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Performance of Dual Photoelectric/ Ionization Smoke Alarms in Full-Scale Fire Tests

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Abstract. Data from two full-scale residential smoke alarm fire test series were analyzed to estimate the performance of dual sensor photoelectric/ionization alarms as compared to co-located individual photoelectric and ionization alarms. Dual alarms and aggregated photoelectric and ionization alarm responses were used to estimate dual alarm performance. It was observed that dual alarms with equivalent or higher sensitivity settings performed better than individual photoelectric or ionization alarms over a range of flaming and smoldering fire scenarios. In one test series, dual alarms activated 539 s faster than ionization alarms and 79 s faster than photoelectric alarms on average. In another test series, individual alarm sensor outputs were calibrated against a reference smoke source in terms of light obscuration over a path length (percent smoke obscuration per unit length) so that alarm thresholds could be defined by the sensor outputs. In that test series, dual alarms, with individual sensor sensitivities equal to their counterpart alarm sensitivities, activated 261 s faster on average than ionization alarms (with sensitivity settings of 4.3%/m smoke obscuration for the ionization sensors) and 35 s faster on average than the photoelectric alarms (with sensitivity settings of 6.6%/m, for the photoelectric sensors.) In cases where an ionization sensor was the first to reach the alarm threshold, the dual alarm activated 67 s faster on average than the photoelectric alarm. While in cases were a photoelectric sensor was the first to reach the alarm threshold, the dual alarm activated 523 s faster on average than the ionization alarm. Over a range of ionization sensor settings examined, dual alarm response was insensitive to the ionization sensor setting for initially smoldering fires and fires with the bedroom door closed, while dual alarm response to the kitchen fires was very sensitive to the ionization sensor setting. Tests conducted in the National Institute of Standards and Technology (NIST) fire emulator/detector evaluator showed that the ionization sensors in off-the-shelf ionization alarms and dual alarms span a range of sensitivity settings. While there appears to be no consensus on sensitivity setting for ionization sensors, it may be desirable to tailor sensor sensitivities in dual alarms for specific applications, such as near kitchens where reducing nuisance alarms may be a goal, or in bedrooms where higher smoke sensitivity may be a goal.

Keywords: Smoke alarms, Dual alarms, Fire tests

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1. Introduction

The performance of ionization and photoelectric smoke alarms in various fire scenarios has been the subject of several research studies over the past 30+ years. Studies that have investigated flaming and smoldering fire scenarios have observed that in general, ionization smoke alarms sense flaming fires sooner than photoelectric smoke alarms, while photoelectric smoke alarms sense smoldering fires typically much sooner than ionization alarms [1–5]. These observations suggest that in order to achieve a higher level of performance from either ionization or photoelectric alarms, a mix of these technologies is a solution. Several organizations have taken the position that such a mix provides a greater level of fire safety since the benefits of each technology is realized. Smoke alarms that possess both photoelectric and ionization-type sensors have been available to consumers for residential applications in the US for over 10 years. They are currently available as a battery powered stand-alone unit, and as an AC power source alarm with battery backup and interconnection capability from multiple manufacturers. The convenience and aesthetics of a dual alarm as opposed to separate photoelectric and ionization alarms are motivations for consumer acceptance.

The UL Standard 217, "*Single and Multiple Station Smoke Alarms*" allows for dual sensor alarms so long as the each sensor is primarily a smoke sensor and the design meets the Standard [6]. The alarm logic is an {OR}-type such that the alarm is activated if either the photoelectric sensor or ionization sensor alarm threshold is met. The individual sensor sensitivities are not tested separately. Therefore, manufacturers have the freedom to set each sensor's sensitivity separately. One strategy would be to set each sensor's sensitivity at the nominal sensitivity of individual photoelectric and ionization alarms, respectively to improve fire detection. Alternatively another strategy would be to lower each sensor's sensitivity to reduce nuisance alarms while still providing adequate fire detection performance.

This paper examines data from two full-scale smoke alarm fire tests to provide some insight into the performance of dual photoelectric/ionization alarms as compared to individual photoelectric or ionization alarms. The two test series are the NIST home smoke alarm tests [4] and the National Research Council (NRC) Canada home smoke alarm tests [5]. Both test series had co-located photoelectric, ionization and dual sensor alarm technologies in various locations of the test homes. The NRC Canada study used off-the-shelf smoke alarms. The NIST study used smoke alarms that were modified to provide a continuous voltage signal. The signal from each of these alarms was calibrated at NIST to known smoke obscuration and reference measuring ionization chamber (MIC) levels. Thus, equivalent alarm thresholds can be specified by determining the required signal to reach a threshold. Therefore, the effect of sensor sensitivity levels on the dual sensor detection performance can be estimated with the NIST data.

The analysis presented below focuses on a single aspect of alarm performance: the time to alarm during exposure to various fire smokes. It is a relative comparison applicable to four alarm strategies employed at a given location: an ionization alarm, a photoelectric alarm, ionization and photoelectric alarms, and a dual photoelectric/ionization alarm. No consideration was made to account for tenability conditions anywhere in the homes, nor any egress scenarios. Furthermore, nuisance alarm susceptibilities that may factor into the overall alarm performance were not considered. A brief description of each test series and the data is given below, followed by analysis of the test data, results from sensitivity tests of ionization sensors, and conclusions.

2. Data Sources

The NRC Canada test series in Kemano, British Columbia was conducted in 2001 and consisted of tests using small fire sources in a single-story (nine tests) and two-story home (four tests). Fire originating in living rooms and bedrooms were examined. Fuels included pine wood sticks, newspaper, cotton flannel fabric, and polyurethane foam rapped in cotton flannel fabric. An electric heating element ignitor was placed on top of a ceramic mat on the floor and combustible materials placed on top of the heater. A perforated metal can was placed over the combustible materials. When power was applied to the ignitor all combustibles initially smoldered and some transitioned to flaming fires later during the tests. An upholstered chair was used as the fire source during one test. It was initiated by placing the electric heating element between the seat cushion and arm and applying power. The chair smoldered then transitioned to flaming later during the test. One test was conducted in a kitchen using vegetable cooking oil as the fuel where 450 ml of cooking oil was placed in a pan and heated with the electrical heating element. Upon heating the oil, smoke was generated from condensing oil vapors. After about 25 min of heating the oil 10 ml accelerant consisting of 25% toluene and 75% heptane was added to the pan which initiated a short period of flaming. After two more additions of accelerant, sustained flaming of the cooking oil was achieved.

