line to red line in this figure. The radial width measured in this figure in 0.22 mm.

The edges of the particulate rings were measured conservatively to find the upper bound of radial widths, outward from the nominal center of the opening perpendicular to the edge. The misleading depositions observed in this study were found to have maximum radial dimensions of 0.3 mm. The depositions therefore extend less than 0.3 mm onto the internal face. The soot hangs or extends into the horn opening itself. These depositions are clearly different from the enhanced soot depositions present on the internal, external, and vertical faces of the horn openings.

7.5.2.4 Tarry Enhanced Depositions

The tarry smoke condensate associated with smoldering fires was very likely to be asymmetric and non-uniform. Additionally, the examinations showed that soot depositions from smoldering sources did not have either the ring or radial characteristics, although tarry depositions were recorded with the other enhanced soot deposition patterns. The hydrocarbon microdroplets from smoldering sources that deposited as tarry spots were yellow to brown in color. Tarry depositions by virtue of their asymmetry and non-uniformity were apparently excluded from the Worrell et al. definition of enhanced depositions. In this study the microdroplet depositions appeared less frequently and less predictably than carbonaceous deposits, but were also less ambiguous. In a smoldering fire, the alarm cover was stained whether the alarm sounded or not. However, the tarry spots appeared solely around the smoke alarm horns in alarms that sounded. Tarry depositions were never found on any alarm surface other than the smoke alarm horn openings and thus were easily discernable from the general staining of the other surfaces. Figure 7.19 contains an example of the staining during exposure to a smoldering source while Figure 7.20 contains an example of a tarry enhanced deposition.

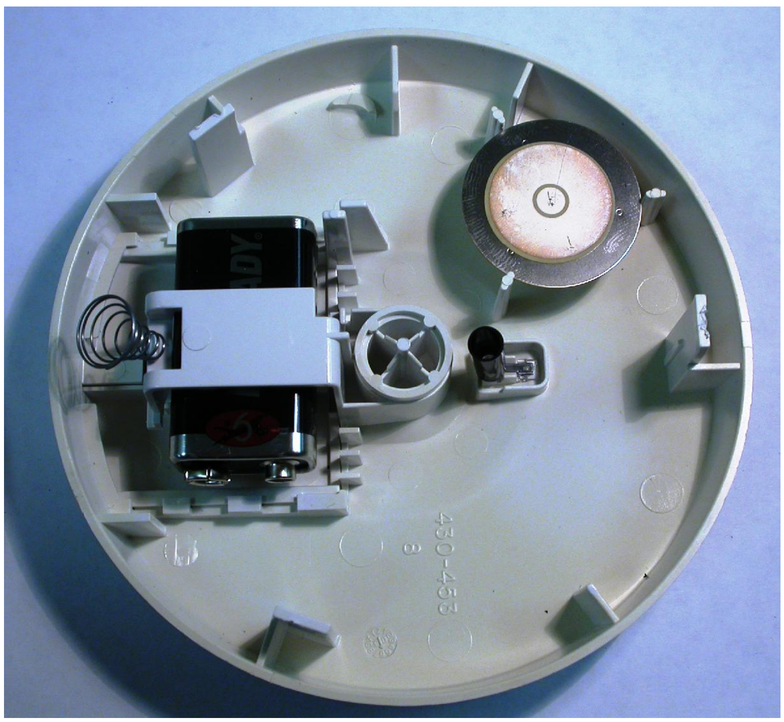

Figure 7.19 This figure shows the interior cover of an alarm exposed to a smoldering polyurethane fire. There is a light yellow staining over the interior of the alarm cover that is seen in both alarms that sounded and alarms that did not sound.

Figure 7.20 This figure displays tarry enhanced deposition on the interior face of an FACI alarm exposed to a smoldering polyurethane fire. The orange enhanced deposition was only seen in alarms sounding. The yellow staining of the alarm cover outside the horn chamber was seen on all alarms exposed to smoldering polyurethane, regardless of sounding.

7.5.3 Identifying Enhanced Soot Deposition

All of the references in this thesis of enhanced soot deposition have referred to increased agglomerate size and higher deposition density. The acoustic field generated by a sounding horn will increase the agglomerate size and induces a pulsed flow into and out of the alarm horn chamber. Enhanced soot deposition should include larger soot agglomerates deposited in higher densities. Identifying enhanced soot deposition relies greatly on comparing the density of depositions between the edge of the horn opening and farther away.

In Section 7.5.2.2 the characteristics observed in the enhanced soot depositions and a method for measuring the radial widths of the enhanced depositions were discussed. The characteristic universally observed in the enhanced soot depositions was the decrease in deposition density radially from the horn opening. The measurement of the enhanced soot depositions defined the end of the enhanced deposition as the last agglomerate, within the gradation from high to low density, of larger size than the ambient agglomerate size. Positive identification of enhanced soot deposition required identification of soot agglomerates deposited adjacent to the alarm horn opening of larger size and greater number or area coverage density than the soot agglomerates deposited farther away from the horn opening. Image analysis revealed the observed enhanced soot depositions to have widths larger than 0.4mm. Also, it became apparent that area 1-2 cm away from the horn opening is sufficiently distant to ensure that the soot agglomerates there were not subject to acoustic effects. Therefore, when comparing soot proximate and distant from the horn openings, soot representative of the ambient deposition, in an area 1-2 cm away from the horn opening was used.

In 7.5.2.2 it was discussed that the agglomerates are not required to be deposited uniformly around the entire opening. In the cases of the moon and slat style openings, FACI, FBI, and PHOTO alarms, the soot was not deposited uniformly around the entire horn opening. The enhanced deposition was most likely to be concentrated on the shorter edges and corners. The depositions here were also found to move from a higher density, measured in area coverage or number density, to a lower density moving radially away from the alarm horn. Soot depositions that consist of similar sized agglomerates to the agglomerates ambiently deposited on the alarm and deposited in the same direction are most likely due to the bulk movement of smoke across the alarm and not attributed to the alarm sounding.

When verifying the presence of enhanced soot deposition by comparing the densities inside and outside the suspected enhanced deposition, magnifications of 40x and greater proved instructive. At these magnifications, the difference in agglomerates sizes is most obvious. The same magnification was used to examine the enhanced deposition and the areas outside the enhanced deposition. When examining the external face of the smoke alarm, the enhanced deposition on the horn openings was compared to the ambient soot deposition on any part of the external face of the smoke alarm further away from the smoke alarm horn opening. Image analysis of the patterns has shown that 1-2 cm is sufficiently far away from the horn openings for the soot deposited there to be unaffected by the sounding horn. Comparisons were made between depositions on the horn openings and 1-2 cm away from the horn openings. For internal examinations the soot deposition in the suspected pattern is compared to the soot deposition on the internal face outside of the suspected pattern and outside the horn chamber.

7.5.3.1 Horn Chamber Deposition

A comparison of soot density inside and outside the horn chamber was recorded. In cases where the horn chamber is sealed to the external face of the smoke alarm, as in Figure 0.6, the overall density of the soot deposition inside the horn chamber was compared to the soot deposition outside the horn chamber.

When a smoke alarm sounds, a pulsed flow is induced in the smoke alarm horn chamber [Worrell, et al., 2003], increasing the amount of soot entering the horn chamber over that occurring if the horn did not sound. Soot exposure to the inside face of the smoke alarm cover is the same regardless of whether the horn sounds or not. Therefore, in the case where the horn sounded, the soot deposited on the inside of the horn chamber is of comparable density to that deposited outside of the chamber on the inside face of the smoke alarm. In cases where the horn did not sound, the soot deposited inside of the horn chamber will be of a lower density than the soot deposited outside the chamber on the inside face of the smoke alarm cover. This comparison forfends false positive identification, as it may appear that there is enhanced soot deposition on the internal face of the smoke alarm when the density proximate to the horn opening is compared to density further from the opening but still inside the horn chamber. This may be caused by smoke entering the horn chamber owing to the turbulence in flow of smoke around the alarm. Even when an alarm does not sound, some smoke may move in and out of the horn chamber. However this flow will be smaller than in an alarm that sounds. In cases of exposure to sources with the highest soot yields, the deposition on the inside of the horn opening will reflect the flow of smoke into the horn chamber and could cause the mistaken identification of alarm sounding. The following series of photos, Figures 7.21-7.25, illustrate the case outlined above for two alarms exposed to a turpentine fire. The alarms were mounted side-by-side one sounded one did not. Figure 7.21 shows the interiors of both alarms. Figure 7.22 shows the external face of the alarm from the pair in 7.21 that did not sound. In Figure 7.22 the internal cover of that same alarm displays distinct contrast between the soot deposited inside and outside the horn chamber. Figures 7.24 and 7.25 further magnify the disparity in soot density inside and outside the horn chamber in the alarm that did not sound.

Figure 7.21 The alarms above were mounted side-by-side. The alarm on top sounded the bottom alarm did not. In the top alarm the soot deposition inside and outside the horn chamber is comparable. In the bottom alarm the soot density outside the horn chamber is denser than the soot deposition inside the horn chamber.

Figure 7.22 This is the external face of the bottom alarm in Figure 7.21. There is some visible soot deposited but no evidence of enhanced deposition.

Figure 7.23 This is the internal cover of the alarm in Figures 7.19 and 7.22 that did not sound. Notice the difference in soot deposition density inside and outside the smoke alarm horn chamber.

Figure 7.24 This is the horn chamber of the alarm (shown in Figures 7.21-7.23) that did not sound. Notice the thin ring of soot around the horn openings, but the lower soot density in the horn chamber otherwise. Compare this to Figure 7.25.

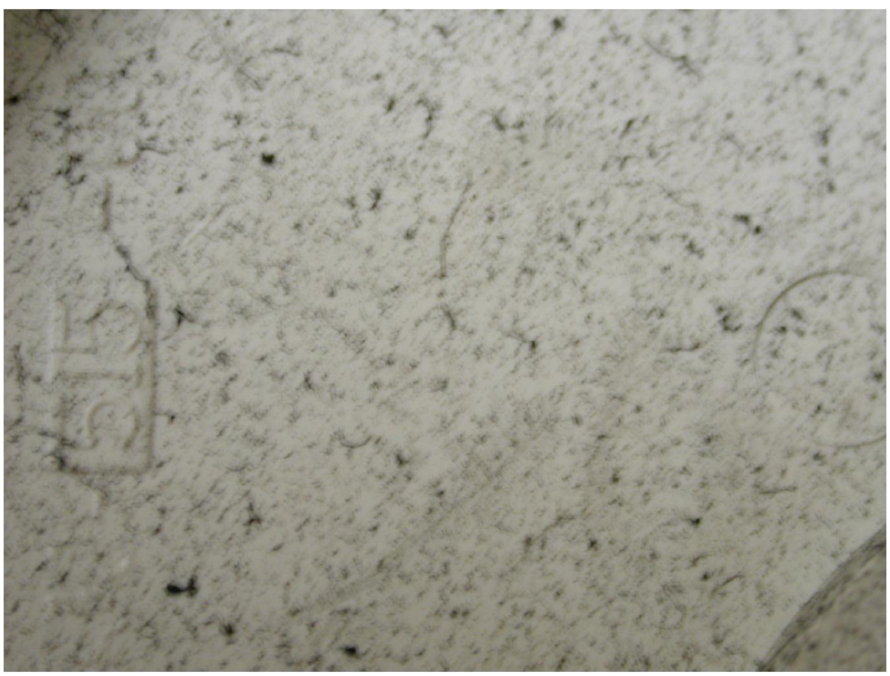

Figure 7.25 This is the ambient soot deposition on the body of the alarm in Figure 7.24. This photo is taken at the same magnification as the previous figure. Notice the higher density and similar agglomerate size of soot in this figure to the last figure. The difference in deposition density is an indication the alarm did not sound.

Figure 7.26 contains the horn chamber from the sounding alarm in the top portion of Figure 7.21. The similar soot density inside and outside the alarm horn chamber in the alarm that sounded is distinctly contrasted by the difference in soot deposition in and outside the horn chamber of the alarm in Figure 7.24.

Figure 7.26 This figure contains the horn chamber to the alarm that sounded during the same exposure as Figure 7.24. Notice the larger soot agglomerates and higher density of soot within this horn chamber than in Figure 7.24. Also, the density within the horn chamber is of equal or greater density to that outside the chamber.

7.5.4 Locations of Enhanced Soot Deposition

Patterns of enhanced soot deposition can occur on three faces of the smoke alarm horn opening: the external, internal, and vertical faces. These are most affected by the acoustic field and the induced pulsed flow and accompanying eddies of a sounding alarm. The following series of figures, 7.27-7.30, show a variety of depositions indicative of sounding. Figures 7.27 and 7.28 show the external and internal faces, respectively, of an FSBI alarm that sounded. Figure 7.29 shows the internal face of an FBI alarm that sounded during the cabinet assembly fire. The FGBI alarm pictured in Figure 7.30 has carbonaceous patterns on the external, vertical, and internal faces of the horn opening.

Figure 7.27 An example of macroscopically observable enhanced soot deposition on the external face of an FSBI alarm. This is representative of the result of an alarm sounding during exposure to a flaming polyurethane exposure.

Figure 7.28 An example of macroscopically observable enhanced soot deposition on the internal face of an FSBI alarm. This is representative of an alarm sounding during exposure to a flaming polyurethane source.

Figure 7.29 An example of microscopically observable enhanced deposition on the internal face of an FBI horn opening that sounded from a smoldering/flaming cabinet assembly fire.

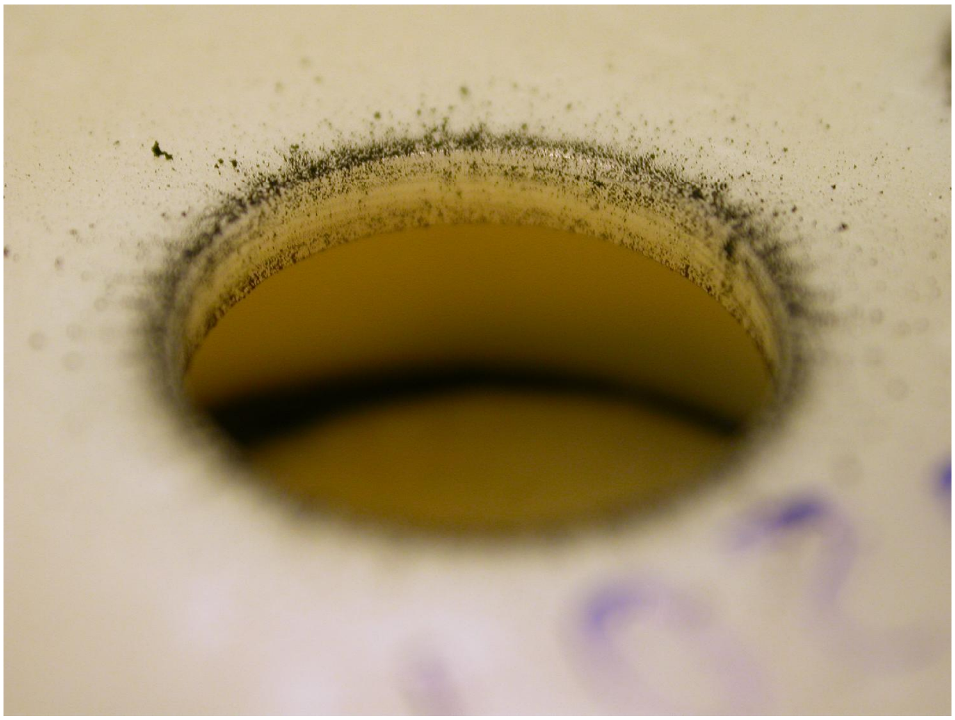

Figure 7.30 Macroscopically observable enhanced soot deposition patterns on the vertical and external faces of an FGBI alarm horn opening that sounded during exposure to a flaming couch. Notice the bands of enhanced soot deposition on the vertical face of near each the internal and external faces of the horn opening.

7.5.4.1 External Face

The external face of the smoke alarm horn opening has been defined in the nomenclature section and can be seen in Figure 0.1. It is affected by the acoustic field from a sounding alarm and the eddies that accompany the induced pulsed flow [Worrell, et al., 2003], which results in enhanced deposition on the external face. This deposition is the most easily observed, but also the most likely to be obscured through handling. Deposition of the external face is typically the last location to develop. They were less likely to develop than patterns on the interior face and, in most cases, were less dense when compared to patterns on the interior face. Standard evidence handling procedures [NFPA 921, 2003] can affect patterns found on the external face.

7.5.4.2 Vertical Face

The vertical face is the sheer face of the smoke alarm horn opening connecting the external and internal faces (see Figure 7.30). This face is subject to the acoustic field and the induced pulsed flow. Enhanced soot deposition can be found on the vertical face of smoke alarm horn openings proximate to either or both edges (see Figure 7.30). The enhanced deposition will occur on the sheer face and not on the corners between the edges as seen with the misleading depositions (see Section 7.5.4.2). The enhanced depositions on the vertical face displayed both ring and radial characteristics proximate to both edges. In some cases, as in Figure 7.29, separate patterns of enhanced soot deposition were seen proximate to both edges with separation between. Figure 7.31 shows a pattern on the vertical face closest to the internal face of the horn opening only. Enhanced deposition can be more difficult to differentiate on the vertical face than on the internal and external faces, because there is no surface with which to compare soot deposition density. Figure 7.32 shows the deposition on the vertical face of an alarm that did not sound.

Figure 7.31 This figure shows enhanced soot deposition on a vertical face of an FBI alarm that sounded during exposure to a flaming polyurethane fire. The deposition starts at higher density close to the internal face and decrease toward the external face. Compare this to Figure 7.32.

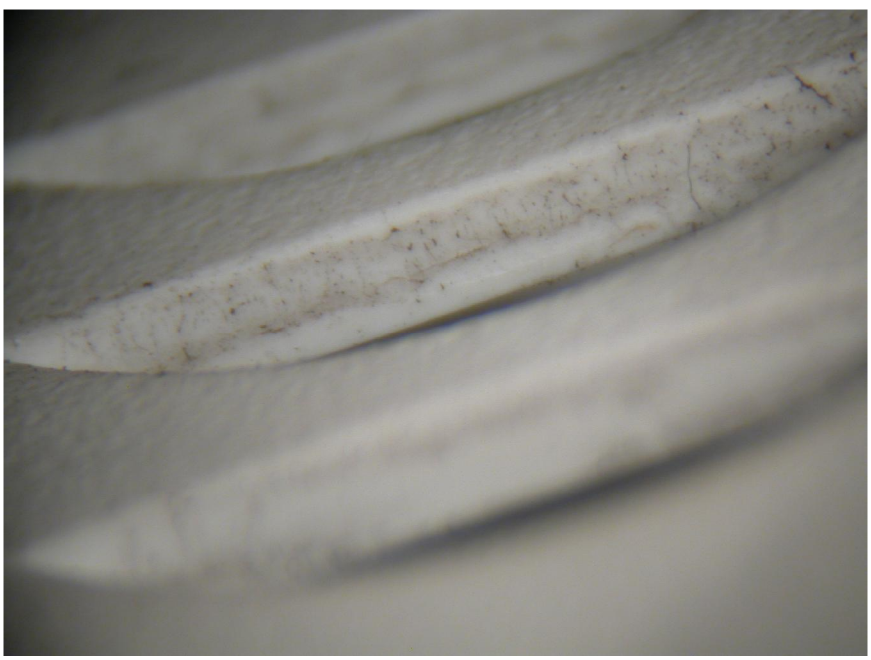

Figure 7.32 This figure displays soot deposited on the vertical face of an FBI alarm that did not sound during exposure to flaming polyurethane. The deposition does not display any of the characteristics of enhanced deposition seen in Figure 7.31.

The difference between deposition and enhanced soot deposition on the vertical face is similar to that for the internal and external faces, the marked gradation in density being the primary characteristic. Simple deposition on the vertical face was not shown to be a predictive measure of sounding. Only enhanced soot deposition had a positive correlation with alarm sounding.

7.5.4.3 Internal Face

The internal face is the face inside of the smoke alarm horn opening. It is the reverse of the external face, opposite the visible side. The acoustic field is expected to be the strongest within the horn chamber and eddies similar to those that occur on the exterior face should be expected on the interior face. Enhanced deposition is observed first on the internal face and has the same characteristics as enhanced deposition on the external and vertical faces. Enhanced soot deposition on the internal face can be identified via similar methods as those for the vertical and external faces, described in the previous section. The enhanced soot deposition on the interior face was found to be of higher density than that on the exterior face. The interior face is also the least likely of the faces to be affected by evidence handling procedures.

8 Analysis

8.1 Correlation of Observations

After documenting the observations it was necessary to assess their utility as positive and negative indicators of alarm sounding. A complete list of the observations is found in Section 7.5.1. Each observation or lack thereof was correlated with sounding of the horn. The number of times the observation positively correlated with the alarm having sounded, the number of times the lack of the observation correlated with the alarm not having sounded, the number of times each of these conflicted with the alarm state, and the number of times the observation or the lack thereof correctly corresponded to the alarm state were calculated. This led to the following hierarchy of the observations utility of the observations as positive indicators of sounding ranked according to the number of alarms that are correctly correlated as having sounded using only the indicated criterion:

1. Microscopic Internal Patterns
2. Microscopic Vertical Face Patterns
3. Macroscopic Vertical Face Patterns
4. Microscopic External Patterns
5. Macroscopic Internal Patterns
6. Horn Chamber Deposition Density
7. Macroscopic External Patterns

There are cases, as previously described in the Section 7.5.1.3, where using only one of these observations yields false determinations of alarms sounding. The macroscopic external patterns are the most robust in that they do not yield false positive determinations; however, dependence on such patterns alone results in fewer positive determinations than can be achieved with a combination of observations. Accuracy in the identification of activates alarms, without false positives, was improved by relying on multiple independent observations, a method that forms the basis for an inspection heuristic, detailed in Section 8.4.

The following hierarchy was established for the utility of the absence of characteristics as negative indicators of sounding ranked according to the number of alarms correctly correlated as having remained silent during the exposure:

1. Macroscopic External Patterns
2. Macroscopic Internal Patterns
3. Microscopic External Patterns
4. Microscopic Vertical Face Patterns
5. Microscopic Internal Patterns
6. Macroscopic Vertical Face Patterns
7. Horn Chamber deposition Density

The conclusion that an alarm did not sound in a fire condition is not sufficiently predicted by a lack of discernable enhanced soot deposition; such logic leads to significant false negative identifications. Comparing the density of soot deposition inside and outside the horn chamber yields the lowest number of correct negative correlations but also the lowest number of false negative determinations. The false negative determinations, generated solely through the use of this one criteria, are due to the ambiguity of this correlation in cases where the fuel source yields a very little amount of soot or is a nuisance source. All of the false determinations result from a lack of sufficient soot to make a determination whether there is a difference in deposition density inside and outside the horn chamber or not, as is also the case with nuisance sources or undetermined sources.

8.2 Methodology of Evaluation

The procedure used to examine and document exposed alarms is outlined below. (A set of sample photographs with commentary from a typical alarm examination is located in Appendix B.)

1. A thorough naked eye examination of the exterior of the smoke alarm cover, including photographs of the entire smoke alarm. Where applicable, side on photographs documenting deposition indicative of the direction of smoke flow into and around the smoke alarm, noting direction relative to horn placement.

2. A macroscopic examination and photograph(s) of the external face of the smoke alarm horn openings, clearly depicting macroscopic enhanced soot depositions where applicable. The horn openings and deposition patterns fill the entire field of the photograph.
3. An examination of the ambient soot deposition on the exterior cover of the smoke alarm. This examination includes a photograph of an area of average ambient soot deposition on the exterior cover taken at the same scale as the photograph of the horn openings. Areas 1-2 cm away from the horn openings was far enough away to avoid the localized effects owing to pulsed flow. At 1-2 cm from the horn opening the soot deposited from the bulk flow of smoke is comparable to that at the horn openings. The density of soot deposition outside the pattern is compared to the density of deposition within any suspected patterns. In cases where the suspected enhanced deposition is of higher density than the ambient deposition, a macroscopic enhanced deposition is identified. In cases where the deposition within the suspected pattern is of the same or less density as the density outside the suspected pattern, no macroscopic external pattern is identified. In cases of FGBI alarms (internal horn configurations), the comparison of densities is made between the areas proximate to the horn opening and farther out on the external face of the horn opening, not on the external or internal faces of the alarm cover.
4. Preliminary judgments are formed about whether there was enough soot on the alarm to make a determination of sounding. In cases where there was little to no evidence of soot proximate to the horn openings or on the alarm cover, it was unlikely there would be indications positively or negatively as to alarm sounding.
5. Next, the external face of the alarm horn openings was examined microscopically, from 10-90x magnification. Photographs of soot deposition were taken at the lowest magnification that resolved their presence. Under magnification, any decrease in soot density moving away from the horn opening and increased agglomerate size identify enhanced deposition, as outlined in Section 7.5.2 identified enhanced soot deposition.

6. At the same magnification used in step 5, areas 1-2cm from the horn openings are inspected for ambient soot deposition. The deposition found here is compared to the deposition density at the horn openings. If the density of soot deposits at the horn openings is greater than the ambient soot deposition at the same magnification, microscopic external enhanced deposition is identified. While magnifications much greater than 40x can serve to confuse in the identification of a pattern they can be helpful in the comparison of the density of a suspected pattern and the density of the ambient soot deposition. For FGBI alarms, the comparison of densities is made between the areas proximate to the horn opening and further out on the external face of the horn opening, not on the external or internal faces of the alarm cover.
7. Based on steps 5 and 6, preliminary judgments about the quality of the soot depositions can be made; e.g., the delineation between carbonaceous and tarry deposits and the differentiation between dust and other nuisance products and carbonaceous soot.
8. A macroscopic inspection of the vertical faces of the smoke alarm horn openings is performed, including photographs. Enhanced depositions on a vertical face appear in the same way as on the external or internal faces. The deposition changes from high to low density starting at the internal face and moving towards the external face or starting at the external face and moving towards the internal face, or both. Some cases were observed where there were two bands evident on the same vertical face, see Figure 7.30. Identification of enhanced deposition on the vertical face requires obviously higher deposition density and bands or gradations, not simply the presence of soot particulate on the vertical face.
9. The macroscopic examination of the vertical face was followed by a microscopic examination of the vertical face. Observations and documentation are conducted at magnifications between 10 and 90x. The deposition density decreases starting at the internal face and moving towards the external face, starting at the external face and moving towards the internal face, or both. Some cases have been observed where there were two bands evident on the vertical face. Identification of a pattern on the vertical face requires obviously higher deposition density and

bands or gradations, not simply the presence of soot particulate on the vertical face.

10. At this point, the alarm cover was removed for externally mounted alarm horns. A naked eye examination of the interior surface of the alarm cover and the interior components of the alarm was conducted. Documentation included, at least, photographs of the entire interior surface of the alarm cover and the alarm base and components. Evidence of bulk flow patterns through the alarm and yellow orange staining of the interior of the alarm cover indicative of a smoldering source was noted.
11. A macroscopic examination of the internal face of the smoke alarm horn opening is conducted, including photographs where the horn chamber fills the entire field of view. Identification of patterns on the interior face remains consistent with that on the external face.
12. An examination of the ambient soot deposition on the interior cover of the smoke alarm. This examination includes a photograph of an area of average ambient soot deposition on the exterior cover at the same distance from the alarm as the photograph of the horn openings. The examination and photograph center on a comparison of areas inside and outside the horn chamber. In cases where the deposition inside the horn chamber is of higher density than the ambient deposition, macroscopic interior enhanced deposition is identified. In cases where the ambient deposition is of the same or less density and agglomerate size as the suspected enhanced deposition, no macroscopic external pattern is identified.
13. The internal face of the alarm horn openings is examined microscopically, from 10-90x magnification. Photographs of enhanced depositions are taken at the lowest magnification that resolves their presence. Under magnification, a decrease in soot density moving away from the horn opening and increase agglomerate size identified enhanced soot deposition.
14. At the same magnification as used above, areas inside and outside the horn chamber are compared to the ambient soot deposition. The deposition found outside the horn chamber is compared to the deposition density within suspected patterns. If the density of soot deposited in suspected depositions is greater than

the ambient soot deposition compared at the same magnification, a microscopic external pattern is identified. While magnifications much greater than 40x can serve to confuse in the identification of a pattern they can be helpful in the comparison of the density of a suspected pattern and the density of the ambient soot deposition.

15. For FGBI alarms, the examination of the internal face is completed using a small mirror to inspect the internal face of the smoke alarm horn opening, macroscopically and microscopically.

8.3 Heuristics

As outlined in Section 8.1, correlation of a single observation to alarm sounding is of limited utility. A Visual Basic routine was written to combine observations using Boolean operations. Heuristics were generated separately for the positive and negative determination of sounding. The following heuristic was generated to optimize the predictive capacity of the observations in determining that an alarm had sounded. The positive determination heuristic, in Figure 8.1, resulted in no false positive determinations when applied to the observations made during the blind study (see Section 8.4.1).

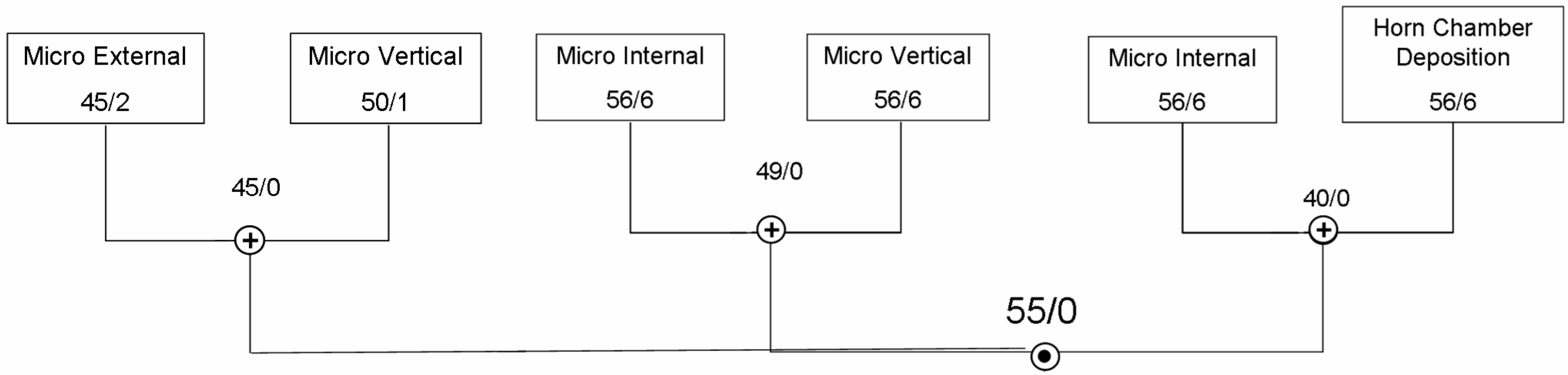

Figure 8.1 The positive identification heuristic. Combining the observations from the blind study using the heuristic results in 55 alarms correctly identified as having sounded and 0 alarms incorrectly identified as having sounded.

A second heuristic was developed to correctly identify that an alarm had not sounded. The heuristic is based on the lack of the specified patterns, observations of soot type and density, and the result that the FGBI alarms were unlikely to generate patterns indicative of alarm when subjected to smoldering fire sources. The heuristic optimizes the number of alarms correctly identified as not having sounded and eliminates false negative determinations.

