STUDY

Smoke alarm efficiency

Waking sleeping occupants

Fact box

Smoke alarm efficiency – Waking sleeping occupants

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A literature survey was conducted to study available research connected to wakening of sleeping people from the sound of a smoke alarm. The nature of the signal can have a large impact on who will be woken by a common smoke alarm, and there are alternative solutions that can be expected to be more efficient. The effect on the sound attenuation from typical building materials has also been studied.

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Summary

A literature survey was conducted to study the available research connected to wakening of sleeping people from the sound of a smoke alarm. The effect on the sound attenuation from typical building materials has also been studied.

While the common high frequency signal used in residential smoke alarms will wake up most unimpaired adults, is not the most efficient alarm type to awaken certain groups of the population. Children, elderly and people influenced by alcohol or medicines that affect sleep belong to the group at risk of not being awaken by the sound of the common smoke alarm.

A 520 Hz alarm signal have been shown to efficiently wake up the general population as well as people at risk. This signal has also been shown to maintain its sound level more efficiently when transmitted through and via ordinary building components in dwellings.

For this reason, it is recommended that product documentation related to the CE-marked smoke alarm should include both minimum sound output (dB(A)) as well as describing the tone (e.g. frequency) in order for the consumer to be able to make an informed choice that fits their needs.

1. Introduction

1.1 Background

The Swedish Civil Contingencies Agency (MSB) has a general advise on fire alarms in housing and is also behind the joint-industry recommendations about smoke alarms in dwellings [1,2]. MSB also participates in smoke alarm standardisation work in which knowledge about the state-of-the-art research is important.

1.2 Objective

The main objective of this report is to present information from relevant research related to the sound level of smoke alarms, and to attempt to answer the following questions:

- What sound output (volume) is required to awaken sleeping persons?
- Which sound pattern is most suitable to awaken sleeping persons (continuous signal, pulsating signal, voice signal)?
- How is a person's ability to register different sound frequencies affected by age?
- What different challenges can persons with hearing disabilities experience with regards to the sound from the smoke alarm (e.g. the ability to perceive different sound frequencies), and what is their need for alternative solutions?
- To what extent will typical indoor walls and doors in Sweden between rooms attenuate sound?

1.3 Scope

The main focus in this report is on the requirements related to alarm signal referenced in EN 14604:2005, i.e. smoke alarms intended for dwellings or similar residential applications.

The study investigates the ability to awake sleeping people, even though smoke alarms can be useful for occupants that are awake also.

Smoke alarms comprise two main components; smoke detector and an alarm sounding device. The function of the smoke detector will not be covered in this report.

1.4 Method

A literature study has been conducted, with the aim to collect information about the ability of different alarm sounds to awake sleeping occupants. Different aspect that affect how people register alarm sounds have been investigated.

Different standards databases have been searched. (standard.no, enav.sis.se, nfpa.org/Codes-and Standards)

ScienceDirect and Google Scholar have been searched for relevant research publications using the following main keywords:

- Smoke alarm
- Fire alarm
- Alarm sounder sleeping
- Pressure level fire alarm
- Sound attenuation fire alarm

2. Terminology

Table 2-1 below presents terms and their description as they are used in this report.

Table 2-1 Terms and description as used in the report.

Term	**Description**
Alarm condition	Audible signal specified by the manufacturer as indicating the existence of a fire [3,4].
A-weighted sound pressure level	Sound pressure level, expressed in dB(A), which is 20 times the logarithm to base ten of the ratio of the A-weighted sound pressure level to the reference pressure of 20 µPa at 1 kHz [5]. This is the sound pressure level when taking into account the attenuation and the perception of the human ear [6].
Harmonized standard	A harmonized standard is a European standard developed by a recognised European Standards Organisation. Manufacturers, other economic operators, or conformity assessment bodies can use harmonized standards to demonstrate that products, services, or processes comply with relevant EU legislation [7].
Interconnectable smoke alarm	Smoke alarm which may be interconnected with other smoke alarms to provide a common alarm condition [4].
Sound	a) acoustic oscillation of such character as to be capable of exciting a sensation of hearing. b) sensation of hearing excited by an acoustic oscillation or vibration [8].
Sound output	Term used for characterizing the sound with regard to sound pressure level and sound frequency [3].
Sound pattern	Pre-defined acoustic alarm signal, also referred to as tone [5].

