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

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PURPOSE OF THIS RESEARCH

In modern fire incident analysis and the litigations that frequently follow 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. Whether a given smoke alarm had actually properly activated is often an area of dispute in ensuing litigation. This issue has lead 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.

Scientific Research Needed

Like so many other issues involving the interpretation of fire analysis data, some scientifically verifiable means of determining if a given smoke alarm 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 in the form of Chladni Figures 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 [Munger] and later updated research published in 2001 [Worrell *et al*] began to address the issue scientifically. Producing new test data, and combining that with previously reported data, this current research work concludes that the presence or absence of acoustic soot agglomeration patterns, in both ionization and photo-electric single station residential smoke alarms, which had been exposed to sooty smoke atmospheres, was in fact a viable fire analysis tool.

Building on Previous Research

Building on the ground breaking work of Worrell, Roby, Striet, and Torero, 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 was an indicator of smoke alarm activation, the absence of soot agglomeration was not a viable indicator of smoke alarm failure. 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. 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.

SOOT DEPOSITION AND ACOUSTIC SOOT AGGLOMERATION

The simple definition of Acoustic Agglomeration from Morfey in the Dictionary of Acoustics is: "the grouping of suspended particles into larger aggregates by the action of sound waves in the suspending fluid, usually at high intensity."

Acoustic agglomeration of aerosols has been known since at least 1931 when it was first observed that small particles tend to "adhere" together in the presence of an intense acoustic field, thereby forming larger particles. 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.

TEST PROCEDURES

Equipment

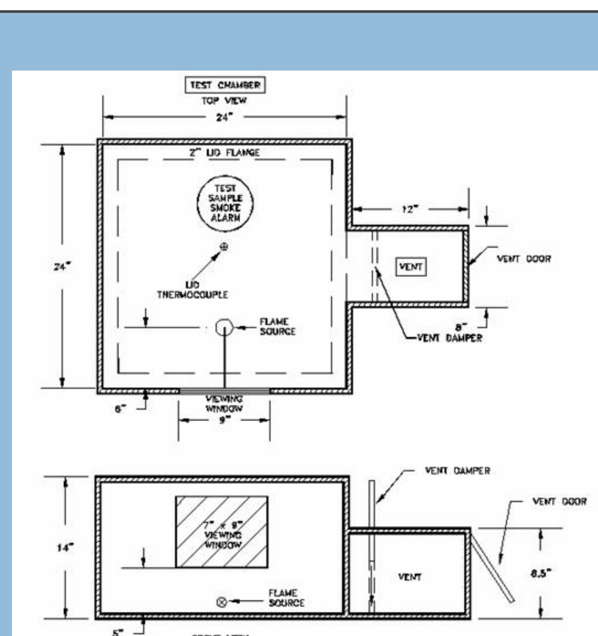

Figure 1 - Top and Front View Drawing of Smoke Test Chamber

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 wall board ceiling, on the lateral centerline, with the rear edge of the smoke alarm 5" from the rear wall.

Figure 2 - Smoke Source, 2" laminar MAPP Gas flame

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.

The smoke source was a ~2" laminar gas flame of MAPP Gas (C_3H_4) (mixture of 56.0% Propane and 44% methlacetylene-propadiene) from a ¼" diameter copper tube burner. The ~2" flame produces an extremely sooty black smoke which is primarily 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 in to the chamber at floor level a distance of 6".

Protocol

A test smoke alarm was powered, either with a prescribed internal 9V battery or in 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.

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 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.

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

TESTS	WORRELL TESTS	KENNEDY TESTS	TOTAL TESTS
Total tests	30	22	52
Powered Tests	15	12	27
Non-Powered Tests	15	10	25
Anomalous Tests	9	0	9
Anomalous Powered Tests	6	0	6
Anomalous Non-Powered Tests	3	0	3
Tests with Viable Data	21	22	43
Powered - Soot Agglomeration	9	12	21
Non-Powered - Soot Agglomeration	0	0	0
Non-Powered w/o Soot Agglomeration	12	10	22

Combining the data from the Worrell *et al* and our testing effectively doubles the database. The combined Worrell *et al* and Kennedy *et al* tests results (less anomalous tests) encompassed a total of 43 tests, 21 powered and 22 non-powered.