Off-the-shelf residential ULC listed smoke-alarms, conforming to CAN/ULC-S531-M87, *"Standard for Smoke-Alarms"* [7] were used; alarms activated at their preset sensitivity. Photoelectric, ionization, and dual alarms were located on the ceiling in a linear or triangular pattern with a separation distance measured from the center of alarms of ~30 cm. Sets of alarms were located in bedrooms, living rooms, corridors, foyers, and at the top and bottom of stairs. There were 13 tests conducted and 56 instances of co-located alarms. Recorded alarm times are provided in the report appendix [5].

The NIST home smoke alarm tests were conducted during 2001–2002, and consisted of 24 tests performed in a manufactured home placed inside the NIST large fire laboratory and six tests performed in a two-story house in Kinston, North Carolina that was slated for demolition [4]. The fire sources were initially smoldering and flaming upholstered chairs in living rooms, initially smoldering and flaming mattresses in bedrooms and a cooking oil fire in the kitchens. Flaming chair tests were conducted by igniting the chair with a paper matchbook rapped in a paper towel and tucked under the seat cushion in the front of the chair. Electrical power to a wire heating element ignited the matches with flaming spreading to the paper towel then chair fabric. Flaming mattress tests were initiated in essentially the same manner. Smoldering chair and mattress tests were initiated by inserting a nichrome heating wire into a slit in the fabric and foam and controlling the electrical power to the element to sustain smoldering of the foam until the smoldering chair or mattress transitioned to flaming. Cooking oil fires were conducted by placing 500 ml of cooking oil in a pan and placing the pan on a gas stove burner and heating it until the cooking oil ignited. During the heating phase, but prior to ignition, a significant amount of smoke was generated during these tests. There were 30 tests conducted and a total of 92 instances of co-located alarms.

The data collected included analog voltage signals from a number of smoke alarms. Co-located alarms were confined to a 0.50 m by 0.25 m area of the ceiling. Computed alarm times were provided for all alarms in Appendix A of the NIST report [4]. The individual smoke sensors were calibrated to smoke obscuration levels (reported as a percentage of light obscured per unit length) in the NIST fire emulator/detector evaluator using smoldering cotton wick. The NIST tabulated results include alarm times for high, middle and low sensitivity settings of 2.6%/m, 4.3%/m, and 5.9%/m for ionization sensors, and 3.3%/m, 6.6%/m, and 9.8%/m for photoelectric sensors. The alarm analysis conducted in the report only considered the middle sensor sensitivity settings for photoelectric, ionization, and dual alarms.

In the analysis of the NIST data, alarm times from co-located sensors were averaged for both photoelectric and ionization sensors at specified sensitivities. It was possible to have two photoelectric sensors and three ionization sensors co-located from one photoelectric alarm, two ionization alarms, and one dual alarm. Thus at each location, representative photoelectric, ionization, and dual alarm times were computed. The photoelectric sensor sensitivity was fixed at 6.6%/m for both the photoelectric and dual alarms. This sensitivity setting was found to be consistent with measured sensitivities of off-the-shelf photoelectric alarms used in the NIST study [4]. All three ionization alarm sensitivities were considered for the ionization and dual alarms to provide results for a range of ionization sensor sensitivity settings.

The rationale for examining ionization sensor sensitivities related to dual alarm performance is based on the expectation of the desire to optimize dual alarm sensitivity with respect to smoke detection and nuisance alarm reduction. Optimization of the photoelectric sensor sensitivity in a dual alarm should also be considered in an optimum design. However, in this analysis, a comparison of the middle sensitivity setting results for photoelectric, ionization, and dual alarms is consistent with the sensitivity settings used in the NIST report analysis.

3. Alarm Time Analysis

The NRC Canada tests that used solid combustible sources all started out as smoldering fires with most transitioning to flaming at some time during each test. Likewise, the cooking oil fire produced smoke from the heated oil before igniting.

Alarm sensitivities were not measured prior to testing, thus there is no information on relative sensitivity between ionization, photoelectric or dual alarms. There were 54 instances where a set of alarms were co-located during the 13 individual tests. The average alarm time and standard deviation (SD) for each type of alarm are given in Table 1. The dual alarm responded 616 s faster on average than the ionization alarm, and 72 s faster on average than the photoelectric alarm.

Figures 1–3 show the distributions of ionization, photoelectric, and dual alarm times in histograms with the median and mean alarm times indicated. These particular distributions arise in part from the variation of the fire sources and locations of the alarms.

Since individual sensor sensitivities were not known, an estimate of which ionization and photoelectric sensor was more sensitive was made (either the ionization alarm or the ionization sensor in the dual alarm, and either the photoelectric alarm or the photoelectric sensor in the dual alarm). To make this judgment, the following logic was considered. Between the ionization and photoelectric alarm, the ionization alarm was the first to respond in 18 of the 54 instances, responding

Table 1
Average Alarm Times for NRC Canada Test Series [5]

Alarm type	Average alarm time (s)	Standard deviation (SD) (s)
Ionization alarm	1205	1102
Photoelectric alarm	666	537
Dual alarm	587	450

All were initially smoldering fires

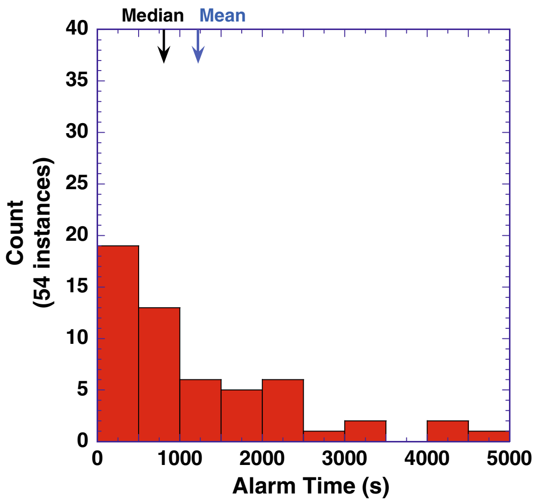

Figure 1. Histogram of NRC Canada co-located ionization alarm times.