Table 2-1 continued

Term	Description
Sound pressure level	Sound pressure level is the difference between average local pressure and the pressure in the sound wave. The sound pressure level is adjusted by means of volume control [5].
Square wave sound	A square wave is a wave form where the frequency first rises sharply, then becoming flat, to then drop sharply to zero, thus creating a rectangular form. With the same duration at minimum and maximum a square wave is formed [9,10].

3. Requirements and national recommendations

For a quick smoke detection and efficient activation of smoke alarms, they should be positioned close to the fire. To be able to warn people efficiently the sound from the alarm must be easily heard. Based on a study covering fires in Sweden between 1999-2013, the room of fire origin for fatal fires was identified as the living room (27 %), followed by the bedroom (22 %) and the kitchen (18%) [11]. In Norway, similar results are shown by studying fatal fires between 2005-2014: living room (37 %), kitchen (18,8 %), bedroom (12,7 %) [12]. The most common room for fire origin for residential fires in Sweden in general was identified as the kitchen (27 %) followed by the chimney (19 %) and living room (8 %) [11]. Hence, based on common fire start rooms, it can be recommended to place smoke detectors near the kitchen, living room and the bedroom. Smoke alarms should in general not be placed in the kitchen, in order to avoid nuisance alarms due to normal cooking fumes. However, if more suitable detection principles are used, efficient detection without nuisance alarms can be achieved in kitchen areas as well [13].

From the location of the smoke alarm, the sound should be able to efficiently awake occupants where they sleep. A common recommendation is to place at least one smoke alarm at each floor, and at least one for each 60 m^2, but preferably one smoke alarm in or in connection with each bedroom in the dwelling [14,15].

As the best location for a detector is not necessarily the best location for the alarm device, interconnected multiple smoke alarms are recommended [16].

According to recommendations from MSB, smoke alarms should be designed according to the standard EN 14604. Further it is recommended that there should be at least one working smoke alarm at each floor in a dwelling. The smoke alarm should be placed according to the manufacturer's instructions, in a way so that a fire can be detected early and so that sleeping persons can be awaken by the signal. The placing of the smoke alarm should consider the floor plan of the dwelling, and the distance between smoke alarms should not exceed 12 metres. It is also stated that a smoke alarm normally covers approximately 60 m^2 [1].

The Swedish National Board of Housing, Building and Planning (Boverket) have similar advice and states in addition that smoke alarms should be placed in or just outside of each room intended for sleeping. Where there is a stairwell, smoke alarms should also be placed directly above the staircase [17].

According to the Norwegian regulations on technical requirements for construction works, buildings shall have equipment for early fire detection in order to reduce the time needed for evacuation. Domestic smoke alarms can be used in residential houses, using one smoke alarm per floor, and the alarms shall be installed so that the sound output is at least 60 dB in living rooms and bedrooms when the doors between the smoke alarm and the rooms are closed. The smoke alarms must fulfil the requirements int EN 14604:2005 or have a detector that fulfils EN 54-7:2000 and a sounder according to EN 14604:2005 [18,19].

4. Smoke alarms –standards

The following chapter summarizes and describes requirements in standards on domestic smoke alarm, relevant for the objective of this report in which the harmonized standard EN 14604 forms the basis.

EN 54-3 is referenced in EN 14604 regarding how the sound level of the alarm should be tested.

NFPA 72 is described, as this standard includes requirements for smoke alarms that are specifically aimed at those with hearing loss.

4.1 EN 14604:2005 Smoke alarm devices

EN 14604:2005 [3] is a harmonized standard for requirements connected to smoke alarm devices. Test and criteria for sound output are given in section 5.17 of the standard, which entails sound level and frequency.

When verifying the design of the smoke alarm the sound level is measured 3 m from the device, either in front of it or at an angle specified by the manufacturer within 45° of this. The measurements shall be made in free field conditions to minimize the effects of reflected sound energy. The ambient noise level shall be at least 10 dB(A). Free field conditions can be obtained through testing to specified conditions outdoors, as well as testing in an anechoic chamber.

