

Consideration of Domestic Smoke Alarms as a System

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Introduction

This paper reports on one aspect of a recent literature and statistical study of domestic smoke alarms that set out to answer questions such as: “Which is best?” and “How effective are they in Australia and New Zealand?”

The fire brigades in Australia and New Zealand wanted to update their advice on:

- the need for domestic smoke alarms
- the most appropriate type(s) of alarms for use in dwellings
- where they should be located
- how effective they are in reducing occupant fatalities and injuries

Not all aspects of the report will be covered in this paper. This paper concentrates on consideration of domestic smoke alarms as a system that is designed, installed and hopefully maintained for specific purposes that are discussed below.

In the context of this paper *domestic* refers to smoke alarms that are intended for use within single dwellings, whether the dwelling is a separate building or a dwelling within a building containing other dwellings or other occupancies. Additional smoke or fire alarms might be required in these more complex buildings to notify occupants of a particular dwelling of smoke or fire detected elsewhere in the building, but those alarms are not covered here.

The study was based on a systematic analysis of a system intended to warn asleep or awake occupants of any fire with the objective of making the occupants aware of the fire and allowing the occupants to safely react to the fire. It was recognised that the actual smoke alarms are not the whole system, merely one part of a system that when considered in detail is revealed to be surprisingly complex. This paper presents an overview of this analysis and of the structure of the conceptual system developed.

It is possible to conceive of benefits other than the safety of the occupants that might be obtained from the use of domestic smoke alarms in a dwelling, and it would be possible to add them as additional objectives for the system. However, for simplicity, benefits such as reduced damage to the contents and the structure are not added to the objectives considered herein, such possible outcomes are considered here to be *collateral benefits* and are not considered further.

A wide range of fires occur within dwellings. Historically, fires have occurred in every room and space and have involved every type and form of combustible material that occurs within dwellings. Thus a very wide range of locations and types of fire can occur. In considering domestic smoke alarms two particular types of fire are often mentioned: smouldering fires and flaming fires. Smouldering fires are generally considered to produce a sufficient quantity of smoke to be of concern, at least in some circumstances, but very little heat; while flaming fires produce heat, but sometimes a relatively small quantity of visible smoke. More detailed consideration of the quantity and characteristics of the smoke produced by fires, whether smouldering or flaming, is beyond the scope of this paper. Smoke, when considered below, will be simplistically considered as either being from

smouldering fires, flaming fires or fires of either type. In the following when a fire is referred to without the qualification smouldering or flaming, it is assumed it may be either.

While this paper deals with domestic smoke alarms as a system it needs to be remembered that the smoke alarm system is usually only part of a comprehensive fire safety system even in the domestic environment. The fire safety system may incorporate smoke alarms but it may also incorporate a wide range of other components including, for example:

- a plan and action intended to reduce the ignition of unwanted fires
- a plan of action to be undertaken upon the occurrence of a fire (whether the plans are documented or not)
- means of extinguishment, training
- the provision of more than one exit from an area

Components of a Domestic Smoke Alarm System

The smoke alarms used in domestic smoke alarm systems are usually purchased as individual self-contained units. They may be entirely self-contained, being powered by a battery within the unit, or they may be mains powered and thus require connection to the electrical wiring of the dwelling. They may also be capable of interconnection so that activation of one alarm will actuate the warning device in connected alarms. Nevertheless smoke alarms themselves may be considered to consist essentially of two components, a *detector* and a *sounder*.

The *detector* is, in some way, triggered by outputs of the fire to be detected, though it may also (unfortunately) be triggered by similar phenomena not resulting from a fire. It is, of course, desirable that the second method of triggering is minimised to reduce the occurrence of false, or as they are sometimes called, nuisance alarms. These occurrences should, in an objective analysis of a smoke alarm system, be considered to constitute a failure of the system.

The *sounder* is intended to be activated when the *detector* is triggered. Its sole purpose is to make occupants of the dwelling aware of the fire.

