Reducing Fire Deaths in Older Adults: Optimizing the Smoke Alarm Signal
Research Project

Summary technical report

THE FIRE PROTECTION RESEARCH FOUNDATION

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Prepared by

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FOREWORD

Smoke alarm and signaling systems are a proven strategy for reduction of fire fatalities in the general population. However, studies have shown that the elderly do not fully benefit from conventional smoke alarm systems, particularly during the sleeping hours. In April of 2005, the Fire Protection Research Foundation was awarded a Fire Prevention and Safety Grant by the US Fire Administration for a new project to study this topic.

The overall goal of the project was to optimize the performance requirements for alarm and signaling systems to meet the needs of an aging population. This reports presents the results of the study, which involved several tasks including a risk assessment to estimate the potential impact in lives saved of changes in waking effectiveness of smoke alarms for older adults, quantifying the human behavior aspects of the problem, developing benchmark performance criteria for alarm and signaling systems, and reviewing new and promising technologies that address the performance criteria.

A portion of the study involved the conduct of human behavior studies to investigate the arousal thresholds from sleep in older adults to the current US smoke alarm and compare these thresholds to several alternative signals, and to investigate the performance abilities of older adults when awoken suddenly by an alarm. The detailed results of this portion of the study are presented in a companion report entitled "Investigation of Auditory Arousal With Different Alarm Signals in Sleeping Older Adults".

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Reducing Fire Deaths in Older Adults: Optimizing the Smoke Alarm Signal Research Project

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Reducing Fire Deaths in Older Adults: Optimizing the Smoke Alarm Signal

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EXECUTIVE SUMMARY

Older adults (those 65 years of age and over) have been identified as a high risk group in terms of fire safety. People age 65 and over have a fire death rate more than twice that of the national average and the disparity in fire death rate increases with age. Given that the U.S. Census Bureau estimates that the older adult population will more than double over the next thirty years, there is certainly cause for concern. The use of smoke alarm and signaling systems is associated with a reduction in fire fatalities in the general population—reducing the chances of dying in a fire by 40 to 50 percent when present. However, recent studies suggest that older adults may not fully benefit from conventional smoke alarm systems, particularly during sleeping hours. The tendency for older adults to experience high frequency hearing loss has been attributed as a potential fire safety problem since typical residential smoke alarms have a high frequency signal, between 3,000–4,000 Hertz (Hz).

The objective of this project was to assess and optimize the performance requirements for alarm and signaling systems to meet the needs of an aging population. This project was separated into several tasks in order to achieve its objective. First, the older adult population was characterized relative to potential risk factors. Second, a risk assessment of older adults was performed to quantify the potential impact of improving the waking effectiveness of smoke alarms, in terms of the number of potential lives saved. This assessment was based on existing data regarding the characteristics of fire victims and fires. Third, the human behavior aspects of the problem were addressed; this work consisted of a sleep study of older adults and the details are presented in a companion report. Both the arousal thresholds from sleep for various frequencies and types of alarm signals, as well as the cognitive and physical abilities upon waking were examined in the sleep study. Fourth, a review was conducted of new and promising technologies that may improve the waking effectiveness of smoke alarms for older adults and improve their overall fire safety.

Numerous factors associated with the risk of fire death have been identified in the literature, including many that are likely to be significant to older adults. The primary focus of this study is on risk factors such as the age of the occupant, whether the victim was sleeping at the time of the fire, and whether smoke alarms were present and operated. Beyond simply the age of the occupant, other characteristics and behaviors of the occupant likely affect the fire risk of older adults, such as disabilities, smoking, chemical substance use (e.g., medicine and alcohol), and being home alone at the time of the fire. The rate of disabilities among older adults are at least two to three times that of the general population. Intuitively, since many disabilities impact the ability to quickly escape, the high rate of disabilities among older adults may be a primary factor in their higher risk of fire death. However, little data exists to assess the importance of disabilities to the fire death risk of older adults. Smoking materials are the leading cause of death in all age groups over 35, including older adults. Despite having the lowest prevalence of smokers (less than half of the general population), older adults have an equal or greater risk of dying in smoking related fires. Alcohol intoxication is a significant and often underreported factor in fire deaths. Although intoxicated older adults certainly are at a higher risk of death in fire, alcohol intoxication appears to be less common in older adults than the general population. In several studies, around half of all adult fire victims were legally intoxicated. However, for older adults the proportion of fire victims that were intoxicated was as low as one in five. Another risk factor that is not often addressed, but may be a contributor for older adults with

disabilities or for those with difficulty hearing the alarm, is whether the victim was alone at the time of the fire. Older adults, particularly women, are approximately three times more likely than the general population to be living alone. One study found that nearly half of all older adult fire victims that died despite having a smoke alarm that operated were alone at the time of the fire.