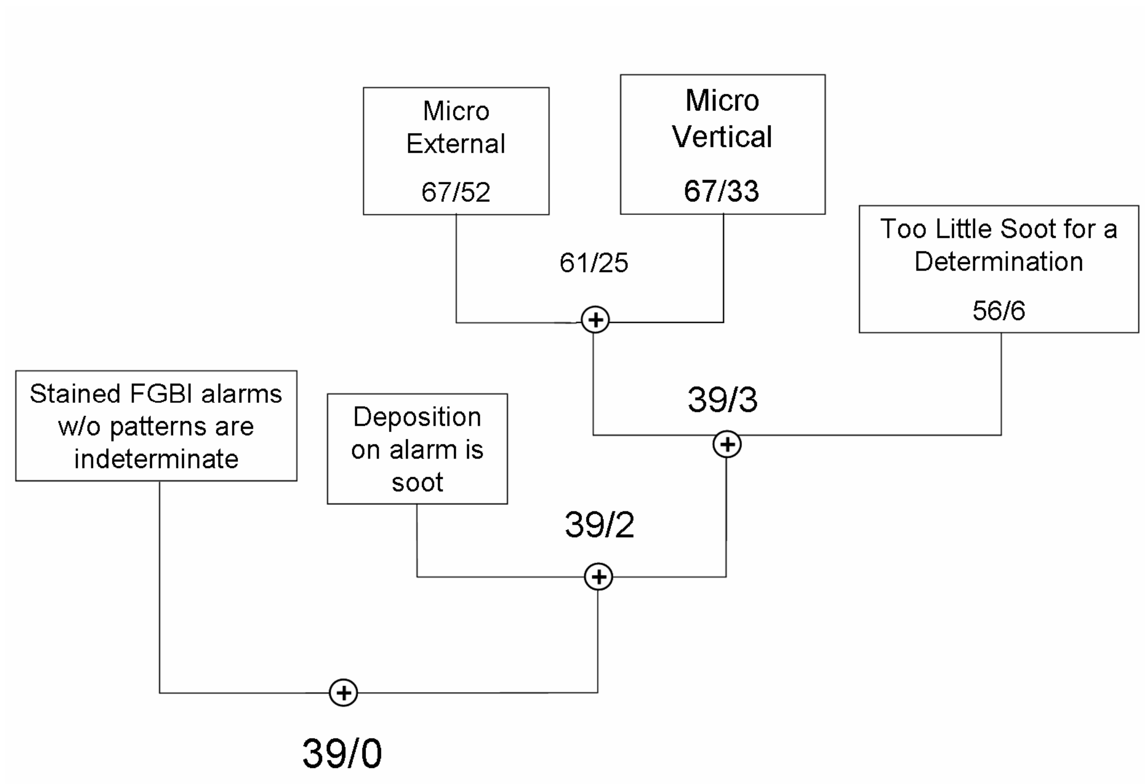

Figure 8.2 The negative alarm sounding heuristic. The pluses represent Boolean AND combinations and the dots represent Boolean OR combinations. Combining the absence of patterns and the rules to the observations from the blind study results in 39 alarms correctly identified as not having sounded and 0 incorrectly identified.

In Figure 8.2 above, the heuristic for correctly determining that an alarm had not sounded utilizes the absence of enhanced soot deposition, depositions, and observations. First, observing that the deposition on an alarm is only composed of nuisance products eliminates the possibility that it sounded due to a fire source. Second, the FGBI horns did not often yield indicative patterns when solely exposed to smoldering sources. Therefore, based on the tests conducted, it was not possible to make a negative determination for FGBI alarms that have only smoldering deposition, a yellow or orange staining. When this rule is applied, if an FGBI alarm has only yellow orange staining on the inside face of the alarm and no tarry patterns, there is not sufficient evidence to determine the alarm had not sounded. Strict observation of the heuristic in Figure 8.3 would result in determining that 39 alarms had not sounded.

8.4 Results

8.4.1 Summary

Through the course of this study the four experimental series were conducted generating a population of alarms for evaluation. Immediately following the experiments, the alarms were observed and documented. The observations were correlated with whether or not the alarms had sounded. From these correlations a set of heuristics was developed. A blind study was then undertaken to evaluate the identification methodology and heuristics. In order to fully evaluate the methodology, the alarms exposed during the experiments were observed and documented without knowledge of their exposure history. Observations were made as previously defined in Section 7.5 and in the method outlined in Section 8.2, with an example evaluation including photographs found in Appendix B. These observations were then run through the positive and negative determination heuristics detailed in Section 8.3 to yield determinations of alarm sounding or not. Examination of these results led to slight modification of the negative determination heuristic. The final heuristics were then reapplied to the blind study observations generating the results, which are presented.

The results of the blind study and observations are provided below. First, a summary of the observations and their utility is provided. Understanding the utility of each observation and its relation to other observations provides support for a hierarchy and a further understanding of the construction of the heuristics. For sake of numerical evaluation and tabulation, as the results are presented the observation of a pattern or deposition is considered a positive indication of alarm and the lack of that enhanced soot deposition or ambient deposition is considered an indication that the alarm did not sound. Table 8.1 shows the results of each observation as a tool, providing the number and percentage of alarms correctly identified, positively identified as sounded and positively identified as not sounded, indeterminate, false positives and false negatives based on each observation alone and based on the identification methodology and application of the developed heuristics. The calculation of the percentages in the table for the total number of alarms correctly identified and identified as indeterminate are based on the total number of alarms evaluated, 151. For the number of alarms correctly identified as having sounded and the number identified as false positives the percentage is based on the number of alarms evaluated that sounded, 83. For the number of alarms correctly identified as not having sounded and the number of alarms identified as false negatives the percentages are based on the number of alarms evaluated that did not sound, 68.

The data in Table 8.1 is arranged with the observation on the left and the resulting determinations and utility following across the table. For example the first row uses only a macroscopic pattern on the external face of alarm horn openings as an indication of whether or not an alarm had sounded. It assumes that the presence of an external macroscopic pattern on the external face of an alarm indicates the alarm sounded and the lack of pattern as an indication the alarm did not sound. The first column totals the number of alarms that would have been correctly identified in total using only this observation, 95. The percentage of the total number of alarms in the population, 151, is in parentheses, or 95/151 = 63%. The next column contains the number of alarms correctly identified as sounding by only the presence of macroscopic pattern on the external face, 27. The number in parentheses is the percentage of alarms that sounded, 83, that were correctly identified using this observation, or 27/83 = 33%. The third column contains the number of times the lack of a macroscopic pattern on the external face would have correctly identified an alarm as not having sounded, 68. The number in parentheses is the percentage of the alarms that did not sound, 68, that were correctly identified as not having sounded by the lack of this observation, or 68/68 = 100%. The fourth column contains the number of times that utilizing only this observation would have resulted in an indeterminate conclusion, 0. The fifth column contains the number of times that using a macroscopic pattern on the external face would have misidentified an alarm as having sounded when it did not, a false positive, 0. Finally, the sixth column contains the number of times the lack of a macroscopic pattern on the external face of an alarm would have misidentified an alarm as not having sounded when in fact it did sound, a false positive, 56. The percentage in parentheses is the percent of alarms that did not sound, 68, that would have been misidentified as a false positive, or 56/68 = 82%.

Table 8.1 Summary of blind study results with number of alarms and percentage of total in parentheses

Result		Correctly Identified			Identified		
Characteristic		Total Number	As Sounded	As Did not Sound	As Indeterminate	False Positives	False Negative
External Face	Macroscopic Pattern	95 (63%)	27 (33%)	68 (100%)	0	0	56 (82%)
	Microscopic Pattern	111 (74%)	45 (54%)	66 (97%)	0	2 (2%)	38 (56%)
Horn Chamber Density		91 (60%)	43 (52%)	48 (58%)	37 (24%)	4 (5%)	18 (26%)
Internal Face	Macroscopic Pattern	111 (73%)	43 (52%)	68 (100%)	1 (1%)	0	39 (57%)
	Microscopic Pattern	118 (78%)	56 (67%)	62 (91%)	1 (1%)	6 (7%)	26 (38%)
Vertical Face	Macroscopic Deposition	101 (67%)	62 (75%)	39 (57%)	0	29 (35%)	21 (31%)
	Macroscopic Pattern	117 (77%)	50 (60%)	67 (99%)	0	1 (1%)	33 (21.8%)
	Microscopic Deposition	88 (58%)	79 (95%)	9 (13%)	0	59 (71%)	4 (6%)
	Microscopic Pattern	117 (77%)	52 (63%)	65 (96%)	0	3 (4%)	31 (20.5%)
Heuristic Determination		94 (62%)	55 (66%)	39 (54%)	57 (38%)	0	0

Table 8.1 outlines the observations from the blind study and their utility in determining whether or not an alarm had sounded. The heuristic determination in Table 8.1 was based on identifying the enhanced soot deposition via the descriptions in Section 7.5, the procedure outlined in Section 8.2, and the application of the positive and negative heuristics detailed in Section 8.3. There were no false positive and no false negative determinations of sounding.

One conclusion is the ranking of utility of the individual observations previously outlined. In addition, to eliminate all false positive and negative determinations, combinations of observations are necessary. While some observations may yield no false positive determinations, their use alone would result in identifying only a portion of those alarms that have sufficient indicators to make a determination. For example, using macroscopic enhanced soot deposition on the external face correctly identifies 27 alarms as having sounded and incorrectly identifies 0 alarms as having sounded. However, when all of the observations are combined within the heuristic 55 alarms can be correctly identified as having sounded while still avoiding incorrectly identifying any alarms as having sounded.

Table 8.2 provides a summary of the totals and percentages of alarms positively identified, positively identified as having sounded and not sounded and the total number of alarms for each population. The calculation of the percentages are based on the total number of alarms evaluated in that population for the total number of alarms correctly identified, identified as indeterminate, alarms evaluated that sounded, and alarms evaluated that did not sound. For the number of alarms correctly identified as having sounded, the percentage is based on the number of alarms evaluated that sounded in that population. For the number of alarms correctly identified as not having sounded, the percentages are based on the number of alarms evaluated that did not sound in that population.

Table 8.2 Summary of blind study heuristic determinations for the entire study and for specific variables.

Population		Heuristic Identified: Total Correctly Determined	Heuristic Identified: Correctly as Sounded	Heuristic Identified: Correctly as Did not Sound	Heuristic Identified: As Indeterminate	Alarms Evaluated: That Sounded	Alarms Evaluated: That Did not Sound	Alarms Evaluated: Total Number
Entire Study	Number of Alarms	94	55	39	57	83	68	151
	Percentage (%)	62	66	57	38	55	45	
Smoldering Polyurethane	Number of Alarms	9	5	4	2	6	5	11
	Percentage (%)	82	83	80	18	55	45	
Flaming Polyurethane	Number of Alarms	18	11	7	2	11	9	20
	Percentage (%)	90	100	78	10	55	45	
Flaming Wood	Number of Alarms	2	0	2	7	5	4	9
	Percentage (%)	22	0	50	78	56	44	
Turpentine	Number of Alarms	9	5	4	1	5	5	10
	Percentage (%)	90	100	80	10	50	50	
Smoldering Cable	Number of Alarms	2	0	2	14	8	8	16
	Percentage (%)	25	0	25	88	50	50	
Flaming Cable	Number of Alarms	5	4	1	3	4	4	8
	Percentage (%)	62	100	25	38	50	50	
Box and Paper	Number of Alarms	0	0	0	8	4	4	8
	Percentage (%)	0	0	0	100	50	50	
Box and Plastic	Number of Alarms	8	4	4	0	4	4	8
	Percentage (%)	100	100	100	0	50	50	
Cabinet Assembly	Number of Alarms	17	11	6	9	14	12	26
	Percentage (%)	65	79	50	35	54	46	
Couch Assembly	Number of Alarms	25	15	10	2	15	12	27
	Percentage (%)	96	100	83	7	54	46	
Fires	Number of Alarms	85	55	39	48	74	68	142
	Percentage (%)	60	74	57	34	52	48	
EN/UL test fires	Number of Alarms	32	21	18	11	27	23	50
	Percentage (%)	64	78	78	22	54	46	
Nuisance Exposures	Number of Alarms	0	0	0	9	9	0	9
	Percentage (%)	0	0	0	100	100	0	100
Additional test fires	Number of Alarms	13	8	5	27	18	22	40
	Percentage (%)	32	44	23	68	45	55	
Larger Scale Fire	Number of Alarms	41	25	16	12	26	24	53
	Percentage (%)	77	96	67	23	49	45	
FSBI alarms	Number of Alarms	24	15	9	15	21	18	39
	Percentage (%)	61	71	50	38	54	46	
FACI alarms	Number of Alarms	17	10	7	13	17	13	30
	Percentage (%)	57	59	54	43	57	43	
FBI alarms	Number of Alarms	29	16	13	11	20	20	40
	Percentage (%)	72	80	65	28	50	50	
FGBI alarms	Number of Alarms	22	12	10	15	20	17	37
	Percentage (%)	59	60	59	41	54	46	
Adjacent Spaces	Number of Alarms	57	36	23	35	55	39	94
	Percentage (%)	61	65	59	37	59	41	
Fire Room	Number of Alarms	33	19	14	15	25	23	48
	Percentage (%)	60	76	61	31	52	48	
New Alarms	Number of Alarms	12	7	5	3	7	8	15
	Percentage (%)	80	100	63	20	47	53	
Previously Exposed	Number of Alarms	14	8	6	2	8	8	16
	Percentage (%)	87	100	75	13	50	50	
Comparable Exposures	Number of Alarms	32	17	15	13	23	22	45
	Percentage (%)	71	74	68	29	51	49	
Previous Studies*	Number of Alarms	135	79	56	173	152	157	308
	Percentage (%)	44	52	36	56	49	51	

*Results represent those provided by other investigators [Worrell, et al., 2001 & 2003] and do not utilize the heuristic developed in this study.

Table 8.2 above summarizes the results of the blind study according to a number of populations of alarms as well as the entire study. A further discussion of each of the populations follows in the sub-sections of Section 8.2. Table 8.2 outlines the populations that were divided to allow for investigation of the variables with potential impact on enhanced soot deposition; nuisance behavior, fuel type and mode, fire scale, horn configuration, distance from source, effect of previous exposure, and comparison with the results of previous studies. For the total population of this study the percentage of alarms that sounded that were correctly identified as having sounded (positive) is higher than those that did not sound and were correctly identified as having not sounded (negative) (66% > 57%). This indicates that there is greater difficulty in determining that an alarm did not sound than did sound. The results of the alarms analyses have been reported without any estimation of error or deviation due to the limited population size. An analysis of the reproducibility of the observations generated by the methodology was beyond the scope of this study.

The results of this summary table are graphically represented in Figures 8.3 and 8.4, which contain the results of the percentage of alarms correctly identified as having sounded and not having sounded, respectively. Throughout these analyses each population is color coded as well as labeled 1-26 for each corresponding data point. On all plots, circles represent alarms correctly identified as having sounded and squares represent alarms correctly identified as not having sounded. For the former, the percentage is based on the number of alarms evaluated that sounded in that population (i.e. column 6 in Table 8.2). For the latter the percentages are based on the number of alarms evaluated that did not sound in that population (i.e. column 7 in Table 8.2).

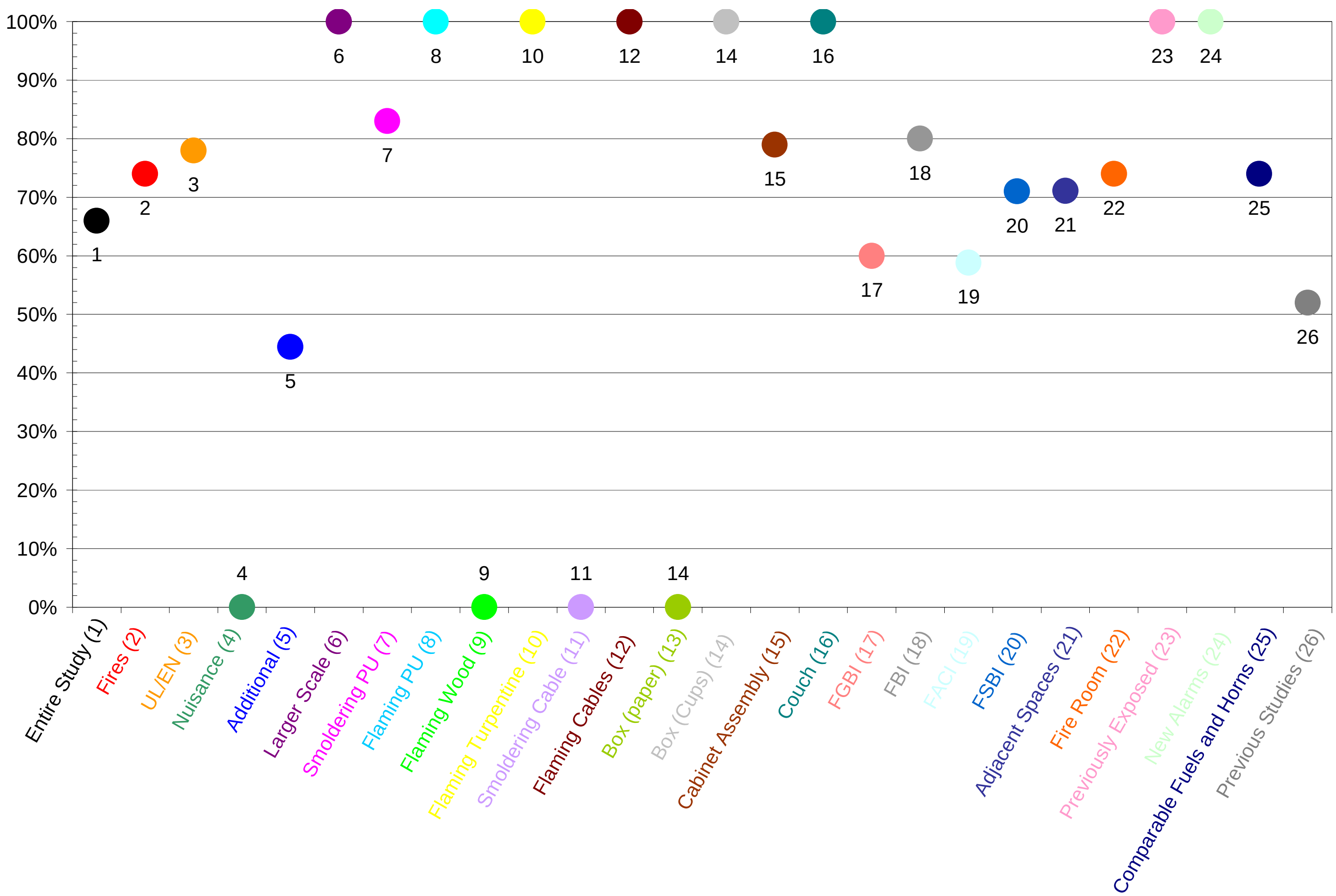

Figure 8.3 This figure summarizes the results of the application of the positive identification heuristic to the blind study observations by population. This figure contains the percentage of alarms that were positively identified as having sounded in the specified population. There were no false determinations of sounding for any population in this study.

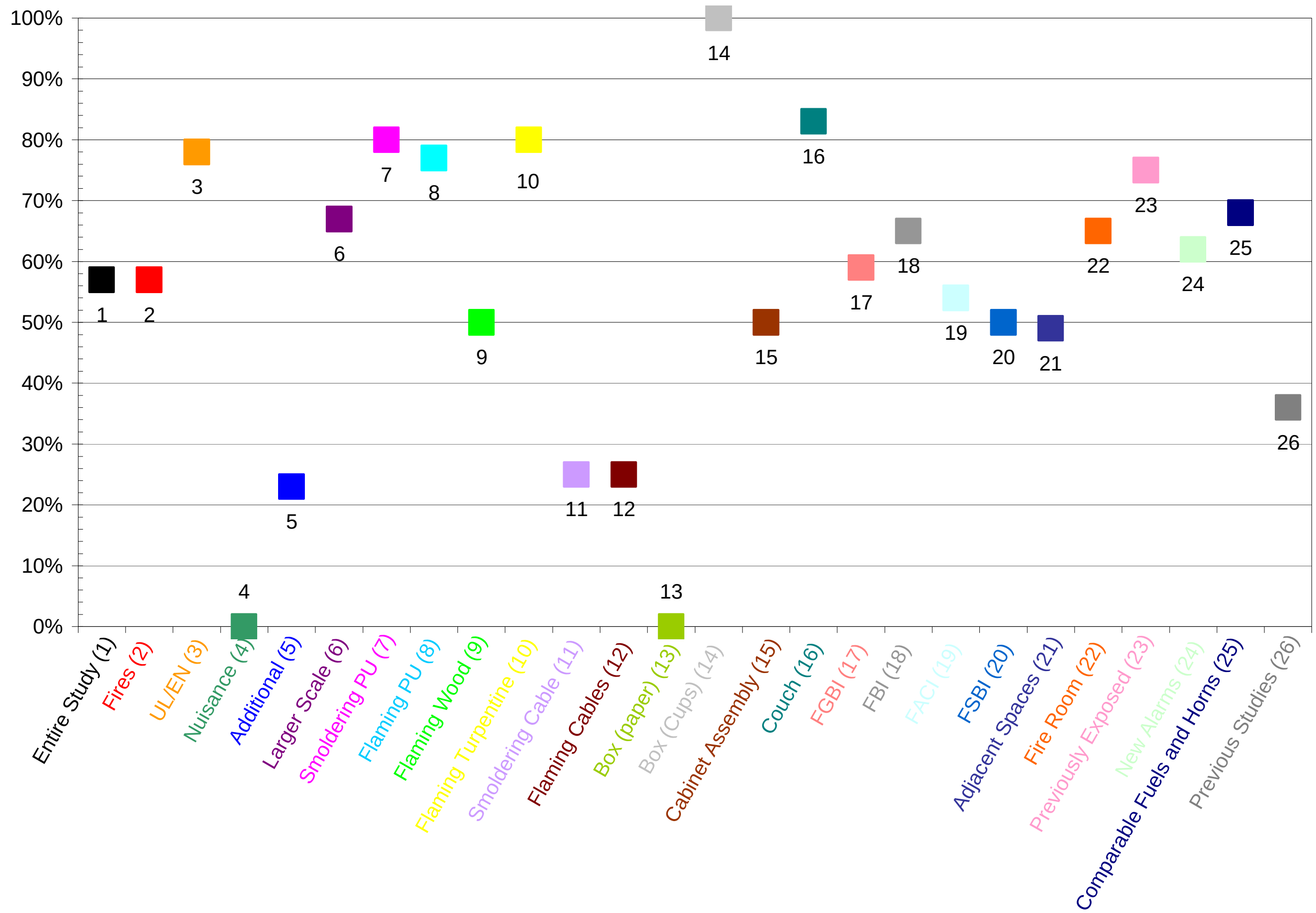

Figure 8.4 This figure summarizes the results of the application of the negative identification heuristic to the blind study observations by population. This figure contains the percentage of alarms identified as not having sounded per the number of alarms that actually had not sounded in the specified population. There were no false determinations of not having sounded for any of the populations in this study.

8.4.2 Fire Exposures only

In the application of this heuristic technique, the alarms being evaluated will have been exposed to a fire event of one sort or another. So while it was important to understand how nuisance sources behave in comparison to fire sources and whether or not there is an effect of previous nuisance exposure, inclusion of alarms that had been subjected only to nuisance exposure is generally not germane to the application of the methodology. Figure 8.5 includes the percentage of alarms identified for the entire study and the population of alarms subjected to fire exposures. The results are calculated in the same manner as for Figures 8.3 and 8.4: however, both the results of the alarms that sounded and did not sound are included.

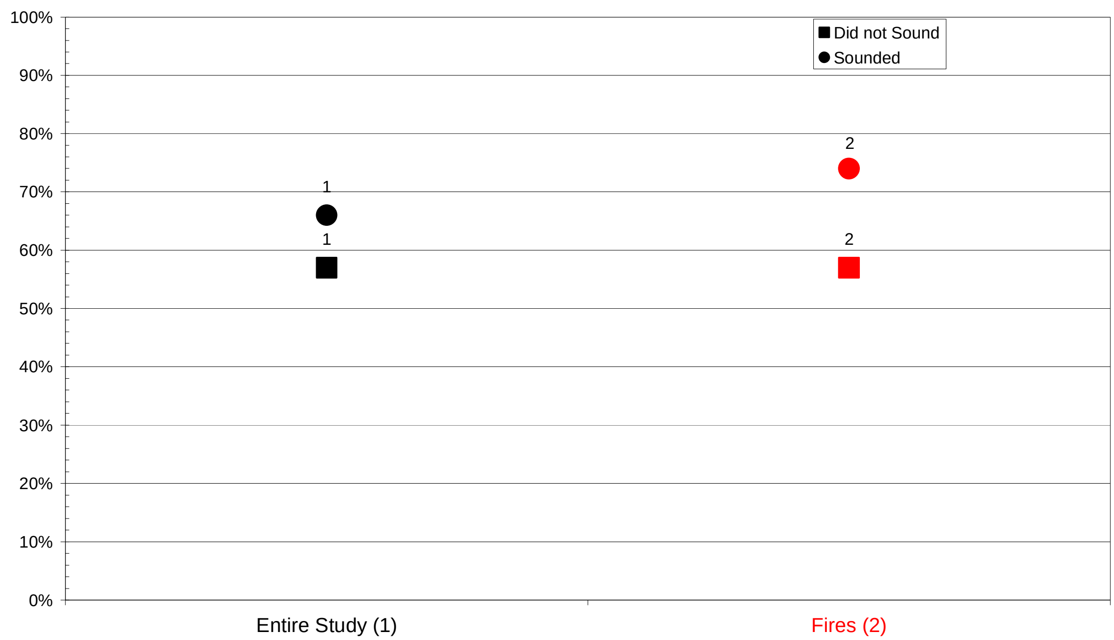

Figure 8.5 Summary of the percent of the determinations made during the blind study to the entire study observations and the population composed of only the fire exposures. This figure contains the percentage results based on the number of alarms that sounded, 83 and 74 respectively, and that remained silent in each population, 68 and 68 respectively.

The nuisance exposures could not be determined to have sounded, but had sounded during the tests, so the removal of the nuisance exposure data manifests in noticeably higher, almost 10%, results for identification of alarms that sounded. Figure 8.5 shows that the technique was able to correctly identify almost half of the alarms that did not sound when exposed to a fire source. The technique also positively identified over 70% of those alarms that did sound.

8.4.3 By Test Series

Figure 8.6 presents identical analyses as Figure 8.5 with respect to the populations of each test series.

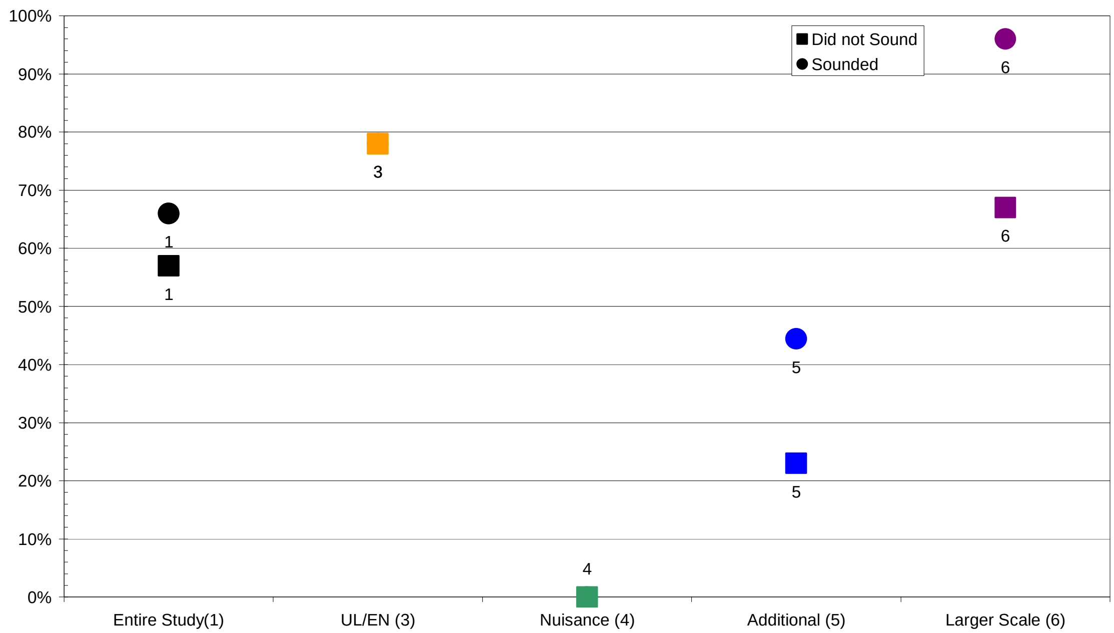

Figure 8.6 Graphical summary of results of the determinations made on the blind study by test series. This figure contains the percentage of alarms identified based on the total number of alarms that sounded, 83, 27, 9, 18, and 26 respectively, and the percentage based on the number of alarms that remained silent in each population, 68, 23, 0, 22, and 24 respectively.

The UL/EN population of alarms included 50 exposures, roughly 1/3 of the total conducted during this study. The overall ability of the technique to identify whether or not alarms sounded increased in comparison to the whole population of exposures. The increase in the determination that an alarm had not sounded becomes more apparent moving from left to right across Figure 8.6. It is of interest that for the EN/UL population of alarms there is no difference in the ability to determine that an alarm has or has not sounded, both are 78%. Also, of interest is the lower percentage of indeterminate alarms, or the difference between 100% and the percentage determined, in comparison to the total population of alarms, 22% versus 57% respectively.

The results from the evaluation of the nuisance exposures, Test Series 2, show that nuisance exposures do not behave analogously to fire exposures in ways that would cause them to be misidentified as having alarmed during a fire exposure. Both the percentage of alarms identified as having sounded and the percentage of alarms identified as not having sounded are 0 for Test Series 2. In Test Series 3, the test fires conducted in the hallway, there was a much larger difference between the identification of alarms that did sound, 44%, and alarms that did not sound, 23%. A large percentage of exposures were smoldering cables and boxes filled with paper, which resulted almost exclusively in indeterminate alarms. The determinate alarms in this population were exposed to either smoldering to flaming cable or boxes filled with plastic cups. Determination of both sounding and not sounding is lower for this test series than either of the other test series that included fire exposures.

Figure 8.6 clearly illustrates the applicability of the technique to realistic fire scenarios. When realistic fuel packages and layouts were used, 96% of the alarms that sounded were identified as having sounded and 67% of those that did not sound were correctly determined to have not sounded. The percentages correctly identified, 96% and 67%, in the larger scale test series are improvements over the other two of the series of test fires. Note that the evaluation of enhanced soot deposition does not necessarily yield determinate results in all cases of exposure; however, in the larger scale fire exposures almost 80% of the alarms were determinate with 96% of the alarms that sounded, correctly identified without any cases of false positive or negative identification.

8.4.4 By Fuel and Mode

Figure 8.9 presents the percentage of alarms identified in the same structure as has been established while dividing the study results by fuel source and mode of combustion.

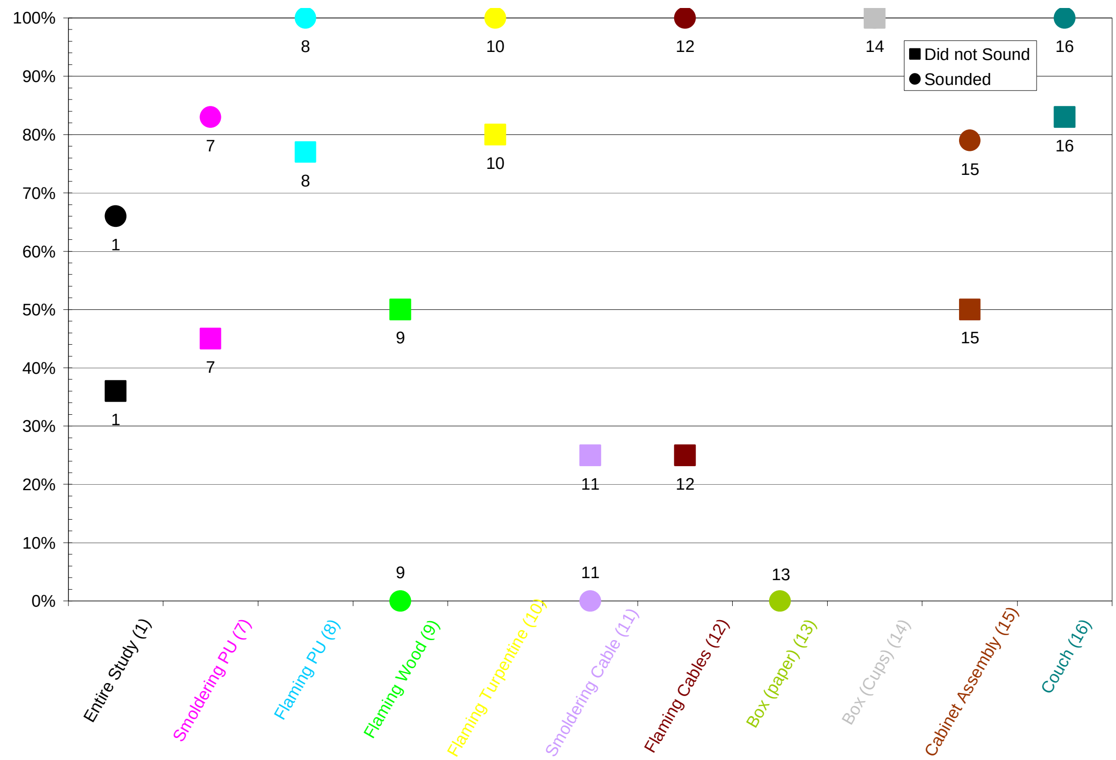

Figure 8.7 This is the graphical summary of results of the entire study and the populations by fuel source. This figure contains the percentage based on the number of alarms that sounded and the number of alarms that remained silent in each population.

