IN THE UNITED STATES DISTRICT COURT
EASTERN DISTRICT OF ARKANSAS
WESTERN DIVISION

FURLANDARE SINGLETON, *et al*. **PLAINTIFFS**

v. **Case No. 4:15-cv-205-KGB**

ARKANSAS HOUSING AUTHORITIES PROPERTY & CASUALTY SELF-INSURED FUND, INC., *et al*. **DEFENDANTS**

ORDER

Before the Court is plaintiff Marilyn Beavers' motion to strike affidavit of Daniel Gottuk and to exclude his testimony in this matter (Dkt. No. 106). Defendants Arkansas Housing Authorities Property & Casualty Self-Insured Fund, Inc., Evanston Insurance Company, and Phil Nix (collectively, "Housing Authority Defendants"), and separate defendant BRK Brands, Inc. ("BRK"), filed responses in opposition to Ms. Beavers' motion to strike (Dkt. Nos. 113; 112). Ms. Beavers replied to these responses (Dkt. No. 115). For the following reasons, the Court denies Ms. Beavers' motion to strike (Dkt. No. 106).

I. Background

The Housing Authority defendants and BRK have filed separate motions for summary judgment (Dkt. Nos. 56; 88). Both rely on an affidavit provided by Daniel Gottuk, who states that, in his expert opinion, the smoke alarm in Ms. Beavers' apartment sounded on the night of the fire that gave rise to this action (Dkt. No. 56-2, ¶ 13; Dkt. No. 88-1, ¶ 13). Dr. Gottuk used enhanced soot deposition ("ESD") methodology to reach this conclusion (Dkt. No. 56-2, ¶ 9; Dkt. No. 88-1, ¶ 9).

Ms. Beavers moves to strike Dr. Gottuk's affidavit and to exclude Dr. Gottuk from offering expert testimony in this action (Dkt. No. 106, at 2). She argues that "the methods used by [Dr.]

Gottuk fail to meet the reliability requirements for expert testimony" (Dkt. No. 107, at 3). In support of this argument, Ms. Beavers provides the affidavit of B. Don Russell (Dkt. No. 106-2).[1] Ms. Beavers contends that Dr. Russell's affidavit "demonstrates that the method upon which [Dr.] Gottuk bases his opinions face multiple reliability issues which warrant exclusion of [Dr.] Gottuk's opinions" (Dkt. No. 107, at 7).

II. Discussion

Ms. Beavers' motion to strike is a *Daubert* motion. *See Daubert v. Merrell Dow Pharm., Inc.*, 509 U.S. 579 (1993). The Court will analyze it as one. The "[a]dmissibility of expert testimony is governed by Federal Rules of Evidence 702 and 703." *Johnson v. Mead Johnson & Co., LLC*, 754 F.3d 557, 561 (8th Cir. 2014). Ms. Beavers moves to exclude Dr. Gottuk's testimony pursuant to Rule 702 (Dkt. No. 107, at 3-4). Under Rule 702, the Court is responsible for screening expert testimony to ensure that it "rests on a reliable foundation and is relevant to the task at hand." *Daubert*, 509 U.S. at 597. "'Rule 702 reflects an attempt to liberalize the rules governing the admission of expert testimony. The rule clearly is one of admissibility rather than exclusion.'" *Sappington v. Skyjack, Inc.*, 512 F.3d 440, 448 (8th Cir. 2008) (quoting *Lauzon v. Senco Prods., Inc.*, 270 F.3d 681, 686 (8th Cir. 2001)).

Courts use a three-part test to screen expert testimony under Rule 702:

> First, evidence based on scientific, technical, or other specialized knowledge must be useful to the finder of fact in deciding the ultimate issue of fact. This is the basic rule of relevancy. Second, the proposed witness must be qualified to assist the finder of fact. Third, the proposed evidence must be reliable or trustworthy in an evidentiary sense, so that, if the finder of fact accepts it as true, it provides the assistance the finder of fact requires.

[1] Plaintiffs untimely disclosed Dr. Russell as an expert witness (Dkt. No. 176, at 4). However, by previous Order, the Court found that Dr. Russell should not be excluded as an expert witness, despite his untimely disclosure (*Id.*, at 9).

Johnson, 754 F.3d at 561 (quoting *Polski v. Quigley Corp.*, 538 F.3d 836, 839 (8th Cir. 2008)). Ms. Beavers argues that Dr. Gottuk's testimony in his affidavit fails to meet the third prong of this three-part test (Dkt. No. 107, at 5). She argues that "the method upon which [Dr.] Gottuk bases his opinions face[s] multiple reliability issues which warrant exclusion of [Dr.] Gottuk's opinions" (*Id.*, at 7).

Courts consider four non-exclusive factors in evaluating an expert witness's methodology: "'(1) whether the theory or technique can be (and has been) tested; (2) whether the theory or technique has been subjected to peer review and publication; (3) the known or potential rate of error; and (4) whether the theory has been generally accepted.'" *Shuck v. CNH Am., LLC*, 498 F.3d 868, 874 (8th Cir. 2007) (quoting *Peitzmeier v. Hennessy Indus., Inc.*, 97 F.3d 293, 297 (8th Cir. 1996)). In addition to these factors, courts "can weigh 'whether the expertise was developed for litigation or naturally flowed from the expert's research; whether the proposed expert ruled out other alternative explanations; and whether the proposed expert sufficiently connected the proposed testimony with the facts of the case.'" *Presley v. Lakewood Eng'g & Mfg. Co.*, 553 F.3d 638, 643 (8th Cir. 2009) (quoting *Sappington*, 512 F.3d at 449).

A. Whether ESD Can Be And Has Been Tested And Whether ESD Has Been Subjected To Peer Review And Publication

Relying on Dr. Russell's affidavit, Ms. Beavers argues that the "ESD method used by [Dr.] Gottuk fails to meet the testing requirement," because "[t]here has been little or no testing of the method by independent researchers" and "[t]he number of scientific experiments and tests that have been conducted on this method is extremely limited and have been primarily performed by a small group of researchers with vested and specific interest in the outcome of the tests" (Dkt. No. 107, at 8). Ms. Beavers also argues that "[t]here has been no publication of the data from a statistically significant number of full scale fire experiments conducted under a wide range of fire conditions analyzed and evaluated by independent researchers" (*Id.*). Ms. Beavers contends that ESD has not been subjected to peer review and publication because ESD "has not received widespread acceptance or use in the broader scientific community and is not governed by any standards that establish a use protocol" (Dkt. No. 107, at 9).

BRK and the Housing Authority defendants dispute Dr. Russell's claims that little to no testing has been done on ESD and that it has not been subjected to peer review and publication (Dkt. No. 112, at 3-7; Dkt. No. 113, at 9). In support of its argument, BRK attaches an affidavit from its independent expert, Lori Streit (Dkt. No. 112-1). In support of their argument, the Housing Authority defendants attach a supplemental affidavit from Dr. Gottuk (Dkt. No. 113-1).

Dr. Streit states that she participated in the "first study to apply the science of acoustic agglomeration to smoke alarms" (Dkt. No. 112, at 4). The results of this study, which involved mounting alarms for testing in a full-scale house fire, were presented and published in the Proceedings of the Fire Suppression and Detection Research Application Symposium at the Fire Protection Research Foundation annual meeting in January of 2001 (*Id.*; Dkt. No. 112-1, at 2-3). The study "was the winner of the William M. Carey Award in recognition of the best paper presented at the meeting" (Dkt. No. 112, at 4). The paper subsequently "passed a rigorous peer review process and was published in Fire Technology[,] . . . the foremost refereed journal in the Fire Science field[,]" in 2001 (*Id.*; Dkt. No. 112-3).

According to Dr. Streit, "a second study was published the following year using 389 smoke alarms with different horn configurations exposed to an array of controlled UL fire test configurations" (Dkt. No. 112, at 4-5). Dr. Streit contends that the second study "resulted in a paper presented and published in the Proceedings of the Fire Suppression and Research Application Symposium at The Fire Protection Research Foundation Annual Meeting" in January of 2002 (*Id.*, at 5). Dr. Streit states that the second paper "was also subjected to and passed the peer review process and was published in Fire Technology . . . in 2003" (*Id.*; Dkt. No. 112-4).

Dr. Streit claims that she "personally examined over 400 smoke alarms for these studies" (Dkt. No. 112, at 5). She contends that the results of these tests are statistically significant, and she notes that the smoke alarms were tested "as part of a double blind study[] and the first set of tests were conducted in an actual full-scale house fire" (*Id.*).

Dr. Streit states that, subsequent to the publication of the two studies in which she participated, "the technique used to determine the presence of acoustic agglomeration was substantiated and verified by research that was authored by P. Kennedy, K. Kennedy and G. Gorbett[,]" who "combined the first two studies' data with theirs to create a larger database of tests" (*Id.*, at 5-6). The Investigative Institute published a paper presenting their findings in August of 2003 (*Id.*; Dkt. No. 112-5). Dr. Streit states that "another confirmation study of the acoustic agglomeration technique was performed as part of a Masters' Thesis concerning the validity of the ESD method for ascertaining whether a smoke alarm sounded during a fire" (Dkt. No. 112, at 6; Dkt. No. 112-6). She asserts that "[a]dditional research followed to ensure the validity of the ESD method was not limited to 'controlled' fire scenarios" (Dkt. No. 112, at 6). The study, which was authored by Dr. Gottuk and another individual, "found that following the ESD methodology resulted in 'a total of forty-seven alarms accurately identified as having either sounded or not sounded during exposures to enclosure fire conditions'" (*Id.*; Dkt. No. 112-7). The study concluded that, "'based upon these results and those of the previous studies, it is apparent that [ESD] provides a valid methodology for evaluating soot deposition around smoke alarm horn openings as an indication as to whether o not the devise sounded during a fire'" (Dkt. No. 112, at 6).

In his supplemental affidavit, Dr. Gottuk states that, in addition to his own testing on ESD, "the methodology has been tested and validated by multiple scientists (Worrell 2001, Worrell 2003, Phelan 2004, Kennedy 2004, Mealy 2008, Mealy 2011, Woycheese 2006) and evaluated and accepted by the forensic community" (Dkt. No. 113-1, at 3). He notes that the studies on ESD "have been performed by at least four independent organizations and have included multiple faculty members at leading fire science universities, that is, University of Maryland, Worcester Polytechnic Institute and University of Edinburgh" (*Id.*). He states that "[p]ublications on ESD have appeared in at least three separate papers in a leading fire science peer-reviewed journal (Fire Technology) and presented in a range of venues, including Interflam, the International Symposium on Fire Investigations, NFPA 921 Technical Committee, and as a master's thesis at Worcester Polytechnic Institute" (*Id.*, at 3-4).

After reviewing the record materials submitted by BRK and the Housing Authority defendants, the Court rejects Ms. Beavers' claim that ESD has not been sufficiently tested or subjected to peer review and publication. The Court finds that both the testing and peer review factors weigh against excluding consideration of Dr. Gottuk's affidavit.

B. Rate Of Error

Ms. Beavers does not address whether the known or potential rate of error of ESD weighs in favor or against the exclusion of Dr. Gottuk's affidavit. In their response to Ms. Beavers' motion to strike, the Housing Authority defendants argue that this factor weighs against excluding Dr. Gottuk's affidavit (Dkt. No. 113, at 10-11). They note that "BRK's expert Streit, in a blind study, personally examined over 400 smoke alarms without knowing which alarms had activated and was able to identify, for those alarms in which there was sufficient soot to create a distinct pattern, the alarms that had activated with 100% accuracy" (*Id.*, at 10). They also contend that:

> [Dr.] Gottuk conducted a statistical analysis to the available data regarding ESD methodology applied to smoke alarms. The resulting analysis, using a Bayesian method, shows that ESD can correctly identify whether a smoke detector activated with a 99.6% confidence level. Similarly, ESD can be used to determine that a smoke detector failed to activate with 99.5% accuracy.

(*Id.*, at 10-11; Dkt. No. 113-1, at 6). Based on the record evidence, the Court finds that the rate of error factor weighs against excluding consideration of Dr. Gottuk's affidavit.

C. General Acceptance

Ms. Beavers argues that "Dr. Russell's Affidavit demonstrates that the ESD method used by [Dr.] Gottuk has not received widespread acceptance or use in the broader scientific community and is not governed by any standards that establish a use protocol" (Dkt. No.107, at 10). In his affidavit, Dr. Russell specifically claims that ESD "has not received widespread acceptance or use in the broader scientific community and is not governed by any standards that establish a use protocol" (Dkt. No. 106-2, at 2).

In response, BRK and the Housing Authority defendants argue that ESD is generally accepted as a reliable methodology as evidenced by the fact that, "beginning in 2011, the National Fire Protection Agency ('NFPA') incorporated ESD into the national industry standard for fire investigations, known as NFPA 921" (Dkt. No. 112, at 6-7; Dkt. No. 113, at 11). The Housing Authority defendants argue that "NFPA 921 is recognized as an authoritative reference for fire investigators" and "the Eighth Circuit has held that NFPA 921 'qualifies as a reliable method endorsed by a professional organization' for purposes of *Daubert*'" (Dkt. No. 113, at 11) (quoting *Fireman's Fund Ins. Co v. Canon U.S.A.*, 394 F.3d 1054, 1058-59 (8th Cir. 2005)).

BRK and the Housing Authority defendants also note that the:

> NFPA specifically rejected Russell's effort to keep ESD from inclusion in NFPA 921. In 2010, Russell argued to the NFPA that ESD was still a hypothesis and could not be scientifically validated. The NFPA Committee rejected Russell's proposal and issued the following statement: "The use of acoustic soot agglomeration for the determination of smoke detector activation is supported in the scientific literature, as referenced in the original proposal."

(*Id.*, at 12; Dkt. No. 112, at 7; Dkt. No. 112-10).

Dr. Russell provides no specific facts to support his conclusory assertion that ESD has not been generally accepted as a reliable methodology. The inclusion of ESD in NFPA 921 indicates that ESD has been generally accepted as a reliable method. *See Fireman's Fund*, 394 F.3d at 1057–58 ("[NFPA 921 qualifies as a reliable method endorsed by a professional organization."). Therefore, the Court finds that the general acceptance factor weighs against excluding consideration of Dr. Gottuk's affidavit.

D. Other Factors

Ms. Beavers argues that two other factors weigh in favor of excluding Dr. Gottuk's affidavit. In determining whether an expert witness's methodology is reliable, courts can consider "whether the expertise was developed for litigation or naturally flowed from the expert's research." *Presley*, 553 F.3d at 643 (internal quotation marks omitted). Ms. Beavers argues that this factor weighs in favor of excluding Dr. Gottuk's affidavit because:

> The development of the ESD method does not appear to be a result of [Dr.] Gottuk's own research, independent of litigation. . . . From reading [Dr.] Gottuk's Affidavit, it appears that he merely used the ESD theory developed by others, and attempts to apply it to the circumstances of the current case to provide an opinion that the smoke alarm sounded.

(Dkt. No. 107, at 11).

In his original affidavit, Dr. Gottuk states that he has "extensively studied smoke detectors and alarms and the presence or absence of enhanced soot deposition patterns on various alarms" and that, "[a]s a result of those examinations, there is an accepted methodology for determining whether a smoke alarm has sounded which is accepted by experts in the field" (Dkt. No. 56-2, at 3). Furthermore, Dr. Gottuk was involved in at least one of the studies provided by BRK as an attachment to its response to Ms. Beavers' motion to strike (Dkt. No. 112-7). That study was prepared independent of this action. The Court rejects Ms. Beavers' argument that this factor weighs in favor of excluding Dr. Gottuk's affidavit. Conversely, this factor weighs against excluding his affidavit.

Ms. Beavers also argues that "the failure to rule out other possibilities in regards to [Dr.] Gottuk's ESD method-based conclusions is illustrative of the broader lack of reliability with this method" (Dkt. No. 107, at 12). Courts commonly consider whether a proposed expert is able "to rule out other possibilities" in determining whether an expert's opinion is admissible. *Lauzon*, 270 F.3d at 693. Ms. Beavers argues that this factor weighs in favor of excluding Dr. Gottuk's affidavit. She argues that "the soot deposits on a smoke detector horn cannot be uniquely linked to a specific fire[,]" meaning ESD cannot be used to determine if the subject smoke alarm sounded in the fire at issue in this case, as the soot deposits could be "latent and preexisting conditions which pre-dated the subject fire" (Dkt. No. 107, at 12).

In response, the Housing Authority defendants note that, "as a general proposition, [Mr.] Gottuk agrees with [Dr.] Russell that due to the persistence of ESD patterns, observing a distinct pattern alone may not suffice to support the conclusion that an alarm sounded during a particular fire" (Dkt. No. 113, at 12). However, they argue that "with additional information regarding case facts and timeline of events, the occurrence of the ESD can be made with certainty and correlated to a specific fire" (*Id.*) (internal quotation marks omitted). In his supplemental affidavit, Dr. Gottuk states:

> No evidence exists that this particular alarm had been in an earlier fire, period, much less an earlier fire resulting in smoke exposure significant enough to have caused the distinct ESD patterns I observed on the subject smoke alarm. Typical cooking and nuisance alarms have been shown to not produce ESD associated with a sounding alarm in response to a fire. (Phelan, 2004). Also, the tests cited above have shown that if a fire is not large enough or does not burn for a sufficient amount of time, distinct enhanced soot deposition will not occur. Thus, the technical literature demonstrates numerous cases in which smoke alarms have been exposed to fire, but the resulting smoke and soot was insufficient to leave a discernable pattern.
>
> Based on the ESD testing combined with inquiry into relevant historical facts, it is my scientific opinion that the prominent ESD patterns I observed on the subject smoke alarm could not have been caused by a prior fire. I also learned in my investigation that the subject smoke alarm had been inspected and tested within months of the subject fire and determined to be in good working order. Finally, circumstantial evidence suggesting the subject alarm had been knocked from its ceiling mount at some point during the fire also is consistent with the alarm having sounded during this fire.
>
> In conclusion, in the absence of any evidence whatsoever that would suggest that the subject smoke alarm had been previously exposed to another fire or soot sufficient to create distinct soot deposition patterns, it is my opinion, to a reasonable degree of scientific certainty, that the distinct soot deposition patterns I observed on the subject smoke alarm indicate that the alarm sounded in this fire.

(*Id.*, at 13-14; Dkt. No. 113-1, at 7-8). Based on this explanation, the Housing Authority defendants argue that Mr. "Gottuk's overall methodology is reliable because it was founded on a NFPA 921 approved scientific methodology and supplemented with an examination of relevant case evidence to exclude any other possible explanation for the distinct soot deposition patterns on the subject smoke alarm" (Dkt. No. 113, at 14).

While courts consider whether an expert is able "to rule out other possibilities" in determining whether the expert's opinion is admissible, the Eighth Circuit Court of Appeals has cautioned that "this requirement cannot be carried to a quixotic extreme." *Lauzon*, 270 F.3d at 693. After reviewing Dr. Gottuk's explanation of how he considered relevant historical facts in conjunction with the ESD methodology, the Court finds that this factor does not weigh in favor of excluding his affidavit.

Ms. Beavers also argues that Dr. Gottuk's affidavit should be excluded because ESD cannot show "whether the detector sounded in a timely or adequate way as to warn the residents sufficiently" (Dkt. No. 107, at 12). The Court finds that Dr. Gottuk affidavit should not be excluded on this basis. Plaintiffs claim that the subject smoke alarm "did not sound" after a fire ignited in Ms. Beavers' apartment (Dkt. No. 27, ¶ 36). The Court, in its gatekeeping function, finds that Dr. Gottuk's expert opinion is reliable and trustworthy as to that issue. The Court does not discount that, at a trial, the opinions expressed in his affidavit may be subject to vigorous cross examination, but that is not a basis to exclude his affidavit.

III. Conclusion

After weighing the relevant factors, the Court finds that ESD, and Dr. Gottuk's application of ESD in reaching his expert opinion in this action, is sufficiently reliable and trustworthy so as to pass the Court's gatekeeping function. Ms. Beavers' motion to strike affidavit of Daniel Gottuk and to exclude his testimony in this matter is denied (Dkt. No. 106).

So ordered this the 31st day of March, 2017.

Kristine G. Baker
United States District Judge

IN THE UNITED STATES DISTRICT COURT
EASTERN DISTRICT OF ARKANSAS
WESTERN DIVISION

FURLANDARE SINGLETON, Individually and as Administrator of the Estate of Dequan Singleton, Syndi Singleton, and Haylee Singleton, Decedents; and CLYDE HATCHETT, Individually, and as Administrator of the Estate of Emily Beavers, Deceased	:	Case No.: 4:15-CV-205-KGB
v.	:	
ARKANSAS HOUSING AUTHORITIES PROPERTY & CASUALTY SELF-INSURED FUND, INC., *et al.*	:	

MARILYN LOUISE BEAVERS, Individually, and as Administrator of the Estate of MARILYN BEAVERS, DECEASED	:	
v.	:	
ARKANSAS HOUSING AUTHORITIES PROPERTY & CASUALTY SELF-INSURED FUND, INC., *et al.*	:	

DEFENDANT, BRK BRANDS, INC.'S RESPONSE TO PLAINTIFF'S MOTION TO STRIKE THE AFFIDAVIT OF DANIEL GOTTUK AND TO EXCLUDE HIS TESTIMONY IN THIS MATTER

Defendant, BRK Brands, Inc. ("BRK"), by and through its attorneys, Wright, Lindsey & Jennings, LLP, and Cozen O'Connor, oppose Plaintiff's Motion to strike the affidavit of Daniel Gottuk and to exclude his testimony because Plaintiff's contention that the methodology was flawed is misinformed and without basis. The enhanced soot deposition ("ESD") methodology Gottuk followed to conclude that "there was a working smoke alarm that did sound at the time of the fire in this case" is scientifically valid, peer-reviewed, generally accepted and incorporated into the industry standard that governs fire investigations.

Plaintiff's position is supported only by the affidavit of a (previously undisclosed and entirely new) expert[1], who is not a fire scientist or fire protection engineer. B. Don Russell ("Russell") is an *electrical* engineer. Russell does not know and has never attempted to conduct an ESD or acoustic agglomeration analysis and does not know and has never attempted to come up with an alternative way of determining whether or when a smoke alarm sounded in response to a fire. His criticism that ESD analysis is unscientific and not generally accepted is misinformed and wrong.

ESD is not only the subject of several peer-reviewed scientifically valid and statistically significant studies, the National Fire Protection Agency ("NFPA"), comprised of industry experts, recognized its reliability and industry-wide acceptance by incorporating it into the national standard which governs fire investigations, NFPA 921. The NFPA is a global non-profit organization devoted to eliminating death, injury, property and economic loss due to fire and related hazards through the promulgation of consensus-based codes and standards. (Affidavit of Lori A. Streit, Ph.D. ("Streit Aff."), submitted in support hereof and attached as Exhibit A hereto at ¶ 22.) In fact, in 2010, the NFPA rejected similar contentions by Russell, concluding that ESD was accepted science. (Streit Aff. at ¶¶ 21-23.)

Unlike Russell, Dr. Gottuk is a fire protection engineer and fire scientist. Unlike Russell, Dr. Gottuk has conducted scientific and statistically significant research into ESD as a method for determining whether a smoke alarm sounded during a fire. Unlike Russell, Dr. Gottuk wrote and published a peer-reviewed article on the topic. Several other fire protection engineers and scientists similarly researched ESD and concur that it is a valid methodology for determining whether a smoke alarm sounded during a fire.

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[1] BRK opposes Plaintiff's Motion to extend the expert deadlines to permit the untimely disclosure of Dr. Russell. To the extent Plaintiff's motion is denied, as it should be, Plaintiff has positively no evidentiary support for moving to strike Dr. Gottuk.

Dr. Gottuk is not alone in his opinion that the smoke alarm sounded here. BRK's independent expert, Lori A. Streit, Ph.D., (the scientist and author or published and peer reviewed ESD scientific analyses) also inspected the smoke alarm at issue macroscopically and microscopically pursuant to the developed and generally accepted ESD methodology and agreed-upon inspection protocol using specialized instruments. Based on her training, extensive experience and observations, Dr. Streit concurs with Dr. Gottuk that the smoke alarm sounded during this fire. (Streit Aff. ¶ 23.)

The Plaintiff cannot exclude evidence just because it does not support her case. This is especially true when that evidence comports with Plaintiff's admission that the decedents were awake and aware of the fire, tried to extinguish it, and at some point, knocked the smoke alarm down off the ceiling (likely to get it to stop sounding). It is undisputed that a smoke alarm's job is to notify occupants of a fire. The decedents here were undisputedly aware of this fire. While no one knows (nor can know) what alerted them to the fire nor when, nor why they did not escape, a jury should at least be able to hear what we do know - that this smoke alarm sounded. Where there is no reasonable basis to exclude Dr. Gottuk's opinions as unreliable, Plaintiff's motion to strike should be denied.

ARGUMENT

I. ESD Is A Scientific, Peer-Reviewed, Reliable And Industry Accepted Methodology For Determining Whether A Smoke Alarm Sounded During A Fire

In support of her motion to strike, the Plaintiff asserts that the scientific analysis known as "acoustic agglomeration" or "ESD" is not reliable because the work "has been statistically [in]significant". (*See* Affidavit of B. Don Russell ("Russell Aff.") at ¶ 10.) Dr. Russell is clearly unfamiliar with the body of scientific literature on acoustic agglomeration and appears to only be aware of the first publication as it relates to smoke alarm.

Scientific research and analysis of the phenomenon of what is known as "acoustic agglomeration" or the study of enhanced soot deposition patterns, is well documented throughout the literature and dates back to the scientist, Kundt's findings in 1866. (*See* Streit Aff. at ¶ 9 and Exhibit B thereto.) It is well established that an acoustic field can greatly enhance the rate of particle agglomeration. (*See id,* references 2, 5-9). It is also been shown by Tiwary et. al (*id.,* ref. 8) and Mendiknow (*id.,* ref. 2) that the conditions optimum for acoustic agglomeration are substantially similar to those exhibited by a sounding smoke alarm.

Contrary to Russell's complaint that only a select group with vested interests (Russell Aff. ¶ 10) have researched this area, many scientists independently contributed to the body of research on ESD and acoustic agglomeration as a means to scientifically assess whether a smoke alarm sounded during a fire. (Streit Aff. ¶ 8.) This research is the subject of several peer-reviewed and published journal articles. (*Id.*)

The first study to apply the science of acoustic agglomeration to smoke alarm was published in January 2001 by several eminent fire scientists, including Dr. Streit. (Streit Aff. Ex. B.) In that study, numerous smoke alarms were mounted for testing in an actual full-scale house fire. The results of that research was presented and published in the Proceedings of the Fire Suppression and Detection Research Application Symposium at The Fire Protection Research Foundation Annual Meeting in January of 2001. (Streit Aff. ¶ 10.) This paper was the winner of the William M. Carey Award in recognition of the best paper presented at the meeting. (*Id.*) Subsequently, that paper passed a rigorous peer review process and was published in Fire Technology, volume 37, pages 343-362 in 2001. (*Id.* at ¶ 11.) Fire Technology is the foremost refereed journal in the Fire Science field. (*Id.*)

In order to further the understanding of acoustic agglomeration, a second study was published the following year using 389 smoke alarms with different horn configurations exposed to an array of controlled UL fire test configurations. (*Id.* at ¶ 12.) That work resulted in a paper presented and published in the Proceedings of the Fire Suppression and Research Application Symposium at The Fire Protection Research Foundation Annual Meeting, Jan. 2002. (*See* C. Worrell, J. Lynch, G. Jomaas, R. Roby, L. Streit and J. Torero, "*Effect of Smoke Source and Horn Configuration on Enhanced Deposition Acoustic Agglomeration, and Chladni Figures in Smoke Alarms*", Streit Aff., Exhibit C.) This paper was also subjected to and passed the peer review process and was published in Fire Technology, volume 39, pages 309-346 in 2003. (Streit Aff. at ¶ 12.)

Dr. Russell's concern that ESD research is not statistically significant or the result of full-scale fire tests is just as misplaced. Dr. Streit personally examined over 400 smoke alarms for these studies. (Streit Aff. at ¶ 13.) Any scientist would consider that to be a statically valid number of tests. (*Id.*) Not only are the results statistically significant, the smoke alarms tested were examined and evaluated as part of a double blind study, and the first set of tests were conducted in an actual full-scale house fire. (*Id.* at ¶¶ 10, 13.) In other words, Dr. Streit and others examined over 400 smoke alarms for acoustic agglomeration without knowing which alarms had activated and which had not. (*Id.* at ¶ 13.) In regards to the smoke alarms in the study that possessed sufficient soot to evaluate an acoustic agglomeration, there was one hundred percent correct determination of activation. (*Id.*) Therefore, the technique is clearly reliable, even under Russell's standards. (*Id.*)

Subsequent to those publications, the technique used to determine the presence of acoustic agglomeration was substantiated and verified by research that was authored by P. Kennedy, K. Kennedy and G. Gorbett entitled "*A Fire Analysis Tool Revisited: Acoustic Soot Agglomeration in Residential Smoke Alarms*" and was published by the Investigative Institute in

August, 2003. (Streit Aff. at ¶ 14 and Ex. D thereto.) In fact, those authors combined the first two studies' data with theirs to create a larger database of tests. (*Id.*)

Yet another confirmation study of the acoustic agglomeration technique was performed as part of a Masters' Thesis concerning the validity of the ESD method for ascertaining whether a smoke alarm sounded during a fire. (Streit Aff. at ¶ 15 and Ex. E thereto, P. Phelan, "*An Investigation of Enhanced Soot Deposition on Smoke Alarm Horns*", Master of Science Thesis, Worcester Polytechnic Institute, Worcester, MA, 250 p., 2005.) Additional research followed to ensure the validity of the ESD method was not limited to "controlled" fire scenarios as Russell complains herein. (Streit Aff. at 16 and Ex. F thereto, Mealy, C.L. and D. Gottuk, *Full-Scale Validation Tests of a Forensic Methodology to Determine Smoke Alarm Response,* ISFI 2008 Proceedings, International Symposium on Fire Investigation Science and Technology, NAFI, Sarasota, FL, 2008.) That study found that following the ESD methodology resulted in "a total of forty-seven alarms accurately identified as having either sounded or not sounded during exposures to enclosure fire conditions". (*Id.* at Conclusions.) The conclusion was that "based upon these results and those of the previous studies, it is apparent that [ESD] provides a valid methodology for evaluating soot deposition around smoke alarm horn openings as an indication as to whether or not the device sounded during a fire." (*Id.*)

Each and all of these research efforts satisfy Dr. Russell's own stated criteria for verification of the reliability of the experimental data. It appears Russell has simply failed to attend fire science meetings, conveniently ignored or otherwise failed to keep current with the fire science technical literature and therefore was unaware of all the additional work in the field of acoustic agglomeration science since the initial publication in 2001.

In fact, everyone other than Russell recognizes ESD as a reliable methodology. It is so widely accepted that beginning in 2011, the National Fire Protection Agency ("NFPA") incorporated ESD into the national industry standard for fire investigations, known as NFPA 921. (NFPA 921, §6.2.10.3 (2011 ed.), *see* relevant portions at Streit Aff., Ex. G.) ESD remains a standard methodology for use in NFPA fire investigations today. (Streit Aff. at ¶ 17 and NFPA 921, §6.2.10.3 (2014 ed.), relevant portions at Streit Aff. Ex. H.) Interestingly, prior to NFPA's adoption of ESD as a standard methodology for use in 921 fire investigations, in 2010, Dr. Russell attempted to dissuade the NFPA from incorporating it with the same reasoning and arguments included in his affidavit here. (*See* Streit Aff. at ¶ 19 and NFPA 921 Report on Comments, November 2010, Log # 84, a copy of which is at Streit Aff. Ex. I.) The NFPA considered and rejected this initiative, stating "the use of acoustic soot agglomeration for the determination of smoke detector activation **is supported in the scientific literature**". (*Id.* at Committee Statement, p. 13.) (emphasis added) The "scientific literature" the NFPA was referring to is included in the reference section for 6.2.10.3. Note that all of the studies discussed herein are listed there. (*See* Streit Aff. Ex. G, NFPA 921 (2011 ed.) at references for 6.2.10.3.)

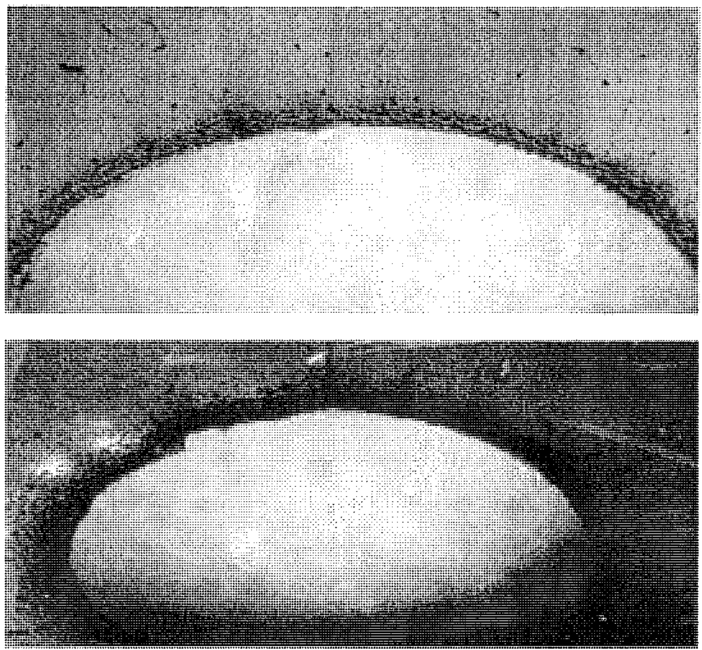
Notwithstanding Russell's personal unfounded opinions, it is well established that ESD, or acoustic agglomeration analysis, is a scientifically valid, industry proscribed and reliable methodology for determining whether a smoke alarm sounded during a fire. Plaintiff's motion to strike Dr. Gottuk's opinion that the smoke alarm sounded solely on the basis that this methodology is flawed should be denied.

