A REVIEW OF THE SOUND EFFECTIVENESS OF RESIDENTIAL SMOKE ALARMS

December 2004 (Revised)

CPSC-ES-0502

U.S. CONSUMER PRODUCT SAFETY COMMISSION
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U.S. CONSUMER PRODUCT SAFETY COMMISSION

The U.S. Consumer Product Safety Commission (CPSC) was created in 1972 by Congress under the Consumer Product Safety Act and began operating in 1973. In the Consumer Product Safety Act, Congress directed CPSC to protect the public "against unreasonable risks of injuries associated with consumer products."

CPSC is charged with protecting the public from unreasonable risks of serious injury or death from more than 15,000 types of consumer products under the agency's jurisdiction. Deaths, injuries and property damage from consumer product incidents cost the nation more than $700 billion annually. The CPSC is committed to protecting consumers and families from products that pose a fire, electrical, chemical, or mechanical hazard or can injure children. The CPSC's work to ensure the safety of consumer products - such as toys, cribs, power tools, cigarette lighters, and household chemicals - contributed significantly to the 30 percent decline in the rate of deaths and injuries associated with consumer products over the past 30 years.

U.S. CONSUMER PRODUCT SAFETY COMMISSION
DIRECTORATE FOR ENGINEERING SCIENCES

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The views expressed in this report are those of the CPSC staff and have not been reviewed or approved by, and may not necessarily reflect the views of, the Commission.

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EXECUTIVE SUMMARY

In 2003, the U.S. Consumer Product Safety Commission (CPSC) initiated a project to review the audibility effectiveness of residential smoke alarms for the older population. The scope of the project was broadened to address recent concerns that children may not wake to the sound of a smoke alarm. The CPSC staff estimates that in 1999 there were 337,300 unintentional residential structure fires resulting in 2,390 civilian deaths, 14,550 civilian injuries, and $4.24 billion in property losses. The National Fire Protection Association (NFPA) reports that, during the 24-year period from 1977 to 2001, home fires and home fire deaths dropped 49% and 47%, respectively, excluding events from September 11, 2001. In 2001, four of every five fire deaths occurred in home structure fires, excluding 9/11, according to NFPA.

An estimated 35 million people in the United States were 65 years old or older in 2000, or almost 13% of the population. In 2010, the "baby boom" generation will begin to turn 65. As more of the baby boomers become 65 and older, the number of people over the age of 65 is expected to double by the year 2030, growing to 70 million. The number of people over the age of 65 will have increased to 20% of the population, or one in five people in the United States, by 2030.

The NFPA reports for 1999 that the fire death rate for people over 65 is 25.3 fire deaths per million, or more than twice the national average. The fire death rate increases for older age groups. For example, for those over the age of 75, the fire death rate (32.9 fire deaths per million) is about three times the national average.

The NFPA also reports for 1999 that preschool children (under age 5) accounted for a disproportionate number of fire deaths in homes. Preschool children had a fire death rate of 19.9 fire deaths per million, or roughly twice the national average (10.5). The number of fire deaths involving preschool children has been on the decline. NFPA attributes the declining number of fire deaths to the CPSC regulation requiring child-resistant cigarette lighters, which became effective in 1994. NFPA reported that, if this trend continues, preschool children may no longer be a high-risk age group.

For 1999, the NFPA report also states that children ages 5 to 9 had a fire death rate (10.1 fire deaths per million) similar to the national average. Older children, ages 10 to 19, experienced the lowest death rate – approximately 4.4 fire deaths per million.

This report presents a literature review of the sound effectiveness of residential smoke alarms in waking sleeping children and in producing audible signals suitable for older adults. The staff also reviewed possible alternatives to current smoke alarms, such as changes in smoke alarm horn frequency, cues, or other methods that may improve alarm sound effectiveness.

The CPSC staff believes that improvements in smoke alarm sound effectiveness could lead to increased escape time for occupants in a residential fire. It should be noted that any recommendations for change to increase sound effectiveness for waking children and alerting older adults must also be evaluated to determine that there is not a reduction in the current level of effectiveness for other age groups.

The following conclusions are based on the information presented in this report.

- Children under the age of 16 have longer periods of deep sleep compared to adults.
- Current smoke alarms do not reliably wake children under the age of 16.
- There is no evidence that children have a higher fire death rate because of the inability to wake to a smoke alarm.
- Current smoke alarms are effective in waking most adults not under the influence of drugs, alcohol, and sleep deprivation. However, current smoke alarms may not reliably notify or alert seniors who are hearing impaired.
- The fire death rate for older adults is higher than the national average. This may be attributed to many factors – mobility, awareness, loss of hearing, etc.
- Various home configurations and locations of smoke alarms can limit the transmission of sound throughout the house.
- Interconnected smoke alarms can provide earlier warning of smoke and fire.
- The addition of interconnected smoke alarms inside bedrooms may provide improved warning of smoke and fire where bedroom doors are closed.
- Alternative warning systems and sounds warrant further exploration to account for as many home configurations and occupant needs as possible.

Additional research is needed to better understand potential deficiencies in the audibility of smoke alarms. CPSC staff believes the following areas of research need to be explored to gather additional data to help determine possible technical solutions and/or public education campaigns:

<u>Training Approach vs. Sleep-Induced Incapacity</u>.

Determine whether children can be awakened by an alarm through training.

<u>Exploration of Alternative Cues.</u>

Investigate whether alternative cues can reliably wake children (e.g. strobe light, alternative sounds and sound characteristics, human voice, etc.).

<u>Smoke Alarm Sound Uniqueness.</u>

Determine whether current smoke alarm patterns/tones are identifiable and unique when compared to other alerting sounds.

Alternative Sound Frequency of Smoke Alarm Signal.

Explore feasibility and effectiveness of lowering the sound frequency of the smoke alarm signal, and/or use of alternative signals such as a high-low frequency combination.

Improving the Detection Capability of Smoke Alarms.

Examine possible technical solutions to improve smoke alarm detection capabilities, such as alternative or combination sensors.

Interaction of Multiple Smoke Alarm Cues.

For different alarm cues sounding simultaneously, determine if alarm sounds are still recognizable.

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1.0 INTRODUCTION

The U.S. Consumer Product Safety Commission (CPSC) staff initiated a project in 2003 to review the audibility effectiveness of residential smoke alarms for older adults. Currently, residential smoke alarms operate at sound frequencies that may produce alarm sound characteristics poorly suited for the older population. The scope of the project was broadened to address recent concerns that children may not wake to the sound of a smoke alarm.

CPSC staff also participated in a working group sponsored by Underwriters Laboratories, Inc (UL). The working group examined the issue of children not awakening to the sound of a smoke alarm and issued a report of its findings in July 2003 (UL, 2003). The working group concluded that there is a "preponderance of evidence that acoustic stimuli at the level currently used in smoke alarms will not reliably awaken children." The working group recommended that future studies should be directed at evaluating alternative stimuli. The working group suggested examining other acoustic stimuli, such as a recorded human voice; optical stimulation, such as strobe lights; and other stimuli, such as buzzers/vibrators and cold air jets, or olfactory stimuli. The findings of the CPSC staff regarding children not awakening to the sound of a smoke alarm, which are presented in this report, are similar to those of the working group.

This report presents a literature review of the sound effectiveness of residential smoke alarms in waking children and in producing audible signals for older adults. The report also presents ideas that could improve alarm audibility, as well as CPSC staff recommendations for additional research that may lead to improvements in alarm effectiveness and smoke alarm technology.

1.1 Fire Hazard

In 1999, the CPSC staff estimates that there were 337,300 unintentional residential structure fires resulting in 2,390 civilian deaths, 14,550 civilian injuries, and $4.24 billion in property losses (Miller, et al., 2003). The National Fire Protection Association (NFPA) reports that, during the 24-year period from 1977 to 2001, home fires and home fire deaths dropped 49% and 47%, respectively, excluding the events of September 11, 2001. Home fire deaths fell 9% from 3,420 in 2000 to 3,110 in 2001 (excluding 9/11) (Ahrens, June 2003). The NFPA report for 2001 states that four of every five fire deaths occurred in home structure fires, again excluding September 11.

As of 1999, 19 of every 20 homes in the United States had at least one smoke alarm (Ahrens, Nov 2003). Ahrens reported that 40% percent of home fire deaths occurred in homes with no smoke alarms.

In 1992, the U.S. Consumer Product Safety Commission sent surveys to people's homes to find out how many had smoke alarms and what proportion of these installed smoke alarms were functional. This study showed that in one-fifth (20%) of the homes with at least one smoke alarm, none were working (Smith, Nov 1993). Reasons that smoke alarms did not function were usually attributed to dead, missing, or disconnected batteries or AC power (Smith, January 1995).

There are some concerns that special populations may be at a higher risk of not hearing or responding to smoke alarms. Specifically, children do not seem to be reliably awakened by alarms; and seniors may commonly experience hearing loss in the frequencies at which smoke alarms operate.

1.1.1 Children at Risk

In 1999, preschool children (under age 5) accounted for a disproportionate number of fire deaths in homes (Hall, 2004). Preschool children had a fire death rate of 19.0 fire deaths per million, or roughly twice the national average (10.5 fire deaths per million). The number of fire deaths of preschool children has been declining. NFPA attributes the decline to the 1994 CPSC regulation requiring cigarette lighters to be child-resistant (CFR, 2003). In 1994, there were 664 fire deaths involving preschool children and in 1999, there were 360. NFPA stated that, if this trend continues, preschool children may no longer be a high-risk age group.

For 1999, the NFPA report also states that children ages 5 to 9 had a fire death rate (10.1 fire deaths per million) similar to the national average (Hall, 2004). Older children, ages 10 to 19, experienced the lowest death rate – approximately 4.4 fire deaths per million.

1.1.2 Older Adults at Risk

It is estimated that 35 million people in the United States – almost 13% of the U.S. population – were 65 years old or older in 2000 (Federal Interagency Forum, 2000). The number of people over the age of 65 is expected to double by 2030, increasing to 70 million. By 2030, the number of people over the age of 65 will have increased to 20% of the population, or one in five people in the United States (Federal Interagency Forum, 2000).

According to a 1999 report by the U.S. Fire Administration (USFA), residential fires injure approximately 3,000 older adults each year (USFA, 1999). In comparison to the rest of the population, older adults – those over 65 years of age – represent one of the highest fire risk groups in the United States, in large part because they are the fastest growing segment of the U.S. population. For 1999, the fire death rate for people over 65 was 25.3 fire deaths per million, or more than twice the national average (Hall, 2004). The fire death rate is higher for older age groups. For those over the ages of 75, the fire death rates (32.9 fire deaths per million) is about three times the national average.

1.2 Project Objectives

The CPSC initiated this study to determine if improvements in smoke alarm sound effectiveness could lead to increased escape time for occupants in a residential fire. The objective of the 2003 project was to review studies and reports to help evaluate smoke alarm sound effectiveness in waking children and alerting older adults. The staff also reviewed possible alternatives to current smoke alarms, such as changes in smoke alarm horn frequency, cues, or other methods that may improve alarm sound effectiveness. It should be noted that any recommendations for change to increase sound effectiveness for waking children and alerting older adults must also be evaluated to determine that there is not a reduction in the current level of effectiveness for other age groups.

1.3 Technical Approach

This evaluation is presented in two parts. The first part presents the results of a literature search of studies on audibility and sound effectiveness of residential smoke alarms. A compilation of the studies is provided, along with a CPSC staff assessment of the information, to determine if sufficient data is available to draw reliable conclusions. This part also includes a review of pertinent sections of the voluntary standard requirements for residential smoke alarms.

The second part of the evaluation includes an examination of possible technical approaches that may be more effective in alerting individuals to fire. The technologies can be devices that are currently available, but are being used in other applications; or technologies that may be available in the near future devices.

CPSC staff recommendations for additional research needed to support proposals for improvements to the voluntary standard are also presented.

2.0 LITERATURE SEARCH

Several aspects of smoke alarms and sound effectiveness are examined in this section: the waking effectiveness of smoke alarms and behavioral characteristics that might be associated with an individual waking to an alarm, hearing loss in older adults, current smoke alarm technology and voluntary standard requirements for the horn, and the technical aspects and physics associated with the sound of an alarm.

2.1 Residential Smoke Alarms

Smoke alarms (both the ionization and photoelectric types) use a common piezoelectric horn, as shown in Figure 1, to indicate to an occupant that the smoke alarm has activated. The sound source for a piezoelectric horn is the piezoelectric diaphragm. The diaphragm consists of a piezoelectric ceramic plate, which has electrodes on both sides, and a metal plate typically made of brass or stainless steel. The ceramic plate is attached to the metal plate with an adhesive.