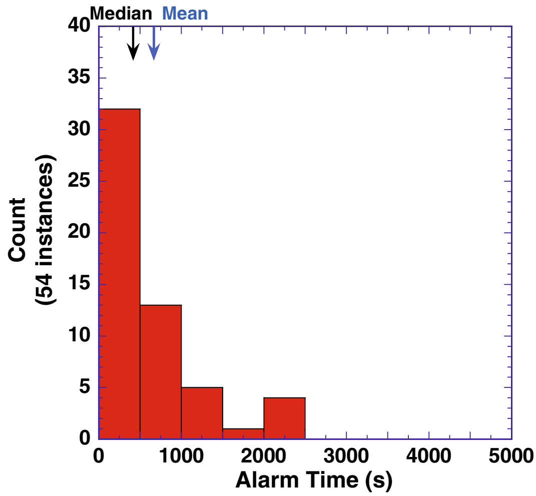

Figure 2. Histogram of NRC Canada co-located photoelectric alarm times.

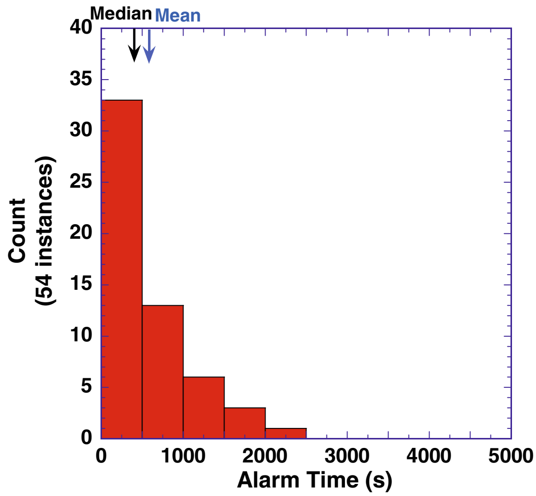

Figure 3. Histogram of NRC Canada co-located dual alarm times.

83 s faster on average than the photoelectric alarms. Considering those 18 instances, the dual alarm responded first in 17 of those instances, and responded 81 s faster on average than the ionization alarm (SD = 158 s), with a median response 19 s faster. Figure 4 is a scatter plot of the difference for each instance. Thus, if the photoelectric alarm and dual alarm photoelectric sensor had equivalent sensitivities, then one can conclude that the ionization sensor in the dual alarm was more sensitive than the sensor in the ionization alarm.

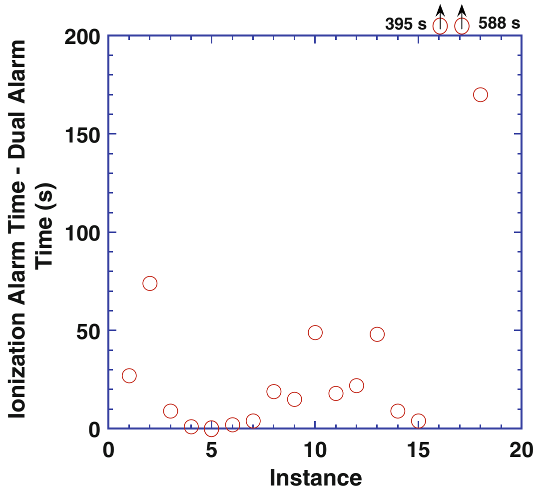

Figure 4. The difference between the ionization alarm time and the dual alarm time for co-located alarms when the ionization alarm was the first to respond in the NRC Canada tests. Two instances at 395 s and 588 s that lie outside the *y*-axis range are indicated by *arrows*.

In the remaining 36 instances, the photoelectric alarm responded 874 s faster on average than the ionization alarm. The dual alarm responded first in 21 of the 36 instances, responding 26 s faster on average than the photoelectric alarm (SD = 161 s) with a median response 6 s faster. Figure 5 is a scatter plot of the difference for each instance. If the extreme instance is removed (where the dual alarm responded 740 s faster), the average drops to 6 s (SD = 106 s) with a median of 5 s. These statistics lead to the conclusion that the dual photoelectric sensor and the photoelectric alarm had nominally the same alarm sensitivity settings, and conversely, the ionization sensor in the dual alarm was more sensitive than the ionization alarm sensor. Also, one can conclude that some of the benefit of the dual alarm used in this study can be attributed to a more sensitive ionization sensor, compared to the stand-alone ionization alarm.

The NIST test series allowed for more detailed analysis due to the adjustable alarm sensitivities. In addition, the NIST test series also included initially flaming and initially smoldering fire sources, so the performance in different fire scenarios could be assessed. The sensor sensitivity combinations examined were as follows. The middle sensitivity setting for photoelectric alarms specified in the NIST report (6.6%/m) was used for the individual photoelectric alarms and for the photoelectric sensor in the dual alarm configurations. While all three ionization sensitivity settings specified in the NIST report (2.6%/m, 4.3%/m, and 5.9%/m) were used for both ionization alarms and dual alarm configurations. Therefore, a comparison was made between the photoelectric alarm, and three ionization alarms and dual alarm configurations with differing ionization sensor sensitivities.