II. BRK's Expert Concurs With, And Thereby Validates, Dr. Gottuk's Opinion That The Smoke Alarm Sounded In This Case

Dr. Streit personally attended the inspection of the smoke alarm at issue in this case on behalf of BRK. (Streit Aff. at ¶ 22.) She conducted an independent examination of the horn of the involved smoke alarm in accordance with the industry standard and accepted ESD methodology and the parties' agreed-upon protocol. (*Id.*) She personally viewed the soot agglomeration patterns on the horn - first macroscopically and then microscopically - using a

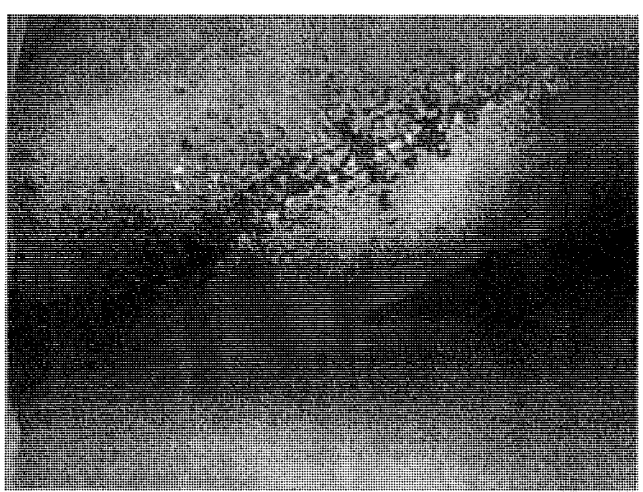
Nikon stereomicroscope. (*Id.*) She took photographs of what she saw during that inspection. (*Id.*)

Below are photos from the first Worrell (2001) paper (Streit Aff. Ex. B) following full-scale fire testing showing ESD patterns on the horns of alarms which were confirmed to have sounded during that fire:



(Streit Aff. Ex. B at Figure 13.)

By way of comparison, here is a photo of the ESD patterns on the horn of the smoke alarm involved in this fire displaying similar ESD evidence:



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(Streit Aff. Ex. J.) Based on her ESD analysis, her extensive experience and expertise, Dr. Streit concurs with Dr. Gottuk's findings and opinion that this smoke alarm sounded during this fire. (Streit Aff. at ¶ 23.) All experts other than Russell therefore agree that the ESD pattern on this horn is conclusive evidence that this smoke alarm sounded at some point during this fire. (*Id.*)

In addition to being supported by this empirical evidence, Dr. Gottuk's determination that the smoke alarm sounded during this fire is consistent with evidence presented in this case, including Plaintiff's admission in her Complaint that the decedent was aware of the fire and attempted to extinguish it and that the alarm appears to have been knocked from its ceiling mount at some point during this fire. (Streit Aff. at ¶ 24.) There is no evidence of a prior fire in Plaintiffs' apartment and no evidence to support Russell's baseless speculation that the ESD pattern is the result of a prior fire. In fact, witnesses, including the named Plaintiff, testified that they never heard the smoke alarm go off in response to prior "kitchen smoke", as Russell suggests. (Deposition of Furlandare Singleton at 109:6-110:18, relevant portions of which are attached hereto as Exhibit B; Deposition of Tamara Braxton at 49:7-50:2, relevant portions of which are attached hereto at Exhibit C.) Dr. Gottuk's opinion is conversely reasonable, reliable and is consistent with the evidence.

CONCLUSION

Plaintiff's attack on the methodology employed by Dr. Gottuk is entirely unsubstantiated. ESD as a scientifically valid and reliable method to determine whether a smoke alarm sounded. The NFPA has incorporated ESD into its universally accepted standard for fire investigations over Russell's baseless objections. While ESD cannot independently tell you when a smoke alarm sounded, it can tell you is that the smoke alarm sounded. Plaintiffs' motion should be denied.

Respectfully submitted,

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CERTIFICATE OF SERVICE

I hereby certify that on June 1, 2016, I electronically filed the foregoing with the Clerk of Court using the CM/ECF system, which shall send notification of such filing to the following:

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/s/ *Kathryn A. Pryor*
Kathryn A. Pryor

AFFIDAVIT OF LORI STREIT, PH.D.

STATE OF ILLINOIS :
COUNTY OF DUPAGE :

Lori A. Streit, being duly sworn deposes and says:

1. I hold a Ph.D. degree in Analytical Chemistry/Surface Analysis from Arizona State University.

2. I am a Principal of Unified Engineering, Inc. of Lombard, Illinois, where I am employed as a chemist and materials analyst. My qualifications are as set forth in my curriculum vitae, a copy of which is attached hereto as Exhibit A.

3. My education and experience is in the areas of, among other things, surface analysis, microanalysis, material characterization, chemistry, chemical analysis and acoustic agglomeration or enhanced soot deposition ("ESD") analysis.

4. I have been extensively involved with the examination, analysis and testing of smoke alarms. More specifically, I have extensive experience in the examination, analysis and testing of smoke alarms that have been involved in fires and exposed to products of combustion.

5. As part of my duties and responsibilities as a chemist and materials analyst, I routinely examine, analyze and test smoke alarms, to determine the manner in which the product operated when exposed to combustion products. I have specific knowledge, training and experience in fire investigation. Over the course of the last 20 years, I have conducted hundreds of investigations on smoke alarms that were exposed to fire and heat. With regard to smoke alarms, I have created analytical tools, which have been peer reviewed and accepted by the scientific community, which assists me in the examination of particular aspects of smoke alarms exposed to a fire.

6. These peer reviewed analytical tools permit the analysis of smoke alarm physical damage and contamination, thermal deformation, soot patterns, smoke, soot and other evidentiary patterns on the battery, acoustic agglomeration (enhanced soot deposition)

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tabbies
A

patterns, wires, etc. to determine, among other things, how the alarm was mounted, whether the alarm was properly powered, and whether the it alarmed during the fire. I have also constructed specific measurement and reflective tools, which have been peer reviewed and accepted by the scientific community which aid in the analysis of battery soot protected area patterns and acoustic agglomeration pattern evaluation.

7. In support of her motion to strike, the Plaintiff has asserted that the scientific analysis known as "acoustic agglomeration" or "ESD" is not reliable because the work "has been statistically [in]significant". (*See* Affidavit of B. Don Russell ("Russell Aff.") at 10.)

8. I have independently researched ESD and acoustic agglomeration as a means to scientifically assess whether a smoke alarm sounded during a fire. My research in this regard is the subject of several peer-reviewed and published journal articles.

9. As a brief overview and as further described in our initial paper that applied the science of acoustic agglomeration to smoke alarms, acoustic agglomeration is well documented throughout the literature and dates back to Kundt's findings in 1866. (*See* C.L. Worrell, L. Streit, et al., Enhanced Deposition, Acoustic Agglomeration, and Chladni Figures in Smoke Alarms, Fire Technology, 37, 343-362 (2001) at ref. 5, a copy of which is attached hereto at Exhibit B.) It is well established that an acoustic field can greatly enhance the rate of particle agglomeration. (*See id,* references 2, 5-9). It is also been shown by Tiwary et. al (*id.,* ref. 8) and Mendiknow (*id.,* ref. 2) that the conditions optimum for acoustic agglomeration are substantially similar to those exhibited by a sounding smoke alarm.

10. In January of 2001, my scientific analyses applying the science of acoustic agglomeration to smoke alarms, alarms which were mounted for testing in an actual full-scale house fire, was presented and published in the Proceedings of the Fire Suppression and Detection Research Application Symposium at The Fire Protection Research

Foundation Annual Meeting, Jan. 2001. (*Id.*) This paper was the winner of the William M. Carey Award in recognition of the best paper presented at the meeting.

11. Subsequently, the paper passed a rigorous peer review process and was published in Fire Technology, volume 37, pages 343-362 in 2001. (*Id.*) Fire Technology is the foremost refereed journal in the Fire Science field.

12. In order to further our understanding of acoustic agglomeration, a second study was published using 389 smoke alarms with different horn configurations exposed to an array of controlled UL fire test configurations. That work constituted a 2nd paper presented and published in the Proceedings of the Fire Suppression and Research Application Symposium at The Fire Protection Research Foundation Annual Meeting, Jan. 2002. (*See* C. Worrell, J. Lynch, G. Jomaas, R. Roby, L. Streit and J. Torero, "*Effect of Smoke Source and Horn Configuration on Enhanced Deposition Acoustic Agglomeration, and Chladni Figures in Smoke Alarms*", a copy of which is attached hereto as Exhibit C. This paper was also subjected to and passed the peer review process and was published in Fire Technology, volume 39, pages 309-346 in 2003.

13. I personally examined over 400 smoke alarms for these studies. Any scientist would consider that to be a statistically valid number of tests. As a further note, all of the smoke alarms tested were examined and evaluated as part of a double-blind study. In other words, I examined over 400 smoke alarms for acoustic agglomeration without knowing which alarms had activated and which had not. In the smoke alarms where there was sufficient soot to evaluate an acoustic agglomeration, I had one hundred percent correct determination of activation. Therefore, the technique is clearly reliable.

14. Subsequent to those publications, the technique used to determine the presence of acoustic agglomeration has been substantiated and verified by research that was authored by P. Kennedy, K. Kennedy and G. Gorbett entitled "*A Fire Analysis Tool Revisited: Acoustic Soot Agglomeration in Residential Smoke Alarms*" and was published by the

Investigative Institute in August, 2003. A copy of this study is attached hereto as Exhibit D. In fact, the authors combined our data with theirs to create a larger database of tests.

15. A second confirmation study of the acoustic agglomeration technique was performed as part of a Masters' Thesis. This study further confirmed the validity of the ESD method for ascertaining whether a smoke alarm sounded during a fire. (P. Phelan, "*An Investigation of Enhanced Soot Deposition on Smoke Alarm Horns*", Master of Science Thesis, Worcester Polytechnic Institute, Worcester, MA, 250 p., 2005, a copy of which is attached hereto as Exhibit E.)

16. Additional research on this subject followed to ensure the validity of the ESD method was not limited to "controlled" fire scenarios. (Mealy, C.L. and D. Gottuk, *Full-Scale Validation Tests of a Forensic Methodology to Determine Smoke Alarm Response,* ISFI 2008 Proceedings, International Symposium on Fire Investigation Science and Technology, NAFI, Sarasota, FL, 2008, a copy of which is attached hereto as Exhibit F.) That study found that ESD methodology resulted in "a total of forty-seven alarms accurately identified as having either sounded or not sounded during exposures to enclosure fire conditions". (*Id.* at Conclusions.) The conclusion was that "based upon these results and those of the previous studies, it is apparent that [ESD] provides a valid methodology for evaluating soot deposition around smoke alarm horn openings as an indication as to whether or not the device sounded during a fire." *(Id.)*

17. In recognition of all of the scientific research and in further support of the reliability of ESD as a means to determine whether a smoke alarm sounded during a fire, beginning in 2011, the National Fire Protection Agency ("NFPA") incorporated ESD into the national industry standard for fire investigations, known as NFPA 921. (NFPA 921, §6.2.10.3 (2011 ed.), relevant portions of which are attached hereto as Exhibit G.) ESD remains a standard methodology for use in NFPA fire investigations today. (*See* NFPA 921, §6.2.10.3 (2014 ed.), relevant portions of which are attached hereto as Exhibit H.)

18. The NFPA is a global non-profit organization devoted to eliminating death, injury, property and economic loss due to fire and related hazards through the promulgation of consensus-based codes and standards.

19. Prior to NFPA's adoption of ESD as a standard methodology for use in 921 fire investigations, in 2010, Dr. Russell attempted to dissuade the NFPA from incorporating it with the same reasoning and arguments included in his affidavit here. (*See* NFPA 921 Report on Comments, November 2010, Log # 84, a copy of which is attached hereto as Exhibit I.) The NFPA considered and rejected his initiative, stating "the use of acoustic soot agglomeration for the determination of smoke detector activation is supported in the scientific literature". (*Id.* at p. 13.)

20. The "scientific literature" upon which the NFPA relied to incorporate ESD into NFPA 921 is included in the reference section for 6.2.10.3. All of the studies discussed in this affidavit are listed there. (*See* Ex. G, NFPA 921 (2011 ed.) at references for 6.2.10.3.)

21. ESD, or acoustic agglomeration analysis, is a scientifically valid, industry proscribed and reliable methodology for determining whether a smoke alarm sounded during a fire.

22. I personally attended the inspection of the smoke alarm at issue in this case on behalf of BRK Brands, Inc. I conducted an independent examination of the horn of the involved smoke alarm in accordance with the industry standard and accepted ESD methodology and the parties' agreed-upon protocol. I viewed the soot agglomeration patterns on the horn first macroscopically and then microscopically, using a Nikon stereomicroscope. I took photographs of what I saw during that inspection. A true and correct copy of a photo (Image DSCN0121) depicting the ESD patterns on the subject alarm's horn which I took at the smoke alarm inspection in this matter is attached hereto as Exhibit J.

23. I concur with Dr. Gottuk, to a reasonable degree of scientific certainty, based on all my years of research, training and experience and my own independent ESD analysis that the smoke alarm at issue in this case sounded during this fire.

24. In addition to being supported by empirical evidence, Dr. Gottuk's determination that the smoke alarm sounded conforms with the other circumstantial evidence presented in this case, including Plaintiff's admission in her Complaint that the decedent was aware of the fire and attempted to extinguish it, and that the alarm appears to have been knocked from its ceiling mount at some point during this fire.

25. Each and all of these research efforts satisfy Dr. Russell's own stated criteria for verification of the reliability of the experimental data and must therefore be deemed "reliable".

26. By Dr. Russell's standards, the technique of "Enhanced Soot Deposition" has been validated by his peer review criteria and independent scientific experimental verification requirements.

27. I have been admitted to testify as an expert in numerous state and federal courts around the country as to whether a smoke alarm sounded during a fire based on the results of my ESD and acoustic agglomeration analysis. My opinions and testimony in this regard has never been stricken or limited.

28. This affidavit is offered in opposition to Plaintiff's motion to strike the affidavit and testimony of Dan Gottuk related to his opinion, based on the presence of enhanced soot deposition ("ESD") patterns observed on the subject smoke alarm's horn, that it sounded during this fire.

Further affiant sayeth not.

Lori A. Streit, Ph.D.

Sworn and subscribed before me
on this the 24th day of May, 2016.

NOTARY PUBLIC
My Commission Expires 03/03/2020

"OFFICIAL SEAL"
KATHLEEN M BROCKMAN
NOTARY PUBLIC, STATE OF ILLINOIS
My Commission Expires 03/03/2020

EXHIBIT C

Fire Technology, 39, 309–346, 2003

Effect of Smoke Source and Horn Configuration on Enhanced Deposition, Acoustic Agglomeration, and Chladni Figures in Smoke Detectors*

C.L. Worrell, J.A. Lynch, G. Jomaas, and R.J. Roby, Combustion Science & Engineering, Inc., Columbia, MD

L. Streit, Unified Engineering, Inc.

J.L. Torero, School of Civil and Environmental Engineering, The University of Edinburgh, Edinburgh, UK

Abstract. A series of UL/EN based test fires was conducted in a two room/corridor enclosure to investigate the viability of methods for determining whether a smoke detector sounded under a variety of smoke conditions and to see if this methodology could be applied to a detector with a different horn configuration. The presence of enhanced deposition in the form of a black or orange-brown ring and agglomerates around the central opening of a smoke detector horn was found to be a reliable indicator that the horn sounded when it was exposed to smoke from eight standardized, single-substrate fuel sources including hydrocarbon pool, flaming polyurethane foam, and smoldering polyurethane foam fires. Determinations could generally not be made for detectors exposed to white or gray smoke generated by flaming paper, smoldering paper, flaming wood, smoldering wood, and smoldering cotton wick due to a general lack of visible soot deposition within the detector. Therefore, it is not recommended to use the absence of a black or orange-brown ring of enhanced deposition, in and of itself, as an indicator that the horn did not sound. Nevertheless, this conclusion can be reached when the absence of enhanced deposition is combined with evidence supporting the presence of flaming fuels that produce black, sooty smoke. Test series were conducted using two different smoke detector brands, each having a different horn configuration. Findings suggest that the same type of methodology for determining whether the detector sounded is applicable to both models. Chladni figures were not found on any of the smoke detectors, whether they sounded or not; hence, the absence of a Chladni figure was not an indicator that the detector did not sound. A smoke flow visualization technique was used to determine the mechanism that caused the observed enhanced deposition and agglomerates on horns that sounded during a smoke exposure. Additionally, a smoke box test series showed that the extent of observed soot deposition increased with increasing smoke exposure.

Key words: smoke detector, deposition, agglomeration, Chladni figures, soot pattern, acoustic

* An earlier version of this paper was presented at the 2002 Fire Protection Research Foundation *Fire Suppression and Detection Research Application Symposium.* Many figures that could not be included here due to length considerations will be presented in the proceedings of the symposium.

EXHIBIT
C

Background

In fire reconstruction, knowledge of whether a particular smoke detector sounded during the fire can be valuable. It may be of special interest if there were fatalities involved. Knowing whether a detector sounded can provide information as to when, or if, an occupant may have been alerted to a developing fire. Before the observation of soot deposition patterns made by Worrell et al. [1] and Munger [2], smoke detector forensics was limited to determining whether the detector was operable. Such a determination might include checking whether the battery was properly in place and charged if it was a battery-powered device, checking whether the power was properly connected if it was an AC-powered device, or conducting a "canned smoke" test to check if the smoke-sensing system was operational. In addition, smoke detector horns can be so thermally damaged prior to the arrival of fire/rescue personnel that the horn may not be operable when the personnel arrive.

Recently, Worrell et al. [1] investigated the presence of enhanced soot deposition, agglomerates, and Chladni figures as post-fire indicators of smoke detector activation. In this study, a full-scale house fire test was conducted in which thirty smoke and CO detectors were mounted throughout the house. Half of the detectors had their batteries properly inserted and were operational. The other half had their batteries intentionally disconnected and were thus prevented from sounding during the fire. This study focused on the accumulation of soot on the piezoelectric horn case and disk of the detector. The horn style studied in this previous research is shown in the left photo of Figure 1, which is a photo of an

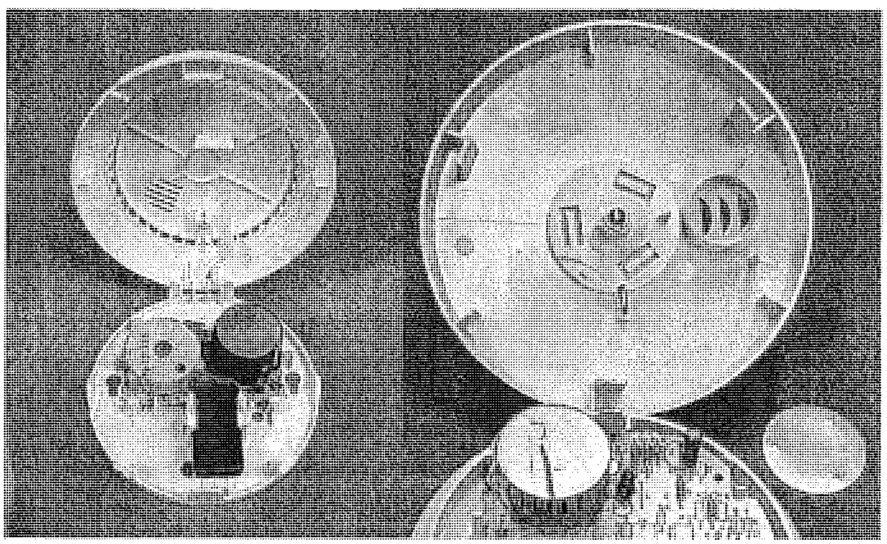


Figure 1. Open detector with "Horn Configuration #1" on left and "Horn Configuration #2" on right. Central circular opening of plastic horn case serves as primary horn opening for Configuration #1 (left). Three moon-shaped slotted openings on detector lid serve as primary horn openings for Configuration #2 (right).

ionization type smoke detector with its lid open. The authors observed enhanced deposition and sometimes very large soot agglomerates (of order 200–500 micrometers in length) on many detector horns that sounded during the test. The enhanced deposition was observed macroscopically, with the naked eye, in the form of a "black ring" around the central horn opening. Microscopically, it was apparent that the individual soot particles deposited on the edge of the horn opening were spaced closer together and were often much larger in size than particles deposited adjacent to the edge of the opening. This study theorized that various acoustic mechanisms, occurring when the alarms sounded, caused an increased rate of soot deposition onto the central horn opening. One effect of this enhanced rate of deposition was hypothesized to be a soot layering or stacking effect that resulted in the presence of very large soot agglomerates on the edge of the central horn opening. In addition, many studies reported in the aerosol and combustion literature support the hypothesis that smoke particles within the acoustic field of an alarming detector may experience greatly enhanced agglomeration or particle growth rates [3–7]. This study concluded that the presence of an increased number density and increased size of particles deposited locally about the central opening of the horn case was a reliable indicator that the alarm sounded. However, it was also concluded that the absence of such enhanced deposition and agglomerates did not necessarily exclude the possibility that the alarm sounded.

A Chladni figure is a pattern formed by particulates settling into the nodes of a vibrating surface [8]. The pattern formed is a mirror image of the nodal pattern of that surface. Nodal patterns can theoretically take the shape of concentric rings, a wagon wheel, or variations of the two [9, 10]. Some have proposed that Chladni figures of soot may form on the surface of the vibrating disc of a smoke detectors piezoelectric horn. If this were the case, the presence of a Chladni figure would be an indication that the alarm sounded. Although this theory has been proposed in litigation [11], no supporting studies have been performed. Munger [11] conducted a brief investigation in which he exposed six smoke detectors to smoke from a sample of flaming polyurethane foam. Half of the detectors were set up so that they could sound during the test, and the other half were disabled from sounding. Munger found that "... there was no discernable difference in the smoke patterns on the disks in the horns regardless of whether the device was operational or not" [11]. Similarly, Chladni figures were not observed macroscopically or microscopically on any of the piezoelectric discs in detectors from the full-scale house fire test of Worrell et al. [1].

The study described by Worrell et al. [1] was a preliminary investigation of enhanced deposition, acoustic agglomeration, and Chladni figures limited to one scenario: a flaming couch fire that was extinguished shortly after flashover. Worrell et al. [1] studied the phenomena in ionization, photoelectric, and carbon monoxide detectors; however, all of these detectors had the same horn configuration. This paper is intended to be a continuation of the earlier work [1] that focuses on the applicability of the methodology for determining activation under a variety of well-defined standardized smoke conditions and with different horn configurations.

This study attempted generalization of the methodology to a comprehensive set of fire scenarios. Pairs of ionization type smoke detectors mounted in a two-room/corridor test facility were exposed to various levels and types of smoke generated from eight different Underwriters Laboratories, Inc. (UL) and European Committee for Standardization (EN) based test fires. One detector in each pair was set up so that it could alarm, and the other was disabled from alarming during the test. This test configuration was also utilized with detectors of a different brand, which had a different horn configuration than the previously tested detectors. This detector and horn configuration, referred to as "horn configuration #2", is shown in photo to the right in Figure 1. A total of 270 configuration #1 detectors and 119 configuration #2 detectors were tested. All detectors were inspected both macroscopically and microscopically for enhanced deposition, agglomerates, and Chladni figures. In addition, ultraviolet irradiation (UV) was used as an illumination source in an attempt to see deposits undetectable with visible light.

An effort was also made to better understand the mechanism that causes enhanced deposition and presence of agglomerates. Acoustic fields, such as those created by the detector horn, induce a flow field in the air. For this particular case, the air is seeded with smoke particles, which are then transported by the flow field. Depending on its structure, the flow field may create specific areas of preferential soot deposition. Additionally, this process may have a significant effect on the agglomeration rate of soot, especially if recirculation eddies are present. It is therefore of importance to better understand the flow field induced by the detector horn. This was accomplished by using a particle flow visualization technique similar to that described by Hoffmann and Koopmann [4, 5], which involves projecting a vertical laser light sheet across the horn opening of the smoke detector, which was ceiling-mounted in a small smoke box. The technique was applied to detectors with both horn configuration #1 and #2. This technique illuminated soot particles in a single plane, permitting the visualization of particle movement and interaction with the acoustic field generated by an alarming smoke detector.

Additionally, it was established that the extent of observed soot deposition depended on the extent of smoke exposure. This was accomplished by permitting a smoke detector to alarm to a steady smoke source for an incrementally increasing length of time. Photographs of the soot deposition on the detector horn were taken after each incremental smoke exposure.

Experimental Setup

Full-Scale Test Facility

Figure 2 is a schematic of the test facility. The facility consisted of two 2.3 m (7.5 ft.) by 2.6 m (8.5 ft.) rooms connected by a 1.1 m (3.5 ft.) by 4.6 m (15 ft.) corridor. The facility had standard 5.1 cm (2″) by 10.2 cm (4″) wood studs with 0.9 cm (3/8″) gypsum wall construction and an acoustic tile drop-down ceiling, creating a ceiling height of 2.4 m (8 ft.) Pairs of ionization type smoke detectors were mounted in the fire room, corridor, and in the second room. In the fire room and the hallway, both ceiling and sidewall detectors were installed. During the testing, one detector from each pair was intentionally disabled from alarming. This was accomplished by disconnecting its nine-volt battery. The other detector in each pair had its battery properly inserted.

Detectors within each pair were spaced about 14.0 cm (5.5″) apart. A voltage output was recorded from detectors that had their battery properly inserted. This measurement was used to determine when the detector began sounding and when the detector stopped sounding. A laser beam and photodiode assembly was mounted 5.1 cm (2″) in front of each pair of detectors to measure the obscuration of the smoke just before it entered the detector. The path length of each laser/photodiode assembly was 45.7 cm (18″). In addition, temperature

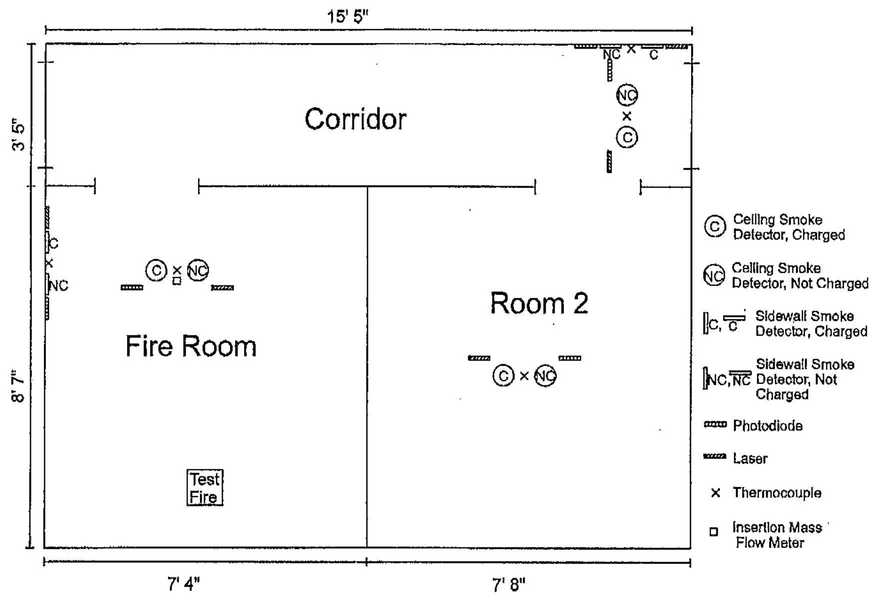


Figure 2. Schematic of test facility.

was measured with a type-K bare bead thermocouple that was mounted between each pair of detectors. A thermal convection mass flow meter was mounted with its 5.1 cm (2″) probe tip just below the ceiling of the fire room. This instrument was included as an attempt to measure ceiling jet velocities for each test fire. Finally, fuel mass was continuously recorded using a 11.3 kg (25 lb.) capacity scale with an analogue voltage output. A data acquisition system recorded the measurements. All of the above measurements were collected for testing of detectors with horn configuration #1, while only light absorption and analogue detector output were recorded for detectors with horn configuration #2.

The measurements described above are important since quantitative determination of the relative intensity of the fire and characteristics of smoke at the detector location is of importance when comparing different experiments. Furthermore, they allow establishing the detector response to different qualities and quantities of smoke. Within the context of this study, the measurements described above were used to determine the relative intensity of the different fires as well as to establish the smoke density at the detector location. These measurements ensured that the detectors were tested for a wide range of conditions. This data is not presented in detail here since the focus of this paper is not on the characterization of the detector response to the fire. Instead, emphasis is given to the characteristics of soot deposition patterns generated by the acoustic field. All data presented and proposed explanations are limited to this aspect of the tests.

Eight different UL/EN style test fires were conducted in the two room/corridor facility using detectors with horn configuration #1 (Figure 1). These standard test fires are used in the certification of smoke detectors. They included a flaming liquid hydrocarbon pool fire [12],

TABLE 1
Representative, Average Maximum Temperatures and Optical Densities Created at the Room 1 and Room 2 Ceiling Detector Locations During the Test Series for Horn Configuration #1

	Maximum Temperature (°C)		Maximum Optical Density (m^{-1})	
Fire Type	Room 1, Ceiling	Room 2, Ceiling	Room 1, Ceiling	Room 2, Ceiling
Heptane/toluene pool—400 mL	168	72	2.8*	0.4
Heptane/toluene pool—100 mL	99	45	0.6	0.2
Flaming polyurethane	42	32	0.05	0.08
Smoldering polyurethane	31	31	0.18	0.09
Flaming wood	51	38	0.22	0.10
Smoldering wood	33	32	0.19	0.03
Flaming paper	39	32	0.07	0.03
Smoldering paper	39	34	0.05	0.09
Smoldering cotton wick	35	33	0.09	0.11

*Optical density measuring system was saturated at this value.

a flaming wood crib fire [12], a flaming polyurethane foam fire, a flaming paper fire [12], a smoldering wood fire [12], a smoldering polyurethane foam fire, a smoldering paper fire, and a smoldering cotton wick fire [13]. For tests involving detectors with horn configuration #2 (Figure 1), only the flaming hydrocarbon pool fire, flaming polyurethane foam fire, smoldering polyurethane foam fire, and smoldering wood fire tests were conducted. The fire tests were set up to represent the corresponding standardized test in fuel configuration, but only for the purpose of generating several types of smoke. No substantial effort was made to adhere to the light obscuration, measuring ionization chamber output, and other criteria specified by the UL and EN standards. Each fire was set up 30.5 cm (1 foot) from the floor near the center of the far wall of the fire room. The doors leading from each room to the corridor remained open during the testing. Each fire type was carried out three times with new detectors for each test. Table 1 includes some representative, average temperatures and optical densities created by each of the fire types, and is indicative of the range of conditions that was generated during the test series.

For the hydrocarbon pool fires, a mixture of 25% toluene and 75% heptane (by volume) was burned in a 15.2 cm (6″) diameter, 3.8 cm (1.5″) deep circular metal pan. For the first test, 400 mL of the mixture was burned. For the second and third tests, 100 mL was burned because the longer duration fire was too hazardous to be repeated in the available test facility. Apparent in Table 1, which shows the average maximum temperatures and optical densities observed at the Room 1 and Room 2 ceiling detector locations, these two fire durations created a range of conditions that might be encountered during a residential fire. The mixture was ignited manually at the beginning of each test using a butane lighter.

For the flaming wood fires, a wood crib was constructed of 18 pieces of fir, each measuring 15.2 cm (6″) by 1.9 cm (0.75″) by 1.9 cm (0.75″). The crib consisted of three layers of six wood pieces each, and the overall dimensions of each crib were approximately 15.2 cm (6″) by 15.2 cm (6″) by 5.7 cm (2.25″). The crib was placed on a coarse wire mesh supported by a 15.2 cm (6″) diameter ring stand. The crib was ignited by burning a small amount of denatured alcohol in a 3.8 cm (1.5″) diameter container placed 8.9 cm (3.5″) below the crib per UL 217 [12].

The flaming polyurethane fires had a fuel configuration of a triangular prism shaped piece of polyurethane foam. The polyurethane was ignited at the top crest of the prism with a butane lighter. The prism had a base width of 34.3 cm (13.5″), a height of 17.8 cm (7″), and a depth of 6.0 cm (2 3/8″). This fuel configuration was used due to the repeatable nature of the fire.

The flaming paper fires consisted of shredded newspaper lightly tamped into a 10.2 cm (4″) diameter sheet metal cylinder that was 30.5 cm (1 ft.) tall. The bottom end of the cylinder was placed on a course wire mesh, which was supported by a ring stand. The top end of the cylinder was open. The shredded newspaper consisted of 0.6 cm ($\frac{1}{4}$″) to 1.0 cm (3/8") wide strips varying from 2.5 cm (1″) to 10.2 cm (4″) in length. Before the newspaper was poured into the receptacle, a 2.5 cm (1″) diameter rod was temporarily placed in the center of the receptacle. The newspaper was then poured and tamped around the rod, forming a 2.5 cm (1″) hole in the center of the newsprint from the base of the receptacle to the top. The newspaper was tamped until the paper was approximately 10.2 cm (4″) below the top of the metal receptacle. Flaming ignition was initiated with a butane lighter at the base of the receptacle.