The results from the flaming polyurethane foam test fires represent a limited data set, 20 total alarm exposures. Despite this, the results are significantly higher than for the total population of alarms. Specifically, 78% of the alarms that did not sound were determinate and all of the alarms that did sound were determinate. As polyurethane is commonly found in the combustibles involved in residential fires, this would support the applicability of the technique in that setting.

There is a lower rate of determination for the smoldering than for the flaming polyurethane. The two indeterminate alarms were the only two internal horn styles (FGBI alarms) included in the experiments. This could be due to the lower level of smoke exposure to the internal horns or the difference in the plastic used in the horns. The plastic composition of the alarm cover may be more prone to deposition than the plastic composing the internal horn chamber of the FGBI style alarms. The color of the FGBI horns is very similar to that of the tarry deposition, which could make small depositions more difficult to recognize. The previous studies also found a decreased ability to determine that an alarm had sounded when exposed to smoldering polyurethane [Worrell, et al., 2003].

The fact that all of the alarms could be determined to have sounded or not sounded in the box and cups experiment suggests a high soot production fire. This test was a high soot yield fire containing plastics resulting in clear indications and contraindications of sounding. The results of the flaming boxes containing paper stand in stark contrast to the flaming box containing plastic cups. None of the alarms exposed to light colored smoke from the boxes and paper were determinate, which illustrate the difference in the smoke and soot produced from cellulosic fuels compared to fuels containing polymers. The lack of determinate results from the paper products fires is commensurate with previous studies [Worrell, et al. 2003].

The smoke from the smoldering cables is very light in color and comparable to the smoke from paper products in both appearance and deposition behavior. The smoldering cable fires yielded similar results to the box and paper exposures, and were less easily identified than the flaming cable exposure.

Turpentine is another high soot yield fire similar to the boxes with cups. The results are highly determinate, but contain one indeterminate alarm. As discussed, in Section 7.1, the ODM's were saturated during this fire. In two cases, the high density of the ambient deposition was such that it was impossible to categorize two alarms. Of note, these high soot yield fires are those most likely to manifest the potentially misleading depositions described in Section 7.5.2.3. The higher soot yield fires can produce potentially misleading depositions through the turbulent mixing of the smoke into and out of the horn chamber. Potentially misleading depositions are much less dense than the patterns caused by the pulsed flow of a sounding alarm. A comparison of the ambient soot deposition outside the horn chamber with the soot deposition inside the horn chamber will show less dense soot deposition inside the horn chamber accompanying the potentially misleading observations.

The flaming wood test fire is another exposure containing light colored smoke, akin to the smoldering cables and flaming paper products. There is a low ability to determine whether or not these alarms had sounded, 0% of the alarms that sounded and 50% of the alarms that did not sound were correctly identified. For these exposures the ambient deposition is similar in quality and density to that seen on the nuisance-exposed alarms; however, by using the density of deposition in the horn chamber and lack of indicative patterns, it was possible to identify half of the alarms that had not sounded. No indicative patterns developed, so it was not possible to identify any of the alarms that had sounded. This is the only sub-population where more alarms were negatively determined than positively determined to have sounded.

The cabinet assembly exposure led to far fewer determinate, 13 versus 25, results than the other Test Series 4 fuel package, the couch. This is due largely to two factors. First, the fire smoldered for the bulk of the experiment and produced light smoke during this period. Second, the cabinet was empty, and therefore was not a mixed fuel with highly sooting components. The results still show a high ability to determine that alarms had sounded, 10 of 12 alarms. The exposure created far less clear indications that an alarm had not sounded, so only 50% of the alarms that did not sound were so identified.

As would be expected from a large soot yield, mixed fuel source, the alarms exposed to the couch fire were predominately determinate. In fact, only two of the exposed alarms that did not sound, did not present clear enough evidence to negatively identify it as not having sounded. The highly determinate results of this exposure support the applicability of this technique to residential fire scenarios.

8.4.5 By Horn Geometry

The variety of horn geometries evaluated during the study has been outlined previously in the Nomenclature Section. One objective of this investigation was to determine the effect horn geometry has on the manifestation of enhanced soot deposition. In Figure 8.8 the results are separated by horn geometries for the major horn geometries investigated. One horn style, FGBI, is fundamentally different than the other horn geometries studied, in that the horn is not connected to the alarm cover. The ability to determine whether or not an FGBI alarm sounded is slightly less than that for the entire study and in the middle of the bounds set by the other horn configurations.

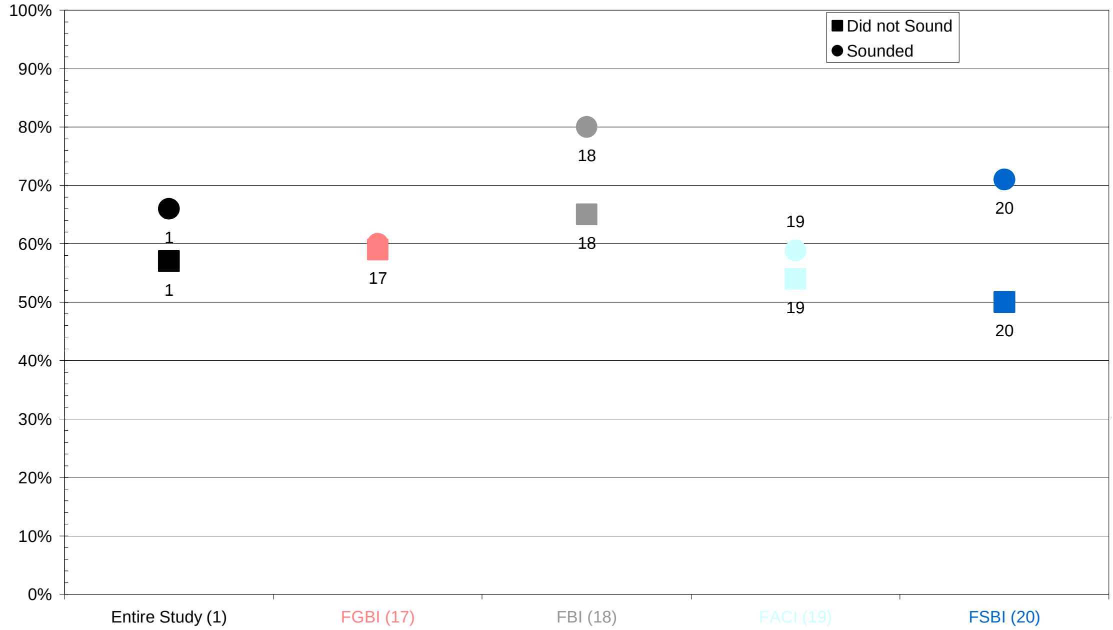

Figure 8.8 This figure contains a summary of the percentage of alarms identified by the technique, during the blind study for the entire study and the populations of horn configuration. This figure contains the percentage results based on the number of alarms that sounded, 83, 20, 20, 17, and 21 respectively, and the number of alarms that remained silent in each population, 68, 17, 20, 13, and 18 respectively.

In Figure 8.8, note that the FGBI and the FACI horns styles show the same propensity for positive and negative determination which are slightly below the results of the entire study. Furthermore, the results for the FBI population, the largest of the horn configuration populations, show a larger difference between the ability to identify alarms that did and did not sound. While the results for both positive and negative identification are higher than those for the entire study, the difference is also larger. Finally, for the FSBI alarms there is an even greater difference in the ability to identify those alarms that sounded and those that did not than in the FBI alarms. The percentage of FBI alarms that sounded and were determinate is slightly higher than the percentage of alarms that sounded and were determinate for the entire study. The percentage of alarms that did not sound and were determined as such is slightly lower for FBI alarms than for the entire study. Though the results vary somewhat between horn configurations it is of note that the differences are not great enough to preclude the evaluation of enhanced soot deposition for any of these horn configurations. The results also suggest that the evaluation of enhanced soot deposition is applicable as a forensic technique to plastic horns of varying size and shape.

8.4.6 Duration of Sounding

From this study the manifestation of enhanced soot deposition has not been directly correlated to the length of exposure to the products of combustion.   The much larger dependence on fuel source and mode of combustion appear to obscure any temporal dependence. Alarms having sounded for as little as one minute during exposure to flaming fire sources have proven determinate while alarms having sounded for close to one hour during exposure to smoldering sources have proven indeterminate. This is supported by the conclusions of previous studies, [Worrell, et al., 2003], which found the volume of smoke was not as important as the nature of the smoke. Enhanced soot deposition becomes more pronounced or more dense with extended exposure, but there is no apparent temporal “threshold” for enhanced soot deposition pattern development.

8.4.7 Distance from Source

One of the goals of this investigation was to understand the effect of the distance of the alarm from the fire source on enhanced soot deposition. Figure 8.9 outlines the results for the populations of alarms within the fire source room and in adjacent spaces, as compared to the results of the entire study. The nuisance exposures were removed from the fire room population because there were no nuisance exposed alarms outside the fire room. If the nuisance exposures were included their effect would have biased the results for the determinations within the fire room.

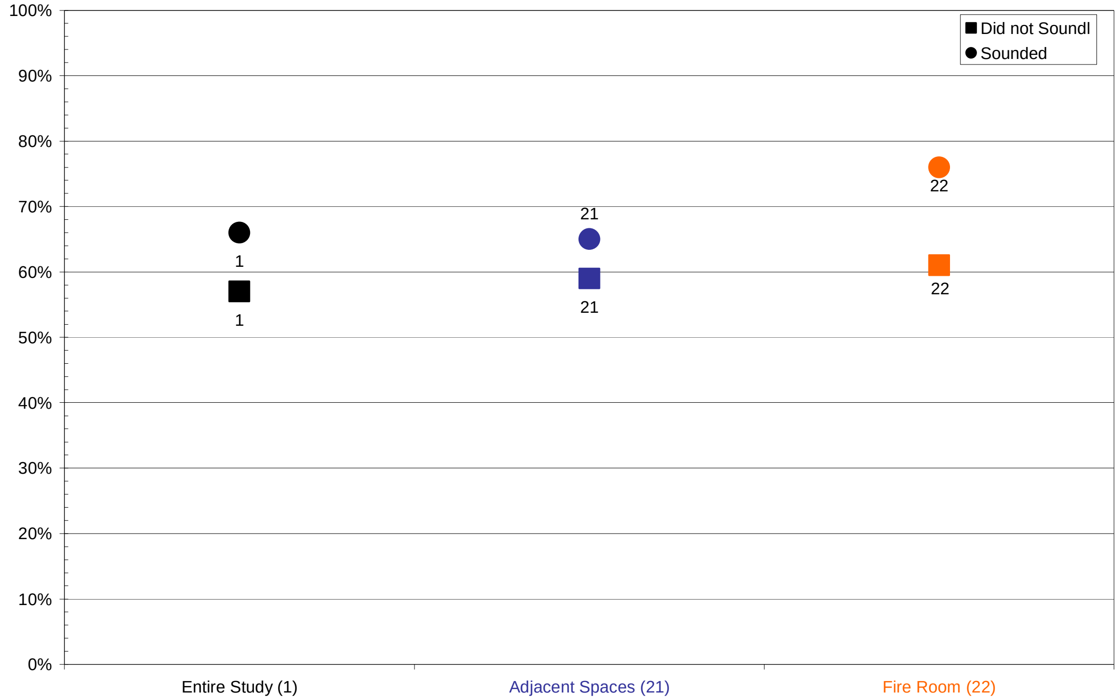

Figure 8.9 The summary of percentage of alarms identified as having sounded and not having sounded during the blind study for the entire study and the populations separated by distance from source. This figure contains the percentages based on the number of alarms that sounded, 83, 55, and 25 respectively, and the number of alarms that remained silent, 68, 39, and 23 respectively, in each population.

The percentage of determinate alarms outside of the fire source room is commensurate with the overall results. The results for the alarms within the fire room show little difference in the ability to determine an alarm had not sounded. There is a difference between the ability to determine that an alarm had sounded based on distance from the source. 76% of the alarms that sounded within the fire room could be determined to have sounded versus 65% of the alarms in adjacent spaces. It is intuitive that the closer an alarm is to the fire source the more likely it would be determinate. This was the case with alarms that sounded, but not with alarms that did not sound.

It was previously discussed that for one fuel source, the cabinet assembly, there was a difference in the ability to determine sounding alarms which was influenced by distance. The alarms 45 feet from the fire source were less prone to display signs which could be used to determine pro or con. The quantitative results suggest that overall there is a greater ability to determine that an alarm had sounded in the fire room than elsewhere. It is not the case that the alarms are determined more or less accurately based on distance. If a determination was made on an alarm, inside or outside the fire room, sounded or not sounded, there were no false positives or negatives. It is just that alarms outside the fire room were less likely to show evidence of enhanced soot deposition than those inside the fire room.

8.4.8 Exposure History

The exposure of smoke alarms to nuisance sources was designed to evaluate two things. First, whether nuisance sources behave analogously to fire sources with respect to enhanced deposition, which could lead to false positive identifications. This has not proven to be the case. None of the nuisance exposed alarms developed enhanced depositions or were identified as having sounded. The second purpose was to evaluate whether or not previous exposure and alarm to nuisance sources has any effect on enhanced soot deposition when subsequently exposed to a "real" fire source. As outlined, alarms exposed to nuisance sources in Test Series 2 were then placed in enabled/disabled pairs in the small room, see Figure 8.10, along with new alarms in Test Series 4.

The percentages of new alarms in the small room in Test Series 4 are higher with respect to identification of sounding and not sounding than the results for the overall population, but commensurate with the overall results for Test Series 4. Specifically, 100% of the sounding alarms were identified. Figure 8.10 shows the same results for the previously exposed alarms in the small room in Test Series 4.

Figure 8.10 Summary of results of the blind study for the entire study and the populations separated by exposure history. This figure contains the percentage results based on the number of alarms that sounded, 83, 7 and 8 respectively, and the number of alarms that remained silent, 68, 8, and 8 respectively, in each population.

The previously exposed alarms show higher rates of identification than the new alarms, specifically in identifying alarms that did not sound, 75% versus 63%. However, due to the small population size, 8, it is difficult to say there is a significant difference. During the qualitative assessment of the alarms, there were cases where the previously exposed alarms had more distinct patterns than the new alarms and vice versa.

Comparison of the determinations for alarms that did not sound show slightly higher results for the previously exposed alarms, 76%, compared to 66% of the new alarms and 57% for the whole population of alarms. That the previously exposed alarms performed similarly to the new alarms is important. First, previously exposed alarms behave comparably to new alarms with respect to enhanced soot deposition. Second, if there is a difference, previously exposed alarms are more likely to be determinate than new alarms. That is important for past and future studies. Obviously, for future studies it is not necessary to run all alarms through nuisance exposures in order to assure behavior commensurate with those alarms *in situ*. The results of new alarms, in fact, may represent a conservative lower bound of accuracy, which is important to understand. It also validates previous studies' experimental methodologies, which used only new alarms. Finally, these results validate the forensic application of this technique. Because alarms *in situ* are highly unlikely to be new it is important the technique can be accurately applied to alarms with various and even unknown exposure histories.

8.4.9 Comparison to Previous Studies Results

The goals of this study included providing an assessment of the previous studies on enhanced soot deposition and establishing a methodology. The previous section established, post facto that the previous studies results were not likely to be significantly affected by the sole use of new alarms. The current study contains a number of experiments, which are similar to the experiments undertaken previous studies [Worrell, et al., 2001 & 2003]. The results of the similar experiments from the current study were compared with the reported results of previous studies. Because a goal of the current study was to establish a methodology that could be used to evaluate enhanced soot deposition it is also instructive to compare the results of the methodology generated by this study to the reported results of the previous studies. Figure 8.11 contains the results of the population of alarms subjected to experiments with similar fuel sources and configurations to the previous studies. The results included are from Test Series 1 the flaming and smoldering polyurethane tests, the turpentine fire, the wood crib, from Test Series 3 the box filled with paper, and from Test Series 4 the couch fire. The results from previous studies include the UL/EN style smoldering and flaming polyurethane fires, the wood crib fires, and the flaming paper fires from [Worrell, et al., 2003] and the results from [Worrell, et al., 2001] including only the alarms that could be recovered.

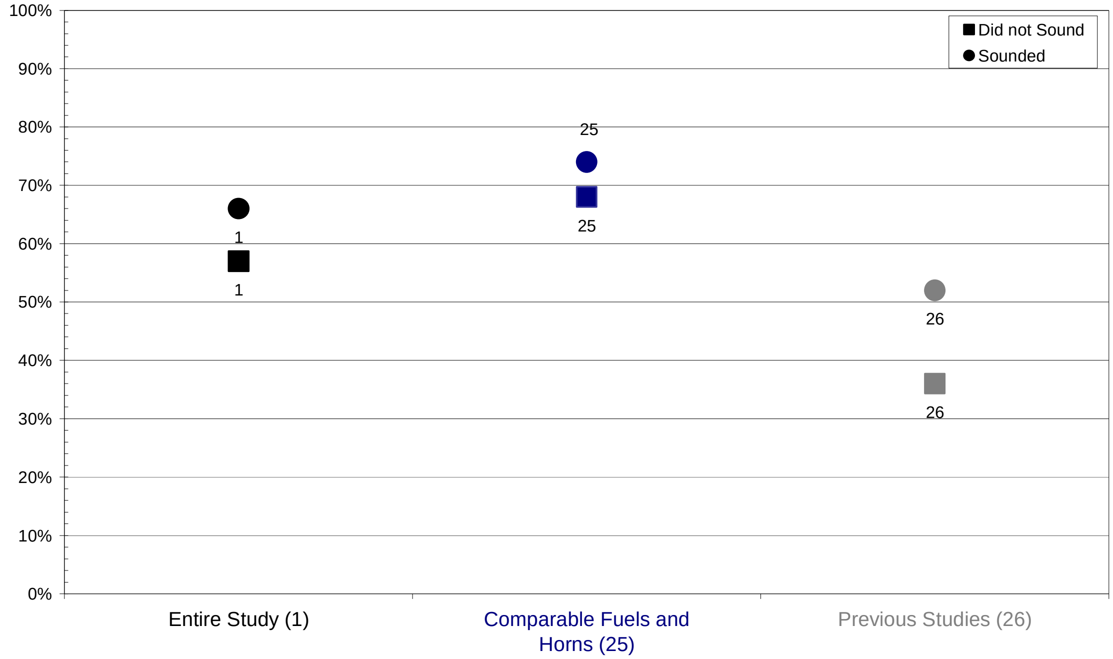

Figure 8.11 Summary percentage of alarms identified in blind study for the entire study, the fuel and horn combinations comparable to previous studies, and the results of previous studies as determined by the authors. This figure contains the percentages based on the number of alarms that sounded, 83, 23, and 152 respectively, and the number of alarms that remained silent, 68, 22, and 157 respectively, in each population.

The results of this subset of alarms are not especially different than the overall results. More alarms were correctly identified as not having sounded than the overall population, 32% compared to 25%, but the results are not significantly divergent. This is important because it is then a reasonable extrapolation to say that the comparison of this subset is a reasonable comparison to the whole data set.

Table 8.3 summarizes the comparable results from previous studies, and summary of the results from the Figure 8.11 above, and their comparison. The row of data labeled Comparison contains the difference between the percentages identified by the developed methodology during the current study minus the reported results of the previous results for the experiments with comparable fuel and horn combinations. Therefore, a positive difference represents an improvement over previous studies.

Table 8.3 Summary and comparison of results of this study and previous studies.

Sub-Population		Identified:				Alarms Evaluated:		
		Total Correctly Determined	Correctly as Sounded	Correctly as Did Not Sound	As Indeterminate	That Sounded	That Did not Sound	Total Number
Entire Study	Number	93	55	36	57	83	68	151
	Percentage (%)	62	36	26	38	55	45	
Comparable Fuels and Horns	Number	32	17	15	13	23	22	45
	Percentage (%)	71	74	68	29	51	49	
Previous Studies	Number	135	79	56	173	152	157	308
	Percentage (%)	44	52	36	56	49	51	
Comparison	Results	27	22	33				

*This row of data contains the difference between the percentage of alarms correctly identified during this study and the results reported within the previous studies.

They key points to retrieve from the table are first the distinct difference in the percent of alarms correctly identified, 44% vs. 71%. There is a difference of 27% in the correct identification of alarms. The comparison shows that there is a proportionately larger improvement in the ability to identify alarms that have not sounded, 36% vs. 68%, than those that have, 52% vs. 74%. However, the improvements in both are significant, 32% and 22% respectively. The comparison shows a much lower percentage of indeterminate alarms as follows the previous comparisons. The fact that the populations from this study to the previous studies agree in the percentage of alarms that sounded versus did not sound to 2% assures that the populations were comparably constituted. Overall, the comparison in Table 8.3 displays that there is a significant and distinct improvement in the ability to identify whether or not alarms have sounded through the use of the methodology developed in this thesis.

9 Conclusions

9.1 Utility

Previous studies have determined that enhanced soot deposition around smoke alarm horn openings can be used to positively identify that an alarm has sounded during a fire event. In different papers, these studies have also conflictingly concluded that these patterns can and cannot be used in determining that an alarm has not sounded during a fire event.

This study has shown that a thorough examination of an alarm can provide sufficient observations to conclude that an alarm has sounded and also that an alarm has not sounded during a fire event, assuming sufficient soot deposition has occurred on the alarm. This determination can be made without prior knowledge of the fuel source and mode of combustion during exposure. The capacity of the proposed methodology to identify whether an alarm has or has not sounded has been compared with the results of the previous studies [Worrell, et al., 2001 & 2003]. The comparison of these results, in Section 8.3.1.10, displays a significant improvement in the ability to identify whether or not alarms have sounded through the use of the procedures and heuristics presented.

What follows are the primary conclusions of the study. All of these have been previously outlined and supported in this thesis and demonstrate the utility of the evaluation of enhanced soot deposition on smoke alarms as a sound forensic technique. The methodology developed in this study provided positive identification of sounding and non-sounding alarms in all cases with sufficient soot deposition with no false determinations.

9.2 Enhanced Soot Deposition

Patterns of enhanced carbonaceous soot deposition are, and have been previously described as, areas of higher soot deposition uniform around the entire circumference of the smoke alarm horn opening [Worrell, et al., 2001 & 2003]. This description is neither fully accurate nor complete enough to be practically applicable. The area of enhanced soot deposition can be distinguished from the ambient soot deposition on the comparable face of the smoke alarm by a comparison of the deposition densities. Within the enhanced deposition itself, the deposited soot agglomerates will be of larger agglomerate size and directed primarily radially outward from the horn opening. The density of the soot agglomerates deposited within the enhanced deposition decreases from inside to outside or radially outward from the horn opening. A pattern is comprised of the soot agglomerates deposited in the gradation between high and low density, or between highest density and density of approximately equal to the level of ambient soot deposition. Enhanced depositions indicative of alarm were observed to have some radial, out from the nominal center of the horn opening perpendicular to the edge of the horn opening, dimension of at least 0.4 mm measured from the edge of the horn opening over the extent of the pattern. The width of a pattern was defined as the furthest agglomerates within the gradation, from high to low density, of larger size than the agglomerates outside the enhanced deposition (i.e., deposited ambiently on the alarm). A distance of 1-2 cm away from the alarm horn openings was found to be sufficient to avoid the acoustic affects on soot agglomeration. Areas at least 1-2 cm away from the horn openings were compared for number and area coverage density to the enhanced soot depositions to verify their presence.

Enhanced soot deposition indicative of alarm was not found to form only on the corners between the internal or external faces and the vertical face. Thin lines of soot along these corners that hang into the horn opening were not indicative of alarms sounding but may be confused with enhanced soot deposition. These misleading depositions were observed to have radial dimensions of 0.3 mm and less, measured across the entire width of the contiguous deposition. Misleading depositions were effectively eliminated from generating false positive determinations through the comparison of soot densities inside and outside the horn chamber and through the use of the devised heuristics.

It was determined that enhanced depositions need not be uniform about the entire circumference of the horn opening to be indicative of alarm sounding. This was especially true in the case of the moon and slat shaped horn openings that create non-uniform flow through pinch points or flow constrictions. Enhanced depositions were likely to be macroscopically identifiable, but the microscopic identification and/or verification improved the accuracy and ability to identify alarms as having sounded or not.

It is necessary to separate enhanced soot deposition from enhanced deposition from tarry hydrocarbon microdroplets. Because the particles are fundamentally different, the enhanced deposition they form are similarly divergent and require separate descriptions. Enhanced depositions manifested from smoldering fuel sources are composed of tarry microdroplets and are in stark contrast to the furry depositions left by carbonaceous soot. The tarry depositions were darker than the staining of the inside face of the smoke alarm cover that accompanies smoldering source exposure but is not indicative of alarm sounding. Enhanced tarry depositions were only found on the internal, external, and vertical faces of the alarm horn openings. The nature of these depositions leads them to be predominately non-uniform. In all cases the enhanced tarry depositions of all sizes and distributions were found to be indicative of alarm sounding.

9.3 Where patterns develop

As previously discussed the entirety of the smoke alarms were examined to determine the presence of enhanced soot deposition. The thorough examination yielded three areas of the smoke alarm horn where patterns of enhanced soot deposition were observed. As introduced in the Nomenclature Section, they are the external, vertical, and internal faces of the smoke alarm horn openings. The patterns observed on these faces all contained similar characteristics.

9.3.1 External Face

The external face of the smoke alarm horn opening is subject to an acoustic field and induced eddies in a sounding alarm [Worrell, et al., 2003]. These mechanisms can generate enhanced soot deposition patterns of larger agglomerate sizes and higher densities than soot deposited on alarms that did not sound and on the same alarm outside the acoustic effects. Enhanced depositions that develop on the external face are the most prominent and easily observed. They are also the most likely to be obscured through handling. Even standard NFPA 921 evidence handling/best practice handling procedures can affect patterns found on the external face. (See Section 8.2 for the procedure utilized in analyzing an alarm and Appendix B for a complete exemplar alarm evaluation.) Enhanced depositions have been found to develop later on the exterior face than on the internal face and in most cases were less dense when compared to the enhanced depositions on the internal face.

9.3.2 Internal Face

The internal face is the inside face of the smoke alarm horn opening. The internal face is subjected to a more powerful acoustic field than the external face and should be subject to similar eddies as those seen on the external face [Worrell, et al., 2003]. This supports the observations that the internal face of the smoke alarm horn was first/most likely place for patterns to develop. This was especially true when the fire was predominantly a smoldering fire. The current understanding of the mechanisms that generated enhanced deposition also support the observations that depositions on the internal face were of higher density than those on the external face. Because the enhanced soot deposition was found to occur first on the internal face of the alarm there was a higher correlation with alarm sounding for these patterns than for the external patterns. The internal face is less likely to be affected by handling than the external face. As discussed by Worrell, et al. with the circular style horn (their horn configuration #1 referred to as FGBI in this study) it is necessary to use a small mirror to examine the internal face of these horn openings. Extreme care must be used in doing so as to not disturb the depositions being assessed.

9.3.3 Vertical Face

The vertical face is the sheer face of the smoke alarm horn opening connecting the external and internal faces of the smoke alarm horn opening. This face is subject to the acoustic field and induced pulsed flow in a sounding alarm [Worrell, et al., 2003]. These mechanisms were found to generate enhanced soot deposition on the vertical face of smoke alarm horn openings, proximate to the edges with the external or internal faces or both. Enhanced deposition indicative of alarm sounding was not found to occur on the sharp edge/corner between the vertical face and the external face, and the vertical face and the internal face. In some case separate enhanced soot deposition patterns were observed proximate to both edges with separation between. With respect to identification, enhanced deposition proximate to either edge or both was found to be indicative of alarm sounding and verified the presence of enhanced soot deposition. The difference between ambient deposition and an enhanced deposition was the same for the vertical face as for the internal and external faces, the gradation in density from high to low being of primary importance.

9.4 Heuristics

Heuristics were generated by combining observations using Boolean AND/OR operators. The heuristics were generated through combinations based on an understanding of the mechanisms generating enhanced soot deposition and the correlation of individual observations and their absence with alarm sounding and not sounding, respectively. Independent heuristics were devised for the positive and negative determination of alarm sounding. The positive identification heuristic was based on observations. The negative heuristic was based on the absence of observations and rules generated from the observation process. The heuristics effectively eliminated false positive and negative determinations when applied to blind observations of the alarms in the study.

9.5 Factors Affecting Enhanced Soot Deposition Development

9.5.1 Fuel Source and Burning Mode

Based on this study, fuels that consistently generated enhanced deposition:

- Flaming Polyurethane
- Flaming Hydrocarbon Pools
- Flaming Cables
- Mixed Fuels including Plastics
- Smoldering Polyurethane (except the internal, FGBI, horn configuration)
- Cabinet assemblies (when alarm is <45 feet from the source)
- Flaming Upholstered furniture

Based on this study, fuel sources that inconsistently generated enhanced deposition:

- Cabinet assembly (when alarm is $\geq$ 45 feet from the source)
- Flaming Wood
- Smoldering Polyurethane (for the circular horn configuration)

Based on this study, fuel sources that did not generate enhanced deposition:

- Nuisance Sources
  - Bacon Frying
  - Burning Toast
  - Frying Tortillas
  - Deep-frying Batter
  - Airborne Dust
- Flaming Paper-based Products
- Smoldering Cables

- Smoldering Polyurethane (for the internal, FGBI, horn configuration)

9.5.2 Duration of Alarm Sounding

It has been established in this work that the duration of sounding during smoke exposure is not an important factor in the manifestation of patterns of enhanced soot deposition. While it is true that the longer the duration of sounding during exposure, the denser and more pronounced the enhanced deposition will be, the fuel and mode of combustion appear to dictate whether or not enhanced soot deposition will develop. In this way, duration affects but does not dictate the appearance of a pattern.

9.5.3 Distance from Source

The analysis of the observations has shown that there is a link between the distance from the source and the ability to determine that an alarm has sounded. There was no difference in the ability to determine that an alarm had not sounded based on distance from the fuel source. Qualitatively this was observed with the alarms 45 feet away from the cabinet fire. Quantitatively it was proven to apply to the entire populations of alarms subjected to fire sources. It should be noted that the accuracy of the determinations made was not affected by the alarm distance from the fire sources. It is simply less likely that a positive determination of alarm will be possible further from the fire source (i.e., there may not be sufficient soot exposure to the alarm).

9.5.4 Exposure History

A numerical comparison of the alarms that had been previously exposed to nuisance sources and new alarms within the same experiment showed no difference in the ability to determine whether or not the alarms had sounded. A comparison of the alarms and their patterns did not yield a systematic link between exposure history and the qualitative appearance of a pattern, e.g. more or less dense with previous exposure. It was also shown that the products of nuisance exposures in this study did not behave analogously to the products of combustion, they did not manifest patterns. It is reasonable to expect that the occurrence of nuisance exposures to alarms will not have an effect on the utility of this technique.

9.5.5 Horn Geometry

The comparison of results based on horn geometry shows that details of the horn configurations did not have a drastic effect on the ability to predict whether or not an alarm had sounded. The results show a slightly higher ability to identify alarms that sounded than alarms that did not sound for most horn configurations. Though the results varied somewhat between horn configurations it is of note that the differences are not great enough to preclude the evaluation of enhanced soot deposition for any of these horn configurations. The results also suggest that the evaluation of enhanced soot deposition is applicable as a forensic technique to plastic horns of varying size and shape.