There were 92 instances where a set of alarms were co-located during the 30 fire tests. The average alarm times and standard deviations for the ionization,

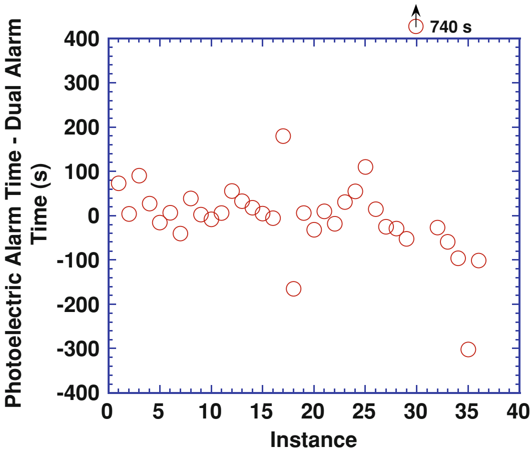

Figure 5. The difference between the photoelectric alarm time and the dual alarm time when the photoelectric alarm was the first to respond in the NRC Canada tests. One instance at 740 s that lies outside the *y*-axis range is indicated by an *arrow*.

Table 2
Average Alarm Times for the NIST Test Series

Alarm type	Average time to alarm (s)	Standard deviation (s)
Ionization (2.6%/m)	1929	2104
Ionization (4.3%/m)	*1981*	*2132*
Ionization (5.9%/m)	2006	2138
Photoelectric	*1755*	*1915*
Dual 1 (2.6%/m)	1702	1945
Dual 2 (4.3%/m)	*1720*	*1936*
Dual 3 (5.9%/m)	1730	1929

Italicized entries highlight sensitivity settings used in the NIST report analysis

photoelectric, and dual alarm configurations are shown in Table 2. On average, all three dual alarm configurations provide faster average alarm times compared to the photoelectric, or ionization alarms at any one of the three ionization sensor sensitivities.

Considering the instances when the ionization alarm (at a sensitivity setting of 4.3%/m) responded first, the dual alarm configurations (from high to low sensitivities) activated 89 s, 67 s, and 47 s faster on average than the photoelectric alarms. Conversely, considering the instances when the photoelectric alarms responded first, the dual alarm configurations (from high to low sensitivities) activated 535 s, 523 s, and 518 s faster on average than the ionization alarms.

There were 36 instances of co-located alarms during initially flaming fires, 35 instances during initially smoldering fires, and 12 instances during kitchen fires.

The last category considered was bedroom mattress fires with the bedroom door closed. These tests were grouped together because they experienced delayed smoke alarm times due to the fact that the door acted as a barrier to smoke flow. There were two initially flaming and one initially smoldering fire test conducted with the bedroom door closed with nine instances of co-located alarms, and no instance of calibrated alarms in the fire origin bedroom.

Table 3 gives the mean, median and standard deviation of the alarm times for initially flaming fires with the bedroom door opened. Figures 6–9 show histograms of the alarm times of the middle sensitivity ionization alarm, photoelectric alarm, dual 1 alarm configuration, and dual 3 alarm configuration for this set of tests. The dual alarm configurations yielded faster average alarm times than the photoelectric alarm and average alarm times nearly equivalent to the ionization alarms.

Table 3
Alarm Time Statistics for the NIST Test Series of Initially Flaming Fires (36 Instances)

Alarm type	Average alarm time (s)	Median alarm time (s)	Standard deviation (s)
Ionization (2.6%/m)	107	107	35
Ionization (4.3%/m)	*113*	*113*	*36*
Ionization (5.9%/m)	118	118	36
Photoelectric	*143*	*149*	*33*
Dual 1 (2.6%/m)	105	107	29
Dual 2 (4.3%/m)	*109*	*112*	*30*
Dual 3 (5.9%/m)	114	115	29

Italicized entries highlight sensitivity settings used in the NIST report analysis

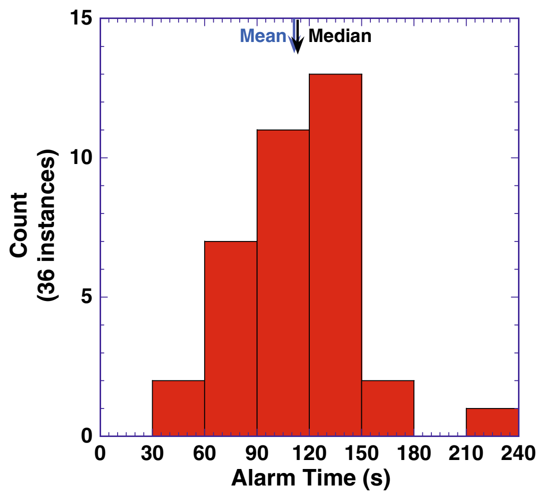

Figure 6. Histogram of NIST ionization alarms for flaming fires.

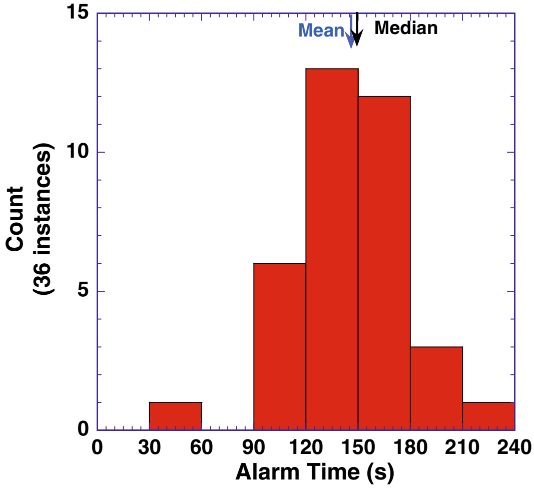

Figure 7. Histogram of NIST photoelectric alarm times for flaming fires.

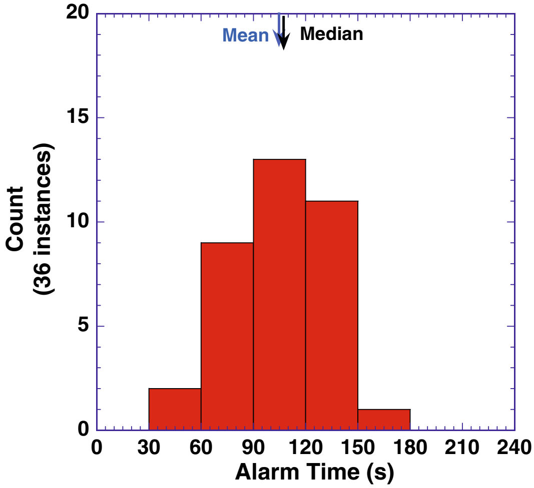

Figure 8. Histogram of NIST high sensitivity dual 1 alarm times for flaming fires.