The sound output from battery powered alarms shall be at least 85 dB(A) at 3 m after 1 minute of alarm operation and at least 82 dB(A) at 3 m after 4 minutes of alarm operation. The sound output from mains operated alarms is required to be at least 85 dB(A) after 4 minutes of operation. The maximum sound output from both variants is 110 dB(A) at 3 m after 1 minute of alarm operation, and the maximum nominal frequency of the sound shall not exceed 3500 Hz.

EN 14604:2005 does not specify the type of signal, only its sound output with maximum frequency, hence it allows for different sound patterns and variations in the frequency used.

4.2 EN 54-3:2014 Fire detection and fire alarm systems – Part 3: Fire alarm devices – Sounders

EN 54-3 [5] specifies requirements, test methods and performance criteria related to fixed installations. It is mentioned as a normative reference in EN 14604 specifically regarding the sound output test method.

The test requirements for testing sound pressure levels are stated in EN 54-3. The sounder shall produce A-weighted sound pressure levels of at least 65 dB(A) in one direction and the sound pressure level measured at each of the specified angles shall not be less than that declared by the manufacturer of the alarm.

The standard covers sounders that produce different frequencies and sound patterns and does not specify a minimum or maximum frequency or specific sound patterns. However, it includes some informative examples of standards where sound patterns are defined, e.g. ISO 8201.

4.3 ISO 8201 – Alarm systems – Audible emergency evacuation signal – Requirements

To increase the recognition of an alarm as a fire alarm a standardized sound pattern was developed, the “Temporal-Three pattern” (T-3 pulse) described in ISO 8201 [20]. The sound pattern consists of three pulses with 0.5 seconds on and 0.5 seconds off in between. The three pulses are then repeated after 1.5 seconds off. See Figure 4-1 below [20,21].

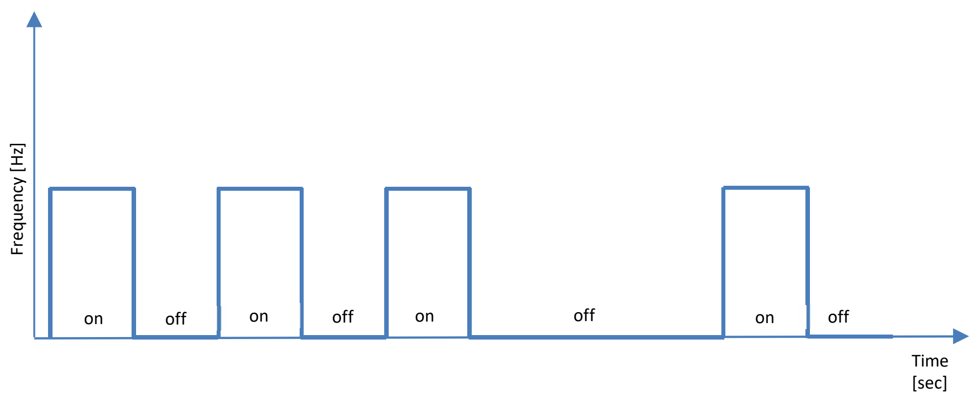

Figure 4-1 Temporal three pattern (T-3 pulse), based on [20].

While Figure 4-1 describes a constant frequency during the “on” pulse phase, it can also be designed with variable frequencies, e.g. stepwise two-tone (switching from one frequency to another during the pulse phase) or sweep frequency (begin at one frequency and gradually change to another during the pulse phase).

The signal specified in ISO 8201 is intended to signal an emergency (fire, gas leaks, explosion, nuclear radiation etc.) that requires evacuation and is intended to be used in buildings, e.g. schools, hotels, residential buildings, public institutions and work places, as well as in outside areas. The minimum sound pressure level shall be at least 75 dB(A) at the bedhead with all doors closed. The duration of an alarm should be at least 180 seconds and correspond to the time needed to evacuate the building. The signal can also be combined with a voice message with informative instructions. It is specifically noted that the signal specified in ISO 8201 may be inadequate to awaken all sleeping occupants.