The domestic smoke alarm system as conceptualised incorporates (Figure 1):

- the fire
- the physical environment
- the smoke alarm(s)
- the human occupants of the dwelling

The arrows in Figure 1 reflect the influence each component of the system can have on the other components up to the point that the occupants become aware of the fire by whatever means, at which point the smoke alarm system has served its purpose or was not actually needed in this instance. In principle, it is assumed that the smoke alarm will provide warning of a fire. In many cases, if the occupant is awake and close to the fire they may become aware of the fire without needing to be alerted by a smoke alarm. However, if the occupant is remote from the fire or is close to the fire and asleep, they may need the sound from a smoke alarm to become aware of the fire (although even in these situations in some cases they will become aware of the fire without needing the smoke alarm). In these cases the proximity of the occupant to an operating alarm sounder and the proximity of a detector to the fire are likely to significantly influence the effectiveness of the smoke alarm system in detecting the fire quickly, in making the occupants aware of the fire (and safe) as illustrated in Figure 2.

The arrows in Figure 1 also reflect recognition of the fact that interactions occur before and during the fire. The physical environment of/in a dwelling is partly a result of the architectural and structural design of the dwelling but it is also a result of the capabilities, attitudes and behaviour of the

occupants. For example, put simplistically, the amount and composition of furniture in any dwelling will vary according to an individual's personal taste and financial capabilities. Similarly, the condition of the smoke alarm is at least partly a reflection of the capabilities, attitudes and actions of the occupants. Different individuals will have varying capacity to appropriately select, purchase and maintain smoke alarms that is based upon their level of awareness, and their cognitive, physical and financial capabilities. As a consequence the occupants have an influence on the probability of occurrence of a fire, the type of fire, the location of the fire, the availability, type and quantity of fuel, on the condition and operation of smoke detectors, etc.

