A Comparison of Carbon Monoxide Gas Sensing to Particle Smoke Detection in Residential Fire Scenarios

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Abstract

Recent research has suggested that carbon monoxide (CO) sensing might be better than photoelectric detectors for detecting smoldering fires in dwellings. Results from that research were compared to full-scale experimental data sets, where carbon monoxide concentration and smoke alarm response were gathered during smoldering polyurethane foam furniture and furniture mockup experiments. Based on the analysis of those data sets, CO gas sensing is complementary to particulate smoke detection, but does not appear to rise to a level suggesting it should be a required in a standalone smoke detector.

Keywords: Smoke alarms, carbon monoxide detection, smoldering fire

Introduction

Sesseng and Reitan presented research they assert demonstrated that carbon monoxide (CO) sensing might be better than photoelectric detectors for detecting smoldering fires in dwellings [1]. Specifically, they claimed that photoelectric detectors may not be safe in a smoldering fire because a sleeping occupant may be overcome by CO before a photoelectric alarm triggers, and earlier notification of the fire brigade from CO detection may save lives and reduce property damage. While they do acknowledge the need for particulate smoke detection of flaming fires where CO production is relatively low and fire development is rapid, their research poses a question: Should CO sensing be a requirement for residential fire detection?

While research has demonstrated the utility of CO and other gas sensing in early fire detection, there is a lack of analyzed data suggesting its superiority over particulate sensing. To provide guidance in answering the question above, the experimental set-up used by Sesseng and Reitan is described and critiqued as to its relevance in mimicking realistic scenarios, and their results are compared to full-scale experiments conducted by the National Institute of Standards and Technology (NIST).

Sesseng and Reitan Experiments

The experiments were conducted in a test room of interior dimensions 3.6 m × 2.4 m × 2.4 m high which met the ISO 9705 Standard [2]. This room size is typical of a small bedroom with a volume of 21 m^3. The door opening was kept closed during the experiments. A piece of polyurethane foam mattress 0.7 m × 0.5 m × 0.1 m was the fuel source. To initiate smoldering, a resistance heating wire was wrapped in cotton batting and placed on top of the mattress segment. The entire mattress segment was covered with insulating ceramic fiber blanket material. Finally, a wooden box with a 51 cm diameter hole in the center of the top surface was placed over the mattress segment to force the smoke through that central aperture. The heater was energized to about 23 W for 10 minutes to initiate smoldering in the foam.

Ten experiments were conducted with the smoldering source placed in various locations including on a raised platform representing a bedframe, under the platform, and on the floor. Carbon monoxide concentration was measured at a location representing the toxic gas exposure of an occupant sleeping on the bed platform. The CO concentrations measured at that location were consistent with CO sensors placed in various locations of the room, indicating an even distribution of CO in the room. Those concentrations at the minimum and average alarm times for both CO and photoelectric alarms were tabulated. Additionally, a CO dose was computed by integrating the CO concentration (reported as volume fraction$\times 10^6$ or ppm) as a function of time, up to the point of alarm. The CO dose was compared to a median incapacitation dose (IC_{50}) of 35,000 ppm×min.

First, it is noted that the room was relatively small and unventilated, which would be a worst-case scenario for CO build-up for a given source. Second, it appears that the ceramic blanket would filter some of the smoke particulate while allowing gaseous CO to diffuse through it and then throughout the room. Third, the confining box, while providing a repeatable location for the smoke to emanate from, most-likely affected the natural plume(s) from the smoldering foam, affecting buoyancy and the transport of smoke to the ceiling.

It seems that the experimental set-up was likely to produce results where CO sensing would outperform particulate sensing and may not mimic realistic smoldering upholstered furniture fire scenarios. Nonetheless, their results taken at face value demand a more detailed evaluation of existing data from smoldering fire experiments to make a judgement if CO sensing should be considered as a requirement.

NIST Experiments

Two full-scale experimental data sets were analyzed to compare carbon monoxide sensing to photoelectric or ionization smoke alarm response in smoldering furniture or polyurethane foam chair mockup fire scenarios.

The first data set was the NIST smoke alarm sensitivity study where chair mockups, consisting of non-fire-retarded polyurethane foam covered with cotton cushion covers, were smoldered [3]. Figure 1 shows the mockup and the ignition set-up. The cushions rested on a metal frame that was placed on a raised platform attached to a load cell. A small square of cotton fabric was place at a front corner location and a 50 W electric cartridge heater about the size of a cigarette was place on the fabric. After energizing the heater for about 6 minutes, the heater was removed and seat cushions smoldered. Eventually, smoldering reached the back cushion and transitioning to flaming in about 90 minutes on average in 11 of 12 experiments. One chair mockup did not transition to flaming before the end of the experiment.

Figure 1. Chair mockup consisting of polyurethane foam slabs with cotton seat cushion and chair back cushion covers.

Figure 2 is a schematic of the small apartment mockup experimental space. Experiments were conducted with the smoldering source located in the living room with the door to the master bedroom closed as shown, and in the master bedroom with the door either open or closed. Twelve initially smoldering fire experiments were conducted, six with the source in the living room, and three each with the source in the master bedroom with the door open or closed. The volume of the master bedroom was 38 m^3 and the volume of the living room and attached spaces excluding the master bedroom was 92 m^3.

