The Time of Activation of Smoke Alarms in Houses - the effect of location, smoke source, alarm type and manufacturer, and other factors

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Introduction

This presentation reports on the results of a project intended to help determine the most appropriate location(s) of smoke alarms in dwellings which was undertaken for the Australian Building Codes Board, the organization responsible for the Building Code of Australia [1]. It is notable that in the USA NFPA has required smoke alarms in bedrooms since 1993 and interconnection of smoke alarms since 1989 [2,3] but in Australia the BCA even now does not have these requirements. The BCA currently only requires smoke alarms in dwellings on or near the ceiling in: [4]

- any storey containing bedrooms, between each part of the dwelling with bedrooms and the rest of the dwelling, and in the hallways serving the bedrooms
- any other storey not containing bedrooms

In addition to helping to determine the most appropriate location(s) of smoke alarms in dwellings the project was intended to provide cost-benefit data on the use of non-interconnected and interconnected smoke alarms. The project had two experimental phases to determine:

- the loudness of the received alarm sound in real houses depending on the relative locations of the sound emitter (the smoke alarm) and the sound receiver (the occupant)
- the effect on smoke alarm activation time of the location(s) of smoke alarms in relation to the location(s) of fire starts in representative Australian dwellings for smoke alarms using ionization and photoelectric smoke detectors (the two predominant domestic smoke alarm detection technologies currently in use) and dual detector smoke alarms

In relation to the first experimental phase the sound level in each room was measured with various combinations of doors open and closed in five real (currently occupied) houses. Two sounds at set levels were emitted from likely smoke alarm positions in each room (generally close to the middle of the ceiling) and hallway. Sound levels were measured using Lutron SI-4001 sound meters with the settings on “slow response” and “maximum hold”.

The sound levels in each room were measured in positions diagonally opposite the room doors at approximately pillow height. The recorded smoke alarm sounds were emitted from a large speaker at 85 and 105 dBA sound levels measured 1 m from the speaker. All of these tests were conducted during the day with the house unoccupied and in most the ambient sound level was in the range 35-40 dBA with occasional higher excursions when, for example, an aeroplane passed overhead or a truck passed by. The sounds used were the ~3100 Hz current smoke alarm sound and the 520 Hz square wave sound used in the testing of the arousal of various groups of sleeping people [5-14].

The reduced sound level measured in the “other” (not the room where the sound was emitted) rooms was very variable. However, statistical analysis of the sound levels recorded produced very consistent results in all five houses and showed that on average, with the room of origin door open and other room doors also open, the sound level of the ~3100 Hz sound emitted:

- at 85 dbA at the point of origin was on average reduced to 52 dbA in other rooms
- at 105 dbA was on average reduced to 67 dbA in other rooms

Again for the ~3100 Hz sound, with room of origin door and other room doors closed:

- the 85 dbA sound level was reduced on average to a nominal 36 dbA in other rooms (but this level may actually be below the ambient sound levels mentioned above and thus may hardly be audible even to a person who is listening for the sound)
- the 105 dbA sound level was reduced on average to 51 dbA in the other rooms

The sound level reduction was affected by the characteristics (for example, furnishings and wall and floor coverings) of the room of origin and the other rooms, and the characteristics of the path of travel of the sound (including the distance between the rooms). These factors are one of the main sources of the variability mentioned above.

The sound level reduction was also affected by the sound emitted, the reduction between rooms being about 6 dbA greater on average for the ~3100 Hz standard smoke alarm sound than for the 520 Hz square wave sound.

Smoke Alarm Response Time

As large quantities of smoke could not be emitted in the real houses, full scale models of four of the houses used for the sound measurements were constructed at the VU Large Scale Fire Testing Facility and the time of activation of the domestic smoke alarms in each room and hallway was recorded. The test variables included open and closed doors and windows and seven sources of smoke (some from smouldering combustion and some from flaming fires) using a variety of fuels. The smoke alarms used were bought from large hardware stores and were the types and brands most widely available in Australia at present.

Method

The full scale model houses were constructed of cardboard with the doors and windows cut out and opened and shut as required for each case tested. The smoke sources tested included burning ethanol, braided wick, heptane, decalin, smouldering wood, wood cribs, smouldering towel and polyurethane foam. These materials and the form of combustion were based on those specified in ISO/TS 7240-9 (2006) “Test fires for fire detectors” [15] for the testing of smoke detectors. It was found in preliminary tests that none of the smoke alarms were activated (even in the room of origin) by the burning ethanol, and consequently this fuel was not used in subsequent testing.