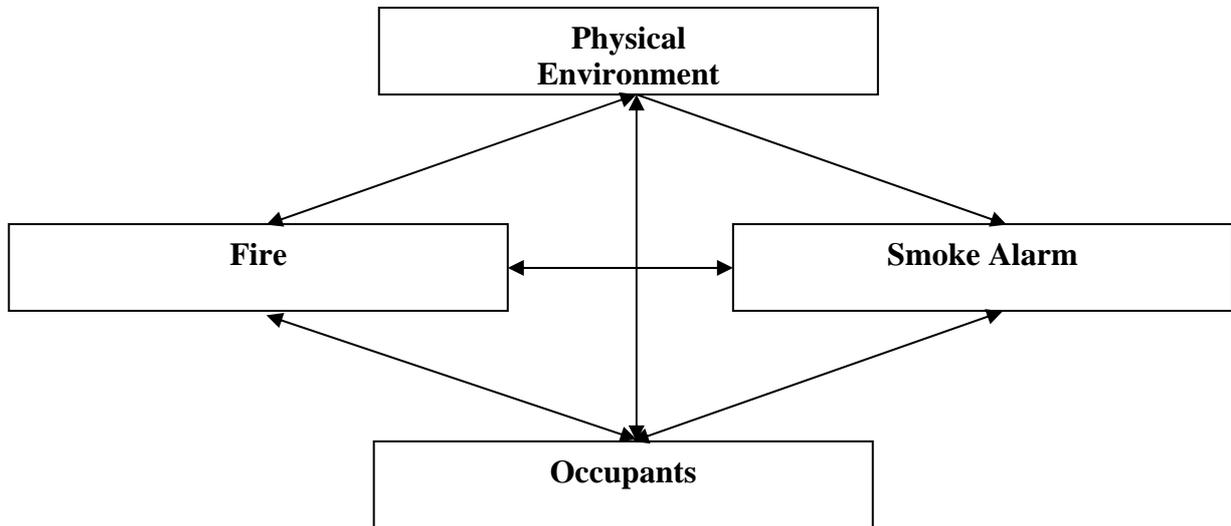


Figure 1 Components of Conceptual Domestic Smoke Alarm System

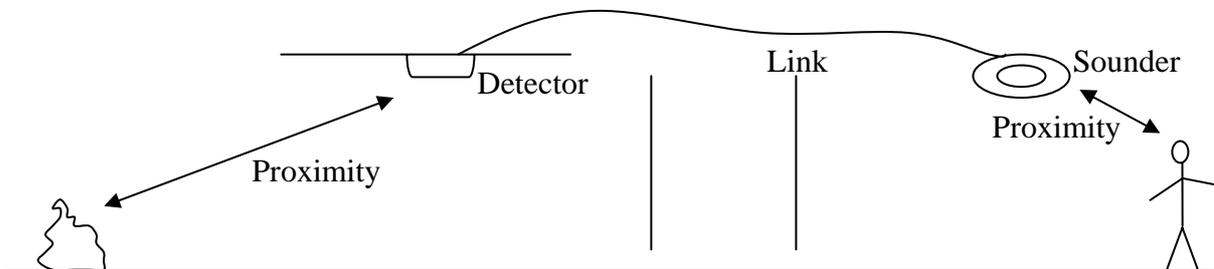


Figure 2 Proximity Considerations

Similarly, the physical environment affects the fire. For example the types and forms of fuel available and the ventilation conditions affect the fire. The fire itself may also affect the physical environment although these effects might not be expected to be major (in changing the geometry or ventilation, etc) during the period before smoke alarms operate. In turn the changes in the physical environment may affect the development of the fire, for example, increased ventilation may accelerate fire growth.

The components of a domestic smoke alarm system shown in Figure 1 are considered in more detail in Figure 3 and in the following sections.

Occupants (Before Fire)

The actions of the occupants over the long term prior to a fire are likely to affect the likelihood of a fire and the environment in which the fire takes place in that they affect the condition of the dwelling, its fittings and contents including the components of the smoke alarm system, and, indeed, whether there is a smoke alarm system at all.

The condition of the dwelling and the type and condition of furnishings and other contents are likely to be influenced by occupant characteristics such as age, income, source of income, their physical, cognitive and emotional condition, and many others. The occupants are also likely to strongly influence the probability of an unwanted fire, the occurrence of possible sources of ignition of such fires, the availability and quantity of combustible contents, etc (eg a smoker's risk of causing a fire is greater than a non-smoker's, a cluttered environment is likely to provide more fuel than a non-cluttered environment).

In addition to their long term behaviour the actions of the occupants immediately prior to the ignition of a fire will also influence the system and the likely outcomes. Important aspects include:

- whether they were directly involved with the ignition of the fire
- were intimately involved in the fire at or immediately following ignition
- where the fire begins