4.4 NFPA 72 National Alarm and Signaling Code

NFPA 72 [22] is a comprehensive standard developed by the National Fire Protection Association (NFPA) which covers different areas of requirements connected to detection, warning and emergency communication systems. Included are also specific requirements for alarms intended for people with hearing disabilities. According to NFPA 72, audible notification appliances provided for people with mild to severe hearing loss shall produce a low frequency signal of 520 Hz ± 10 % at a sound level that is the greatest of any of the following: 75 dBA at the pillow, 15 dB above the average ambient sound level or 5 dB above the maximum sound level. The duration of the signal shall be at least 60 seconds.

NFPA 72 defines hearing loss in terms of the degree of loudness that a sound must attain before being detected by an individual and is ranked in categories:

- Mild hearing loss
    - Adults: 25-40 dB
    - Children: 15-40 dB
- Moderate hearing loss: 41-55 dB
- Moderately severe: 56-70 dB
- Severe: 71-90 dB
- Profound: 90 dB or greater

5. Waking sleeping persons

The purpose of smoke alarms is to detect and warn people of fire so that they can take appropriate action [5]. As many fatal fires occur during the night, when people are normally asleep, it is for obvious reasons important that the smoke alarm can wake people up and alert them to take appropriate action. In addition, it has been showed that certain risk factors are often associated with fire fatalities, e.g. alcohol influence. There is also an increased risk of dying in fire with increasing age [12,23].

Andersson et al. [24] recommended that the authorities should implement a requirement for one smoke alarm per bedroom, instead of just one on each floor in a home. In addition, all the smoke alarms should be interconnected. This is supported elsewhere [25], where it was shown that when a smoke alarm is placed in a hallway outside the room of fire origin it takes 200-300 seconds longer time to activate the alarm than if it would be placed in the room of origin, even though the door from the hall is kept open. Hence, by placing interconnected smoke alarms in each bedroom, instead of in hallways outside of the bedrooms, the notification perceived by of the individual will be louder and quicker. It is also suggested that the latest changes in the harmonized standard EN 14604 have made the requirements on the sound output of the signal too weak and that that would cause more people not hearing the alarm sound [24].

Numerous studies report that fire fatalities often occur during the night, when people normally are asleep. In many countries it has been shown that the majority of residential fires occur in the afternoon or early night, while most fatal fires occur late at night or early morning with the highest numbers on Saturdays and Sundays [11,12,26–30].

To be able to wake people up from sleeping in an emergency situation the alarm must have [31]:

1. The required signal
    a. It must be recognizable and so that people quickly respond with the appropriate action.
    b. It must have the appropriate type of sound, or frequency, in order to be audible.

2. The required sound pressure level
   To ensure that everyone that is relying on hearing the alarm can do so, both regarding hearing abilities and to attenuation through the media in which the sound must travel.

3. The required duration
   The time to wake up differs between individuals as well as depending on which stage of sleep the individual experiences while the alarm sounds.

For various reasons alarm signals do not have the same effect on everyone. I.e. it takes longer for some to be woken or some individuals do not wake up from the sound at all. This can for example be connected to the interpretation of the sounds, hearing loss and sleeping patterns that can be attributed to age or use of alcohol or medicines [31].

There is evidence that people tend to be woken more easily to sounds that they are prepared to interpret, and that is not confused with other types of similar alarms. It is also shown that while sleeping we are responsive to speech level frequencies, so that voice alarms may be more efficient to wake someone than would an ordinary smoke alarm signal [32,33].

5.1 Risk groups

In this context, "risk groups" relates to categories of people that will be harder to wake up and to react to an alarm.

Most adults will quickly be woken by a residential smoke alarm (common signal at approximately 3000 Hz) well below 75 dB(A) measured at the pillow, which is necessary if there is for example a closed door between the subject to be woken and the fire alarm. One door would attenuate the sound from the fire alarm to 60 dB(A) as measured by the pillow [31,34].

Children are much less likely to wake up to these sound levels and patterns. This may be connected to the fact that younger children experience a larger amount of deep sleep during the night as well as developments in a part of the brain which influences judgement-making behaviour. This development takes place at ages 12 to 24 [35].