Analysis of preliminary experimental results showed that the activation time (when activation occurred: in many tests some alarms did not activate at all) was very strongly influenced by whether interconnecting doors were open or shut. However, under the controlled (very still) environmental conditions in the Large Scale Fire Testing Facility for these tests it was very little influenced by whether windows were open or closed. Consequently all of the results reported here unless noted otherwise were for tests with the windows closed.

Despite the fact that there was a small gap at the top, bottom and on one side of each door, initial testing indicated that even when the room of fire origin was full of dense smoke, virtually no smoke was emitted into the adjacent room or hallway and that there was no detection of this smoke by alarms in these locations. On this basis it was decided not to continue with tests with the door closed. The movement of smoke through closed doors was checked using real doors in laboratory buildings (it was not considered acceptable to severely smoke log rooms in occupied houses) and the situation described above for the model building was found to be representative of that in these situations: that unless there was some pressure difference induced between the two rooms by mechanical ventilation or external wind there was very little smoke movement from one room to another with the door closed. Thus it was concluded that the movement of smoke through closed doors from low energy smoke sources is minimal and that the time for detection in adjacent rooms is likely to be unacceptably prolonged. Consequently all of the results reported here are for the case with all room doors open.

In each of the model houses smoke was produced using each of the fuels in each room (here called the room of fire origin (RFO)) and the time to activation of the smoke alarms fitted in each room and hallway recorded. The smoke alarms were fitted on the ceiling at the centre of the room with approximately equal distance from the doorway to each alarm. Each room was fitted with two ionization alarms, two photoelectric alarms and one dual (ionization and photoelectric) alarm. In hallways the dual alarm was omitted. The alarms were from two manufacturers here called manufacturer 1 and manufacturer 2. The response of the alarms of each type and from each manufacturer were initially compared and found to be very similar.

Results

In many tests some alarms did not activate. Generally the smoke alarms that did not activate were those most remote from the room of fire origin but this was also influenced by the fuel and other (some unidentified) factors. Table 1 shows the proportion of alarms that did not activate overall in these tests. In Table 1 and subsequent tables the alarm type is signified as follows:

- I = ionization
- P= photoelectric
- D = dual ionization and photoelectric

The numerical suffix signifies the manufacturer.

Table 1 Proportion of smoke alarms of each type and manufacturer that did not activate

House	I1	I2	P1	P2	D2
1	20%	15%	48%	40%	12%
2	17%	20%	37%	30%	25%
3	41%	40%	50%	46%	39%
4	8%	5%	27%	29%	12%
Average	22%	21%	41%	36%	24%

Inspection of Table 1 reveals that there was a minor difference between the manufacturers, but that the major difference was between the ionization and photoelectric alarms, with the photoelectric alarms not activating much more frequently. The other major difference was between the two storey house (House 3) and the other houses which were all single storey. This difference is principally due to the smoke alarms in the lower storey not activating when the room of fire origin was on the second storey. There was a weak trend to a greater proportion of non-activations in the larger houses compared with the smaller houses and in the more compartmented houses compared with the more open plan house.

In the following analysis the smoke alarm non-activations have been ignored entirely, the analysis is of actual activation times (that is, activation did occur).

As the houses differed quite considerably in geometry (shape, number of rooms, size, etc) a categorical least squares regression analysis has been used to initially investigate the importance of various factors in determining the smoke alarm activation time and to enable the results for the houses to be compared. This analysis has been conducted separately for each house and the results combined to consider the overall situation.

The categorical analysis uses a formula of the form:

$$t_A = C_1 + C_2(\text{RFO}) + C_3(\text{ROOM}) + C_4(\text{FUEL}) + C_5(\text{TYPE}) \qquad \text{(Equation 1)}$$

Where:

- t_A = time of smoke alarm activation in seconds
- C_1 = constant (s)
- C_2(RFO) = constant, value depends on room of fire origin (s)
- C_3(ROOM) = constant, value depends on room in which the smoke alarm is located (s)
- C_4(FUEL) = constant, value depends on smoke source (fuel and combustion type) (s)
- C_5(TYPE) = constant, value depends on alarm type and manufacturer (s)