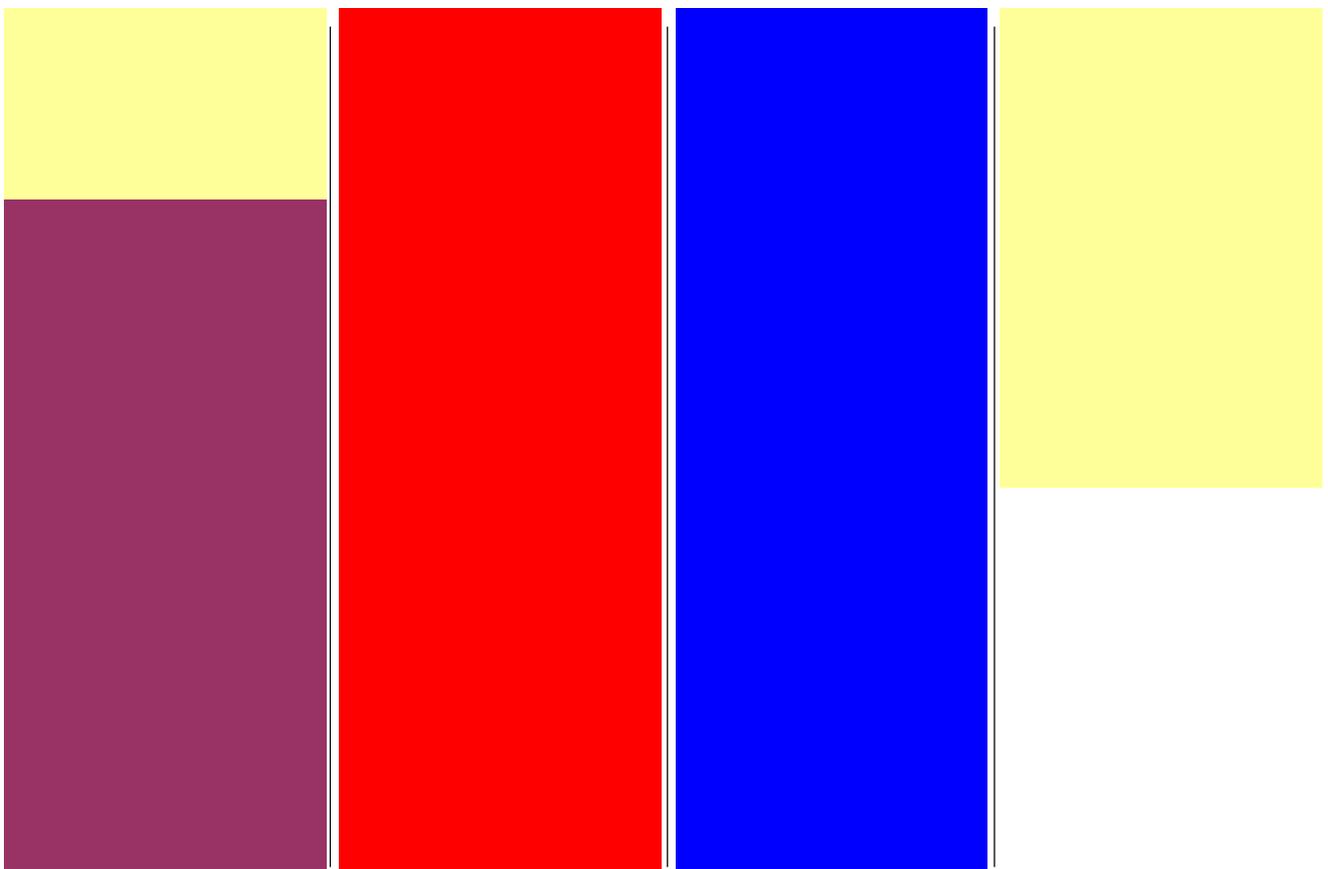


Figure 3 Details of Conceptual Domestic Smoke Alarm System

Physical Environment

The physical environment in the area of fire origin is obviously of great importance as it may greatly influence the development of a fire and the smoke produced, etc. Many of the characteristics of the environment are largely related to the type of room (or other space). For example, a fire in a kitchen is likely to involve sources of ignition and fuels different to those in a fire in a lounge or bedroom.

The geometry of the room of fire origin (length, width, ceiling height), the number and dimensions of doors and windows and whether they are open or closed, the characteristics of the ceiling (flat or sloped, exposed beams, etc) is likely to influence the fire itself but also may influence the movement

of smoke and time of detection for a given smoke alarm. The ventilation of the fire and time of detection may also be influenced by the effects of air conditioning, ducted heating, a ceiling fan and possibly external weather conditions. The latter, in addition to the obvious effects such as wind, can also influence whether and to what degree doors and windows are open.

The overall layout of the dwelling, the connection of the room of fire origin to other rooms, hallways, stairways, whether the dwelling is single or multiple storeys obviously may influence the movement of smoke and even the fire around the dwelling.

Possibly of greatest importance in relation to the physical environment and its effect on the occurrence and development of a fire are the furnishings and other contents of the room of fire origin. Obvious parameters such as the type and quantity of furnishings and the materials used in their construction and decoration may greatly influence the rate of fire development and smoke production.

Fire

The type of fire as reflected in the rate of growth, the maximum heat release rate, the rate of fire spread, the quantity and characteristics of the smoke produced is influenced by ignition factors such as how the fire was ignited and the type and form of material ignited. Fires are often simplistically classified using terms such as smouldering, flaming, smoky, etc.

The term *ignition factor* is used in fire statistics systems (such as NFIRS) for a mixed classification that includes an indication of who was involved (children playing, etc), the means of ignition (smoking materials, etc) and other considerations.

