Thermally-Induced Failure of Smoke Alarms

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Abstract

Residential smoke alarms have been shown to be an integral part of home fire safety. Recent research has focused primarily on the activation times of smoke alarms and the amount of escape time they provide. There has been a significant increase in fire growth rate in the past four decades, often attributed to the construction and materials of modern day upholstered furniture compared to that in the 1970s. Research has also shown that approximately 30 seconds of sounding time is necessary to reliably awaken a sleeping occupant [1]. With this time limit in mind, the functionality of the residential smoke alarm in possibly elevated temperature environments is critical and generally unknown. Accordingly, there is a gap in the research of smoke alarm activation and alerting.

Experiments were undertaken in a realistic velocity-induced heating tunnel for two different smoke alarm designs. The alarms were heated until they reached a failure criterion as mandated by code as well as complete cessation of the alarm sound. The results were then used to compute a generalized two-stage RTI for thermal response of each type of smoke alarm tested. To evaluate these findings against real world data, the results from a series of compartment fire experiments [2] were analyzed. The output data from select tests were used to calculate the estimated time when the smoke alarms become thermally incapacitated, or incapable of sounding audibly, according to the heating experiment findings. The calculations showed that both smoke alarm designs tested would provide more than the required 30 seconds of continuous alarm time before reduced audibility or failure occurs.

Keywords: Smoke Alarm, Smoke Alarm Thermal Incapacitation, Smoke Alarm Failure, Smoke Alarm Thermal Failure, Smoke Alarm Sounding Time

Background

The ability of smoke alarms to activate in a timely manner and notify occupants has historically been the focus of many research projects [1]-[8]. The culmination of this research on smoke alarms is that they are now installed in over 95 % of homes in the United States and are considered an integral piece of residential fire safety [5]. In extensive awakening testing, Ashley et al. [1] determined that the critical window for awakening a non-medicated, sleeping occupant was 30 seconds. Thus, a smoke alarm needs to sound audibly for at least that long. With modern construction techniques and materials causing an increase in fire growth rate in the decades since smoke alarms became prevalent, there is considerable interest in whether current smoke alarm designs can adequately provide the 30 seconds of sounding time.

Olenick et al. [9] has reported on experiments regarding the audibility and incapacitation of smoke alarms in elevated temperature environments. While these findings are useful for assessing when a smoke alarm will have its audibility affected or completely silenced, the tests have several shortcomings for comparison with actual smoke alarm installations in fires, mainly failure to mimic the ceiling jet environment, and not reporting solid phase temperature of the alarm plastic or the temperature rate of rise of the oven. Therefore, there is a gap in the research of smoke alarm activation and alerting. It is not known with certainty under what conditions residential smoke alarms will have their audibility reduced and ultimately cease to sound. Additionally, it is unknown at what time in a typical fire this thermal failure of the smoke alarm will occur and if the smoke alarm provides the requisite 30 seconds of sounding time.

The objectives of this investigation were to determine the temperature range for failure for smoke alarms subjected to a thermal insult. This was primarily accomplished with a series of heating experiments and the results were put in context with the results from the literature [1] on full-scale experiments of smoke alarm activation times and untenability times to determine whether smoke alarms are providing 30 seconds of alarm time. The results could also be used to determine forensically when the smoke alarm would cease to sound due to the heat to determine if fire department personnel and witness statements of not hearing an alarm are the result of a failure of the alarm to sound at all, or simply thermal incapacitation of the alarm.

Experimentation

Two 9 volt battery-operated, ionization-type residential smoke alarms were selected for analysis, both listed as in compliance with UL 217 [10]. Smoke Alarm A has a contained alarm horn that is attached to the cover and wired to the circuit board. The piezo disk is encased in two pieces of plastic, one above and one below. Smoke Alarm B has a contained alarm horn that is attached to the circuit board directly. The piezo disk is encased by a single piece of plastic from above.