Elderly people may be at risk of not hearing or wakening to a typical smoke alarm due to increasing likelihood of hearing loss at those frequencies commonly used by residential smoke detectors, as well as increasing likelihood of using sleeping medicine [32]. Hearing loss is affecting more than 50 % of those aged 85 years and older, and 1/3 of those older than 60 years (Norwegian numbers) and the cause is mainly hereditary and long-term noise exposure that causes damage to the internal ear. Damage to the internal ear cannot be mended, but there are hearing aids. When the cells in the internal ear is damaged, high frequency (particularly in the region 2000-8000 Hz) sounds become increasingly more difficult to hear and there is need to increase the volume (sound output) in order to hear as good as before[1]. People with this problem may be largely unaware of their condition, because they may still hear lower frequency signals, such as the doorbell. Hence, they are not aware that

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[1] The normal human ear can *detect* sounds with frequencies between 20 Hz and 20,000 Hz [36].

they are unable to hear the smoke alarm and will not take action to install any alternative alarms. [37–39].

Using sleeping medicine places an individual in a risk group in this context because they will experience difficulties in waking at the sound of the alarm. The drug is designed to reduce the number of wake-ups during the night, which is achieved by longer periods of deeper sleep. This effect will have a large impact in the responsiveness to smoke alarms since the arousal threshold is increased [32].

Alcohol intake may affect the responsiveness to smoke alarm in a similar manner; even at low levels of intake the amount of deep sleep during the first few hours of the night is increased. The effect of periods of deeper sleep together with drowsiness has also been observed in connection with marijuana use, which would both affect the responsiveness to a smoke alarm [32].

The background noise, if it is substantial, will have an impact on the effectiveness of the alarm. With significant background noise levels, the responsiveness to the alarm may be reduced [32].

5.2 Alternative alarms

Voice alarms have been shown to be significantly more effective in waking children (5-12 years old) than the common 3000 Hz signal, at 85 dB(A) at the pillow. Reported experiments have used both the child's mother's voice and an actor's voice both with an urgent message, and with the mother calling the child's name. With almost equal effectiveness, it appears that personalizing the messages with the child's name does not seem to increase the efficiency further. A 520 Hz square wave sound in a temporal-three pattern has also been tested, resulting in equal effectiveness on children as the voice alarms [31,32,35,40].

The 520 Hz square wave sound has consistently been found to be the most effective of the sounds tested in waking sleeping people in general. This also includes the elderly, children and young adults generally and adults with hearing loss, which are at risk not to hear and awake by the most common residential smoke alarm. Sounds with a primary peak at 500 Hz with a fast modulation rate is effective for both elderly and children [31,35,38,41].

Commonly, the experiments in the reported research are performed by investigating how many people in the population wake up from the sound, and after how long [42].

In a study including participants with severe hearing loss, different signals using the T-3 pulse was tested. The signals were 400 Hz square wave, 520 Hz square wave, 3199 Hz pure tone, bed shaker, pillow shaker and strobe light [38].

Bed and pillow shakers are devises that can be placed under the pillow or mattress and which will vibrate when the alarm is set off. It has been shown that this may be more efficient in waking people below 60 years old than those older than 60 years [38].

Strobe lights, flashing visual devises, are shown not to be an efficient means of waking up adults with mild to moderately severe hearing loss, and a low frequency square wave auditory signal is superior to both bed shakers, pillow shakers and strobe lights for this category of people. Less than a third of the participants were waken by strobe lights when used alone. It was shown that it may be useful to combine an auditory signal with a tactile signal, and hence, strobe light could be more efficient when used together with an audible signal such as the 520 Hz square wave signal. The NFPA is now advising older adults or other people with mild to severe hearing loss should use a devise that emits a mixed, low-pitch sound, because older adults are less likely to respond to alarms with strobe light [31,38,43].

6. Attenuation of smoke alarm signal

6.1 Sound insulation regulations and standards

The National Board of Housing, Building and Planning (Boverket) requires that buildings containing dwellings shall be designed to ensure that noise from these and adjacent premises is attenuated [17]. These noise requirements do not include installations that the user can control (e.g. dishwasher and kitchen hood at forced flow) and that do not affect the noise levels in someone else's dwelling in the same building.

Previous editions of Boverket's building regulations (Svensk Byggnorm) had similar requirements as the current edition [44–46].