The smoldering wood fire consisted of 10 sticks of white pine placed in a spoke pattern on a 1.1 kW hotplate. Each stick was 7.6 cm (3″) by 2.5 cm (1″) by 1.9 cm (3/4″), and the 7.6 cm (3″) by 1.9 cm (3/4″) side was in contact with the hotplate during each test. For the tests involving horn configuration #1, a surface mount type K thermocouple was thermally pasted to the surface of the hotplate to ensure that its temperature profile roughly matched that specified by UL 217 [12] during the test. Because it was questioned as to whether pure smoldering was achieved during the first test series, the setting on the hotplate was significantly increased in the following tests.

For the smoldering polyurethane foam tests, two 20.3 cm (8″) by 20.3 cm (8″) by 10.2 cm (4″) slabs of foam were fastened together on the 20.3 cm (8″) by 20.3 cm (8″) side using metal tie wire. The entire 12.1 cm (4.75″) metal tip of a 30-watt pen style soldering iron was inserted between the two slabs as an ignition source. This configuration was intended to represent the initiation of smoldering between two foam cushions.

The smoldering paper tests consisted of shredded newspaper in the same configuration as the flaming paper fires. The paper was ignited with a butane lighter at the base of the receptacle and then quickly extinguished. This process was repeated until sustained smoldering of the paper was initiated.

Finally, for the smoldering cotton wick tests, 90 pieces of 80.0 cm (31.5″) long cotton wick were hung from a 10.2 cm (4″) diameter circular ring. Each cotton wick was approximately 1.0 cm (3/8″) in diameter. The bottom edge of the cotton wicks was positioned so that it was 2.1 m (7 ft.) below the ceiling. The wicks were ignited at the base with a butane lighter and quickly extinguished. This process was repeated until sustained smoldering of the wick was achieved.

Small-Scale Smoke Visualization Tests

Figure 3 is a schematic of the smoke flow visualization apparatus. A 5 mW helium-neon laser and two cylindrical lenses were used to create a vertical light sheet. The beam was

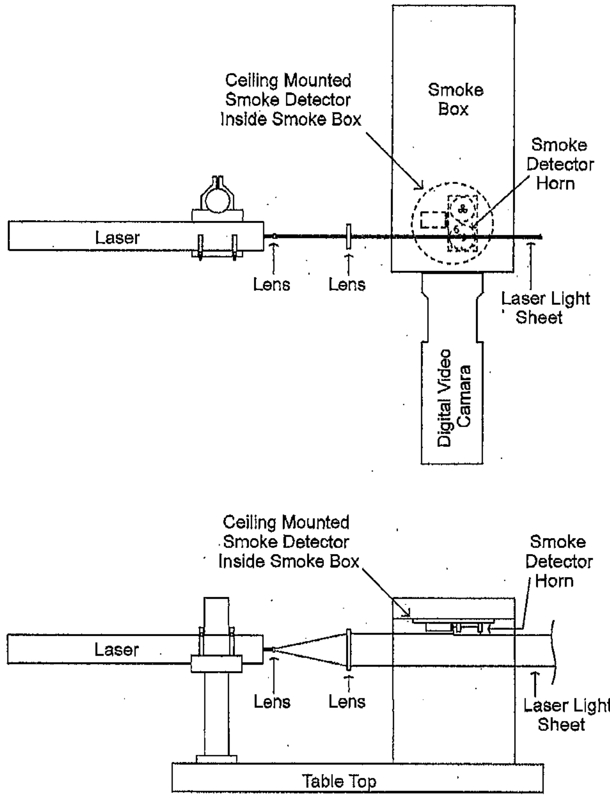


Figure 3. Schematic of smoke flow visualization apparatus.

first passed through a cylindrical lens oriented to expand the beam in the vertical plane. This expanding sheet was passed through another cylindrical lens to collimate the sheet to a constant width of about 3.2 cm ($1\frac{1}{4}''$). The vertical light sheet was passed through a plexiglass smoke box, in which an ionization smoke detector was mounted on the ceiling. The smoke box walls and tabletop on which the assembly was mounted were located far enough away from the detector horn as not to influence any flow patterns acoustically induced when the detector alarmed. The detector's battery was wired to a switch outside the smoke box that permitted control of the detector's alarm. Detectors with horn configuration #1 were mounted with their lids removed to permit the visualization of smoke flow directly below the horn. The laser sheet passed directly underneath the central horn opening. Detectors with horn configuration #2 were mounted with their lids in place since the three moon-shaped slotted openings on the lid actually served as the primary horn opening for this detector. The laser sheet was thus passed directly underneath these slotted openings on the detector lid. A digital video camera was mounted perpendicularly to the light sheet and focused on the area directly underneath the horn opening.

For each test, a small amount of smoke generated by small-scale versions of the UL and EN style test fires was introduced into the smoke box. In addition, a few tests were conducted with smoke from a toluene pool fire. The smoke particles were illuminated as they passed through the vertical light sheet. This setup thus permitted the visualization of a vertical cross section of smoke particles directly underneath the detector horn. When the detector alarmed, the setup enabled the visualization of smoke particle interaction with the acoustic field generated by the sounding horn.

Smoke Box Tests

This test was conducted within the same smoke box used for the flow visualization test series. A smoke detector with horn configuration #1 was mounted at the center of the smoke box and wired so that power could be supplied to the detector via a switch external to the box. A 6.4 cm (2.5″) diameter cup of a mixture containing 75% heptane and 25% toluene was ignited approximately 0.9 m (3 feet) below the open-bottomed box. After 30 seconds of burning, the power supply circuit to the smoke detector was closed. The lag time ensured that the detector would sound immediately after the circuit was closed and that the pool fire had reached steady state burning. The detector was allowed to alarm for two minutes before the power supply circuit was opened. The detector was removed from the box and a photograph of the soot deposition on the central horn opening was taken. The detector was then remounted inside the box. Using the same detector, this process was repeated for two-minute intervals up to 16 minutes, then four-minute intervals up to 28 minutes, and one final two-minute interval up to 30 minutes. For each interval, the same 6.4 cm (2.5″) diameter fire source was used to ensure an approximately equivalent smoke evolution for each interval. This test series established that the extent of observed soot deposition is related to the extent of smoke exposure.

Observations

After all test burns were complete, each detector was first inspected macroscopically with the naked eye. Then, without prior knowledge of which detectors sounded and which did not, a "blind" microscopic inspection was performed on each detector to determine whether or not it sounded during the test. This microscopic inspection was performed using a Nikon stereo-optical microscope with magnification levels between 8x and 80x. The magnification level was chosen depending on the extent of soot deposition. Some of the detectors that did not have visible soot deposition were also inspected under an intense UV light source using a BLAK-RAY long wave (580 nm) ultraviolet lamp Model B. A summary of the microscopic determinations for each detector is included in Tables 2 and 3. These results are discussed in more detail later.

Direct observation of different areas of the detector allowed establishing repeatable patterns that distinguished detectors that sounded from those that did not. These patterns corresponded to enhanced deposition and the presence of large agglomerates around the perimeter of the primary horn opening. This deposition pattern was observed on both horn configuration #1 and #2. The enhanced deposition and presence of large agglomerates can easily be contrasted from regular soot deposition throughout the rest of the detector.

TABLE 2
Summary of Microscopic Determination for Detectors with Horn Configuration #1

Fire Type	Correct "Positive"	Correct "Negative"	Undetermined	Incorrect
Heptane/toluene pool	15/15	15/15	0	0
Flaming polyurethane	17/17	11/11	22	0
Smoldering polyurethane	8/8 "possible"	0/0	22	0
Flaming wood	0/0	0/0	30	0
Smoldering wood	0/0	0/0	30	0
Flaming paper	0/0	0/0	30	0
Smoldering paper	1/1 "possible"	0/0	39	0
Smoldering cotton wick	2/2 "possible"	0/0	28	0

TABLE 3
Summary of Microscopic Determination for Detectors with Horn Configuration #2

Fire Type	Correct "Positive"	Correct "Negative"	Undetermined	Incorrect
Heptane/toluene pool	15/15	15/15	1**	0
Flaming polyurethane	13/13*	13/13	6	0
Smoldering polyurethane	4/4	1/1	19	0
Smoldering wood	1/1	1/1	30	0

*Includes one marked as "possibly" sounding due to faint soot.
**Detector MC78 included as "undetermined" because there was a missing observation as to whether or not a battery was installed in this detector.

For horn configuration #1, the microscopic determination of whether the detector sounded during the test was based on a comparison of soot deposits primarily on the central horn opening to 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 indication that the horn sounded. Determination that the detector sounded required that enhanced 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 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. The inspection also included examining the piezoelectric disc of the horn for Chladni figures.

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.

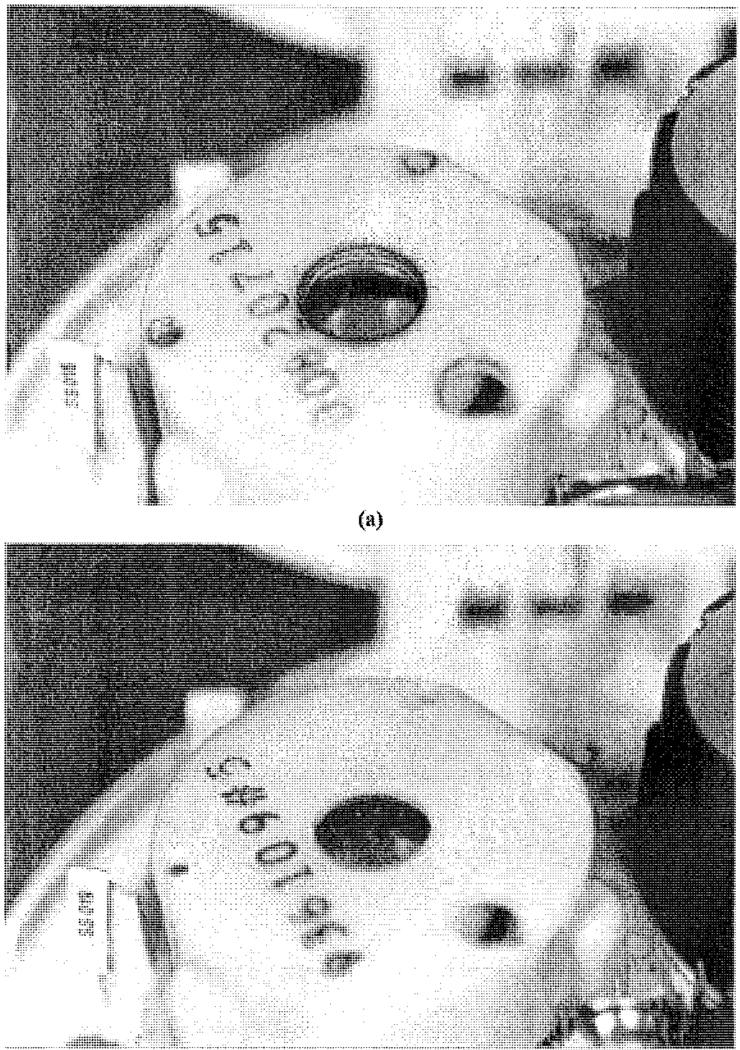
Macroscopic Observations

The flaming hydrocarbon pool and flaming polyurethane foam fires resulted in black, carbonaceous soot deposition. The smoldering polyurethane foam generated tarry, orange-brown deposition. Such deposition is consistent with observations described in the literature [14–16]. For horn configuration #1, enhanced soot deposition was observed around the perimeter of the central horn opening and sometimes on the inside edges of the slotted lid opening in detectors that sounded. For horn configuration #2, enhanced soot deposition was observed around the inside perimeter of the three moon-shaped slotted openings on the detector lid. Enhanced soot deposition was not observed on detectors that did not sound.

All 15 detectors with horn configuration #1 that sounded due to exposure to hydrocarbon pool fire smoke had black enhanced soot deposition visible to the naked eye. As can be seen from Figure 4(a), configuration #1 horns that sounded during the hydrocarbon pool fires displayed soot deposition that was more concentrated around the perimeter of the central horn opening. This concentrated deposition was clearly observed on both the inside and outside edges of the horn opening. Deposition across the rest of the horn surface was lighter and more uniform. Also evident, soot traces just outside the concentrated deposition on the horn edge often appeared to be directed radially outward. Figure 4(b) shows a detector horn that was mounted adjacent to the detector in 4(a), but that did not alarm during the smoke exposure. As is apparent, there is no increased concentration of soot on the edges of the central opening in 4(b). This observation of black enhanced soot deposition in alarming detectors is consistent with observations of detectors from the full-scale house fire test described by Worrell et al. [1].

Of the 24 detectors with horn configuration #1 that sounded during the flaming polyurethane foam fire tests, 13 had black enhanced soot deposition visible to the naked eye. The same enhanced concentration of soot was observed around the perimeter of the inside and outside opening edges of horn configuration #1, except to a lesser extent than observed from the heptane/toluene tests. Soot deposition throughout the detector was generally light for the flaming polyurethane foam fires, which was thought to be a result of less smoke being generated during these tests. Soot deposition on the horns that did not sound was uniform across the edges of the horn opening and the top surface of the horn enclosure.

Regarding the smoldering polyurethane fires, 8 of the 12 configuration #1 detectors that sounded during the pure smoldering tests displayed a tarry orange/brown residue deposited around the perimeter of the inside edge of the central horn opening and to a lesser extent around the wall of the horn opening. This tarry residue is also mentioned in the literature [14–16]. The deposition on the horn opening was in clear contrast with the deposition on across the surface of the horn enclosure. The top surface of the horn and other areas throughout the detector were stained a light orange color. Similarly, many detectors from the smoldering wood and cotton wick tests were stained light orange throughout. However, of all 30 sounding detectors from the smoldering wood and cotton tests, only two from one particular smoldering cotton test produced enhanced deposition of the tarry residue. It was also noted that the enhanced deposition of the tarry residue only occurred on the inside edge of the horn opening, whereas it was observed on both the inside and outside edges of sounding detectors from the hydrocarbon pool and flaming polyurethane fires (Figure 4 for example). Non-alarming detectors had the light orange deposition throughout the detector, but no increased concentration of the residue on the horn opening. The absence



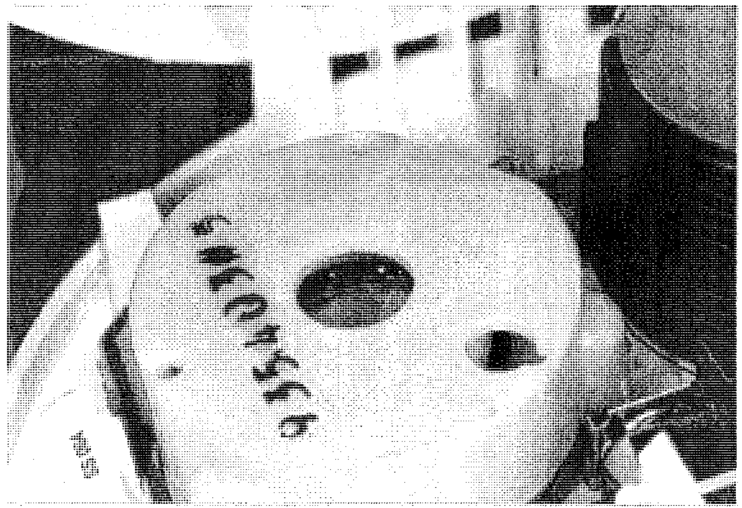
(a)

(b)

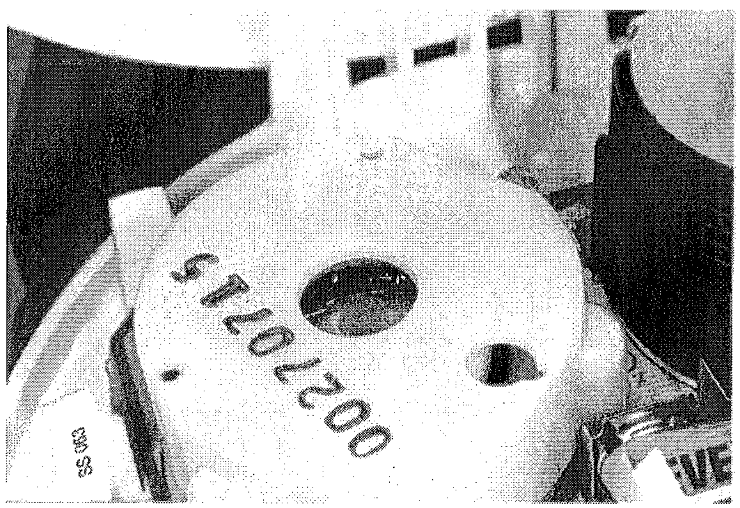
Figure 4. Macroscopic photos of two adjacent detectors exposed to smoke from a heptane/toluene pool fire. The horn in the top photo sounded and the horn in the bottom photo did not sound.

of the concentrated deposition was characteristic of the non-sounding detectors for all of the smoldering fire sources.

Finally, Figure 5 shows a configuration #1 horn that sounded during a flaming paper test and the adjacent detector that did not sound. There was no observable difference in soot deposition around the perimeter of the central horn opening compared to the adjacent



(a)



(b)

Figure 5. Macroscopic photos of two adjacent detectors exposed to smoke from a flaming paper fire. The horn in the top photo sounded and the horn in the bottom photo did not sound. The absence of observable soot deposition is generally representative of detectors from the flaming paper, smoldering paper, flaming wood, smoldering wood (configuration #1 series only), and smoldering cotton wick tests.

area on the top surface of the horn enclosure. This was true for both the outside and inside edge of the horn opening. In fact, very little visible soot was observed throughout either detector. These observations were generally representative of detectors from the flaming paper, smoldering paper, and flaming wood tests.

As also observed by Worrell et al. [1], enhanced deposition occurred for the hydrocarbon pool, flaming polyurethane, and smoldering polyurethane tests around the edges of the smaller configuration #1 horn openings in many detectors that sounded. Enhanced soot deposition around the smaller horn openings can be seen in Figure 4(a). This deposition was similar to that around the central horn opening in that it occurred uniformly around the entire circumference and on both inside and outside edges of the opening. However, the magnitude of deposition around the smaller openings was much less than deposition around the central opening.

In addition, on some of the configuration #1 detectors where a black ring of enhanced soot deposition was evident, enhanced deposition was also observed on the edges of the slotted openings located on the smoke detector lid. This deposition was most notable on the inside edges of the slotted openings. Figure 6 shows an example of this type of deposition. Consistent with findings from Worrell et al. [1] and Munger [11], no Chladni figures were observed on any of the piezoelectric horn discs on any of the 270 configuration #1 detectors, whether they sounded or not.

Several configuration #1 detectors that sounded during one particular polyurethane test contained both an orange ring of enhanced soot deposition and a black ring of enhanced deposition on the same horn. Figure 7 shows an example of such a deposition. Previous observations indicated that a tarry orange deposition occurred during smoldering combustion while the sooty black deposition occurred during flaming combustion of the polyurethane

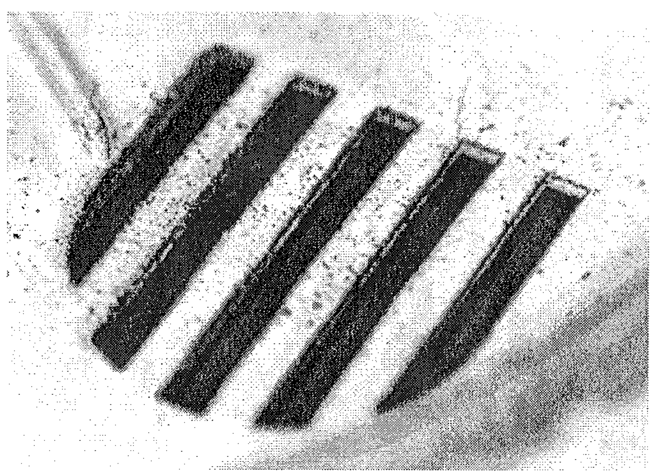


Figure 6. Example of enhanced soot deposition on the inside edges of the slotted openings on a configuration #1 detector lid.

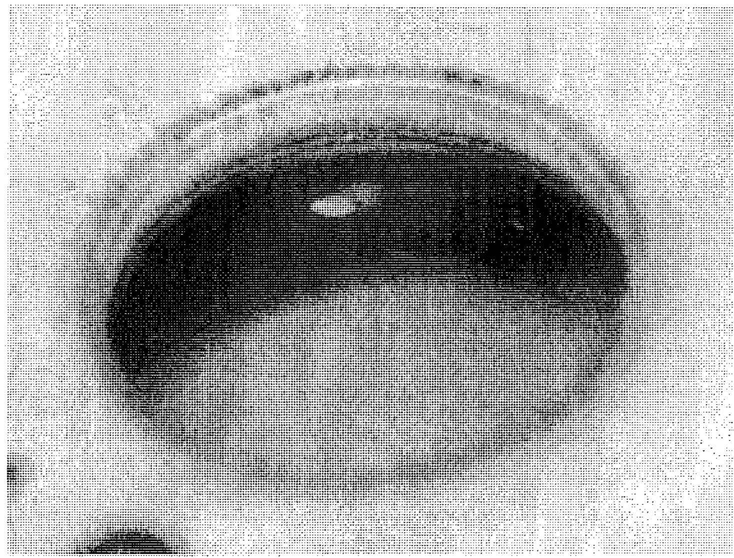


Figure 7. Example of the horn of a detector exposed to smoke from polyurethane foam that initially smoldered and then transitioned to flaming combustion. The horn has both an orange-brown ring, characteristic on horns sounding during smoldering combustion of polyurethane foam, and also a black ring, characteristic on horns sounding during flaming combustion of polyurethane foam.

foam. Indeed, during the progression of this particular test, the polyurethane foam initially smoldered for some time and then transitioned to flaming.

Whether or not enhanced deposition actually formed did not appear to be dependent on the extent of smoke exposure. Figure 8 shows representative values of the smoke concentration, integrated with time, in front of each ceiling mounted detector pair for each test type. This integral was only calculated while the detector was alarming, as this is when the enhanced deposition mechanism occurs. The integral is a measure of the magnitude of smoke the detector was exposed to during alarm. High values of this integral can result from short exposures to high concentration smoke or long exposures to low concentration smoke. Using the smoke obscuration measurements recorded during each test, smoke mass concentration was determined from the following expression:

$$m = \frac{K}{K_m}$$

where m is the smoke mass concentration in g/m^3, K is the extinction coefficient in m^{-1}, and K_m is the specific extinction coefficient in m^2/g. Values for K_m of 7.6 m^2/g for flaming combustion and 4.4 m^2/g for smoldering combustion were taken from Mulholland [17].

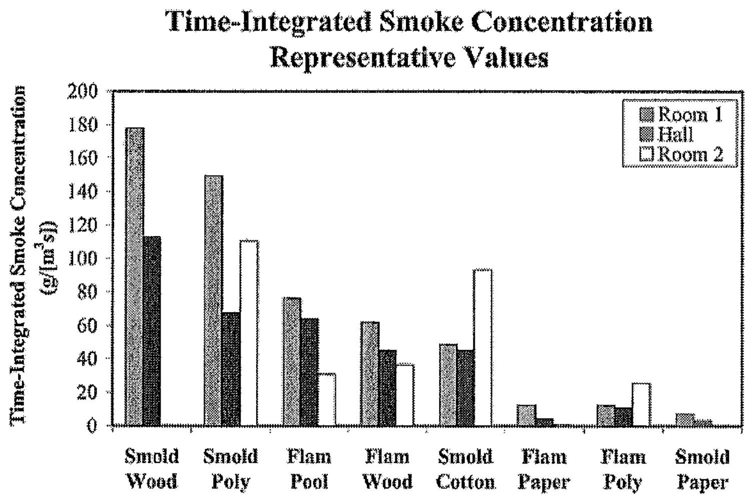


Figure 8. Representative values of the time-integral of smoke concentration in front of each ceiling mounted detector pair for each test type. This integral was only calculated while the detector was alarming.

The extinction coefficient, K, is defined from

$$\frac{I}{I_0} = e^{-KL}.$$

Figure 8 shows that the highest time-integrated smoke concentrations occurred during the smoldering wood tests. However, no pattern of enhanced soot deposition was observed in detectors from these tests. On the other hand, the chart shows that flaming polyurethane produced one of the lightest smoke exposures. Although the smoke exposures during the flaming polyurethane tests were one order of magnitude lower than those during the smoldering wood tests, enhanced soot deposition was clearly observed on detectors from the flaming polyurethane tests. This suggests that the formation of visible enhanced soot deposition pattern is not a result of the magnitude of smoke exposure, but rather a result of the type of smoke the detector is exposed to.

Regarding horn configuration #2, Figures 9 and 10 show examples of the macroscopic observation of one detector that sounded and one that did not for a flaming heptane/toluene and a smoldering wood test. Enhanced soot deposition was observed on detectors that sounded during the flaming hydrocarbon pool, flaming polyurethane foam, and smoldering polyurethane foam tests. This deposition was most notable around the perimeter of the inside edges of the three moon-shaped openings on the detector lid. This location in detectors with horn configuration #2 was similar to the location of deposition observed on the inside edges of the slotted opening of horn configuration #1, however deposition was much heavier on the slotted openings of horn configuration #2. In some detectors, enhanced

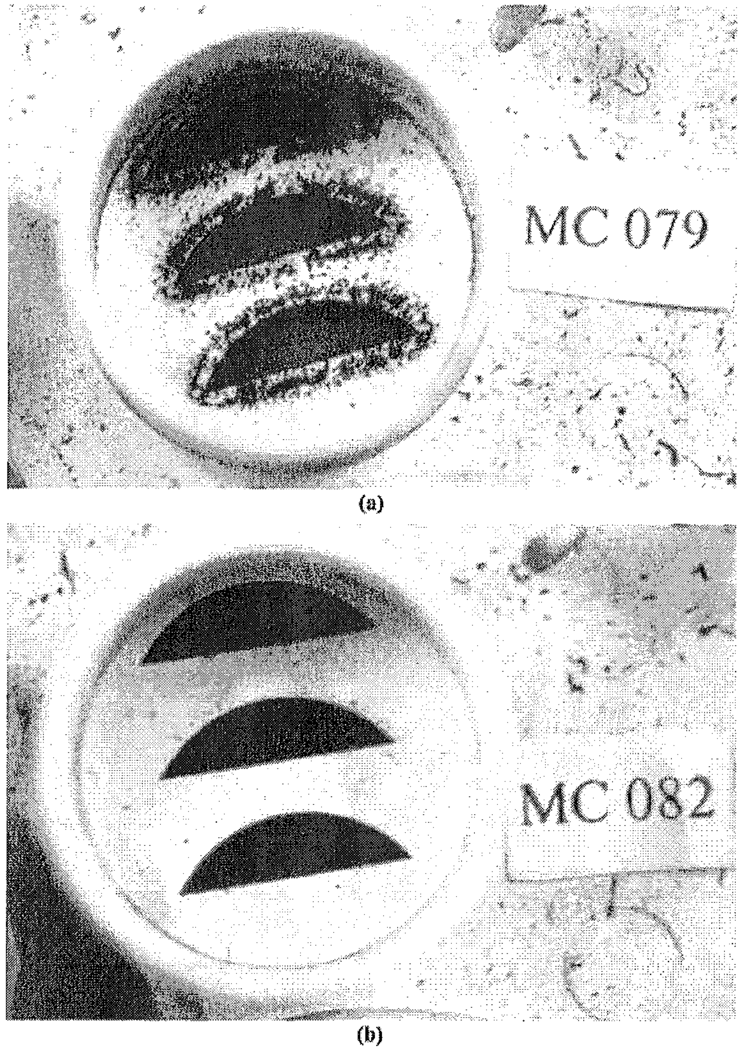
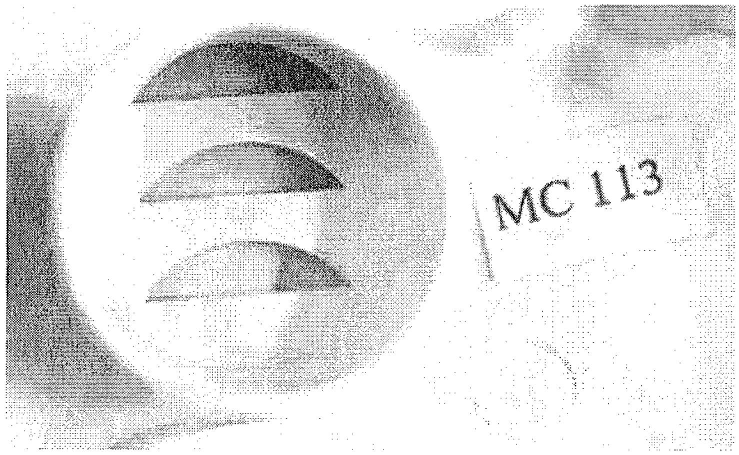
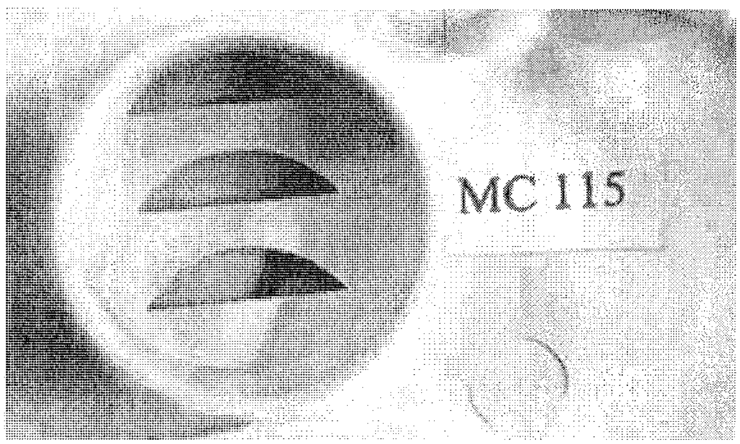


Figure 9. Macroscopic photos of the inside of the moon-shaped slotted openings of two detectors with horn configuration #2. These detectors were exposed to smoke from a heptane/toluene pool fire. The horn in the top photo sounded and the horn in the bottom photo did not sound.

deposition was observed to a lesser extent around the perimeter of the outside edges of the three slotted openings on the detector lid. The enhanced deposition for the hydrocarbon pool and flaming polyurethane foam tests was black and sooty while the enhanced deposition for the smoldering polyurethane foam tests was orange and tarry. Also, the orange



(a)



(b)

Figure 10. Macroscopic photos of the inside of the moon-shaped slotted openings of two detectors with horn configuration #2. These detectors were exposed to smoke from a smoldering wood fire. The horn in the top photo sounded and the horn in the bottom photo did not sound.

enhanced deposition tended to be most notable at the corners of the grated openings. Unlike observations from horn configuration #1, trace amounts of enhanced soot deposition were observed in some of the detectors that sounded during exposure to smoke from the smoldering wood tests. This deposition was minute and found on the inside edges of the moon-shaped slotted openings on the detector lid. Although difficult to see macroscopically, this deposition occurred in the detector in Figure 10(a). Enhanced soot deposition around the inside edges of the grated opening was not observed on any detectors that did not sound.

One detector displayed an obvious ring of black soot deposition on the very edge or far perimeter of the piezoelectric disc in addition to enhanced soot deposition observed on the moon-shaped slotted openings of the detector lid. Such deposition on the perimeter of the horn disc was not observed in any detectors that did not sound.

"Blind" Microscopic Determinations

The microscopic determinations were consistent with the macroscopic observations; however, on some detectors the microscopic inspection revealed enhanced deposition and agglomerates that were not macroscopically apparent. This occurred in particular with detectors from the flaming polyurethane foam tests, which generally had very light soot deposition due to the small fire source and resulting small smoke exposure (see Figure 8).

Figures 11–14 show examples of the microscopic observations of the central horn opening of pairs of configuration #1 detectors from a flaming polyurethane, smoldering polyurethane, and flaming paper test. Figure 11 shows the outside edge of a sounding and non-sounding detector exposed to flaming polyurethane smoke. A band of fine carbon soot particles, spaced closely together, is apparent around the perimeter of the horn opening. Some larger agglomerate structures are also present at the very edge of the horn opening. On the other hand, very little visible deposition is present on the non-sounding detector despite being exposed to the same smoke exposure as the sounding detector. Figure 12 shows the inside edges of a sounding and non-sounding detector exposed to smoke from flaming polyurethane. A small mirror carefully inserted through the central horn opening was used to take these photographs. Again, a band of closely spaced soot particles is observed around the perimeter of the opening edge. In addition, this view also shows that enhanced deposition also occurred on the wall, close to the edge of the opening. Again, the non-sounding detector displays very little visible soot deposition. Finally, Figure 13 shows the inside edges of a sounding and non-sounding detector exposed to smoke from smoldering polyurethane. The sounding detector displays a very obvious band of liquid-like, tarry orange deposition near the inside edge of the opening. This band of deposition also extended onto the wall of the horn opening. The orange band is in clear contrast with the adjacent horn surface, which displays very little evidence of soot deposition. For these three fire types, many of the sounding horns that had significant soot deposition also displayed enhanced deposition on the edges of the smaller horn openings. On detectors that did not sound, but had enough soot deposition to be classified, soot deposition was uniform across the edges of the horn openings and the area adjacent to these edges. In other words, there were no observable rings of enhanced soot deposition on either the central horn opening or the smaller horn openings of detectors that did not sound during the testing.