The test apparatus consisted of a blower pushing air through a three-phase in-line air heater via a reducer, which output to an expander connected to a square steel duct measuring 20.3 cm by 20.3 cm by 294.6 cm. The smoke alarm test specimen was mounted to drywall and secured at the top of the duct. The blower was set such that the velocity at the smoke alarm was approximately 0.35 m/s at ambient temperature and was approximately 0.45 m/s at an elevated temperature of 220 °C. This is in the range of expected ceiling jet velocities for a 2.4 m ceiling at a temperature of 136 °C close to a fire and at 9.1 m from a fire, the maximum distance allowed by NFPA 72 [11]. The value of 136 °C is the maximum failure temperature noted previously in Olenick et al. [9].

The smoke alarm specimens were manipulated so the device was in a state of continuous alarm. Four type K thermocouples were secured to the smoke alarms using a highly conductive epoxy including both the interior and exterior surfaces, as well as the horn housing. An Earthworks M30BX Measurement Microphone was mounted in the duct and used to monitor frequency and amplitude of the alarm tone during experimental testing. A baseline measurement was taken, and a high-pass filter was used to isolate the smoke alarm tone. The sound pressure level above ambient was calculated and weighted using the A scale to yield measurements in dBA.

The heater was initially set to 95 °C and the temperature was increased in increments of 5 degrees every 90 or 180 seconds (± 5 seconds) (shown as 5K/90s and 5K/180s) during independent experiments. The experiment was concluded when the microphone was no longer able to distinguish the signal from the smoke alarm due to attenuation of the tone. Five specimens of each of the two smoke alarm models were tested at each of the two heating rates, resulting in a total of 20 individual tests.

The failure criterion was established based on the audibility requirements from *NFPA 72: National Fire Alarm Signaling Code* [11] which requires that the tone be 5 dBA above any maximum ambient sound that has a duration greater than 60 seconds, representing a worst-case scenario in a loud residence. The temperature of the internal components and gaseous temperature of the airflow at the smoke alarm were recorded.

Results

Figure **1** shows the average temperatures of the internal components and the air at the smoke alarm at the time when the microphone was no longer able to distinguish the tone produced by the alarm from the ambient noise, as well as the time the alarm went silent, for both alarms

A and B. The figure shows the results from the two alarm types and the two heating rates.

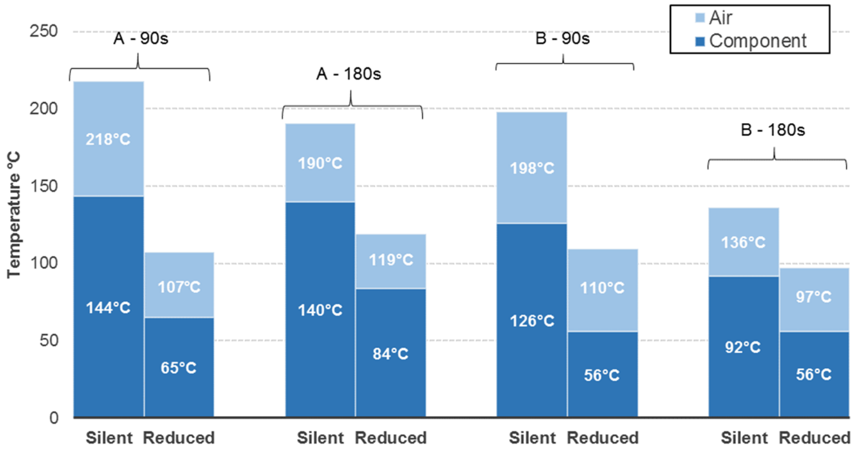

Figure 1. Temperature where smoke alarms have sound reduced and silenced.

Across all the tests the average plastic temperature at which alarm A became reduced was 74 °C, and silent at 142 °C. For alarm B the temperatures were 56 °C and 109 °C respectively.