The standard SS 25267:2015 *Acoustics – Sound classification of spaces in buildings – Dwellings* includes requirements of sound level differences within dwellings. It divides requirements of sound insulation in four sound classes [47]:

A. High level sound conditions, improvements compared to sound class B.
B. Considerable sound condition improvements compared to sound class C.
C. Corresponds to minimum requirements in Boverket's building regulations [17].
D. Poor sound conditions. Applied only when requirements in sound class C is not fulfilled due to technical, architectural value or economic reasons, such as e.g. rebuilding or simple, temporary spaces.

Minimum sound pressure level difference between rooms in the same dwelling according to SS 25267:2015 is given in Table 6-1. Levels for sound class C and D in this category is not given in the standard. The building regulations do not cover noise requirements within dwellings, hence there are no sound class C requirements for these spaces.

Table 6-1 Minimum sound level difference between rooms in the same dwelling, $D_{nT,w,100}$[2]. Partitions includes air transfer units and hearing through ventilation ducts, based on [47].

	Sound pressure level difference [dB]	
	Sound class A	Sound class B
Between rooms in the same dwelling		
• Partitions without door	40	35
• Partition with door to minimum one bedroom in dwelling with more than two rooms	30	-*
From hygiene room to bedroom in the same dwelling		
• Partitions without door	44	40
• Partition with door	30	-*

*Sound insulated door is recommended to reach minimum $D_{nT,w,100}$ = 30 dB.

Standard SS 25268:2007 +T1:2017 *Acoustics- Sound classification of spaces in buildings – Institutional premises, rooms for education, preschools and leisure-time centres, rooms for office work and hotels* describes sound insulation requirements for other parts of buildings than dwellings as listed in the title.

6.2 Published research

In this literature study, it has been considered that building construction materials and building techniques in Sweden may vary depending on type of building, building age, builder etc. In do-it-yourself guides for building inner walls available at homepages of building supplier stores, construction materials such as plasterboards, plywood, OSB (oriented strand board) and mineral wool are generally recommended for inner wall construction [48–52]. The literature study presented here is based on research including various types of buildings and construction materials.

6.2.1 Attenuation by construction materials in walls

Sound transmission loss through building construction materials is a major parameter that influences the efficiency of an audible alarm signal in a

[2] Weighted standardized sound level difference [dB] with spectrum adaption term 100 Hz-3150 Hz.

residential building. Acoustical treatment, such as sound absorbing fabrics, panels and insulation, is commonly used to reduce and control noise between rooms in buildings by increasing the propagation loss. These measures additionally inhibit the alarm signals passing from the alarm source to receiving rooms [39,53].

The sound attenuation through a material will be dependent on factors such as mass, density, thickness, porosity and stiffness [54]. Thermal insulation in partitions does not necessarily increase the sound insulation. In fact, it has been seen that technical measures and solutions that improve the thermal insulation often reduce sound insulation. This is explained by a dependency by the acoustic performance and degree of room-to-room transmission on the barrier surface mass. An increase in surface mass gives higher degree of sound insulation. Walls of concrete, ceramic bricks and calcium silicate blocks, for example, usually have good sound insulating properties, while insulating external lightweight composite systems (ETICS) with mineral wool or expanded polystyrene (EPS) have shown less sound insulation. Multilayer and more complex partitions may behave differently than bare homogeneous structures. Sound absorption of gypsum plaster board walls will, for example, increase if glued together with a viscoelastic glue [53–56].

Sound transmission loss will also be dependent on source sound frequency. In general, sound pressure level reduction provided by absorption in walls, doors, furnishings etc. increase with increasing frequency. A low frequency sound using 520 Hz square wave signal has shown in experiments to be less affected than the higher frequency sound of 3100 Hz, thereby giving a more efficient transmission of the alarm signal [16,57].

When looking at different frequency regions it has for example been demonstrated that the sound insulation difference achieved by adding mineral wool to a masonry wall gives an increase in sound insulation in a frequency region up to 2500 Hz, while in regions above 2500 Hz, the sound attenuation increased even more significantly. The sound reduction increased by roughly 10 dB at 520 Hz and by roughly 20 dB at 3500 Hz after insulating the masonry wall with mineral wool [58].

The type of furnishing and interior, “soft” (as in bedrooms) or “hard” (as in bathrooms and kitchens), the floor area size and the presence of forced air heating will further influence the propagation of smoke alarm sounds. This can be explained by different room sizes and shapes, and construction materials which will influence the absorption and reverberation of the sound within the room. [16].