Photoelectric and ionization smoke alarms were located at various ceiling locations. Gas samples were extracted from a height of 1.5 m from the floor at the locations indicated. Here, alarm times for photoelectric and ionization alarms in either the master bedroom (S5 or S6) or hallway locations (S2 or S3) were tabulated along with the CO concentration at alarm from the nearest sampling location and the corresponding computed fractional effective dose of the toxic gases (FED) [4]. For the smoldering phase, the toxic gases considered were CO and hydrogen cyanide. (In these experiments, hydrogen cyanide grab samples were analyzed and correlated to CO concentration during the smoldering and flaming stages of combustion [5].) The fractional effective dose for toxic gases increased more rapidly when estimated hydrogen cyanide concentration was included.

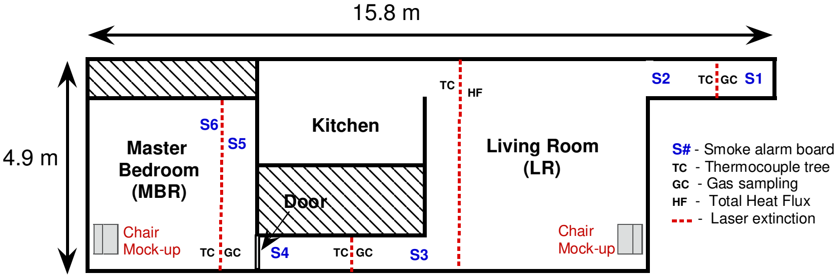

Figure 2. Schematic of the small apartment mockup space showing the location of the smoldering sources.

The second data set is from the NIST home smoke alarm project where upholstered chairs and mattresses were smoldered by inserting an electric wire resistance heater into a slit in the covering fabric and foam of the chairs or mattresses [6]. The experiments were conducted in a single-story manufactured home and a two-story home slated for demolition. The experiments were conducted without any forced ventilation. Individually calibrated smoke and CO alarms were installed at various ceiling locations in groups that included multiple photoelectric, ionization, CO alarms. Alarms were calibrated with smoldering cotton wick smoke in the NIST fire emulator/detector evaluator tunnel. Alarm points were chosen as 6.4 %/m obscuration (2.0 %/ft. in U.S. industry standard units) and 50 ppm for photoelectric and CO alarms respectively. Alarm locations in hallways adjacent to the room of fire origin were selected, and the average time to reach the alarm threshold for the photoelectric and CO alarms was computed.

Comparison of Results

Tabulated results from each of the experimental data sets is presented below. First, Table 1 shows the results from Sesseng and Reitan. In addition to their computed dose, a computed FED for CO was tabulated for each averaged photoelectric and CO alarm time by dividing the CO dose by 35,000 ppm×min to facilitate comparison to other experimental data. A FED of 1.0 indicates an exposure that incapacitates 50% of a normally susceptible population [4].

In four out of seven cases, the averaged photoelectric alarm time yielded a FED greater than 1.0, hence at least half of sleeping occupants exposed may not have been alerted prior to an incapacitating dose. Conversely, in all cases the average CO alarm time yielded very low FED exposures presumably providing alert to all sleeping occupants.

Table 1. Results from Sesseng and Reitan for the CO concentration, dose and FED at the average photoelectric or CO alarm time for each experiment [1].

Exp. #	Photoelectric Alarm			CO Alarm		
	CO (ppm)	CO Dose (ppm×min)	FED	CO (ppm)	CO Dose (ppm×min)	FED
1	664	37593	1.07	35	875	0.03
2	1453	63957	1.83	42	766	0.02
3	638	24371	0.70	62	1236	0.04
4	907	39325	1.12	61	965	0.03
6	933	32547	0.93	35	315	0.01
7	1075	64184	1.83	37	554	0.02
8				46	1019	0.03
9				36	489	0.01
10				46	960	0.03

Table 2 shows the results from the NIST smoke alarm sensitivity study for both photoelectric and ionization alarms. The FED computation includes the effects of hydrogen cyanide, thus is more conservative than computed values of CO alone.

Table 2. Results from the NIST smoke alarm sensitivity study for photoelectric and ionization alarms [3].

Experimental Configuration	Photoelectric Alarm		Ionization Alarm	
	CO (ppm)	FED	CO (ppm)	FED
BR door closed	34	0.02	26	0.01
BR door closed	104	0.05	46	0.02
BR door closed	20	0.01	40	0.01
BR door closed	25	0.01	44	0.01
BR door opened	22	0.01	15	0.01
BR door opened	16	0.01	20	0.01
BR door opened	37	0.01	45	0.02
LR	135	0.03	250	0.03
LR	-	-	260	0.03
LR	85	0.05	375	0.17
LR	50	0.02	400	0.20
LR	88	0.01	202	0.03
LR	-	-	25	0.002
LR	30	0.02	29	0.004
LR	40	0.01	62	0.03
LR	-	-	54	0.02

The concentration of CO at alarm was lower on average for photoelectric alarms than for ionization alarms, and the computed FED was below 0.1 for all average photoelectric alarm times and above 0.1 for only two average ionization alarm times.