Table 4 gives the mean, median and standard deviation of the alarm times for initially smoldering fires with the bedroom door opened. Figures 10–13 show histograms of the alarm times of the middle sensitivity ionization alarm, photoelectric alarm, dual 1 alarm configuration, and dual 3 alarm configuration for this set of tests. The dual alarm configurations yielded much faster average alarm times

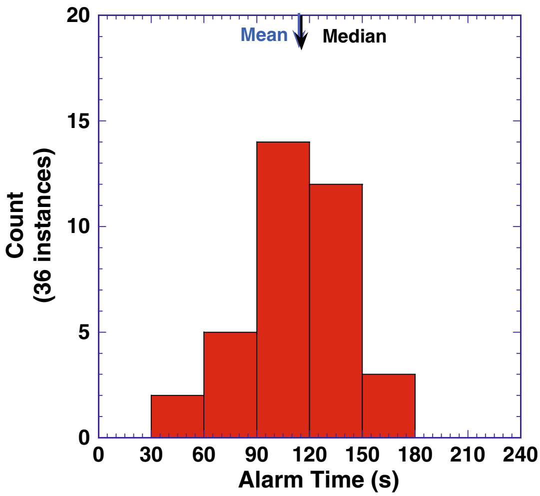

Figure 9. Histogram of NIST low sensitivity dual 3 alarm times for flaming fires.

Table 4
Alarm Time Statistics for the NIST Test Series of Initially Smoldering Fires (35 Instances)

Alarm type	Average alarm time (s)	Median alarm time (s)	Standard deviation (s)
Ionization (2.6%/m)	4228	4213	1282
Ionization (4.3%/m)	*4281*	*4242*	*1343*
Ionization (5.9%/m)	4296	4244	1350
Photoelectric	*3656*	*3753*	*1558*
Dual 1 (2.6%/m)	3652	3749	1554
Dual 2 (4.3%/m)	*3653*	*3751*	*1555*
Dual 3 (5.9%/m)	3653	3751	1555

Italicized entries highlight sensitivity settings used in the NIST report analysis

than the ionization alarms and average alarm times nearly equivalent to the photoelectric alarm.

Table 5 gives the mean, median and standard deviation of the alarm times for the cooking fires. Figures 14–17 show histograms of the alarm times for the middle sensitivity ionization alarm, photoelectric alarm, dual 1 alarm configuration, and dual 3 alarm configuration for this set of tests. The dual alarm configurations yielded faster average alarm times than the photoelectric alarm.

Table 6 gives the mean, median and standard deviation of the alarm times for the three fires with the bedroom door closed. The dual alarm configurations perform about the same or better than the ionization and photoelectric alarms.

Table 7 shows the average alarm time difference between the dual alarm configurations and the photoelectric alarm for the scenarios considered. Over the sensitivity

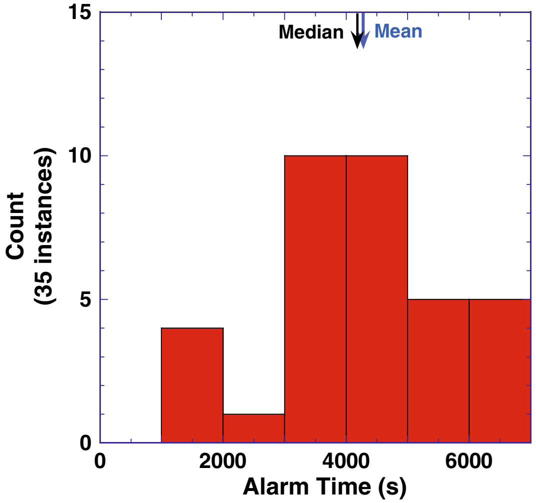

Figure 10. Histogram of NIST ionization alarm times for smoldering fires.

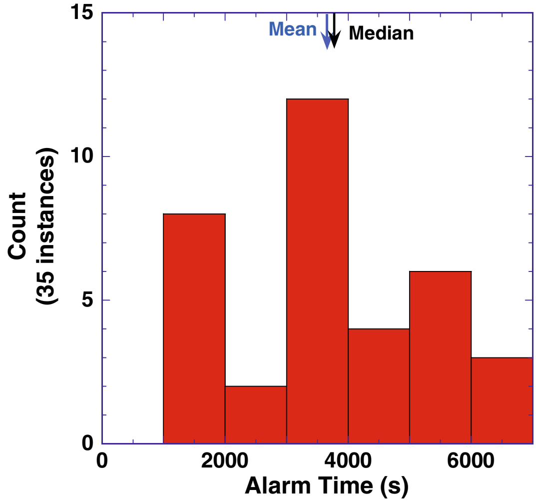

Figure 11. Histogram of NIST photoelectric alarm times for smoldering fires.

range of ionization sensors examined, dual alarms exhibited almost no average decrease in alarm time compared to photoelectric alarms during initially smoldering fire scenarios (4 s to 3 s), a pronounced average decrease for initially flaming fire scenarios (38 s to 29 s), an average decrease that was a strong function of sensitivity for kitchen fires (197 s to 18 s), and a sustained decrease for fires with the bedroom door closed (103 s to 94 s).