The results of these regression analyses are summarised in Table 2. In Table 2 the maximum and minimum values of the constants C_2 to C_5 are shown. Thus, using the values from Table 2 in Equation 1, the longest estimated activation time for a smoke alarm in House 1 is:

$$t_A = 493 + 109 + 187 + 419 + 55 = 1263 \text{ seconds}$$

Similarly, the shortest activation time for House 3 is:

$$t_A = 500 - 39 - 92 - 317 - 12 = 40 \text{ seconds}$$

Table 2 Summary of results of categorical regression analysis using Equation 1

House	C_1	C_2 (RFO)		C_3 (ROOM)		C_4 (FUEL)		C_5 (TYPE)	
		max	min	max	min	max	min	max	min
1	493	109	-82	187	-88	419	-323	55	-45
2	425	74	-106	81	-63	406	-290	44	-37
3	500	35	-39	56	-92	379	-317	11	-12
4	509	105	-98	105	-51	350	-312	41	-45
Averages	482	81	-81	107	-74	389	-311	38	-35

The importance of each of the factors represented by the constants C_2 to C_5 is more easily appreciated from the range of each of these constants as shown in Table 3.

Table 3 Range of values for constants C_2 to C_5 from regression analysis using Equation 1

House	**C_1**	**C_2 (RFO)**	**C_3 (ROOM)**	**C_4 (FUEL)**	**C_5 (TYPE)**
1	493	191	275	742	100
2	425	180	144	696	81
3	500	74	148	696	23
4	509	203	156	662	86
Average	482	162	181	699	73

It is apparent from Table 3 that the most important factor determining the activation time is the fuel and combustion type with an average range of about 700 seconds. The room of fire origin and the room in which the smoke alarms are located are also important (with average ranges of about 160 and 180 seconds respectively about a quarter of that for the fuel and combustion type) and the least important factor is the type and manufacturer of the smoke alarm with an average range of about 70 seconds (about one tenth of that for the fuel and combustion type.

Figures 1 to 4 show the comparison of the predicted values from these regression formulae with the actual activation time for houses 1 to 4 respectively.