Figure 2 is a scatter plot of all FED values from the Sesseng and Reitan experiments (SP) and the NIST smoke alarm sensitivity study. This plot illustrates the difference between Sesseng and Reitan's photoelectric alarm results and their CO alarm and NIST smoke alarm results. The differences in room volume range from 21 m^3 in the SP study to 38 m^3, 92 m^3, and 130 m^3 for the various experimental configurations in the NIST study. While room size may have influenced CO concentration, it was observed in the NIST study that smoke alarms tended to respond much sooner when the source and alarms were confined to the smaller master bedroom space.

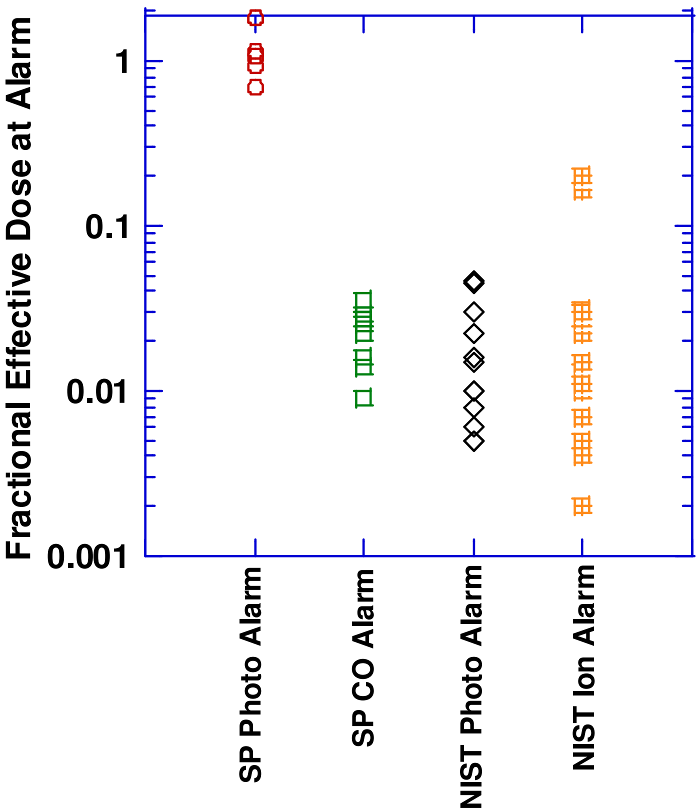

Figure 2. FED values from the Sesseng and Reitan experiments (SP) [1] and the NIST smoke alarm sensitivity study [3] at various average alarm times.

Table 3 shows results from smoldering chairs and mattresses in the NIST home smoke alarm study. Those results compare the average time to alarm for co-located CO alarms (with a calibrated alarm concentration of 50 ppm) and co-located photoelectric alarms (with a smoke box alarm obscuration of 6.4 %/m). Also tabulated are CO concentrations at 1.5 m from the floor at the average photoelectric alarm times.

Table 3. Results from the NIST home smoke alarm study [6].

Experiment	Avg CO Alarm (s)	Avg Photoelectric Alarm (s)	CO conc, at Photoelectric alarm (ppm)
SDC01	3302	5382	230
SDC04	3403	1153	-
SDC06	4741	3473	-
SDC11	3942	4241	117
SDC31	5092	5041	225
SDC34	-	-	100
SDC37	-	-	50
SDC40	-	-	38
SDC23	4599	4664	-
SDC27	2761	1366	-

The average time to CO alarm was shorter in only three of seven experiments. The CO concentration at the average photoelectric alarm time was significantly lower than the values recorded by Sesseng and Reitan.

Conclusions

Analysis of the NIST data sets showed photoelectric detection in the room of fire origin was sufficient in all smoldering fire cases to provide early warning prior to hazardous CO exposures at the specific locations. CO detection may provide significantly earlier warning than ionization alarms for some smoldering scenarios which could provide earlier notification to the fire brigade. However, the new fire test requirements of ANSI/UL 217-2015 [7] will improve alarm response to smoldering upholstered furniture fires containing polyurethane foam, ameliorating the relatively slower response of ionization alarms compared to photoelectric alarms for such smoldering fire scenarios.

Based on the analysis of existing data sets, CO gas sensing can be complementary to particulate smoke detection, but does not appear to rise to a level suggesting it should be a required in a standalone smoke detector. Nonetheless, the new fire and cooking nuisance tests introduced in ANSI/UL 217-2015 may provide an incentive for smoke alarm designs to include CO gas sensing for nuisance alarm resistance. In addition, several manufacturers currently produce combination smoke / CO alarms combining the functions of standalone smoke and CO alarms. Smoke alarm manufacturers may find benefits in considering CO gas sensors to compliment smoke alarm activation in smoldering fires as a detection enhancement.

Acknowledgements and Disclaimer

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