Kennedy *et al* produced a total of 22 tests, 12 powered and 10 non-powered. 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 Kennedy *et al* testing was classified as anomalous.

All of the powered tests (21) displayed acoustic soot agglomeration and none of the no-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.

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 4). 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 4, 6, 7 and 8).

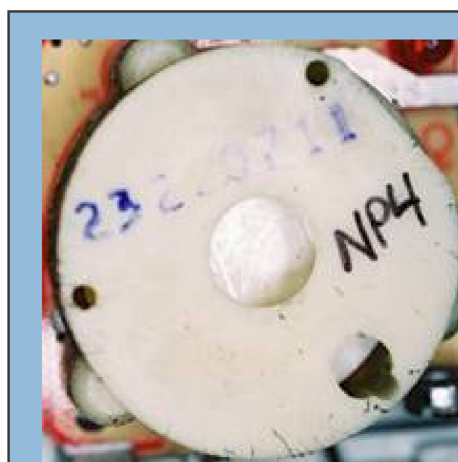

Figure 3 – Lack of Acoustic Soot Agglomeration on the horn disk enclosure of a non-powered smoke alarm

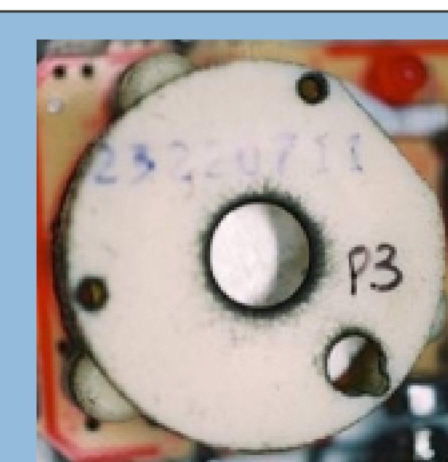

Figure 4 – Acoustic Soot Agglomeration around central and circumferential sound holes of a powered horn disk enclosure

External agglomeration will appear in the cover grillwork of properly operating smoke alarms, particularly in the areas of horn chamber sound outlets (see Figure 6).

Figure 5 – Non-powered Kidde Smoke Alarm without Acoustic Soot Agglomeration on the sound exit grillwork

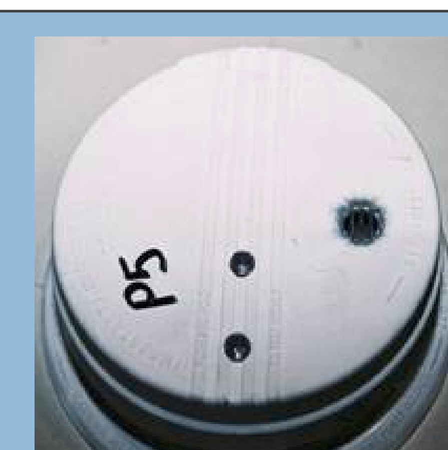

Figure 6 – Acoustic Soot Agglomeration around the sound exit grillwork of a powered Kidde Smoke Alarm

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 7a and 7b).

Figure 7 a and b – Acoustic Soot Agglomeration on the interior surface of the smoke alarm case directly over the horn compartment central sound exit opening.

Chladni Figures

Chaldni figures were frequently present on the external surfaces of the horn enclosures immediately adjacent to the large sound outlet holes. On one occasion a figure was circumferential, others were recurrently star burst shaped (see Figure 4). No Chlandi figures were found on any horn discs themselves.

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 at a high frequency (~4000 hz).

Patterns Persistence

Through heating to temperatures exceeding the approximate temperature at which smoke alarm fall down occurs, 293° F (139° C), soot deposit patterns persistence occurs as long as the subject smoke alarm is not completely destroyed by the subsequent burning.

Figures 8 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