As the temperature of the internal components increased, they underwent thermally induced expansion resulting in stress on the piezoelectric disk and a reduced resonance to create the audible tone. Ultimately, the plastic temperatures reached the HIPS softening point, and began to undergo a phase change. The Vicat softening point of HIPS is generally in the range of 93 – 105 °C [9]. The distortion of the piezoelectric disk within the plastic horn changed the tone produced by the alarming horn and led to the eventual failure of the alarm.

Discussion and Analysis

The results from the heating experiments were analyzed to estimate an RTI for the smoke alarms. The smoke alarm is a complicated geometry with many narrow paths for hot gas to enter, and is constructed of multiple materials with different heating characteristics. The RTI value calculated for these alarms should therefore only be considered an estimate. Based on plunge test data it was found that the thermal response of the alarm was best represented using two RTI values; one during heating of the plastic up to the point where it starts to soften and deform, and one for the heating beyond the phase transition temperature. After the plastic body and horn of the alarm start to soften the heat energy will go to both melting the plastic and further conducting into and heating the material, resulting in a different RTI value. This change was found to occur at 105 °C (Alarm A) and 60 °C (Alarm B).

Averaging the test data yields RTI values of 363 $\sqrt{m/s}$ up to the phase transition and 800 $\sqrt{m/s}$ after for Alarm A, and 900/200 $\sqrt{m/s}$ for Alarm B. Using these values, the heating rate of the smoke alarm can be calculated based on the gas temperature around it, per [12]:

$$\frac{dT_s}{dt} = \frac{U^{1/2}}{RTI}(T - T_S) \tag{1}$$

Where:
T_s = Temperature of smoke alarm [K]
T = Gas temperature [K]
U = Ceiling jet velocity [m/s]

For the configuration where the ratio of the smoke alarm distance from the fire over the ceiling height, r/H > 0.15, the ceiling jet velocity is given as [13]:

$$\mathrm{U} = 0.197\frac{\left(\dot{Q}/H\right)^{1/3}}{(r/H)^{5/6}} \tag{2}$$

The heat release rate was estimated using mass loss rate data from the load cell, multiplied by an assumed heat of combustion of 25,300 kJ/kg for polyurethane foam [14]. With an estimated ceiling jet velocity, the gas temperature at the ceiling can be used to calculate the increase in smoke alarm temperature at each time step.

To evaluate these findings against real world data, the results from a series of compartment fire experiments conducted by NIST [1] were analyzed. The NIST tests were a set of full scale tests conducted in two different residential structures. The compartments were heavily instrumented but for this analysis the test data used was:

- Time to smoke alarm activation, for the ionization alarms
- Gas temperature at the ceiling in the fire room
- Mass load cell, to calculate ceiling jet velocity
- Tenability conditions in fire room; visibility and gas temperature.

The output data from select tests were used to estimate the time when the smoke alarms become incapacitated according to the previous findings. Evaluated against the alarm time and the time when untenable conditions develop, this will indicate whether the alarms provide sufficient sounding time before the heating of the device causes reduction of the alarm volume, and eventually total silencing of the alarm.

Two of the NIST tests had the data necessary for the analysis, and ceiling temperatures sufficiently high to cause alarm damage: SDC07 and SDC09. These were manufactured home tests with a flaming mattress in the bedroom. The temperature of the alarm horn plastic was calculated for the two tests using equations (1) and (2) and the gas temperature at the ceiling in the fire room. The results were analyzed to calculate the time when the alarm volume would be reduced by 5 dBA ("Reduced") and the alarm silenced ("Silenced"). The findings from the heating tunnel tests gave different incapacitation times for the two types of alarms, referred to as Alarm A and Alarm B. The calculated incapacitation times are shown in Table 1.

Table 1. Calculated time for smoke alarm incapacitation due to heat based on Dunes experimental data.

Test	Max Alarm Temperature	Alarm Incapacitation Time [s]			
		Reduced		Silence	
		Alarm A	Alarm B	Alarm A	Alarm B
SDC07	136.4 °C	181	163	231	203
SDC09	139.5 °C	159	143	237	181

The times to reach untenable conditions at a 1.50 m elevation in the fire room were taken from the NIST test report (ASET). The alarm activation times were averages from the NIST report as well. The main concern for this analysis was whether the smoke alarm could provide a full 30 seconds of alarm before the sound volume became reduced. Table 2 summarizes the times until alarm activation plus a 30 second alarm time, compared to the times for smoke alarms to become incapacitated and untenable conditions to occur in the fire compartment.