10 Future Work

10.1 Further Determination of Mechanisms

Further insight into the mechanisms that lead to enhanced soot deposition would prove valuable in advancing the science and utility of the technique. Previous work has been successful in illustrating the combined mechanisms of pulsed flow and acoustic agglomeration. A study that induced a pulsed flow through an orifice in the presence of smoke without an accompanying acoustic field would improve comprehension of the contribution of the pulsed flow phenomena versus the induced sonic field. Likewise, a study that induced an acoustic field around an orifice without the pulsed flow phenomena would be of similar interest. Studies that separated the two mechanisms and evaluated their separate effects in comparison to their synergistic effects would help bring the scope of the evaluation of enhanced soot deposition further into focus.

10.1.1 Examination of Agglomerate Size

A detailed examination of the soot agglomerate sizes for assorted "common" fuel sources would be of interest. At a minimum, determination of the following agglomerate sizes would be valuable:

- Deposited soot particulate around the horn opening
- Deposited soot particulate on the alarm face
- Airborne particulate
- Within the sonic field of a smoke alarm
- Outside the sonic field of a smoke alarm

A detailed comparison would augment understanding of the enhanced soot deposition phenomenon and soot interaction and deposition in smoke layers.

10.1.1.1 Image Analysis

There are a number of techniques currently used for quantitative analysis of images of all sorts. Quantification of soot depositions and densities through image processing techniques might provide further insight into enhanced soot deposition. It may prove feasible to adapt current image analysis techniques to further quantify soot agglomerate number and area densities, as wells as, agglomerate and deposition dimensions.

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12 Appendix A: Acoustic Monitor Circuit Diagram

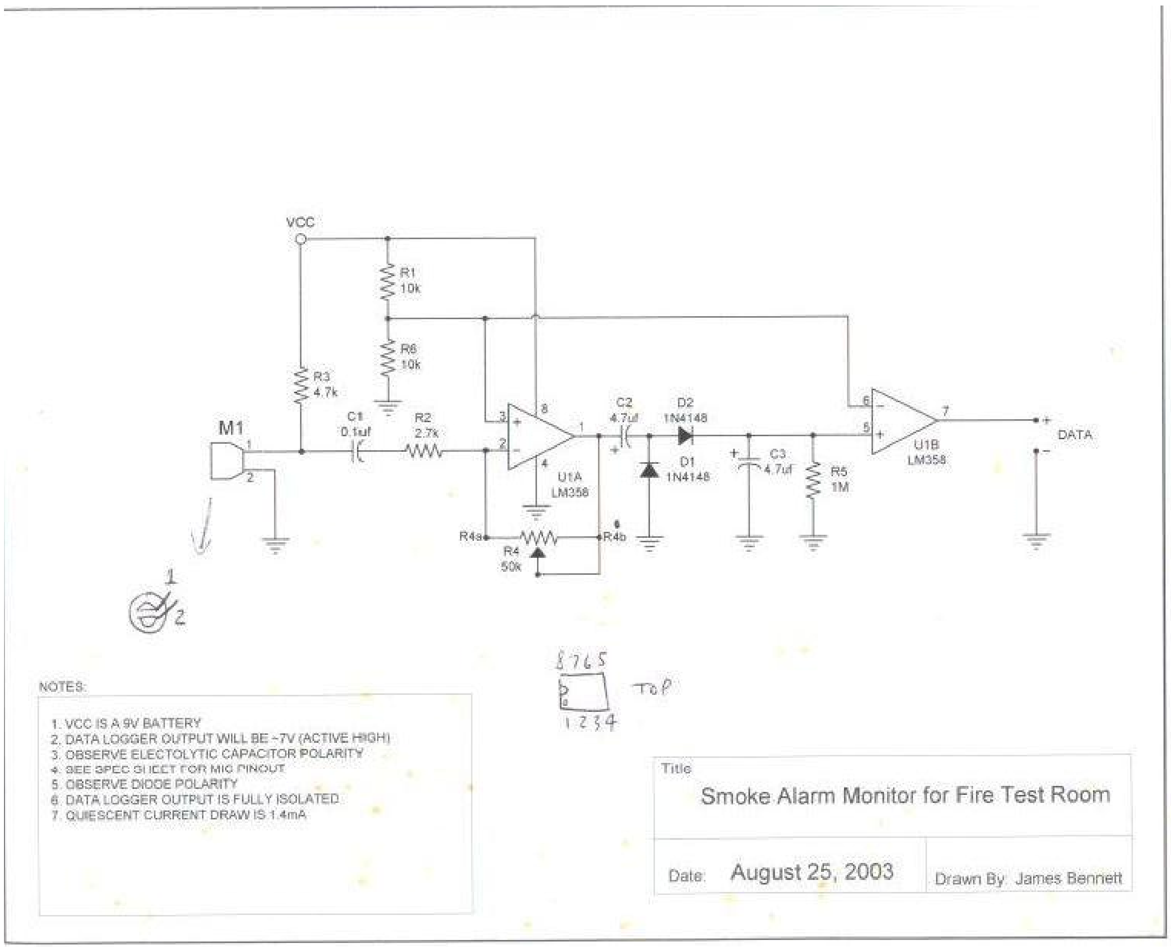

Figure 12.1 This figure contains the circuit diagram for the acoustic monitors utilized during this study to establish start, cessation, and duration of alarm sounding.

13 Appendix B: Sample Alarm Documentation and Evaluation

The following series of photographs are samples from an alarm evaluation done on an alarm exposed to a flaming polyurethane fire during Test Series 1. The evaluation was done following the procedure outlined in the body of this document.

Figure 13.1 This figure shows an overall view of the exterior of the alarm cover. Some ambient soot deposition is apparent on the alarm cover. There is not however enough soot to determine the direction of bulk flow past the alarm.

Figure 13.2 This figure shows the next step in documenting the alarm state. It contains a macroscopic view of the alarm horn openings. There is very little soot apparent at this magnification. There appear to be slight indications of possible enhanced soot deposition on the flat edge of the lowest opening. There is not enough soot to make a conclusive determination of sounding.

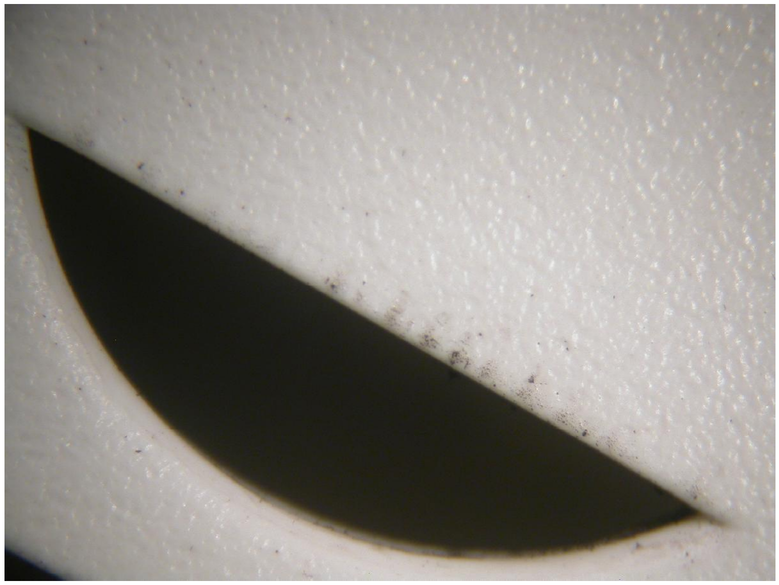

Figure 13.3 This figure contains a microscopic view of the lowest horn opening from Figure 13.2. The soot deposited on the lower edge of the opening is much more apparent and has some radial characteristics. The deposition changes from higher to lower density moving away from the horn opening. Because the deposition is very light and the only evidence of enhanced soot deposition is directed in the same direction. It can not be conclusively determined that this is evidence of enhanced soot deposition indicative of sounding.

Figure 13.4 This figure contains the ambient soot deposition on the external cover of the smoke alarm. This photo was taken at the same magnification as Figure 13.3 to allow the comparison of soot deposition density proximate and farther from the horn openings (approximately 2 cm). There is little appreciable soot deposited on the alarm cover compared to the horn opening supporting the identification of enhanced soot deposition indicative of sounding.

Figure 13.5 This figure along with Figures 13.6 and 13.7 show views of the vertical face of the alarm horn opening. All three photos show darker deposition on the vertical face than was apparent on the external face of the alarm horn opening. The density decreases from the internal towards the external face on the vertical face. The depositions are the whole vertical face and not just on the corner between the vertical and internal faces.

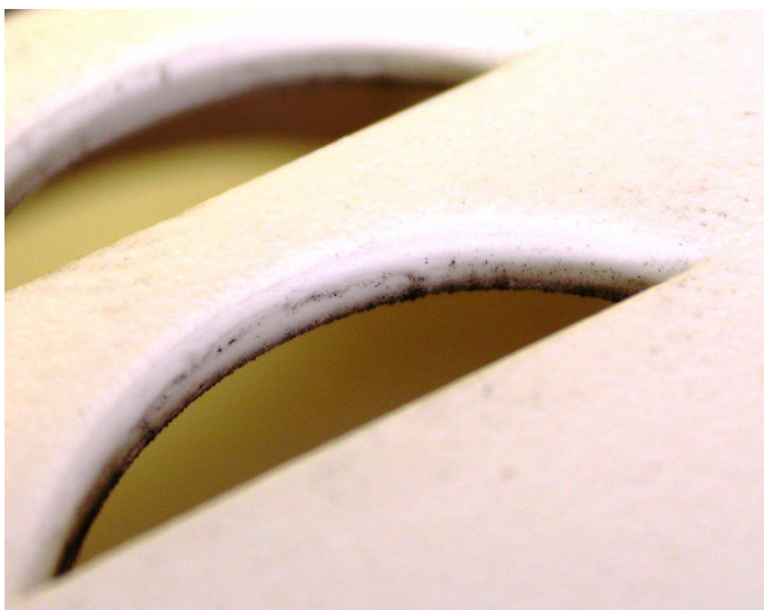

Figure 13.6 This figure shows another view of a single vertical face of the alarm. The deposition is again denser than was seen on the alarm cover or external face, especially toward the corners of the moon shapes. The deposition density changes from higher to lower density moving from the internal to external face of the horn opening.

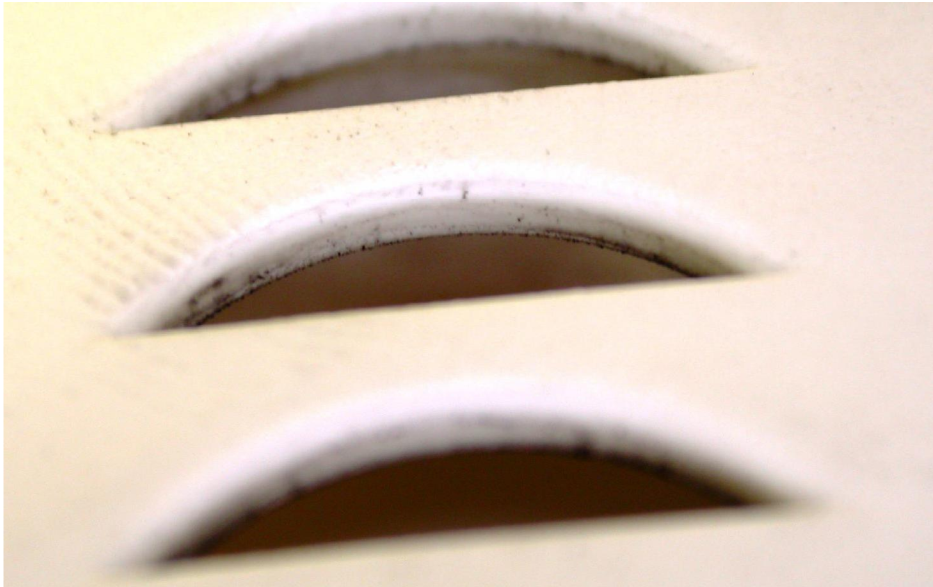

Figure 13.7 A different view of the vertical faces of the smoke alarm horn openings. Deposition on the vertical face is darker than has been seen on the alarm cover or external face of the alarm horn openings. The deposition density moves from higher to lower density from the internal towards the external face. Combining the observations of Figures 13.2-13.7, it can be concluded that there is macroscopic, and therefore also microscopic enhanced soot deposition on the vertical face.

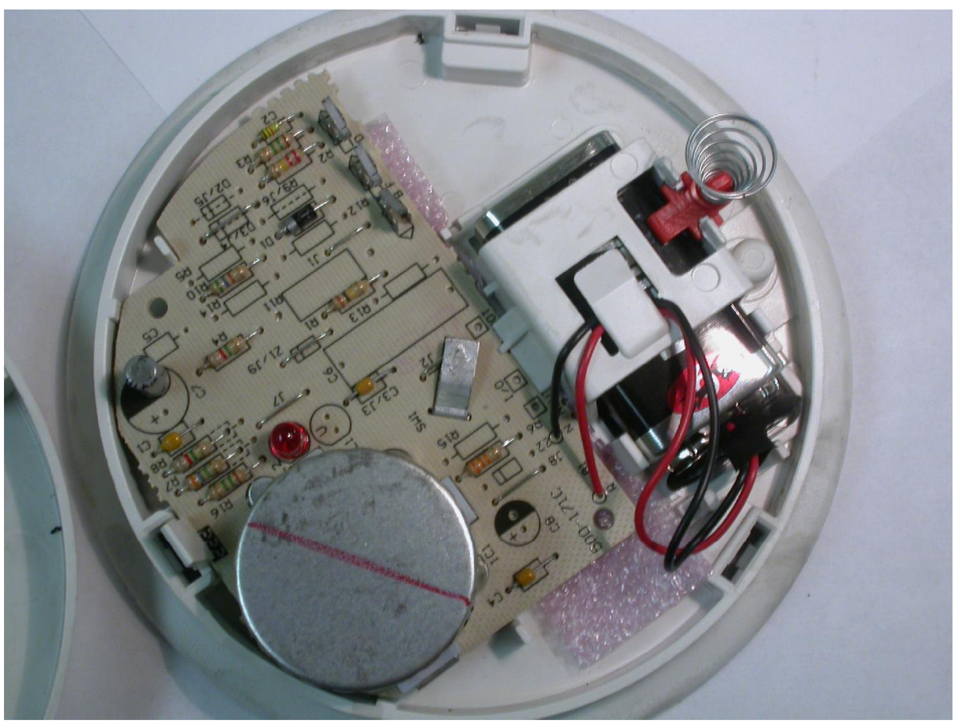

Figure 13.8 This figure shows a macro view of the components of the smoke alarm after the cover has been removed. There is little evident soot deposition on the alarm components and no evidence of bulk flow of smoke through the alarm.

Figure 13.9 This figure contains a view of the entire internal cover of the smoke alarm. There is some evidence of soot deposition on the cover, but no evidence supporting the direction of bulk flow of smoke through the alarm.

Figure 13.10 This figure contains a macro view of the inside surface of the smoke alarm horn chamber. There is a ring of darker soot around each of the alarm horn openings. At the magnification shown the soot deposition on the internal surfaces of the alarm horn chamber appears greater than or equal to the ambient soot deposition outside the horn chamber.

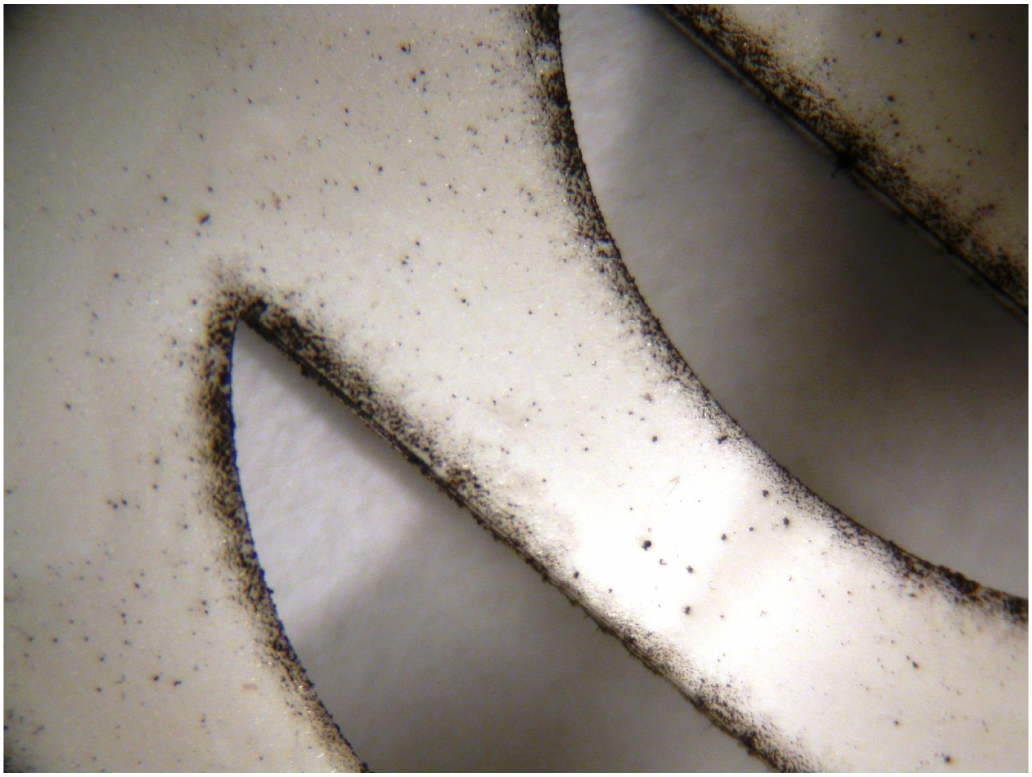

Figure 13.11 This figure shows a microscopic view of the internal face of the alarm horn openings. The soot deposited adjacent to the horn openings is of higher density than the soot farther away from the horn openings. In some places the radial gradation in density is also apparent. Examining the edge between the internal and vertical faces it can be seen that the pattern most obvious in this view is on the internal face. Pattern does not continue into the horn opening and in fact the corner is bare is some places. (The soot visible inside the horn openings is the enhanced soot deposition on the vertical faces observed in Figures 13.5-13.7.) This Figure supports the identification of enhanced soot deposition on the internal face that is indicative of sounding.

Figure 13.12 This figure shows a view that is half inside and half outside the horn chamber. The enhanced deposition around the horn opening is visible on the left and the density of soot deposited inside the horn chamber is greater than or equal to that deposited outside the chamber. This observation verifies the identification of microscopic enhanced soot deposition on the internal face.

Enhanced soot deposition was verified macroscopically and microscopically on the vertical faces and on the internal faces of the smoke alarm horn openings. The horn chamber smoke deposition density was also greater than or equal to that outside the horn chamber. Applying the positive identification heuristic, this alarm would be determined as having sounded by the combination of either the vertical face enhanced deposition and the internal face enhanced deposition or the internal face enhanced deposition and the horn chamber density criterion. To further verify the determination of sounding, the negative heuristic is applied. The negative heuristic is used to confirm that an alarm did not sound. This alarm does not satisfy the negative heuristic because of the existence of both the internal and vertical face depositions. The results of this evaluation, a positive determination that the alarm sounded during a fire exposure are verified by the experimental data. This alarm sounded for 21 minutes during exposure to a flaming polyurethane fire.

14 Appendix C: Additional Observations

14.1 Smoke Alarm Staining

During post-fire examination of the smoke alarms exposed to smoldering sources, a yellow-orange staining of the smoke alarm interior was observed. This is in stark contrast to the carbonaceous depositions found on the interior of the alarms exposed to flaming fires. Additionally, the set of alarms that were exposed to both smoldering and flaming polyurethane exhibited a stained yellow interior and carbonaceous soot deposits, see Figure 14.1. This suggests that examination of the smoke alarm interior can aid in the reconstruction of the fire history by indicating the modes of combustion.

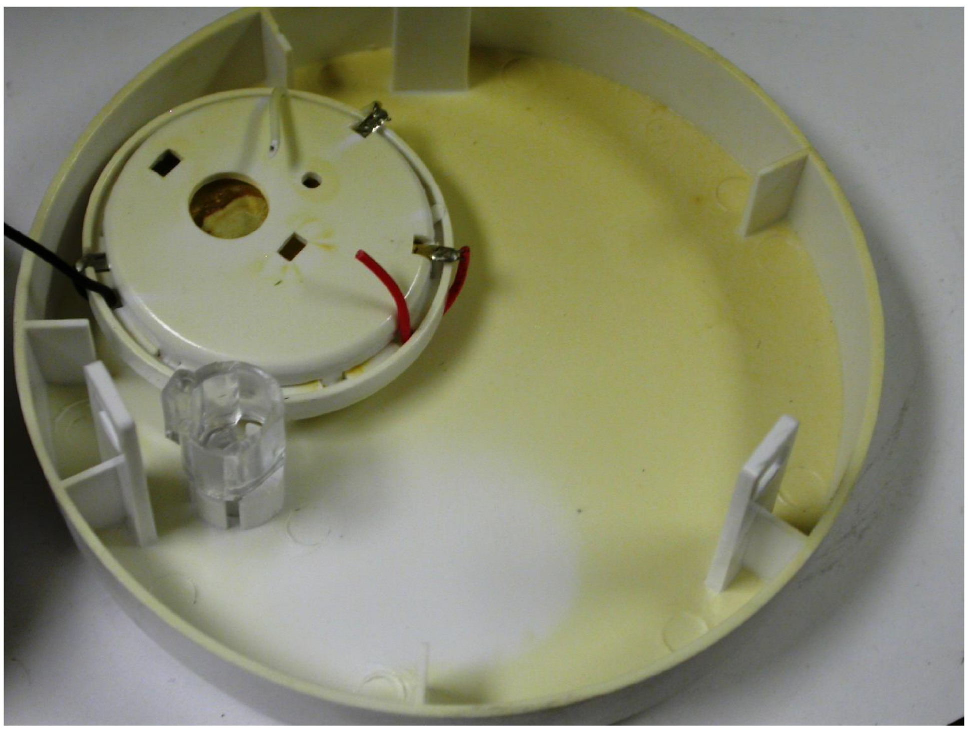

Figure 14.1 The inside cover of an FSBI alarm exposed to a smoldering polyurethane source. The staining of the inside cover is indicative of exposure to a smoldering source, but reveals nothing about whether the alarm sounded or not.

14.2 Soot Deposition on Batteries and Battery Terminals

Soot deposition on smoke alarms is currently used as a forensic tool to determine whether the alarm was powered at the time of the fire event [Colwell, 2003]. This is accomplished by evaluating the soot patterns on the battery body, battery terminals, and smoke alarm terminals.

In the majority of the battery-powered smoke alarms available, the battery is connected to the smoke alarm by terminals that fit tightly around the battery terminals, see Figure 14.2.

Figure 14.2 An FGBI alarm with a properly installed battery. The arms that hold the battery in place form a tight seal to the battery and during some higher soot yield exposures yield the patterns seen in Figure 14.3. The alarm battery terminals also fit tightly around the battery terminals allowing for evaluation of soot or lack thereof on both terminal sets.

If the battery is attached during a fire, event soot can only deposit on the exposed portions of the battery and smoke alarm terminals. Detailed examination of the soot deposition on the battery and smoke alarm terminals can indicate whether the battery was connected or disconnected during the fire event. In addition, models of smoke alarms using "arms" that fit tightly to the battery to hold it in place. These arms can yield patterns of soot deposition that can indicate the position of the battery during the fire event, see Figures 14.4 and 14.5.

Figure 14.3 The outline of the battery arms in the soot deposited on the battery installed in an alarm exposed to the flaming couch in Experiment 4.2.

Figure 14.4 Soot covering a battery terminal from a battery improperly installed in an FGBI alarm exposed in Experiment 4.2: Flaming Couch exposure. Soot could not have collected this way on the terminal of a properly installed battery, see Figure 14.2.

Figure 14.5 Clean terminals on a properly installed battery from an FGBI alarm exposed to the flaming couch in Experiment 4.2. Compare the lack of deposition to soot deposited on the terminals of an improperly installed battery in Figure 14.4.

A detailed examination of the soot deposition on the battery body, terminals, smoke alarm arms, and terminals has been used to establish whether alarms could have been powered during a fire event. The scope and applicability of this technique has not been systematically studied. As a logical addition examination of these areas was incorporated into this study. First, it was found that examination of the battery and terminals of FSBI smoke alarms, as shown in Figure 14.6, yielded no conclusive results, regardless of state, exposure type, length, or alarm duration. This result could have been reasonably predicted given the geometry of the battery placement within this alarm, see Figure 14.6.

Figure 14.6 The battery compartment of an FSBI smoke alarm.

In the FSBI alarms the battery terminals do not fit into the mating terminals rather they press against the alarm terminals the battery is also encased outside of the body of the smoke alarm between it and the base. The other smoke alarms studied utilize battery connections that fit into and over the battery terminals as originally described. Smoke alarms of type FGBI were the only alarms with tight fitting battery arms and were consequently the only alarms to display useful soot deposition patterns on the battery body. The batteries and terminals were inspected macro and microscopically to determine the presence and meaning of soot deposits.

As could be expected this examination is only effective in the fires with high carbonaceous soot yields, flaming polyurethane, turpentine, mixed fuels including plastics, and the couch fire. This technique proved more effective on battery terminals of the type pictured in Figure 14.2 than those pictured in Figure 14.6. This technique has proven to have a very limited scope. In some cases of sufficient soot production to yield patterns, it can be used to determine whether or not a battery was connected during the event. In concert with an electrical examination of the battery, it is possible to determine that an alarm was powered during the event.

14.3 Horn Disc Markings

Anecdotal evidence and studies outside the particular application had suggested the possibility of Chladni figures developing on the metal discs of smoke alarm horns. Previous enhanced soot deposition studies [Worrell, et al., 2001 & 2003] had been unable to confirm the presence of Chladni figures on smoke alarm horn discs. During the course of this investigation, the smoke alarm horn discs were also examined for indications of Chladni figures. While soot deposition was present on many horn discs, no evidence was found to support the development of Chladni figures on smoke alarm horn discs. There were indications of other markings on horns discs of the type shown in Figure 14.7.

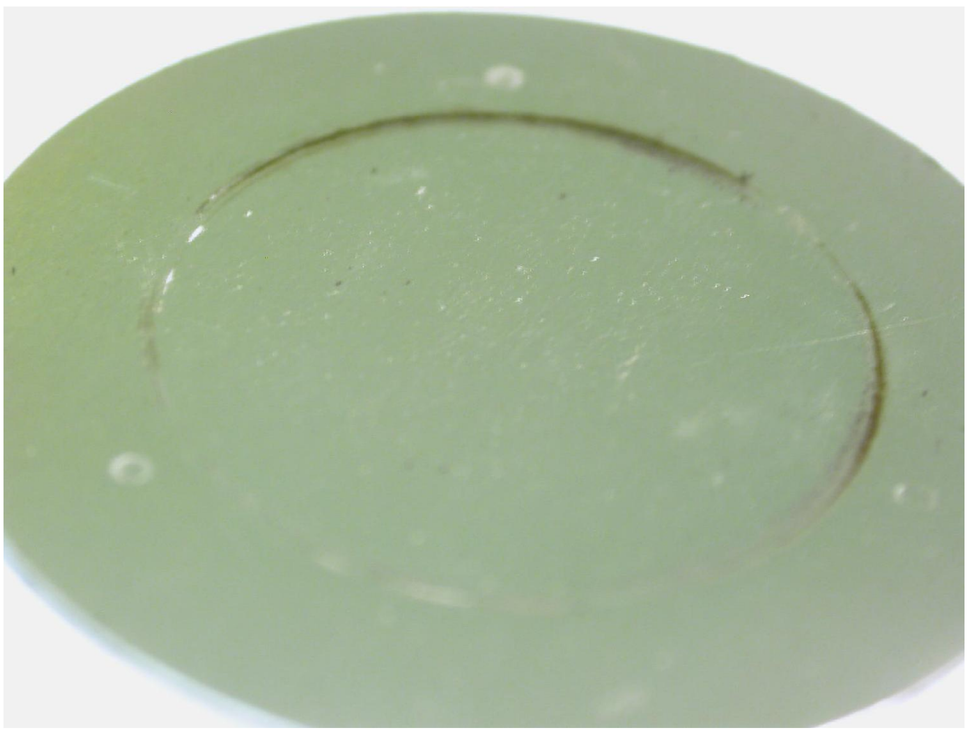

Figure 14.7 Example of a ring marking on a smoke alarm horn disc exposed to a smoldering to flaming cabinet assembly fire.

The horn disc is held in place by a plastic shaft that channels the sound out of the horn opening in the cover, see Figure 0.6. The circular outline of the shaft can leave an impression or scratch on the horn disc. Attempts were made to correlate the presence and magnitude of these markings with both alarm/no alarm events, as well as the alarm duration. The presence of these circular markings has a high correlation with the smoke alarm having sounded. It is not however conclusive enough to be used to indicate that an alarm sounded or did not sound.

There was no indicator found on the disc that could delineate between sounding due to pressing the test button, nuisance source exposure, and exposure to a fire event.

14.4 Exterior Flow Pattern

Thus far the ambient soot deposition present on the exterior of the smoke alarm has only been used in comparison with the soot deposition around the smoke alarm horn. When considering the entire alarm, patterns of soot deposition on the exterior and interior can be seen, as in Figure 14.8. A difference in the density of soot deposition can be seen from one edge of the smoke alarm to the other. The edge with higher density has consistently proven to be the edge oriented toward the fire source. The higher soot-producing sources had higher occurrence of these patterns. These patterns can be used in two ways. First in the case of a known fire origin, the pattern can be used to orient the alarm. Second, in the case of a known alarm placement and orientation, the pattern can be used to indicate the direction of smoke flow.

Figure 14.8 Example of the exterior flow pattern on an FSBI alarm exposed in Experiment 4.2: Flaming Couch Exposure. Note the higher to lower soot density moving from right to left on the alarm cover, signifying smoke flow from right to left across the alarm.

15 Appendix D: Mechanisms

The scientific studies available on the two mechanisms at work concentrate on the enhanced agglomeration of soot particles due to an enhanced acoustic field. As previously discussed, an induced acoustic field produces larger agglomerates. Two variables of acoustic fields are obvious candidates to affect the behavior of the field, volume or sound pressure level, and frequency. The sound pressure level of each alarm signal was measured using a sound pressure meter. The measured variability in the sound pressure level was approximately +/- 5%. UL 217 & NFPA 72 dictates the sound pressure level of the smoke alarms so little variability was expected. It is not expected that this level of variation would cause visible differences in the manifestation and quality of the soot patterns around the smoke alarm horn openings. Over numerous exposures to the alarm signals, differences in the tone quality were observed. The frequency of the alarm signal would seem to be directly related to the level of enhanced Brownian motion within the acoustic field. The alarm signals were recorded using Pro Tools commercial recording and editing software by DigiDesign. Upon comparison of the waveforms, the difference in frequency of the signals is obvious. Unfortunately, although the signal with the highest apparent frequency also appears to have the highest levels of enhanced soot deposition, this is not the only variable that could account for these observations. It will therefore be left to further study to describe these relationships.

The second mechanism of enhanced soot deposition is the pulsed flow phenomena postulated and observed by Worrell, et al., [Worrell, et al., 2003]. This pulsed flow is a phenomenon rather specific to a smoke alarm horn, within the context of a fire. However, flow of smoke through constrictions is a common occurrence. Analogous soot depositions can be found in many constricted flow situations, from fire experiments to actual fire events. The soot shading found around the smoke alarm horn openings is analogous to that found around doorways and openings in ceilings seen in the experimental facilities used and fire events reviewed separate from this investigation. This lends itself to the conclusion that increased flow of smoke into and out of the horn opening is sufficient to establish patterns of soot deposition without increased agglomerate size around smoke alarm horns.