6.2.2 Attenuation by closed doors

Studies of sound attenuation of alarm signals due to closed doors in the propagation path is found in literature. A selection of the results is presented below.

Moinuddin et al. [57] measured the alarm sound level reduction in Australian furnished houses with different combinations of open and closed doors. The floorplan and distances between the rooms varied between the houses, and number of doors in each house varied slightly. The average sound level in other rooms apart from the room of sound origin was reported. The alarm sound pressure levels used in the experiment were 85 and 105 dB(A) at frequencies of both 3100 Hz and 520 Hz. Keeping either the door to the sound origin room or the doors to the sound receiving rooms closed reduced the average sound level by at least approximately 40 dB(A). The 520 Hz sound signal gave less sound level reduction between the rooms compared to the 3100 Hz signal. The difference between the frequencies was most prominent when keeping all doors open. It should be emphasized that even with all doors open, a reduction in sound level by up to approximately 35 dB(A) was observed. The largest sound level reduction (approximately 58 dB(A)) was observed while keeping all doors closed and using a 105 dB(A)/3100 Hz sound source level. The 520 Hz signal at the same conditions gave 2-3 dB(A) higher sound levels compared to the 3100 Hz signal.

Placing smoke alarms in a hallway compared to in rooms will increase the average sound level perceived in other rooms by 10 dBA while keeping doors open, or 4 dBA if the doors to the other rooms are closed [57].

Halliwell et al. [16] developed a model for sound attenuation along a sound propagation path, and a mean value of 10 dB was demonstrated for the attenuation provided by closing a single door, 3 dB for the attenuation by an open door and 10 dB attenuation for each floor between the source and receiver.

A similar study by Robinson [39] from a collage dormitory found that the propagation loss increases with increasing frequency, approximately 0.17 dB per ft at 500 Hz and 0.23 dB per ft at 2000 Hz. The transmission loss along a corridor can be expected to be less than the transmission loss from a corridor to a room with an open door. The loss from the corridor to the room was 12 dB, with additional loss of 15 dB for closed doors or 20 dB for edge sealed doors (quality of the door is unknown). These sound reductions were measured for frequencies above 500 Hz, with somewhat higher losses above 1000 Hz.

7. Summary and discussion

Most unimpaired adults wake up from smells and sounds from the fire. The normal signal used in residential fire alarms at maximum 3500 Hz and 85 dB(A) is efficiently waking those from that group that do not wake from cues from the fire.

However, this relatively high frequency signal has been shown to be less efficient for some categories of people:

- People with hearing loss (people of all ages but also those with age-related hearing-loss).

- People that experience longer periods of deep sleep (e.g children, people that take sleeping medicine and people that are influenced by alcohol).

With increasing age, hearing generally deteriorates because of damages to the nerves in the inner ear, which makes higher frequencies increasingly harder to hear. The 3500 Hz sound is therefore less efficient for the elderly population.

The length of the signal is important as some people need longer time to respond (from waking to acting) to an alarm. By using a known signal either by a well-known or standardized sound pattern, or by priming the individual so that the pattern is recognized, people will quickly know what it means and what they need to do.

A *higher sound pressure level* (higher volume) of the 3500 Hz signal would increase the number of people that would register and wake up to the sound. A *voice signal* is also more efficient than the common residential smoke alarm, to awaken especially children. However, a signal with a significantly *lower frequency*, i.e. 520 Hz, has been proven much more efficient, even at lower sound outputs than 85 dB(A) for all those groups identified as having increased risk of not waking to the alarm.

The alternatives for people with hearing loss or hearing impairment differs depending on the degree of hearing loss. There are alarms that are not dependent on sound; e.g. pillow shakers, bed shakers and strobe lights. Strobe light on its own is not efficient for waking people, especially not elderly people, but can be useful when combined with other sensory alarms.

The large differences in the ability to awake different categories of people (unimpaired adults, children, adults with blood alcohol content, adults with mild to severe hearing loss, etc.) with the most common type of smoke alarm imply that the type of sound should be specified in regulations or standards. At the very least the smoke alarm specifications should include information describing the sound and who might be in danger of not hearing the alarm.