For configuration #1 detectors that had enough soot deposition to be classified, determinations were made with a success rate of 100%; however, many of the horns did not have enough soot deposition to make a determination either way. In other words, many horns did not have enough soot deposition to compare deposits between the edge of the horn opening and the adjacent areas. Table 2 shows that this was especially true for the flaming wood, smoldering wood, flaming paper, smoldering paper, and smoldering cotton wick tests. 98% of detectors were marked as "undetermined" for these tests. In general,

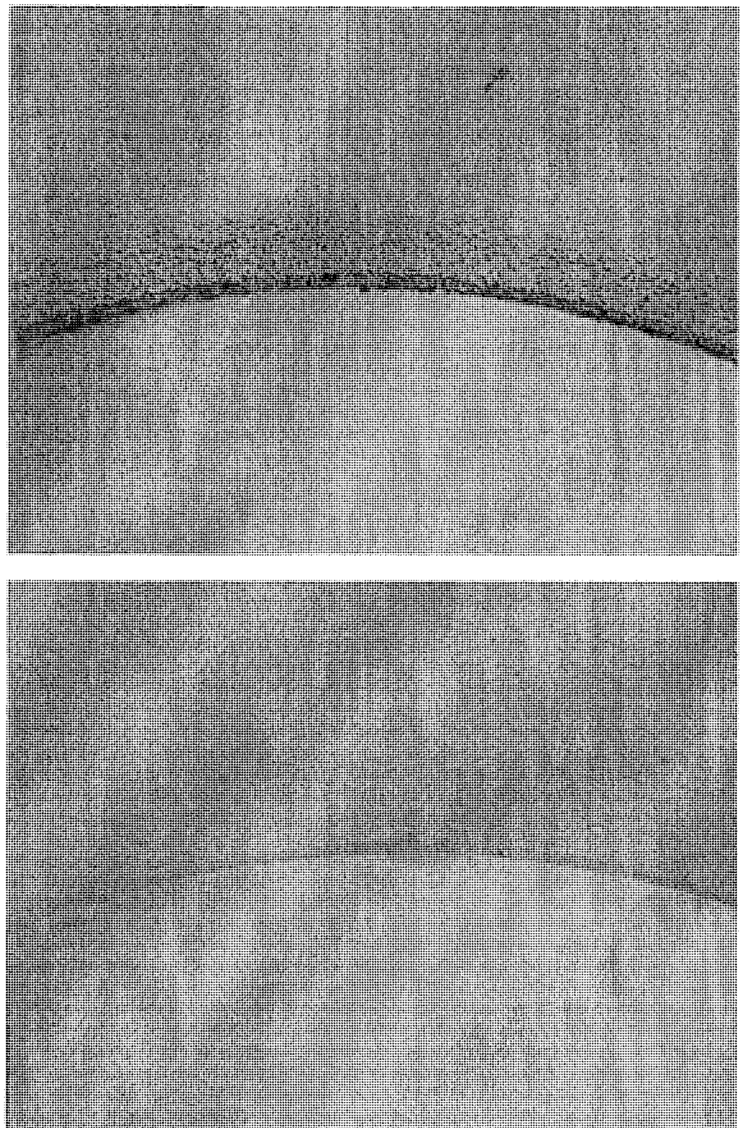


Figure 11. Microscopic photos of the outside edge of the central horn opening of two adjacent detectors exposed to smoke from a flaming polyurethane fire. The horn in the top photo sounded and the horn in the bottom photo did not sound.

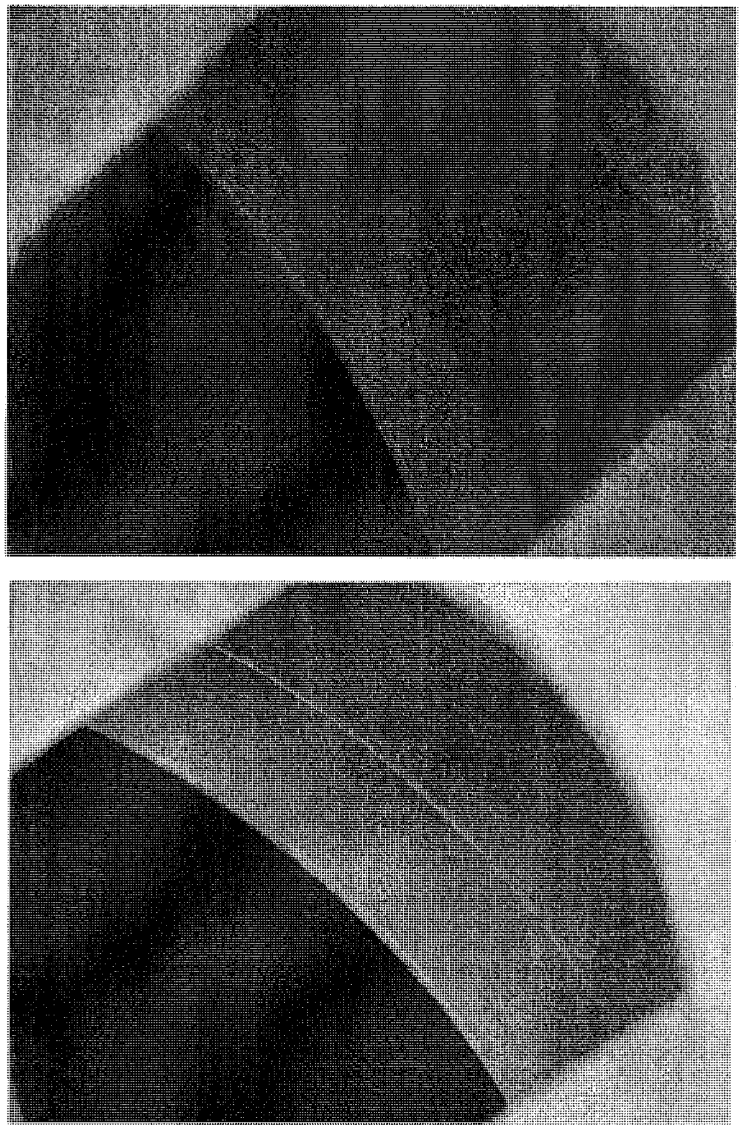


Figure 12. Microscopic photos of the inside edge of the central horn opening of two adjacent detectors exposed to smoke from a flaming polyurethane fire. The horn in the top photo sounded and the horn in the bottom photo did not sound.

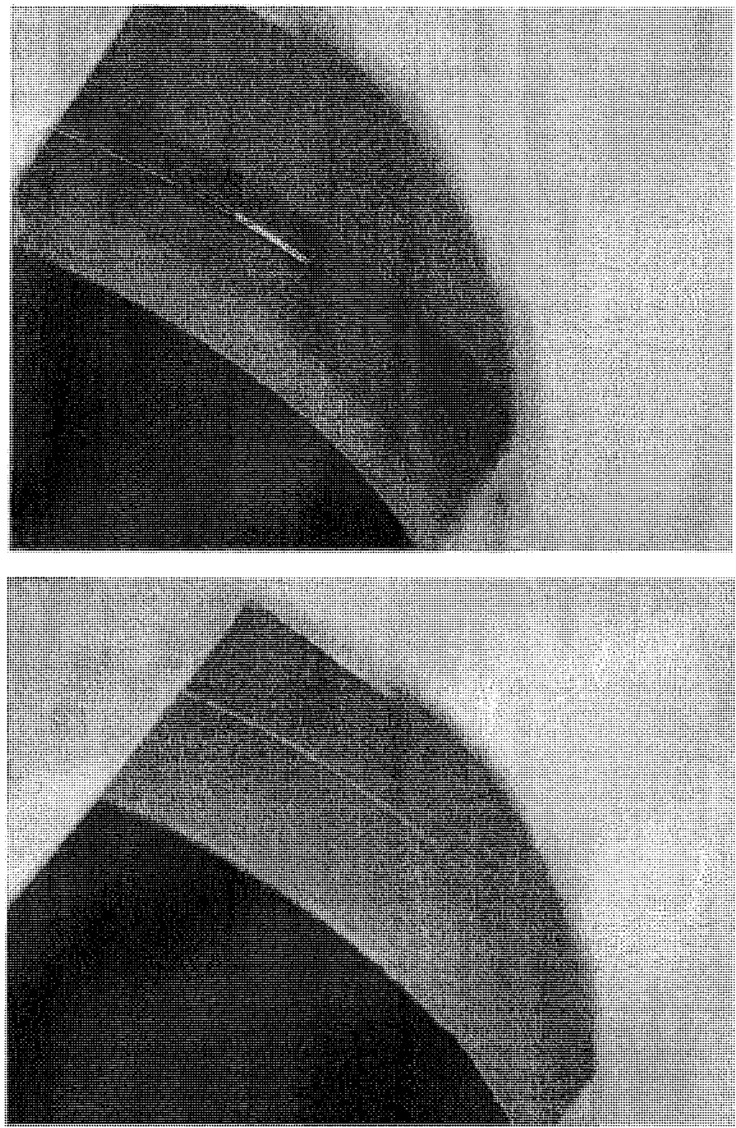


Figure 13. Microscopic photos of the inside edge of the central horn opening of two adjacent detectors exposed to smoke from a smoldering polyurethane fire. The horn in the top photo sounded and the horn in the bottom photo did not sound.

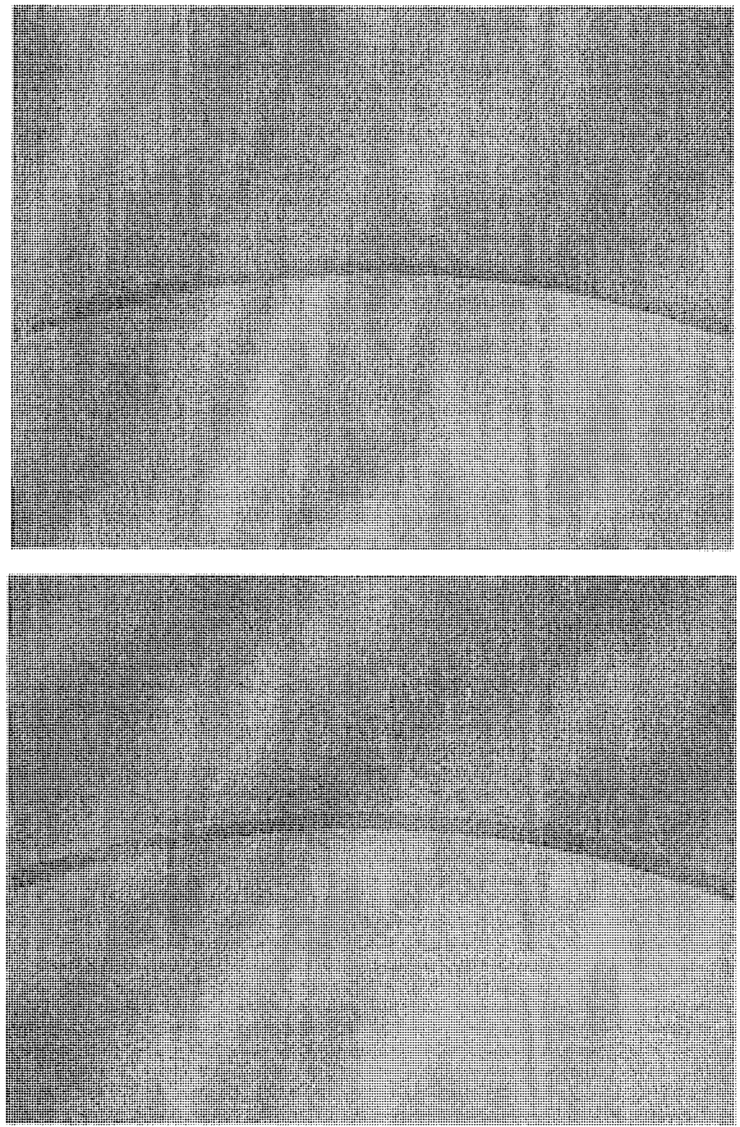


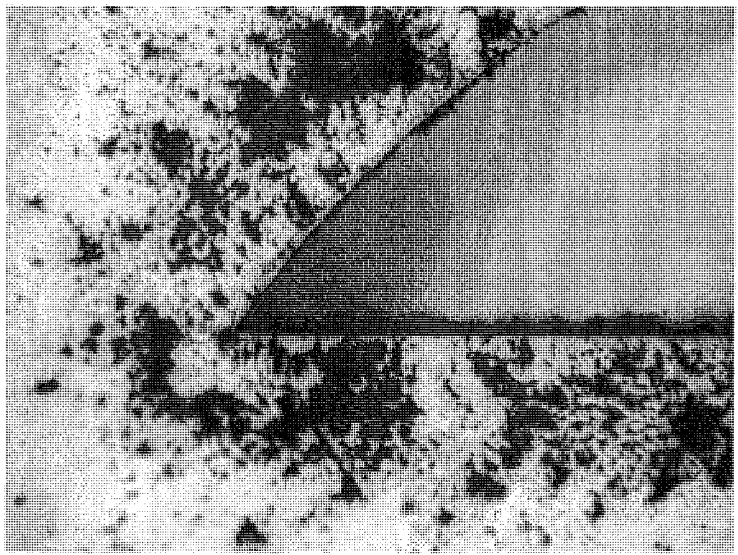
Figure 14. Microscopic photos of the outside edge of the central horn opening of two adjacent detectors exposed to smoke from a flaming paper fire. The horn in the top photo sounded and the horn in the bottom photo did not sound. These detectors were representative of the detectors that did not display observable soot deposition.

very little soot deposition was visible on these detectors. Figure 14 shows an example of a sounding and non-sounding detector that, after exposure to smoke from flaming paper, that did not have enough visible soot deposition to make a determination. For these "undetermined" detectors, use of a UV light source did not illuminate any soot deposits that were not visible to the naked eye. Additionally, a ring of a clear, crystalline substance was noticed on the inside edges of some of the horn openings. The presence of this crystalline ring did not have any correlation with whether the detector sounded or not and is believed to be a natural occurrence in the manufacturing of these horns.

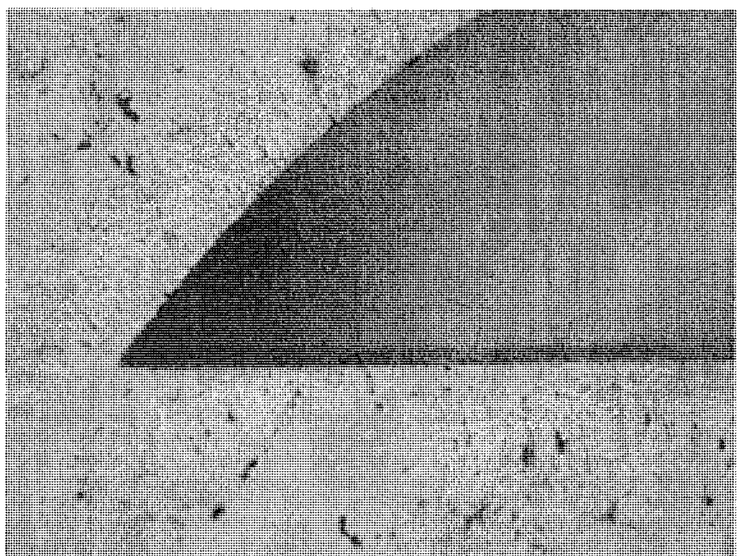
Regarding horn configuration #2, Figures 15–18 each show examples of soot deposition observed on some detectors that sounded and some that did not for tests with flaming heptane/toluene, smoldering polyurethane, and smoldering wood, and a smoldering polyurethane test that transitioned to flaming. Each photo depicts the inside surface of the detector lid, with focus on a corner of one of the three slotted openings. As with configuration #1, microscopic examination revealed enhanced soot deposits and agglomerates that were not visible to the naked eye in several cases. Again, this occurred in particular for the flaming polyurethane fires, which generated a very light smoke exposure (see Figure 8). The enhanced soot deposition was most visible around the perimeter of the inside edges of the three moon-shaped slotted openings for the horns that had enough soot to be classified.

The qualitative nature of the deposits in horn configuration #2 for each fire type was generally consistent with observations from the test series with configuration #1. Figure 15(a) shows the inside edge of one of the moon-shaped openings in a detector that sounded to a flaming heptane/toluene pool fire. Soot deposits are clearly much larger and more densely packed near the edge of the opening. On the other hand, Figure 15(b) is a non-sounding horn from a heptane/toluene pool fire test. Soot particles are evenly spaced and sized across the edge of the horn opening and the surrounding areas. Figures 16(a) and (b) show this inside edge for a sounding and non-sounding detector exposed to smoke from smoldering polyurethane. Figure 16(a) shows that the tarry orange deposition was concentrated at the corners of the inside edge in the sounding detector and absent in the non-sounding detector. On the other hand, Figure 17 shows that the tarry orange deposition occurred uniformly around the horn openings of sounding horns for the smoldering wood tests. Figure 18 shows the inside edge in a horn exposed to smoke from polyurethane that initially smoldered and then transitioned to flaming combustion. Again, both tarry orange deposits characteristic of smoldering combustion and black sooty deposits characteristic of flaming combustion were present. Inconsistent with observations from the horn configuration #1 test series, enhanced deposition of the tarry orange substance was also observed in detectors alarming while exposed to smoke from smoldering wood.

Determinations were made with a success rate of 100% for detectors with horn configuration #2 that had enough soot deposition to be classified. The presence or absence of enhanced deposition and agglomerates on the *inside* edges of the three moon-shaped slotted openings proved to be the most reliable determination source. Although about 88% of detectors from the smoldering tests were marked as "undetermined" due to lack of soot particles, the presence of increased deposition of the tarry, orange substance at the corners of the inside edges of the three moon-shaped slotted openings did appear to be a reliable indicator that the detector activated.

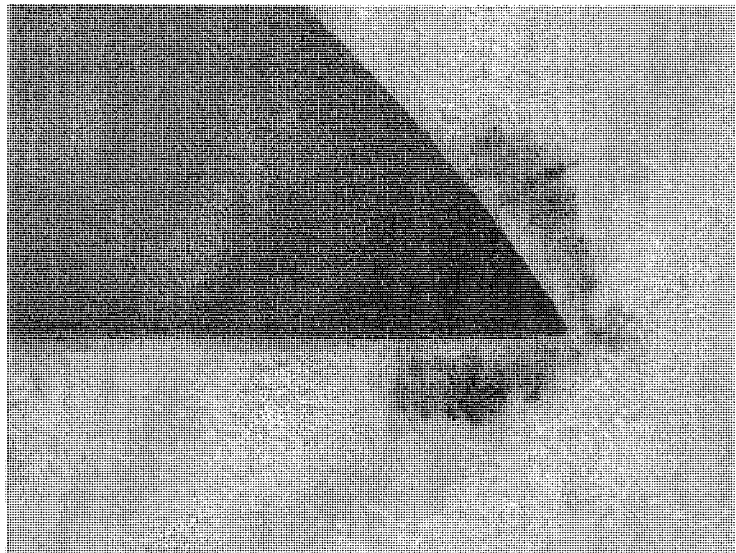


(a)

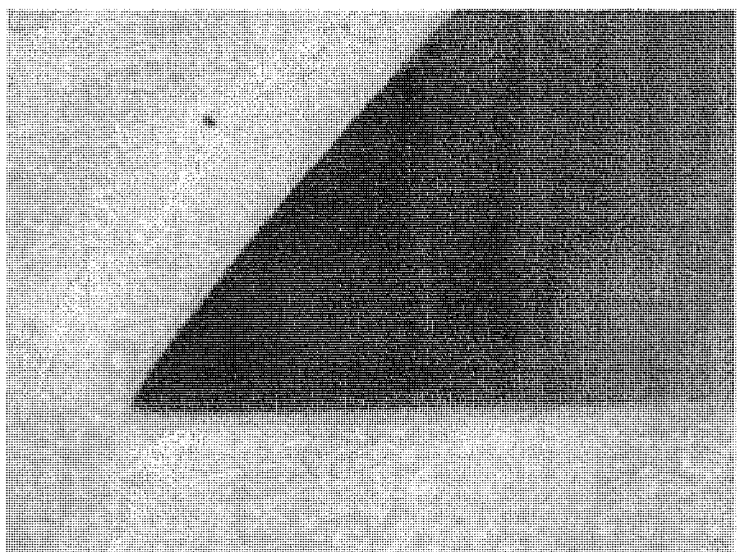


(b)

Figure 15. Microscopic photos (20×) of two detectors exposed to smoke from a heptane/toluene pool fire. The horn in the top photo sounded and the horn in the bottom photo did not sound.



(a)



(b)

Figure 16. Microscopic photos (40×) of two detectors exposed to smoke from smoldering polyurethane. The horn in the top photo sounded and the horn in the bottom photo did not sound.

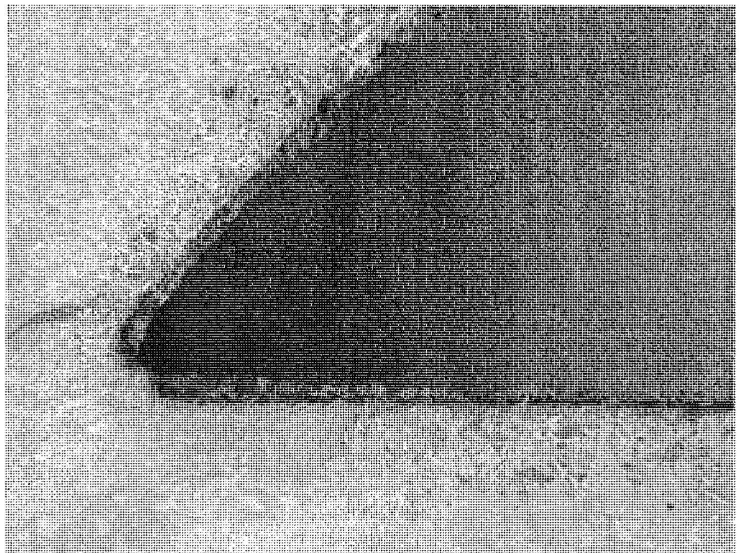


Figure 17. Example of enhanced deposition of a tarry orange substance observed on a horn that sounded during a smoldering wood test.

Small-Scale Visualization Tests

Tests conducted with both horn configurations showed clearly that the presence of enhanced soot deposition and agglomerates in alarming detectors could be explained by an acoustically induced flow field that fostered particle growth and deposition. The following includes observations from the small-scale smoke flow visualization tests.

The visualization tests for horn configuration #1 showed that the alarming piezoelectric horn created a flow field that drew smoke particles toward and through the horn opening. The alarm signal consisted of a three-pulse temporal pattern, which is required by NFPA 72 [18] and specified by ANSI S3.41 [19]. With each sounding of the horn, a strong pulse of smoke was forced out of the horn case through the center of the horn opening. Simultaneously, a pulse of smoke was drawn into the horn around the perimeter of the opening. As with any flow passing through an orifice, a recirculation zone was induced at the edge of the horn opening. Although the setup could not visualize smoke flow inside the horn case, it is expected, based on fluid mechanic principles, that a similar recirculation zone would form near the inside edge of the horn opening.

The pulsing flow field was most easily observed when the horn opening was exposed to smoke generated by burning a small amount of pure toluene since this produced a thick field of soot particles. Figure 19 shows a photo series of the smoke flow field generated over the course of a single pulse of the detector horn. Frame-by-frame processing of the digital video recorded during the visualization tests provided these photos. Each photo shows a side view of a configuration #1 smoke detector horn and the smoke, illuminated by the laser

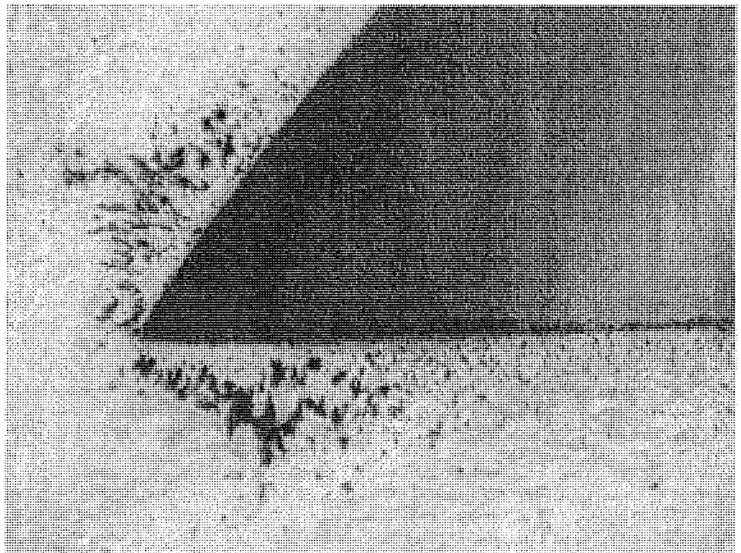


Figure 18. Example of a detector exposed to smoke from polyurethane foam that initially smoldered and then transitioned to flaming combustion. The horn has both tarry orange deposits, characteristic on horns sounding during smoldering combustion of polyurethane foam, and also black soot deposits, characteristic on horns sounding during flaming combustion of polyurethane foam.

light sheet, passing beneath it. The two marks on the side of the horn indicate the location of the central opening located on the bottom face of the horn. Figure 19(a) shows smoke passing underneath the horn just before it sounds. Figure 19(b), (c), and (d) show the smoke flow through the duration of the "beep." These three photos clearly show the jet outflow of smoke from the center of the horn opening and the simultaneous smoke inflow around the perimeter of the opening. The recirculation zone at the outside edge of the horn opening is also visible in Photos 19(c) and (d). Photos 19(e) and (f) show the flow after the "beep" terminates. These photos were extracted from the digital video at a frequency of six frames per second. The same pulsing flow field, which drew smoke toward and through the horn opening, was observed for smoke generated by all eight of the UL and EN style test fires. Figure 20 shows the same flow field for a smoldering wood test, which, in contrast to the pool fire tests, generally did not produce observable deposition on the detector during the configuration #1 test series. This observation seems to indicate that a particular qualitative nature of the smoke coupled with the flow field leads to the enhanced deposition patterns. The absence of one of the two elements would result in no enhanced deposition patterns.

The visualization tests for horn configuration #2 showed that smoke near the moon-shaped slotted openings of the detector lid was clearly influenced by the alarming horn. Figure 21 shows that an acoustically induced smoke flow occurred when the horn sounded. Each pulse of the alarming horn formed eddies near the edges of the slotted openings,

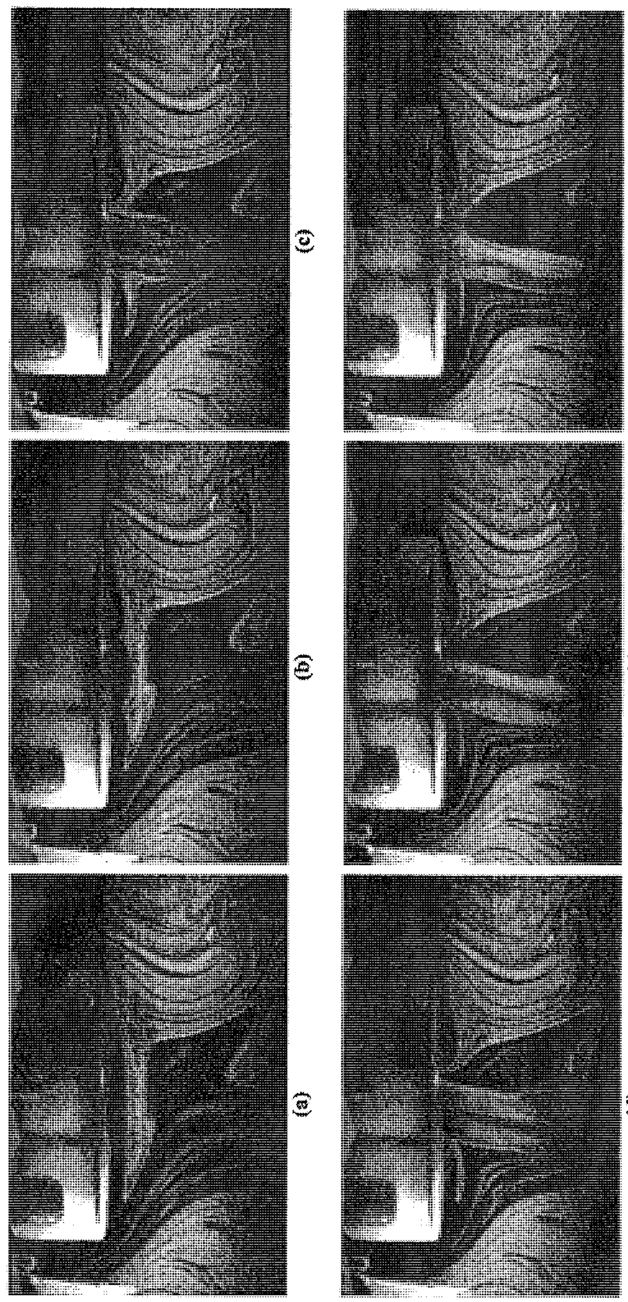


Figure 19. Smoke flow field created by single "beep" of a configuration #1 detector horn visualized using smoke from burning a small amount of pure toluene.

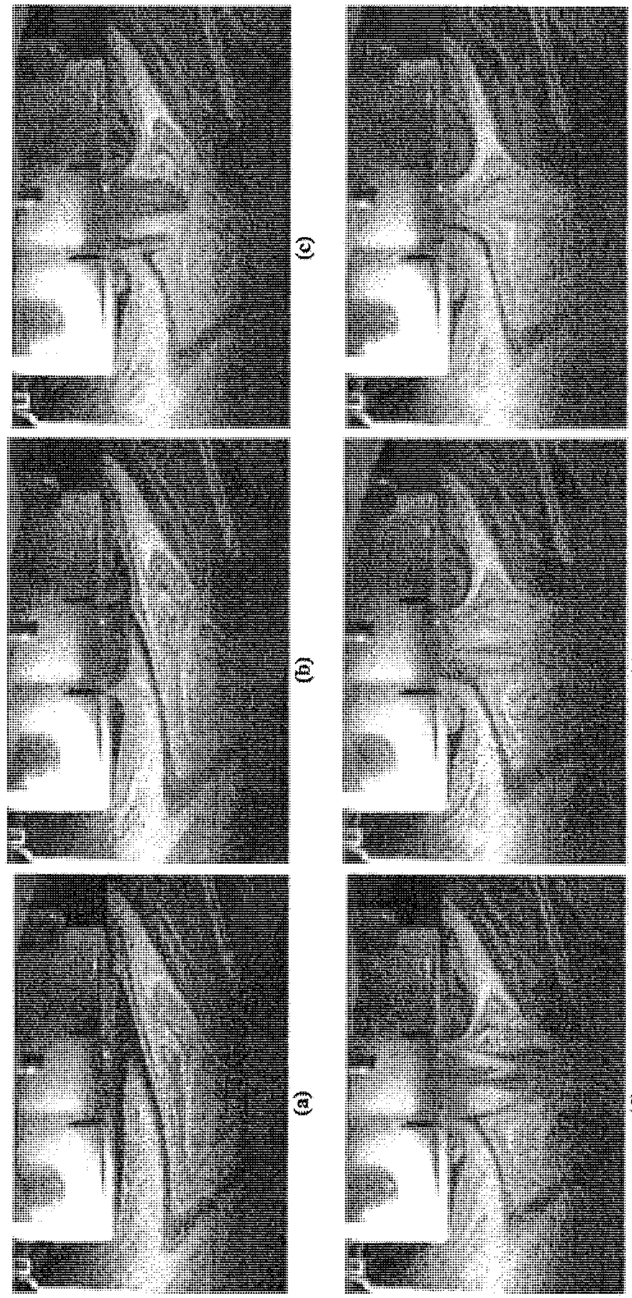


Figure 20. Smoke flow field created by single "beep" of a configuration #1 detector horn visualized using smoke from "smoldering" a small amount wood.

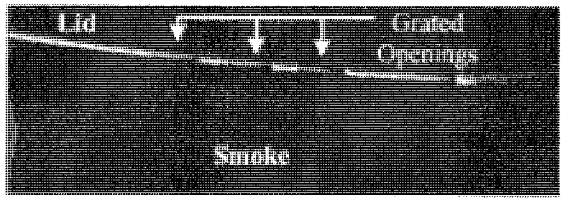


Figure 21. Photo shows acoustically induced flow field established with each pulse of an alarming detector with horn configuration #2. The white diagonal line is the surface of the detector lid. Everything below the lid is smoke. The area above the line is the detector lid. The three lighter areas of the white line are the three grated openings.

and smoke was drawn in through the slots. Due to the geometric complexity of the slotted openings and the small scale of the observed flow structures, a precise flow field could not be established. That is, the exact path of smoke inflow and outflow is unclear. However, it is certain that smoke inflow and recirculation eddies were induced by the alarming horn. The acoustically induced flow was observed for all of the different test fires that detectors with horn configuration #2 were exposed to.

Smoke Box Tests

Figure 22 shows the central horn opening of a smoke detector (horn configuration #1) after alarming for 4, 12, and 30 minutes while exposed to smoke from the 6.4 cm (2.5″) heptane/toluene pool fire described in the experimental setup section. The photo series shows clearly that soot deposition around the perimeter of the horn opening increases with increasing duration of the smoke exposure. Firstly, the soot deposition increases in darkness with increasing exposure time. This corresponds to an increased surface density of soot particles. That is, more particles deposit onto the horn as exposure time increases. Secondly, the boundary between the enhanced soot deposition and the unaffected horn surface appears to move radially away from the center of the horn opening as the exposure

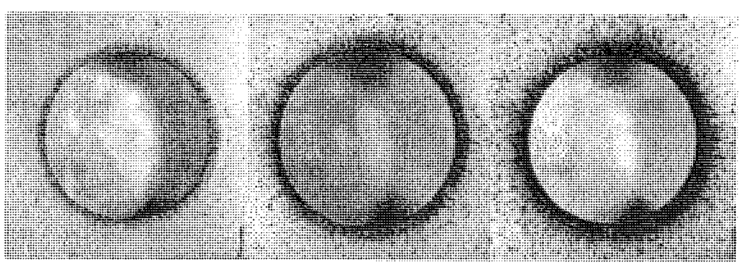


Figure 22. Central horn opening of a smoke detector (horn configuration #1) after alarming for 4, 12, and 30 minutes to smoke from the 2.5 inch heptane/toluene pool fire described in experimental setup section.

time increases. In other words, the ring of enhanced deposition increases its surface area with increased exposure time. Finally, it was also observed that the soot deposition increased in height above the horn surface with longer exposure times. That is, soot particles were visibly piled and raised above the horn surface for longer exposure times.