16 Appendix E: Sample Alarm Photos: Smoldering Polyurethane Exposures

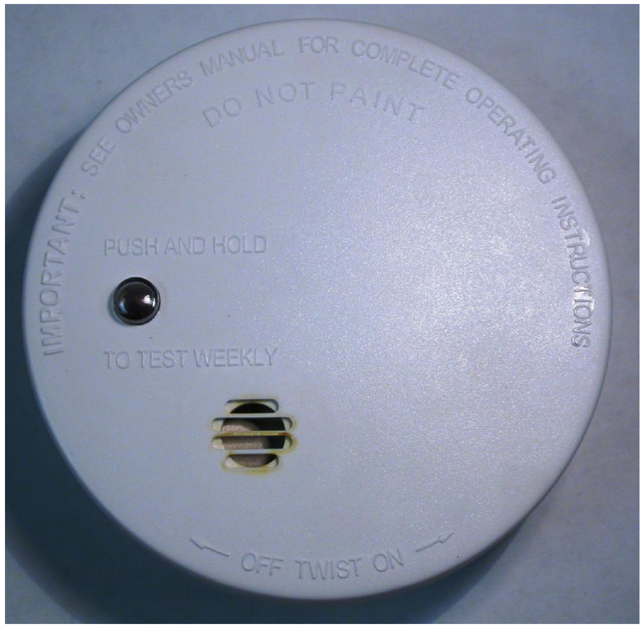

Figure 16.1 This figure shows the exterior of the alarm cover of an alarm that sounded during exposure to a smoldering polyurethane source. Enhanced soot deposition patterns are visible in this figure around the alarm horn openings.

Figure 16.2 This figure shows a macroscopic view of the exterior face of the alarm horn openings in Figure 16.1. This alarm sounded during exposure to a smoldering polyurethane fire source. Tarry enhanced soot deposition is visible around the horn openings.

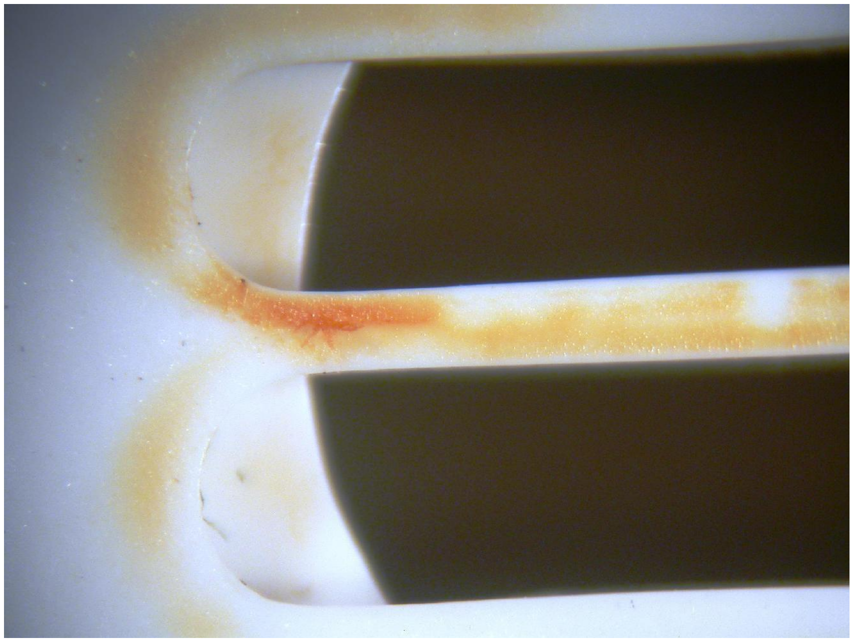

Figure 16.3 This is a microscopic view of some of the alarm horn openings from the alarm in Figures 16.1-16.3. This alarm sounded during exposure to a smoldering polyurethane fire source. Tarry enhanced soot deposition is visible around the horn openings as orange/brown bands.

Figure 16.4 This figure shows a macroscopic view the alarm horn openings of an alarm that did not sound during exposure to smoldering polyurethane fire source. There is no evidence of enhanced deposition around the horn openings as there were on the alarm pictured in Figures 16.1-16.3, which did sound.

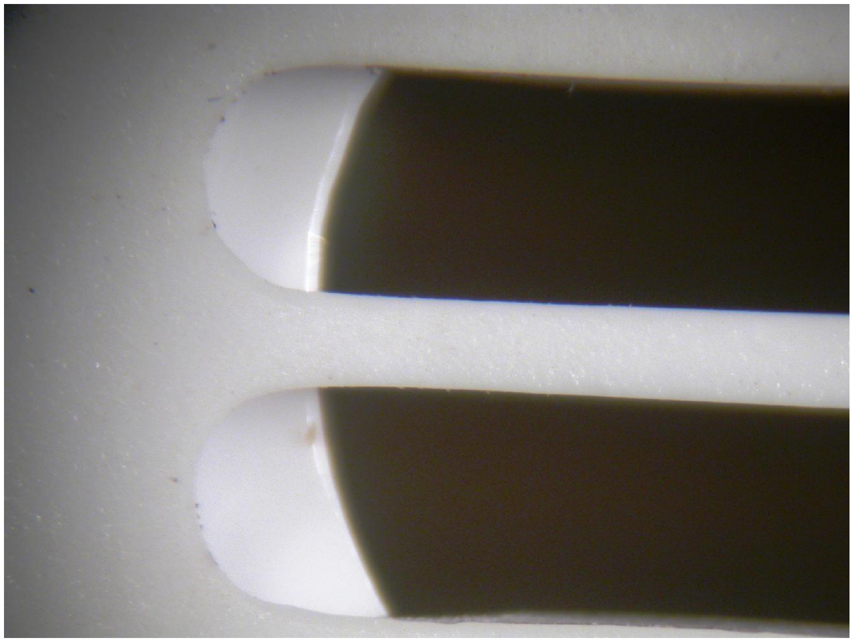

Figure 16.5 This is a microscopic view of the horn openings from the alarm pictured in Figure 16.4. This alarm did not sound during exposure to a smoldering polyurethane fire source and does not show evidence of enhanced soot deposition.

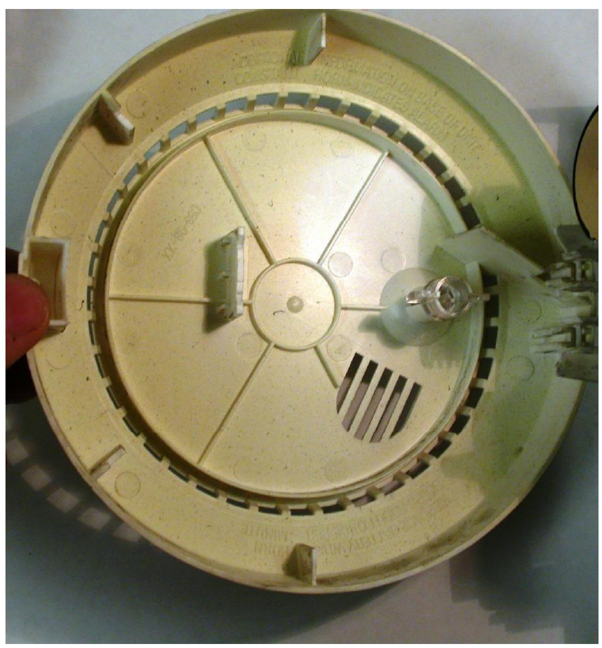

Figure 16.6 This figure pictures the interior of the alarm cover of an FGBI alarm subjected to a smoldering polyurethane source. The alarm shows staining characteristic of an alarm subjected to a smoldering fire source.

Figure 16.7 This figure shows external face of an alarm that sounded during exposure to smoldering polyurethane source. There is no evidence of enhanced soot deposition indicative of sounding.

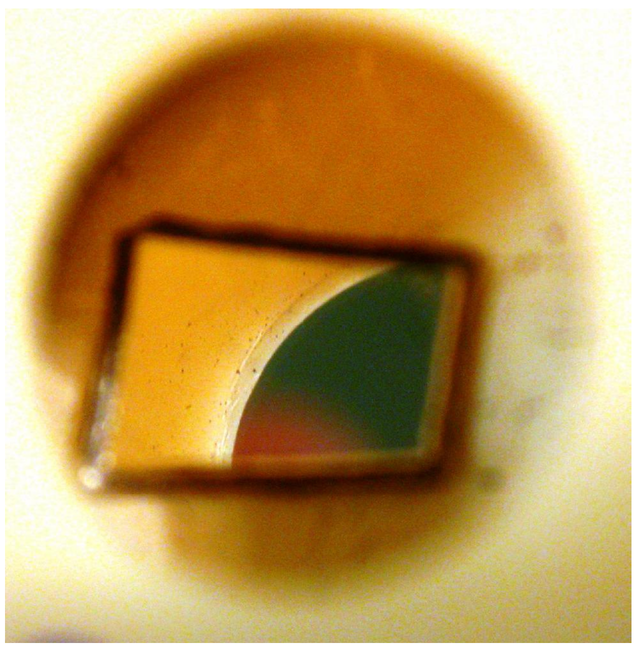

Figure 16.8 This figure shows the interior face of the alarm horn opening in Figure 16.7. A mirror was used to inspect the internal face, which also does not show evidence of enhanced soot deposition despite the fact that alarm did sound during exposure to a smoldering polyurethane fire source.

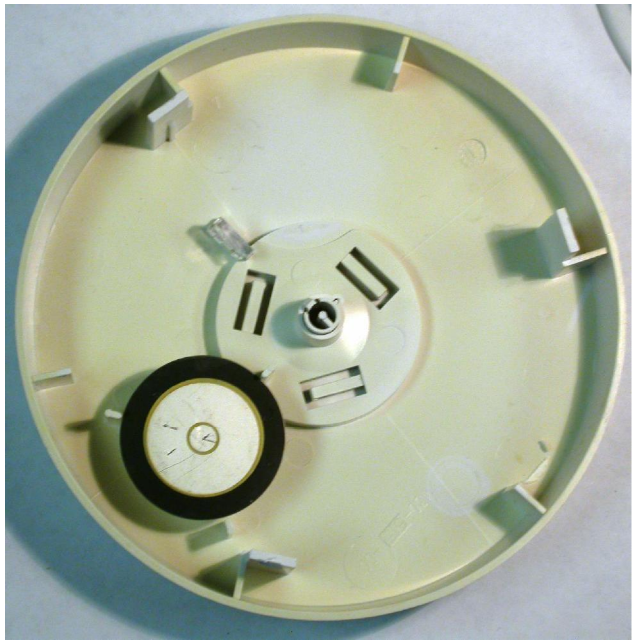

Figure 16.9 This figure shows the interior of a smoke alarm cover that sounded during exposure to a smoldering polyurethane source. The cover shows staining characteristic of exposure to a smoldering fire source.

Figure 16.10 This figure shows a macroscopic view of the internal face of smoke alarm horn openings of an alarm that sounded during exposure to a smoldering polyurethane source. There is evidence of tarry enhanced soot deposition indicative of alarm sounding around the edges of the horn openings.

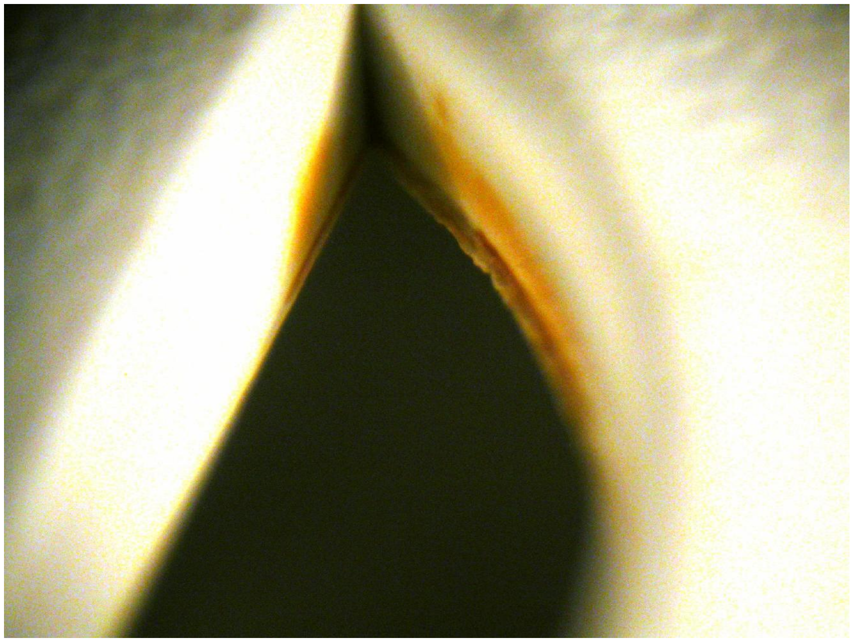

Figure 16.11 This figure shows a microscopic view of the vertical face of one of the alarm horn openings of the alarm pictured in Figures 16.9-16.10. This alarm sounded during the exposure and tarry enhanced soot deposition is visible as the yellow orange depositions in the corner of the opening.

Figure 16.12 This is a macroscopic view of 2 of the vertical faces of the alarm horn openings of the alarm pictured in Figures 16.9-16.12. Enhanced tarry soot deposition visible on both vertical faces but most obvious on the closer vertical face.

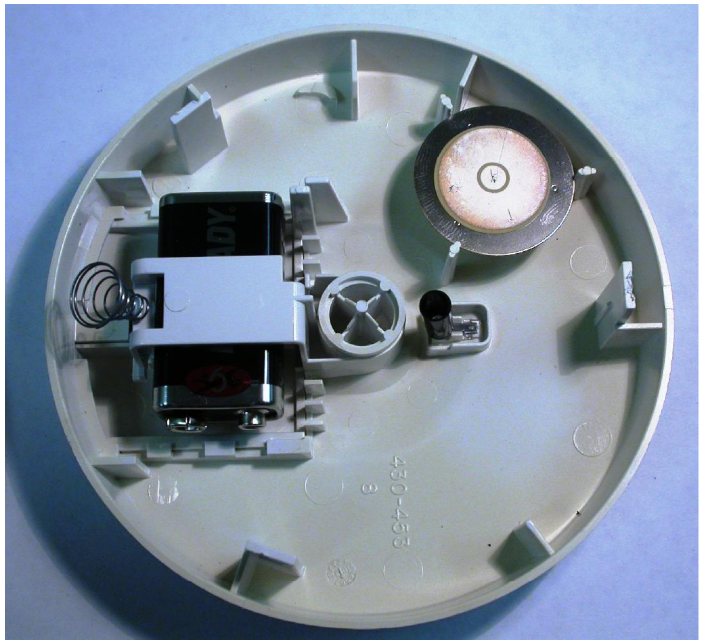

Figure 16.13 This figure shows the interior of an alarm cover that sounded during exposed to a smoldering polyurethane fire source. There is staining characteristic of exposure to a smoldering polyurethane source.

Figure 16.14 This figure shows the internal face of the alarm pictured in Figure 16.13. This alarm sounded during exposure to a smoldering polyurethane source and has tarry enhanced soot deposition indicative of alarm sounding.

17 Appendix F: Sample Alarm Photos: Flaming Polyurethane Exposures

Figure 17.1 This figure shows the exterior of the alarm cover of an alarm that sounded during exposure to a flaming polyurethane fire source. Enhanced soot deposition patterns with radial characteristics are barely visible in this figure around the alarm horn openings.

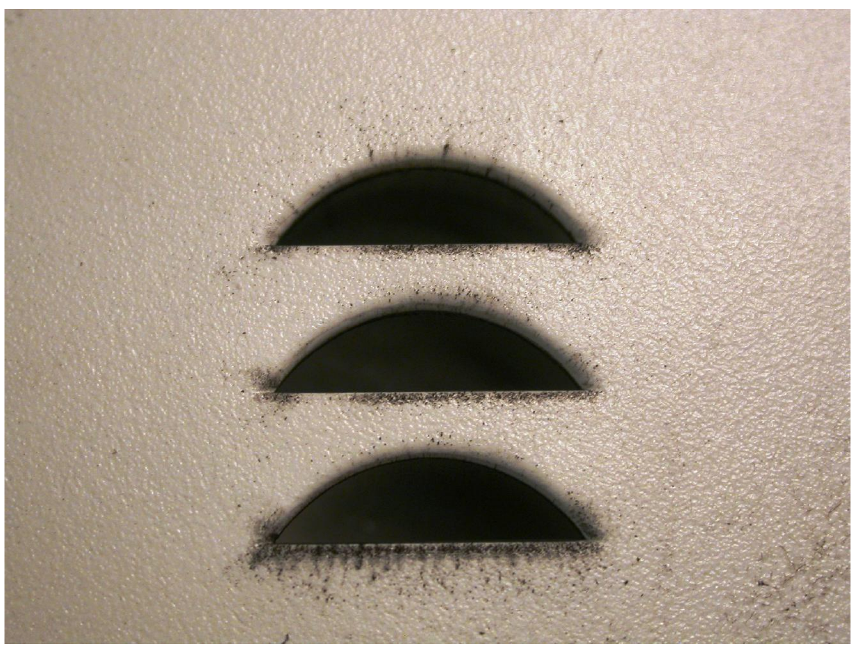

Figure 17.2 This figure shows a macroscopic view of the exterior face of the alarm horn openings of the same alarm in Figure 17.3. This alarm sounded during exposure to a flaming polyurethane fire source. Enhanced soot deposition is visible in places around each of the moon-shaped openings.

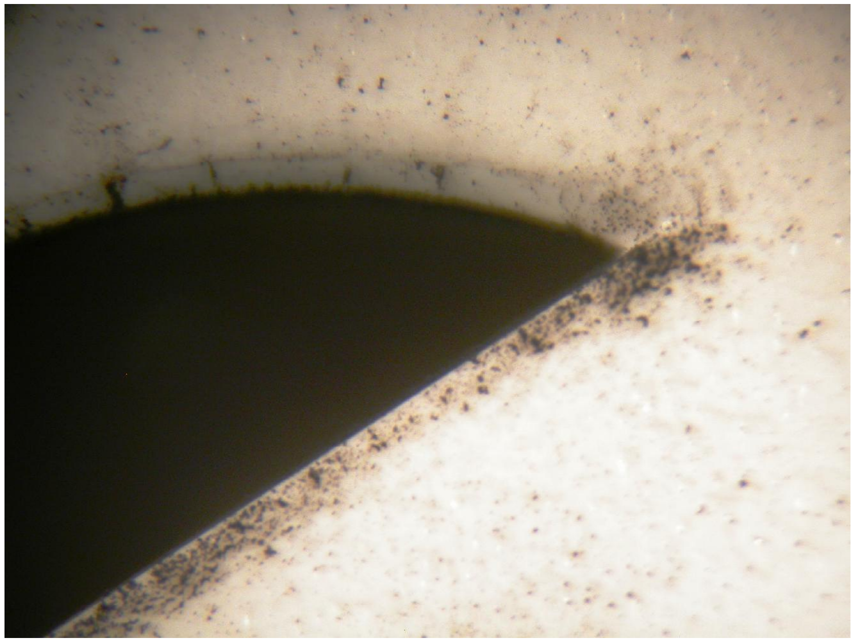

Figure 17.3 This is a macroscopic view of one of the moon shaped openings of the alarm from Figures 17.2 and 17.3. This alarm sounded during exposure to a flaming polyurethane source. Enhanced soot deposition is visible here along the bottom face and corner of the opening.

Figure 17.4 This figure contains a macroscopic view of the vertical faces of the alarm [pictured in Figures 17.1-17.3. This alarm sounded during exposure to a flaming polyurethane fire source. Enhanced soot deposition is visible on all three vertical faces. The deposition density moves from higher to lower density from the internal to external faces of the horn opening.

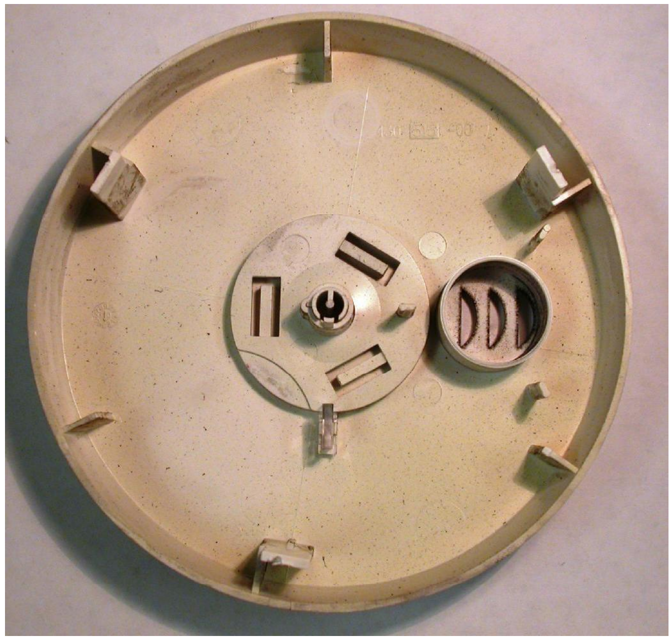

Figure 17.5 This figure contains a view of the interior of the alarm cover from the alarm pictured in Figures 17.1-17.6. This alarm has been exposed to smoldering and flaming polyurethane sources, visible by the staining and carbonaceous soot depositions. The enhanced soot deposition on the interior faces of the horn openings is barely visible in this figure.

Figure 17.6 This figure contains a macroscopic view of the interior face of the alarm horn opening of the alarm pictured in Figures 17.1-17.5. Visible is the enhanced soot deposition around the horn openings and the deposition density of equal or greater inside the horn chamber than outside the horn chamber.

Figure 17.7 This figure contains the external cover of an alarm that did not sound during exposure to a flaming polyurethane source.

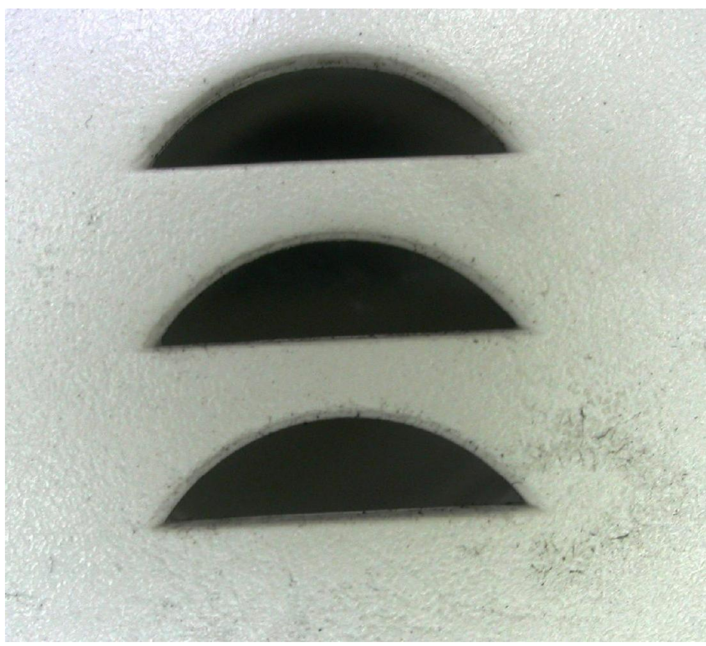

Figure 17.8 This figure contains a macroscopic view of the external face of the alarm horn openings of the same alarm as in Figure 17.7. There is some visible deposition around the alarm horn openings but it is not of any greater density than the deposition on the cover of the alarm further from openings.

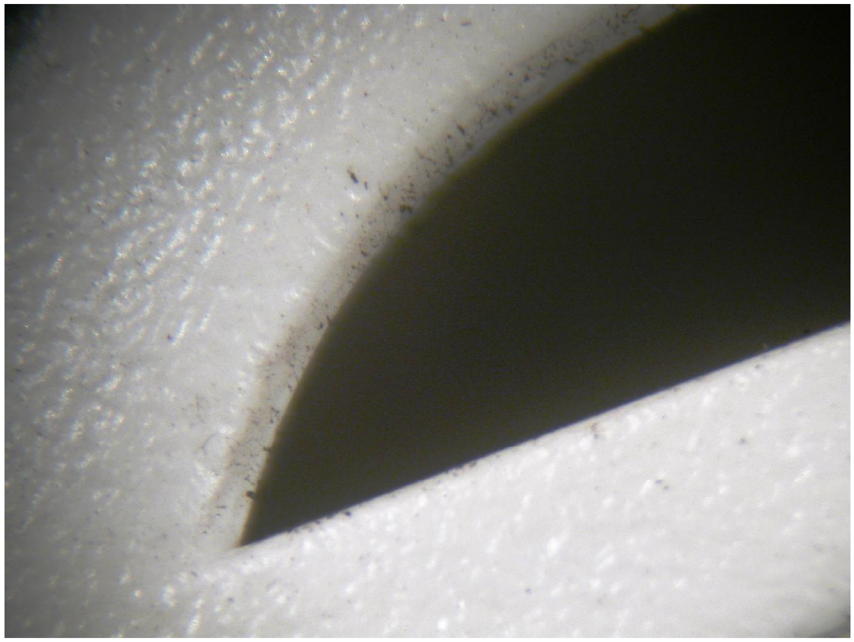

Figure 17.9 This figure contains a microscopic view of the external face of the alarm horn opening from the same alarm pictured in Figures 17.7 and 17.8. There is some minimal deposition around the horn opening, but it is similar in density to the ambient deposition on the alarm cover.

Figure 17.10 This figure pictures the exterior cover of an FGBI alarm that sounded during exposure to a flaming polyurethane source.

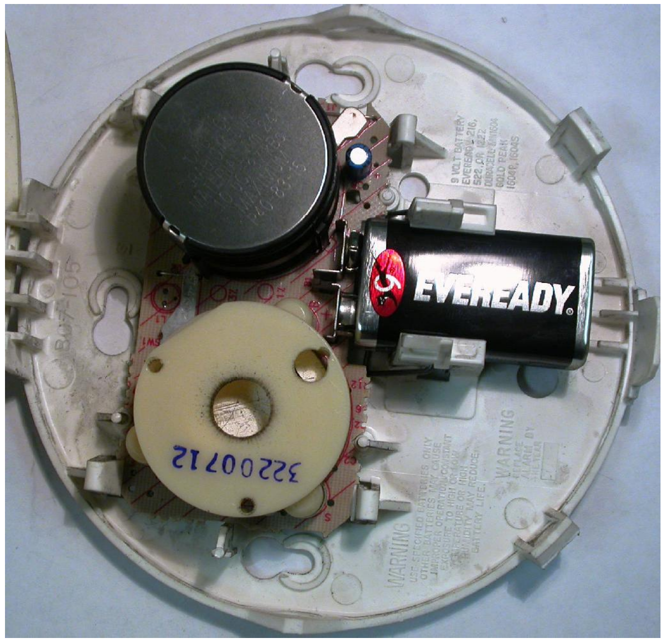

Figure 17.11 This figure shows the interior of the same FGBI alarm seen in Figure 17.10. Enhanced soot deposition is visible on the exterior face of the alarm horn opening.

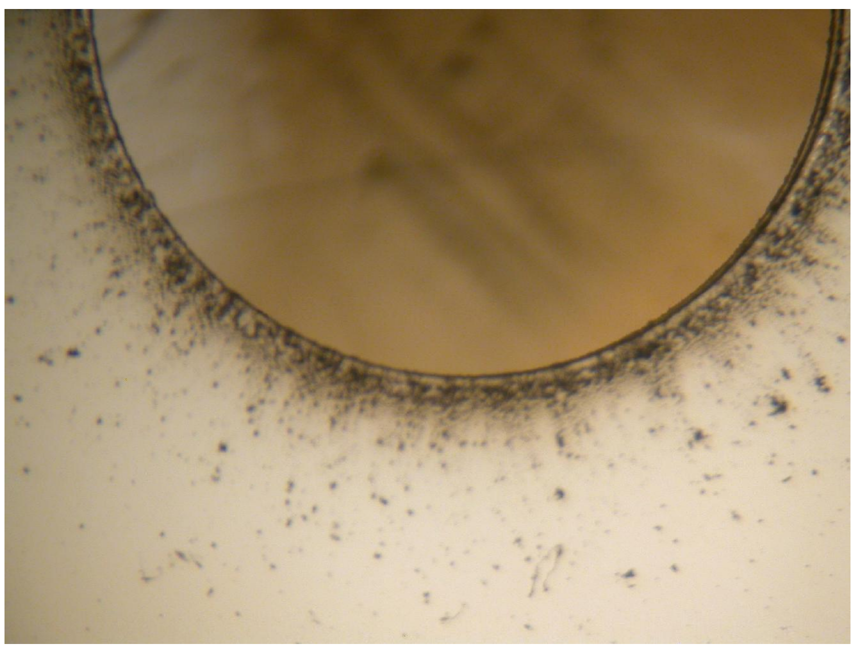

Figure 17.12 This Figure contains a microscopic view of the external face of the alarm horn opening of the alarm pictured in Figures 17.10-17.11. There is a distinct pattern of enhanced soot deposition on this alarm that sounded during exposure to a flaming polyurethane source.

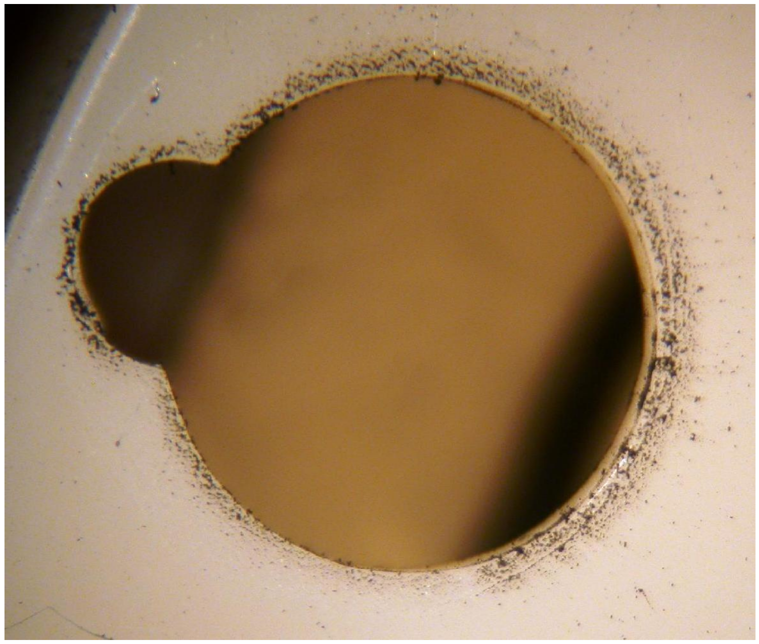

Figure 17.13 This is a macroscopic view of the secondary hole on the horn of the same FGBI alarm pictured in Figures 17.10-17.13. There are obvious patterns of enhanced soot deposition indicating that this alarm sounded during exposure to the flaming polyurethane source.

Figure 17.14 This figure shows the exterior alarm cover of an FGBI alarm that did not sound during exposure to a flaming polyurethane fire.

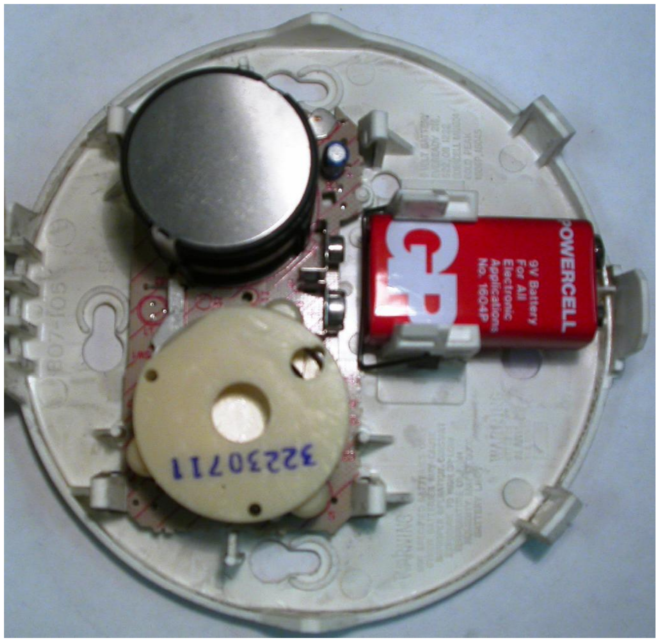

Figure 17.15 This figure shows the interior of the alarm in Figure 17.14, an alarm that did not sound during exposure to a flaming polyurethane fire.