The *means of ignition* often has a strong correlation with the location (kitchen, lounge, bedroom, etc) and may have a great influence on the type of fire. So do the *type of material ignited* (solid, liquid, gas, etc) and the *form of material ignited* (flimsy fabric, floor covering, furniture, etc). The likelihood of ignition, rate of growth and other characteristics of the fire are likely to be greatly influenced by these factors.

The products of the fire in the smoke are important because they provide means of detection of a fire that can be used to distinguish a fire from other phenomena that can trigger a smoke alarm. These include CO, CO₂, soot, reduced visibility, heat (changed/changing temperature), flames, etc. Unfortunately in some physical environments there are other sources of the same products. This means that care needs to be exercised in choosing means of detection that are appropriate for the particular location, and even when this is done, some difficulty in distinguishing fires from other occurrences may occur.

Smoke Alarm(s)

There are two aspects of the location(s) of smoke alarms that are important: their location relative to that of the fire and their location relative to that of the occupants. It is obvious that this potentially leads to opportunities to separate the detector(s) from the sounder(s) and to optimise the location(s) of each of them. In the following it will be assumed that the detector(s) and sounder are not separated, that is, are contained within the one unit. However, the possibility of interconnection of several smoke alarms is considered.

A number of aspects are presumed to affect the reliability of smoke detectors. Perhaps the most obvious of these is the power supply for the detector and sounder. Many are battery powered, but it is often assumed (not necessarily accurately) that the connection of smoke alarms to mains power increases their reliability, particularly as such smoke alarms are usually also fitted with battery backup. The assumption of increased reliability may be little more than an assumption if there are other aspects

of detector maintenance that are equally important – for example, keeping them free of dust, not covered or painted, etc or simply not disabling them because of frustration at *false* (sometimes more kindly referred to as *nuisance*) alarms.

The type of detector used in a smoke alarm is known to affect the time at which a detector in a given position will be activated. A wide range of detectors is possible (ionisation, photoelectric, CO, heat, temperature, combinations of these) though two types are most common at present (ionisation and photoelectric). Each type of detector varies according to the specific product of the fire to which they are sensitive. Therefore use of specific detectors to improve the reliability (fewer false or nuisance alarms) in specific locations is possible as some are better at detecting (or more reliably detecting) the type of fires that most frequently occur in some locations and similarly some are less likely to falsely alarm as they are less sensitive to emissions from non-fire occurrences that occur in some locations (steam, rapid temperature rise, etc).

Detecting the fire is one essential part of the operation of smoke alarms, making the occupants aware of the fire is the other. This requires the use of some sort of signal that most occupants will become aware of quickly whether they are awake or asleep. Traditionally such signals have been provided by sounds but strobes are used in some countries for people with hearing difficulties, and other signals such as pillow or bed shakers (that is, mechanical vibration) are sometimes used, particularly for the hard of hearing.

Whatever the warning signal there are a number of parameters that can be varied. If it is recognised that occupants of the building(s) will vary in their ability to become aware of a given signal, then variation of these parameters is likely to affect the proportion of occupants that will respond to a particular smoke alarm. Signal parameters of interest include the volume or intensity, the pitch or frequency, the pattern, etc.

One way of mitigating the problem of having very loud noises in some areas (where the smoke alarms are located) but much softer noises in the areas where, for example the occupants sleep, is to provide more alarms and interconnectivity between them. The intent of interconnected alarms is that the detectors are in appropriate places but the warning is given at high volume at locations of greatest need, for example in places where the occupants sleep. Interconnection can now be achieved by connection using wires or by wireless technology. However, it should be noted that the additional components and capability may reduce the reliability of the system by providing more points at which the system can fail

The reliability of smoke alarms considered as a system is not entirely straight forward. The usual and most obvious measure is whether an alarm detects a fire and sounds a warning at the specified intensity. But reliance on this as a measure would fail to appreciate and accommodate the smoke alarm system as a whole. Analysis and estimation of the reliability of the system needs to include consideration of a wide variety of factors, for example false alarms. If false (or nuisance) alarms occur with sufficient frequency to cause the building occupants to disable the alarm or to, in some way, desensitise it to certain types of smoke, then the operation of the alarm system may be compromised. Thus false alarms should be considered a failure of the smoke alarm system. Similarly, if the smoke alarm requires care and maintenance that is burdensome or excessive on the part of the occupant then this also is likely to lead to failure to properly care for or maintain the alarm, and therefore should also be considered as contributing to failure of the system.