Table 2. Time to reach untenable conditions in the fire room compared to incapacitation of smoke alarms.

Test	Alarm Activation	30 sec Alarm	Sound Reduced		Untenable Time
			Alarm A	Alarm B	
SDC07	42 s	72 s	181 s	163 s	145 s
SDC09	28 s	58 s	159 s	143 s	163 s

In all cases the smoke alarms are able to provide 30 seconds of alarm, both before untenable conditions and reduction of sound of the alarms. Except for Alarm B in test SDC07, the alarms do not show reduced volume until after untenable conditions. Though Alarm A shows slightly better thermal resistive performance than Alarm B, both provide well above the required 30 seconds of alarm time before they become incapacitated due to heat.

As the RTI value experimentally determined for the two alarms likely represent the largest source of uncertainty, it was of interest to evaluate the effect of varying the RTI. The incapacitation times were recalculated for a series of RTI values varied in increments of 10% for each of the pre-melt and post-melt phases.

The resulting time to reach a temperature associated with reduced audibility and silence is plotted in Figure **2** vs solid phase RTI. With RTI values above 500/1,200 Alarm A does not reach total silence. At no RTI values studied did this occur for Alarm B. The calculated RTI used for the above analysis is indicated with markers.

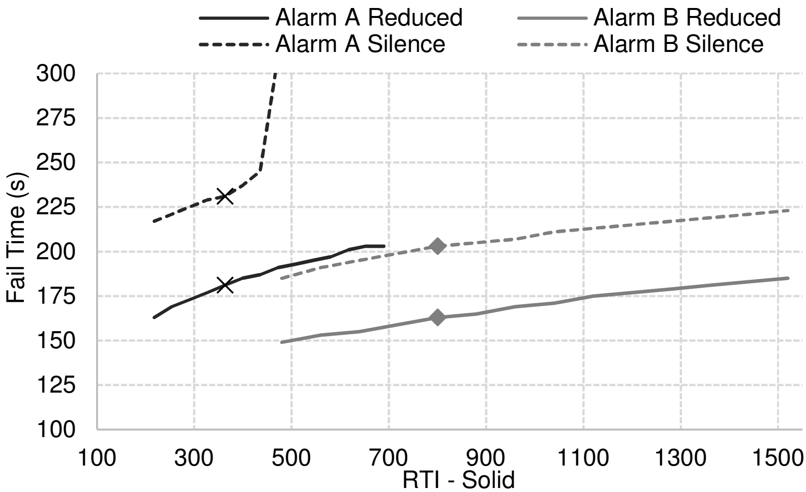

Figure 2. Time to reach reduced audibility versus RTI value in SDC07.

At the lowest RTI values, 40% below that used, Alarm A has reduced sound at 163 s and Alarm B has reduced sound at 149 s, both still above the required 30 second alarm time (72 s, per Table **2**).

Conclusions

Experiments were undertaken in a velocity-induced heating tunnel for two different smoke alarm designs. The alarms were heated until they reached a failure criterion as mandated by code as well as complete cessation of the alarm sound. These results were then used to determine a two-stage RTI for thermal response of the smoke alarms tested. The results from the Indiana Dunes full scale compartment fire experiments were analyzed in combination with the heating test findings. It was found that both smoke alarm designs tested would provide more than the required 30 seconds of alarm time before reduced audibility or failure occurs. A sensitivity analysis showed a near linear relationship between RTI and time to incapacitation and that the results are still valid with 40 % lower RTI values. Future work should focus on increase the data for both parts of the study. The RTI determined in this study is limited by only having two alarm designs and two heating rates. The incapacitation time calculations are limited by the available compartment fire data from the Dunes tests.

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