Operable smoke alarms are associated with a reduction fire death risk. However, several small studies have indicated that older adults may be more likely to have maintenance issues with their smoke alarms than the general population. Also, these studies found a significant number (at least 20 percent) of the alarms found in the homes of older adults were believed to be over 10 years old and needed replacement. Likewise, based on a review of smoke alarm requirements and the ages of homes older adults typically occupy, it is estimated that up to 90 percent of older adult households do not have interconnected smoke alarms or smoke alarms in bedrooms. With interconnected smoke alarms, when one smoke alarm goes into alarm, all connected smoke alarms also alarm. This arrangement increases the sound levels of audible alarms throughout a home so occupants are aware of fires, even if the fire is on the other end of the home or on a different story of the home. Instant notification from the first smoke alarm increases the time available for escape compared to waiting for additional alarms closer to the occupant to respond. Overall, the limited data available on smoke alarm usage among older adults indicates that they may not be receiving the full benefit provided by current code requirements for operational smoke alarms that are interconnected and located on every floor and in bedrooms.

In an effort to understand the potential impact of improving the waking effectiveness of smoke alarms for older adults, a risk analysis was performed to determine the reduction in risk associated with such changes. Based on national estimates derived from the National Fire Incident Reporting System (NFIRS) and annual National Fire Protection Association (NFPA) surveys, smoke alarms that are improved to wake all sleeping occupants would reduce the estimated risk to older adults by 27–32 percent. There are two primary reasons for the modest risk reduction found. First, even if all occupants were awakened, some of the occupants would still be expected to die as a result of unsuccessful escape attempts or because the occupant selects an activity, such as firefighting or attempting to rescue others, that may involve indefinitely extended time in hazardous conditions. Secondly, only 36–38 percent of older adult fire fatalities were reported to be sleeping when fatally injured. Therefore, a 27–32 percent risk reduction for older adults represents a realistic upper bound to the potential impact of improving the smoke alarm signal. This equates to an annual reduction in home fire deaths of 230–270 people age 65 and over, based on the annual average of older adult home fire deaths from 1999–2002.

The practicality of achieving the risk reduction expected from improved waking effectiveness must be assessed in light of the presence and operability of smoke alarms. Victims that do not have an operable smoke alarm will not benefit from an improved smoke alarm signal. Less than one out of four older adult fire victims who were sleeping when fatally injured had an operable smoke alarm.

The risk reduction expected from improvements in the waking effectiveness of smoke alarms for other age groups was also analyzed for comparison to older adults. For both the under 18 and 18–64 age groups, larger risk reductions than those expected for older adults are estimated. The primary driver of the larger risk reduction for these two age groups is that they have a greater percentage of occupants sleeping when fatally injured (56–58 percent for those under age 18 and 44–45 percent for those 18–64 years) compared to older adults (36–38 percent). The statistics on smoke alarm presence and operability for fire fatalities in the under 18 and 18–64 age groups were remarkably similar to those of older adult fire fatalities. The implication of these statistics is that although improving the waking effectiveness of smoke alarms is important, it is also necessary to increase the presence and operability of smoke alarms. In order to realize the benefits of improved smoke alarm waking effectiveness, smoke alarms must be present and operable. This conclusion applies to older adults, as well as the general population.

The sleep study portion of this project provided insights into the human behavior aspects of waking older adults exposed to varying types of signals and varying sound levels. A total of 42 older adults, ranging in age from 65–85 years, participated in the study. Four signals were examined, including a 3000 Hz high-frequency T-3 alarm signal (typical of that used in U.S. smoke alarms), a 500 Hz low-frequency T-3 alarm signal, a 500–2500 Hz mixed frequency T-3 alarm signal, and a male voice (200–2500Hz) alarm signal. The results showed that the mixed frequency T-3 alarm signal provided the greatest waking effectiveness of the signals evaluated, including the high frequency T-3, typical of most current alarms. In fact, the high-frequency T-3 performed the most poorly of the alternative signals tested. There was a substantial difference in the median auditory arousal thresholds (20 dBA) between the high-frequency T-3 alarm signal and the mixed frequency T-3. The results also indicate that a male voice alarm is not suitable for older adults. In terms of the cognitive and physical abilities of older adults upon waking to an alarm, a decrement in physical functioning of around 10–17 percent was observed, with no important effects on simple or cognitive functioning.