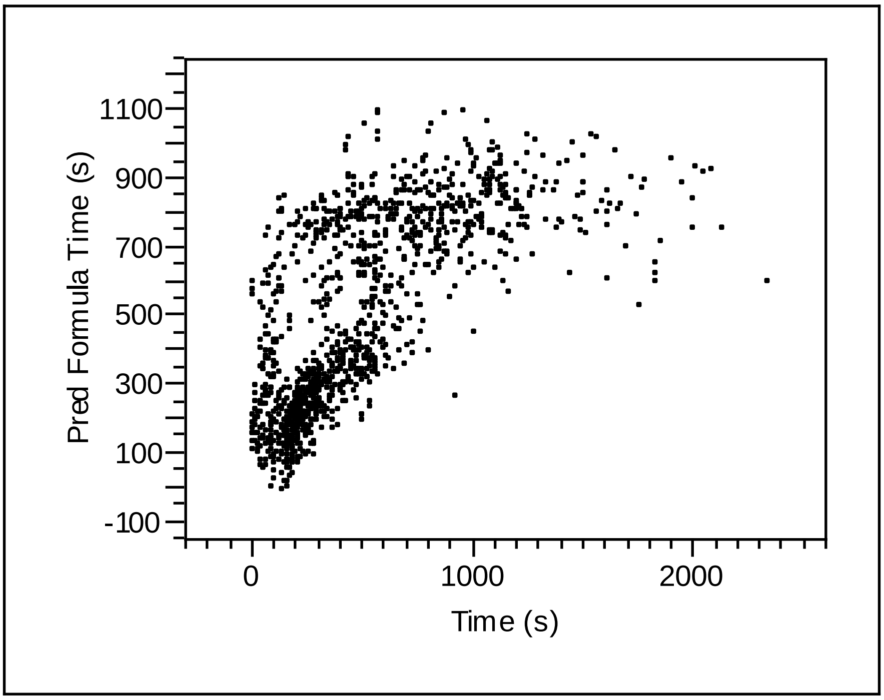

Figure 1 Comparison of Predicted Value with Actuation Time for House 1

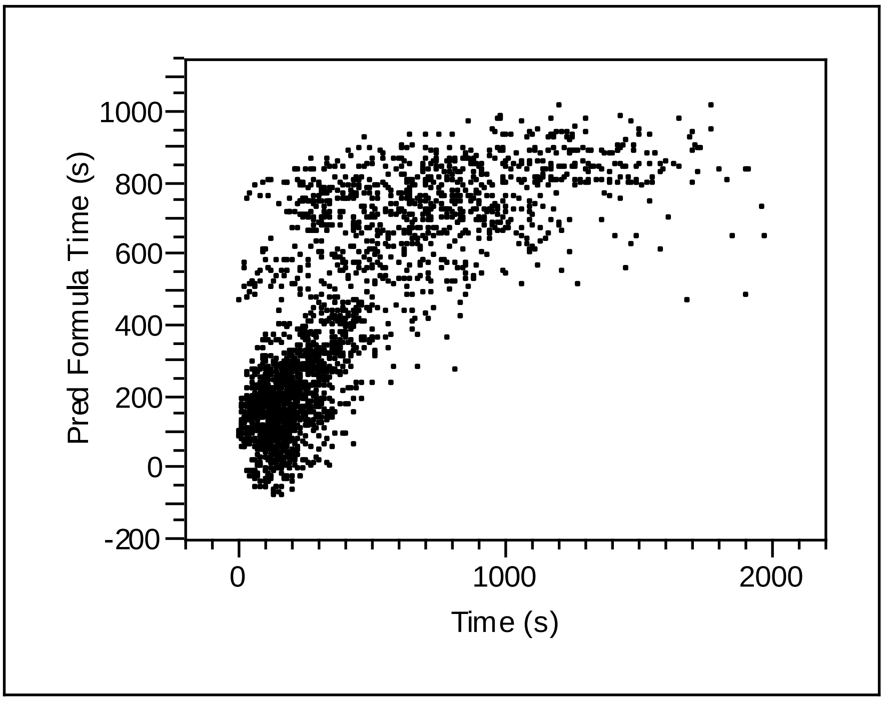

Figure 2 Comparison of Predicted Value with Actuation Time for House 2

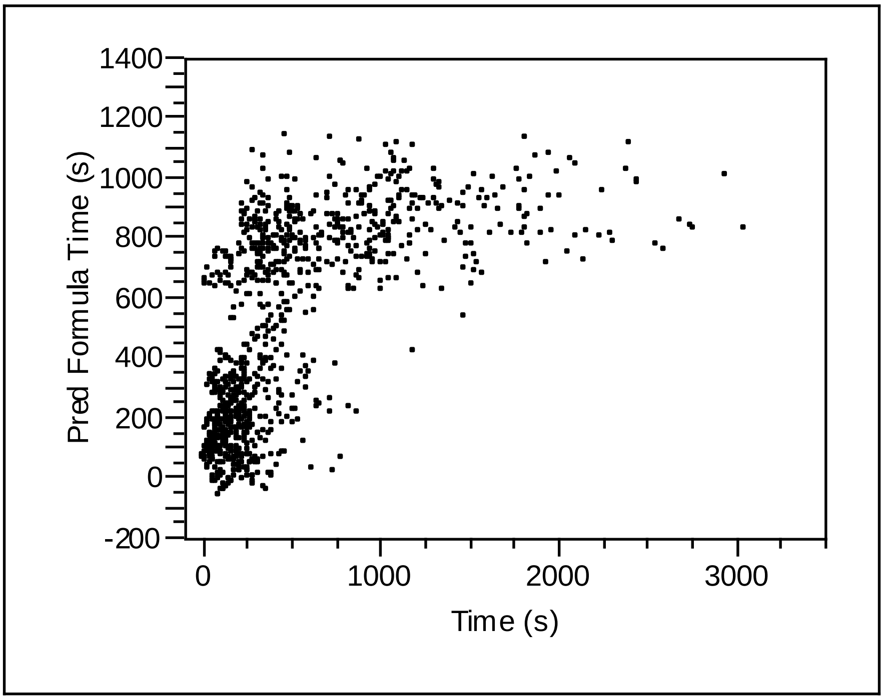

Figure 3 Comparison of Predicted Value with Actuation Time for House 3

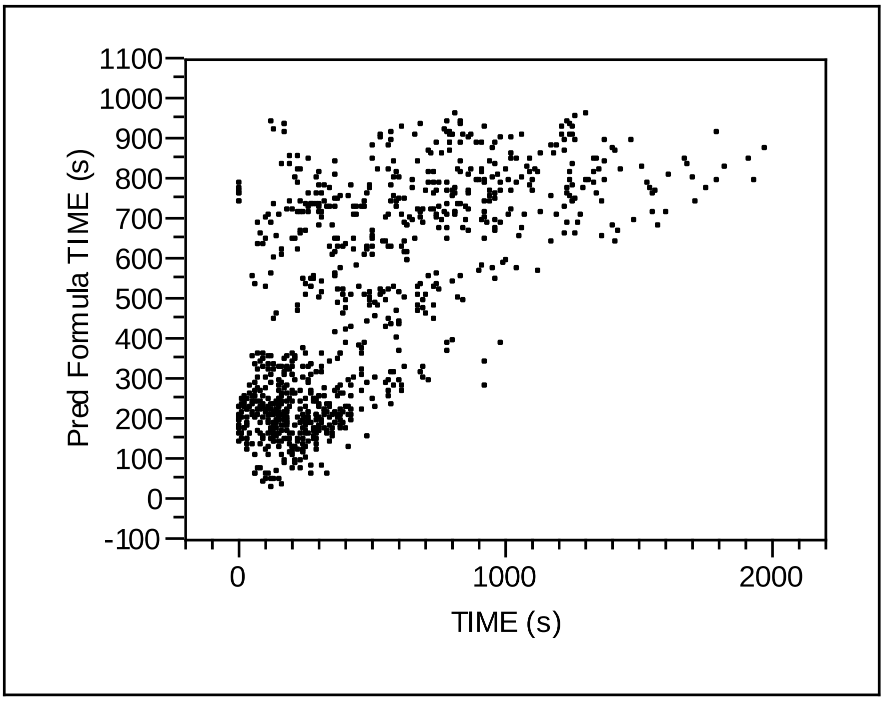

Figure 4 Comparison of Predicted Value with Actuation Time for House 4

These figures show the considerable scatter in the data, particularly at the long activation times. But while there was considerable variability in the activation time data, on average there is great similarity in the response of the various types of smoke alarms. This is illustrated in Figures 5 to 10. Figures 5 to 9 show the least squares line of best