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# An experimental study on timely activation of smoke alarms and their effective notification in typical residential buildings

Khalid A.M. Moinuddin[a,*], Dorothy Bruck[a,b], Long Shi[a]

[a] Centre for Environmental Safety and Risk Engineering, Victoria University, P.O. Box 14428, Melbourne, Victoria, 8001, Australia
[b] Psychology Discipline, College of Health and Biomedicine, Victoria University, P.O. Box 14428, Melbourne, Victoria, 8001, Australia

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ABSTRACT

The volume of smoke alarm sound in rooms (other than room of sound origin) in real houses and smoke alarm activation time in rooms in full-scale model houses using ionization, photoelectric and dual detector smoke alarms were determined in this study. The alarm sound level measurements indicated that the sound level in many locations is likely to be too low to provide reliable notification, particularly for sleeping people, if smoke alarms are not installed in every room. In addition, changing to a lower frequency (520 Hz square wave) alarm would further aid effective notification of building occupants. The smoke alarm activation measurements showed that the time to detection (given a particular smoke source) was influenced by door position (open versus closed), the room in which the fire occurs, the location (room or hallway) of the detector, the type of detector and the smoke alarm manufacturer. Furthermore time to detection is also influenced by the type and form of the material that is burning. It was observed that photoelectric smoke alarms had the highest incidence of non-activation and when they did activate they, on average, took longer to activate than ionization and dual (ionization and photoelectric) smoke alarms over all smoke sources considered in this study. It is concluded that to achieve early detection and provide adequate notification, smoke alarms are necessary in every room and should be interconnected.

## 1. Introduction

Home fires are still a problem in our daily lives. From 2007 to 2011 United States fire departments responded to an average of 1000 home structure fires every day, and home fires killed an average of seven people per day and caused roughly $28 in damage every second [1]. According to the statistics by Australasian Fire and Emergency Service Authorities Council (AFAC) [2], the residential deaths per 100,000 persons is between 0.1 and 0.7 during 1996–2004. According to The United States Fire Administration [3], the estimation of annual residential building fire deaths in United States is between 2385 and 3050 from 2003 to 2012. According to AFAC [4], the time period when most fire fatalities occurred was during the general sleeping times of 8 p.m.–8 a.m. (72%) in Australia, and the figure increases to 78% in New Zealand with a peak occurring between midnight-4 a.m. (42%). The study of Xiong et al. [5] indicates that one out of four surviving occupants (24.2%) (of relatively minor household fires) were asleep at the time of ignition, while in fires that resulted in fatalities, four out of five fatally injured (80.5%) were asleep.

Home smoke alarm technology has been in use since the middle of the 20th century. According to estimates by the National Fire Protection Association (NFPA) and the U.S. Fire Administration, U.S. home usage of smoke alarms rose from less than 10% in 1975 to at least 95% in 2000, while the number of home fire deaths was cut nearly in half [6]. A working smoke alarm has been reported to reduce the risk of death from residential fires by between 50% and 70% [7,8]. The US Fire Administration reports that more than 88% of the homes in United States have at least 1 smoke alarm installed, but 60% of the residential fire deaths occur in homes without an operational alarm. Analysis of data from the United States Fire Administration's National Fire Incident Reporting System (NFIRS) and the NFPA's fire department survey showed that from 2003 to 2006, no smoke alarms were present in 31% of reported home fires and 40% of home fire deaths [9]. Stated another way, smoke alarms were present in 60% of home fire deaths. Notwithstanding that some of these fatalities may have been caused by explosions or similar close physical encounters with fire, the presence of a smoke alarm is most useful if the smoke alarm is activated quickly by the presence of smoke and the alarm signal is such that people in the dwelling are notified as quickly as possible of the fire. There are basically three different types of residential smoke alarm: the ionization alarm, the photoelectric alarm, and the dual

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* Corresponding author.
*E-mail address:* khalid.moinuddin@vu.edu.au (K.A.M. Moinuddin).

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alarm [7]. Ionization and photoelectric alarms operate via different mechanisms, detecting invisible/fine and visible products of combustion, respectively [10]. Photoelectric alarms use optical sensors and are more likely to respond to slow, smouldering conditions. The working principle of ionization detectors is based on a modified theory which includes soot particle charge fraction functionality in addition to the generally accepted particle size and number density dependence [11]. Smoke alarms of either the ionization type or the photoelectric type are designed to activate quickly and thus provide time for alerted occupants to escape from most residential fires, although in some cases the escape time provided can be short [6].