In summary, the sleep study concluded that the high frequency alarm signal that is typically used in current smoke alarms should be replaced by an alternative signal that offers significantly better waking effectiveness across the general population, once the nature of the best signal has been determined. While the research to determine such a signal is ongoing, it is imperative that the use of interconnected smoke alarm in bedrooms be encouraged to provide the maximum potential benefit of current and future alarms. Proper use and maintenance of smoke alarms is also critical to realizing the benefits of smoke alarms.

Numerous, current and promising technologies are available that may improve the waking effectiveness of smoke alarms for older adults and improve their fire safety. These technologies can be broadly categorized as those that provide alternative audible alarm signals, those that provide alternative sensory stimuli (visual, tactile), those related to the interconnection of smoke alarms and notification devices, and those that facilitate testing and maintenance of alarms. Despite research, including the work done as part of this project, that shows alternative audible alarm signals may benefit smoke alarm users, including older adults, there are few products currently available that address this issue. The focus of the smoke alarm industry in terms of addressing the needs of the hearing impaired has largely been on technologies that provide visual stimuli (i.e. strobes) to supplement audible alarms. However, recent research has focused

renewed interest on tactile (vibratory) stimuli as an effective means of waking occupants. Although the technology is available, there has been only limited use and commercial development of tactile (vibratory) notification technology integrated with smoke alarms.

Recent technological advances have occurred that facilitate the interconnection of smoke alarms with other smoke alarms, as well as with supplemental notification devices. Interconnection of smoke alarms and connecting smoke alarms with supplemental notification devices can be achieved with RF wireless technologies, acoustic monitoring, and powerline communication. These emerging technologies and products provide two important improvements to the fire safety of older adults and the entire population. First, they readily enable increased sound levels of audible alarms throughout a home so occupants are aware of fires, even if the fire occurs remote from the current location of the occupant and the nearest smoke alarm. Secondly, the interconnection of supplemental notification devices provides the opportunity to better meet the needs of select populations. Delivery of alternative audible signals, visual signals, and vibratory alarm signals are all possible with supplemental notification devices that are wirelessly connected to smoke alarms.

Although technologies that facilitate testing and maintenance of smoke alarms do not influence the waking effectiveness of smoke alarms, they are expected to be able to impact the overall fire safety of older adults. Maintenance problems with battery-operated smoke alarms, such as difficulty testing alarms or missing, dead, and disconnected batteries, are being addressed by various smoke alarm technologies. Technologies are available that allow users to test the operation of smoke alarms remotely and that eliminate battery changes for the life of the smoke alarm. Designs of battery doors and drawers allow replacement of smoke alarm batteries without removing the alarm from the ceiling, and silence features allow the user to temporarily silence alarms without removing the batteries from the alarm.

ACKNOWLEDGEMENTS

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NOMENCLATURE

AAT	Auditory Arousal Threshold
AC	Alternating Current
ADA	Americans with Disabilities Act
ANSI	American National Standards Institute
CPSC	Consumer Product Safety Commission
dBA	Decibels (A-weighting)
ISO	International Organization for Standardization
NAEEEC	National Appliance and Equipment Energy Efficiency Committee (Australia)
NCHS	National Center for Health Statistics
NFIRS	National Fire Incident Reporting System
NIDCD	National Institute on Deafness and Other Communication Disorders
NRL	Naval Research Laboratory
CDC	Centers for Disease Control and Prevention
NFPA	National Fire Protection Association
RF	Radio Frequency
SHHH	Self Help for Hard of Hearing People
UL	Underwriters Laboratories
USFA	United States Fire Administration

1.0 INTRODUCTION

The U.S. Fire Administration (USFA) has identified older adults (those 65 years of age and over) as a high risk group in terms of fire safety. Recent estimates of fatalities in home fires by NFPA, based on data from 1999–2002, indicate approximately 2,960 fire deaths occur in the U.S. each year. In terms of a fire death rate, or fire risk, this equates to 10.4 deaths per million people annually. People age 65 and older have a fire death rate (22.7 deaths/million) more than twice that of the national average [Hall, 2005]. In total, older adults account for around 800 fire deaths per year. Although older adults comprise around 12 percent of the U.S. population, they experience approximately 27 percent of the home fire fatalities.