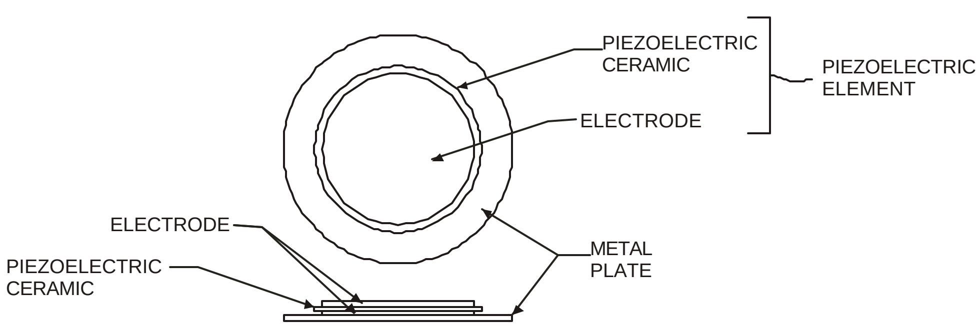

Figure 1. Piezoelectric Diaphragm

When a DC (direct current) voltage is applied to the electrodes of the piezoelectric diaphragm, it causes mechanical distortion of the piezoelectric element. Depending on the polarity of the voltage applied to the piezoelectric element, the piezoelectric element either expands or contracts, as shown in Figure 2. The metal plate, which is bonded to the piezoeletric element, does not expand. When an AC (alternating current) voltage is applied to the electrodes, expansion and contraction are repeated alternately, producing sound waves in the air.

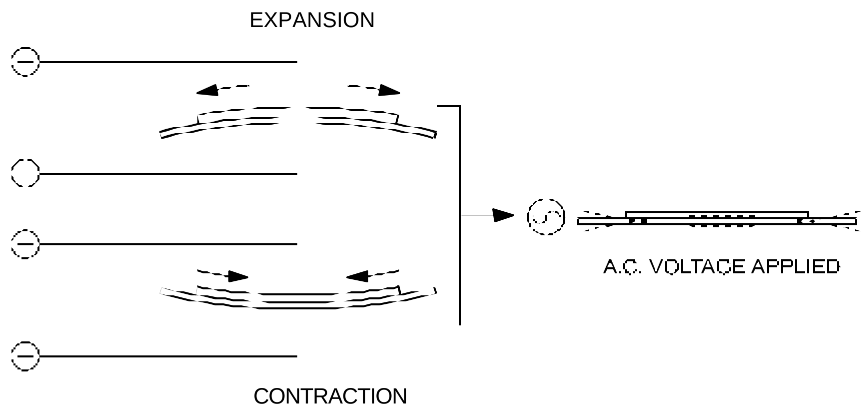

Figure 2. AC Voltage Applied to the Piezoelectric Element

The most common unit used to measure sound intensity is the decibel, or dB. The decibel scale is a logarithmic scale – that is, an increase of 10 dB in sound intensity represents a 10-fold increase in sound power and a 100-fold increase in sound pressure (since sound power is directly proportional to the square of the sound pressure).

Sound pressure is measured using a sound-level meter. The American National Standards Institute (ANSI) and the American Standards Association have established a standard for sound-level meters. This standard requires that three different weighting networks (A-weight, B-Weight, and C-weight) be built into instruments. Each network responds differently to low and high frequencies according to standard frequency-response curves. When sound intensity is referenced, the specific weighting network used for measuring is specified (e.g., 85 dBA or 85 dB A-weight).

2.1.1 Human Response to Sound Intensity and Pitch

Sound is any disturbance of air (or fluid) that is perceptible to the ear. Sound energy is transmitted through an air or fluid medium as sound waves, which are actually pressure waves. The way in which the human ear hears and interprets sound is very complex. Sound loudness is determined by the amplitude of the sound wave. The human ear can respond to sound pressures ranging from 20 micropascals to 200 Pascals (Newtons per square meter), but its response is not linear over this range. Sound pitch is determined by the sound wave frequency, which is typically expressed as the number of cycles per second (Hertz, Hz). Pitch increases as the number of Hz increases. The human ear can discern sounds ranging from 20 to 20,000 Hz, but as with sound pressures, the response is not linear over this range, and hearing is typically optimal between 1000 and 4000 Hz. A sound with a frequency spectrum in the 1000 to 4000 Hz range will be perceived as being louder than a sound of equal sound energy that is comprised predominantly of frequencies outside of this range. As adults age, a significant proportion experience a gradual, subtle hearing impairment, which is typically first manifested as a reduced ability to detect higher frequency sounds (between 3000 and 6000 Hz). The hearing loss can progressively involve detection of higher then lower frequencies, and it is irreversible.

2.1.2 Fire Alarm Patterns and Tones

The frequency of the horn output for a residential smoke alarm is typically between 3,500 to 4,000 Hz (cycles per second). In addition, Underwriters Laboratories voluntary standard, UL 217 – *Single and Multiple Station Smoke Alarms*, requires an A-weighted sound pressure level of at least 85 decibels (dBA) when measured at a distance of 10 feet from the horn, in a room of a specific configuration and under specific conditions (UL, 1997).

UL 217, *Section 34.3, Standardized alarm signal*, requires an audible signal to have a "three pulse" temporal pattern. The signal must have an "ON" phase (sound for 0.5 seconds), followed by an "OFF" phase (silent for 0.5 seconds), as shown in Figure 3. The pattern is repeated for three pulses (ON, OFF, ON, OFF, ON). After the third pulse, a 1.5-second OFF, or silent period, follows before the three-pulse pattern begins again. Prior to this requirement, smoke alarms produced a continuous sound when alarming.

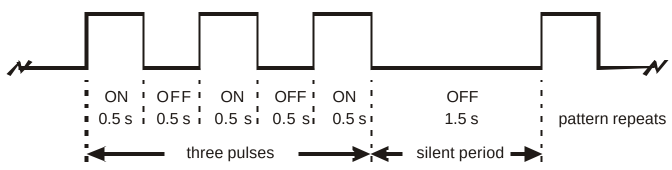

Figure 3. "Three Pulse" Temporal Pattern

The temporal three pattern was standardized to be used as an audible emergency evacuation signal. The American National Standard document, *Audible Emergency Evacuation Signal* (ANSI S3.41), specifies the requirements for the temporal three pattern. The signal is used to indicate imminent danger and signify unambiguously that evacuation from the building is immediately necessary (ASA, 2001). The temporal-three pattern does not limit the signal to one sound (such as a bell, horn, ring, chime, or electronic sound) but, rather, to a sound pattern. This also does not limit the frequency or combinations of sound types that can be used in the temporal-three pattern. The standard also allows supplemental instructions be incorporated into the temporal three pattern. For example words FIRE!, GET OUT!, etc. may be inserted during the 1.5 second off period.

The requirement for the temporal-three pattern for all new residential construction was incorporated into the National Fire Alarm Code, NFPA 72, in 1996 (NFPA, 1996). The NFPA 72 and NFPA 101 are used by most states and jurisdictions in establishing the minimum level for fire safety. Alarm tone requirements may vary in the U.S. commercially and internationally. Table 1 lists some of the alternative alarm tones that are available on commercial fire alarm devices.

Table 1. Alarm Tones from Commercial Fire Alarms (non residential)

Tone	Pattern Description
Horn	Broadband Horn (Continuous)
Bell	1560 Hz Modulated (0.07 second ON/Repeats)
March Time Horn	Horn (0.25 second ON/0.25 seconds OFF/Repeats)
Code 3 Horn	Horn (ANSI S3.41 Temporal pattern)
Code 3 Tone	500 Hz (ANSI S3.41 Temporal pattern)
Slow Whoop	500-1200 Hz Sweep (4.0 seconds ON/0.5 seconds OFF/Repeats)
Siren	600-1200 Hz Sweep (1.0 Seconds ON/Repeats)
High/Low	1000/800 Hz (0.25 Seconds ON/0.25 Seconds OFF)

2.1.2 Sound Level Loss in a Smoke Alarm

A smoke alarm will produce different sound levels in different locations, depending on the room size and the types of furnishings in the room. As discussed in the *Guide to Most Effective Locations for Smoke Detectors in Residential Buildings* (Halliwell and Sultan, 1986), the sound level produced by an alarm is not a fundamental property of the alarm. The audibility of a smoke alarm can be referred to as the sound power. Sultan's *Guide* uses a light bulb to illustrate the relationship between sound level and sound power: Sound power is similar to the wattage of a light bulb, and sound level is similar to the illumination of the light bulb. For example, a 60-watt bulb will use the same wattage in a small or large room, but the illumination will appear brighter in a small room as compared to a large room.

The *Guide* provides methods to estimate the sound level from a smoke alarm at its origin and the reduced sound level as it travels from room to room. Rooms are first categorized as hard, normal, or soft. The hard room is described as having no carpet and no upholstered furnishings (kitchens, bathrooms, etc.). The normal room is one with carpeting, light drapes, and upholstered furnishings (living/dining rooms, halls, etc.). A soft room is a room with thick carpeting, heavy drapes, and soft furnishings (bedrooms, etc.). Correction factors are used to estimate the increase or attenuation in sound level based upon the type of room in which the alarm is installed and the size of the room. A lower correction factor would be required for small rooms, and the sound level correction factor would increase as the room size increases. A soft room would have a higher attenuation factor than a hard room of the same size. For hard and normal rooms that are small, the sound level correction factor can be a positive number, or an increase in the original sound level source.

Sultan explains that sound travels from room to room in the same manner as a person would move from room to room, and sound is attenuated as it travels from room to room. The attenuation correction factor used to determine the sound level in the next or adjacent room is determined by the type of room (soft, normal, or hard) and the size of the room. The least attenuated sound level would be in a small room, and the attenuation correction factor would increase as the room size increases. A soft room would have a higher attenuation factor than a hard room of the same size. The sound level correction factor for an adjacent room is always attenuated, or less than the room of origin.

Two other factors that significantly affect sound level are the position of doors (open or closed) and air heating/cooling systems. If a door between two rooms is closed, the sound level is attenuated (reduced) by 10 dBA. If a home does not have a forced air heating/cooling system, the sound level is attenuated by an additional 6 dBA.

An example of how sound level correction factors can be used in estimating the attenuated sound as it travels through a home is presented below.

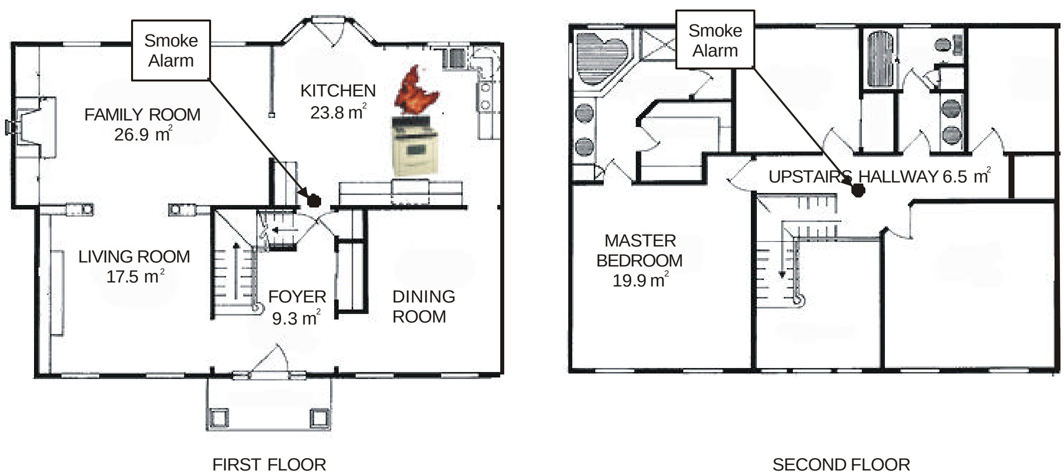

Figure 4. House Layout

In this example, it is assumed that the home shown in Figure 4 has a forced air heating/cooling system. Smoke alarms with a sound power output of 95 dBA are installed on each level of the house, but the alarms are not interconnected. A fire occurs in the kitchen, which is a hard room with an area of 23.8 m^2. Using the correction factor for the room of origin, the sound level for the smoke alarm in the kitchen is 89 dBA [95 - 6 = 89 dBA][1]. Using the attenuation correction factors for adjacent rooms[2], to reach the upstairs master bedroom, the sound must travel through the foyer (-10 dBA), through the upper hallway (-10 dBA), and to the master bedroom (-17 dBA). The final sound level at the master bedroom is 56.5 dBA (as shown in Table 2). In addition, if the door to the master bedroom were closed, the sound level would be attenuated by an additional 10 dBA, or a sound level of 46.5 dBA. A minimum of 75 dBA is required to wake most adults from sleep, although sound levels as low as 55-60 dBA can awaken some adults when the ambient noise levels are low. In this example, the smoke alarm sounding on the first floor may not be adequate to awaken a sleeping adult in the master bedroom, depending on the ambient noise level.