Many studies have been conducted to analyse the performance of different types of smoke alarms. The Consumers Union in the United States [12] tested ionization and photoelectric alarms in 1994 and found that in a smouldering, smoky fire, the ionization alarms responded in 25–35 min, whereas the photoelectric models reacted in half that time. A statistical study was conducted to compare the performance of different residential smoke detector technologies when exposed to different fire types by Milarcik et al. [13]. The results showed that ionization detectors, on average, respond faster to flaming fires, while photoelectric detectors, on average, respond faster to smouldering fires. They further determined that both technologies provide statistically equivalent warning to different types of fires for the next residential fire occurrence i.e. it cannot be determined with confidence which detector will be activated first to the next fire. Cleary [14] conducted a full-scale fire test series in a building mock-up designed to represent a portion of a small house or an apartment to examine smoke alarm sensitivity. Similar to other studies [12,13], he found that in general the photoelectric alarm responded more quickly in a smouldering fire and the ionization alarm responded quicker in flaming fire configurations. One particular brand of dual alarm was found to register in a faster average time compared to other single and dual alarms. Milke and Zevotek [15], through a limited number of cooking fire tests, observed that an ionization alarm provided a faster response than the photoelectric alarm, but was more prone to nuisance alarm. Bukowski et al. [6] performed comprehensive real-scale tests on the performance of different type of smoke alarms. They arrived at similar conclusion that ionization type alarms provide somewhat better response to flaming fires than photoelectrical alarms, and photoelectric alarms provide (often) considerably faster response to smouldering fires than ionization type alarms. Su and Crampton [16] conducted a series of experimental studies in a residential dwelling as well as in a laboratory room to examine the effect of “dead air space” (i.e. a corner where smoke was thought unlikely to reach) on smoke response. The results showed that smoke can reach the “dead air space” under the experimental conditions and the smoke alarms installed in the “dead air space” can respond to the fire at times comparable to, and in many cases even earlier than, the smoke alarms installed at conventional locations.

Determination of the most appropriate locations for smoke alarms in residential buildings requires consideration of many factors. These include the likely smoke sources (particularly those that are involved in fires resulting in injury or death), detector type, alarm sound and the alarm brand (or manufacturer) because these factors affect either the time taken for smoke detection or the likelihood of the alarm signal alerting people. An alarm signal attenuates as it travels and encounters walls and closed doors. Halliwell and Sultan [17] proposed a simple expression to calculate attenuation of the alarm signal including the effects of floor area and closed doors. It is notable that, in the USA, the NFPA has required smoke alarms in bedrooms since 1993 and interconnection[1] of smoke alarms for new homes only since 1989 [18,19] but some countries, such as Australia, did not have these requirements until early 2014 [20]. Lee [21] examined the feasibility of applying modifications to residential smoke alarms or the addition of secondary devices to improve the sound effectiveness for smoke alarms. He also suggested that the use of interconnected smoke alarms and lower frequency alarm tones may result in improved audibility, especially for older adults. Furthermore, the Australian Standard for emergency notification [22] noted that the sound level of a smoke alarm should be at least 75 dBA at the pillow. It is also important to investigate whether a sound level of this can be achieved with the hallway placement of detectors as specified for houses by the Building Code of Australia (BCA) [20].

Any improvement in fire safety due to changes in building regulations requiring smoke alarms necessitates that people similar to those who are currently killed or injured in fires in dwellings be saved from death or injury in similar fires in the future. Thus improvement requires that people, similar to those currently being killed or injured, notice and act on smoke alarm warnings they currently do not notice, or if they do, they do not act on in such a way as to avoid death or injury. In order to help provide evidence about important aspects of smoke alarms, a comprehensive experimental investigation on smoke alarms in typical residential buildings was conducted in this study. It covers the five distinct aspects of (1) type of detector (ionization/photoelectric/both) and time to activation, (2) location of the smoke alarm and time to activation, (3) fuel types and time to activation, (4) volume of the smoke alarm signal in different rooms and (5) comparison of the volume of different signals in different rooms. The first three aspects were studied in full-scale replica model houses using a range of fuels, while the latter two aspects were studied in real (occupied) homes. The information from this study can be used to inform an estimate of the changes in fatalities that would occur if smoke alarms in every room and/or interconnected smoke alarms were required by revised building regulations. The study is unique in combining both consideration of the measurement of sound levels and measurement of activation times of smoke alarms to smoke within dwellings of the same size and dimensions. This combination supports the idea of analysing the smoke alarm in a real world home setting as a single system. It is to be noted that to calculate escape times prior to reaching untenable conditions, there may be delays based on fuel, alarm type, room of origin, room of alarm, etc., beside activation times. Irrespective of whether those delays are short or large, this study is not intended to address whether the alarms are providing enough time for escape.

## 2. Methodology

### 2.1. Smoke alarm sound level tests

The houses used in the experimental investigations were intended to represent typical Australian houses. Three were single storey and one was of two storeys above ground. No houses had basements. Anecdotal evidence suggests that they represent typical Australian houses. Plans of the houses are included in Fig. 1. The houses are numbered from 1 to 4 to allow identification of particular houses, shown in Table 1. House 4 is a two storey house.

The sound level in each room was measured with various combinations of doors open and closed in the four real furnished houses. Two sounds at set levels were emitted from likely smoke alarm positions in each room of sound origin (RSO), generally close to the middle of the ceiling, and in each hallway. The recorded smoke alarm sounds were emitted from a large speaker at 85 and 105 dBA sound levels measured 1 m from the speaker. Lower sound levels were measured at other locations in the RSO, but these measurements do not form part of this study. It is to be noted that AS 1670.1 [22] requires that the sound levels should not be less than 85 dBA and not more than 105 dBA. Similarly UL985 [23] has a requirement of 85 dB at 10 feet for residential sounders which would be around 95 dB at 1 m.

The sounds used were the ~3100 Hz sound currently used in Australia in domestic smoke alarms and the 520 Hz square wave sound,

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[1] Interconnection means all available smoke alarms are interconnected wirelessly (via RF module) or hard-wired and activation of one smoke alarm will cause activation of all interconnected smoke alarms.