fit and the scatter bin the data points for the smoke alarm types I1, I2, P1, P2 and D2 for House 2. This is typical of the data for all of the houses. Figure 10 shows and allows comparison of the lines of best fit from Figures 5 to 9. It shows that at the shorter activation times the ionization alarms activate more quickly than the average, while at longer activation times it is the photoelectric alarms that activate more quickly. In general this is in accord with the observation that ionization alarms activate more quickly than photoelectric alarms to smoke from flaming fires, while photoelectric alarms activate more quickly to smoke from smouldering fires.

I

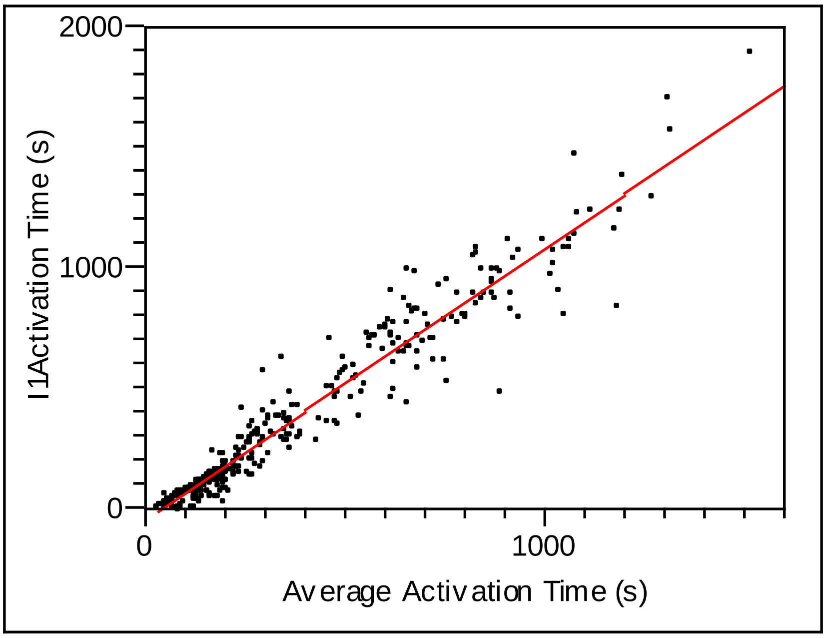

Figure 5 Comparison of smoke alarm I1 activation time with average activation time in House 2