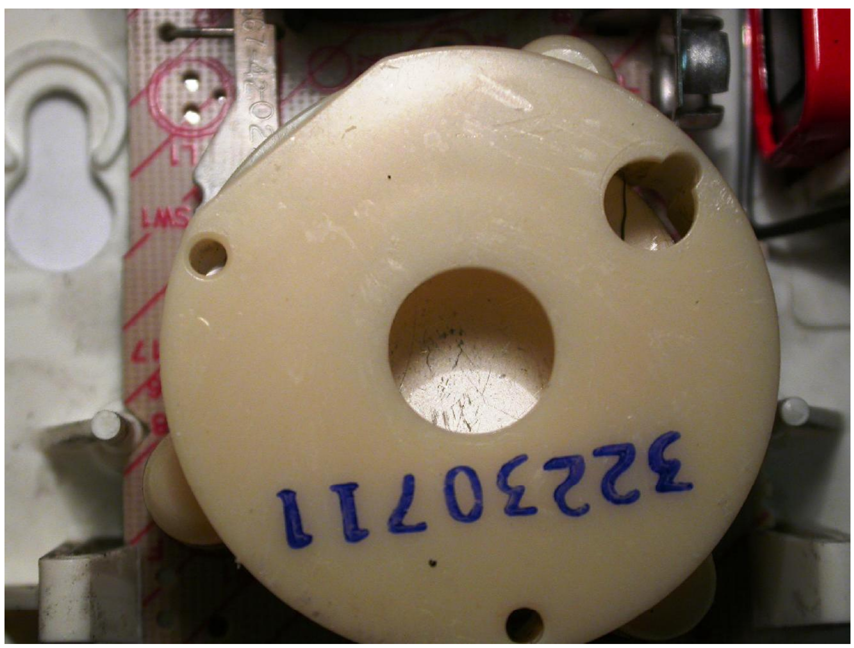

Figure 17.16 This is a macroscopic view of the horn of the alarm pictured in figures 17.14-17.15. This alarm did not sound during exposure to a flaming polyurethane source and shows no signs of enhanced soot deposition.

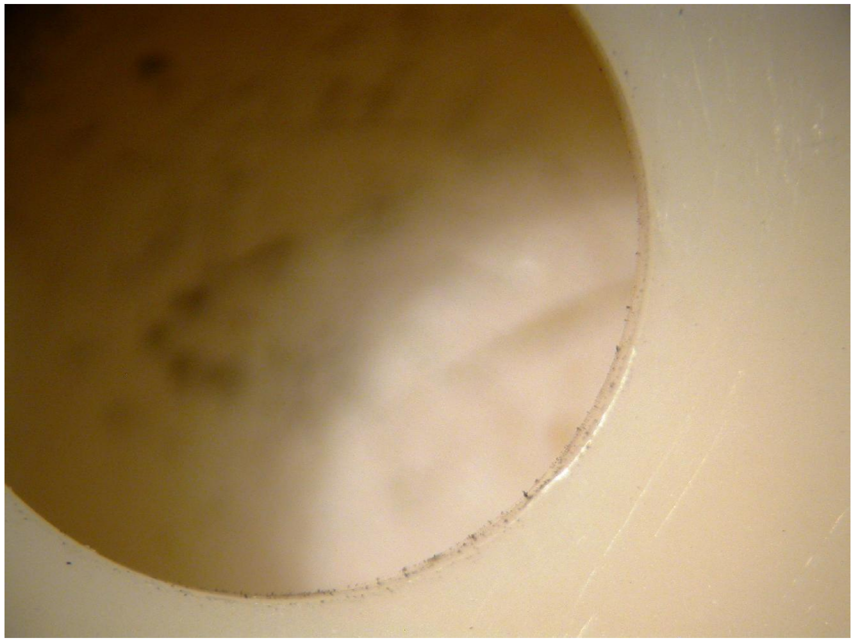

Figure 17.17 This is a microscopic view of the horn from the alarm pictured in Figures 17.14-17.17. There is some soot deposited on the horn, but no evidence of enhanced soot deposition indicative of sounding.

Figure 17.18 This is the exterior of the cover of an FACI alarm that sounded during exposure to a flaming polyurethane fire.

Figure 17.19 This is a macroscopic view of the external face of the horn openings of the alarm pictured in Figure 17.18. This alarm did sound during exposure to a flaming polyurethane source and shows evidence of enhanced soot deposition.

Figure 17.20 This figure shows the level of ambient soot deposited on the cover of the alarm pictured in Figures 17.14-17.19 (photo at the same magnification as Figure 17.19). The density of soot deposited farther from the opening is lower than the density of soot in the pattern of enhanced soot deposition from the previous figure.

Figure 17.21 This figure pictures the external cover of an FACI alarm that did not sound during exposure to a flaming polyurethane source.

Figure 17.22 This figure shows a macroscopic view of the external face of the alarm horn opening of the FACI alarm pictured in Figure 17.21. There is no indication of enhanced soot deposition, as this alarm did not sound during exposure to the flaming polyurethane fire.

Figure 17.23 This figure shows the level of ambient soot deposition on the external cover of the FACI alarm pictured in Figures 17.21 and 17.22.

Figure 17.24 This figure shows the external cover of an FSBI alarm that sounded during exposure to a flaming polyurethane fire. Enhanced soot deposition is evident even from this view.

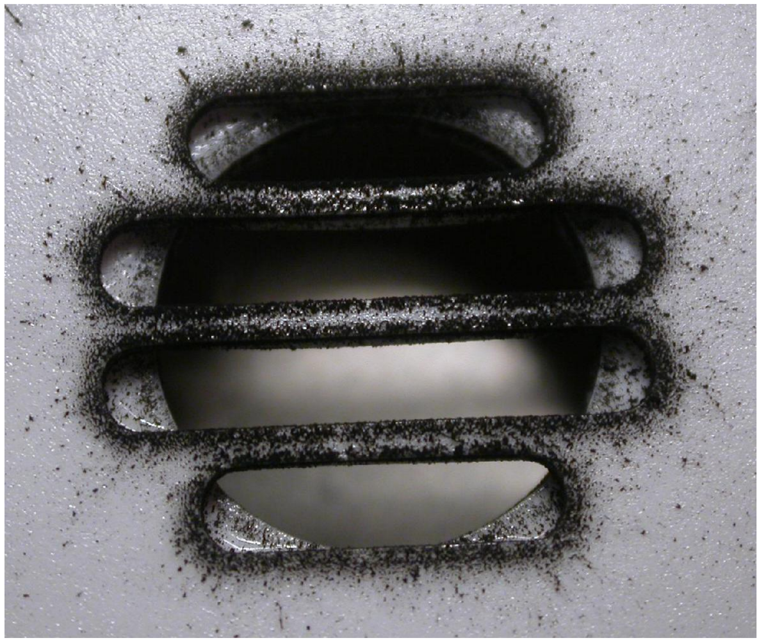

Figure 17.25 This is a macroscopic view of the alarm horn opening seen from afar in Figure 17.24. The FSBI alarm sounded during exposure to a flaming polyurethane fire and displays evidence of enhanced soot deposition.

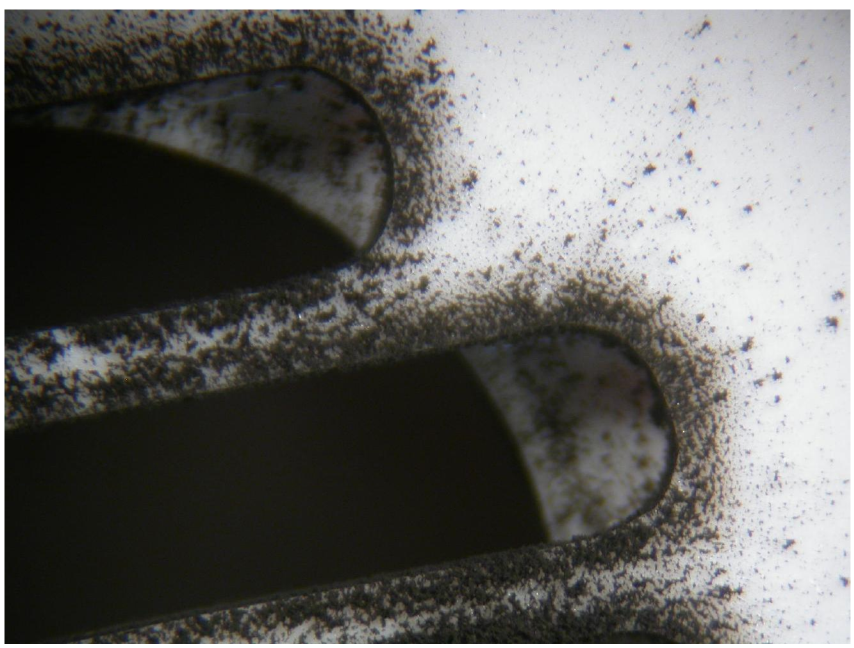

Figure 17.26 This is a microscopic view of the pattern of enhanced soot deposition seen in Figure 17.25. This alarm sounded during exposure to a flaming polyurethane source.

Figure 17.27 This figure shows the external cover of an FSBI alarm that did not sound during exposure to flaming polyurethane.

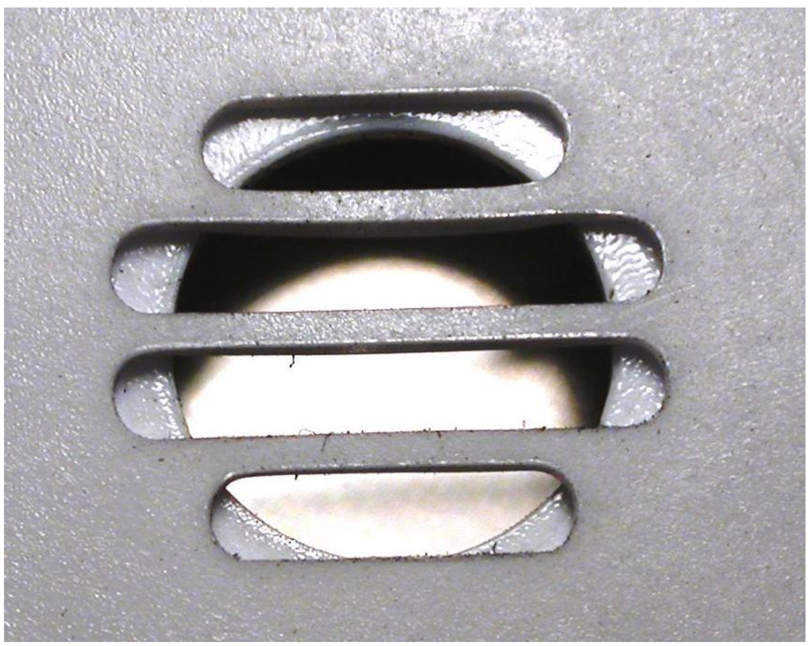

Figure 17.28 This is a macroscopic view of the external face of the alarm horn opening from the alarm pictured in Figure 17.27. This alarm does not display evidence of enhanced soot deposition, as it did not alarm.

Figure 17.29 This figure shows the ambient soot deposited on the external cover of the alarm pictured in Figures 17.27-17.28.

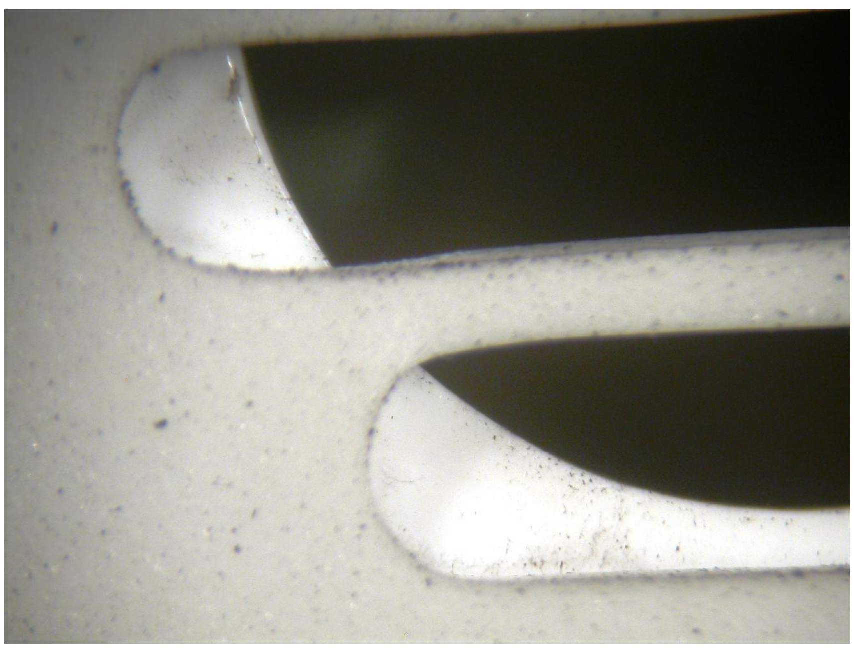

Figure 17.30 This is a microscopic view of the alarm horn opening of the alarm from Figures 17.27-17.30. This alarm did not sound during exposure to flaming polyurethane. There is evidence of soot deposited on the horn openings but not evidence of enhanced soot deposition as pictured in Figure 17.26.

Figure 17.31 This is the exterior cover of a Photo alarm that sounded during exposure to a flaming polyurethane fire.

Figure 17.32 This is a macroscopic view of the alarm horn from Figure 17.31. This alarm sounded during exposure to flaming polyurethane.

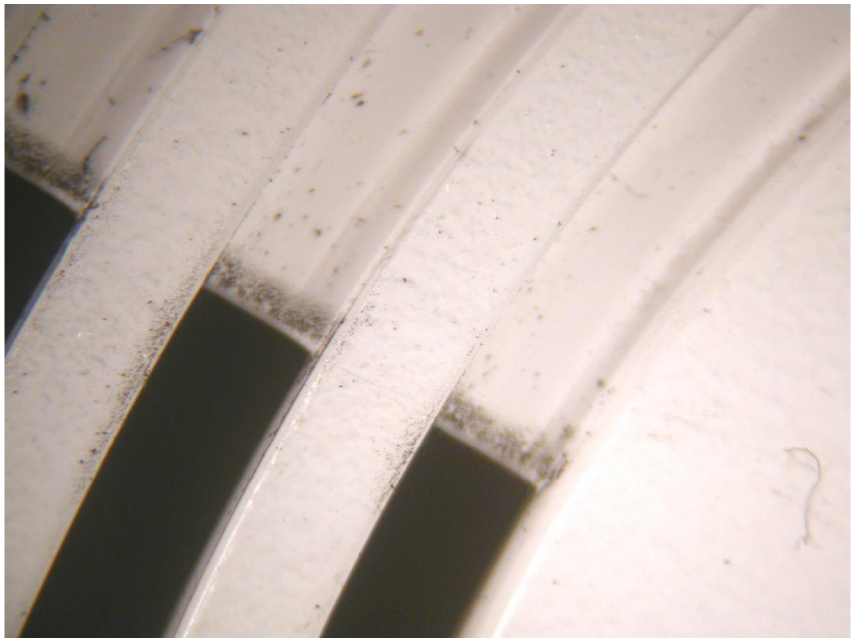

Figure 17.33 This is a macroscopic view of the horn openings from Figures 17.31 and 17.32. This alarm sounded during exposure to a flaming polyurethane source. There is evidence of enhanced soot deposition on the short edges of all of the alarm horn openings.

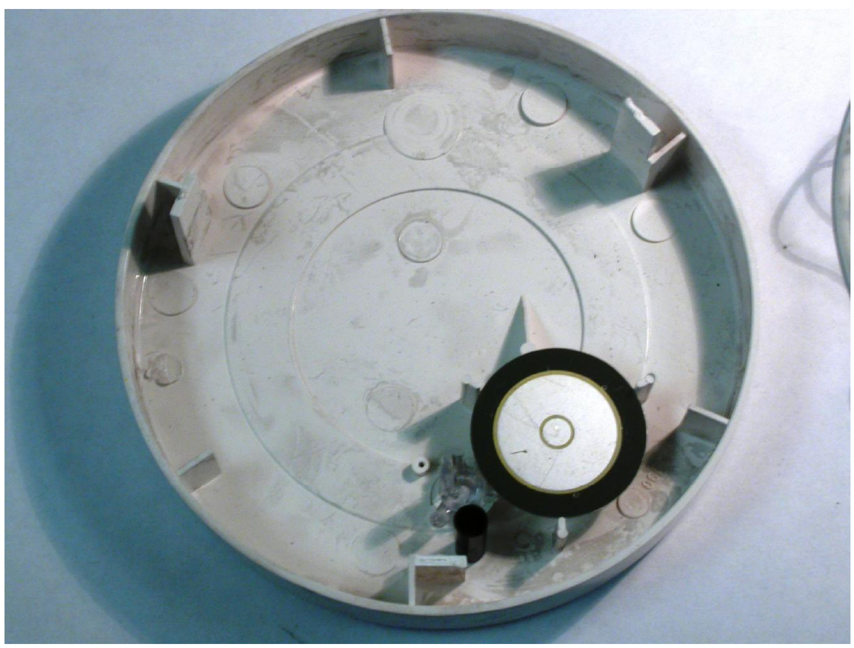

Figure 17.34 This is a view of the interior of the alarm from Figures 17.31-17.33.

Figure 17.35 This is a macroscopic view of the interior face of the alarm pictured in Figures 17.31-17.34. There are rings of enhanced soot deposition visible around the horn openings. The enhanced soot deposition is more distinct on the interior face than the exterior face, Figure 17.32.

18 Appendix G: Sample Alarm Photos: Flaming Wood Exposures

Figure 18.1 This figure shows the outer cover of an FBI alarm that sounded during exposure to a flaming wood fire.

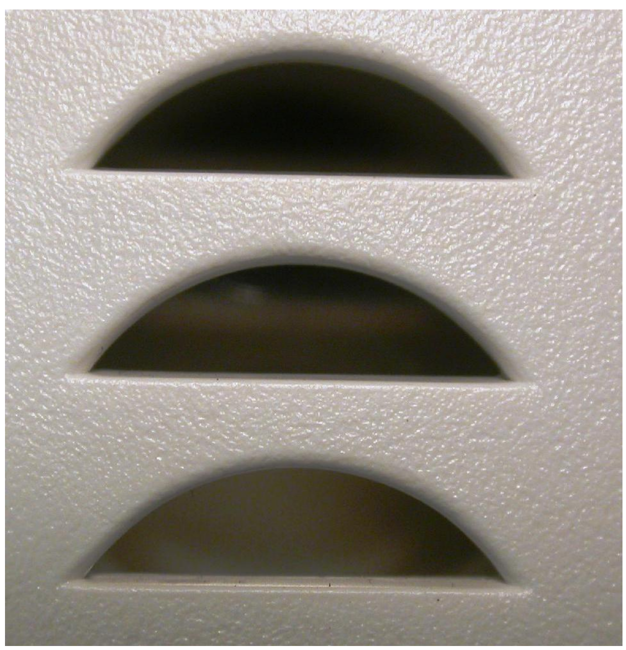

Figure 18.2 This is a macroscopic view of the alarm horn openings pictured in Figure 18.1. The alarm sounded during the exposure, but does not show evidence of enhanced soot deposition on the exterior of the cover.

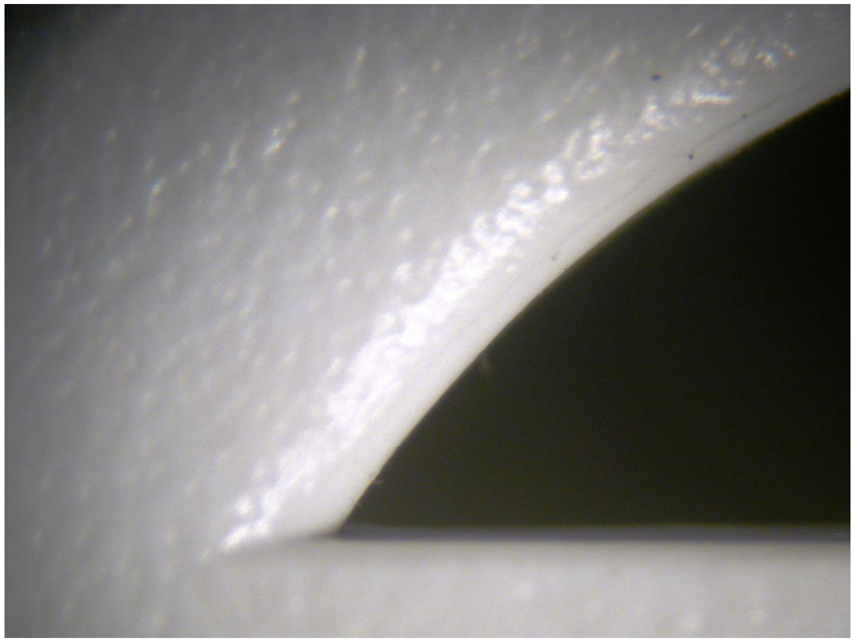

Figure 18.3 This is a microscopic view of the alarm horn openings of Figure 18.2. There is no evidence of enhanced soot deposition on the vertical surface. This case did not present sufficient evidence to yield a determination.

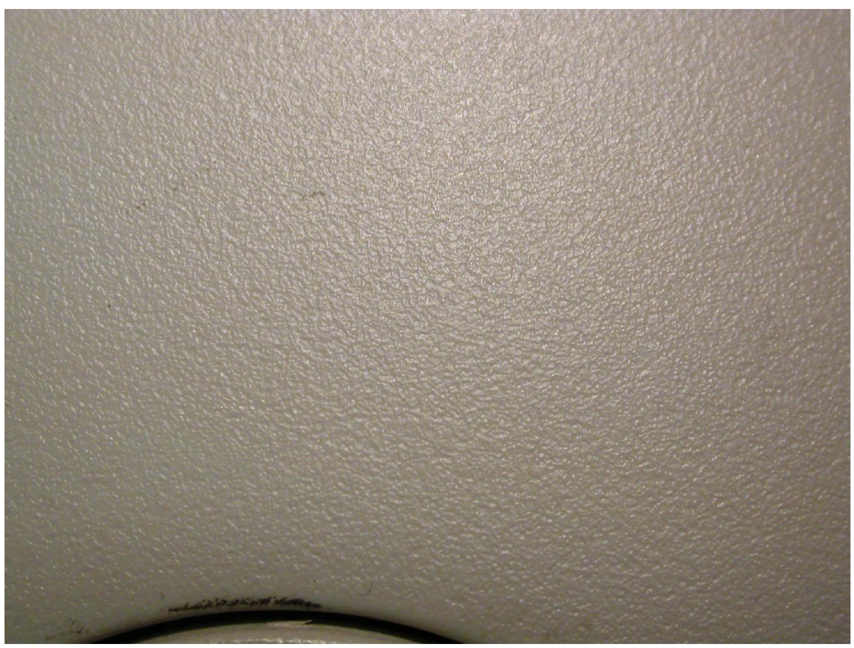

Figure 18.4 This figure shows the ambient deposition on the exterior cover of the alarm in Figures 18.1-18.3.

Figure 18.5 This figure shows the exterior cover of an FBI alarm that did not sound during exposure to a flaming wood fire.

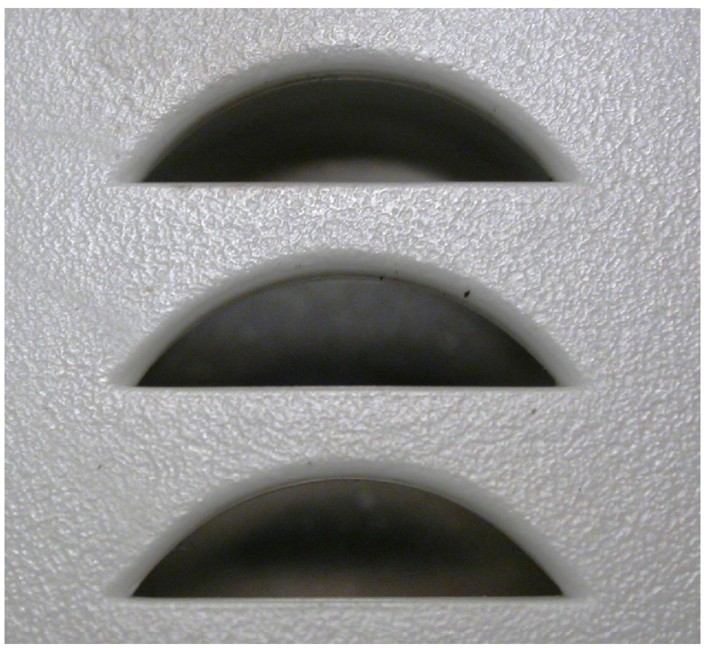

Figure 18.6 This figure is a macroscopic view of the alarm horn openings of the alarm pictured in Figure 18.5. This alarm did not sound during the exposure.

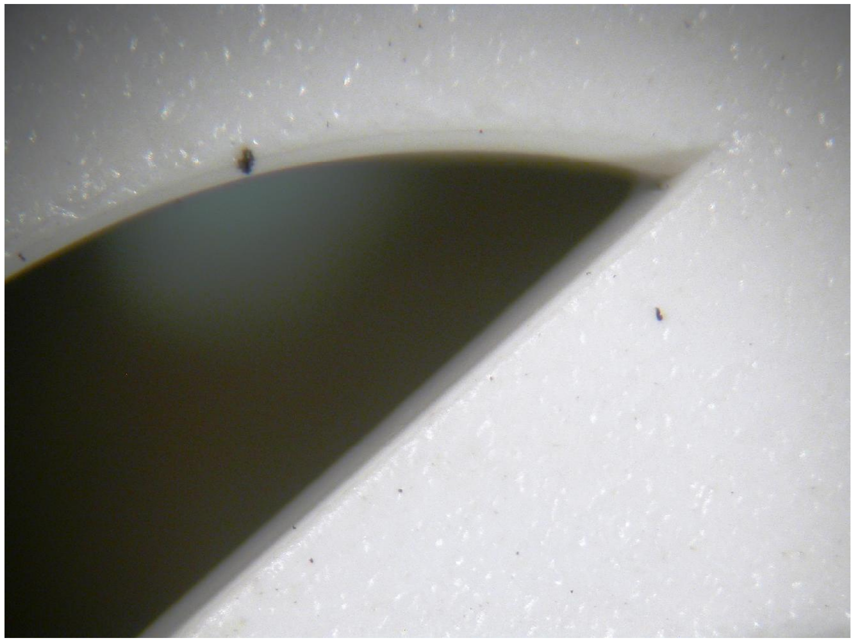

Figure 18.7 This is a microscopic view of a horn opening pictured in Figure 18.6. This alarm did not sound and does not show evidence of enhanced soot deposition.

Figure 18.8 This figure shows the ambient soot deposited on the exterior cover of the alarm that did not sound during exposure to a flaming wood fire.

Figure 18.9 This figure shows an overview of an FACI alarm that sounded during exposure to a flaming wood fire.

Figure 18.10 This figure contains a macroscopic view of the alarm horn openings from the alarm pictured in Figure 18.9. This alarm sounded but does not show evidence of enhanced soot deposition on the surface.

Figure 18.11 This figure shows the exterior cover of and FGBI alarm that sounded during exposure to a flaming wood fire.

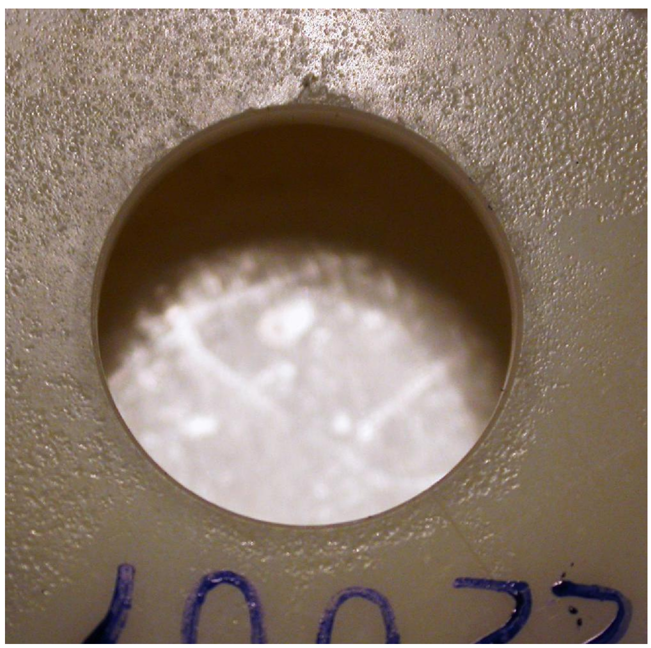

Figure 18.12 This is a macroscopic view of the alarm horn opening of the alarm pictured in Figure 18.11. This alarm sounded during exposure to a flaming wood fire but does not show evidence of enhanced soot deposition.

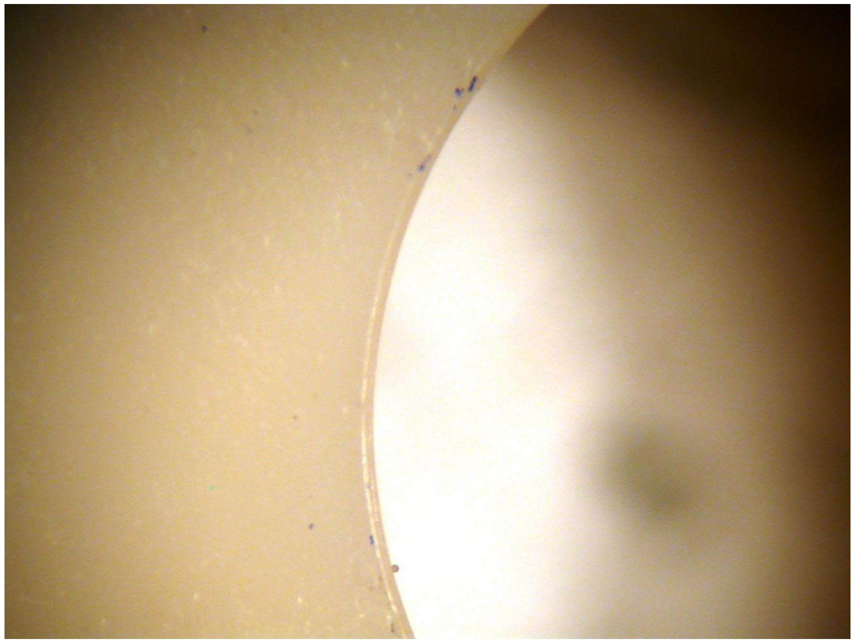

Figure 18.13 This is a microscopic view of the alarm horn opening of the alarm pictured in Figure 18.12. This alarm sounded during exposure to a flaming wood fire but does not show evidence of enhanced soot deposition.

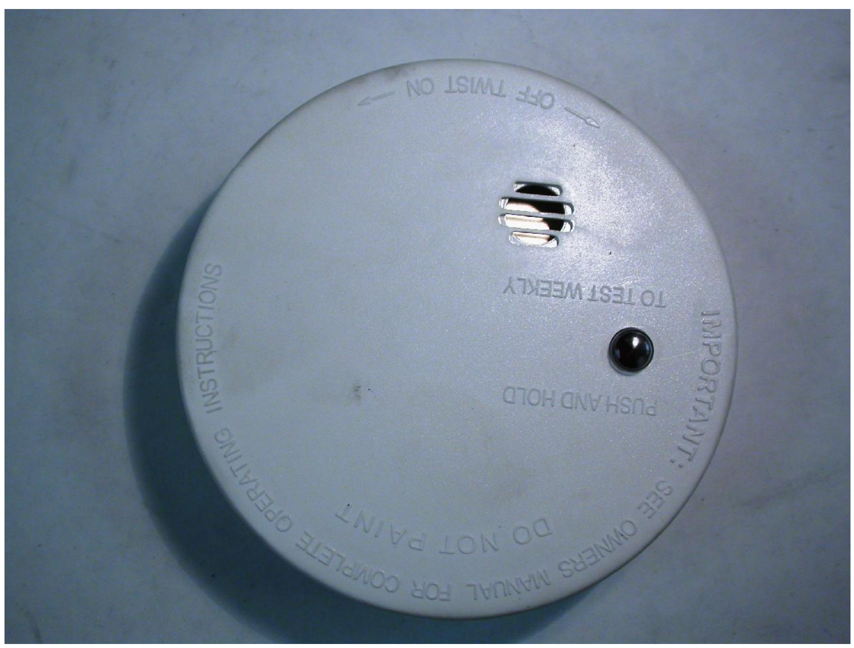

Figure 18.14 This figure shows the exterior cover of FSBI alarm that sounded during exposure to a flaming wood fire.