[1] From: *Guide to Most Effective Locations for Smoke Detectors in Residential Buildings*, Table 2, Correction to be added to the sound power level of a smoke detector to determine the sound level

[2] From: *Guide to Most Effective Locations for Smoke Detectors in Residential Buildings*, Table 3, Attenuation of sound level in going from one room to the next

Table 2. Example Calculation of Sound Level Attenuation

Room	Area (m^2)	Room Category	Attenuation (dBA)	Combined Attenuation (dBA)*
Kitchen	23.8	Hard	6	89
Foyer	9.3	Hard	10	79
Upper Hallway	6.5	Normal	10	72.5
Master Bedroom	19.9	Soft	17	56.5

*Assumes an initial sound level of 95 dBA

Beginning in 1989, the NFPA 74 *Standard for the Installation, Maintenance and Use of Household Fire Warning Equipment*, required newly constructed residential homes to have interconnected (hard-wired) smoke alarms on every level of the home and outside the sleeping areas (NFPA 74-1989). The interconnection of smoke alarms allows all the smoke alarms to sound if any individual smoke alarm detects smoke.

Using the previous house layout example, if the lower and upper level smoke alarms are interconnected, the smoke alarm sounding outside the bedroom would be attenuated by the upper hallway and the master bedroom by 2 and 17 dBA, respectively. The final sound level in the bedroom would be 76 dBA [95 -2 -17 = 76 dBA]. This is just above the 75 dBA required to wake an adult. If the bedroom door were closed, the sound level would be attenuated another 10 dBA, or a final sound level of 66 dBA, which may not wake a sleeping adult.

If an additional smoke alarm was installed in the master bedroom and all the smoke alarms were interconnected, the sound level would only be attenuated 9 dBA by the master bedroom. The sound level in the bedroom would be 86 dBA, which would most likely wake an adult.

For this example, interconnection of smoke alarms may effectively provide increased sound levels that can increase available escape time and life protection for occupants if a smoke alarm sounds in other parts of the home. Testing between interconnected and non-interconnected smoke alarms in various home configurations would help in quantifying the benefits for interconnected smoke alarms in residential homes.

2.2 Waking Effectiveness

Recently, there have been a number of television reports in which the media, with the help of local fire services and families, have conducted smoke alarm tests in consumers' homes. These tests were conducted at night, while the children were sleeping. The homes' smoke alarms were activated to examine the responses of the children. In most tests, sleeping children did not wake to the sound of a smoke alarm. After the initial test, the children were trained to respond to the sound of the smoke alarm before the media returned on a later night. Some media reports showed that children awakened after training and other media reports showed that children slept through the sound of the smoke alarm again. These media reports have prompted increased awareness among the fire community that smoke alarms may not be adequate to wake children.

CPSC staff believes that firm conclusions should not be drawn from these demonstrations because they had some significant confounding variables (e.g., the presence of camera crews, fake smoke, parents in the child's room, etc.).

To better understand why children may not be effectively waking to the sound of a smoke alarm, CPSC staff reviewed available studies involving the effectiveness of alarms in waking people.

During sleep, the human brain undergoes several distinct changes in consciousness. These changes have been studied by correlating them with various physiological indicators, such as brain waves, breathing, and heart rate. Using these indicators, researchers can reliably identify five stages of sleep (four non-REM and one REM) and have described the development of sleep patterns across the lifespan. The stages of non-REM sleep (NREM) are comprised of stages 1 to 4. Sleep progresses from light sleep (stage 1) to deep sleep (stage 4). Deep sleep is referred to as "slow-wave sleep" because brainwaves during this stage appear less jagged and frenetic. Rapid Eye Movement (REM) sleep is distinguishable by physiological states, including its characteristic rapid eye movements. Humans generally cycle through several waves of sleep, from light sleep to deep sleep. However, stages 2 and 3 repeat backwards before the REM sleep stage. A typical sleep cycle may have this pattern: stage 1, 2, 3, 4, 3, 2, REM. Several episodes of deep sleep are usual; and as humans age, their nightly stages of deep sleep become shorter and overall sleep quality is lighter.

Awakening from sleep and subsequent alertness have also been examined. Auditory arousal from sleep is affected by many variables, such as sound intensity and frequency, bedroom acoustics and background noise, the time of night, the current sleep stage, the level of fatigue or sleep deprivation, the use of medication, alcohol or drugs, hearing loss, and whether or not the subject is primed to hear an alarm (Bruck, 2001). All of these variables could influence the effectiveness of a smoke alarm in waking people during emergencies.

Research (Bruck & Horasan, 1995) in a sleep laboratory indicates that adults can usually be aroused with 55-60 dB of sound at 2000-4000 Hz, as measured at their pillow. In the study, 20% of the test subjects (all adults) stayed asleep at least once during several trials with an alarm blaring for 10 minutes. Some evidence suggested that the people who did not wake were sleep deprived from studying for exams. No gender differences or effects from priming subjects to expect an alarm were found in this study. A review of smoke alarm effectiveness studies suggests that normal, unimpaired adults who are not over-tired can be reliably aroused by commonly-available smoke alarms that are placed near sleeping quarters (Bruck, 2001). Adding background noises, drugs, alcohol, or fatigue to the situation will decrease a normal alarm's effectiveness. Other fire cues, such as crackling noises of 42-48 dB, have also been shown to wake 85% of normal, unimpaired adults (Bruck, 2001).

Whether or not a sleeping individual will be awakened by a sounding smoke alarm appears to be primarily influenced by their age. Infants and children have very different sleep patterns from adults. For instance, in the same stages of sleep, infants and children are more difficult to arouse. The relevant stages of sleep are known as "deep sleep" or "slow-wave sleep." Infants and children generally require more sleep and have longer stages of deep sleep. Infants and children are more difficult to arouse than adults. Researchers are not exactly sure what the brain is doing while in deep sleep, or even why the human brain sleeps; however, preventing a person from sleeping has adverse health effects. The important side effect of deep sleep is a normal, strong "sleep maintenance response" in children – that is, a high resistance to being awakened by external stimuli.

Children's powerful sleep maintenance faculties were recently given national attention during a televised fire drill in which the young subjects slept soundly for over 3 minutes through the sound of their home's smoke alarm. Fire marshals and caregivers alike were surprised. However, the fact that people are hard to arouse from sleep has been known from sleep research since the early years of psychological research (Mulin, 1937). Researchers at the University of Ottawa (Busby, et al., 1994) tried to wake 36 male subjects (ages 5 to 24 years old) using earphone-delivered, 3-second 1,500-Hz pure tones at regularly ascending intensities during various stages of sleep across successive nights. Because their research design included multiple ages (children, pre-adolescents, adolescents, and adults), both slow-wave and non-deep sleep stages, and increasingly louder stimuli (30 dB to 120 dB maximum), the results show the differences between adults and children and the increased sensitivity to alarms that adults gain. Children under the age of 17 years were sometimes roused but not *reliably* awakened by even very loud tones (>100 dB). No one under the age of 15 was awakened by tones with less than an 80-dB average intensity across trials. After age 17, the subjects in this study were awakened 100% of the time by reasonably loud tones (<100 dB) with intensity averages mostly under 90 dB. The oldest subjects were awakened by sounds with an average intensity of 50 dB. This study still leaves possible gender effects, alternate frequencies, and alternate sounds unexplored.

Other night-time studies also found that smoke alarms sounding for up to 3 minutes at 60 to 75 dB failed to awaken 85% or more of the child (preadolescent and adolescent) subjects in the study (Bruck, 1999; Duncan, 1999). This research has important implications for smoke alarm effectiveness. It provides good evidence that preadolescent and adolescent children will be very difficult to wake at night during certain stages of sleep. The study does not indicate that smoke alarms are ineffective or useless when used with children. It provides evidence that smoke alarms will wake children sometimes, especially during stage 2 and REM sleep. Significant portions of a child's night are spent in these stages, so smoke alarms can be a valuable and practical aid for escaping a fire. However, the possibility exists that an alarm sounding during children's slow-wave, deep sleep will be insufficient to arouse them.

The following section lists the reference and verbatim abstracts of several peer-reviewed studies of the effectiveness of alarms for waking children. Refer to the original articles for more details.

2.2.1 Past Studies of Sound Effectiveness for Children

Busby, K. & Pivik, R.T. (1983). Failure of high intensity stimuli to affect behavioral arousal in children during the first sleep cycle. Pediatric Research, 17, 802-805.

Behavioral and physiologic indices of arousal to auditory stimuli were examined during the first cycle of sleep in 8-12 year old hyperactive children and non-hyperactive controls. No behavioral responses or sustained awakenings were obtained for any child during the first cycle of sleep to stimuli at intensities up to 123 dB sound pressure level re 0.0002 dynes/cm2 (i.e., at intensities more than 90 dB above waking threshold values). Half of the arousal attempts in stage 2 and a quarter of those in stage 4 elicited a partial or momentary physiologic arousal response (i.e., EEG desynchronization and/ or change in skin potential response or respiratory activity rates). These arousals were short-lived, with the subjects returning to sleep even with continuing or increased stimulus intensity. Neither the incidence of partial arousals nor the associated threshold intensities differentiated subject groups. Although increased skin potential response activity to wakefulness – and a predominance of skin potential response activity was noted in stage 4 sleep – no significant differences in frequency (rate/minute) of autonomic response measures were obtained when rates before and during auditory stimulation were compared.

Busby, K.A., Mercier, L., & Pivik, R.T. (1994). Ontogenetic variations in auditory arousal threshold during sleep. Psychophysiology, 31, 182-188.

Developmental variations in auditory arousal thresholds during sleep were investigated in 4 groups totaling 36 normal males: children, preadolescents, adolescents, and young adults. Arousal thresholds were determined during non-REM and REM sleep for tones presented via earphone insert on a single night following 2 adaptation nights of undisturbed sleep. Age-related relationships were observed for both awakening frequency and stimulus intensity required to effect awakening, with awakenings occurring more frequently in response to lower stimulus intensities with increasing age. Although stimulus intensities required for awakening were high and equivalent across sleep stages in non-adults, higher intensity stimuli were required in Stage 4 relative to Stage 2 and REM sleep in adults. Results confirm previous observations of marked resistance to waking during sleep in preadolescent children.

Bruck, D. & Horasan, M. (1995). Non-arousal and non-action of normal sleepers in response to a smoke detector alarm. Fire Safety Journal, 25, 125-139.

Twenty-four young adults were exposed twice to a smoke detector alarm activated at 60 dBA. Unlike previous studies, all subjects were unprepared for the first activation (naïve) and the stage of sleep in which the alarms occurred was manipulated, with the alarm being activated twice in either stage 4, stage 2 or REM sleep for each subject. Upon being wakened, estimations of time taken to wake, dream reports, alarm interpretations and computer reaction times were collected. Five subjects (20%) did not reliably wake to the alarms, and this was associated with their reported lack of sleep the night before and unrelated to the stage of sleep or whether it was the first or second (non-naïve) alarm presentation. Of the awakenings, 87% occurred within 1 minute of the alarm; and no differences in time to wake were evident between the first "naïve" and second "non-naïve" awakening. When wakened by the first alarm, 95% took no action within 2 minutes. Ninety-two percent did not correctly interpret the alarm nature of the signal. Dream incorporation was not an important variable. Estimations of time to wake were highly correlated with actual time to wake for the "non-naïve" condition. Neither time to wake across different sleep stages nor analysis of the reaction time data revealed significant differences.

Bruck, D. (1999). Non-awakening in children in response to a smoke detector alarm. Fire Safety Journal, 32, 369-376.

Twenty juniors (aged 6-17 years) and their parents (aged 30-59 years) participated. Sleeping participants were exposed, on two different nights in their own homes, to an alarm, which was received at 60 dBA at the pillow. Sleep/wake behavior was determined objectively using wrist actigraphy and confirmed by self-report questionnaires, which also asked about levels of clear-headedness and sleepiness. It was found that 17 of the 20 juniors (85%) slept through one or both of the alarm presentations, while 100% of the adults awakened reliably. Where a participant awakened, almost all (95%) did so within 32 seconds of alarm activation. On average, those who awakened reported feeling moderately clearheaded straight away and continued to improve. The author concludes that further research is called for to determine whether children will wake to a louder alarm signal (e.g. 85 dBA) being received at the pillow. She further notes that in the absence of data demonstrating this, the best recommendation may be to install interconnected detectors and alarms in residential dwellings so that adults can be awakened if a fire occurs in or near children's bedrooms.

Bruck, D. (2001). The who, what, where and why of waking to fire alarms: A review. Fire Safety Journal, 36, 623 –39.