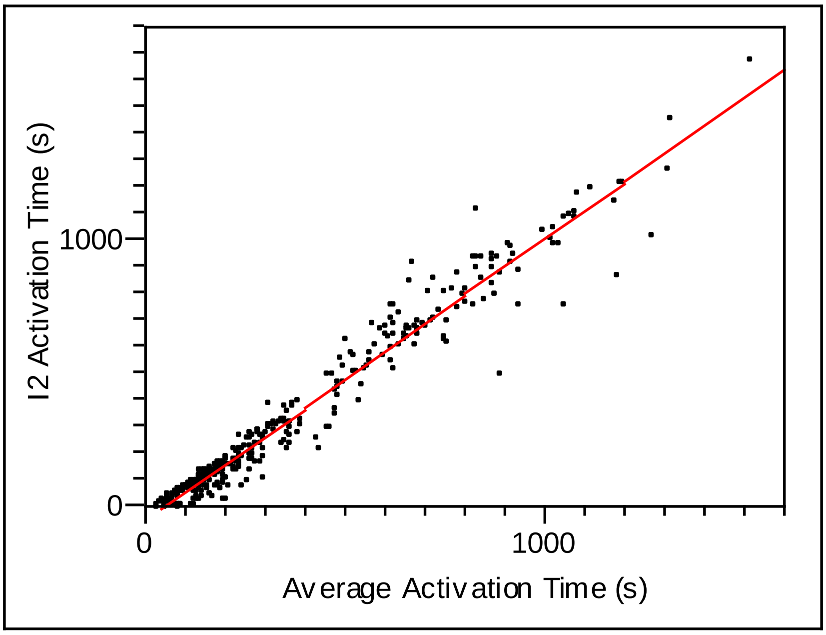

Figure 6 Comparison of smoke alarm I2 activation time with average activation time in House 2

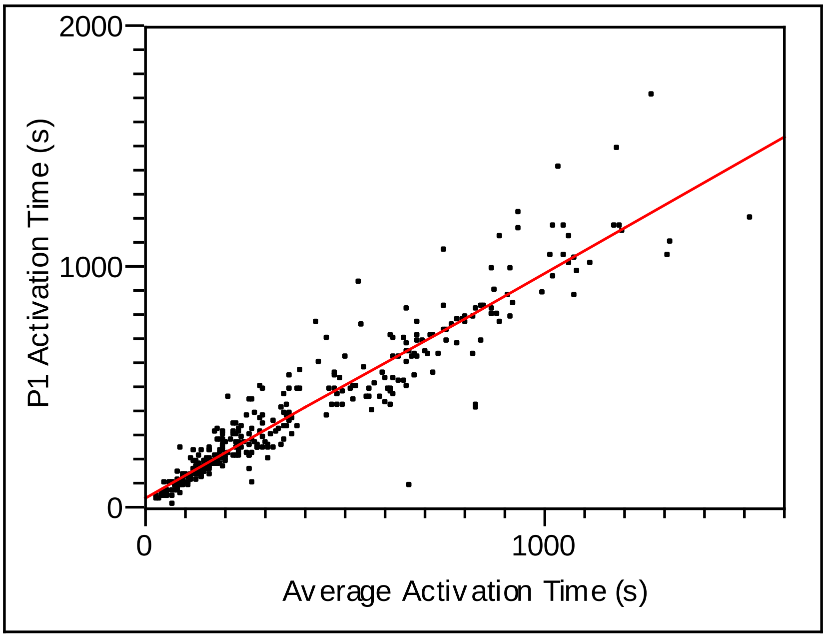

Figure 7 Comparison of smoke alarm P1 activation time with average activation time in House 2