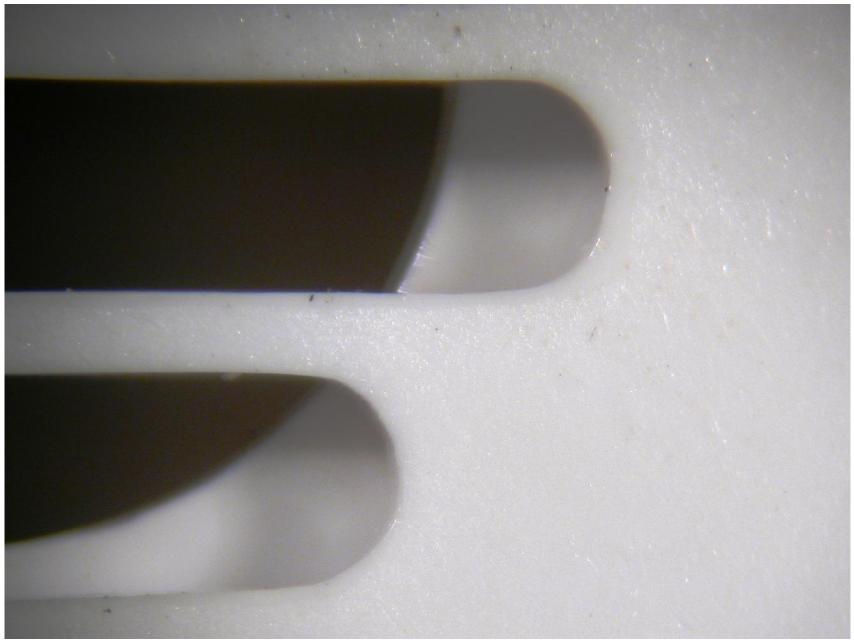

Figure 18.15 This is a microscopic view of the alarm horn opening of the alarm pictured in Figure 18.14. This alarm sounded during exposure to a flaming wood fire but does not show evidence of enhanced soot deposition.

19 Appendix H: Sample Alarm Photos: Nuisance Exposures

Figure 19.1 This figure shows the exterior cover of an FBI alarm that sounded during multiple nuisance exposures.

Figure 19.2 This figure is a macroscopic view of the alarm horn openings of the alarm pictured in Figure 19.1. This alarm sounded during multiple nuisance exposures but does not show evidence of enhanced soot deposition.

Figure 19.3 This figure shows the exterior cover of an FACI alarm that sounded during multiple nuisance exposures.

Figure 19.4 This figure is a macroscopic view of the alarm horn openings of the alarm pictured in Figure 19.3. This alarm sounded during multiple nuisance exposures but does not show evidence of enhanced soot deposition.

Figure 19.5 This figure shows the exterior cover of an FGBI alarm that sounded during multiple nuisance exposures.

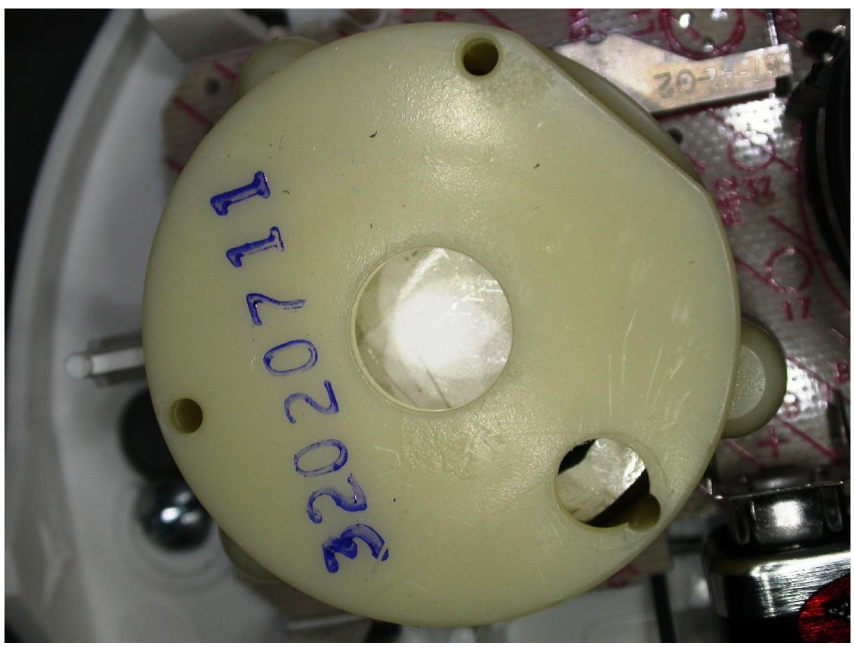

Figure 19.6 This figure is a macroscopic view of the alarm horn openings of the alarm pictured in Figure 19.5. This alarm sounded during multiple nuisance exposures but does not show evidence of enhanced soot deposition.

Figure 19.7 This figure shows the exterior cover of an FSBI alarm that sounded during multiple nuisance exposures.

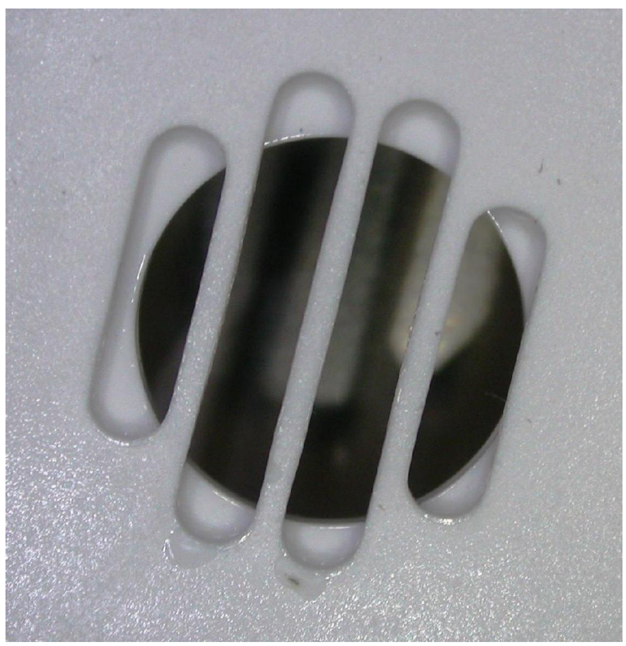

Figure 19.8 This figure is a macroscopic view of the alarm horn openings of the alarm pictured in Figure 19.8. This alarm sounded during multiple nuisance exposures but does not show evidence of enhanced soot deposition.

20 Appendix I: Sample Alarm Photos: Smoldering Cable Exposures

Figure 20.1 This figure shows the cover of an FBI alarm that sounded during exposure to a smoldering cable fire.

Figure 20.2 This is a macroscopic view of the alarm horn openings from the alarm pictured in Figure 20.1. This alarm sounded but does not show any evidence of enhanced soot deposition.

Figure 20.3 This figure shows the cover of an FACI alarm that sounded during exposure to a smoldering cable fire.

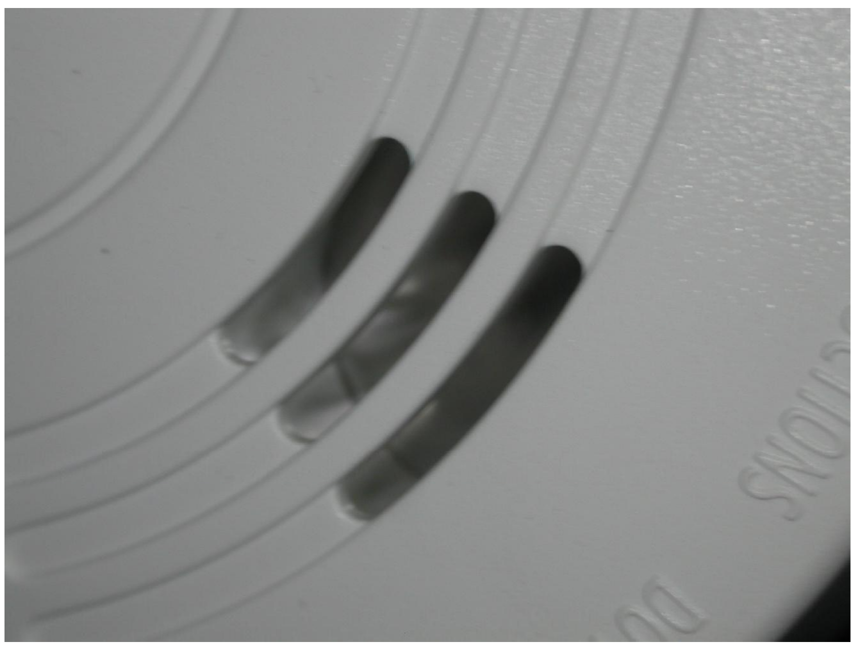

Figure 20.4 This is a macroscopic view of the alarm horn openings from the alarm pictured in Figure 20.3. This alarm sounded but does not show any evidence of enhanced soot deposition.

Figure 20.5 This figure shows the cover of an FGBI alarm that sounded during exposure to a smoldering cable fire.

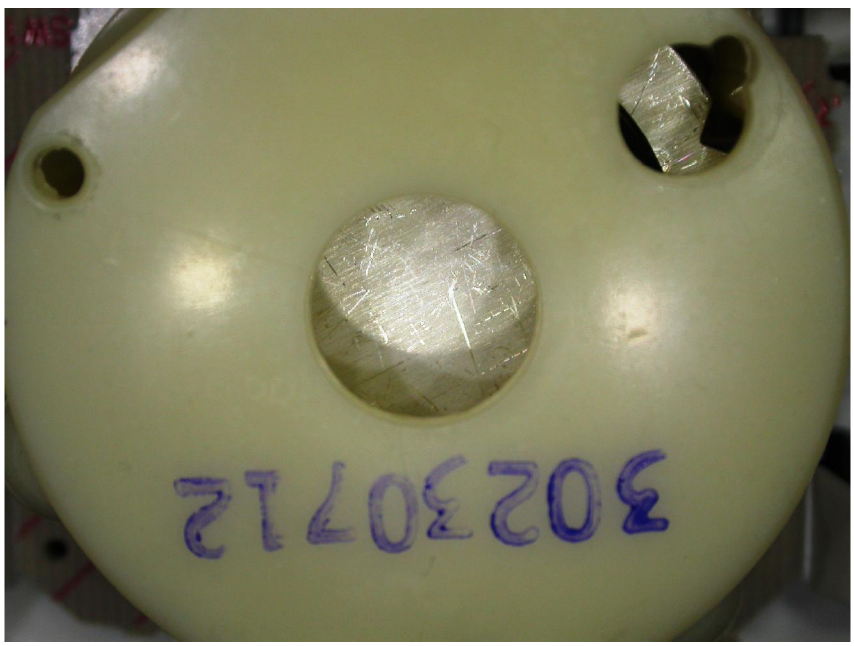

Figure 20.6 This is a macroscopic view of the alarm horn openings from the alarm pictured in Figure 20.5. This alarm sounded but does not show any evidence of enhanced soot deposition.

Figure 20.7 This figure shows the cover of an FSBI alarm that sounded during exposure to a smoldering cable fire.

Figure 20.8 This is a macroscopic view of the alarm horn openings from the alarm pictured in Figure 20.7. This alarm sounded but does not show any evidence of enhanced soot deposition.

21 Appendix J: Sample Alarm Photos: Flaming Box Filled with Cup Exposures

Figure 21.1This figure shows the exterior cover of an FBI alarm that sounded during exposure to a flaming box with cups fire. Enhanced soot deposition is visible around the horn openings.

Figure 21.2 This is a macroscopic view of the horn openings of the alarm in Figure 21.1. Enhanced soot deposition is apparent around each of the openings as evidence that the alarm sounded.

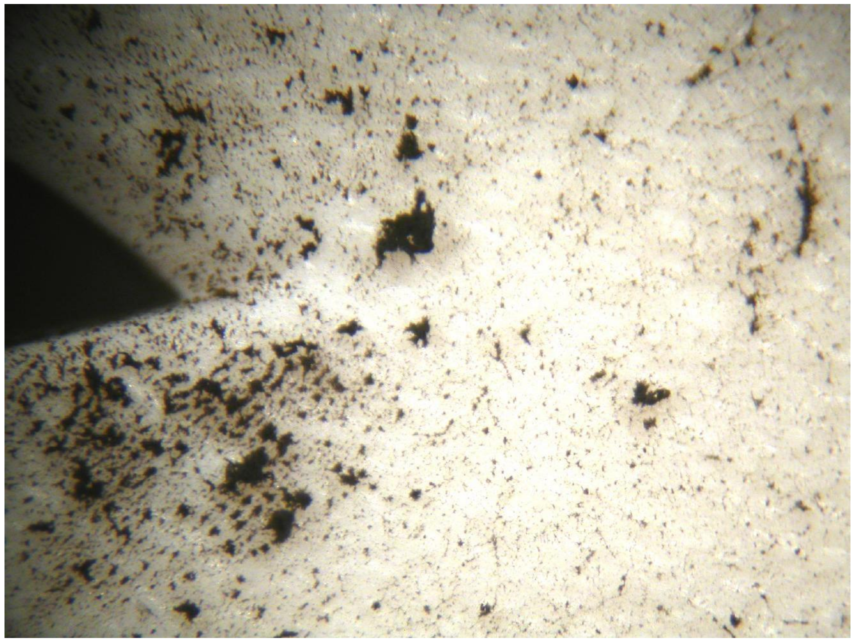

Figure 21.3 This is a microscopic view of the corner of one of the alarm horn openings from Figure 21.2. Enhanced soot deposition is evident from the larger soot agglomerates and higher deposition density near the opening.

Figure 21.4 This figure shows the ambient soot deposition on the exterior of the alarm cover taken at the same magnification as Figure 21.3. The deposition density and agglomerate size are much lower than those in the pattern of enhanced soot deposition.

Figure 21.5 This figure shows the interior face of the alarm horn opening pictured in Figures 21.1-21.4. There is evidence of enhanced soot deposition around the alarm horn openings, as the alarm sounded. Also of note is the soot deposited within the horn chamber is of equal or greater density than that outside the horn chamber.

Figure 21.6 This figure shows the exterior cover of an FBI alarm that did not sound during exposure to a flaming box with cups fire. Enhanced soot deposition is not visible around the horn openings.

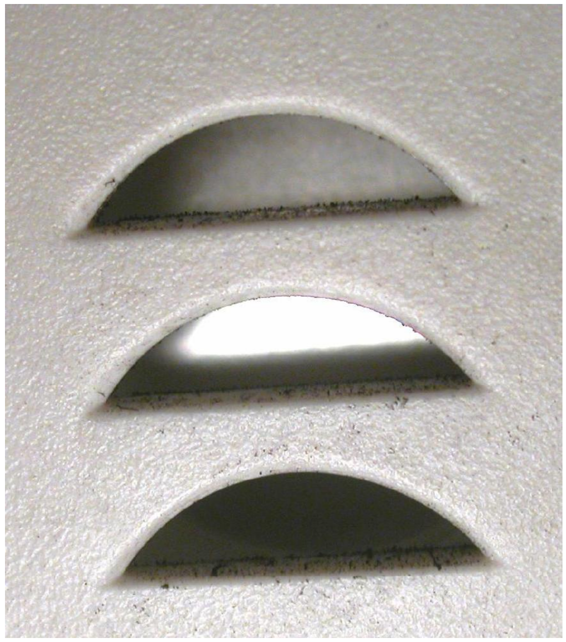

Figure 21.7 This is a macroscopic view of the horn openings from the alarm pictured in Figure 21.6. This alarm did not sound during the exposure but there is ambient soot deposition on the vertical face of the alarm.

Figure 21.8 This is a microscopic view of one of the alarm horn openings from Figure 21.7. This alarm did not sound and there is soot deposited around the horn opening, but no evidence of enhanced soot deposition.

Figure 21.9 This figure shows the exterior of the alarm cover of an FACI alarm that sounded during exposure to a flaming box with cups fire.

Figure 21.10 This is a macroscopic view of the horn openings from the alarm pictured in Figure 21.9. This alarm sounded during the exposure and shows some evidence of enhance soot deposition.

Figure 21.11 This is a macroscopic view of the interior face of the alarm pictured in Figures 21.9-21.10. This alarm sounded and shows evidence of enhanced soot deposition. Also of note, the deposition density inside the horn chamber is of equal or greater density than that outside the horn chamber.

Figure 21.12 This figure shows the exterior of the alarm cover of an alarm that did not sound during exposure to a flaming box with cups fire.

Figure 21.13 this is a macroscopic view of the horn openings from the alarm pictured in Figure 21.12. This alarm did not sound and does not show evidence of enhanced soot deposition.

Figure 21.14 This figure is a macroscopic view of the interior face of the horn openings of the alarm pictured in Figures 21.12-21.13. This alarm did not sound. The thin line of soot deposited around the horn openings is not characteristic of sounding. The soot is deposited on the edge between the vertical and internal faces of the alarm horn opening not on either face. Also evidence that the alarm did not sound is the lower density of soot deposited inside the horn chamber in comparison to outside the horn chamber.

Figure 21.15 This figure shows the external cover of an FGBI alarm that sounded during exposure to a flaming box with cups fire.

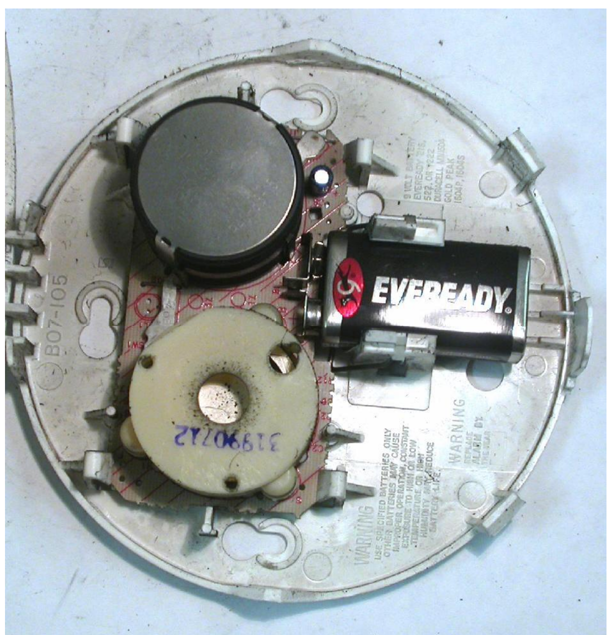

Figure 21.16 This figure shows the interior of the alarm pictured in Figure 20.15. Enhanced soot deposition around the horn opening is visible in this view.

Figure 21.17 This is a macroscopic view of the horn opening of the alarm pictured in Figures 21.15 and 21.16. Evidence of enhanced soot deposition indicates that the alarm sounded during the exposure.

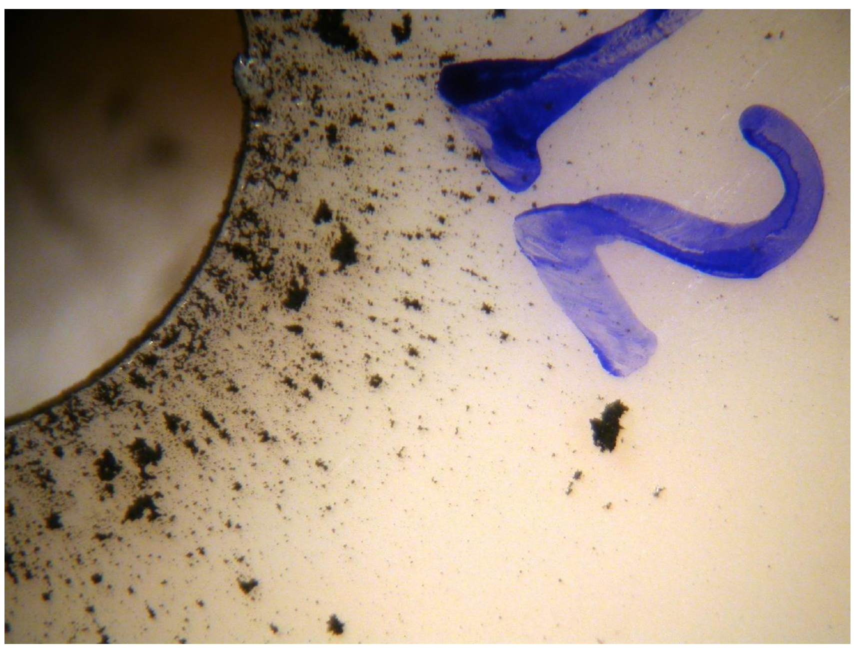

Figure 21.18 This is a microscopic view of the horn opening of the alarm from Figures 21.15-21.17. This alarm displays enhanced soot deposition indicative of sounding with larger agglomerates and higher density soot near the opening.

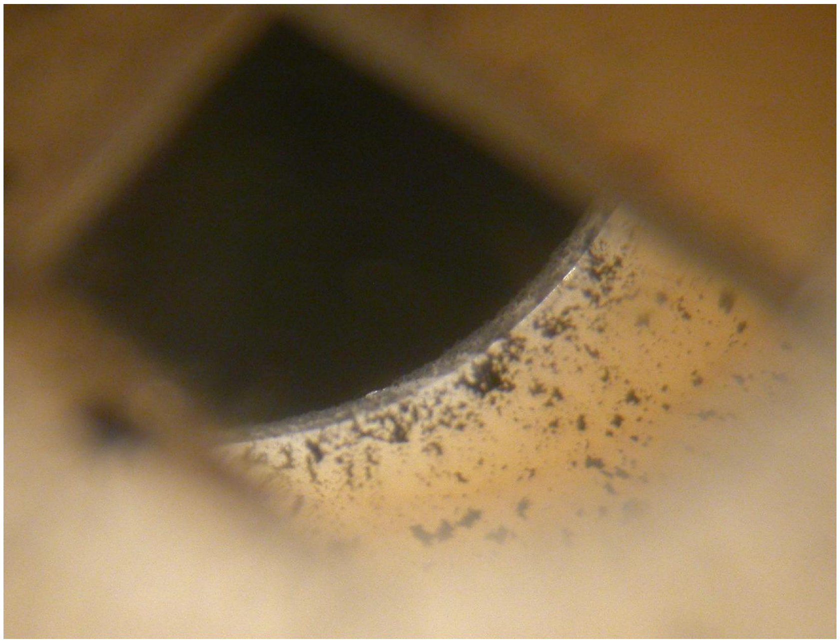

Figure 21.19 this is a microscopic view of the internal face of the alarm horn opening from the alarm in Figures 21.15-21.18. There is evidence of enhanced soot deposition as there was on the external face of the horn opening.

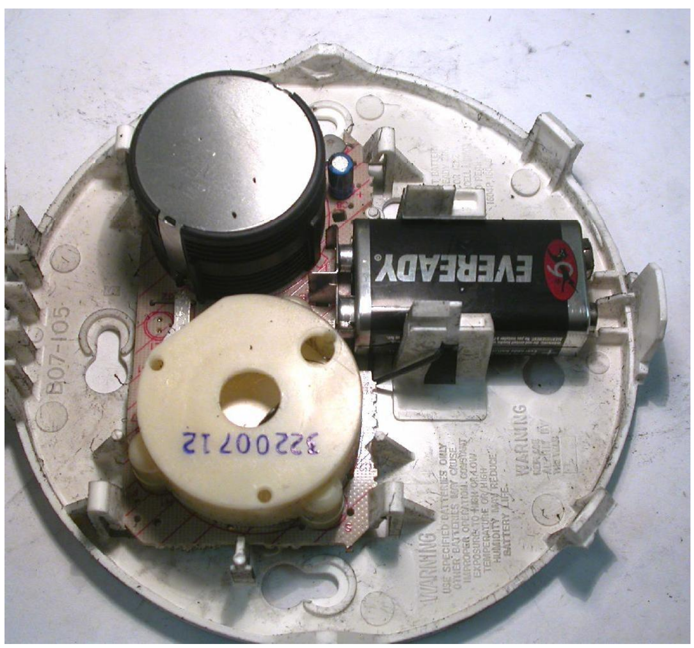

Figure 21.20 This figures shows the interior of an alarm that did not sound during exposure to the flaming box with cups fire.

Figure 21.21 This figure is a macroscopic view of the horn opening of the alarm from Figure 21.20. This alarm did not sound and does not show evidence of enhanced soot deposition.

Figure 21.22 This is a microscopic view of the horn opening pictured in Figures 21.20 and 21.21. this alarm did not sound and shows no evidence of enhanced soot deposition.

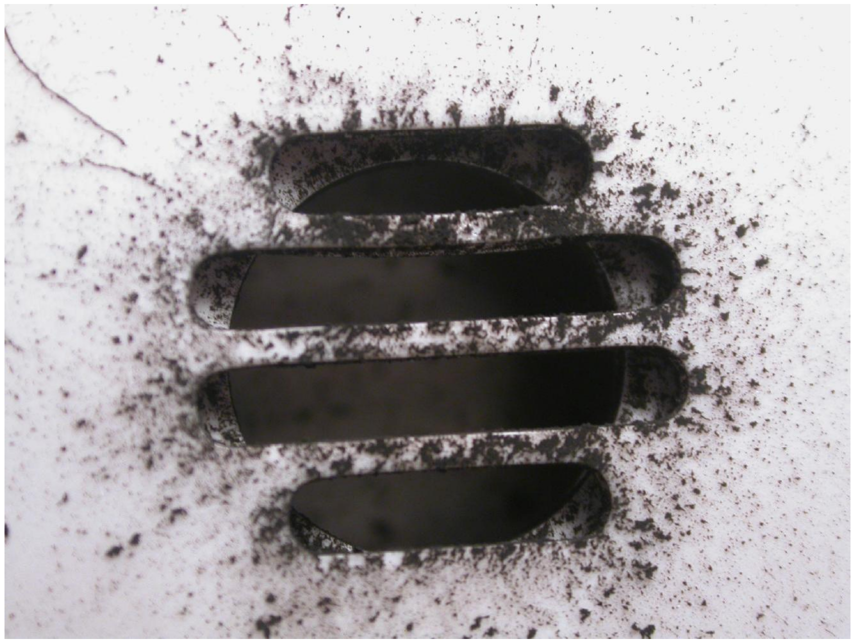

Figure 21.23 This figure shows a macroscopic view of an alarm horn opening of an FSBI alarm that sounded during exposure to a flaming box filled with cups. There is evidence of enhanced soot deposition with higher density and larger soot agglomerates around the openings.

Figure 21.24 This is a microscopic view of the alarm horn openings from Figure 21.23. This shows the high density of soot deposition and larger agglomerates closer to the horn openings.

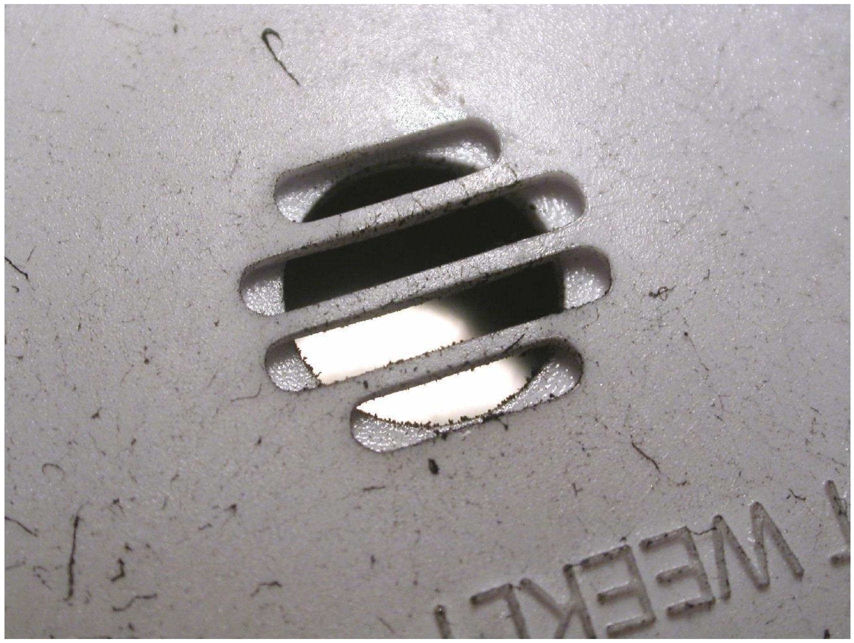

Figure 21.25 This is a macroscopic view of the alarm horn openings from an FSBI alarm that did not sound during exposure to a flaming box filled with cups. There is soot deposited around the horn openings of the same size and density as that deposited away from the horn openings.

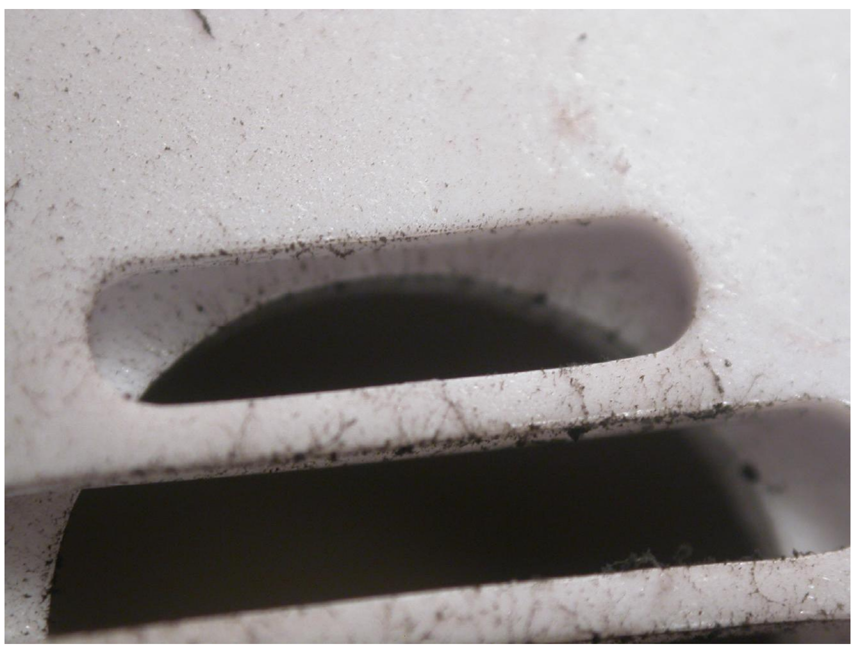

Figure 21.26 This is a microscopic view of the alarm horn openings from Figure 21.26. This alarm did not sounded shows soot deposition commensurate with exposure to a high soot yield fire, but not enhanced soot deposition indicative of sounding.

22 Appendix K: Sample Alarm Photos: Smoldering to Flaming Cabinet Exposures

Figure 22.1 This figure shows the external cover of an FBI alarm sounded during exposure to the smoldering to flaming cabinet assembly.

Figure 22.2 This figure shows a macroscopic view of the horn openings from the alarm in Figure 22.1. This alarm sounded but shows only the slightest evidence of enhanced deposition at the corner of the upper right horn opening.

Figure 22.3 This is a macroscopic view of the internal face of the horn openings of the alarm pictured in Figures 22.1 and 22.2. There is evidence of enhanced deposition along the flat edges and corners of the horn openings.

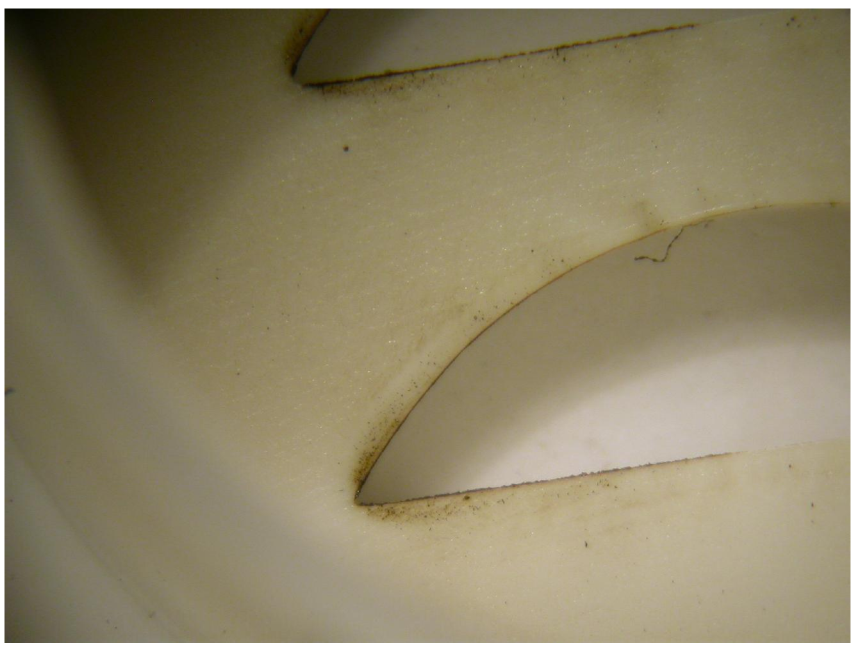

Figure 22.4 This is a microscopic view of one of the alarm horn openings from Figure 22.3. There is evidence of enhanced deposition consistent with the tarry deposition indicative of alarm sounding.