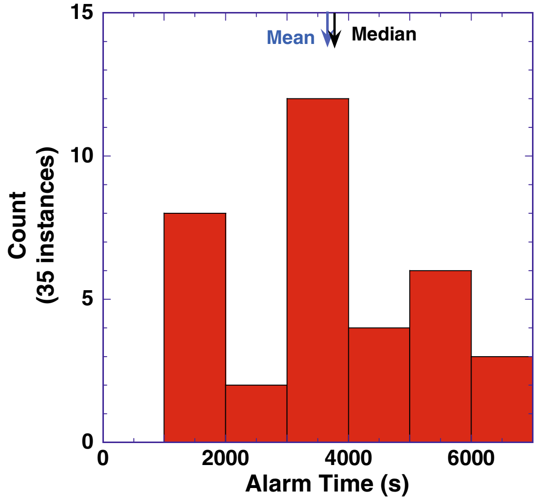

Figure 12. Histogram of NIST high sensitivity dual 1 alarm times for smoldering fires.

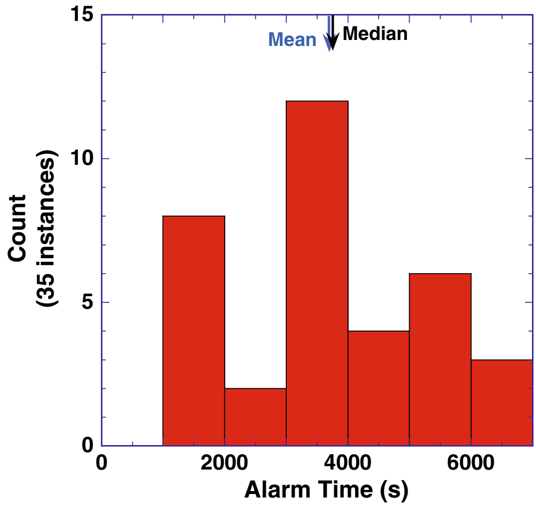

Figure 13. Histogram of NIST low sensitivity dual 3 alarm times for smoldering fires.

4. Ionization Sensor Sensitivity Measurements

In general, the sensitivity range recorded on the back of residential smoke alarms (photoelectric, ionization, or dual alarms) is not predictive of relative alarm performance when comparing any two alarms due to the width of the allowable sensitivity

Table 5
Alarm Time Statistics for the NIST Test Series of Kitchen Fires (12 Instances)

Alarm type	Average alarm time (s)	Median alarm time (s)	Standard deviation (s)
Ionization (2.6%/m)	774	704	406
Ionization (4.3%/m)	*954*	*849*	*402*
Ionization (5.9%/m)	1080	992	342
Photoelectric	*922*	*867*	*166*
Dual 1 (2.6%/m)	725	704	309
Dual 2 (4.3%/m)	*845*	*830*	*269*
Dual 3 (5.9%/m)	904	866	189

Italicised entries highlight sensitivity settings used in the NIST report analysis

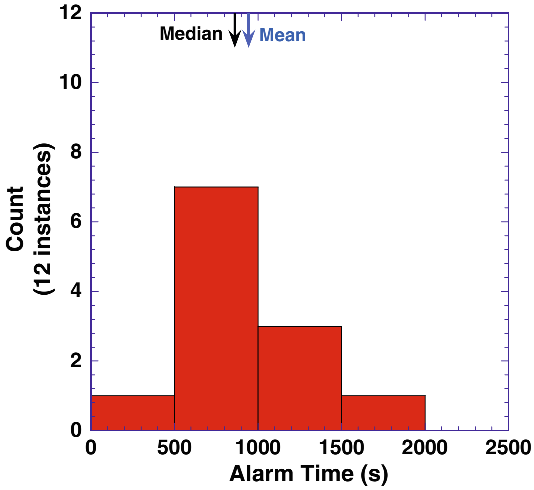

Figure 14. Histogram of NIST ionization alarm times for kitchen fires.

range, and the variation in sensor response to different types of smoke. The sensitivity range (the allowable range for production of a listed alarm) typically spans one-third or more of the obscuration range in the UL standard (1.6%/m to 13%/m). Furthermore, sensitivities are provided in terms of a smoke obscuration value, which for ionization alarms is generally not predictive of alarm sensitivity. The UL standard addresses this issue by specifying a cotton wick smoldering smoke for sensitivity test limits, expressed both in terms of light extinction and the response from a reference chamber, the measuring ionization chamber, (MIC) [6]. The MIC operates on the same physical principles of the ionization chamber in smoke alarms. Thus, it is predictive of ionization alarm performance. The chamber current limits of the MIC are 93 pA to 37.5 pA, with an initial clean air current of

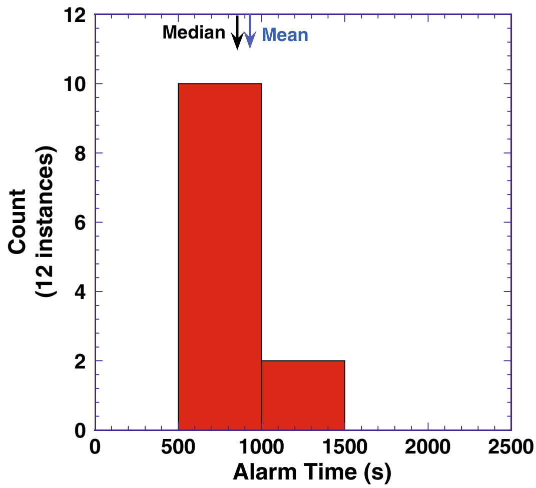

Figure 15. Histogram of NIST photoelectric alarm times for kitchen fires.

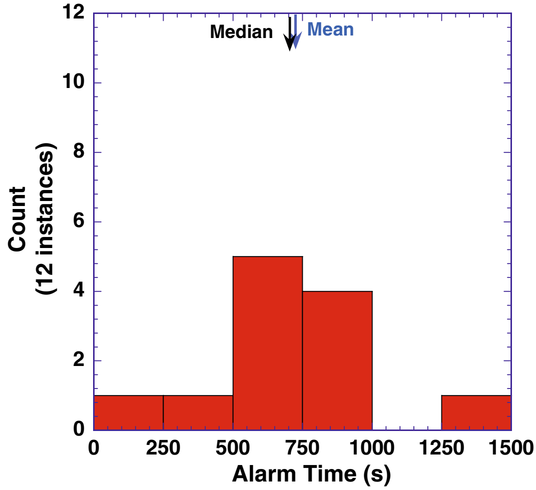

Figure 16. Histogram of NIST high sensitivity dual 1 alarm times for kitchen fires.