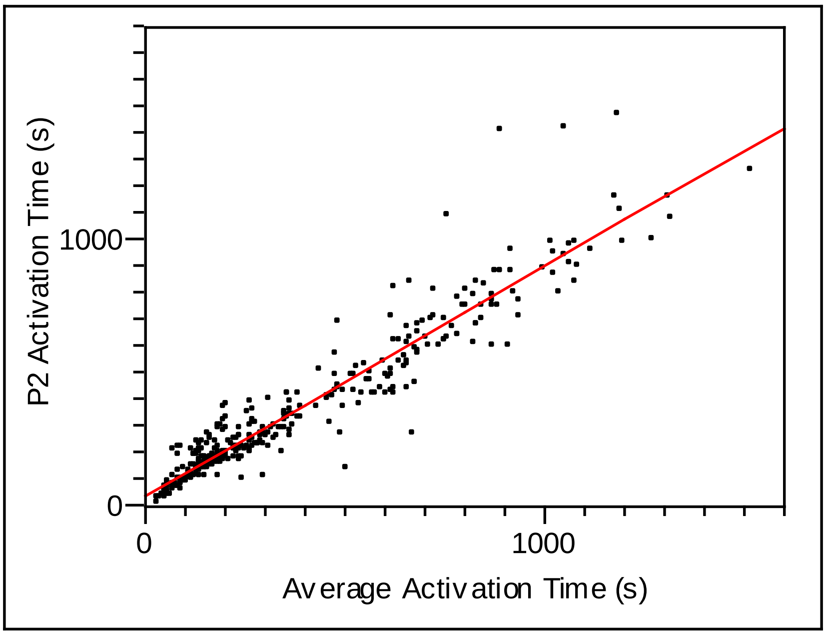

Figure 8 Comparison of smoke alarm P2 activation time with average activation time in House 2

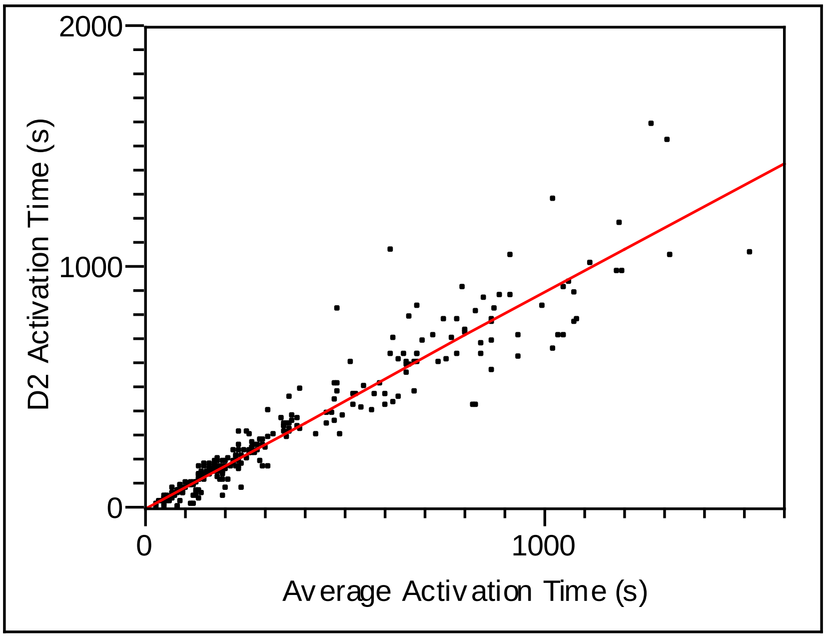

Figure 9 Comparison of smoke alarm D2 activation time with average activation time in House 2

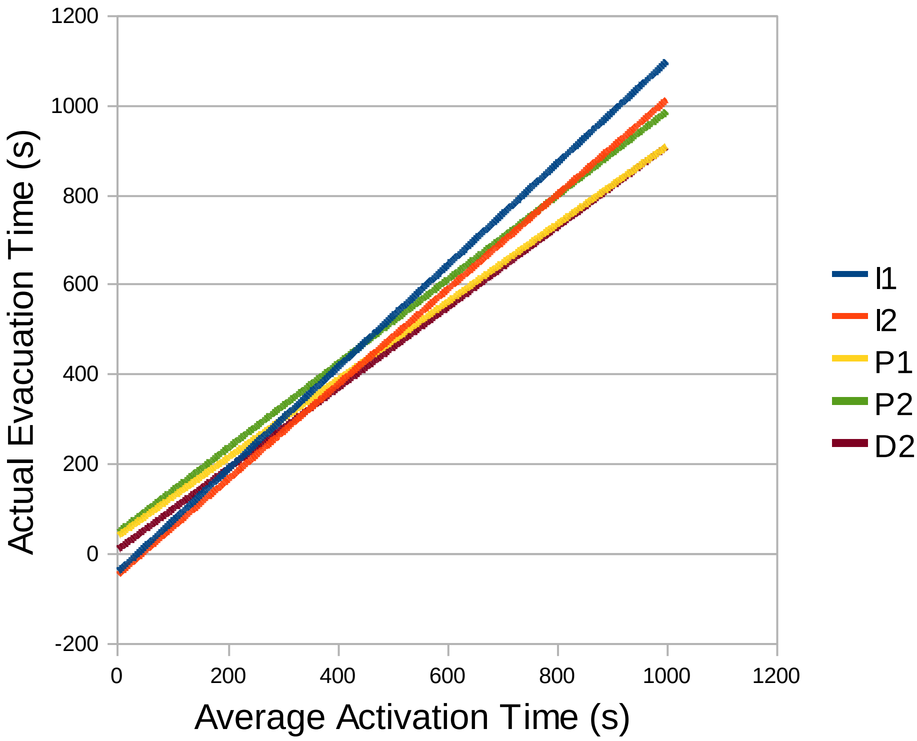

Figure 10 Comparison of lines of best fit for the five smoke alarm types in House 2