Discussion

Enhanced black soot deposition was clearly observed on detector horns that sounded during the flaming hydrocarbon pool and flaming polyurethane foam tests. Tarry, orange deposition was observed on most of the sounding horns from the smoldering polyurethane tests and on some of the sounding horns from the smoldering wood and smoldering cotton tests. This enhanced deposition was found to occur regardless of detector orientation or placement (i.e. ceiling or sidewall). Such depositions were not observed on horns from tests with flaming paper, smoldering paper, and flaming wood tests. However, the flow visualization study clearly demonstrated that the acoustic flow field causing the enhanced deposition occurred for all types of smoke investigated, including those that did not cause visible enhanced deposition.

The observation that the acoustic flow field causing enhanced deposition occurred with all smokes suggested that some form of enhanced deposition did occur on the horns that sounded during the flaming paper, smoldering paper, and flaming wood tests, but that this deposition was invisible with the macroscopic and microscopic inspection techniques utilized. UV illumination did not reveal such deposition either. The smoke generated by the flaming hydrocarbon pool and flaming polyurethane foam tests was black in color, indicating high carbon content. Composition of the remaining types of smoke is less clear based on qualitative observations of the smoke during testing alone.

Based on a series of smoke particle characterization studies, Bankston [20] described smoke particles generated by smoldering combustion as droplets composed of "a complex mixture of liquid and/or solid organic materials". In the present study, the enhanced deposition of smoke droplets from smoldering polyurethane in sounding horns created a visible tarry orange-brown residue. The qualitative nature of this deposition has been observed in previous studies [14–16].

Regarding the smoldering wood tests, visible deposition was not observed in the test series for horn configuration #1; however a tarry orange deposition, similar to that observed for the smoldering polyurethane tests, was observed in detectors from the smoldering wood tests for horn configuration #2. One possible explanation is that pure smoldering was achieved in the second test series, whereas pyrolysis was the major smoke source in the first test series. Responding to such suspicions, a much higher heat flux setting was used on the hotplate for the second test series.

At this point, it is unclear why smoke from smoldering paper and smoldering cotton wick generally did not lead to visible soot deposition. As an exception, the tarry deposition was observed on two (2) of the 15 sounding detectors from the smoldering cotton tests. Bankston and Powell's studies [14, 20–23] did document a high liquid content for smolder smoke particles in general. One possible explanation for the lack of visible deposition of smoke from smoldering paper and cotton wick is that the liquid smoke droplets contained a larger fraction of water, whereas the droplets from the smoke produced by smoldering polyurethane had higher "large hydrocarbon" content. The presence of water is also suggested by the white color of the smoke for these two fuels. After such particles deposit onto the detector horn, the water content may evaporate leaving behind only a small nucleation particle and/or a light residue. Such deposits could not be detected with the inspection techniques utilized in this study. Investigation of much higher magnification techniques such as scanning electron microscopy or even fluorescence of polycyclic aromatic hydrocarbons (PAH) may prove useful for visualizing such deposits.

A similar phenomenon may be responsible for the lack of visible soot deposition from smoke produced by flaming wood and flaming paper. Although it was generalized that flaming fires produce predominantly carbonaceous smoke, Bankston found evidence of a significant liquid or tar fraction in smoke from flaming wood [22]. He suggested that this might be attributed to the formation of a char layer causing the flame to be "more unstable and less efficient... causing pyrolysis products to escape without passing through the flame reaction zone" [22]. A similar effect might occur for the flaming paper scenario if the fire were ventilation restricted. A degree of ventilation-restricted combustion is not inconceivable with the UL217 flaming paper test since the shredded paper is tamped together into a 30.5 cm (1 foot) tall metal cylinder with a 10.2 cm (4″) diameter.

In practice, the current inability to visualize deposits of smoke from flaming paper, smoldering paper, flaming wood, and in many cases, smoldering wood, and smoldering cotton wicks is not likely to be significant. The standardized UL/EN style tests were designed to provide a very light smoke exposure intended to challenge the sensitivity of a detector to respond early in a fire. It is believed that the light smoke exposure during the flaming polyurethane tests resulted in the large number of detectors that did not have enough soot deposition to make determinations. Such a light exposure is not comparable to the heavy smoke exposure a detector would be exposed to throughout the course of an unwanted fire. A heavier, sooty smoke exposure is expected during unwanted fires for two reasons: (1) The standard test fires generally reach steady state relatively quickly and then decay. On the other hand, an unwanted fire generally continues to grow until it becomes ventilation limited, at which point very sooty smoke is produced; and (2) unwanted fires generally involve a mixture of fuels including polyurethane foam, upholstery, wood, and many others, while the UL/EN fires generally involve single-substrate fuels. Indeed, during the full-scale house fire test [1], only one of the *smoke* detectors had too little soot to make a determination, and this was a detector located the farthest from the fire origin.

At this point, it should be emphasized that the current methodology for determining *whether* a detector sounded does not give information as to *when* the detector sounded during a smoke exposure. At present, if enhanced deposition and soot agglomerates are observed on a detector horn recovered from a fire scene, it can only be concluded that the detector sounded at some point during the smoke exposure. The smoke box study in which a detector was permitted to alarm for an incrementally increasing duration did show clearly that the extent of observed soot deposition increased with increasing alarm duration. So, with additional research, it may be possible to estimate the duration of alarm if the extent of enhanced soot deposition can somehow be quantified. Such quantification might include measuring the surface density of particles deposited onto the horn (i.e. how closely spaced the particles are), a mass measurement of the deposition, or perhaps the radial thickness of the deposit with respect to the center of the horn opening. A practical limitation of estimating alarm duration is the uncertainty in the smoke concentration profile that occurred during the fire. Another potential limitation is the possible formation of a critical mass of soot deposition above which soot would no longer accumulate despite continued alarming. If the alarm duration could be estimated and the time at which the detector stopped alarming was known (e.g. time at which power to residence was shut down), the time at which the detector began alarming may be estimated. These potential applications require the development of a repeatable relationship between the smoke concentration profile and a quantitative measurement of the enhanced soot deposition.

The visualization study clearly demonstrated that the acoustic field of an alarming horn strongly affects the flow of local smoke with both horn configurations. This suggests that areas of enhanced soot deposition may form in many devices that create a strong acoustic field during a smoke exposure. Provided that they are sounding during the smoke exposure, areas of enhanced deposition may occur in other models of smoke detectors, audible notification appliances, or even infrared motion detectors used as burglar alarms. Flow visualization studies similar to the one described in this paper can be performed to determine locations within a given unit where enhanced deposition will occur. In addition, numerical modeling could establish the precise structure of the flow fields.

Some of the detectors used in the flaming polyurethane foam tests showed that microscopic inspection can visualize enhanced soot deposition that is not seen macroscopically. In these cases, the macroscopic invisibility of the enhanced deposition was often the result of very light soot deposition. On the other hand, in the full-scale house fire test [1], soot deposition was generally heavy and dark throughout the detectors. Such heavy deposition is expected in full-scale fires. Because deposition may be heavy throughout the detector, enhanced soot deposition may be difficult to discern without microscopic inspection, especially inside the horn housing. In addition, some of the horns in the full-scale study [1] were severely deformed due to heat exposure. These horns tended to collapse in on themselves when exposed to heat, making simple exterior macroscopic inspection more difficult. In these cases, the use of a small mirror or removal of the horn and disc from the circuit board to look at the underside of the horn openings proved helpful. In addition, only microscopic inspection can detect the presence of large soot agglomerates, which is an indicator that the horn sounded. These findings indicate the importance of microscopic inspection when determining whether a detector sounded during a fire.

The formation of large soot agglomerates is acoustically induced and a result of the horn sounding. Agglomeration refers to the growth of soot particles when they collide and adhere together. It has been well established that exposure of soot particles to an acoustic field greatly increases the rate of agglomeration or particle growth [3–7]. A second mechanism resulting in particle growth may be the formation of recirculation eddies at the inside and outside edges of the horn opening. These recirculation eddies can lead to long soot particle residence times, allowing for more particle collisions and agglomeration to take place. The recirculation eddy near the outside edge of the horn opening is most visible in the photo series shown in Figure 20. From fluid mechanic principles, a similar recirculation eddy is expected to form near the inside edge of the horn opening; however, this could not be visualized due to the opacity of the horn. Finally, the smoke flow visualization study showed that the alarming horn drew smoke in through the horn opening, resulting in soot deposition around the perimeter of the opening. This acoustically induced flow may be an additional mechanism resulting in particle growth on the horn surface due to a stacking of smaller soot particles on top of each other. For these reasons, microscopic inspection for the presence of soot agglomerates on the central horn opening of horn configuration #1 and the inside edges of the slotted opening of horn configuration #2 should be performed and taken as an indication that the horn sounded.

The presence of enhanced soot deposition around the central horn opening of horn configuration #1 and slotted opening of horn configuration #2 was found to be a reliable indicator that the horn sounded. Results from this and the previous study [1] suggest that if enough soot is present, the lack of enhanced soot deposition on the horn openings is a good indicator that the detector did not alarm. In fact, all of the detectors in these studies that were microscopically determined not to have sounded did indeed fail to sound. This observation should however be noted with caution because there may exist situations in which the alarm sounded but enhanced deposition is difficult to detect. Examples of situations that make enhanced deposition difficult to notice include extreme heat deformation and melting of the horn or excessive jarring/scraping/smearing that might occur during overhaul operations. Another conceivable scenario is that during a real fire, the detector may initially alarm but become so thermally damaged later in the fire that the horn stops sounding. If the fire were to continue, soot deposition would continue to accumulate on the detector after it had ceased sounding. Such an additional soot buildup could make the enhanced ring of soot deposition that formed while the horn was sounding difficult to detect. On the other hand, given that the flow visualization study clearly showed an acoustically induced smoke flow during alarm, it is difficult to imagine a scenario that could create a uniform ring of enhanced soot deposition on the central horn opening in configuration #1 or around the perimeters of the slotted openings in configuration #2 without the alarm having sounded.

Regarding handling practices, experience from the present study and the full-scale house fire test [1] indicated that the enhanced soot deposition was resistant to damage from normal evidence handling practices, such as those described in NFPA 921 [24]. Care should be taken to avoid direct contact with the horn as this may cause smearing of any soot deposition present. Preferably, the detector should be handled with its lid closed to reduce the risk of an object contacting the horn surface. Consideration should also be given to the state in which the detector is found in the field. For example, if the detector is found underneath a pile of drywall with its lid broken off, the investigator should be aware of the possibility of damage to soot deposition on the horn.

Chladni figures were not observed on any of the piezoelectric discs or horn case in any of the 270 detectors with horn configuration #1 from this study. This is consistent with Munger's investigation [11]. No Chladni figures were observed on any of the piezoelectric discs in any of the detectors from the previous full-scale study [1]. As previously noted, an obvious circular soot deposition around the perimeter edge of the piezoelectric disc was observed in one of the 119 detectors that alarmed with horn configuration #2. Whether this deposition is related to a nodal pattern of the disc or some other phenomenon is not known. A type of Chladni figure was observed on the top surface of one of horn cases from the full-scale test. The fact that this particular form of a Chladni figure was observed on only one of 294 total configuration #1 detectors tested in this and the previous study [1] reinforces the idea that these patterns form under a very narrow set of conditions. So, it is strongly recommended that the absence of a wagon wheel or circular Chladni figure on the piezoelectric disc not be taken as indication of non-activation of the detector.

Enhanced deposition observed on the edges of the slotted opening above the horn can provide additional support that a configuration #1 horn sounded. It is not recommended to use deposition on this grating as the sole indicator of activation or non-activation. Instead, enhanced deposition or the lack of enhanced deposition around the central opening of the configuration #1 horn case should be used as the primary indicator of activation or non-activation since the acoustically induced smoke flow is strongest at this part of the detector. As a result, any enhanced soot deposition will be most apparent at this location. Following the same logic, the presence or absence of enhanced deposition around the three smaller horn openings can provide additional support as to whether the horn sounded. Regarding horn configuration #2, deposition on the inside edges of the slotted openings proved the most reliable indicator of activation. Deposition on the outside edges of the slotted openings was generally lighter, and its presence should only be taken as additional support of the conclusion based on the inside edges.

Qualitative observation of the soot deposited on smoke detectors may provide information about the development of the fire. Black carbonaceous soot deposition was observed in detectors exposed to smoke from flaming polyurethane foam. Orange tarry deposition was observed in detectors exposed to smoke from smoldering polyurethane foam. The presence of both orange enhanced deposition and black enhanced deposition on the sounding horns shown in Figures 7 and 18 reflected the fact that the polyurethane fuel underwent both smoldering and flaming combustion. Further, the presence of the both orange and black enhanced deposition indicated that the detector was alarming during both smoldering and flaming phases. This may apply not only to smoke detectors but also to soot deposition throughout the fire scene. Due to the limited nature of this study, it is not known whether this orange liquid-like deposition would survive in detectors with a significant heat exposure, as may be expected during a real fire. As a result, it is only suggested that the observation of such deposition yields information about the fire source, but it cannot yet be stated that such deposition would be observed in all detectors from actual fires that smoldered and transitioned to flaming.

Conclusions

Enhanced soot deposition and the presence of agglomerates on the edge of the central horn opening in a smoke detector with horn configuration #1 was found to be a reliable indicator that the detector sounded during an exposure to smoke from flaming hydrocarbon pool, flaming polyurethane foam, and smoldering polyurethane foam fires. The presence of enhanced deposition and agglomerates around the perimeter of the inside edges of the slotted openings in horn configuration #2 was also a reliable indicator of activation. If enough soot deposition was present within the detector, the absence of an increased density of soot deposited around the edges of the primary horn openings was an indicator that the horn did not sound. However, for reasons discussed in this paper, a determination of non-activation is inherently more subjective than determination of activation and should thus be noted with caution. Detector orientation and location (sidewall versus ceiling mounted) did not affect enhanced soot deposition and agglomeration. It is hypothesized that any device creating a strong acoustic field during a smoke exposure could create areas of enhanced soot deposition indicative that the device sounded. Chladni figures were not observed on any of the 270 detectors with horn configuration #1 in this study. The absence of Chladni figures on the horn of a smoke detector was thus found not to be a reliable indicator that the detector did not sound.

Acknowledgments

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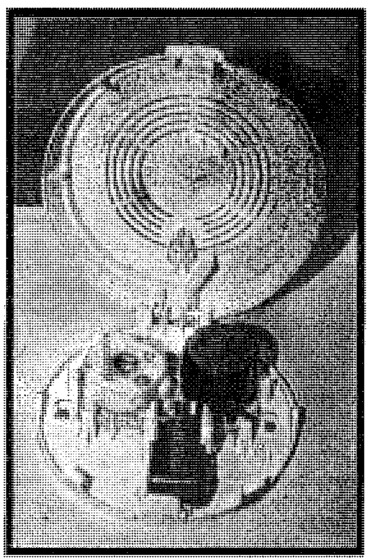
EXHIBIT D

A FIRE ANALYSIS TOOL REVISITED

ACOUSTIC SOOT AGGLOMERATION IN RESIDENTIAL SMOKE ALARMS



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Edinburgh, Scotland
July 4-7. 2004

EXHIBIT
D

A FIRE ANALYSIS TOOL - REVISITED ACOUSTIC SOOT AGGLOMERATION IN RESIDENTIAL SMOKE ALARMS

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Abstract
In modern fire incident analysis and the litigations that frequently follow from them, it is often of great importance to know whether a particular smoke alarm operated during a fire event. Like so many other issues involving the interpretation of fire analysis data, some scientifically verifiable means of determining if a given smoke alarm had activated properly was needed. Best would be some identifiable physical evidence of smoke alarm activation. As early as 1996, it had been put forward that the presence of enhanced soot patterns on fire event exposed smoke alarms was a useable method of determining that a particular smoke alarm had or had not properly activated. Research first published in 1999 and later updated research published in 2001 began to scientifically address the issue. Building on that earlier research, this paper produces additional research particularly focusing on the production of acoustic soot agglomeration patterns in both ionization and photo-electric single station residential smoke alarms. Producing new test data, and combining that with previously reported data, this research work concludes that the presence or absence of acoustic soot agglomeration patterns on smoke detectors exposed to sooty smoke atmospheres was in fact a viable fire analysis tool.

Introduction
Since the early 1970s, single station smoke alarms, both 9-volt battery and 120-volt AC powered, have been the chief fire protection device in most homes and residential occupancies. Over the ensuing years, the early fire warning that these devices have provided to potential fire victims has saved thousands of lives. In household settings it is clear that a well-functioning smoke alarm is the most important fire safety innovation ever. The National Fire Protection Association (NFPA) estimates that 94% of U.S. homes have at least one smoke alarm today, and most states have laws requiring them in residential dwellings.[1] Millions of people have come to rely upon the residential smoke alarm as their primary fire safety resource.

The NFPA also reports that in three of every ten reported fires in homes equipped with smoke alarms, the devices did not work. Households with non-working smoke alarms now outnumber those with no smoke alarms.[2]

In modern fire incident analysis and the litigations that frequently follow from them, it is often of great importance to know whether a particular smoke alarm operated during a fire event. Issues of available egress time can become paramount in establishing whether fire victims could have been saved if timely smoke alarm activation had occurred. It is not uncommon for surviving witnesses to report that no alarm was heard. This is often an area of dispute in ensuing litigations. The cognitive abilities and accuracy of the memories, and even the veracity of individuals who suffer the trauma of having to escape from burning buildings are frequently questioned.

This issue has led to many important and costly civil law suits. Smoke alarm manufacturers, marketers, installers, and landlords frequently find themselves as defendants in multimillion-dollar lawsuits hinging in whole or in part on the question of smoke alarm performance.

Like so many other issues involving the interpretation of fire analysis data, some scientifically verifiable means of determining if a given smoke alarm had activated properly was needed. Best would be some identifiable physical evidence of smoke alarm activation.

Single Station Residential Smoke Alarms

Most modern single station residential smoke alarms are designed and operate similarly. The basic components are a power source, smoke-sensing chamber, printed circuit board, horn, and an outer container or cover (See Figure 1).

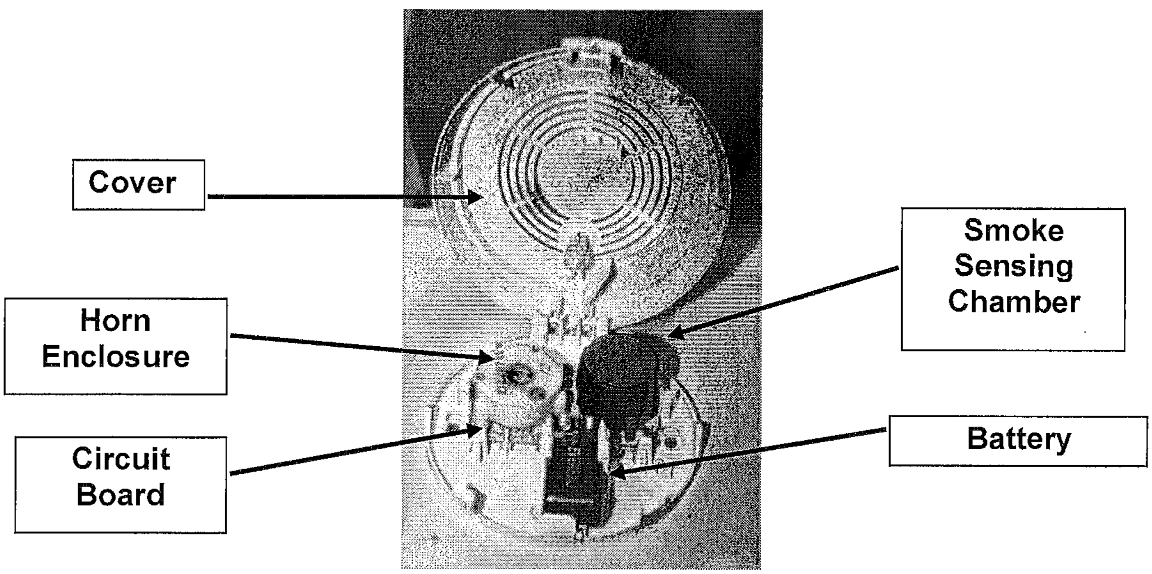


Figure 1 – Typical smoke alarm components

The power sources include a 9-volt battery, hardwired connection to a household 120 volt AC electrical system, or both hardwired as a primary power source with a battery backup in the event of power failure.

Smoke sensing chambers are of two basic types, ionization or photoelectric. Ionization types detect smoke particles by sensing small decreases in current in a monitored circuit. Inside an ionization smoke detection chamber is a small amount of the radioactive element Americium-

241. The alpha-radiation from this material ionizes the oxygen and nitrogen atoms of the air between two parallel plate electrodes. The detector senses the small amount of electrical current that flows between these plates. When smoke enters the ionization smoke detection chamber, it disrupts this current and the smoke alarm senses the drop in current between the plates and sends an alarm signal to the horn.

Photoelectric types detect smoke particles by sensing small increases in current in a monitored photoelectric cell. Inside the photoelectric smoke sensing chamber there is a small light source and a light sensitive sensor. They are positioned at right angles from one another, so that the light source does not normally illuminate the photo sensor. When smoke enters the chamber, however, the smoke particles scatter the light and some amount of light hits the sensor. This creates a small increased current flow and the smoke alarm senses the increased current and sends an alarm signal to the horn. Some more up-to-date smoke alarms are available with dual (ionization and photoelectric) sensor systems.

Underwriters Laboratories[3] sets the Visible Smoke Obscuration Limits within which a smoke alarm must activate at 0.5 – 4.0% / ft. Most smoke alarms on the market today list their smoke obscuration sensitivity between 0.64% / ft. ± 0.14% / ft. and 2.08% / ft. ±1.23% / ft. The majority of smoke alarms have their sensitivities the area of 1.1% / ft. ±0.4% / ft.

The printed circuit boards contain the circuitry for power input connections (either pigtail connections for AC or battery connection terminals for 9 volt operation), smoke detection chamber operation, alarm activation, low battery (no power) alert, the test button function, temporary alarm deactivation warning, escape or test light circuits, and LED indicator light. The actual smoke detection chambers and horn assemblies are often attached to the circuit boards themselves as well.

Modern smoke alarm horns are small ~1.25" diameter stainless steel disks. They are frequently, but not always, enclosed in molded thermoplastic compartments, which have small (0.43" and 0.375") central openings that serve as sound outlets. In some older model smoke alarms the horn compartments and the horns themselves are of a brass alloy. Some horn enclosures have additional smaller openings. The horn is activated by electrical current that causes the horn disk to vibrate at frequencies up to ~4000 hz, depending upon which function the circuitry is calling for (full alarm, low battery warning, temporary alarm deactivation warning).

The outer covers and bases of modern smoke alarms are constructed of thermoplastics. They are capable of melting and deforming at elevated temperatures. UL 217 section 62.2 sets the maximum temperature to which smoke alarm thermoplastic components must maintain their shapes at 194° F. (90° C).[4] Our testing disclosed an initial softening temperature of a representative smoke alarm cover at 199° F. (93° C), initial softening of the plastic horn compartment at 250° F. (121° C), and smoke sensing chamber plastic components at 351° F. (177° C).

Among the various manufactures there are many minor design differences, but virtually every manufacturer's smoke alarm covers contain some arrangement of grillwork or other opening for smoke entrance, for alarm sound exit, and an opening for a test button and or alarm condition

LED indicator light. Most smoke alarms are basically designed as a squat cylinder in shape with outside diameters ranging from ~5.0" to ~5.5" and heights from ~1.25" to ~1.5." They are all designed to be installed in the ceilings of rooms not closer than 4" from the sidewalls or on sidewalls not less than 4" nor more than 12" down from the ceiling.[5]

Background in Previous Research

In 1999 Munger produced his doctoral thesis on residential smoke alarms.[6] Prior to that time he had become aware of theories put forward by some smoke alarm manufacturer's defense experts that the presence of certain soot patterns (Chladni Figures) on alarm horn disk plates could be used as proof that a particular alarm had sounded.[7] As part of his doctoral dissertation research, Munger conducted an experiment in which he placed six smoke alarms, (three energized and three de-energized) in a "smoke box" and exposed them to a burning polyurethane smoke source for fifteen minutes. His results were "… [that] there was no discernable difference in the smoke patterns on the discs of the horns regardless of whether the device was operational or not." Munger's testing was quite limited in its scope, involving only three energized smoke alarms. Also, Munger's experiment was pointed entirely to an investigation of the production of Chladni Figures on the horn disks themselves and not on other areas or types of soot deposition.

Worrell *et al* reported in 2001, and citing Munger, that up until that time there had been "…no published methods for determining whether a particular detector actually sounded in response to a smoke exposure."[8] Their testing appears to be the first published work on the topic. In their article abstract they reported:

> "A full scale house test was conducted to investigate the accuracy of two proposed methods for determining whether a smoke or carbon monoxide (CO) alarm sounded during smoke exposure. One method involves examining the plastic case of the alarm's piezoelectric horn for locally enhanced soot deposition and agglomerated soot particles. The other method involves examining the metal disc of the piezoelectric horn for a Chladni figure. Pairs of detectors, each consisting of one detector with its battery properly inserted and the other with its battery disconnected, were placed throughout the house. Each of the properly charged detectors was monitored to determine if and when the detector sounded. It was found that the presence of locally enhanced deposition and soot agglomerates on the main central opening of the plastic horn enclosure of a smoke or CO detector was a strong indicator that the alarm sounded. It was also found that the use of Chladni figures on the piezoelectric discs as an indication of the smoke detector sounding was not an accurate predictor."[9]

Chladni Figures

The experiments of both the Worrell *et al* group and Munger dealt to a certain extent with the production "Chladni Figures," the earliest experimental technique to visualize patterns of vibration. Ernst Chladni (klahd'nee) (1756-1827) first published his method in 1787. He excited a plate into vibration with a violin bow and sprinkled sand on the surface. The sand gathered at the nodal lines, revealing the vibration pattern. Chladni had used this method to study vibration of plates of many shapes, and these results were important in validating the theoretical models for plate vibration that were developed during the nineteenth century.[10] The method is still in wide use today for varying vibration wave inquiries and as a teaching method for elementary wave theory physics.

On circular plates, similar in shape to the smoke alarm horn disk, Chladni Figures can be displayed as circumferential circles centered at the center of the flat disk (see a. in Figure 2a), radial arms radiating outward from the center of the disk or combinations (see Figure 2b and c) and variations of both including certain "starburst" type shapes (see Figure 3, nos. 4, 6, 8, 11 and 12).

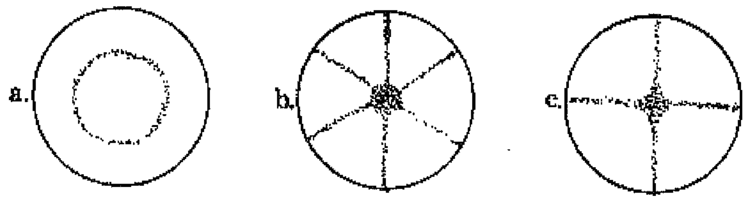


Figure 2 - Examples of Circumferential (circular) and radial Chladni figures

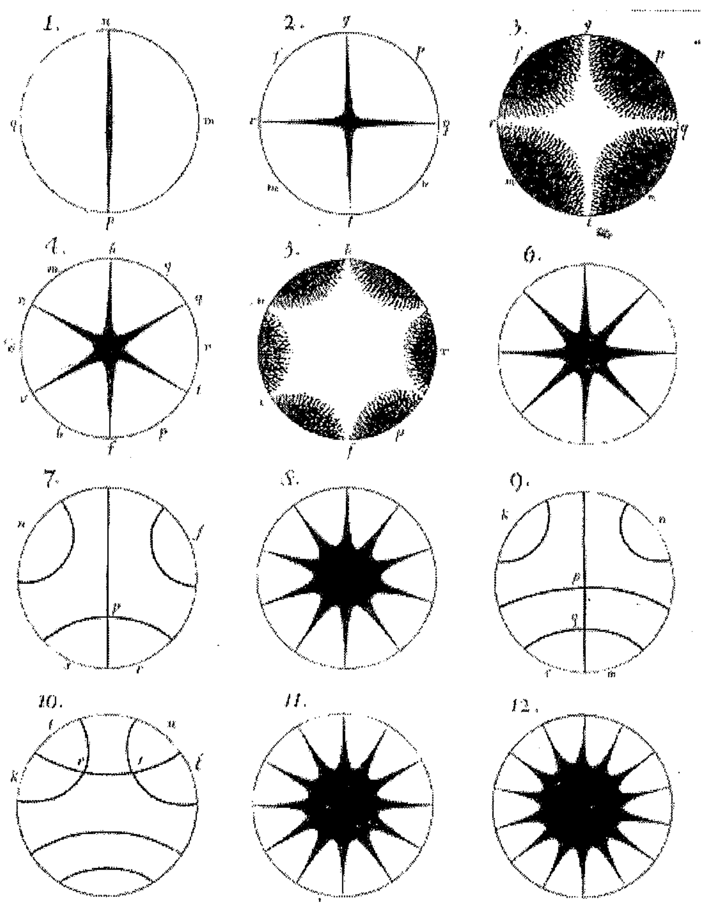


Figure 3 – Additional Chladni Figures (from Chladni's original text).[11,12]

Soot Deposition and Acoustic Soot Agglomeration

The other physical phenomenon particularly addressed by Worrell *et al* is Acoustic Soot Agglomeration in the activation of a smoke alarm. The simple definition of Acoustic Agglomeration from Morfey in the <u>Dictionary of Acoustics</u> is: "the grouping of suspended particles into larger aggregates by the action of sound waves in the suspending fluid, usually at high intensity."[13]

Acoustic agglomeration of aerosols has been known since at least 1931 when it was first observed that small particles tend to "stick" together in the presence of an intense acoustic field, thereby forming larger particles. NFPA 921 defines smoke as: "an airborne particulate product of incomplete combustion suspended in gases, vapors, or solid and liquid aerosols" and soot as: "black particles of carbon produced in a flame"[14] The smoke produced in a structure fire contains both soot and other liquid and solid aerosols. Smoke and soot in combination with the high frequency (~4000 hz) and high sound pressure (~>85 decibels) of a properly operating smoke alarm are key elements for producing localized soot agglomeration on surfaces of the smoke alarm.

Though Worrell *et al* use the separate terms of "Enhanced [Soot] Deposition" and "Acoustic Soot Agglomeration," they give this explanation of both terms by way of a definition, "When individual soot particles collide under certain conditions, they adhere or agglomerate to form larger particles."[15]

Focusing their research on Enhanced Deposition, Acoustic Soot Agglomeration and Chladni Figures, the Worrell *et al* research reported three main conclusions.[16]

1. "For the conditions generated by a room fire that grows to flashover in a typical residential occupancy, the presence of locally enhanced deposition and soot agglomerates on the main opening of a smoke or CO detectors horn case, relative to soot deposits elsewhere on the case, is a strong indication that the alarm sounded"

2. "Due to the limited focus of the current research, the absence of such enhanced deposition and agglomerates does not necessarily indicate that the alarm did not sound."

3. "The absence of a Chladni figure on the piezoelectric horn disc or horn enclosure does not necessarily exclude the possibility that the alarm sounded."

Purpose of Kennedy *et al* Testing/Research

Building on the ground breaking work of Worrell, Roby, Streit, and Torero,[17] and also in part on Munger, we proposed to produce additional research particularly focusing on the production of acoustic soot agglomeration in both ionization and photo-electric single station residential smoke alarms.

There were several aspects of the Worrell *et al* testing which we felt limited and called into question the breadth of some of their conclusions. We were particularly interested in their conclusion that while the presence of soot agglomeration <u>was</u> an indicator of smoke alarm activation, the absence of soot agglomeration <u>was not</u> a viable indicator of smoke alarm failure. There are many aspects of acoustic soot agglomeration that must be fully and objectively evaluated in order to reach the conclusion that the absence of soot agglomeration was not a viable indicator of smoke alarm failure. Among these are particle size distribution (10μm), smoke mass loading, gas temperature (25-1000 C), sound pressure level (≧ 85 dbA), and frequency of the acoustic field (~4000 hz). Most important of these is the presence of a truly sooty environment. In real world fire conditions, knowing the actual smoke or soot distribution and density to which a smoke alarm is exposed is problematical. In the bench-type testing which forms the basis of our research we can quantify and reproduce the amount of soot and smoke exposure of the test alarms. The Worrell *et al* group's testing cannot.

The conclusion that the absence of enhanced soot deposition does not accurately report the non-operation of a smoke alarm is totally dependant on some reasonable report of the nature and amount of smoke and soot to which the subject smoke alarm was exposed. In real world investigation conditions this can only be accomplished by accurate description of the visual obscuration by eyewitnesses, post-fire examinations of the soot deposition in the burned structure and perhaps by mathematical modeling of the fire. Though each of these data collection methods is somewhat subjective, reasonable estimations can be made if the analyst is conservative and objective in his or her analysis.