This review brings together several different strands of research: (i) the sleep arousal literature pertaining to auditory arousal thresholds (AATs), (ii) studies on factors affecting responsiveness to auditory signals during sleep, (iii) literature on responsiveness to smoke detector alarms during sleep and (iv) research on fire fatality statistics and victim characteristics. The review discusses the influence of age, sleep deprivation, signal frequency, background noise, hearing loss, time of night, stage of sleep, sex differences, dream incorporation, depression, signal meaningfulness, sleeping tablets, alcohol and marijuana on responsiveness during sleep. Studies using smoke alarms clearly suggest that an unimpaired sleeping adult will wake quickly to a 55.0 dBA alarm (such as with a hallway installation), while the AAT literature suggests higher thresholds (most likely due to differences in signal frequency). However, it is argued that the level required to wake such adults under the ideal circumstances of an experimental situation should not be the minimum pillow audibility. Such a level is unlikely to arouse children, those on sleep inducing medication, people with high frequency hearing loss (as may occur with age), those who are sleep deprived or those under the influence of alcohol or marijuana. The responsiveness of the unimpaired adults tested is not generalizable to the responsiveness of the people most likely to be the victims of fire occurring while they are asleep (the very young, elderly, intoxicated, or sick). The author notes that the sound intensity of the alarm at the pillow should have the highest chance of arousing those most at risk of dying. It is, therefore, recommended that smoke alarms be installed in the bedrooms themselves such that the signal intensity is at the maximum level tolerable to the human ear, that is, approximately 90 dBA.

Table 3 summarizes studies regarding the waking of individuals from an external sound. The table lists the age range, stimuli, frequency, dB level, and results for each of the studies.

Table 3. Study Comparison

Report	**n**	**Age Range (yr)**	**Stimuli**	**Frequency (Hz)**	**dB**	**Results**
Busby & Pivik (1983)	12	8-12	Earphone delivered, 3 sec tones	1500	0-123 gradually ascending	No sustained waking.
Busby, Mercier & Pivik (1994)	36	5-24	Earphone delivered, 3 sec tones	1500	0-120 gradually ascending	Preadolescent and adolescent children not reliably wakened. Younger children less likely to wake.
Bruck & Horasan (1995)	24	18-24	Smoke Alarm	2000-4000	60 (at pillow)	87% of naïve subjects woke in less than 1 minute. 5 fatigued subjects not awakened.
Bruck (1999)	20	6-59	Smoke Alarm	unknown	60 (at pillow)	85% of subjects under 17 slept through alarm.

2.2.2 Decision Making after Waking from an Alarm

Immediately after waking to an alarm, people will often be disoriented, uncoordinated, and sluggish. Depending on a number of factors like fatigue, the time of night, and individual differences, this cognitive and motor impairment quickly dissipates. Adults and children aroused by a smoke alarm generally reported being "moderately clearheaded" upon waking, "quite a bit clearheaded" 3 minutes later, and "extremely clearheaded" 4 to 7 minutes after waking (Bruck, 1999). Another study failed to find significant reaction time decrements after waking (Bruck and Horasan, 1995).

If an alarm sounds and people recognize it, there is a high likelihood that they can escape. Estimates of survival using National Fire Incident Reporting System (NFIRS) data on U.S. apartment building fires that occurred between 1:00 am and 5:00 am suggest that 97% of occupants escape (Bruck, 2001). This number may even be an underestimate of escape rates because it assumes only one person is present per fire (724 deaths in 32,077 fires). This suggests that smoke alarms can be relied on when used with non-impaired, non-fatigued adults. Most studies without confounding drug, alcohol, or sleep deprivation effects find that adults can be aroused nearly 100% of the time by reasonably loud alarms (55 dB to 90 dB at the pillow). Another study reported that even special populations (seniors and "mentally retarded" (*sic*) people) can be aroused by smoke alarms and self-evacuated in under a minute (Nober, et al., 1983). Closed doors and background noises, like air conditioners or fans, can decrease an alarm's audibility effectiveness.

2.2.3 Discussion

The fire safety community is continuing to educate the public about developing and practicing a fire escape plan. Discussing and practicing an escape plan can increase the awareness and importance of safely exiting a home during a fire. The age at which a child can reliably perform and execute an escape plan after being awakened by a smoke alarm is unknown. However, children should not be relied upon to be consistently conscious of hazards to themselves, or be expected to act appropriately in the event of a real fire. Training and education may not be effective or show immediate results for young children, but can be beneficial in the long term as they become older, and have a growing awareness of safety issues.

Children may be able to hear an alarm while they are in slow-wave sleep; but it may not be perceived as being important or meaningful. If a sound is interpreted as meaningless, their brains would treat it like any other benign disturbance and suppress the arousal it causes in order to maintain their deep sleep. If this is the case, a solution may be to verify whether, through training, children can recognize and value the sound of their home's smoke alarm. This will determine if the failure to be awakened by a smoke alarm is a training issue or a normal psycho-physiological feature of childhood. If training is done effectively through positive rewards and practice, children may wake to a smoke alarm reliably, like adults. If they do not wake reliably when a familiar and meaningful sound is presented during slow-wave sleep, researchers can conclude that their sleep-induced arousal-suppression brain functions are too strong for an alarm to reliably overcome. If this is the case, the problem will be defined as a normal psycho-physiological event, rather than a training issue.

This is important because it means that behavioral interventions will not help wake children and that alternative smoke alarm sounds are worth exploring.

If training fails to make current smoke alarms significantly more effective for some children in the short term, researchers should investigate alternative stimuli cues, tone, and/or frequency . It is possible that another sound would break through the arousal suppression more efficiently than a pure tone. For instance, a voice may be impossible to ignore. Even if training is found to be effective, exploring alternative cues may also be beneficial in finding one or a combination of stimuli cues that would be more effective in alerting a broader age group.

If finding, testing, and proving that an alternative sound that wakes children is more effective than the common beeping smoke alarm employed in most residential homes, additional testing to demonstrate that the alternative sound is just as effective in waking and alerting adults also needs to be performed, or an alternative may be used in conjunction with current smoke alarm technology.

2.3 Sound Effectiveness for Older Adults

Impairments associated with the aging process, such as difficulty of hearing, predispose the elderly to accidental injuries, including injuries from fires (USFA, 1999). One-third of all persons 70 years of age and older have some form of hearing impairment. This number has remained constant for the period 1984 to 1995. As the older population increases over the next 30 years, the number of older persons with hearing impairments may increase significantly (CDC, 2001).

Hearing loss caused by noise exposure can occur acutely as a result of acoustic trauma from exposure to extremely loud noises (>120 decibels); or it may occur more gradually and insidiously over time, as a consequence of accumulated exposure to loud, but not necessarily painful, noise, i.e. noise-induced hearing loss. Given the general lack of knowledge of a person's lifetime noise exposure, it is difficult to determine whether the hearing loss manifested in a significant proportion of the elderly population, is due to a natural aging effect or to cumulative lifetime noise exposure. Age related hearing loss is more significant in men than women, and it is the upper frequency ranges that are most affected. At 65 years of age, there is a loss of approximately 30 dB with a sound source that has a frequency of 3000 Hz.

In a study (Pederson et al., 1989) that looked at hearing loss for adults age 70 and born in 1901, hearing loss was most pronounced at higher frequencies for both sexes. The study also showed that men had an average of 10 dB greater hearing loss at 8 kHz than did women.

Another study (Keay et al., 1988) tracked hearing levels of 261 randomly selected elderly people for 5 years, from 1968 to 1973. The results indicated that the deterioration rate in hearing loss is much greater for the higher frequencies, with losses of 1.89 dB annually at 6 kHz compared with 0.35 dB annually for 1 kHz.

For the older population with hearing impairment, the use of hearing aids is not very widespread as compared with use of correctional glasses (CDC, 2001). Only 76% of persons 70-74 years old with hearing impairment had seen a doctor, whereas 98% of those with visual impairment had seen a doctor. The gap dramatically increased with the number of persons over the age of 70 who wore glasses and used hearing aids. Over 98% of persons over age 70 with visual problems wore glasses, whereas only 34% with hearing impairments used hearing aids. The fact that older adults do not seek a remedy for their hearing loss may prevent them from effectively hearing a sounding smoke alarm, which likely places them at a higher risk of injury or death from fire.

The following section lists the reference and verbatim abstracts of several studies of adult hearing. Refer to the original articles for more details.

2.3.1 Past Studies of Sound Effectiveness for Older Adults

Brant, L.J. and Fozard, J.L.(1989), "Age changes in pure-tone hearing thresholds in a longitudinal study of normal human aging", <u>*J. Acoustic Soc. Am. 88*</u>*, 2, 813 – 820.*

This longitudinal study presented data on hearing thresholds for 813 males between the ages of 20-95 years. Hearing thresholds were measured at 11 frequencies ranging from 0.124-8 kHz for pure-tone audiograms. The data were collected over a 20-year period from 1968-1987. Subjects over seven 15-year age intervals (20-35, 30-45, 40-55, etc.) were observed. The males were participants in the Baltimore Longitudinal Study of Aging, a multidisciplinary community-based study of normal human aging. Changes in hearing threshold occurred in all age groups during the 15-year follow-up period. For example at 0.5 and 8 kHz for combined left and right ears, there was an average longitudinal loss of 5.7-7.6 and 5.1-21.1dB, respectively, for 20-year-olds; 10.0-12.7 and 35.2-53.0 dB for 50-year-olds; and 22.9-48.5 and 69.0-84.5 dB for 80-year-olds. Hearing loss was the greatest at the highest frequencies. The rate of change for these older males was faster in the speech-range frequencies, 0.5-2 kHz, than in the higher frequencies, since their hearing had already diminished at the high frequencies.

Pederson, K.E.; Rosenhall, U.; and Moller, M.B. (1989), "Changes in Pure-Tone Thresholds in Individuals Aged 70-81: Results from a Longitudinal Study", <u>*Audiology*</u>*,* <u>*28*</u>*, 194 – 204.*

This study presented the results of audiometric evaluation of 376 randomly selected men and women who were aged 70 years and born in 1901. This evaluation was part of a large study on a gerontological population in which the original subjects were tested again with pure-tone and speech audiometry at ages 75, 79, and 81. This study also presents audiometric results obtained at ages 70 and 75 from a second group, consisting of 297 men and women born in 1906. Hearing loss was most pronounced at higher frequencies for both sexes, and men had an average of 10 dB greater hearing loss at 8 kHz than women. The decrease in hearing threshold in men between the ages of 70 and 81 was more pronounced at 2 kHz (27 dB) than at 4 and 8 kHz (15 and 20 dB, respectively). The average hearing loss in women increased at a constant rate between the ages of 70 and 79 (15dB), while between the ages of 79 and 81 the change in pure-tone threshold was minimal. There were no significant differences in pure-tone thresholds for women born in 1901 when compared to those born in 1906 at the ages of 70 and 75. However, men born in 1906 had a more pronounced hearing loss at the age of 75 than those born in 1901.

Wallace, M.S.; Ashman, M.D., M.S., M.N.; and Matjasko, M.D., M.J. (1994), "Hearing Acuity of Anesthesiologists and Alarm Detection", Anesthesiology 81, 13-28.

This study assessed the impact of hearing loss on alarm detection. Hearing acuities of 188 anesthesiologists who volunteered to participate were measured. Subjects were divided into six age groups (25-34, 35-44, 45-54, 55-64, 65-74, and greater than 75 years of age). Abnormal audiograms were compared to the intensity and frequency of alarms in an operating room to determine which alarms were out of hearing range. The study concluded that although high-frequency hearing acuity of subjects was better than that of the general population, hearing deficits at high frequencies were of a magnitude that could interfere with alarm detection. The aging human ear may not be capable of accurately detecting some auditory alarms in the operating room. Alarm design should consider hearing acuity, because high-frequency alarms may go undetected.

Berkowitz, J.P. and Casali, S.P. (1990), "Influence of Age on the Ability to Hear Telephone Ringers of Different Spectral Content" Proceedings of the Human Factors Society 34th Annual Meeting, Santa Monica, CA: Human Factors Society, 132-136.

This study investigated the detectability of three acoustically different telephone ringer signals under two masking noise conditions (24dB quiet and 65 dBA pink noise) for two subject age groups: 20-30 years of age and over 70 years of age. Common residential telephone ringers were sampled, with three acoustically different ringers selected for study. Pure tone audiograms were administered to all subjects to determine hearing ability. Subjects' threshold levels for each ringer were then determined. Significant differences were found between the two age groups, both across telephone ringers and across noise conditions. For the older group, an advantage was found for the ringer signal that contained low- to mid-range frequency components. The results suggest that certain electronic ringers that are currently in use may be unsuitable for use by the elderly or by any individual with significant high-frequency hearing loss.

Keay, DG and Murray, JAM (1988), "Hearing loss in the elderly: a 17-year longitudinal study", Clinical Otolaryngology, 13, 31-35.

A 5-year longitudinal study into hearing levels of 261 randomly selected elderly people was performed between 1968 and 1973. Thirty-seven of 47 survivors were traced and their hearing retested with pure tone audiometry. The age range of those followed up was 80-85 years. The results indicate that the rate of hearing loss found after 5 years remained the same over the next 12 years. The deterioration rate is very much greater for the higher frequencies with losses of 1.89 dB annually at 6 kHz compared with 0.35 dB per annum for 1 kHz. The findings confirm that hearing loss continues steadily into the ninth decade.