Figure 22.5 This figure shows the alarm cover of an FBI alarm that did not sound during exposure to the smoldering to flaming cabinet assembly.

Figure 22.6 This is a macroscopic view of the alarm horn openings from the alarm pictured in figure 22.5. This alarm did not sound during the exposure and shows no evidence of enhanced deposition.

Figure 22.7 This figure shows a macroscopic view of the internal face of the alarm horn openings from Figures 22.5 and 22.6. There is no evidence of enhanced deposition consistent with the fact that the alarm did not sound.

Figure 22.8 This figure shows the external cover of an FACI alarm sounded during exposure to the smoldering to flaming cabinet assembly.

Figure 22.9 This figure shows a macroscopic view of the horn openings from the alarm in Figure 22.8. This alarm sounded but shows only the slightest evidence of enhanced deposition.

Figure 22.10 This figure shows a macroscopic view of the vertical faces of the horn openings of the alarm pictured in Figures 22.8 and 22.9. There is evidence of enhanced depositions on all three of the vertical faces pictured.

Figure 22.11 This is a macroscopic view of the internal faces of the alarm horn openings from Figures 22.8-22.10. There is evidence of enhanced deposition around all three of the horn openings that was not apparent around the external faces.

Figure 22.12 This figure shows the external cover of an FACI alarm that did not sound during exposure to the smoldering to flaming cabinet assembly.

Figure 22.13 This figure shows a macroscopic view of the horn openings from Figure 22.12. This alarm did not sound and does not show any evidence of enhanced depositions.

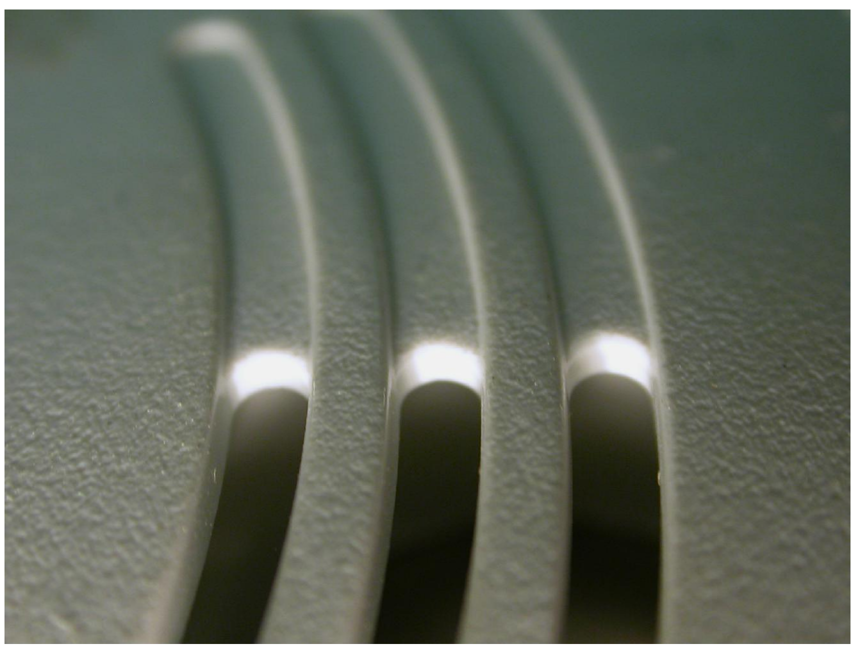

Figure 22.14 This figure is a macroscopic view of the horn openings from Figure 22.13. The alarm did not sound during the exposure and shows no evidence of enhanced deposition on the vertical faces.

Figure 22.15 This is a macroscopic view of the internal faces of the alarm horn openings from Figures 22.12-22.14. There is no evidence of enhanced deposition consistent with the fact that the alarm did not sound.

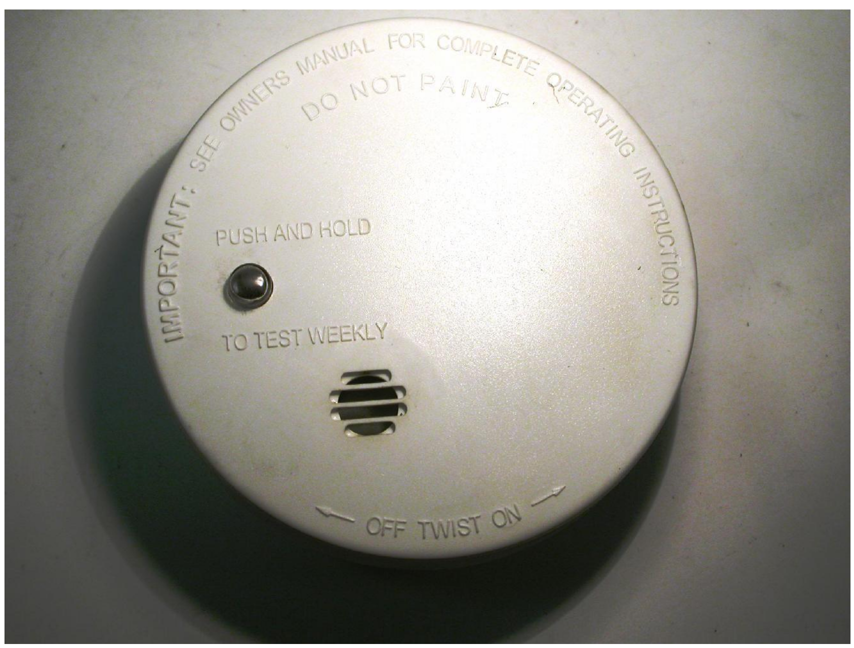

Figure 22.16 This figure shows the external cover of an FSBI alarm that sounded during exposure to the smoldering to flaming cabinet assembly.

Figure 22.17 This figure shows a macroscopic view of the horn openings from Figure 22.16. (Compare to Figures 20.20 and 20.25)

Figure 22.18 This figure shows the vertical faces of the alarm from Figure 22.17. There are spots of enhanced depositions consistent with the fact that the alarm sounded.

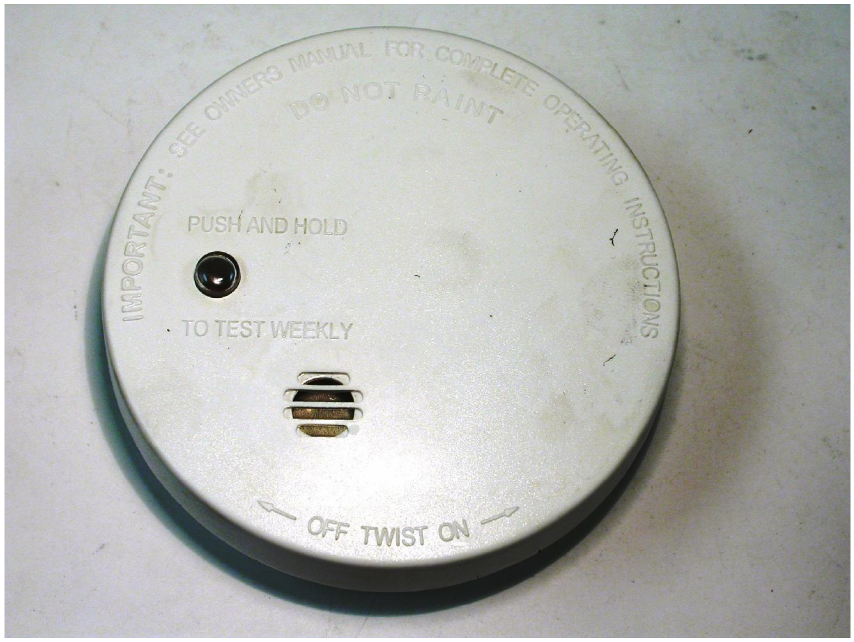

Figure 22.19 This figure shows the external cover of an FSBI alarm that did not sound during exposure to the smoldering to flaming cabinet assembly.

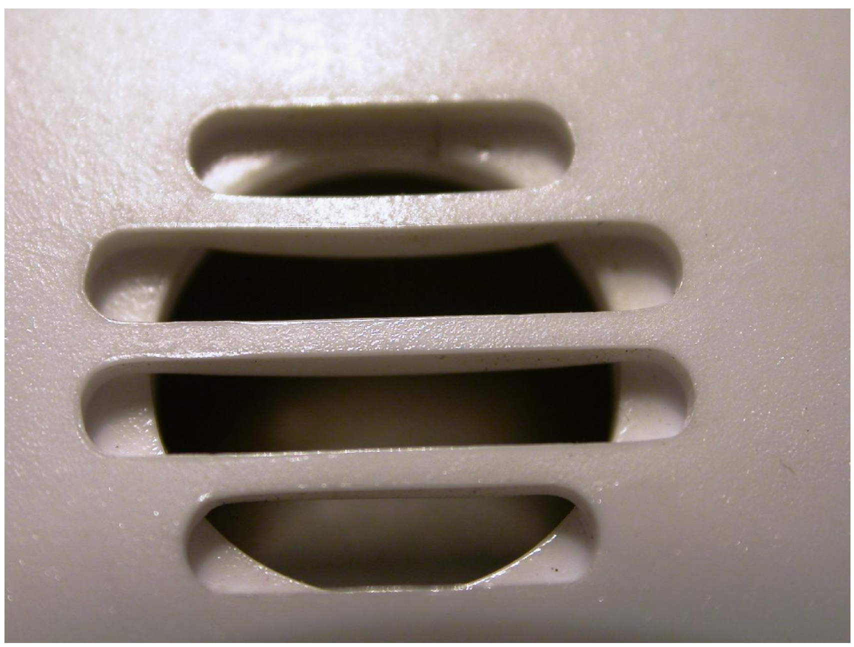

Figure 22.20 This figure shows a macroscopic view of the horn openings from Figure 22.19. This alarm did not sound and does not show any evidence of enhanced depositions.

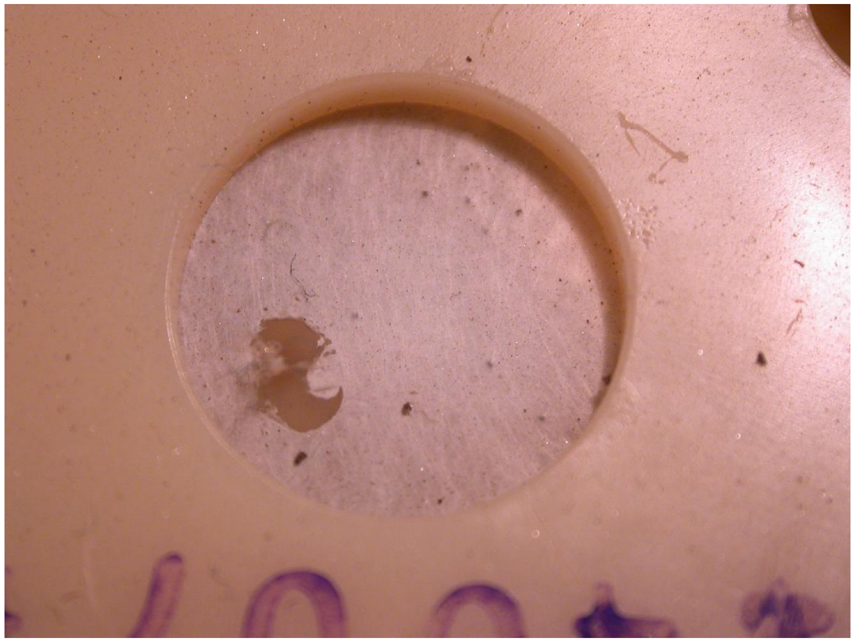

Figure 22.21 This figure shows a macroscopic view of the horn opening of a used alarm. The alarm horn was covered by a cocoon that had a hole in it. This picture is prior to exposure to the smoldering to flaming cabinet assembly fire.

Figure 22.22 This figure shows the alarm from Figure 22.21 post-test. This alarm sounded during the exposure and shows evidence of enhanced depositions around the improvised horn opening in the cocoon.

23 Appendix L: Sample Alarm Photos: Flaming Couch Exposures

Figure 23.1 Macroscopic view of the external face of the alarm horn openings of an alarm that sounded during exposure to a flaming couch. Enhanced soot deposition is apparent on the flat edges of the moon-shapes.

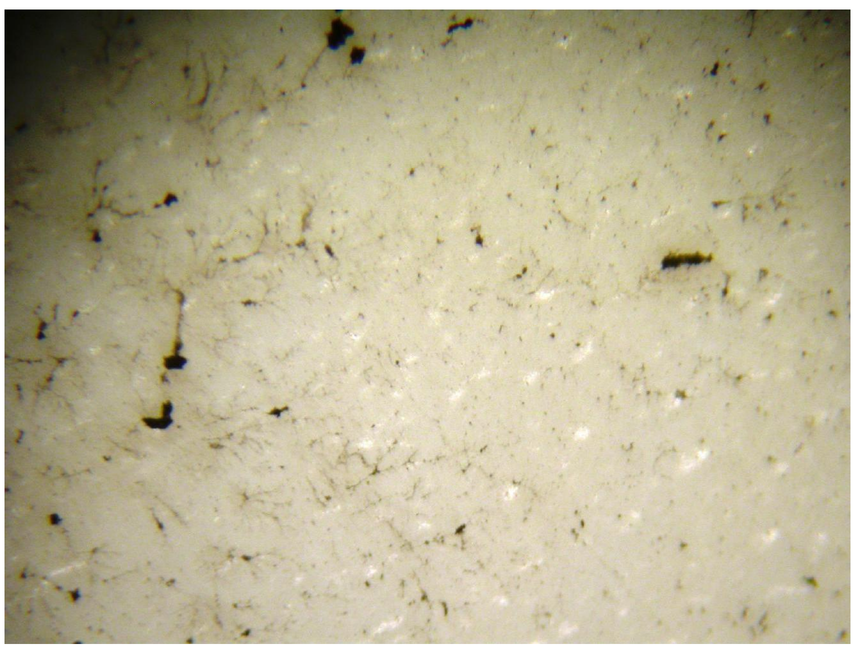

Figure 23.2 This figure shows the ambient soot deposited on the cover of the alarm from Figure 23.1. This soot is lees dense than that in enhanced depositions.

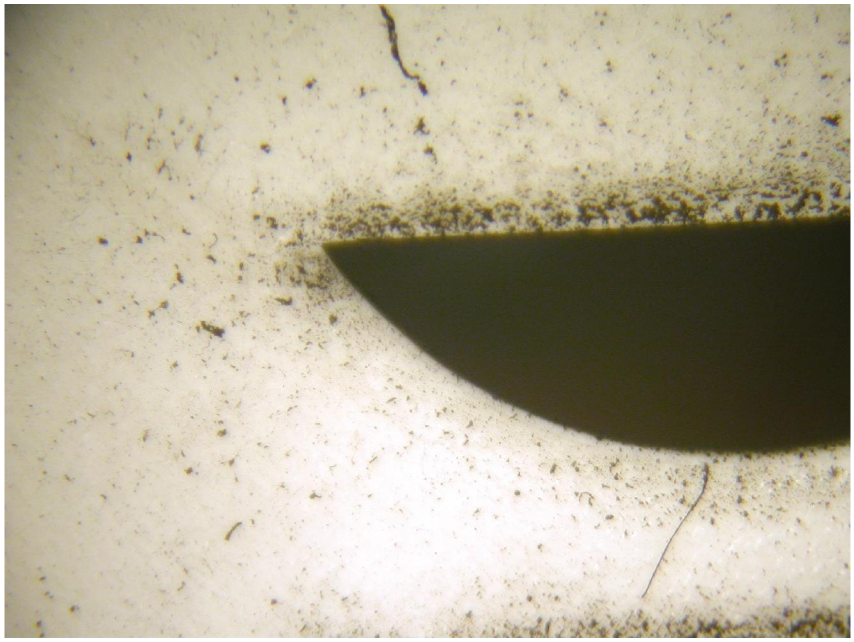

Figure 23.3 This is a microscopic view of the corner of the alarm horn opening from Figure 23.2. The enhanced soot deposition is distinctly apparent in this view.

Figure 23.4 This is a macroscopic view of the interior face of the alarm horn opening from Figures 23.1-23.3. The enhanced soot deposition is more developed on the interior face than the exterior face.

Figure 23.5 This is the external cover of an FBI alarm that did not sound during exposure to the flaming couch.

Figure 23.6 This is a macroscopic view of the interior face of the horn openings of the alarm from Figure 23.5. This alarm did not sound and there is no enhanced soot deposition indicative of sounding. Although there is some soot deposition on the edges the soot deposition density inside the horn chamber is less dense than that deposited outside the horn chamber.

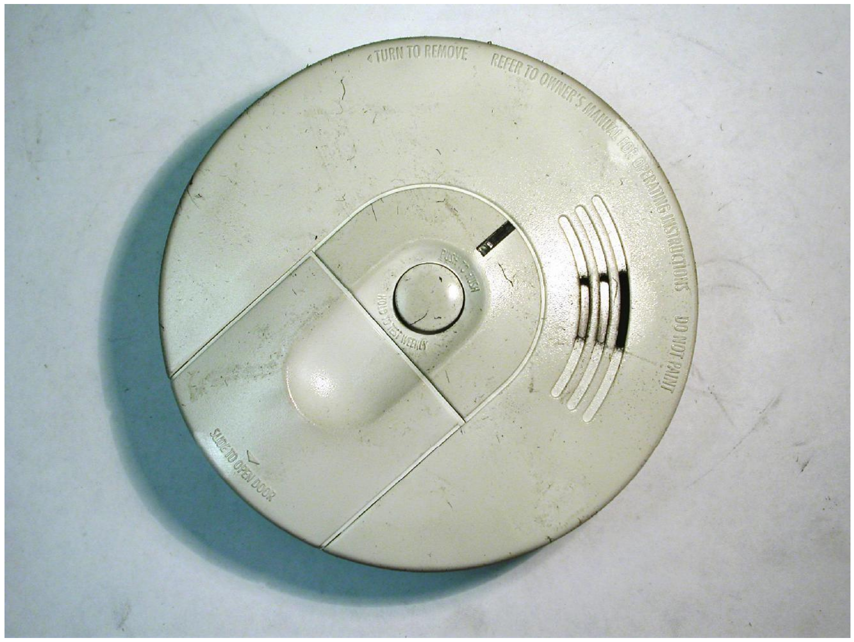

Figure 23.7 This figure shows the external cover of an FACI alarm that sounded during exposure to the flaming couch section.

Figure 23.8 This is a macroscopic view of the horn openings from the alarm in Figure 23.7. Enhanced deposition is apparent around portions of all of the horn openings.

Figure 23.9 This figure shows the internal face of the alarm horn openings from Figure 23.8. The enhanced soot deposition is more developed on the internal face than the external face, evidence of the alarm sounding. There is also more soot deposited inside the horn chamber than outside.

Figure 23.10 This is the external cover of an FACI alarm that did not sound during exposure to the flaming couch fire.

Figure 23.11 This is a macroscopic view of the horn openings from the alarm in Figure 23.10. This alarm did not sound and does not show any enhanced soot deposition.

Figure 23.12 This is a macroscopic view of the horn openings from Figures 23.9-23.10. This alarm did not sound during the exposure and does not show evidence of enhanced deposition. The soot deposited on the internal face of the alarm is similar in density inside and outside horn chamber on the same face.

Figure 23.13 This figure shows the external cover of the an FGBI alarm that sounded during exposure to the flaming couch section. The alarm cover was distorted by the elevated temperatures of the upper layer.

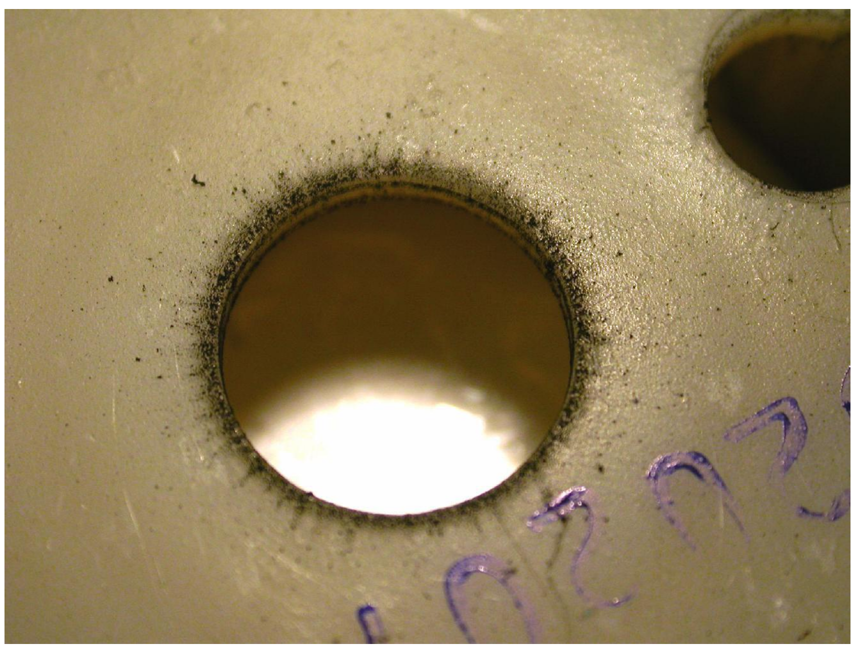

Figure 23.14 This figure is a macroscopic view of the horn opening of the alarm pictured in Figure 23.13. The horn opening has enhanced soot depositions encircling the opening as evidence of the alarm sounding.

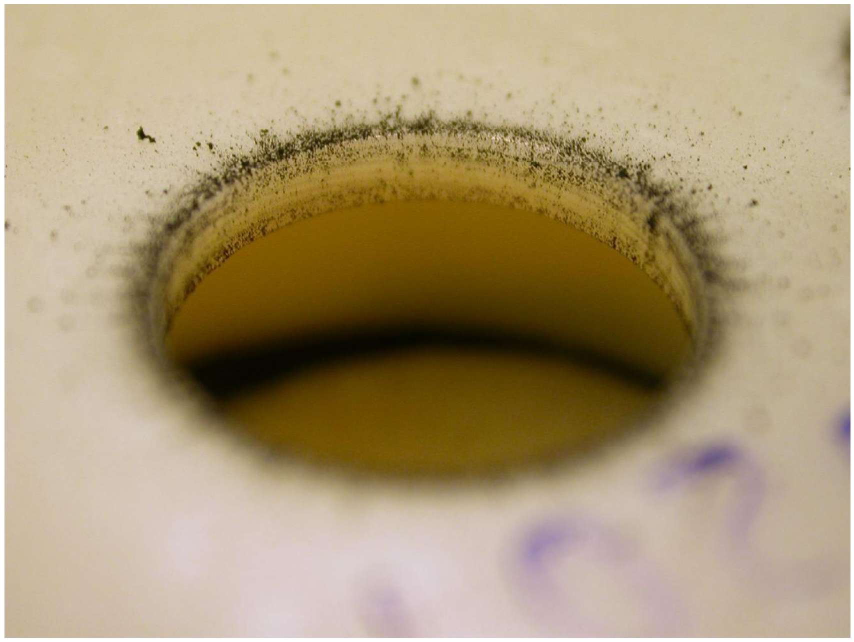

Figure 23.15 This figure is a macroscopic view of the vertical face of the alarm horn opening from Figure 23.14. There are two bands of enhanced soot deposited proximate to the internal and external faces of the alarm horn openings, further evidence of alarm sounding.

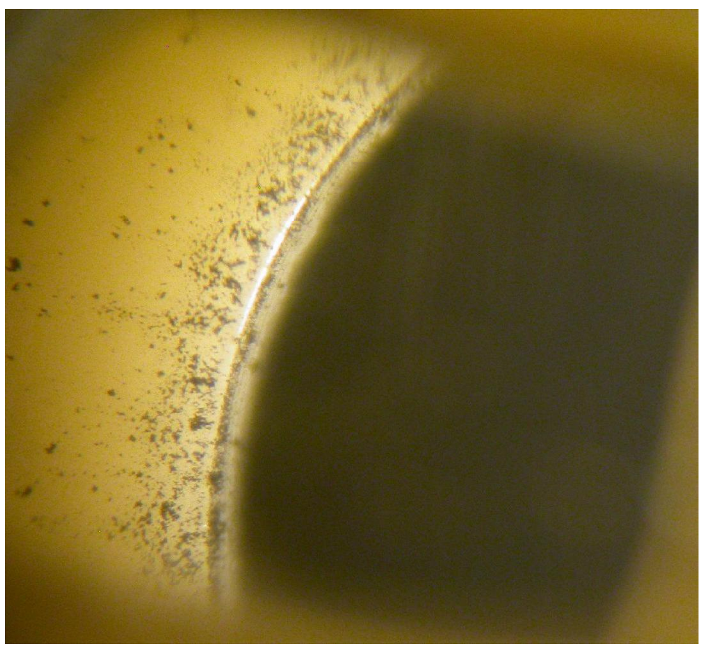

Figure 23.16 This is a microscopic view of the internal face of the alarm horn opening form the alarm in Figures 23.13-23.15. The enhanced soot deposition visible is evidence of the alarm sounding.

Figure 23.17 This is the external cover of an FGBI alarm did not sound during exposure to the flaming couch fire. The cover was distorted by the elevated temperatures of the upper layer.

Figure 23.18 This is a macroscopic view of the alarm horn opening of the alarm in Figure 23.17. There is no enhanced deposition visible on this horn, consistent with it not sounding.

Figure 23.19 This figure shows and FSBI alarm that sounded during exposure to the flaming couch fire. Enhanced deposition indicative of alarm sounding is visible in around the horn openings.

Figure 23.20 This is a macroscopic view of the horn openings of the alarm in Figure 23.19. The alarm sounded during the fire exposure which is indicated through the enhanced soot deposition around the horn openings.

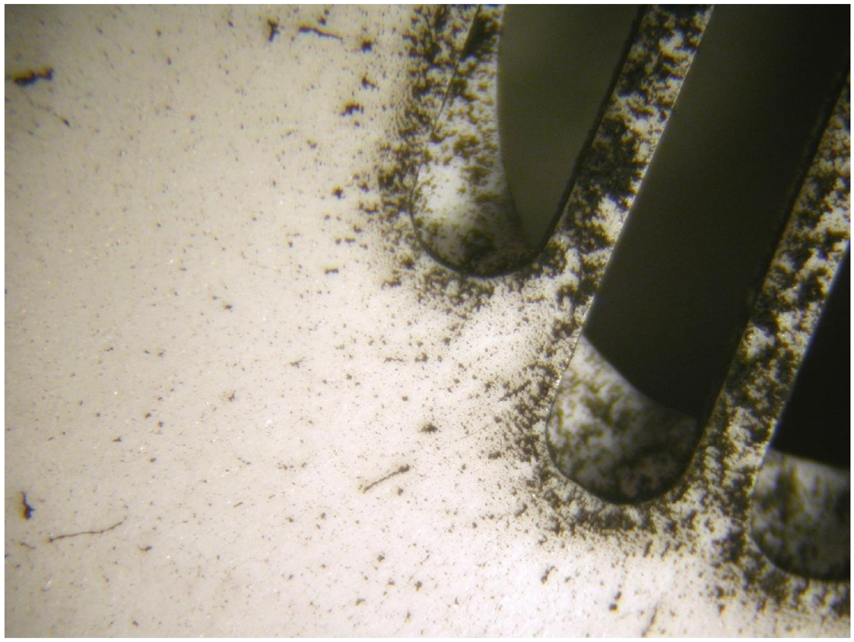

Figure 23.21 This is a microscopic view of the horn openings from Figure 23.20. The enhanced soot deposition, indicative of alarm sounding, is evident from the higher density and larger agglomerates proximate to the horn openings.

Figure 23.22 This figure shows the cover of an FSBI alarm that did not sound during exposure to the flaming couch. The cover has soot deposited consistent with a high soot yield fire, but no signs of enhanced deposition.

Figure 23.23 This is a macroscopic view of the horn openings of the alarm from Figure 23.22. This alarm did not sound and does not have enhanced deposition.

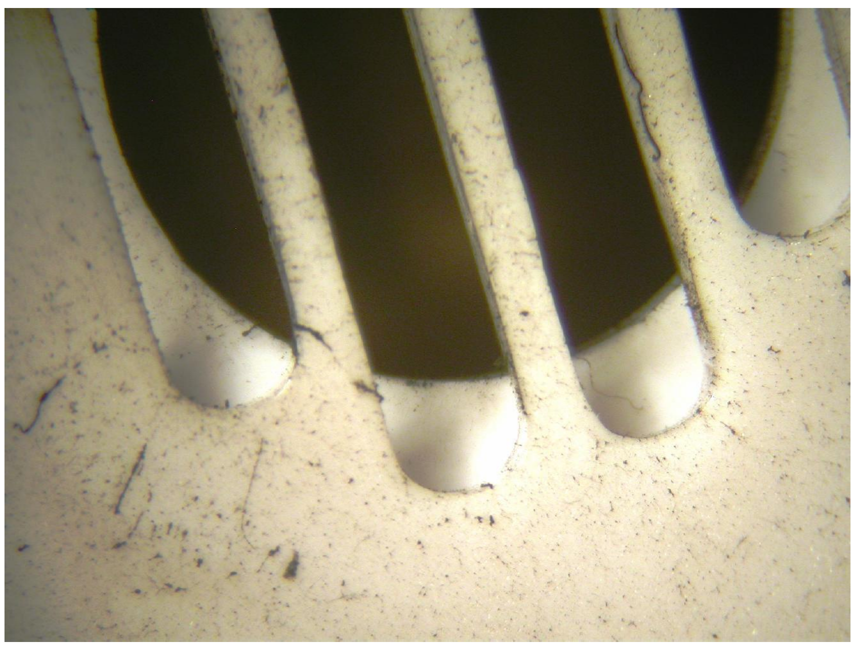

Figure 23.24 This is a microscopic view of the horn openings of the alarm from Figure 23.23. The alarm did not sound and the soot deposition is commensurate with exposure to a high soot yield fire, but not enhanced deposition indicative of alarm.

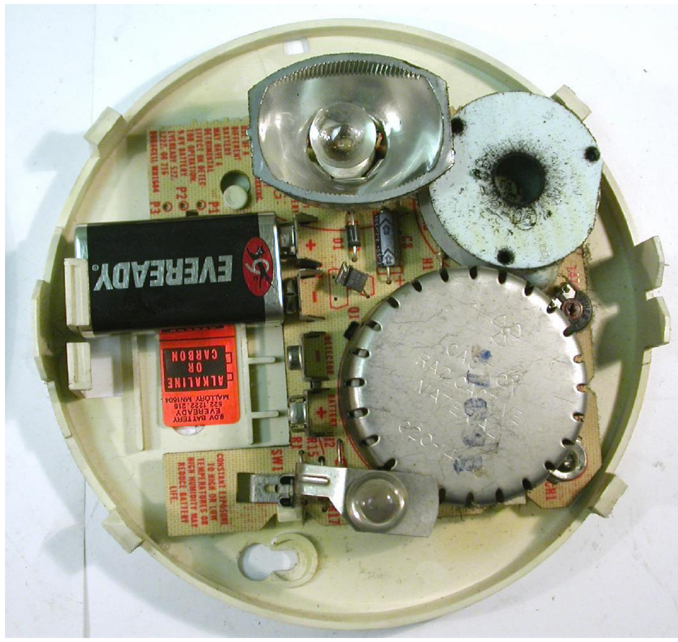

Figure 23.25 This figure shows the interior of a used alarm exposed to the flaming couch section. This alarm sounded and shows enhanced soot deposition around the horn opening.