In addition, though the Worrell *et al* research was partially concerned with an inquiry into the production of Chladni Figures on the horn disks themselves, we found what appeared to be the presence of unreported "starburst" radial Chladni Figures on five of the photographs of soot agglomeration presented in the Worrell *et al* paper.[18] These photographs displayed soot agglomerations around the tops of the "main central opening[s]" of horn disk enclosures. Our testing also produced similar Chladni Figures. This was in addition to the one circumferential Chladni Figure on the exterior top surface of a horn enclosure that Worrell *et al* did report, but which our testing did not reproduce.[19]

The purpose of our current research is to further refine the question of whether the presence or absence of acoustic soot agglomeration and Chladni Figures are in fact viable tools in the determination of whether or not a smoke alarm had activated in an actual fire incident.

Research Testing Considerations

The only previous published testing in the subject area [Worrell *et al*] was conducted in a full-scale house fire. While real world conditions testing is an important part of such research, conditions with such a "test chamber" are extremely difficult to control. Witness that fully 30% of their test data was lost due to complete destruction of some of the subject alarms themselves by the fire (six units), other data acquisition failures (four units), and one case in which they were unable to recover a unit horn. While the house fire scenario did give the testing a wide variety of test media (smoke, soot, pyrolysis products, etc.), control of the test media (e.g. mass optical density, smoke obscuration, time of exposure, and chemical composition) is impossible in such a test environment. In addition trans- and post-test conditions: wind, continued emberous fire exposure, extinguishment water, disturbance of the test area by firefighters, etc. is remarkably difficult or impossible to control.

In formulating our test protocols and conducting the actual research testing we focused on six issues of consideration. Each of which was lacking in the previous research.

Reproducibility of Testing Results

The testing and data must be reproducible. For this, the test protocol, testing equipment, subject smoke alarms, smoke test chamber, smoke/soot medium, and smoke/soot generation system must be simple enough so that they can be reproduced in any competent fire science laboratory. At the same time the test set-up must have the characteristics to be serviceable for the production, confinement, and control of the test environment. The testing protocol must be carefully crafted so as to allow identical testing of each subject smoke alarm, and reduce the effect of uncontrolled variables on test results.

Reduction in Test Variables

Test variables must be kept to a minimum. In our testing we tried to limit the variables to only the actual smoke alarm units themselves. Each unit tested was of a basically similar design, with some slight variations in physical size. Each smoke alarm was purchased locally, "off-the-shelf" from regular home improvement style venders and was representative of the most common and popular manufacturers of single station residential smoke alarms. Each was basically cylindrical in shape with outside diameters ranging from ~5.0" to ~5.5" and heights from ~1.25" to ~1.5." A variety of AC and battery powered, and ionization and photoelectric models was utilized. Each tested unit was placed in the same position on the ceiling of the test chamber. Each unit was tested under the same smoke conditions and for the same time of smoke exposure.

The variable of actual elapsed time of alarming was uncontrolled by the testing lab technicians and depended solely upon the functional characteristics of the smoke alarms themselves. Not all of the smoke alarms tested began alarming at the same point in time relative to initial smoke exposure nor persisted in the alarm mode for the same time periods, but these time factors were recorded in the data collection stage.

Control of Test Conditions

Test conditions must be controllable, particularly the most important factors of extent and time of smoke exposure. Outside variable factors such as ambient conditions of temperature, humidity, and wind outside the test chamber must also be eliminated as test variables. This simply cannot be done in a full-scale acquired house burn. In most cases the agglomerated soot is fragile and susceptible to disturbance and removal by careless handling. Therefore post-testing conditions; such as careful removal of the test subject smoke alarms from the test chamber without disturbance to the important soot evidence, and limiting handling and transportation before laboratory examination are also important. Here the advantage of in-lab bench testing comes into play.

Increased Database Size

One of our primary concerns was to increase the information database of tested smoke alarms, both in total number and in variety of smoke alarm designs. This was accomplished by combining and, to the extent possible, integrating the tests results from the Worrell *et al* research and our own test results. Thusly, the database upon which Worrell *et al*'s conclusions were drawn can be more than doubled and we gain the benefit of their viable and diverse test data as well as our own.

The integration of the two databases can be justified if the following key points of difference between the sets of data are duly noted and kept in mind: The Worrell *et al* data was achieved from a full-scale, largely uncontrolled house burn; 30% of their data was lost or deemed by them as not reliable; their smoke and CO alarm database designs, consisted entirely of BRK manufacture; and subjective, qualitative data analysis, particularly with regard to the presence of Chladni Figures and the sufficiency of soot deposition for analysis, may vary widely between the two research teams. So in order to use the two sets of data we must take the Worrell *et al* data reporting as accurate as given.

Two of the key elements in differing alarm manufacturers' designs are smoke inlet grill design and horn enclosure or compartment design. The horn enclosure design displayed in the Worrell *et al* paper is completely of the BRK type (e.g. BRK, First Alert, Sears brands). Other manufacturers such as Kidde employ different horn enclosure or compartment designs or in the case of FireX, no horn enclosure or separate chamber at all. While BRK-types and Kidde both employ the relatively large central opening in their respective horn enclosures (approximately 0.43" and 0.375" diameter, respectively), FireX has no such construction at all other than a relatively small cover grill work sound exit hole as also do Kidde, Family-Guard, and First Alert.

Similarly, widely differing designs in the size and style of smoke inlet grills are employed among the BRK-type, Kidde, Family-Guard, and FireX brands, with the Kidde and FireX brands being considerably smaller in overall entrance area and the inlet area of the tested First Alerts being roughly one-half the size of the BRKs.

<u>*Data Collection*</u>

We endeavored to keep our data collection simple and accurate. Worrell *et al*'s 30 % data loss was important in our thinking. Two kinds of data are needed and collected in this type of research, quantitative data and the more subjective observational data. Quantitative data includes temperatures, timing of events such as initial smoke alarm activation, and total smoke exposure and alarm activation times. The more subjective data is the recognition and characterization of soot patterns. Both are important to this kind of smoke alarm activation recognition research. Technicians' observations and notes, particularly with respect to alarm initial activation and total alarm activation times, were backed-up by temperature and time data-logger input. In this topic area the advantage of in-lab bench testing over field-testing is apparent. Technicians in the laboratory could actually hear and note when the smoke alarms went into alarm and did not have to rely solely upon the electrical data acquisition which was sometimes lost in the full-scale house fire field tests. In addition, it is not unheard of that when a smoke alarm sensor detects a fire and sends an electrical signal to the horn, the horn does not sound properly. The mere monitoring for the presence of the alarm electrical activation signal will not verify that the horn is in fact sounding or sounding with the prescribed minimum sound pressure level ($\geqq$ 85 dBA).[20] It is in fact this elevated sound pressure level that is a key factor in whether Acoustic Soot Agglomeration will occur at all - the very point of the entire research. "Do properly sounding smoke alarms produce enhanced soot patterns while improperly operating smoke alarms do not?"

Qualitative data recognition, particularly the presence or absence of enhanced soot deposition, Acoustic Soot Agglomeration, and Chladni Figures, was particularly more subjective. We are acutely aware of our opinions that the Worrell *et al* researchers missed or failed to report the presence of "starburst" Chladni Figures on the horn enclosures displayed in their report. We have the utmost respect for the expertise of our colleagues among the Worrell *et al* researchers. It is, in fact, this unequivocal respect that points up the pitfalls of these subjective characterizations of the presence of Chladni Figures. There is no doubt that we see these figures both in their published photographs as well as in the soot agglomeration test results of our own work. That our much-esteemed colleagues failed to cite them in their work points up the importance, and pitfalls, of the qualitative nature of these observations. In order to mitigate these kinds of subjective evaluations, we utilized a "triple blind" analysis technique for all of our agglomeration and Chladni Figure opinions. Each of the three authors of our research independently examined visually, with naked eye, and with both macro- and micro-magnification, the presence of soot depositions, particularly with reference to agglomerations on the outer covers of the smoke alarm bodies, the inner and outer surfaces of the horn enclosures, and the Chladni Figures present.

Exploring Pattern Persistence

Lastly, an issue that frequently comes up in other pattern-based fire analyses, including smoke alarm acoustic soot agglomeration litigation cases, is the issue of patterns persistence.[21] Pattern's persistence is commonly defined as a fire pattern's ability to endure through the continued fire growth affecting the surface[s] upon which the patterns occur and still be present for post-fire analysis. Smoke alarms are frequently heated by their presence on walls and ceilings within the hot upper layers of compartment fires. This heating takes place within the same upper smoke layer that distributes the smoke that causes the smoke alarm to activate and the production of acoustic soot agglomeration, soot deposition, and Chladni Figures that are the subject of this research. After fire events, the remnants of smoke alarms are seldom found in their original pristine conditions. In fact they are seldom found in their original positions at all. The thermoplastics of which smoke alarms are commonly constructed have a softening and melting temperature of approximately >199-351° F. (93-177° C). Thereby when heated to those temperatures both the outer covers and the horn enclosures begin to soften, melt, and frequently fall to the floor, with their previously deposited soot patterns already applied.

In a single, specific bench test in a laboratory Transit oven, a specimen smoke alarm fell from its gypsum wallboard vertically mounted position at a temperature of 283° F. (139° C).

The question of patterns persistence is whether the previously deposited soot patterns have the ability to persist through the continued increased heating which takes place while the smoke alarms are in place on the ceiling or upper walls or ultimately on the floor as the compartment fire continues to grow through flashover where average upper layer temperatures approach and exceed 1112° F. (600° C).[22]

In a second single specific bench test, a previously smoke tested smoke alarm, (P3) bearing acoustic soot agglomeration was subjected to 30 minutes of heating to a temperature of 433° F. (223 C) in a lab furnace. After air cooling the resultant softened and re-solidified plastic of the outer cover and the horn enclosure were examined to see if the deposited Acoustic Soot Agglomerations persisted.

Test Procedures

Equipment

A specially constructed smoke chamber was used in all testing. It measured 24"L x 24"W x 14"H, producing an interior volume of 2.8 cu. ft. There was a 9"W x 7"H glass viewing window placed 5" above the chamber floor in the center of the front wall. The 24" x 24" lid of the chamber was constructed of ½" gypsum wallboard and fit (smoke-tight) into the top of the chamber on nominal 2" horizontal flanges. In the center of the right wall of the smoke chamber was an 8"W x 8.5"H manually operated dampered smoke vent. This vent remained closed during testing.

The test smoke alarms were attached to the underside of the gypsum wallboard ceiling, on the lateral centerline, with the rear edge of the smoke alarm 5" from the rear wall.

A type "K" thermocouple was attached to the inside surface of the chamber ceiling on the lateral centerline ~2" forward of the tested smoke alarm (see Figures 5 and 6).

The smoke source was an ~2" laminar gas flame of MAPP Gas (C_3H_4) (mixture of 56.0% Propane and 44.0% methylacetylene-propadiene) from a ¼" diameter copper tube burner. The ~2" MAPP Gas laminar flame from a ¼" diameter copper tube burner produces an extremely sooty black smoke which is primary carbon soot in composition. The smoke source is inserted into a hole in the lower center of the chamber front wall beneath the viewing window and extends into the chamber at floor level a distance of 6" (see Figure 4).

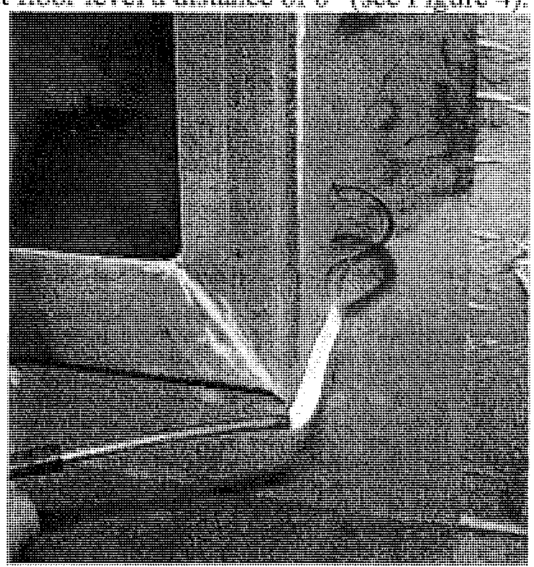


Figure 4 – Smoke Source, 2" laminar MAPP Gas flame

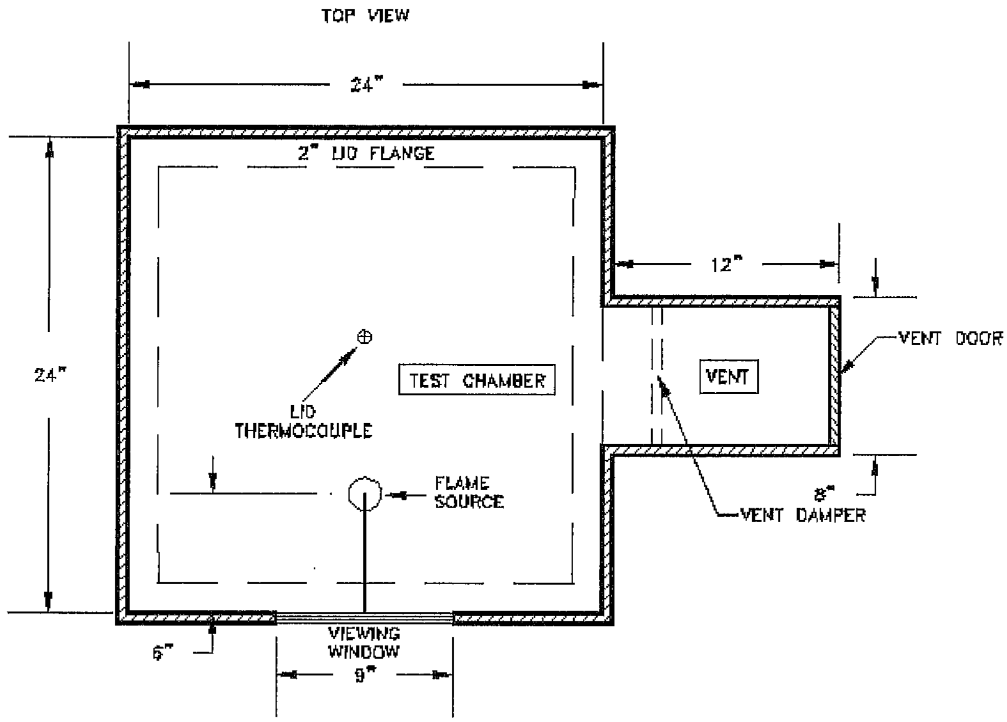


Figure 5 - Top View Drawing of Smoke Test Chamber

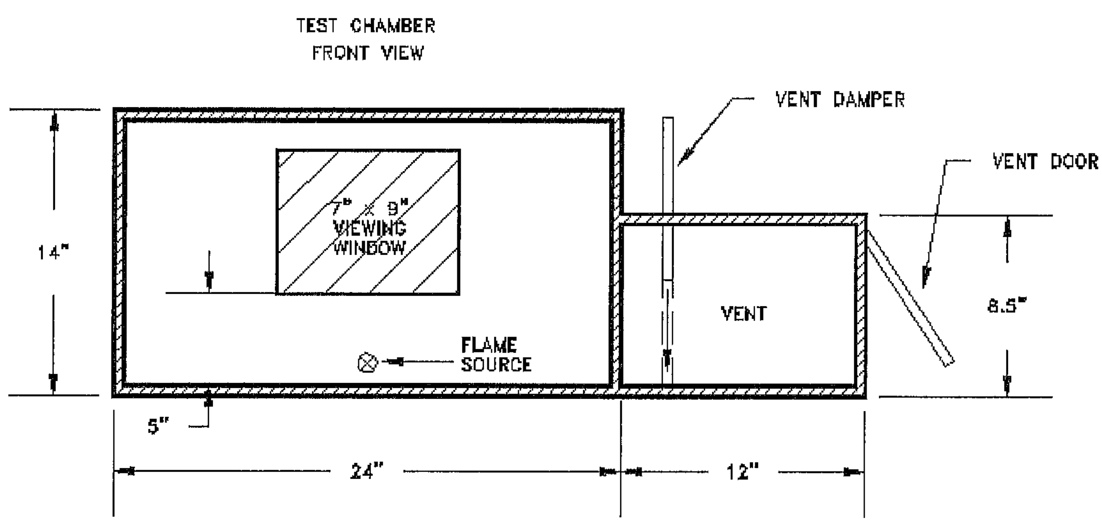


Figure 6 - Front View Drawing of Smoke Test Chamber

Protocol

A test smoke alarm was powered, either with a prescribed internal 9V battery or if a hard wired designed unit, with external standard house line 120V AC, and attached in place on the interior ceiling (lid) of the test chamber. The monitoring thermocouple was attached through the top of the chamber lid and the lid is screwed in place onto the nominal 2" flanges. (See Figure 7).

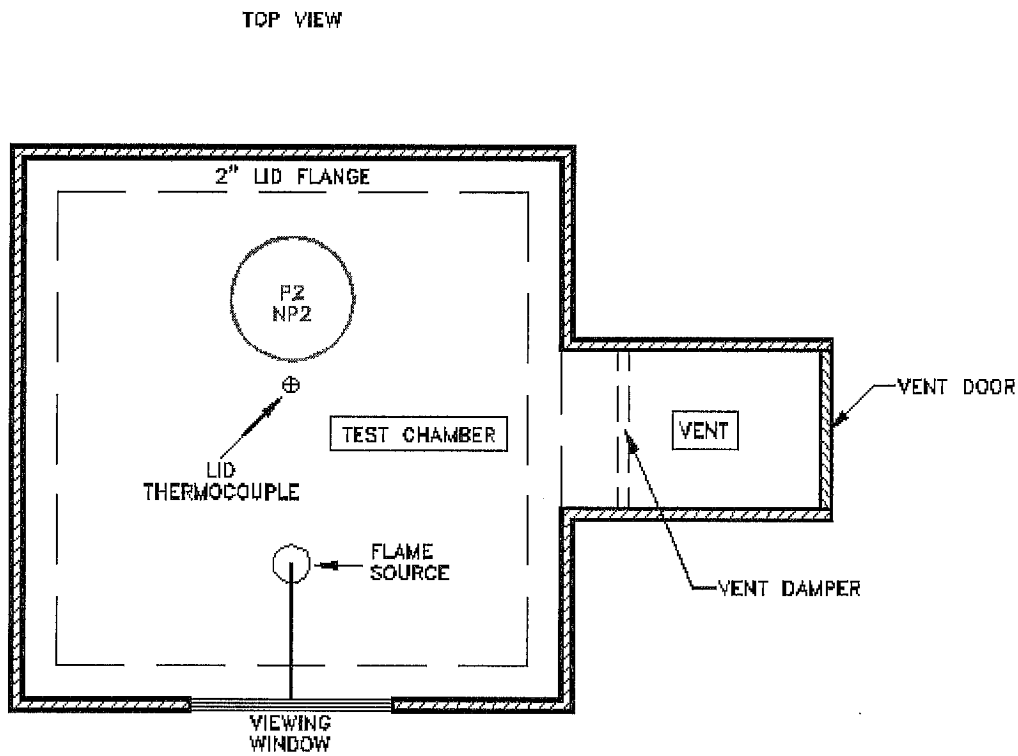


Figure 7 – Top View of Smoke Test Chamber displaying Smoke Alarm Placement

The smoke source was lighted outside of the chamber and inserted into place within the chamber through a hole in the lower front center of the chamber and extended into the chamber a distance of 6".

Timing begins when the smoke source is inserted. Temperature in the upper layer of the chamber is recorded each minute. Time and duration of alarming are recorded. Total time of smoke exposure is 15 minutes. Immediately thereafter the smoke source is promptly removed and the vent damper and chamber lid are opened.

After allowing the smoke alarm to air cool, its outer surface is visually examined and photographed. Then the smoke alarm is carefully disassembled and any interior soot patterns are noted and photographed.

The testing is then repeated with a duplicate smoke alarm that is not energized.

Discussion

Chladni Figures on Horn Enclosures – Horn enclosures are not true disks as is the horn disk itself. Therefore Chladni Figures do not appear in the classical fully developed forms.

In the combined Worrell *et al* and Kennedy *et al* data we found both circumferential (Worrell *et al* only) and radial "starburst" Chladni Figures on the horn enclosures (both Worrell *et al* and Kennedy *et al*).

Though the basic operational design (sensing chamber, circuit board and horn) are in all residential smoke alarms, Individual Smoke alarm designs differ greatly from manufacturer to manufacturer, particularly with respect to horn enclosures or compartments and smoke inlet grills. For example, FireX Brand alarms do not have separate horn compartments.

The presence of Chladni figures in the agglomerated soot is important because it is also indicative of the vibrating nature of the dynamics of the horn operation – proving that the horn had activated a high frequency (~4000 hz)

Sympathetic Vibrations - Sympathetic vibrations can produce acoustic soot agglomeration in non-operating alarms if they are placed too close to other operating alarms of the same manufacturer (i.e. identical horn disks), for example if a CO alarm, a photoelectric smoke alarm, and an ionization smoke alarm are mounted close together by an installer in an attempt to provide a wider coverage of various expected unsafe atmospheres. Manufacturers frequently recommend the installation of multiple types of alarms to increase safety from the various types of fires (smoldering and fast flaming).

In our earliest test, two identical smoke alarms, one powered (P1) and one not powered (NP1) were tested simultaneously installed in the smoke test chamber about 4 inches apart. The powered alarm produced easily identifiable soot agglomeration depositions. Surprisingly the non-powered alarm produced similar, though much lighter, soot agglomeration. We attributed this to sympathetic acoustic vibration of the identical non-powered horn from the high frequency high sound pressure activation of its nearby, twin, powered horn; and to the vibrations transmitted to the non-powered horn from the powered horn through the gypsum wallboard ceiling of the test chamber itself. In all subsequent testing we tested powered and non-powered horns separately and no non-powered horn produced any evidence of agglomerated sooting patterns.

Patterns Persistence – To test patterns persistence, a previously smoke tested alarm, (P3) bearing acoustic soot agglomeration was subjected to 30 minutes of heating in a lab furnace to a temperature of 433° F. (223° C). After air-cooling the resultant softened and re-solidified plastic of the outer cover and the horn enclosure were examined to see if the deposited Acoustic Soot Agglomerations persisted. Patterns persistence was evident.

Evaluation of Combined Data

Combining the data from the Worrell *et al* and our testing effectively doubles the database. Worrell *et al* produced a total of 30 tests, 15 powered and 15 non-powered. Table A displays the test results for the Worrell *et al* testing.

Of the Worrell *et al* testing, 9 tests produced anomalous or unusable data. A listing of these anomalous tests can be found in Table D.

Removing the anomalous tests from the database, Worrell *et al* produced 9 powered tests (Table B) and 12 non-powered tests (Table C).

Kennedy *et al* produced a total of 22 tests, 12 powered and 10 non-powered (Table E). The first two of the powered tests were for preliminary equipment setup and were labeled Exemplar 1 and Exemplar 2. The exemplar tests smoke alarms were subjected to less total smoke exposure than the subsequent tests, but because they did produce identifiable results, they were included in the total test database. None of the test data from the Kennedy et al testing was classified as anomalous.

The combined Worrell *et al* and Kennedy *et al* tests results (less anomalous tests) encompassed a total of 42 tests, 21 powered and 22 non-powered (see Table F).

All of the powered tests (21) displayed acoustic soot agglomeration and none of the non-powered tests (22) produced any enhanced soot deposition.

None of the tests (Worrell *et al* or Kennedy *et al*) produced any Chladni Figures on the horn disks. Five of the Kennedy *et al* tests produced "starburst" type Chladni figures, 4 on the outer surfaces of the horn compartments around the central sound outlet hole and 1 on a smoke alarm outer case. Though the exact number is unknown, several of the Worrell *et al* tests also produced "starburst" type Chladni Figures on the outer surfaces of the horn compartments around the central sound outlet hole.

More information on the evaluation of the combined Worrell *et al* and Kennedy *et al* test data can be found in Table F.

Findings

Acoustic Soot Agglomeration

The presence of soot agglomerations is a strong indicator that a particular smoke alarm activated properly in a fire (see Figure 8).

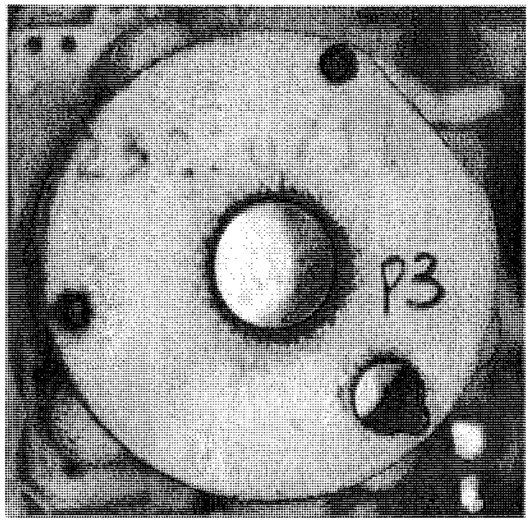


Figure 8 – Acoustic Soot Agglomeration around central and circumferential sound holes of a powered horn disk enclosure.

Absence of soot agglomeration products on a fire exposed smoke alarm is evidence that the alarm did not sound, providing that the atmosphere to which the smoke alarm was exposed was sufficiently sooty (see Figure 9).

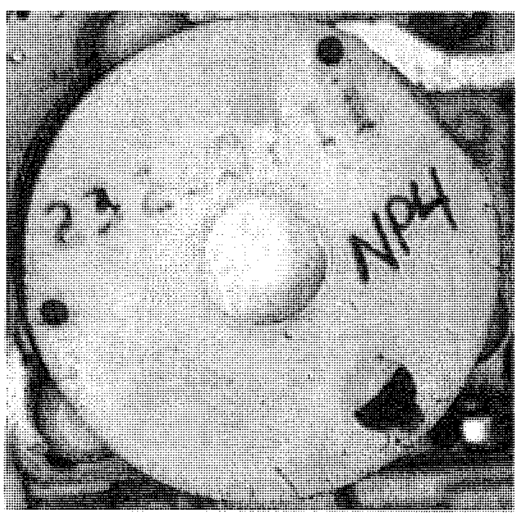
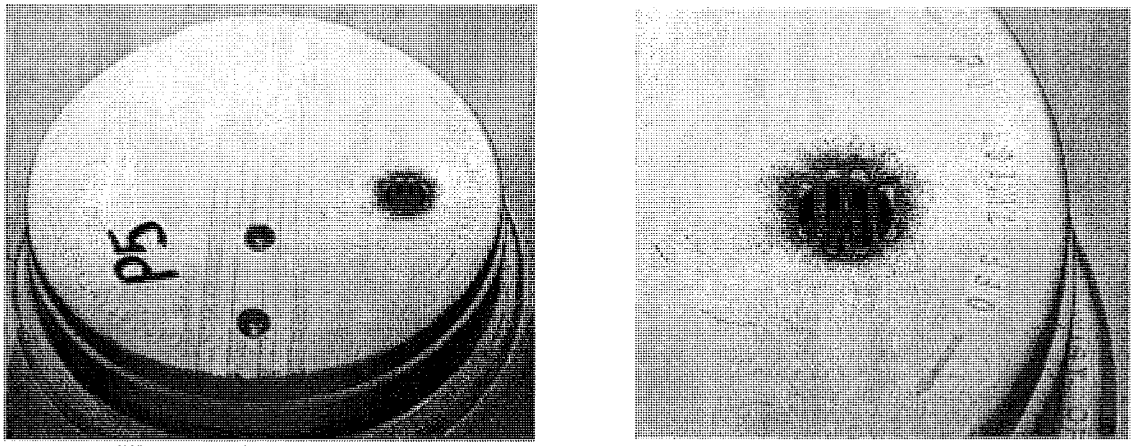


Figure 9 – Lack of Acoustic Soot Agglomeration on the horn enclosure of a non-powered smoke alarm

External agglomeration will appear in the cover grillwork of properly operating smoke alarms, particularly in the areas of horn chamber sound outlets (see Figures 10a and 10b and Figure 11).



Figures 10 a. and b. – Acoustic Soot Agglomeration around the sound exit grillwork of a Kidde Smoke Alarm

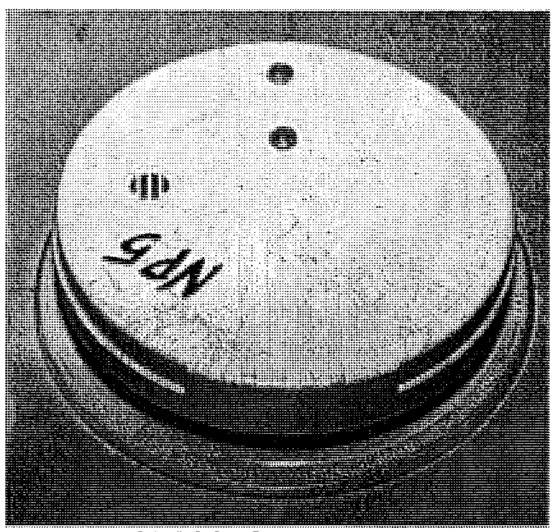
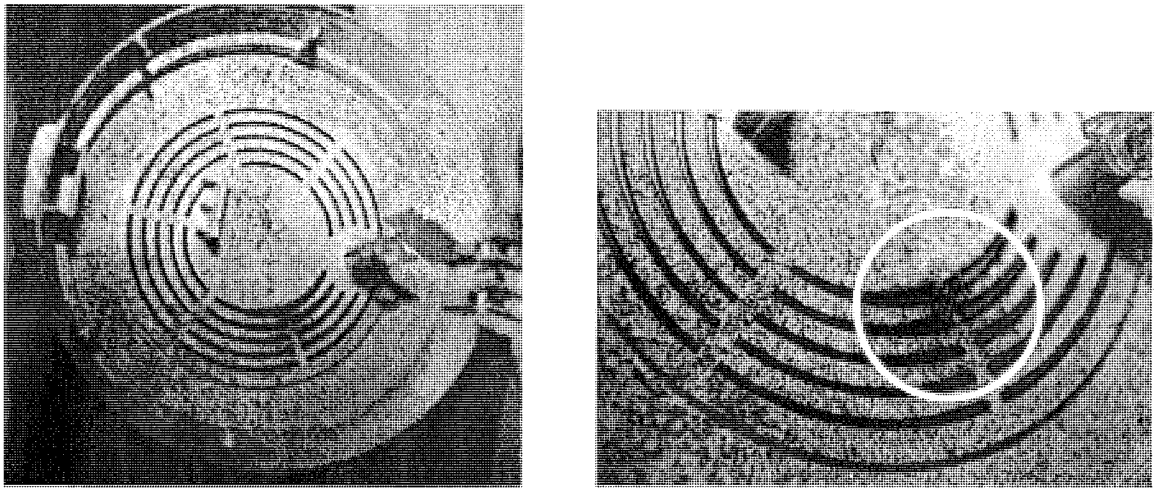


Figure 11 – Non-powered Kidde Smoke Alarm without Acoustic Soot Agglomeration on the sound exit grillwork

Internal Agglomeration will appear on various internal parts of a properly operating smoke alarm, particularly the sound exit openings of horn enclosures, but also frequently on such other parts as electrical components, circuit boards, and the inside surfaces of the cover grillwork close to the horn disks or horn enclosures (see Figures 12a. and 12b.).



Figures 12a. and b. - Acoustic Soot Agglomeration on the interior surface of the smoke alarm case directly over the horn compartment central sound exit opening

Agglomerated soot deposits were found on the top surfaces of several horn disks themselves, but not in the form of Chladni figures.

Chladni Figures

Chladni figures, on one occasion circumferential, but recurrently starburst-shaped, were frequently present on the external surfaces of horn enclosures immediately adjacent to the large sound outlet holes.

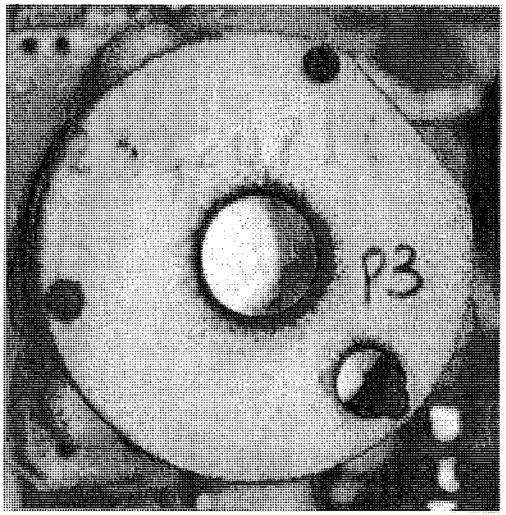
No Chladni figures were found on any horn disks themselves.

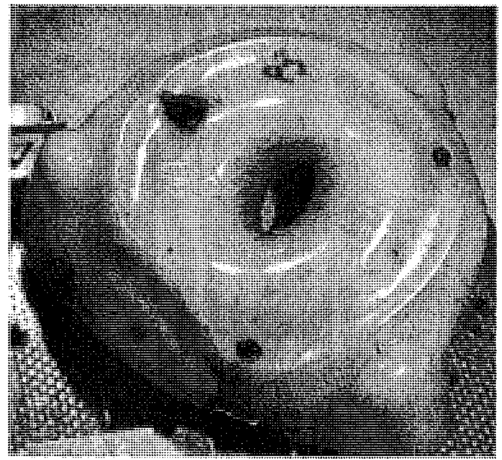
Sympathetic Vibrations

Sympathetic vibrations can produce acoustic soot agglomeration in non-operating alarms if they are placed too close to other operating alarms of the same manufacturer (i.e. identical horn disks).