Occupants (During Fire)

The role of occupants in the smoke alarm system during a fire is as a receiver and user of the smoke alarm signal. Once the occupant hears the signal, they need to recognise it for what it is and react to it appropriately – actions may include evacuating, investigating or warning or assisting others. Their

ability to do this will vary depending on their state of consciousness (conscious/unconscious), state of sleep (awake/asleep). If they are conscious and awake or initially asleep and waken in response to the signal, their cognitive and physical ability to plan and undertake whatever action is appropriate, perhaps very quickly, may be a key factor in achieving a successful outcome. Their ability to react to the signal will also depend on their location compared with the location of the sounder and the other cues or information they perceive. In general, it is reasonable to assume that the further they are from the sounder, the higher the probability they will not hear it, and the further they are from the detector the higher the probability that other fire cues will not be perceptible. Importantly, if the alarm sounds but the occupant fails to respond to it, *the system has failed* (even though the smoke alarm itself has emitted the signal).

There are a number of reasons (other than excessive distance to the sounder or detector) why the occupant may fail to act or not be able to receive or recognise the signal. Some of these are endogenous factors, which means they are characteristics of the person or arise from within the person. These might include disabilities such as being deaf or having a cognitive impairment, having a physical disability or, more simplistically stated, being too young, too old, etc.

The reason may also be associated with other factors affecting performance, such as alcohol or drugs, etc, which may not only affect their ability to hear the signal, it may also affect their speed of reaction or their ability to react appropriately at all^{1,2}. These are exogenous factors, or those that occur due to external causes.

The individual's interaction with the environment can also be important. For example, the general noise level in the environment may affect the occupant's ability to hear the alarm signal and other conditions in the area at the time may affect their ability to react effectively^{2, 3, 4} and without error (eg power failure, too dark, smoke too thick, unexpected objects blocking path, etc).

If the occupant hears the alarm signal but deliberately ignores it ("fails to act appropriately") then the system has failed, whatever the reason for this action. This is particularly (but not only) the case if this behaviour is *a learned reaction* due to previous experience with false alarms (habituation), etc. If the signal to the occupant occurs too late for the occupant to react successfully (either because the signal is too late or because the occupant is unable to react quickly enough) again the system has effectively failed. If the signal is too late for anyone to react successfully then clearly this indicates a problem with the smoke alarm that may be associated with smoke alarm sensitivity to the particular type of smoke and therefore the particular type of fuel involved or something similar. If the problem lies with the ability of the person to react quickly enough, perhaps because of age, illness or disability, then the appropriateness of the device used, or the appropriateness of an alarm system in general, needs to be questioned.

Analysis of Effectiveness of a Domestic Smoke Alarm System

Many of the factors that influence the effectiveness of smoke alarm systems particularly in relation to their effectiveness in reducing occupant fatalities and injuries resulting from fires in dwellings are fairly obvious, but some are not. The obvious factors include the speed of response of the detector(s) (the usual focus), the reliability of the detector in responding to and accurately identifying actual fires, and the volume of the signal (sound) emitted. Less obvious factors include:

- the number of alarms in the dwelling
- their positioning in relation to the fires most likely to result in occupant fatalities and injuries
- their positioning in relation to the likely locations of occupants most likely to be injured or killed
- their positioning in relation to the likely locations of occupants most likely to be able to respond to the alarms appropriately
- the influence of the occupants on the operation and reliability of the smoke alarm(s)

- the ability of occupants to become aware of the signals emitted by the alarm(s) and to react to them appropriately

Dealing with the obvious factors first:

- speed of detector response
- reliability of detector in responding to and accurately identifying real fires
- volume of sound emitted

There is always a tension between the first two of these points. In general the more sensitive the detector the quicker the response but the more likely it is to generate false alarms. Thus a balance has to be struck between sensitivity and avoidance of false alarms, and there will inevitably be compromise involved. Another way of treating this issue is to require activation of more than one detector but again this is likely to lead to some delay compared to the response possible with just the fastest detector.