100 pA. Figure 18 is a plot of the sensitivity test limits for cotton wick smoke in the UL smoke box [6].

The corresponding MIC sensitivity values for the three ionization alarm settings specified in the NIST report were approximately 73 pA, 61 pA. and 52 pA with an estimated uncertainty of 2 pA for high, middle and low sensitivity settings (2.6%/m, 4.3%/m, and 5.9%/m), respectively.

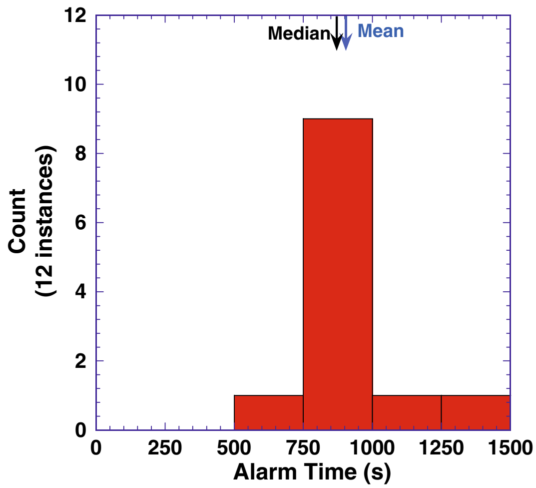

Figure 17. Histogram of NIST low sensitivity dual 3 alarm times for kitchen fires.

Table 6
Alarm Time Statistics for the NIST Test Series of Bedroom Fires with the Door Closed (9 Instances)

Alarm type	Average alarm time (s)	Median alarm time (s)	Standard deviation (s)
Ionization (2.6%/m)	1813	1108	1751
Ionization (4.3%/m)	*1876*	*1109*	*1823*
Ionization (5.9%/m)	1883	1112	1820
Photoelectric	*1913*	*1107*	*1667*
Dual 1 (2.6%/m)	1810	1107	1751
Dual 2 (4.3%/m)	*1811*	*1107*	*1750*
Dual 3 (5.9%/m)	1816	1107	1746

Italicized entries highlight sensitivity settings used in the NIST report analysis

Tests were conducted in the NIST Fire Emulator/Detector Evaluator (FE/DE) [8] to estimate the sensitivity of ionization chambers in three residential dual photoelectric/ionization alarms and four residential ionization alarms purchased from retail establishments. A measuring ionization chamber was used to monitor the smoke concentration, and specify ionization sensor sensitivities. Thus, the ionization sensor sensitivity settings for the specified dual alarm configurations (dual 1, dual 2, and dual 3) above were compared to off-the-shelf products.

The testing protocol used in the FE/DE was to install two alarms side-by-side in the test section and expose the alarms to increasing levels of cotton smolder smoke. Tests were conducted in a similar fashion to the smoldering smoke calibration tests reported in the NIST Home Smoke Alarm report [4]. By bracketing

Table 7
Average Alarm Time Difference Between Photoelectric and Dual Alarms in the NIST Test Series

Scenario	Alarm time difference (photoelectric − dual) (s)		
	High sensitivity	Middle sensitivity	Low sensitivity
Initially flaming	38	34	29
Initially smoldering	4	3	3
Kitchen fire	197	77	18
Bedroom door closed	103	102	94

Dual alarms responded faster on average in all cases

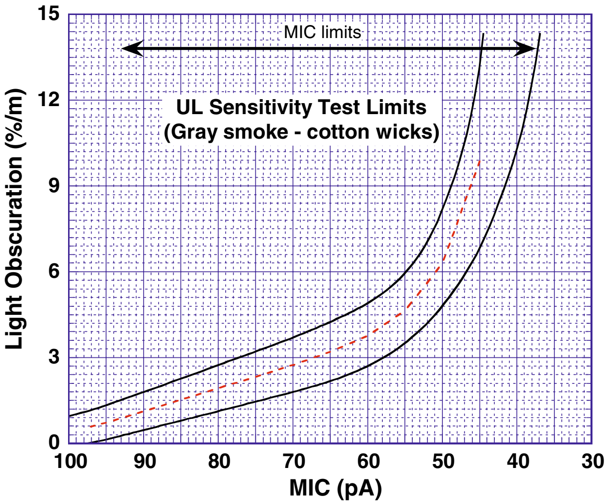

Figure 18. UL 217 standard sensitivity test limits for smoldering cotton wick smoke produced in the UL smoke box [6]. Smoke produced must fall between the two solid curves. *Dashed curve* is the mean value of the allowed range. Ionization alarms must respond within the MIC limits indicated.

steady smoke MIC levels where a particular alarm was not sounding and where it was sounding, an estimate of the alarm sensitivity was made. In the case of dual alarms, the photoelectric sensors were sealed so that a dual alarm only activated at the ionization sensor limit. Table 8 shows the results for all tests. The MIC current was monitored by a picoammeter and the uncertainty was estimated to be 0.1 pA. An estimated average sensitivity was computed from the mean of the four highest no alarm bounds and the four lowest alarm bounds. An uncertainty in the alarm sensitivity was estimated as the value that covers half the range of the difference

Table 8
Ionization Sensor Sensitivity Bounds

Bounding MIC current for no alarm {NA} and alarm {A} smoke concentrations (pA)													
Dual alarm a		Dual alarm b		Dual alarm c		Ionization alarm a		Ionization alarm b		Ionization alarm c		Ionization alarm d	
NA	A	NA	A	NA	A	NA	A	NA	A	NA	A	NA	A
60.0	64.8	63.8	76.2	86.6	100								
						85.3	90.8	69.0	73.0	86.3	88.2	66.2	75.4
64.6	75.5	61.0	66.1	86.3	92.0								
						84.9	91.2	67.2	75.1	87.6	93.7	65.6	74.3
62.0	70.0	68.5	76.2	81.7	87.9								
						78.7	85.2	69.3	75.6	79.4	87.4	66.2	75.4
63.1	83.2	66.1	75.3	83.4	92.8								
						84.9	91.2	68.0	79.9	85.2	87.8	65.6	74.3
67.7	67.9			77.8	88.8								
										81.7	90.7		
63.9	71.9			83.4	92.8								
										79.9	88.5		
64.7	73.7			77.0	88.8								