Other Influences on Smoke Alarm Activation

Environmental conditions such as external wind through open windows and ventilation flows can have an important influence on smoke alarm response. These influences were investigated in House 3 and the results of these tests will be presented in the report on the project.

Conclusions

It is concerning that even with doors open there was a large percentage of tests in which smoke alarms in other rooms did not activate. Also of concern is the degree of variability in the alarm activation times. However, it is clear that knowledge of the fires that kill and injure people is important in optimisation of smoke alarms, because the fuel and type of fire to be detected is of great importance in determining the alarm activation time.

The possibility of closed doors between the detectors and the fire and between the smoke alarm and any responsible adults who could reliably respond to an alarm is clearly an argument for interconnected smoke alarms. Even with doors open there can be considerable delay in activation (and considerably increased likelihood of non-activation) of smoke alarms that are in another room or remote from the fire. The type of detector technology used appears to have a relatively minor influence on alarm activation time compared with these factors.

References

1. ABCB, (2008) Building Code of Australia Volumes 1 and 2, Australian Building Codes Board, Canberra
2. Lee A (2005) The Audibility of Smoke Alarms in Residential Homes, CPSC-ES-0503, US Consumer Product Safety Commission, Bethesda, MD Retrieved from http://www.cpsc.gov/LIBRARY/FOIA/foia05/os/audibility.pdf on November 12, 2007.
3. NFPA 72 (2002), National Fire Alarm Code, National Fire Protection Association, Quincy, MA
4. ABCB, (2008) Building Code of Australia Volume 2, Class 1 and Class 10 Buildings, Australian Building Codes Board, Canberra
5. Bruck D, Thomas I (2008) Comparison of the effectiveness of different emergency notification signals in sleeping older adults. Fire Technol 44:15-38.
6. Bruck D, Reid S, Kouzma J, Ball M (2004) The effectiveness of different alarms in waking sleeping children. Proceedings of the Third Human Behaviour in Fire Conference (Belfast). London: Interscience Communications, pp 279-290.
7. Ball M, Bruck D (2004) The salience of fire alarm signals for sleeping individuals. Proceedings of the Third Human Behaviour in Fire Conference (Belfast). London: Interscience Communications, pp 303-314.
8. Ball M, Bruck D (2004) The effect of alcohol upon response to different fire alarm signals. Proceedings of the Third Human Behaviour in Fire Conference (Belfast). London: Interscience Communications, pp 291-302.
9. Bruck D, Thomas IR (2009) Community based research on the effectiveness of the home smoke alarm in waking up children. In: Shields J (ed) Proceedings of the Fourth Human Behaviour in Fire Conference. Cambridge, pp 335-344.
10. Bruck D, Thomas I (2009) Smoke alarms for sleeping adults who are hard-of-hearing: comparison of auditory, visual and tactile signals. Ear & Hearing, 30:73-80.
11. Bruck D, Ball M, Thomas I, Rouillard V (2009) How does the pitch and pattern of a signal affect auditory arousal thresholds? J Sleep Res, 18:196-203.
12. Bruck D, Thomas I, Ball M (2007) Waking effectiveness of alarms (auditory, visual and tactile) for the alcohol impaired. The Fire Protection Research Foundation (USA).
13. Bruck D, Brennan P (2001) Recognition of fire cues during sleep. In: Shields J (ed) Proceedings of the Second International Symposium on Human Behaviour in Fire. Interscience Communications, London, pp. 241-252.
14. Bruck D, Thomas I (2009) Strobe lights versus auditory smoke alarm signals: Effectiveness for waking up selected populations. Ir J Psychol, 30:21-36.
15. ISO/TS 7240-9 (2006) Fire detection and alarm systems – Part 9 Test fires for fire detectors. International Standards Organisation, Geneva.