Patterns Persistence

Through heating to temperatures exceeding the approximate temperature at which smoke alarm falldown occurs, 283° F. (139° C), soot deposit patterns persistence occurs as long as the subject smoke alarm is not completely destroyed by subsequent burning.





Figures 13 a. and b. – Patterns Persistence
Soot agglomeration on a horn enclosure central sound exit opening before (left) and After (right) heating to 433° F. (223° C) for thirty minutes

Additional Research

Our work is not complete. Such issues as soot particle size, optical obscuration data, agglomeration per unit time, ceiling vs. wall mounted smoke alarms, minimum time for agglomeration to occur, and other soot and smoke sources, all need to be addressed. Work in these regards has already begun both by the Kennedy *at al* and the Worrell *et al* teams.

END

TABLE A - WORRELL *et al* TESTS RESULTS[23]

No.	Type	Powered	Activated	Macro Black Ring	Micro Black Ring
1	Ion	Yes	Yes	A*	A*
2	Ion	No	No	No	No
3	Photo	Yes	Yes	Yes	Yes
4	Photo	No	No	No	No
5	CO	Yes	B*	No	No
6	CO	No	No	No	No
7	Ion	Yes	Yes	Yes	Yes
8	Ion	No	No	No	No
9	Photo	Yes	Yes	Yes	Yes
10	Photo	No	No	No	No
11	CO	Yes	Yes	No	C*
12	CO	No	No	No	C*
13	Ion	Yes	Yes	No	Yes
14	Ion	No	No	No	No
15	Photo	Yes	Yes B*	Yes	Yes
16	Photo	No	No	No	No
17	CO	Yes	B*	Yes	Yes
18	CO	No	No	No	No
19	Ion	Yes	Yes	Yes	Yes
20	Ion	No	No	No	C*
21	Photo	Yes	Yes	Yes	Yes
22	Photo	No	No	No	No
23	CO	Yes	B*	No	C*
24	CO	No	No	No	No
25	Ion	Yes	Yes	D*	D*
26	Ion	No	No	D*	D*
27	Photo	Yes	Yes	D*	D*
28	Photo	No	No	D*	D*
29	CO	Yes	B*	D*	D*
30	CO	No	No	D*	D*

* - Anomalous Tests results

A – Horn not recovered
B – Data acquisition failure
C - Not enough soot to determine
D – Detector Consumed in Fire

TABLE B – COMPILATION OF WORRELL *et al* RESULTS FOR POWERED DETECTORS THAT ACTIVATED

No.	Type	Activated	Macro Black Ring	Micro Black Ring
3	Photo	Yes	Yes	Yes
7	Ion	Yes	Yes	Yes
9	Photo	Yes	Yes	Yes
11	CO	Yes	No	C*
13	Ion	Yes	No	Yes
15	Photo	Yes B*	Yes	Yes
17	CO	B*	Yes	Yes
19	Ion	Yes	Yes	Yes
21	Photo	Yes	Yes	Yes

B – Data acquisition failure
C - Not enough soot to determine

TABLE C – COMPILATION OF WORRELL *et al* RESULTS FOR NON-POWERED DETECTORS THAT DID NOT ACTIVATE

No.	Type	Activated	Macro Black Ring	Micro Black Ring
2	Ion	No	No	No
4	Photo	No	No	No
6	CO	No	No	No
8	Ion	No	No	No
10	Photo	No	No	No
12	CO	No	No	C*
14	Ion	No	No	No
16	Photo	No	No	No
18	CO	No	No	No
20	Ion	No	No	C*
22	Photo	No	No	No
24	CO	No	No	No

C - Not enough soot to determine

TABLE D – COMPILATION OF WORRELL *et al* ANOMALOUS TEST RESULTS

No.	Type	Powered	Activated	Macro Black Ring	Micro Black Ring
1	Ion	Yes	Yes	A*	A*
5	CO	Yes	B*	No	No
23	CO	Yes	B*	No	C*
25	Ion	Yes	Yes	D*	D*
26	Ion	No	No	D*	D*
27	Photo	Yes	Yes	D*	D*
28	Photo	No	No	D*	D*
29	CO	Yes	B*	D*	D*
30	CO	No	No	D*	D*

* - Anomalous Tests results
A – Horn not recovered
B – Data acquisition failure
C - Not enough soot to determine
D – Detector Consumed in Fire

TABLE E - KENNEDY TEST RESULTS

TEST Model
MFG. Code Ionization/
or Photo Powered
Outer case
Agglomeration Horn Case Agglomeration Horn Disk

Agglomeration **Chladni Figure**

Outer Case	Horn Case	Horn Disk							
Exemplar 1	1235K	Ion	Yes	Yes	Yes*[i]	Yes	No	No	No
Exemplar 2	83R	Ion	Yes	Yes*[i]	Yes	No	No	No	No
P1	83R	Ion	Yes	Yes	Yes	No	No	No	No
NP1	83R	Ion	No	No	Yes*[a]	No	No	No	No
P2	83R	Ion	Yes	Yes	Yes	No	No	Yes*[b]	No
NP2	83R	Ion	No	No	No	No	No	No	No
P3	83R	Ion	Yes	Yes	Yes	No	No	No	No
NP3	83R	Ion	No	No	No	No	No	No	No
P4	83R	Ion	Yes	Yes	Yes	No	No	Yes	No
NP4	83R	Ion	No	No	No	No	No	No	No
P5*[c]	1235K	Ion	Yes	Yes	Yes	Yes	Yes*[d]	No	No
NP5	1235K	Ion	No	No	No	No	No	No	No
P6	1235K	Ion	Yes	Yes	Yes	No	Yes	Yes*[e]	No
NP6	1235K	Ion	No	No	No	No	No	No	No
P7*[f]	CPBC	Photo	Yes	Yes	N/A*[g]	No	No	N/A*[g]	No
NP7	CPBC	Photo	No	No	N/A*[g]	No	No	N/A*[g]	No
P8	AD	Ion	Yes	Yes	N/A*[g]	Yes*[h]	No	N/A*[g]	No
NP8	AD	Ion	No	No	No	No	No	N/A*[g]	No
P9	FG888D	Ion	Yes	Yes	Yes	No	No	Yes	No
NP9	FG888D	Ion	No	No	No	No	No	No	No
P10	FG888D	Ion	Yes	Yes	Yes	No	No	Yes	No
NP10	FG888D	Ion	No	No	No	No	No	No	No

* NOTES FOR TABLE V a – Sympathetic vibration from P1; b – side nearest contact "B" has indistinct Chladni Figure; c – Agglomeration on circuit board in area of horn; d – Chladni Figure found inside of outer case near the horn area; e – Chladni Figure found inside of outer case near the horn area and on the inside and outside of the horn case; f – Through exposed to smoke for full 15 minutes, P7 horn only operated for 3 minutes; g – This model has no horn case; h – Agglomeration around outer edge of horn disk; i – Minimal soot for classification

TABLE F - EVALUATION of COMBINED WORRELL *et al* and KENNEDY *et al* TEST DATA

TYPES OF TESTS	WORRELL *et al* TESTS		KENNEDY *et al* TESTS		TOTAL NUMBER OF TESTS	
	Number	Percentage	Number	Percentage	Number	Percentage
Total Number Of Tests	30	30/30 (100%)	22	22/22 (100%)	52	52/52 (100%)
Powered Tests	15	15/30 (50%)	12	12/22 (55%)	27	27/52 (52%)
Non-Powered Tests	15	15/30 (50%)	10	10/22 (45%)	25	25/52 (48%)
Anomalous Tests	9	9/30 (30%)	0	0	9	9/52 (17%)
Anomalous Powered Tests	6	6/15 (40%)	0	0	6	6/52 (12%)
Anomalous Non-Powered Tests	3	3/15 (20%)	0	0	3	3/52 (6%)
Tests with Viable Data	21	**21/30 (70%)**	22	**22/22 (100%)**	**43**	**43/52 (83%)**
Soot Agglomeration (Powered - less Anomalous Tests)	9	**9/9 (100%)**	12	**12/12 (100%)**	**21**	**21/21 (100%)**
Soot Agglomeration (Non-Powered - less Anomalous Tests)	0	**0%**	0	**0%**	**0**	**0%**
Non-Powered Tests w/o Soot Agglomeration (less Anomalous Tests)	12	**12/12 (100%)**	10	**10/10 (100%)**	**22**	**22/22 (100%)**

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Underwriter's Laboratories Standard for Safety UL 217, Single and Multiple Station Smoke Alarms, Fifth Edition, dated February 21, 1999 Northbrook, IL

C. L. Worrell, R. J. Roby, L. Streit, and J. L. Torero, "Enhanced Deposition, Acoustic Agglomeration, and Chladni Figures in Smoke Detectors," Fire Technology, 37, 343-362, (USA: Kluwer Academic Publishing, 2001). 343

J. Munger, "Residential Smoke Alarms: Their Effect on the Reduction of America's Fire Death and Injury rate," Ph.D. dissertation, Columbia Southern University, 1999

Endnotes

[1] NFPA Fact Sheet "Smoke Alarms – Make Them Work for Your Safety," National Fire Protection Association, Quincy, MA, 2003.
[2] NFPA Fact Sheet.
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[4] UL 217, 62.2
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[8] C. L. Worrell, R. J. Roby, L. Streit, and J. L. Torero, "Enhanced Deposition, Acoustic Agglomeration, and Chladni Figures in Smoke Detectors," Fire Technology, 37, 343-362, (USA: Kluwer Academic Publishing, 2001). 343
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[16] Worrell et al. 361
[17] Worrell et al.
[18] Worrell et al, Figures 6a, 9, 11 (top), 13 (top), 13 (center)
[19] Worrell et al. p. 351 and Figures 9, 10
[20] UL 217.
[21] Patrick M. Kennedy and James H. Shanley, Jr., "Report of the United States Fire Administration Program for the Study of Fire Patterns," FA 178, (Emmitsburg, MD: Federal Emergency Management Agency United States Fire Administration 1997)
[22] Patrick Kennedy and Kathryn Kennedy, "Flashover and Fire Analysis," (Sarasota, FL: Investigations Institute, 2003)
[23] Worrell et al. 351

EXHIBIT I

NFPA

MEMORANDUM

TO: NFPA Technical Committee on Fire Investigations

FROM: Stacey Van Zandt

DATE: May 21, 2010

SUBJECT: NFPA 921 F2010 ROC Letter Ballot

The ROC letter ballot for NFPA 921 F2010 is attached. The ballot is for formally voting on whether or not you concur with the committee's actions on the comments. Reasons must accompany all negative and abstention ballots.

Please do not vote negatively because of editorial errors. However, please bring such errors to my attention for action.

Please complete and return your ballot as soon as possible but no later than **Friday, June 4, 2010.** As noted on the ballot form, please return the ballot to Stacey Van Zandt either via e-mail to svanzandt@nfpa.org or via fax to 617.984.7056. You may also mail your ballot to the attention of Stacey Van Zandt at NFPA, 1 Batterymarch Park, Quincy, MA 02169.

The return of ballots is required by the Regulations Governing Committee Projects.

Attachment

EXHIBIT
I

921-20 Log #84 Final Action: Reject
(6.2.10.3)

Submitter: B. Don Russell, Texas A&M University
Comment on Proposal No: 921-79
Recommendation: For the reasons set forth in Section 5 below, the entire proposed methodology on soot deposition should be eliminated and not included in this edition of NFPA 921.
Substantiation: NFPA 921 should only include accepted scientific theories and methods derived therefrom. As a practical document, NFPA 921 should not include any hypotheses that are not broadly proven and practiced. The basic scientific question is how much testing and validation must a hypothesis receive before it can be elevated to a theory. In practical terms, the proof of a hypothesis should not be based on a small handful of researchers running a limited number of experiments, under limited protocols and conditions. I am not questioning the reporting accuracy for the data collected by the researchers cited. However, the hypothesis that soot deposition analysis can generally be used to prove the sounding, or not, of smoke alarms under a broad range of conditions with acceptable levels of false positives and false negatives has not yet been proven by the cited researchers or by broader, independent testing and experiments conducted by researchers outside the current small community.

The theory set forth in 6.2.10.3 "Enhanced Soot Deposition on Smoke Alarms" does not have broad scientific basis and: validation and therefore should not be included. It is still a hypothesis. The number of researchers who have conducted statistically valid experiments and the total body of results that have been presented for scientific review is inadequate to prove this concept and create a theory for practical use. With no criticism of the work of any individual researcher, the total number of independent researchers and their peer reviewed papers that have been published on this subject is miniscule. Without respect to the quality of the individual work of any individual researcher, the total body of work is insufficient to prove the theory reliable under the wide range of fire conditions-that must be addressed by NFPA 921.

There are specific scientific concerns that have not been addressed in the test protocols of researchers. All causes of false positives and false negatives are not yet scientifically established nor is the rate of false indications established using statistically accepted methods. The peer reviewed papers that are cited in substantiation for this modification to NFPA 921 show multiple repetition of authors or dependent connections between authors. One must ask what significant group of informed scientists provided the peer review for this relatively small community of individuals who have acquired data or analyzed data on smoke alarm soot deposition. In truth, the number of practitioners of smoke alarm soot deposition analysis is an exceptionally small community and the peer reviewed literature from this community, to date, is insufficient to support this theory for broad practical application.

While a review of the papers cited in the substantiation cannot be completed here, there are certain obvious questions. The wording leaves the reader with the impression that the presence of soot deposition on a smoke alarm indicates that the alarm has just sounded in the fire under investigation. It must be noted that prior smoky conditions, including specifically previous kitchen fires, may establish various levels of soot patterns that persist over time or are enhanced over time, unrelated to the last fire that occurred or the current fire under investigation. Furthermore, no scientific work has been performed to create a formula or a method where researchers or investigators can determine (a) when the smoke detector first sounded in the subject fire, or (b) how long the smoke alarm sounded in the fire.

Based on the above, investigators using this technique are left with significant scientific uncertainty even with the presence of soot deposition on smoke alarms. If they reach a positive conclusion of soot deposition patterns on a specific smoke alarm, they must also conclude that (1) they do not know when the smoke alarm sounded in the fire, (2) they do not know how long the smoke alarm sounded in the fire, and (3) they do not know if the smoke alarm sounded in this fire or in some previous smoky condition or fire that occurred at an unknown time. Investigators analyzing soot deposition patterns on smoke alarms after a specific fire do not know the condition of the smoke detector prior to the fire with respect to previous soundings to smoke conditions. Therefore, no conclusion can be reached that the mere presence of soot deposition patterns on or inside a given smoke detector originate from the subject fire of investigation as opposed to previous soundings of the detector in previous smoky conditions and/or fires (e.g. kitchen fires). Given these uncertainties that are obvious limitations to the proposed technique as set forth in the cited literature, the technique becomes virtually useless for drawing practical conclusions related to a specific fire under investigation.

I have conducted hundreds of smoke alarm fire tests under a wide range of fire conditions. Figures 6.2.10.3(c),(d) showing soot deposition around the exterior of the horn face are not at all representative of the post fire condition of the vast majority of smoke detectors that I have reviewed from my own experiments of staged fires or in the case of naturally occurring fires I have investigated. In fact, the condition represented in these figures is very rare even after exposure of smoke detectors to multiple fires. Therefore, the inclusion of these figures without qualification as to its representation of an extreme condition is misleading and inappropriate. Based on experiments that are documented with data available from the Smoke Detector Test Facility of the Texas Engineering Experiment Station, deposition of significant patterns at the face of smoke detectors exposed to one significant fire, or multiple significant fires, or multiple low smoke fires do not show the patterns indicated in Figure 6.2.10.3(c),(d) for smoke alarms that sounded. (Data records, Smoke Detector Test Facility, Dr. B. Don Russell, Texas Engineering Experiment Station, Texas A&M University System, College Station, Texas, 77843.)

It should also be qualified in the text of the document that the presence of soot deposition on or inside a smoke alarm provides no indication as to when the smoke alarm sounded in the subject fire under investigation. A smoke alarm sounding late in a fire after victims are deceased may develop smoke deposition patterns (or not!). The levels, and quantity, and characteristics of the smoke and the location of the detector with respect to the fire source will all affect levels of soot deposition, if any, and the time progression of soot deposition in a given fire. There has been no scientific research relating the specific patterns of soot deposition on specific smoke detectors to a timeline of sounding in a given fire under given fire development conditions. Since no such formula exists, an analysis of these factors is speculative based on unknown conditions of a given fire; therefore, no conclusions can be reached based on analysis of soot deposition patterns as to how long a smoke detector sounded and/or when a smoke detector sounded in a given fire.

The language of the proposed additions to NFPA 921 with respect to soot deposition leave the incorrect impression to those not skilled in this specific art that the mere presence of accumulated soot on the outside, inside, or on the horn area of a smoke alarm is an indication that the alarm worked as designed, and is intended, and provided a timely warning, etc. None of these conclusions can be scientifically reached. An investigator seeing soot deposition patterns on a smoke detector following a given fire can only conclude that it is possible that the smoke alarm sounded, with an unknown probability, in one or more fires, not necessarily the subject fire under investigation. Once again, the investigator can conclude nothing as to when the smoke alarm sounded in the fire or the duration of it sounding in the fire, early or late. It should be noted that the design of certain smoke alarm horns allow for the partial failure of the horn resulting in vibration at a low sound level (non resonant condition) without the required volume to awaken residents. Soot deposition patterns could theoretically form around the horn even though the alarm sound level is far too low to be effective. This failure mode of smoke alarms has not been adequately addressed in the proposed method.

Unless the proposed language of soot deposition analysis is highly qualified in this document, many investigators attempting to use this section of NFPA 921 will reach erroneous or misleading conclusions and/or will not understand, the limits of the methodology with respect to conclusions in their specific fire investigation.

In conclusion, soot deposition analysis of smoke alarms is not yet broadly proven nor its limitations fully established by broad experimentation and repetition of experiments by a significant number of independent researchers and practitioners. Without respect to the issue of overall validity, the uncertainties of specific conclusions that can be reached by fife investigators make the technique of little practical use and frequently misleading as to its support for findings in any specific fife investigation.

Even if this technique ultimately is proven reliable, which will require much greater definition of error rates and extensive independent testing under carefully designed protocols, it should not be included in this document at this time because it remains a hypothesis that does not yet meet the requirements of the scientific method to be elevated to a , theory. To include the method at this stage will violate basic principles of the scientific method.

While it is my preference that the proposed analytical method of soot deposition analysis be struck and not included in this revision of NFPA 921, the newness of this proposed technique and the lack of broad, independent testing and validation, coupled with the technical limitations and unknown error rates, demand that the technique be at least qualified significantly with adequate warnings as to the limitations of the technique if it is to be used by fife investigators. Hence, I have proposed 6.2.10.3.4 and 6.2.10.3.5 to provide clarity as to the limitations of the technique under the best of conditions.

My qualifications to offer these opinions as to the scientific validity of the proposed hypothesis (alleged theory) include 35 years of scientific research and experimentation. I am a Regents Professor and Distinguished Professor of the Texas A&M University System. I am a fellow of five societies, hold the Bovay Chair at Texas A&M, and am a member of The National Academy of Engineering. I teach the scientific method and its application to electrical design engineers.

Committee Meeting Action: Reject

Committee Statement: The use of acoustic soot agglomeration for the determination of smoke detector activation is supported in the scientific literature. as referenced in the original proposal.

IN THE UNITED STATES DISTRICT COURT
EASTERN DISTRICT OF ARKANSAS
WESTERN DIVISION

FURLANDARE SINGLETON, Individually and as Administrator of the Estate of Dequan Singleton, Syndi Singleton, and Haylee Singleton, Decedents; and CLYDE HATCHETT, Individually, and as Administrator of the Estate of Emily Beavers, Deceased — PLAINTIFFS

v. Case No.: 4:15-CV-205-KGB

ARKANSAS HOUSING AUTHORITIES PROPERTY & CASUALTY SELF-INSURED FUND, INC., *et al.* — DEFENDANTS

MARILYN LOUISE BEAVERS, Individually and as Administrator of the Estate of MARILYN BEAVERS, DECEASED — PLAINTIFFS

v.

ARKANSAS HOUSING AUTHORITIES PROPERTY & CASUALTY SELF-INSURED FUND, INC., *et al.* — DEFENDANTS

HOUSING AUTHORITY DEFENDANTS MEMORANDUM IN OPPOSITION TO PLAINTIFFS' MOTION TO STRIKE DAN GOTTUK

Separate Defendants Arkansas Housing Authorities Property & Casualty Self-Insured Fund, Inc., Evanston Insurance Company, and Phil Nix ("Housing Authority Defendants") oppose Plaintiff's' Motion to Strike Dan Gottuk as an expert witness, Dkt. No. 106. The Housing Authority Defendants adopt and incorporate by reference Separate Defendant BRK Brands, Inc.'s Memorandum Opposing Plaintiffs' motion, filed earlier today and docketed as Dkt. No. 112 (hereafter, "BRK's response").

I. Overview

Plaintiffs' effort to strike defense expert Daniel Gottuk, Ph.D. lacks any merit and should be summarily denied. Plaintiffs have found a new proposed expert, B. Don Russell, Ph. D., willing to opine that the enhanced soot deposition ("ESD") methodology, also known as acoustic soot agglomeration ("ASA"), relied on by Gottuk to analyze the smoke alarm from the Beavers' residence is not scientifically reliable.

As described in detail in Gottuk's supplemental affidavit, attached hereto as Exhibit 1, and Lori Streit's affidavit, attached to BRK's response as Exhibit A, ESD (or ASA) is a scientifically validated, peer-reviewed, generally accepted method for assessing after-the-fact whether a smoke alarm sounded in a fire. Additionally, Gottuk applied the method properly. Gottuk considered relevant case facts to rule out any other reasonable explanation for the distinct soot pattern he observed on the smoke alarm other than the alarm sounding during this fire. The evidence overwhelmingly supports both ESD analysis in principle and its use by Gottuk (and Streit) in this case. Therefore, Plaintiffs' motion should be denied.

As a threshold matter, Plaintiffs, not Defendants, have the burden to prove their allegation that the smoke alarm failed "to sound an audible alarm," thereby causing the decedents' death. (Am. Complaint at ¶ 46). This should be considered in evaluating Plaintiffs' motion and Don Russell's apparent inability to determine whether the smoke alarm actually sounded.[1] Plaintiffs cannot prevail on their negligence claim without presenting evidence that the smoke alarm failed to sound and that it made a difference – *i.e.* that Plaintiffs' decedents would have survived if the smoke alarm had sounded. Since Marilyn Beavers allegedly was awake; "recognized the blaze"; and fought "to put out the fire"; whether the smoke alarm sounded should be irrelevant. (Am. Comp. at ¶ 17, ¶ 19). Although the defense does not have the burden to disprove Plaintiffs' theory of negligence, Gottuk's valid and admissible opinion testimony, unless excluded, completely undermines Plaintiffs' claim that the Housing Authority Defendants were negligent in failing to have a working smoke alarm installed in the Beavers' apartment and that such failure proximately caused the death of the decedents. These Defendants submit that it is Gottuk's ultimate conclusion that Plaintiffs find objectionable and not the science he used to reach it. As this Court well knows, a party's objection to a conclusion reached through a reliable scientific process is not a legitimate basis for excluding expert opinion testimony.

II. ***Daubert*** standard

The opinion of a qualified expert witness is admissible if: (1) it is based on sufficient facts or data, (2) it is the product of reliable principles and

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[1] Plaintiffs have also tendered Don Russell as a proposed new expert witness and tendered his Affidavit as a basis for further delaying Plaintiffs' response to the Housing Authority Defendants and BRK's motions for summary judgment. The Housing Authority Defendants and BRK have opposed both motions. They specifically object to Russell's identification as a new expert at this point in the case. (*See, e.g.*, Dkt. Nos. 109, 110, and 111).

methods, and (3) the expert has reliably applied the principles and methods to the facts of the case. Fed. R. Evid. 702. The expert's scientific, technical, or specialized knowledge must also "assist the trier of fact to understand the evidence or determine a fact in issue." *Id.* The district court is vested with a gatekeeping function to ensure that "any and all scientific testimony or evidence admitted is not only relevant, but reliable." *Daubert v. Merrell Dow Pharms., Inc.*, 509 U.S. 579, 589, 113 S. Ct. 2786, 125 L. Ed. 2d 469 (1993). The proper focus of a *Daubert* inquiry is on an expert's methods and not his conclusions. *Daubert*, 509 U.S. at 595; *Bonner v. ISP Techs., Inc.*, 259 F.3d 924, 929 (8th Cir. 2001).

Plaintiffs' sole challenge is to the reliability prong. That is, they contend that the method used by Dan Gottuck to formulate his opinion that the smoke alarm sounded is unreliable. As the proponent of Dan Gottuk's testimony, the Housing Authority Defendants embrace their burden to show that his proposed testimony satisfies the standard for admitting expert testimony.

Four non-exclusive factors are relevant to an analysis of the reliability of an expert's opinion: (1) "whether it can be (and has been) tested"; (2) "whether the theory or technique has been subjected to peer review and publication"; (3) "the known or potential rate of error"; and (4) "[the method's] 'general acceptance.'" *Daubert*, 509 U.S. at 593-94. These factors are not exhaustive or limiting. Instead, "the *Daubert* reliability factors should only be relied upon to the extent that they are relevant and the district court must customize its inquiry to fit the facts of each particular case." *Shuck v. CNH Am.*, LLC, 498

F.3d 868, 874 (8th Cir. Neb. 2007) (omitting citation and internal quotes). All four *Daubert* factors are satisfied here.

The judge's role in analyzing Rule 702 and *Daubert* "is to prevent juries from being swayed by dubious scientific testimony." *Russell v. Whirlpool Corp.*, 702 F.3d at 456; *see also In re Zurn Pex Plumbing Prods. Liab. Litig.*, 644 F.3d 604, 613 (8th Cir. 2011) ("The main purpose of Daubert exclusion is to prevent juries from being swayed by dubious scientific testimony").

For the reasons explained below, it cannot be seriously argued that Gottuk has employed "dubious" scientific reasoning.

III. Discussion

As described further below, the ESD method relied upon by defense expert Dan Gottuk has been widely tested, subjected to peer review and publication, has an exceedingly narrow error rate, and has been generally accepted by the scientific community, as reflected by its inclusion in NFPA 21. Therefore, Plaintiffs' *Daubert* challenge should be summarily denied.

A. Factual and Procedural Background

Because of Plaintiffs' allegation that the smoke alarm failed to sound during the March 22, 2012 fire, the inspection of the subject smoke alarm was anticipated and recognized by all interested parties as a very important event in this litigation. On December 7, 2015, after much discussion, multiple pleadings regarding testing specifics, and a hearing in the state court action, the smoke alarm inspection took place. Dan Gottuk, Ph.D., attended for the

Housing Authority Defendants; Lori Streit, Ph.D., attended for Defendant BRK Brands, Inc. Plaintiffs had two experts attend on their behalf, Forest Smith, an electrical engineer, and Roger Tate, an alleged "mechanical and fire prevention expert."[2]

As a result of the December 7, 2015 inspection and as evidenced by their affidavits filed in this matter, both Gottuk and Streit determined that the smoke alarm had sounded during the subject fire.[3] Notably, neither of Plaintiffs' original two experts has come forward with any expert opinions regarding the results of the inspection. Neither is able to offer an opinion to counter Gottuk's (and Streit's) reliance on ESD methodology to determine that the smoke alarm sounded. Instead, albeit belatedly, Plaintiffs have secured the services of a third expert. B. Don Russell, in an effort to exclude Gottuk as an expert witness. Russell's own proposed opinions about the case are unclear as he has not provided an expert report and his affidavit focuses solely on critiquing Gottuk.

What is clear is that Russell is a hired gun who testifies almost exclusively for plaintiffs and whose opinion testimony has been excluded in the past. *See, e.g.*, *Johnson v. Kidde, et al.*, No. 5:03-425- JMH, 2006 U.S. Dist.

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[2] Plaintiffs disclosed Smith and Tate as experts in December of 2014. Roger Tate specifically stated in his December 2014 "supplemental opinion" that the 'fire alarm did not function at the time of the fire." The silence from Mr. Tate following the December 2015 inspection is telling.

[3] *See* Dan Gottuk's original Affidavit filed in support of the Housing Authority Defendants' and BRK's Motions for Summary Judgment. (Doc. Nos. 56, and 88). *See* Streit's Affidavit, filed June 1, 2016 (Doc. No. 112-1).

LEXIS 4218 (E.D. Ky. Feb. 2, 2006) (excluding Russell from testifying that an ionization smoke alarm was defective because it failed to sound in a timely manner); *Garcia v. BRK Brands, Inc.*, 266 F. Supp. 2d 566, 572-575 (2003) (excluding Russell's proposed expert testimony that a smoke alarm should have sounded before the decedent was incapacitated and grating summary judgment to defense based on lack of causation); *Werner v. Pittway Corp.*, 90 F. Supp. 2d 1018 (W.D. Wis. 2000) (striking as a "bare conclusion" Russell's proposed testimony concluding that a missing smoke detector was "most probably" an ionization smoke detector and granting summary judgment where plaintiffs "were awake in time to escape" and "cannot show that any failure of a detector caused the injuries they suffered."). In stark contrast, Gottuk has testified in fire-related and smoke alarm cases in state and federal courts, and his expert opinions have never been stricken or limited. (Supp. Aff. at ¶ 6).

While the present motion before the Court relates solely to whether Gottuk's testimony satisfies *Daubert* and should be permitted, and is not, at this point, a battle of the experts,[4] the Court may consider Russell's history in evaluating the strength and validity of Russell's challenge to Gottuk's testimony. For the reasons stated below, Russell's criticisms of the methodology relied upon by Gottuk and Streit are unfounded and insufficient to justify striking Gottuk's opinion testimony.

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[4] Assuming Russell is not stricken because he was identified too late, Defendants specifically reserve the right to challenge Russell's "opinion" based on *Daubert* once Russell makes those opinions known.

B. Two experts, Gottuk and Streit, independently conducted an ESD analysis of the subject smoke alarm and concluded that it sounded in this fire.

Gottuk describes in his initial affidavit how, using the enhanced soot deposition ("ESD") method, he determined that the horn sounded during the March 22, 2012 fire. (Doc. No. 56-2, Exh. 2, ¶¶ 7-10).[5] In his Supplemental Affidavit, Gottuk describes how ESD methodology "is recognized as a reliable forensic protocol to evaluate the presence of soot particulate around various openings of a horn assembly for the purpose of evaluating whether the alarm sounded during a fire exposure." (Supp. Aff., Exh. 1, ¶ 8). Gottuk also explains how he considered additional information, including case facts and the timeline of events, to conclude that the ESD patterns he observed were caused by this fire. (Id. at ¶ 17). Lori Streit describes how she also used ESD methodology to examine the subject smoke alarm, as a result of which she also concluded that the smoke alarm sounded in this fire. (Streit Aff. at ¶ 23).

Thus, here we have two experts, representing different parties, who separately used ESD methodology and independently concluded that the subject smoke alarm sounded in this fire.

[5] Dan Gottuk's original affidavit is already in the record as Exhibit 2 to the Housing Authority Defendants' Motion for Summary Judgment, Docket # 56-2, and BRK's Motion for Summary Judgment, Docket # 88-1. Rather than increase the already voluminous record, Dan Gottuk's original affidavit is incorporated herein by reference.

C. ESD satisfies the *Daubert* criteria for assessing reliability.

(1) <u>Prior Testing</u>

Defense expert Dan Gottuk explains how in addition to the testing and work he has personally done, the ESD methodology "has been tested and validated by multiple scientists." (Supp. Aff., Gottuk, Exh. 1 at ¶ 8). Gottuk goes on to describe how ESD has been "systematically studied and independently evaluated by multiple investigators" and recognized as a "repeatable phenomenon." (*Id.* at ¶ 9). Additionally, Lori Steit in her affidavit goes into great detail regarding both the testing that she, and others, have done. (Streit Aff. at ¶ 10, 13, 15).

Russell's assertion that there has been "little or no testing of the method by independent researchers" either discounts completely the extensive testifying that has occurred or Russell is unaware of it. (Russell Aff. at ¶ 10). Neither justifies the conclusion that ESD has not been adequately tested.

Assuming that Russell would conclude and be willing to opine that faculty members at leading science universities such as University of Maryland, Worcester Polytechnic Institute and University of Edinburgh are not sufficiently "independent," that is an issue for cross-examination, at best, and not a basis for excluding Gottuk's testimony.

(2) <u>Peer review and publication</u>

Gottuk describes the various peer-reviewed publications on the use of ESD analysis to assess whether a smoke alarm sounded. (*Id.* at ¶ 10; *see also* ¶ 18 (listing publications). Lori Streit goes into considerable detail concerning her research into ESD, her publications and peer-reviewed work, as well as publications and studies by other researchers. (*See*, *e.g.*, Streit Aff. at ¶¶ 8-13, 14-16; BRK's response, Doc. No. 112, at pp.4-6). Additionally, Streit has attached several published studies to her affidavit. In light of this production, Russell cannot seriously contend that ESD methodology has not been peer-reviewed and published.

Considered in light of Gottuk and Streit's presentation, Russell's assertion that there has been "no publication of the data from a statistically significant number" of experiments once again appears to be based on either ignorance or arrogance. (Russell at ¶ 10). Either way, Russell's assertion regarding lack of peer review and publication is simply wrong.

(3) Error rate

BRK's expert Streit, in a blind study, personally examined over 400 smoke alarms without knowing which alarms had activated and was able to identify, for those alarms in which there was sufficient soot to create a distinct pattern, the alarms that had activated with 100% accuracy. (Streit Aff. at ¶ 13; *see also* Gottuk Supp. Aff. at ¶ 15, discussing 100% accuracy in blind studies of alarms using ESD).