Huey, R.W.; Buckly, D.S. and Lerner, N.D. (1994), "Audible Performance of Smoke Alarm Sounds", Designing for an Aging Population, 6-10.

Many current residential smoke detectors have alarms with a frequency in the 4000 Hz region. Additionally, many of these alarms are constant instead of providing temporal modulation of the signal [*at the time of the study*]. This study analyzed a variety of alternative sounds for selection as a better choice for older consumers. A battery of candidate sounds was presented to pairs of subjects aged 65 and older with varying levels of hearing impairment (0 to 45 dB) in their own homes to see which sounds performed best in terms of detection, localization, and attention-getting value. Subjects were placed in various locations and masking-based conditions within their homes during listening periods and subjected to sounds played at a constant level. A computerized system collected response data as the battery of sounds was presented. The data showed improved performance in detection and localization as the sounds decreased from 4000 Hz to 500 Hz and when sounds had a fast modulation rate.

2.3.2 Discussion

Adults experience hearing losses at most frequencies as they age, and the rate of hearing loss is greatest at higher frequencies (above 2 kHz).

The frequency of residential smoke alarm horns is typically from 3.5 kHz to 4 kHz, the same range in which older adults typically experience greater hearing losses. Therefore, lowering the frequency of a smoke alarm horn to a range in which hearing loss is slower (e.g., below 2 kHz) may make the sound of a smoke alarm audible for a much larger percentage of older adults. In one study (Huey, et al., 1994), there was improved performance in detection and localization of an alarm sound if the sound decreased from 4000 Hz to 500 Hz and had a fast modulation rate.

If a lower frequency alarm or other sound characteristics prove to be more effective for older adults than the present smoke alarm sound, additional testing will need to be performed to demonstrate that the lower-frequency alarm is just as effective as current alarms in waking and alerting the other adult age groups, or whether it may be used in conjunction with current alarm technology.

3.0 POSSIBLE TECHNICAL SOLUTIONS

This section examines potential technical solutions that may be effective for waking children and for alerting older adults to a smoke alarm. The discussion considers the possible advantages and disadvantages that might be associated with certain technological solutions.

3.1 Technical Solutions for Waking Children to Smoke Alarms

In the event a smoke alarm activates, the underlying goal is for a child to safely exit the home. Children under 5 years old do not have the mental or physical capabilities to reliably escape a fire or emergency during the night without the assistance of an adult. This is especially true for infants and toddlers who may be sleeping in cribs. For children between the ages of 5 and 16 years, a number of studies and non-scientific media demonstrations have shown that they do not reliably wake to the sound of a smoke alarm.

Technical solutions that may be used to wake children and notify them of a fire or smoke condition can be viewed as either a direct method or an indirect method. Direct methods are those solutions that would directly wake and notify a child of a fire and/or smoke condition, and the child would exit the home without intervention from an adult. Since children may not act appropriately after awakening, this method may not be ideally suited for children. Indirect methods are those solutions that would wake an adult – perhaps sooner than current technology smoke alarms – and the adult, in turn, would wake and assist the child in exiting the home. Studies have shown that adults reliably wake to the sound of a smoke alarm if not hindered by medication, alcohol, drugs, or sleep deprivation.

Direct and indirect technical solutions will be examined to determine what potential solutions exist that may result in a child safely exiting a home in a fire situation.

3.1.1 Direct Methods

In this section, technical solutions will be explored that would directly wake/notify a child of a fire or smoke condition. These are not the only technical solutions that may be feasible but, rather, ideas that can lead to further discussion. These direct methods should result in the child exiting the home without intervention from an adult. As mentioned before, since children may not act appropriately after awakening, this method may not be ideally suited for children.

One solution would be an alarm or warning that effectively wakes both adults and children, who exit the home simultaneously, as depicted in Figure 5. This scenario provides the greatest escape time for family members, but it is most likely that parents would not exit the home without first getting their children. This solution would be most relevant in scenarios where the path between the parents and the children is impassible, due to fire or smoke. The parents and children would leave the home through different exits.

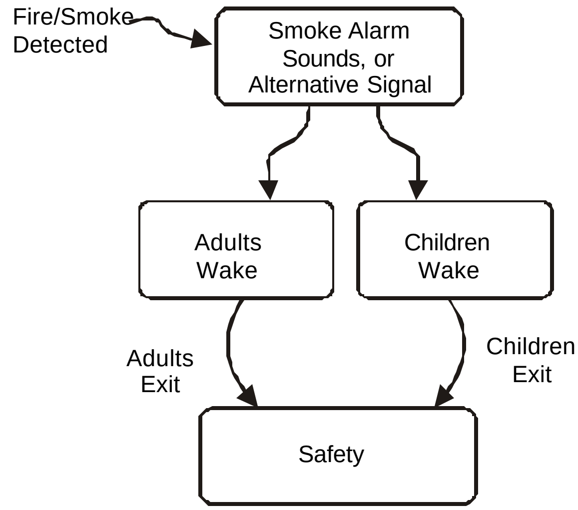

Figure 5. Using Direct Methods to Safely Exit Home

Possible solutions include alternative sounds, strobe lights, or motion. Alternative sounds could range from a familiar voice to a distinctive sound pattern and/or frequency.

Sound identification is an important aspect in alerting occupants that a hazard may exist. Smoke alarms are designed to convey the message that a fire is occurring in the home. Few studies on the identification of meaningful, non-speech, environmental sounds have been conducted. In a study (Ballas, et al., 1987) conducted by researchers at Georgetown University, two sets of 19 sounds were used as the stimuli. In order to determine the effects of stimulus sampling bias and the reliability of the uncertainty, two examples of each sound were recorded and one example was used in each set. The 19 sounds included sounds of animals, a baby crying, church bells, an ambulance siren, etc. In the study, two groups of students (high school and college) listened to the sounds. The results showed that the subjects varied in their ability to identify the different sounds in each set, but the signaling sounds, church bells and ambulance siren, were accurately identifiable in both sets.

Another study (Lynch, 1997) was conducted to determine if the sense of smell would wake a human to a smoke odor stimulus. The study involved 10 adult subjects who ranged in age from 26 to 61 years old. Three test conditions were used in the study. The first was an odorless placebo of only drinking water. The second was a food additive used in barbecue sauces to create a smoke flavor. The food additive, produced from pyrolysis of hardwoods, was described as having a smell similar to that of smoke from a house fire. The third was a strong citrus smell. Prior to the testing, the participants were asked to identify the odors. If the participants were awakened by an odor, they were asked to identify the odor. The study showed that all 10 subjects correctly identified all three test conditions while awake or before sleeping. Two of the 10 subjects, or 20%, were actually aroused out of stage 2 sleep by the stimulus of the smoke odor. None of the subjects were awakened by the stimulus of the citrus odor. The study concluded that olfactory functions cannot reliably wake individuals and recommended that fire prevention programs should include this information.

The unique features of an auditory alarm would have corresponding advantages and limitations in warning an occupant. Table 4 lists characteristics and features of certain other types of audio alarms (Deatherage, 1972).

Table 4. Characteristics and Features of Certain Types of Audio Alarms

Alarm	Intensity	Frequency	Attention-getting ability	Noise-penetration ability
Diaphone (foghorn)	Very High	Very Low	Good	Poor in low-frequency noise
Horn	High	Low to High	Good	Good
Whistle	High	Low to High	Good if intermittent	Good if frequency is properly chosen
Siren	High	Low to High	Very Good if pitch rises and falls	Very good with rising and falling frequencies
Bell	Medium	Medium to High	Good	Good in low frequency noise
Buzzer	Low to Medium	Low to Medium	Good	Fair if spectrum is suited to background noise
Chimes and gong	Low to Medium	Low to Medium	Fair	Fair if spectrum is suited to background noise
Oscillator	Low to High	Medium to High	Good if intermittent	Good if frequency is properly chosen

(Deatherage, 1972)

When selecting a frequency for an alarm or warning, the frequency and sound pattern should be considered. The following guide may be useful in producing a more audible alarm:

- Use frequencies between 500 and 3000 Hz, because the ear is most sensitive to this middle range.
- Use frequencies below 1000 Hz when signals have to travel long distances, because high frequencies do not travel far.
- Use frequencies below 500 Hz when signals have to "bend around" major obstacles or pass through walls.
- Use a modulated signal. For example, use a warbling sound varying from 1 to 3 times per second since it is different enough from other daily sounds such as microwave beeping, clothes dryer buzzer, etc.
- Use signals with frequencies different from those that dominate any background noise (air conditioner, power tools, etc.) to minimize masking.

It is not clear that increasing the volume of the current smoke alarm signal would be helpful in alerting either elderly hearing-impaired adults or sleeping children to a fire situation. Evidence suggests that, depending on the stage of sleep, children can sleep soundly through extremely loud sounds of up to 120 dB (UL, 2003). For elderly adults who have lost the ability to hear the high frequency tones used in current alarms, increasing the volume is unlikely to be beneficial. However, it is possible that louder alarms at lower frequencies might be able to awaken young children and hearing impaired adults, and this should be investigated. In increasing the volume of the alarm, it is important to consider the risks and benefits. Certainly, routine exposure to loud noises can result in damage to hearing that is typically manifested later in life. However, it does not seem appropriate to restrict the volume of an alarm, that can make the difference between life and death, to the time weighted average (TWA) exposures for noise in occupational settings that are currently recommended by the National Institute of Occupational Safety and Health (NIOSH). NIOSH's current recommended noise exposure limits (for workers without hearing protection) are based on an 85 dB, A-weighted noise exposure over an 8 hour exposure period. NIOSH employs a 3 dB exchange rate, meaning that for every doubling of sound energy (3 decibel increase) the exposure time must be halved. This means that alarm signals of 109 decibels for 1 minute and 53 seconds, or 112 dB for almost one minute (56 seconds) would still fall within the acceptable exposure limits recommended by NIOSH. Given that house occupants need to exit the home as rapidly as possible in the event of a fire, the exposure to the loud alarm is likely to be self-limiting. If they do not hear or react appropriately to the alarm, they are likely to perish; thus, fear of delayed hearing impairment does not appear to be the primary safety concern.

Strobe lights have been used in some non-scientific studies in waking children. Past studies have been conducted to determine the effectiveness of strobe lights for waking adults. Using strobe lights to awaken an individual may not be very effective unless the individuals is conditioned to waking to this type of cue.

Motion or vibration is a feasible method for waking an individual but may not be practical for waking children. Vibrating pillows are sometimes used to awaken deaf individuals. These devices may have limited effectiveness on children because children tend to move around more while sleeping; hence, their heads may not be on the pillow. The motion may also not be sufficient to "break through" their deep sleep stage.

3.1.2 Indirect Methods

If a direct technical solution cannot be found, indirect methods may be effective. In this scenario, when fire or smoke is detected and an alarm is sounded, the adult(s) would need to rescue the children and exit the home, as shown in Figure 6. This may require additional escape time compared to the direct method previously shown. Depending on the locations of the bedrooms and the number of children in the home, the amount of time for the adult to wake all the children and exit the home can vary greatly. For example, if the adult's bedroom is on the first floor and the children's bedrooms are on the second floor, the additional time to exit the home could be significant. However, if the adult's bedroom and the children's bedrooms are adjacent to each other, the additional time to exit the home may be very small.

Using this approach produces technical and scenario challenges, if the path to the child is blocked by smoke and fire. In this situation, it would be beneficial for the children to wake on their own and follow a rehearsed escape plan; but, of course, this would not be feasible for infants/children sleeping in cribs.

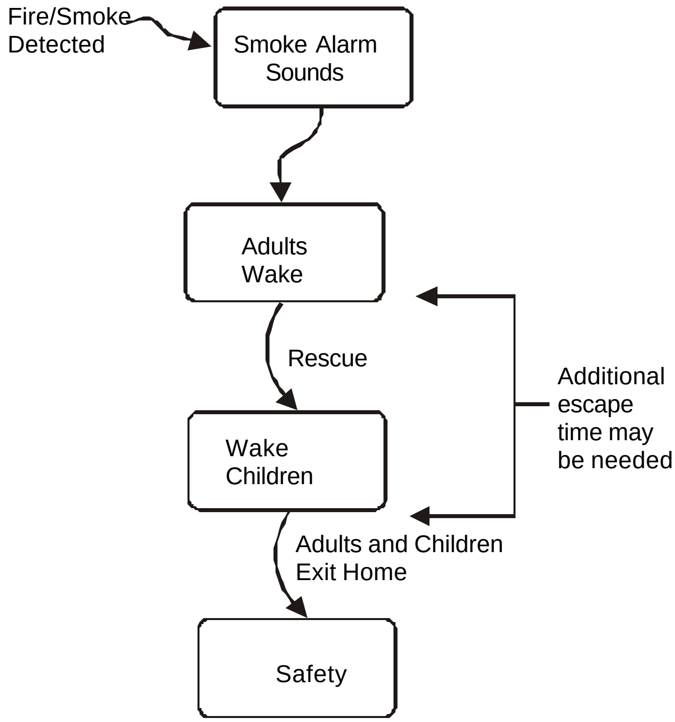

Figure 6. Using Indirect Methods to Safely Exit Home

In this scenario, technical solutions to notify or wake an adult sooner to allow additional time to rescue or wake the children and exit the home would be beneficial. Alternative smoke alarm sensors or improved methods for detecting fire/smoke earlier and alternative locations of smoke alarms for improved detection and notification would be technical methods for attempting to alert the adult of fire/smoke earlier. Combination sensors – for example, ionization/photoelectric and CO sensors – may be better at discriminating between smoke from real fires and nuisance sources. Improved source discrimination may allow lower sensor thresholds for fire detection. This may allow earlier detection of fire and increase the amount of escape time.