It is widely recognised that the volume of the sound emitted affects the ability of people to hear it. It is less often recognised that this implies that whatever level is set **determines** (along with other factors) the proportion of the population that will **not** hear or recognise the alarm. Again there is compromise involved because as the level increases a greater proportion of the population will be discomforted and potentially even harmed by the noise. It is arguable that these effects should be ignored because it is easy to mitigate the loud noise by moving away or covering ears, etc (this assumes a person with sufficient capacity to react appropriately). Other characteristics of the signal that govern the proportion of the population that will not hear or recognise it have been mentioned above. These include the frequency(s), and the pattern of sound emitted. The choice of certain frequencies is now known to affect the proportion of the population that will not hear or recognise the alarm signal. It is less certain that the pattern of sound will also affect this but it appears likely that it will. This is because the signal emitted needs to be immediately recognisable for its purpose, and not confused with other environmental sounds. It should be noted that there may be other factors about the signal that will have a similar effect that has not yet been recognised.

Returning to the less obvious factors, the first of these, the number of alarms in the dwelling may be considered by some to be obvious, but the fact that in many jurisdictions the number of alarms is not specified and the fact that no balance between number of alarms and their placement and the volume of sound, etc is included in codes or recommendations indicates that this is not so. It appears obvious that, in general, more is better, likely to bring about earlier detection and, for a given detection level, the more likely the alarm is noticed. However, more is also likely to increase the rate of false alarms and other failures of the system (simply because of more components) and is also likely to increase the level of frustration and annoyance with false alarms and maintenance, and a greater degree of habituation to the signal. It is also likely to bring about greater cost and greater time and effort in installation and commissioning. In relation to maintenance, it appears likely that, in general, less required maintenance would lead to improved alarm reliability. Thus, for example, it is often assumed that mains powered alarms are likely to be more reliable than battery operated alarms. This is probably correct but assumes that the mains power and battery backup (maintained less frequently) are sufficiently reliable and that there are no other maintenance requirements (cleaning, for example) that are neglected as a consequence of less frequent battery checks.

The positioning of alarms is important when it is considered that this could affect the likelihood and speed of detection of fires in certain locations. In terms of saving lives and injuries, it is obvious that it is best to detect quickly those fires that most frequently result in fatalities and injuries rather than for example, other fires that occur (perhaps even more frequently) but that result in fewer fatalities and/or injuries. Thus the location of detectors is an issue.

Equally important is the positioning of sounders in relation to the likely locations of occupants most likely to be injured or killed. There is little point in warning occupants in locations where few people are killed or injured. Similarly, their positioning in relation to the likely locations of occupants most likely to be able to respond to the alarms appropriately is important. For example, the possibility of fires in children's bedrooms might indicate that it is appropriate to place detectors there, but it might be more appropriate to place sounders in parent's bedrooms, or even kitchens or lounge rooms, than place them in the children's bedrooms because it may be more likely that the parents will act quickly and appropriately than young children.

Clearly the occupants of a dwelling exert a strong influence on the likelihood of fires, the type and location of fires, and on the maintenance and continuing operation (reliability) of smoke alarms. Many of the factors involved have been mentioned above and will not be repeated here.

It is appropriate to raise again the ability of occupants to become aware of the signals emitted by the alarm(s) and to react to them appropriately. Again the example of children and parents is a useful example, although it is not the only case worthy of consideration. It has been shown that children are much less likely to awaken to a smoke alarm signal than are adults, consequently it is, in principle, better to provide the signal to the parents, rather than the children. Provided it is considered likely that the children will react appropriately given that they do notice the alarm, then it would be better to provide the signal to both the children and the parents.

Considerations for the Specification of a Domestic Smoke Alarm System

Much of the analysis above is relevant to consideration of standards for smoke alarms themselves and for regulations requiring and specifying details of their use in dwellings.