Gottuk conducted a statistical analysis to the available data regarding ESD methodology applied to smoke alarms. The resulting analysis, using a Bayesian method, shows that ESD can correctly identify whether a smoke detector activated with a 99.6% confidence level. Similarly, ESD can be used to correctly determine that a smoke detector failed to activate with 99.5% accuracy. (Gottuk Supp. Aff. at ¶ 16).

Russell's conclusory affidavit is unsupported by any scientific evidence or testing. He simply asserts that ESD is not a reliable predictor of whether a given smoke alarm sounded during a fire. Russell's conclusion must yield to the extensive and compelling evidence showing that evidence of distinct soot deposition patterns, when present on a smoke alarm following a fire, is a very reliable indicator that a smoke alarm sounded. Indeed, it is Russell's "opinion" (if one can call it that) that seems suspect.

(4) General acceptance

It is undisputed that the National Fire Protection Association's Guide for Fire and Explosion Investigations ("NFPA 921") recognizes ESD as an approved forensic method for determining whether a smoke alarm sounded during a fire. This establishes general acceptance without need for further inquiry.

NFPA 921 is recognized as an authoritative reference for fire investigators. (Gottuk Aff. at ¶¶ 8-9, Supp. Aff, at ¶ 11; Streit Aff. at ¶¶ 17-20). Additionally, the Eighth Circuit has held that NFPA 921 "qualifies as a reliable method endorsed by a professional organization" for purposes of *Daubert*. *Fireman's Fund Ins. Co v. Canon U.S.A.*, 394 F.3d 1054, 1058-1059 (8th Cir. 2005); *Presley v. Lakewood Eng'g*, 553 F.3d 638, 645 (8th Cir. 2009).

Russell fails to provide any scientific basis for this Court to reject a forensic method approved by NFPA 921. Nor does Russell mention in his supporting affidavit NFPA 921's approval of ESD as a forensic method to determine whether a given smoke alarm sounded during a fire. Moreover, NFPA specifically rejected Russell's effort to keep ESD from inclusion in NFPA 921. In 2010, Russell argued to the NFPA that EDS was still a hypothesis and could not be scientifically validated. The NFPA Committee rejected Russell's proposal and issued the following statement: "The use of acoustic soot agglomeration for the determination of smoke detector activation is supported in the scientific literature, as referenced in the original proposal." (Supp. Aff. of D. Gottuk, at ¶ 12 and Exh. 1-B; *see also* Streit Aff. at ¶ 19).

Should Russell persist, after reviewing all the evidence validating ESD as a forensic method, in refusing to recognize ESD as a valid and reliable method for determining whether a smoke alarm activated in a fire, Russell will be the one going against the grain of the scientific community.

The evidence overwhelmingly supports the use of ESD or ASA as an approved, reliable method for determining whether a given smoke alarm sounded in a particular fire.

D. Gottuk's application of ESD methodology in this case is sufficiently reliable to survive a *Daubert* challenge.

Of course, even when an expert applies a reliable, approved and validated method such as ESD, he must also apply it reliably to the facts of the case. As Dan Gottuk explains in his Supplemental Affidavit, his ultimate conclusion that the smoke alarm in this case sounded in this fire is informed not only by his reliance on ESD analysis, but also by his consideration of case facts and the timeline of events.[6] (Supp. Aff. of Dan Gottuk, at ¶ 17).

First, as a general proposition, Gottuk agrees with Russell that due to the persistence of ESD patterns, observing a distinct pattern alone may not suffice to support the conclusion that an alarm sounded during a particular fire. "However, with additional information regarding case facts and timeline of events, the occurrence of the ESD can be made with certainty and correlated to a specific fire." (*Id.*) Gottuk goes on in this paragraph to explain how he relied on his general specialized knowledge and knowledge of the facts in this case to conclude that that alarm sounded in this fire. In Gottuk's own words:

> No evidence exists that this particular alarm had been in an earlier fire, period, much less an earlier fire resulting in smoke exposure significant enough to have caused the distinct ESD patterns I observed on the subject smoke alarm. Typical cooking and nuisance alarms have been shown to <u>not</u> produce ESD associated with a sounding alarm in response to a fire. (Phelan, 2004). Also, the tests cited above have shown that if a fire is not large enough or does not burn for a sufficient amount of time, distinct enhanced soot deposition will not occur. Thus, the technical literature demonstrates numerous cases in which smoke alarms have been exposed to fire, but the resulting smoke and soot was insufficient to leave a discernable pattern.
>
> Based on the ESD testing combined with inquiry into relevant historical facts, it is my scientific opinion that the prominent ESD patterns I observed on the subject smoke alarm could not have been caused by a prior fire. I also learned in my investigation that the subject smoke alarm had been inspected and tested within months of the subject fire and determined to be in good working order. Finally, circumstantial evidence suggesting the subject alarm had been knocked from its ceiling mount at some point during the fire also is consistent with the alarm having sounded during this fire.

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6 In stark contrast to Gottuk's Affidavit, there is no evidence that Russell considered the case specific facts in any manner whatsoever.

> In conclusion, in the absence of any evidence whatsoever that would suggest that the subject smoke alarm had been previously exposed to another fire or soot sufficient to create distinct soot deposition patterns, it is my opinion, to a reasonable degree of scientific certainty, that the distinct soot deposition patterns I observed on the subject smoke alarm indicate that the alarm sounded in this fire.

(Gottuk Supp. Aff. at ¶ 17).

Gottuk's explanation of how he used ESD in this particular case to reach his particular conclusions is more than adequate to survive a *Daubert* challenge. Under Eighth Circuit precedent, experts' methods are deemed reliable when experts "observed the relevant evidence, applied their specialized knowledge, and systematically included or excluded possible theories of causation." *Shuck v. CNH America*, 498 F.3d 868, 875 (8th Cir. 2007). Gottuk's overall methodology is reliable because it was founded on a NFPA 921 approved scientific methodology and supplemented with an examination of relevant case evidence to exclude any other possible explanation for the distinct soot deposition patterns on the subject smoke alarm.

E. Don Russell's speculation about what *may* have happened is inadmissible and insufficient to justify striking Gottuk's testimony.

Russell also speculates that maybe the smoke alarm had sounded in a previous fire and therefore, that a previous fire *could* be the cause of the soot deposits Gottuk observed. (Russell Aff. at ¶ 12). As Gottuk explained, *supra*, because there was no case specific facts existing to suggest that the smoke alarm had been exposed to a previous fire, no basis existed for Gottuk to attribute the ESD patterns he saw to a non-existent event. (Supp. Aff. of Gottuck, at ¶ 17). Russell's sworn testimony on this point is pure conjecture.

Russell theorizes that even if the "subject smoke detector sounded in the incident fire, the smoke detector *may* have sounded very late in the fire and therefore did not provide a timely or adequate warning." (Russell Aff. at ¶ 13) (emphasis added). Once again, this is speculation that has nothing to do with whether Gottuk's opinion that the alarm sounded should be excluded.

As one court has stated, "the function of expert testimony is to explain how something happened, not to speculate as to how something could possibly have happened." *Estate of Groff v. Aquila, Inc.*, No. 4:05-cv-0250, 2007 U.S. Dist. LEXIS 98729, 2007 WL 4644707, at *10 (S.D. Iowa Sept. 28, 2007); accord, e.g., *Glastetter v. Novartis Pharms. Corp.*, 252 F.3d 986, 989 (8th Cir. 2001) ("[T]he district court's gatekeeping role separates expert opinion evidence based on 'good grounds' from subjective speculation that masquerades as scientific knowledge."); *Concord Boat Corp. v. Brunswick Corp.*, 207 F.3d 1039, 1057 (8th Cir. 2000) ("Expert testimony that is speculative is not competent proof.") (internal quotation marks and citations omitted); *Johnson v. Avco Corp.*, 702 F. Supp. 2d 1093, 1108-09 (E.D. Mo. 2010) ("We do not allow witnesses to tell juries that in their expert opinion something happened simply because it is possible."). Thus, Russell should not be permitted to offer speculative testimony, either at trial (assuming he is permitted to testify and can survive a *Daubert* challenge) or in challenging Gottuk's testimony.

Finally, Russell's affidavit and Plaintiffs' argument evidences a fundamental misunderstanding of the burden of proof in this case. Gottuk is not purporting to offer an opinion as to the precise point in time the alarm began to sound. Nor is he required to do so. It is Plaintiffs, not Defendants, who have the burden to prove negligence and causation. To prevail, Plaintiffs must prove <u>both</u> that the alarm failed to sound <u>and</u> that its failure to sound proximately caused the death of decedents. Russell's affidavit, at ¶ 13, stating that even if the smoke detector sounded, it "*may* have sounded very late in the fire and therefore did not provide a timely or adequate warning to residents" -- is totally speculative and will not permit Plaintiffs to go to the jury on their theory of negligence against the Housing Authority Defendants. Plaintiffs' *Daubert* motion is so weak that it suggests an effort to obfuscate and to further delay the proceedings rather than a legitimate basis for attempting to exclude an expert witness.

IV. Conclusion

Defense expert Dan Gottuk has sufficiently explained both the ESD methodology and his application of it to the facts of this case. Gottuk's opinion may not be stricken simply because Don Russell disagrees with his opinion or because it undercuts Plaintiffs' negligence theory. A difference of opinion between experts, even assuming the Court permits Russell's late identification and Russell can survive a *Daubert* challenge, may be explored through cross-examination and, if permitted, the presentation of rebuttal expert opinion.

The Court should deny Plaintiff's Motion to Exclude Dan Gottuk's opinion testimony in this case.

Respectfully submitted,

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CERTIFICATE OF SERVICE

I, Edie R. Ervin, hereby certify that a copy of the foregoing pleading has been filed using the CM/ECF Filing System on this 1st day of June, 2016, and the Clerk of Court shall serve a copy upon the following counsel of record:

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IN THE UNITED STATES DISTRICT COURT
EASTERN DISTRICT OF ARKANSAS
WESTERN DIVISION

FURLANDARE SINGLETON, *et al.* **PLAINTIFFS**

v. **Case No.: 4:15-CV-205-KGB**

ARKANSAS HOUSING AUTHORITIES PROPERTY & CASUALTY SELF-INSURED FUND, INC., *et al.* **DEFENDANTS**

SUPPLEMENTAL AFFIDAVIT OF DANIEL GOTTUK

I, Daniel Gottuk, of lawful age and having been duly sworn, upon my oath states as follows:

1. My name is Daniel T. Gottuk. I am employed by Jensen Hughes of Baltimore, Maryland.

2. I have been retained by the Defendants, Jacksonville Housing Authority, Evanston Insurance Company and Phil Nix, in this matter. I was specifically retained to review all information regarding the smoke alarm at issue in this case.

3. This Supplemental Affidavit is intended to supplement the Affidavit I gave earlier in this case. My updated Curriculum Vitae and a selected publications list is attached hereto as Exhibit **1-A**.

4. Since 1993, I have conducted thousands of fire detection tests in a wide range of structures and fire conditions (see selected publications list for examples). Analyses have included the investigation and analysis of novel detection technologies, performance of existing technologies and the

PENGAD 800-631-6989 DEFENDANT'S EXHIBIT 1 development of standardized test protocols. I have also conducted many experimental forensic programs for the National Institute of Justice (part of the Department of Justice). My research has included both basic and applied forensic studies to develop fundamental understanding of fire dynamics, pattern formation and damage assessment as well as to develop practical forensic tools for fire scene investigations and analyses.

5. Some of the relevant positions I have held in various organizations include: (1) chair, NFPA 72 Technical Committee on Single- and Multiple-Station Alarms and Household Fire Alarm Systems; (2) member, NFPA 921 Technical Committee on Fire and Explosion Investigation; (3) Chair, Fire Detection and Alarm Research Council; and (4) member, UL Standards Technical Panel 217 for Smoke Detectors and Alarms.

6. I have been qualified and given testimony in fire-related and smoke alarm cases in state and federal courts. My expert opinions have never been stricken or limited.

7. I understand that Plaintiffs, through B. Don Russell, Ph.D., have challenged my opinion in this case that the smoke alarm at issue in this case sounded during the fire. Dr. Russell in his Affidavit contends that the forensic method of enhanced soot deposition ("ESD") is not reliable in that it does not use accepted scientific protocols, has not been peer reviewed, is not repeatable, and has not been tested "under the wide variety of fire conditions that can reasonably be anticipated to occur in a home." Dr. Russell's statements simply

are not true. The ESD method has been tested, peer-reviewed, and deemed scientifically reliable.

8. Among those who regularly work in this field, the method referred to as enhanced soot deposition (also known as acoustic soot agglomeration) is recognized as a reliable forensic protocol to analyze the presence of smoke particulate around various openings of a horn assembly for the purpose of evaluating whether the alarm sounded during a fire exposure. Besides the testing and work I have personally done, the methodology has been tested and validated by multiple scientists (Worrell 2001, Worrell 2003, Phelan 2004, Kennedy 2004, Mealy 2008, Mealy 2011, Woycheese 2006) and evaluated and accepted by the forensic community (NFPA 921). *See* paragraph 11 below re: NFPA 921's acceptance of ESD in its 2011 edition.

9. Enhanced soot deposition ("ESD") during sounding of an alarm has been systematically studied and independently evaluated by multiple investigators and has also been recognized as a repeatable phenomenon by those involved with smoke alarm testing. The studies cited in the literature have been performed by at least four independent organizations and have included multiple faculty members at leading fire science universities, that is, University of Maryland, Worcester Polytechnic Institute and University of Edinburgh.

10. Publications on ESD have appeared in at least three separate papers in a leading fire science peer-reviewed journal (Fire Technology) and presented in a range of venues, including Interflam, the International

Symposium on Fire Investigations, NFPA 921 Technical Committee, and as a master's thesis at Worcester Polytechnic Institute.

11. The National Fire Protection Association ("NFPA"), which was founded in 1896, is a global, nonprofit organization "devoted to eliminating death, injury, property and economic loss due to fire." (As viewed on NFPA's website, http://www.nfpa.org/press-room, on May 31, 2016). NFPA 921 is recognized as an authoritative reference for fire investigation.

Beginning with its 2011 edition, NFPA 921 specifically identified ESD as an appropriate method to determine if a smoke alarm sounded or did not sound during a given fire. Thus, ESD has been recognized as an approved forensic method.

12. Plaintiffs' proposed expert, Dr. Russell, objected to NFPA 921's inclusion of ESD as an approved forensic method in its 2011 edition. NFPA 921's Technical Committee reviewed and rejected Dr. Russell's proposal to exclude ESD from NFPA 921. The explanatory statement for rejecting Dr. Russell's proposal was: "The use of acoustic soot agglomeration for the determination of smoke detector activation is supported in the scientific literature. as referenced in the original proposal." *See* attached excerpt from NFPA 921's 2010 meeting, as Exhibit 1-B. Thus, it is Dr. Russell who is out of the mainstream with his views on ESD.

13. The various studies performed to evaluate and validate the forensic methodology of using enhanced soot deposition have included a range of fire and non-fire conditions, including cooking events and other nuisance sources,

fires in small test chambers, fires in multi-room structures, fires in full-scale apartment and house tests with and without flashover conditions. The wide variety of fire conditions resulted in smoke alarms that ranged from not being thermally affected to those that had charred plastic and some that were largely consumed by the fire. Fuel sources were varied from gas fires to flaming and smoldering polyurethane, wood, paper, cardboard, cables, cotton and upholstered furniture and kitchen cabinets. Besides smoldering and flaming, fires included slow growing to fast developing arson scenarios.

14. Amongst the various studies performed and presented in the literature, over 450 fire exposed smoke alarms (both powered and non-powered) were evaluated in assessing and validating the use of enhanced smoke deposition. The wide range of fire conditions, makes and models of smoke alarms, and different exposure conditions amongst these hundreds of trials has established a significant database to evaluate the use of enhanced soot deposition. (Worrell 2001, Worrell 2003, Phelan 2004, Mealy 2011).

15. ESD has been evaluated using blind studies so that the people evaluating the smoke alarms did not know which alarms had or had not sounded during a fire. The results demonstrate reliable conclusions of determining when a smoke alarm sounded. These results have been reported in the various studies cited above. For example, the work of Mealy et al (2011) validated the use of the heuristics developed by Phelan (2004) by exposing 78 smoke alarms to a range of full-scale apartment structure fire tests. Of the 47 smoke alarms that had sufficient evidence to evaluate (*i.e.*, some were

excessively burned and consumed and some not exposed to enough smoke), alarm activation was determined with 100% accuracy.

16. The data collected over the four main studies (Worrell 2001, Worrell 2003, Phelan 2004, Mealy 2011) that have examined the use of ESD to determine whether or not a smoke alarm activated in a fire demonstrates a statistically significant, strong correlation in the accuracy of the methodology that was used in the determinations. The future distribution of the "success" or "failure" of a determination made by using this methodology was considered to determine the confidence level of the testing. In this analysis, a Bayesian method was determined to be the most appropriate. A Bayesian method considers the weight of the generic data, can account for the statistical significance of the data, and is a consistent way to treat data when the data has no failures (EPRI, 2013). This method is used and supported within the Nuclear industry for probabilistic risk assessment (PRA) and is approved by the Nuclear Regulatory Commission (PRA, 1983).

Based on the Bayesian method using a Jeffreys non-informative priors, the confidence level in the ability of the ESD methodology to correctly determine whether a smoke alarm activated was determined to be 99.6%. This represents almost a three sigma level of confidence in the reliability of the testing. Similarly, when analyzing the testing data for the ability of ESD methodology to correctly determine whether a smoke alarm failed to activate, the confidence level was calculated to be 99.5%.

17. ESD patterns are generally persistent and will remain over the course of time. As such, it is true that one cannot necessarily tell the time that the patterns occurred just by looking at the pattern. However, with additional information regarding case facts and timeline of events, the occurrence of the ESD can be made with certainty and correlated to a specific fire.

No evidence exists that this particular alarm had been in an earlier fire, period, much less an earlier fire resulting in smoke exposure significant enough to have caused the distinct ESD patterns I observed on the subject smoke alarm. Typical cooking and nuisance alarms have been shown to <u>not</u> produce ESD associated with a sounding alarm in response to a fire. (Phelan, 2004). Also, the tests cited above have shown that if a fire is not large enough or does not burn for a sufficient amount of time, distinct enhanced soot deposition will not occur. Thus, the technical literature demonstrates numerous cases in which smoke alarms have been exposed to fire, but the resulting smoke and soot was insufficient to leave a discernable pattern.

Based on the ESD testing combined with inquiry into relevant historical facts, it is my scientific opinion that the prominent ESD patterns I observed on the subject smoke alarm could not have been caused by a prior fire. I also learned in my investigation that the subject smoke alarm had been inspected and tested within months of the subject fire and determined to be in good working order. Finally, circumstantial evidence suggesting the subject alarm had been knocked from its ceiling mount at some point during the fire also is consistent with the alarm having sounded during this fire.

In conclusion, in the absence of any evidence whatsoever that would suggest that the subject smoke alarm had been previously exposed to another fire or soot sufficient to create distinct soot deposition patterns, it is my opinion, to a reasonable degree of scientific certainty, that the distinct soot deposition patterns I observed on the subject smoke alarm indicate that the alarm sounded in this fire.

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FURTHER, AFFIANT SAYETH NOT.

ELIZABETH M. PIGOTT-DUBYOSKI NOTARY PUBLIC BALTIMORE COUNTY, MD

Daniel T. Gottuk

DANIEL T. GOTTUK
VP of Specialty Services, Technical Director

Dated: 5/31/2016

SUBSCRIBED and SWORN to before me this 31st day of May, 2016.

Elizabeth M Pigott Dubyoski

Notary Public

My Commission Expires:

03/19/2017

JENSEN HUGHES

DANIEL T. GOTTUK, PE, PhD

VP of Specialty Services, Technical Director

Experience: 27 Years
Joined JENSEN HUGHES: 1992

Daniel Gottuk, PE, PhD, is VP of Specialty Services and the Technical Director of Jensen Hughes. The Specialty Services group includes forensic, R&D and environmental services. With 27 years of experience, he is a recognized expert in fire detection and fire dynamics and is well published in the technical literature. He draws on his extensive experimental background and his long involvement in national codes and standards to provide clients practical and technically sound solutions to their problems. Dr. Gottuk has evaluated fire development and fire protection systems in shipboard, residential and industrial applications. He has forensically analyzed a wide range of consumer products and assisted clients in product development and litigation matters. His research includes both basic and applied forensic studies to develop fundamental understanding of fire dynamics, pattern formation and damage assessment as well as to develop practical forensic tools for fire scene investigations and analyses.

PROFESSIONAL HIGHLIGHTS

VP of Specialty Services, Technical Director, JENSEN HUGHES, Baltimore, MD, present. Responsible for the forensic, R&D and Environmental services. As Technical Director, Dr. Gottuk is responsible for establishing the overall technical direction and initiatives for the company and maintaining technical excellence. He provides oversight for the supervision and management of senior staff and is involved with strategic planning for the company. He manages Jensen Hughes' on-site engineering support for the ATF Fire Research Laboratory.

Director of Forensics and R&D, JENSEN HUGHES, Baltimore, MD, 2012–2014. Responsible for forensic and R&D services, including the supervision and management of senior and staff engineers. Project manager for a variety of fire related forensic, research, testing, and development programs.

Senior Engineer, JENSEN HUGHES, Baltimore, MD, 1992–2012. Project manager for a variety of fire related research, testing, and development programs. Responsible for the planning execution and analysis of experimental fire research and development studies in the areas of fire dynamics, fire detection and suppression, instrument development, and material performance. Work also includes the use of fire dynamics principles and models in applications of fire hazard analyses, fire investigations, and fire protection code equivalency assessments. Examples of projects include the evaluation and development of advanced fire detection systems; the evaluation of liquid fuel fires; and backdraft explosion environments. Work includes experimental and analytical work in support of litigation. Responsible for the determination of origin and cause, and the analysis of fire growth and the response of fire protection systems.

Education

Ph.D., Mechanical Engineering, Virginia Polytechnic Institute, 1992

B.S., Mechanical Engineering, Virginia Polytechnic Institute, 1989

Registered PE

AL, No. 29227-E (2008)
RI, No. 7087 (1999)
MD, No. 23144 (1998)

Associations

- Member, National Fire Protection Association (NFPA)
- Member, The International Association for Fire Safety Science (IAFSS)
- Member, The Society of Fire Protection Engineers (SFPE)

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PROFESSIONAL HIGHLIGHTS

Researcher, Mechanical Engineering Department, Virginia Polytechnic Institute, Blacksburg, VA, 1989–1992. Conducted experimental research and chemical kinetics modeling of the generation of carbon monoxide in compartment fires. Supervised undergraduate research assistants.

Systems/Integration and Test Engineer, General Electric Astro Space Division, Princeton, NJ, 1988–1989. Developed integration and testing procedures for satellite production.

Research Assistant, Mechanical Engineering Department, Virginia Polytechnic Institute, Blacksburg, VA, 1988–1989. Conducted research and development in the study of flame detection. Examined the feasibility of using flame spectroscopy and chemiluminescence as a fast response method for flame detection.

PROFESSIONAL STANDING (CONTINUED):

Committees, Boards, and Panels

Member, Technical Committee on Single- and Multiple-Station Alarms and Household Fire Alarm Systems (SIG-HOU), NFPA 72
Member/Chair, Technical Committee on Carbon Monoxide Detection (SIG-CAR), NFPA 720
Member, Technical Committee on Fire Investigation (FIA-AAA), NFPA 921
Member, Technical Committee on Fire Investigator Professional Qualifications (PQU-FIV), NFPA 1033
Member/Chair, Fire Detection & Alarm Research Council
Member, UL Standards Technical Panel 217 for Smoke Detectors and Alarms
Member, UL Standards Technical Panel 2034 for Carbon Monoxide Alarms and Gas Detectors

Technical Journals and Books

Editor of the *8th Symposium of the International Association of Fire Safety Science*
Editorial Board, *Fire Technology*
Editorial Board, *Fire Science Reviews*
Reviewer, *International Symposium on Fire Safety Science*
Reviewer, *Fire and Materials*
Reviewer, *Journal of Fire Sciences*
Reviewer, *Fire Safety Journal*

Awards

Foundation Medal for the best and most noteworthy research project, "Development of Standardized Cooking Fires for Evaluation of Prevention Technologies: Data Analysis," 2015
Hats Off Award from the Society of Fire Protection Engineers, 2015
Ronald K. Mengel Award for the most outstanding detection presentation at *Suppression, Detection and Signaling Research and Application Symposium*, SUPDET 2010
Jack Bono Engineering Communications Award for the *Journal of Fire Protection Engineering* paper that most contributed to the achievement and application of professional fire protection in 2006, 2007
Harry C. Bigglestone Award, Excellence in Communication of Fire Protection Concepts, 2004
Royal Institute of Naval Architects/Lloyds Register, Safer Ship Award, Advanced Damage Control Technology, 2003
Alan Berman Research Publication Award, Naval Research Laboratory, 2003
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JENSEN HUGHES

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Rose-Pehrsson, S.L., Minor, C.P., Steinhurst, D.A., Owrutsky, J.C., Lynch, J.A., Gottuk, D.T., Wales, S.C., Farley, J. P., and Williams, F.W., "Volume Sensor for Damage Assessment and Situational Awareness," *Fire Safety Journal*, **41** (4), June 2006, pp. 301–310.

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921-20 Log #84 Final Action: Reject
(6.2.10.3)

Submitter: B. Don Russell, Texas A&M University
Comment on Proposal No: 921-79
Recommendation: For the reasons set forth in Section 5 below, the entire proposed methodology on soot deposition should be eliminated and not included in this edition of NFPA 921.
Substantiation: NFPA 921 should only include accepted scientific theories and methods derived therefrom. As a practical document, NFPA 921 should not include any hypotheses that are not broadly proven and practiced. The basic scientific question is how much testing and validation must a hypothesis receive before it can be elevated to a theory. In practical terms, the proof of a hypothesis should not be based on a small handful of researchers running a limited number of experiments, under limited protocols and conditions. I am not questioning the reporting accuracy for the data collected by the researchers cited. However, the hypothesis that soot deposition analysis can generally be used to prove the sounding, or not, of smoke alarms under a broad range of conditions with acceptable levels of false positives and false negatives has not yet been proven by the cited researchers or by broader, independent testing and experiments conducted by researchers outside the current small community.

The theory set forth in 6.2.10.3 "Enhanced Soot Deposition on Smoke Alarms" does not have broad scientific basis and: validation and therefore should not be included. It is still a hypothesis. The number of researchers who have conducted statistically valid experiments and the total body of results that have been presented for scientific review is inadequate to prove this concept and create a theory for practical use. With no criticism of the work of any individual researcher, the total number of independent researchers and their peer reviewed papers that have been published on this subject is miniscule. Without respect to the quality of the individual work of any individual researcher, the total body of work is insufficient to prove the theory reliable under the wide range of fire conditions-that must be addressed by NFPA 921.

There are specific scientific concerns that have not been addressed in the test protocols of researchers. All causes of false positives and false negatives are not yet scientifically established nor is the rate of false indications established using statistically accepted methods. The peer reviewed papers that are cited in substantiation for this modification to NFPA 921 show multiple repetition of authors or dependent connections between authors. One must ask what significant group of informed scientists provided the peer review for this relatively small community of individuals who have acquired data or analyzed data on smoke alarm soot deposition. In truth, the number of practitioners of smoke alarm soot deposition analysis is an exceptionally small community and the peer reviewed literature from this community, to date, is insufficient to support this theory for broad practical application.

While a review of the papers cited in the substantiation cannot be completed here, there are certain obvious questions. The wording leaves the reader with the impression that the presence of soot deposition on a smoke alarm indicates that the alarm has just sounded in the fire under investigation. It must be noted that prior smoky conditions, including specifically previous kitchen fires, may establish various levels of soot patterns that persist over time or are enhanced over time, unrelated to the last fire that occurred or the current fire under investigation. Furthermore, no scientific work has been performed to create a formula or a method where researchers or investigators can determine (a) when the smoke detector first sounded in the subject fire, or (b) how long the smoke alarm sounded in the fire.

Based on the above, investigators using this technique are left with significant scientific uncertainty even with the presence of soot deposition on smoke alarms. If they reach a positive conclusion of soot deposition patterns on a specific smoke alarm, they must also conclude that (1) they do not know when the smoke alarm sounded in the fire, (2) they do not know how long the smoke alarm sounded in the fire, and (3) they do not know if the smoke alarm sounded in this fire or in some previous smoky condition or fire that occurred at an unknown time. Investigators analyzing soot deposition patterns on smoke alarms after a specific fire do not know the condition of the smoke detector prior to the fire with respect to previous soundings to smoke conditions. Therefore, no conclusion can be reached that the mere presence of soot deposition patterns on or inside a given smoke detector originate from the subject fire of investigation as opposed to previous soundings of the detector in previous smoky conditions and/or fires (e.g. kitchen fires). Given these uncertainties that are obvious limitations to the proposed technique as set forth in the cited literature, the technique becomes virtually useless for drawing practical conclusions related to a specific fire under investigation.

I have conducted hundreds of smoke alarm fire tests under a wide range of fire conditions. Figures 6.2.10.3(c),(d) showing soot deposition around the exterior of the horn face are not at all representative of the post fire condition of the vast majority of smoke detectors that I have reviewed from my own experiments of staged fires or in the case of naturally occurring fires I have investigated. In fact, the condition represented in these figures is very rare even after exposure of smoke detectors to multiple fires. Therefore, the inclusion of these figures without qualification as to its

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representation of an extreme condition is misleading and inappropriate. Based on experiments that are documented with data available from the Smoke Detector Test Facility of the Texas Engineering Experiment Station, deposition of significant patterns at the face of smoke detectors exposed to one significant fire, or multiple significant fires, or multiple low smoke fires do not show the patterns indicated in Figure 6.2.10.3(c),(d) for smoke alarms that sounded. (Data records, Smoke Detector Test Facility, Dr. B. Don Russell, Texas Engineering Experiment Station, Texas A&M University System, College Station, Texas, 77843.)

It should also be qualified in the text of the document that the presence of soot deposition on or inside a smoke alarm provides no indication as to when the smoke alarm sounded in the subject fire under investigation. A smoke alarm sounding late in a fire after victims are deceased may develop smoke deposition patterns (or not!). The levels, and quantity, and characteristics of the smoke and the location of the detector with respect to the fire source will all affect levels of soot deposition, if any, and the time progression of soot deposition in a given fire. There has been no scientific research relating the specific patterns of soot deposition on specific smoke detectors to a timeline of sounding in a given fire under given fire development conditions. Since no such formula exists, an analysis of these factors is speculative based on unknown conditions of a given fire; therefore, no conclusions can be reached based on analysis of soot deposition patterns as to how long a smoke detector sounded and/or when a smoke detector sounded in a given fire.

The language of the proposed additions to NFPA 921 with respect to soot deposition leave the incorrect impression to those not skilled in this specific art that the mere presence of accumulated soot on the outside, inside, or on the horn area of a smoke alarm is an indication that the alarm worked as designed, and is intended, and provided a timely warning, etc. None of these conclusions can be scientifically reached. An investigator seeing soot deposition patterns on a smoke detector following a given fire can only conclude that it is possible that the smoke alarm sounded, with an unknown probability, in one or more fires, not necessarily the subject fire under investigation. Once again, the investigator can conclude nothing as to when the smoke alarm sounded in the fire or the duration of it sounding in the fire, early or late. It should be noted that the design of certain smoke alarm horns allow for the partial failure of the horn resulting in vibration at a low sound level (non resonant condition) without the required volume to awaken residents. Soot deposition patterns could theoretically form around the horn even though the alarm sound level is far too low to be effective. This failure mode of smoke alarms has not been adequately addressed in the proposed method.

Unless the proposed language of soot deposition analysis is highly qualified in this document, many investigators attempting to use this section of NFPA 921 will reach erroneous or misleading conclusions and/or will not understand, the limits of the methodology with respect to conclusions in their specific fire investigation.

In conclusion, soot deposition analysis of smoke alarms is not yet broadly proven nor its limitations fully established by broad experimentation and repetition of experiments by a significant number of independent researchers and practitioners. Without respect to the issue of overall validity, the uncertainties of specific conclusions that can be reached by fife investigators make the technique of little practical use and frequently misleading as to its support for findings in any specific fife investigation.

Even if this technique ultimately is proven reliable, which will require much greater definition of error rates and extensive independent testing under carefully designed protocols, it should not be included in this document at this time because it remains a hypothesis that does not yet meet the requirements of the scientific method to be elevated to a , theory. To include the method at this stage will violate basic principles of the scientific method.

While it is my preference that the proposed analytical method of soot deposition analysis be struck and not included in this revision of NFPA 921, the newness of this proposed technique and the lack of broad, independent testing and validation, coupled with the technical limitations and unknown error rates, demand that the technique be at least qualified significantly with adequate warnings as to the limitations of the technique if it is to be used by fife investigators. Hence, I have proposed 6.2.10.3.4 and 6.2.10.3.5 to provide clarity as to the limitations of the technique under the best of conditions.

My qualifications to offer these opinions as to the scientific validity of the proposed hypothesis (alleged theory) include 35 years of scientific research and experimentation. I am a Regents Professor and Distinguished Professor of the Texas A&M University System. I am a fellow of five societies, hold the Bovay Chair at Texas A&M, and am a member of The National Academy of Engineering. I teach the scientific method and its application to electrical design engineers.

Committee Meeting Action: Reject

Committee Statement: The use of acoustic soot agglomeration for the determination of smoke detector activation is supported in the scientific literature, as referenced in the original proposal.