3.2 Technical Solutions for Alerting Older Adults

For older adults, one technical solution would be to lower the frequency of the smoke alarm horn to an audible range similar to speech (approximately 1,000 Hz) where older adults retain more of their hearing. For an AC powered smoke alarm, it may be possible to power the horn below the 2 kHz range with the appropriate dB output. However, an alerting sound frequency below 2 kHz may not be feasible in a battery-operated smoke alarm because of the amount of power required to drive a horn in that frequency range with the required dB output. There may be some challenges in packaging a 2 kHz horn in the same size (or slightly larger) smoke alarm housing, and there may be additional challenges if a 9-volt battery backup power supply is required. An alternative might be for a smoke alarm to signal a secondary device – plugged into a home's outlet with battery back-up – to produce an alarm in the 1-2 kHz range with the required 85 dBA output. The secondary unit could be triggered by current technology smoke alarms.

Presently, one manufacturer produces a low-frequency smoke alarm for residential installation. The device uses a standard smoke alarm with a second speaker that produces tones at 250 Hz and 2500 kHz. The device is a stand-alone unit and does not allow interconnection to other smoke alarms.

Devices for the hearing impaired are already on the market. The smoke alarms incorporate a strobe light that flashes when alarming. These devices cost approximately $200 more than ionization smoke alarms without the strobe. The strobe light may not be effective in waking adults who are not hearing impaired since they may not be conditioned to wake to this type of cue, as would someone who is deaf.

Other options include secondary devices that produce alternative sounds when triggered by current technology smoke alarms. Smoke alarms with high and low frequency combinations may also be effective in alerting occupants with a wide range of ages. A voice may also be effective as an alarm since speak is typically around 1 kHz frequency.

Considering the number of older adults with hearing impairments who choose not to use a hearing aid, additional research appears necessary to determine if they would benefit from, and choose to install, an alternative device that produces a different frequency when a smoke alarm sounds.

3.3 Implementing a Technical Solution

If an alternative sound is determined to be more effective at waking children and adults, one obvious technical solution would be to incorporate that alternative sound (e.g. voice, or alternative frequencies and patterns) into all smoke alarms.

A less obvious alternative would be to implement a technical solution at a point source, rather than have the technical solution incorporated into a smoke alarm. For example, a device with an alternative sound could be installed where needed – for example, in a child's bedroom or a grandparent's bedroom. The device that outputs the alternative sound could be installed as a secondary unit that is triggered by the sound of a smoke alarm, as depicted in Figure 7a. The secondary unit could also be triggered by a signal on the home's wiring system if the smoke alarm is AC powered, as shown in Figure 7b. This method would be more complicated and would require a compatible smoke alarm that outputs a signal on the AC line when it alarms.

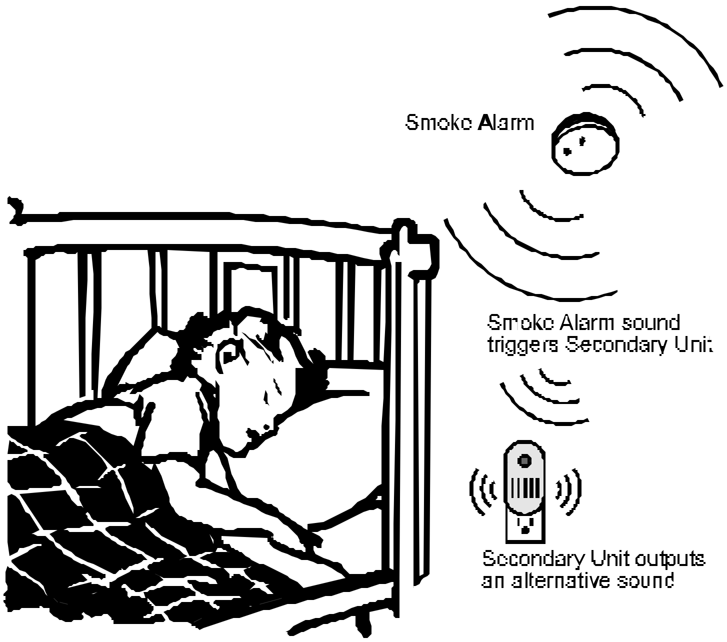

Figure 7a. Secondary Unit Triggered By Smoke Alarm Sound

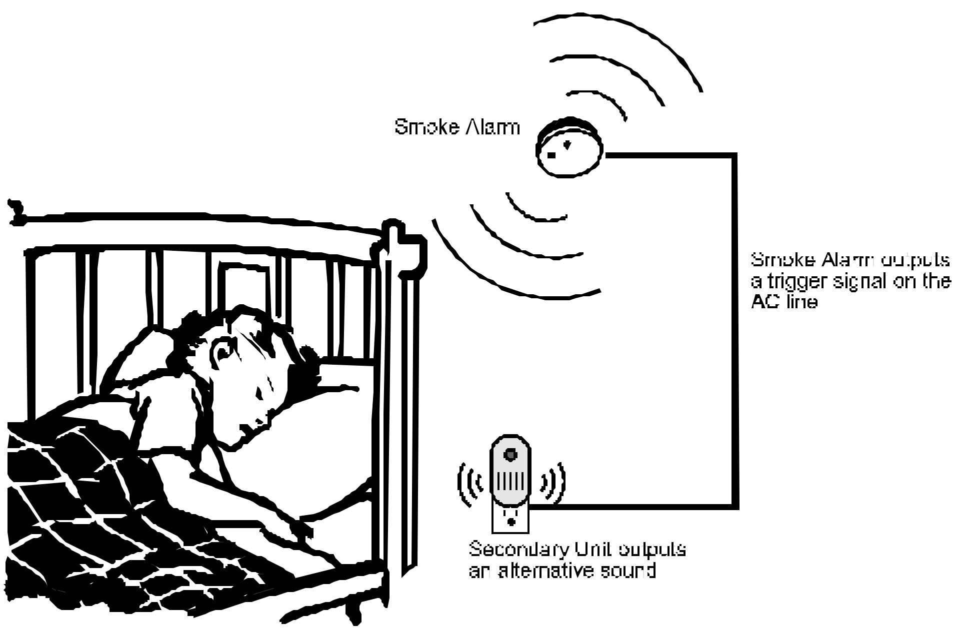

Figure 7b. Secondary Unit Triggered by Signal on the AC Line

Incorporating "satellite" smoke detection devices that communicate with smoke alarms in the home may also provide earlier detection of smoke and fire. The satellite smoke detectors could be placed in various rooms in the home, as shown in Figure 8. If smoke were detected at a satellite unit, the unit would transmit a signal to the smoke alarms and the smoke alarms would sound. This would provide the advantage of additional coverage in a home and earlier detection, since the satellite smoke detectors may be closer to the fire than the smoke alarms. This may be a more cost-effective method in gaining more coverage without the need to install smoke alarms in every room or multiple smoke alarms in large rooms.

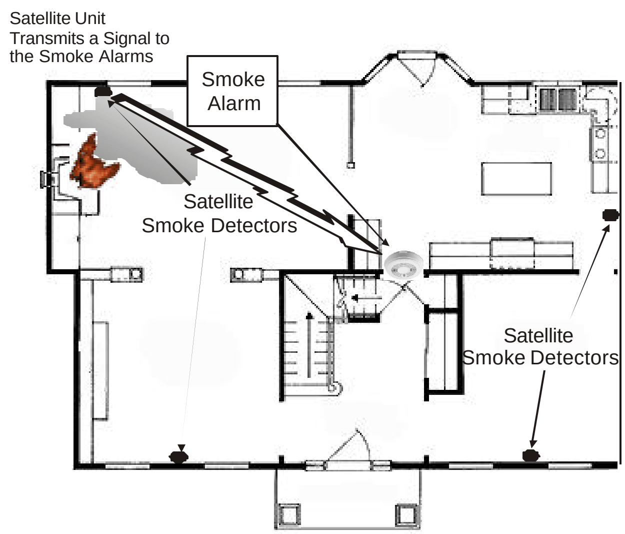

Figure 8. Satellite Smoke Detector Units

An alternative technical solution is to have an adult remotely awaken and instruct a child in a different part of the home. This may provide additional escape time for family members, but again most parents would likely not exit the home without first getting their children. This may have some advantages over the *Direct method*, where the parents and children awaken separately and exit the home, since children may not act appropriately after awakening. The parent's voice may help to calm frightened children and remind them of the appropriate actions in the rehearsed fire escape plan.

In this scenario using this alternative technical solution, the adult is awakened or notified of smoke or a fire condition, by a smoke alarm. The adult then notifies or wakes the children with voice or an alternative alarm using a remote communicator and a receiver unit located in the child's bedroom, as shown in Figures 9 and 10. In this solution, a transmitter unit could be placed in the adult's bedroom and receivers placed in all the children's bedrooms. When the smoke alarm sounds, the adult would speak into the transmitter unit to tell the children to wake up or give additional or alternative instructions. This method could not only be used to wake a child with a familiar voice and/or sound, but the adult could also voice rehearsed or new instructions. This could also allow the adult to awaken and keep the child calm until the parents reach the child's bedroom. This method would allow the adult to give instructions for a particular scenario whereas, in a secondary unit with a prerecorded instruction, the instructions may not be appropriate for every scenario.

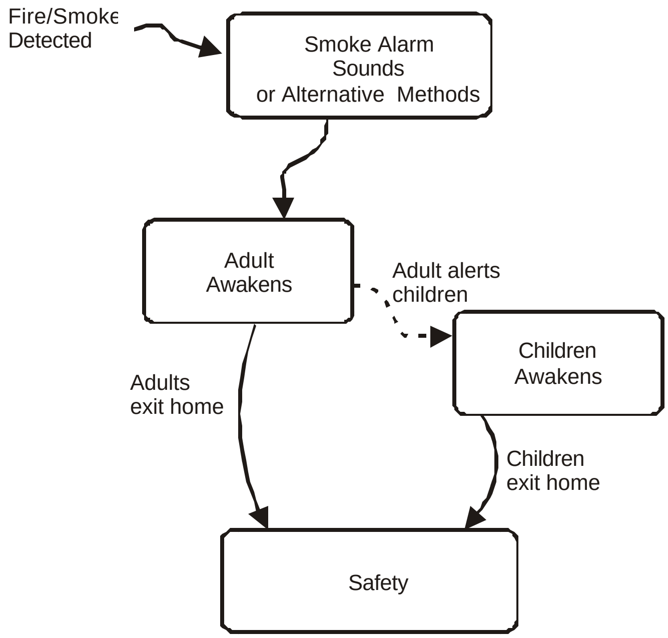

Figure 9. Remotely Notify Occupants in the Home

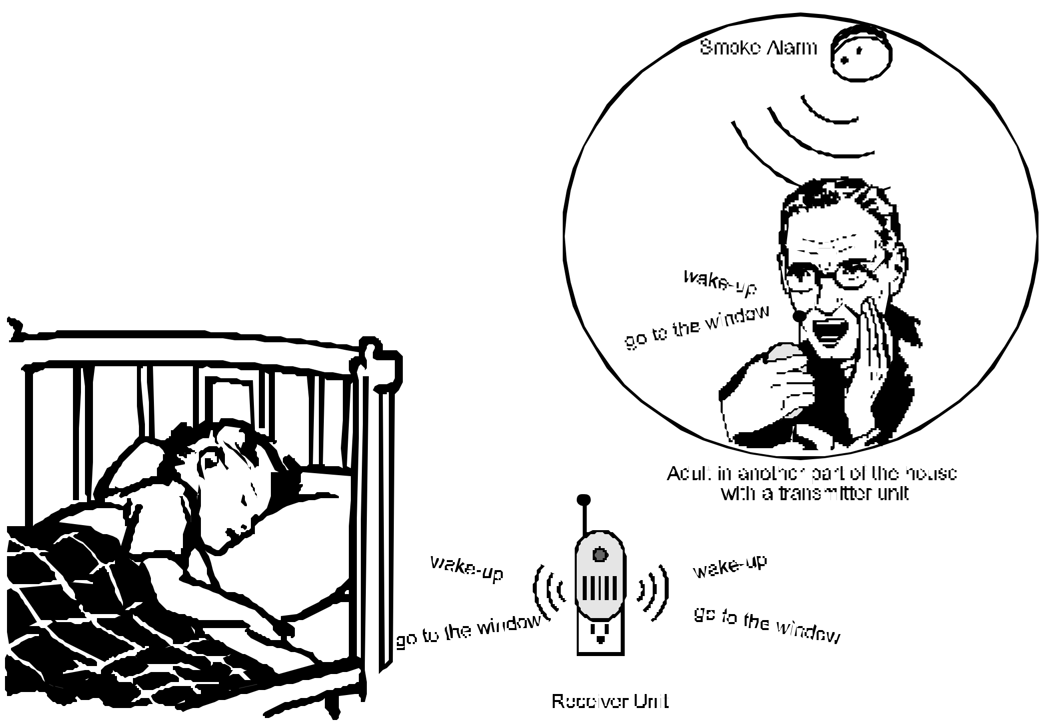

Figure 10. Remote Alerting System

3.3.1 Interconnected Smoke Alarms and Signaling Devices

NFPA 101 *Life Safety Code* requires all smoke alarms in new residential construction to be interconnected, and NFPA 74 *Standard for the Installation, Maintenance and Use of Household Fire Warning Equipment* (the standard was renamed in 1993 to NFPA 72 *National Fire Alarm Code*) has required interconnected smoke alarms in new construction since 1989. Interconnection allows all the smoke alarms to sound if any individual alarm detects smoke. This increases available escape time and life protection for the occupants if a smoke alarm happens to sound in a different area in the home. However, this requirement is only applicable to smoke alarms that are powered by 120 VAC (house wiring).