Table 9
Estimated Ionization Sensor Sensitivity Levels from Data Reported in Table 8

Ionization sensor	Sensitivity (pA)	Uncertainty (pA)
Dual alarm A	66.9	1.7
Dual alarm B	69.2	4.3
Dual alarm C	87.2	2.3
Ionization alarm A	86.6	3.1
Ionization alarm B	72.2	3.8
Ionization alarm C	86.6	1.4
Ionization alarm D	70.4	4.5

between the two average bounds. The average sensitivity and uncertainty estimates are presented in Table 9. Figure 19 shows the average measured sensitivities and the NIST prescribed ionization sensor sensitivities for the three dual alarm configurations.

The ionization sensor sensitivities of two of the ionization alarms were similar to two of the dual alarm ionization sensor sensitivities, falling within a current range of 66.9 pA to 72.2 pA. While the two other ionization alarms tested had sensitivities close to the third dual alarm's ionization sensor, falling within a current range of 86.6 pA to 87.2 pA. The high sensitivity dual alarm configuration specified in the NIST study [4] was 73 pA, closer to the lower ionization sensor sensitivities measured here, while the middle and lower sensitivity dual alarm con-

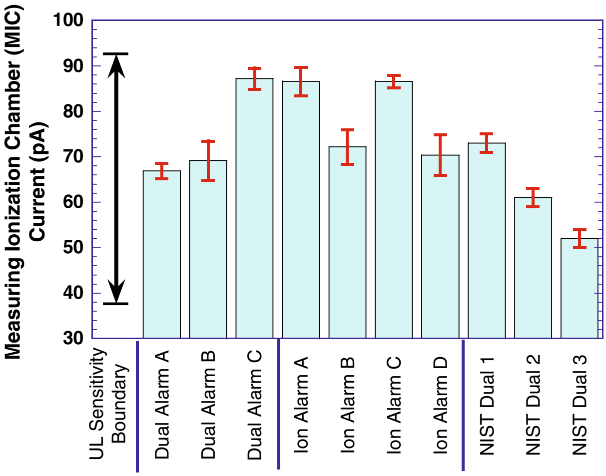

Figure 19. The sensitivity of ionization sensors in select ionization alarms, dual alarms, and the specified NIST dual alarm configurations in the alarm time analysis.

figurations had prescribed ionization sensor sensitivities of 61 pA and 52 pA, respectively which are below all the measured sensitivity values.

It is not clear if there is an optimum threshold value to set the ionization sensor sensitivity in a dual alarm. If one wanted to reduce cooking nuisance alarms, but maintain good overall sensitivity, then a lower ionization sensitivity setting (i.e., higher smoke obscuration value) could be specified. If one wanted the highest practical sensitivity for a wide range of fire types then a higher ionization sensor sensitivity (i.e., lower smoke obscuration value) could be specified.

5. Conclusions

Data collected on the performance of ionization, photoelectric, and dual photoelectric/ionization alarms in two full-scales smoke alarm studies were analyzed to assess the performance of dual alarms as compared to ionization and photoelectric alarms. Alarm times were compared to draw conclusions about the relative performance of smoke alarms. No consideration was made to account for tenability conditions anywhere in the homes, nor any egress scenarios. Furthermore, nuisance alarm susceptibilities that may factor into the overall alarm performance were not considered. Estimates of ionization sensor sensitivities in off-the-shelf ionization and dual alarms were made from measurements conducted at NIST. From the results, the following conclusions were drawn:

1. For both studies, dual alarms with equivalent or more sensitive settings performed better than individual photoelectric or ionization alarms over a range of flaming and smoldering fire scenarios.

2. From the NIST study, when the ionization alarm was the first to respond, the dual alarm configurations (from high to low sensor sensitivities) alarmed 89 s, 67 s, and 47 s, faster on average than the photoelectric alarm. When the photoelectric alarm was the first to respond, the dual alarm configurations (from high to low sensor sensitivities) responded 535 s, 523 s, and 518 s faster on average than the ionization alarm at the middle sensitivity setting.
3. Over the sensitivity range examined in the NIST study, dual alarms exhibited almost no average decrease in alarm time compared to photoelectric alarms during initially smoldering fire scenarios, irrespective of the ionization sensor sensitivity (4 s to 3 s from high to low sensitivity settings). Dual alarms exhibited a pronounced average decrease in alarm times compared to photoelectric alarms for initially flaming fire scenarios (38 s to 29 s from high to low sensitivity settings). For the kitchen fires, the average decrease in alarm time was a strong function of ionization sensor sensitivity (197 s to 18 s from high to low sensitivity settings). For the fires with the bedroom door closed, dual alarms exhibited a sustained average decrease in alarm time compared to photoelectric alarms (103 s to 94 s from high to low sensitivity settings).
4. Tests conducted in the NIST fire emulator/detector evaluator showed that the ionization sensors in off-the-shelf ionization alarms and dual alarms span a range of sensitivity settings as compared to a reference measuring ionization chamber. The prescribed ionization sensor sensitivities in the NIST study [4] were near or lower than the measured ionization sensor sensitivities of three off-the-shelf dual sensor alarms and four ionization alarms.
5. It may be beneficial to tailor sensor sensitivities in dual alarms for specific applications. If one wanted to reduce cooking nuisance alarms, but maintain good overall sensitivity, then a less sensitive ionization sensitivity setting could be specified. If one wanted the highest practical sensitivity to a wide range of fire types, then a more sensitive ionization sensor sensitivity could be specified.

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