Limited amounts of research publications have been found that described the efficiency of alternative solutions to audible alarms. Known alternatives such as mattress shaker, pillow shaker and strobe light have been touched upon. These alarms have been shown to be less efficient in awakening the hearing impaired each on their own. They may however be improved by combining different sensory alarms based on the individual's abilities and preferences.

Sound insulation in Swedish buildings are regulated by the Boverket's building regulations. These requirements do not include walls and doors *within* individual dwellings but will give an indication of which sound insulation conditions to expect in other types of spaces in buildings. In the dwellings of the two highest sound classes (class A or B) according to this system, an attenuation of at least 30 dB can be expected.

Sound transmission loss through building construction materials is a major parameter that influences the efficiency of an audible alarm signal in a residential building. Keeping doors in the propagation path closed will attenuate the alarm sound in nearby rooms. However, even with all doors open, a reduction in sound level can be expected (up to 12 dB transmission loss for a single door has been shown in this review). The size of this reduction can vary greatly, depending on factors such as sound path length, sound path shape (within a corridor or turning into a room etc) and the surface materials along the sound path. The magnitude of the reduction is expected to be higher for rooms furnished with fabric furniture, rugs and various wall treatments. Hence, the alarm sound attenuation will vary between rooms and among different buildings. Sound is transmitted more efficiently in 520 Hz signals than 3100 Hz.

Thermal insulation does not necessarily increase the sound insulation. The degree of sound insulation is dependent on the barrier surface mass. Walls of concrete, ceramic bricks and calcium silicate blocks show relatively good sound insulating properties compared to external thermal lightweight composite systems (ETICS) with mineral wool or expanded polystyrene (EPS) insulation. Multilayer and more complex partitions may behave differently than bare, homogeneous structures.

With this in mind, the Norwegian recommendations about ensuring a sound pressure level of at least 60 dB in living rooms and bedrooms when the doors between the smoke alarm and the room are closed have both advantages and disadvantages.

It is positive that the recommendation exists, since it has been shown that the sound from the common smoke alarm can be considerably reduced from sender to receiver. At the same time, it has been shown that 60 dB, as perceived by the human ear, may not be loud enough to awaken a relatively large proportion of the public. People with common age-related hearing loss, other hearing-impaired people, children, and people that are influenced by alcohol, drugs or medicine in such a way as to affect the deep sleep, may be in danger of not being awaken by the CE-marked residential smoke alarm.

The location of the alarm signal source will be important to assure that the signal is being heard in all parts of a building. The placing of the smoke alarm should both consider the attenuation of the alarm signal sound and promote early fire detection in order to reduce the time needed for evacuation. The best detection position and the best alarm position is not necessarily the same. From an audibility point of view open doors between bedrooms and alarm locations would be preferable. On the other hand, from a fire safety point of view, the doors to bedrooms should be closed as this would delay smoke spread into the bedrooms, should a fire break out in another part of the dwelling. Hence, interconnected smoke alarms should be installed to enhance audibility of alarm signals, ensure early fire detection, and ensure the longest possible evacuation time.

8. Conclusions

Construction and thermal insulation materials, distance and propagation path from alarm origin to receiving rooms, number of doors closed, type of furnishing etc. will influence the degree of sound transmission loss. Hence, the alarm sound attenuation will vary between rooms and among different buildings.

The common up to 3500 Hz signal used in residential smoke alarms is not the most efficient alarm type to awaken persons. Children, elderly and people influenced by alcohol or medicines that affect sleep belong to the group at risk of not being awaken by the sound of the common smoke alarm.

A 520 Hz alarm signal will be efficient in terms of

- waking sleeping people in general, including the elderly, children and young adults and persons with hearing loss
- transmission of alarm signal through dwellings including inner walls and doors

Product documentation related to the CE-marking of the smoke alarm should include both minimum sound output (dB(A)) and describe the tone (e.g. frequency) so that the consumer can make an informed choice.

Advise to the public should include information

- about who might be in danger of not being awaken by the alarm (elderly, children, alcohol influenced).
- that interconnected smoke alarms should be installed to enhance audibility of alarm signals and early fire detection.
- with recommendations to risk groups to choose a low frequency smoke alarm.

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