A large number of homes were constructed before smoke alarms were required, and battery-operated smoke alarms were installed. These homes do not have the added protection of all units alarming when a single smoke alarm has detected smoke. Battery operated smoke alarms installed in the bedrooms are usually not interconnected to any other smoke alarms in the home. If the bedroom doors are closed at night, the occupants may not hear a smoke alarm sounding in another part of the home. This can decrease the amount of available escape time, allowing the home to become untenable from smoke, heat and toxic gases before the occupant can react and try to escape.

In 2002, CPSC contracted with Naval Research Laboratory (NRL) to investigate the feasibility of incorporating wireless communication technology in a battery-operated smoke alarm. This work was conducted in two phases: a literature search on smoke alarms, wireless technology, and alternative power sources (NRL, July 2003); and a demonstration of prototype alarms (NRL, Dec 2003).

The project showed that incorporating wireless communication in battery-operated smoke alarms is feasible. The prototype wireless smoke alarms operated in a manner similar to hardwired, interconnected smoke alarms. When one of the wireless smoke alarms sounded, it signaled the other wireless smoke alarms to sound. The wireless smoke alarm could provide homeowners with a lower cost alternative to installing interconnected smoke alarms without running electrical wires in the walls. This technology could be especially useful in older homes – homes built before hardwired smoke alarms were required. Wireless smoke alarms could increase the amount of escape time available to occupants before a home becomes untenable from smoke, heat and toxic gases.

Incorporating two-way communications between smoke alarms could provide many opportunities for future fire safety and prevention. Figure 11 shows the possible uses for "smart" smoke alarms that can communicate with each other or other appliances and devices. In this figure, a cooking range is equipped with a fire detection system that has transmitted a signal to the closest smoke alarm, indicating a fire has occurred or will imminently breach the appliance. The smoke alarm then transmits a signal to sound all the other smoke alarms.

A smoke alarm could also be equipped to transmit a signal to other devices. For example, the smoke alarm could transmit a signal to:

- a hearing aid that could then output either a voice or a selectable frequency tone indicating an emergency or fire
- a secondary unit, which could output an alternative warning sound or a prerecorded voice with instructions. The secondary unit could be located in a child's bedroom, in an older person's room, or in a remote section of the home (garage, shed, basement)
- a monitoring device that would dial the occupant's mobile phone or alternate number, or it could dial fire and rescue services
- automated devices that turn lights on, turn off the HVAC system, unlock a pet door allowing the family dog or cat to exit the home
- shut off loud power tools so an occupant can hear the smoke alarm sounding.

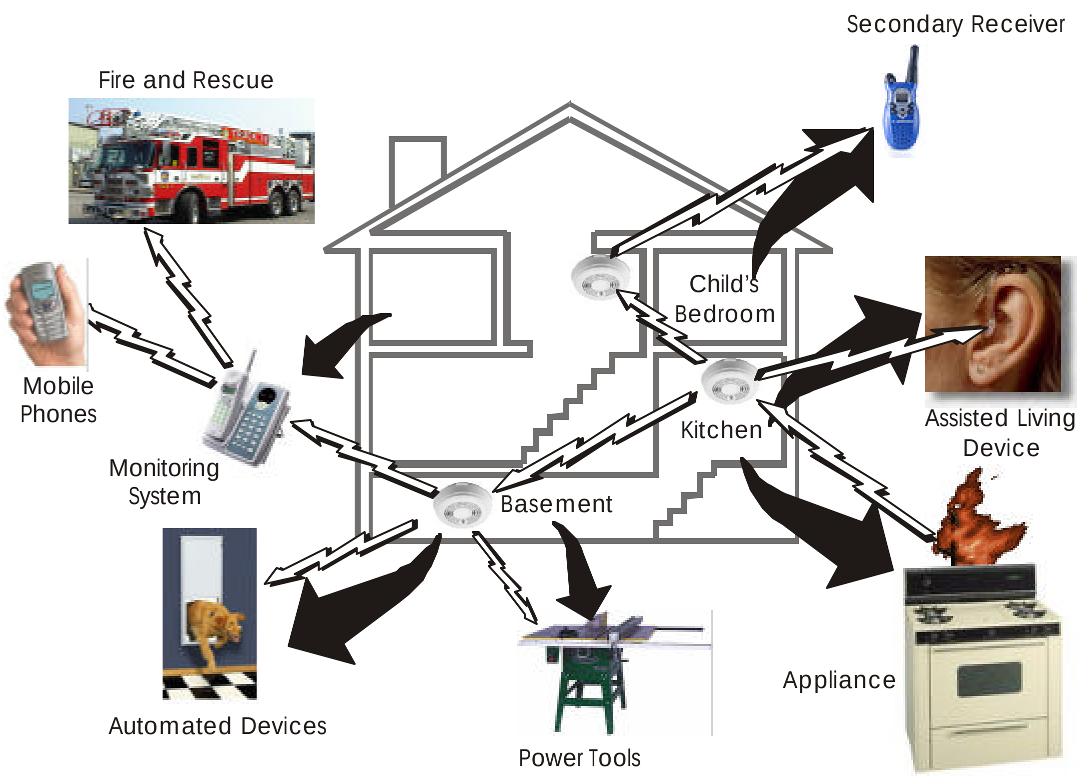

Figure 11. Future Possibilities for Fire Safety and Smoke Alarms

4.0 DISCUSSION

The success of a smoke alarm in preventing injury is also dependent on the configuration of the home and on the occupants. One study (Proulx, 2000) explains why building occupants ignore fire alarms. Although this research investigates occupant responses in commercial buildings, there are many similarities to occupants of homes. Proulx lists four main objectives that a fire alarm is designed to accomplish.

- Warn occupants of a fire.
- Prompt immediate action.
- Initiate evacuation movement.
- Allow sufficient time to escape.

Proulx states that there can be many reasons why occupants may not respond or react quickly enough in an emergency, but the following list captures the most likely reasons:

- The occupant does not hear the alarm.
- The occupant fails to recognize the alarm.
- The occupant ignores the alarm (example - nuisance alarming, frequent false alarming).

An occupant may not hear an alarm for several reasons, including:

- The background noise is excessive.
- The occupant has partial hearing loss preventing them from hearing the high frequency.
- The occupant is located in one part of the home, and the smoke alarm sounds in another part of the home.
- The occupant is in deep sleep.
- The occupant is under the influence of drugs or alcohol.

The occupant's response to an alarm is affected by their ability to distinguish between the occurrence of a fire alarm and other forms of alarm. In the work of Tong and Canter, 1985, 45% of the sample population (taken from a street survey of 71 random individuals) could not distinguish between the occurrence of a fire alarm and a number of other less vital warning systems (e.g. car horn, security alarms, etc.). An explanation for this misinterpretation may be due to a proportion of the population having hearing difficulties; however, this proportion may not be great enough to explain this finding. This misinterpretation may result in a delay in exit from the home. The misinterpretation may also be especially apparent in urban areas populated by a large number of occupants, where the noise levels are high and the sound of an alarm is more frequent.

Successive nuisance alarming may cause an occupant to either disable a smoke alarm or begin to ignore the smoke alarm warning. The first is detrimental because it leaves the occupant unprotected in the event of fire. Ignoring the smoke alarm can have almost the same effect as a disabled smoke alarm because the occupant does not react immediately and therefore compromises his/her ability to escape.

4.1 Children Not Waking by Smoke Alarm Signal

Two possible approaches for achieving the final goal of improving the chances that children will survive a fire are as follows. One approach would be to increase the likelihood that children will awaken to the sound of a smoke alarm and follow the family's fire escape plan. Technical solutions to accomplish this may be alternative alarm sounds (prerecorded or remote voice, frequencies, variable frequencies), strobe light, or motion. This approach may be undesirable because it would place responsibility on the child to wake, identify and respond to an emergency. Children should not be relied upon to be consistently conscious of hazards to themselves, nor should they be expected to act appropriately in the event of a real fire - especially if it has been some time since the last fire escape training occurred. The amount of time that a child retains the necessary information to reliably perform a fire escape plan is unknown, but the general recommendation in the fire community is to review and conduct the fire escape plan at least twice a year.

If an alternative sound and/or method of waking children proves to be more effective than the present technology, additional testing would be required to demonstrate that the alternative alerting method would also be effective for adults, sleeping and awake. Sufficient studies have demonstrated that the present smoke alarm is effective in alerting and waking adults, if not hindered by drugs, alcohol, or sleep deprivation. The present smoke alarm sound should not change until sufficient data demonstrates that an alternative sound or method is as, or more, effective than the present smoke alarm sound, in both adults and children, sleeping or awake.

The other approach is to wake adults sooner in a fire, giving them additional time to retrieve and assist the children in exiting the home. Technical solutions to accomplish this may include combination sensors to detect smoke and fire faster, remote smoke detectors, interconnected battery operated smoke alarms, and interconnected smoke alarms in the bedrooms.

A combination of methods that effectively wakes children and provides earlier detection of smoke and fire may be the best way to prevent fire deaths. This would allow adults and children to be awakened and alerted during early development of smoke and fire, thus increasing their available escape time. The success of this technical approach would depend on effectively developing, implementing, and practicing a fire escape plan.

4.2 Older Adults Unable to Hear Smoke Alarms

Older adults generally experience hearing loss, and it is the upper frequency ranges that are most affected. At 65 years of age, there is a loss of approximately 30 dBA with a sound source that has a frequency of 3000 Hz. Lowering the frequency of smoke alarms, either a single tone or a modulated signal, may be more effective in alerting all adult age ranges. Incorporating voice in the alarm may also be a solution since voice is usually around 1,000 kHz.

One challenge to lowering the smoke alarm frequency would be to incorporate a speaker/horn in a similar size smoke alarm package that can be powered by a battery and meet voluntary standard requirements for battery life.

Other potential solutions include the use of devices with alternative sounds that could be triggered by the sound of a smoke alarm or by a signal on the home's wiring system. Solutions could also include smoke alarms that can communicate with other appliances and devices, such as hearing aids, and output either a voice or a selectable frequency tone indicating an emergency or fire.

4.3 Multiple Smoke Alarms

If an alternative smoke alarm sound is determined to be more effective in waking and alerting a wider range of ages, implementing the new sound may present some technical and logistical challenges. Tests would need to be conducted to determine whether the sound is as effective when multiple smoke alarm sounds are activated. The following should be considered when an alternative alerting sound is used:

- Is the alternative smoke alarm sound more effective than the traditional smoke alarm sound in the same or adjacent room?
- If voice is the alternative alerting sound, can the message be recognizable when multiple, non-synchronized voice alarms are sounding?
- Is the alternative sound, which may be widely used for different purposes in other countries, effective for different cultures?
- The home may have non-English speaking occupants. Does a voice alarm device allow for multi-lingual occupants?
- If voice is the alternative alerting sound, can the message be recognized over loud background noise such as television, radio, or conversation?