The analysis reveals that specification of the level or strength of the signal, the location of the detector(s) and signalling device(s), details of the type of signal specified (eg for sounds: the frequency(s), pattern(s), etc of the sounds) to a large degree determines the proportion of the population that would **not** be aided by the specified smoke alarm system. Currently available information does not allow accurate estimation of the extent of the population that might not be aided by the currently specified smoke alarm systems.

Similarly, specification of the number and locations of alarms to a large degree determines the proportion of the population that would **not** be aided by the specified smoke alarm system. Again, currently available information does not allow accurate estimation of the extent of the population in that category.

The domestic smoke alarm system as laid out in this paper is necessarily complex. It is a fact of life that the more complex a system, the more potential there is for it to break down. The purpose of conceptualising the system is to highlight these for the purpose of uncovering areas that would benefit specifically from future research, and to work towards minimising the effect of known risk factors.

Some the reasons a domestic smoke alarm system might fail to save the occupant(s) of a residential building (given that the occupant(s) have not already become aware of the fire by other means) include:

- the occupant is intimate with the fire at ignition
- the smoke alarm fails to operate at all
- the smoke alarm **fails to detect the fire** early enough for an occupant to avoid being killed or trapped so that escape is not possible
- the smoke alarm fails to sound an alarm

- the smoke alarm fails to sound an alarm loudly enough for an occupant to become aware of it early enough (or even at all) before an occupant is killed or trapped so that escape is not possible
- the occupant fails to hear the smoke alarm (even though it is loud)
- the occupant fails to recognise the smoke alarm
- the occupant fails to (or cannot) respond to an alarm they do hear and recognise
- the occupant fails to respond quickly enough to an alarm they hear and recognise
- the occupant responds to an alarm in a way that, in hindsight, can be termed very risky or inappropriate
- despite responding appropriately the occupant is unable to avoid the fire because their path is blocked in some way

It is clear from this discussion that detection of smoke is only the first step in successful operation of a domestic smoke alarm system. The system may fail to achieve the objective of occupant safety if *any* of the reasons mentioned above occur.

In considering many of these possibilities it is important to answer a key question: what proportion of the population will **not** respond to particular alarm signals? But this question should be refined further. It is not really the proportion of the general population who will or will not respond to alarm signals that is important, it is the proportion of the *at-risk* population (the people who actually need most help from smoke alarms, etc) that needs to be determined, and it is these people who need to be considered when standards are set.

Characteristics of the at-risk population have been identified in many studies. But perhaps the most poignant such listing of the at-risk population, at least in Australia, is from a recent as yet study of Coroner's Court records of adult fire fatalities that occurred in Victoria, Australia over the five years from January 1998 to February 2005. Of the 101 adult fatalities of accidental (not suicide or homicide) domestic building fires:

- 53% were smoking a cigarette prior to ignition
- 55% were mentally ill
- 59% were a cigarette smoker
- 66% were asleep at time of ignition
- 71% were male
- 71% were intimate with ignition
- 75% had alcohol or drugs in bloodstream
- 80% were alone at ignition
- 82% were not in paid employment (including retirees)
- 84% did not have a working smoke alarm

Most of the fatally injured people had more than one, and most, several of these characteristics. In considering these people as both the subject of the fire alarm system and as being involved in the system for its successful operation, it becomes obvious that their capabilities and needs that must be considered in designing the system.

Some of these characteristics appear to be different to those identified from USA fire data by Hall⁵. For example, Hall states that 28% of fatal home fire victims had some sort of disability, age-related limitation or impairment (by alcohol or other drugs) before the fire began. This appears to be a substantially lower percentage than obtained from the Melbourne data. This means that there *may be* differences in the optimum design of smoke alarm systems for the two countries because the population risk profiles *may be* different.

Conclusion

A domestic smoke alarm system is revealed by the analysis above to be a complex system the effectiveness of which may be greatly affected by the specification of the system in standards and regulations. More data is required to enable accurate estimation of the proportion of the population that will not be aided by particular characteristics (such as sound level, pitch and pattern and the number and locations of alarms) and for optimisation of the effectiveness of smoke alarms.

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