5.0 CONCLUSIONS AND RECOMMENDATIONS

The following conclusions are based on the information presented in this report:

- Children under the age of 16 have longer periods of deep sleep compared to adults.
- Current smoke alarms do not reliably wake children under the age of 16.
- With the present fire data, there is no conclusive evidence that children have a higher fire death rate because of their inability to wake to a smoke alarm.
- Current smoke alarms are effective in waking most adults with normal hearing who are not under the influence of drugs, alcohol, or sleep deprivation. Current smoke alarms do not reliably wake people under the influence of drugs, alcohol, or sleep deprivation.
- Current smoke alarms may not reliably notify or alert seniors with hearing loss.

- The fire death rate for older adults is higher than the national average. This may be attributed to many factors – reduced mobility and awareness, loss of hearing, etc.

- Various home configurations and locations of smoke alarms can limit the transmission of sound throughout the house.

- Interconnected smoke alarms can provide earlier warning of smoke and fire.

- The addition of interconnected smoke alarms inside bedrooms may provide improved warning of smoke and fire where bedroom doors are closed.

- Alternative warning systems and sounds warrant further exploration to account for as many home configurations and occupant needs as possible.

Additional research is needed to better understand what potential deficiencies exist regarding the audibility of smoke alarms. The CPSC staff believes the following areas of research need to be explored to help determine possible technical solutions and/or develop public education campaigns:

Changing the Smoke Alarm Frequency

This area involves examining possible technical solutions to lowering the smoke alarm frequency below 2 kHz or implementing a high-low frequency combination. The study would examine commercial alarms that produce alarms in the lower frequencies and determine if they can be incorporated into residential smoke alarm designs. If an alternate frequency or alarm sound is determined to be successful at alerting the older population, the same frequency or alarm should be tested for effectiveness on other age groups. Preferably, the "new" smoke alarm with the improved alarming should also be powered from only a battery to address homes that do not have hardwired smoke alarms. The study would have adults and seniors listen to the lower frequency (or possibly modulated) signal to determine effectiveness of attention getting and perceived urgency.

Training Approach vs. Sleep-Induced Incapacity

Studies have shown that children are difficult to wake with the sound of a smoke alarm. It has also been shown that children have longer periods of deeper sleep than adults. The objective of this study would be to determine whether children could be awakened by an alarm through training. This study would determine if children sleep through an alarm due to a sleep-induced incapacity to perceive sounds or a lack of training and motivation to respond to a sound that they can hear but just do not recognize or care about. The study would train a group of children to recognize their home alarm's sound. A valued awards system would be used to help motivate them in responding to the alarm sound during the night. The children would be trained to the alarm sound during waking hours so that the alarm sound becomes salient and be reminded that they will be rewarded if they hear the sound. The subjects will not be forewarned of when the actual night test would occur. Preferably, the actual alarm testing at night should occur when the subjects are in the slow-wave sleep. Following training, the subjects would be exposed to the smoke alarm sound when asleep. The study will help determine if their sleep suppresses their capability to hear the smoke alarm sound or if highly motivated training is an effective method of overcoming their sleep.

Exploration of Alternative Cues

If the problem is a physiologically induced perceptual impairment, can another cue, besides an electronic tone, reliably wake children? Possibilities include flashing strobe lights, a voice, musical sounds, or environmentally meaningful static noises like crackling leaves (similar to wood burning) or rushing water. The study would select a number of cues that may differ substantially from normal smoke alarms to provide a possible alternative. Preferably, the testing should occur at night when the subjects are in the slow-wave sleep. If the subjects respond to a specific cue, the same cue should be repeated with different aged children to determine the reliability of awakening.

Smoke Alarm Sound Uniqueness

If children or adults cannot identify a smoke alarm sound when they are awake, it would be assumed that they would have a lower probability of recognizing the sound when they are asleep. The study would examine the present smoke alarm pattern and tone (at a lower sound level) to determine if it is similar to other daily sounds. The study would have children and adults listen to various alarms, tones, and other daily sounds to determine if the smoke alarm sound is identifiable and unique. Other daily sounds can be microwave beeping, open car door with keys in the ignition, car horn, security alarms, other alarms, doorbell, etc.

Improving the Detection of Smoke Alarms

The study would examine possible technical solutions in increasing the detection of smoke without increasing nuisance alarms. Possible technical solutions may require different or combination sensors. The sensor(s) may help better discriminate actual smoke from other false inputs such as aerosols, steam, and normal cooking. The combination or alternative sensors may be able to detect smoke sooner, allowing more escape time for the occupants. The alternative or combination sensors would be tested to determine if they perform better than present ionization and photoelectric smoke alarms.

Determining the Effectiveness of Various Alerting Cues Sounding Simultaneously in a Residential Home

The study would examine the effectiveness of different alarm cues sounding simultaneously. The study would examine the present smoke alarm pattern with alternative alarm sounds in the home to determine if the alternative alarm sounds are still recognizable. The study would test and record multiple alarm sounds in the home to determine if the alternative (such as voice) or the present smoke alarm sound is still identifiable and unique.

6.0 REFERENCES

Acoustical Society of America (ASA). Reaffirmed 2001. *American National Standard, Audible Emergency Evacuation Signal*. ANSI S3.41-1990 (ASA 96-1990). Accredited Standards Committee S3, Bioacoustics. New York, New York.

Ahrens, Marty. June 2003. The US Fire Problem Overview Report Leading Causes and Other Patterns and Trends. Quincy: National Fire Protection Association.

Ahrens, Marty. November 2003. *US Experience with Smoke Alarms and other Fire Alarms*. Quincy: National Fire Protection Association.

Ballas, J.A., Dick, K.N., and Groshek, M.R. 1987. "Failure to Identify "Identifiable" Sounds." Proceedings of the Human Factors Society – 31st Annual Meeting, Georgetown University.

Berkowitz, J.P. and Casali, S.P. 1990. "Influence of Age on the Ability to Hear Telephone Ringers of Different Spectral Content." Proceedings of the Human Factors Society 34th Annual Meeting, Santa Monica, CA: Human Factors Society, 132-136.

Bruck, D. 1999. "Non-awakening in children in response to a smoke detector alarm." *Fire Safety Journal* 32: 369-376.

Bruck, D. 2001. "The who, what, where and why of waking to fire alarms: A review." *Fire Safety Journal* 36: 623 –39.

Bruck, D. & Horasan, M. 1995. "Non-arousal and non-action of normal sleepers in response to a smoke detector alarm." *Fire Safety Journal* 25: 125-139.

Busby, K.A., Mercier, L., & Pivik, R.T. 1994. "Ontogenetic variations in auditory arousal threshold during sleep." *Psychophysiology* 31: 182-188.

Centers for Disease Control and Prevention. March 2001. *Trends in Vision and Hearing Among Older Americans*.

Code of Federal Regulations 16 Commercial Practices. January 1, 2003. Part 1210 – Safety Standard for Cigarette Lighters, Part 1212 – Safety Standard for Multi-Purpose Lighters.

Duncan, C. 1999. "The effectiveness of the domestic smoke alarm signal. Fire Engineering Research Report 99/5." Supervised by Charles M. Fleischman. Presented as a project report in partial fulfillment of the M.E. (Fire) degree of the University of Canterbury, Christchurch, New Zealand. ISSN 11734996.

Federal Interagency Forum on Age-Related Statistics. August 2000. *Older Americans 2000: Key Indicators of Well-Being.* Washington DC: United States Government Printing Office.

Hall, John. May 2004. *Characteristics of Home Fire Victims including age and Sex*. Quincy: National Fire Protection Association.

Halliwell, R.E. and Sultan, MA. 1986. "Guide to Most Effective Locations for Smoke Detectors in Residential Buildings." *Building Practice Note 62,* Ottawa: Division of Building Research, National Research Council Canada.

Huey, R.W.; Buckly, D.S. and Lerner, N.D. 1994. "Audible Performance of Smoke Alarm Sounds." *Designing for an Aging Population:* 6-10.

Keay, DG and Murray. 1988. "Hearing loss in the elderly: a 17-year longitudinal study." *Clinical Otolaryngology* 13: 31-35.

Lynch, J.L. June 1997. "Nocturnal Olfactory Response to Smoke Odor." An aplied research project submitted to the National Fire Academy as part of the Executive Fire Officer Program, Irondale Fire and Rescue Service, Irondale, Alabama.

Miller, D. November 2003. *1999 Residential Fire Loss Estimates.* Washington DC: U.S. Consumer Product Safety Commission.

Mullin, F. J. 1937. "Changes in irritability to auditory stimuli on falling asleep." *American Journal of Physiology* 119: 377-378.

National Fire Protection Association. 2000. *NFPA 101, Life Safety Code 2000 edition.* Quincy.

National Fire Protection Association. 1989. *NFPA 74 Standard for the Installation, Maintenance and Use of Household Fire Warning Equipment, 1989 edition.* Quincy, MA.

National Fire Protection Association. 1993. *NFPA 72 National Fire Alarm Code, 1993 edition.* Quincy, MA.

National Fire Protection Association. 1999. *NFPA 72 National Fire Alarm Code, 1999 edition.* Quincy, MA.

National Institute for Occupational Safety and Health US Department of Health and Human Services. June 1998. *Occupational Noise Exposure, Revised Criteria 1998.* Centers for Disease Control and Prevention.

Nober, E. H., Peirce, H. & Well, A. June 1983. *Waking effectiveness of household smoke and fire detection devices*. Bureau of Fire Research, National Bureau of Standards, NBS Grant DA0001.

Pederson, K.E.; Rosenhall, U.; and Moller, M.B. 1989. "Changes in Pure-Tone Thresholds in Individuals Aged 70-81: Results from a Longitudinal Study." *Audiology* 28: 194 – 204.

Proulx, G. December 2000. “Why Building Occupants Ignore Fire Alarms.” *Construction Technology Update No. 42:* Institute for Research in Construction, National Research Council of Canada.

Smith, Charles. November 1993. *Smoke Detector Operability Survey – Report on Findings.* U.S. Consumer Product Safety Commission, Bethesda, Maryland.

Smith, Linda. January 1995. *Fire Incident Study: National Smoke Detector Project.* U.S. Consumer Product Safety Commission, Bethesda, Maryland.

Street, T.T. and Williams, F.W. July 2003. *Smoke Alarms, Low-Cost Batteries, and Wireless Technology Technical Report: Phase I – Preparatory Study and Literature Search.* Naval Research Laboratory, Navy Technology Center for Safety and Survivability Chemistry Division.

Street, T.T. and Williams, F.W. December 2003. The Implementation and Demonstration of Wireless Communications Capabilities in Off-The-Shelf, Battery Powered Smoke Alarms, Phase II Report. Naval Research Laboratory, Navy Technology Center for Safety and Survivability Chemistry Division.

Tong, D. and Canter, D. 1985. *The Decision to Evacuate: A Study of the Motivations which Contribute to Evacuations in the Event of a Fire.* In Gwynne, S.; Galea, E.P; Owen, M.; and Lawrence, P.J., Research report Escape as a Social Response. Society of Fire Protection Engineers: Bethesda, Maryland.

Underwriters Laboratories. February 1997. *UL 217 Single and Multiple Station Smoke Alarms.* Northbrook.

UL Committee. July 2003. *Report from the UL Smoke Alarm STP Research Group on Childhood Awakening in Response to Smoke Alarms.* Paper prepared by a UL working group to address children not awakening to the sound of smoke alarms.

United States Fire Administration. October 1999. *Fire Risks for Adults.* TriData Corporation under subcontract to Ogiluy Public Relations Worldwide for the United States Fire Administration.

Wallace, M.S.; Ashman, M.D., M.S., M.N.; and Matjasko, M.D., M.J. 1994. “Hearing Acuity of Anesthesiologists and Alarm Detection.” *Anesthesiology* 81: 13-28.

7.0 BIBLIOGRAPHY

Bregman, A.S. 2001. Auditory Scene Analysis, The Perceptual Organization of Sound. MIT: MIT press.

Cunningham, T.M. October 2002. "Children and Smoke Detectors." U.S. Naval Academy F.D.

Everest, F.A. 2001. *Mastering Handbook of Acoustics.* Fourth Edition. New York: McGraw-Hill.

Hartman,W.M. 1998. *Signals, Sound, and Sensation.* New York: Springer.

Meacham, B.J. September-October 1999. "Integrating Human Behavior and Response Issues into Fire Safety Management of Facilities." *Facilities* Vol 17 Number 0/10, ISSN 0263-2772, MCB Press.

Moore, B, C.J. 2003. *An Introduction to the Psychology of Hearing.* Fifth Edition. USA: Elsevier Science.

Patterson, C. 1994. "Prevention of Hearing Impairment and Disability in the Elderly." In: Canadian Task Force on the Periodic Health Examination. Canadian Guide to Clinical Preventive Health Care. Ontario: Health Canada.

Pisani, D.L. and Bruck, D. February 1997. "The Effects of Sleep Inertia on Decision Making Performance" *Technical Report FCRC-TR 97-13*. Fire Code Reform Research Program.

Yost, W.A. 2000. *Fundamentals of Hearing.* Fourth Edition. USA: Elsevier Science,.

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