The disparity in fire death rate increases with age. Figure 1 shows the trend in the fire death rate (deaths per million people per year) as a function of the age of the victim. People age 75 and older have a fire death rate three times the national average and those age 85 and over have a fire death rate more than four times the national average [Hall, 2005]. It is believed that various changes associated with aging may be a factor in the increased fire death rate among older adults.

The use of smoke alarm and signaling systems is associated with a reduction of fire fatalities in the general population, particularly for occupants of one and two family dwellings. The chances of dying in a fire are reduced by 40 to 50 percent when smoke alarms are present [Ahrens, 2004]. Sekizawa [2005] found a similar reduction in fire death risk in Japanese and UK fire statistics. When smoke alarms are known to be operational and provide the alarm, Hall [2004] found a 60 to 80 percent reduction in fire death risk. However, older adults may not fully benefit from conventional smoke alarm systems, particularly during sleeping hours. Recent studies [Bruck, 2001] have indicated that as many as 25 percent of older adults may not awake from a hallway smoke alarm; however, this data is incomplete. Reduced waking effectiveness in older adults may be a result of factors such as high frequency hearing loss or ingestion of sleep aid medication. Even when awakened by a smoke alarm, older adults may have a reduced ability to evacuate quickly as a result of impaired mobility or increased cognitive confusion / sleep inertia.

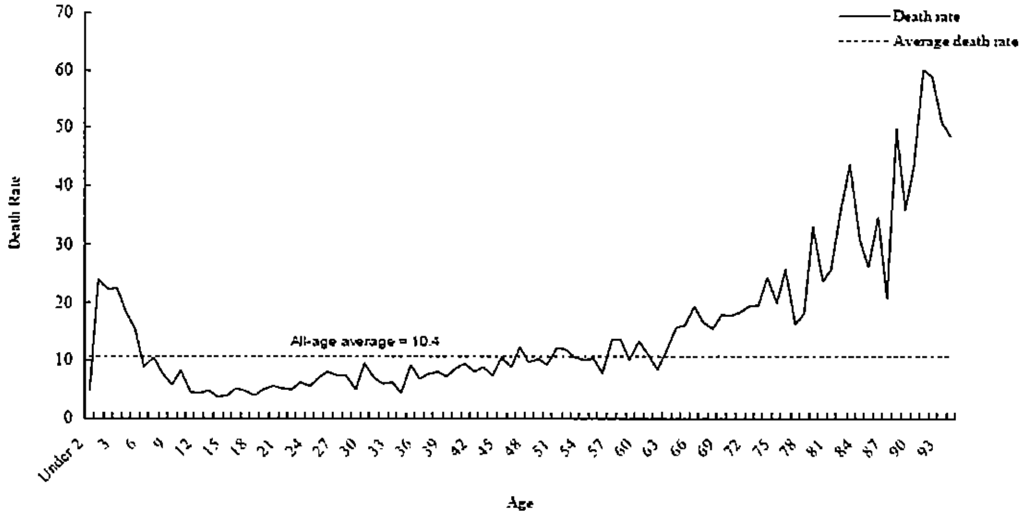


Figure 1 — Fire death rate in home fires as a function of age of the victim [Hall, 2005].

The objective of this project was to assess and optimize the performance requirements for alarm and signaling systems to meet the needs of an aging population. This project was separated into several tasks in order to achieve its objective. First, a risk assessment of older adults was performed to quantify the potential impact of improving the waking effectiveness of smoke alarms, in terms of the number of potential lives saved. This assessment was based on existing data regarding the characteristics of fire victims and fires. Second, the human behavior aspects of the problem were addressed; this work consisted of a sleep study of older adults and is presented in a separate report [Bruck, et al., 2006]. Both the arousal thresholds from sleep for various frequencies and types of alarm signals, as well as the cognitive and physical abilities upon waking were examined in the sleep study. A review was conducted of new and promising technologies that may improve the waking effectiveness of smoke alarms for older adults and improve their overall fire safety. Finally, the previous tasks are integrated to determine research needs to further address the fire safety of older adults.

2.0 THE SMOKE ALARM SIGNAL

It is important to understand the current smoke alarm signal prior to considering alternative signals. Subsequent sections describe the current requirements for the smoke alarm signal, the audibility of the signal in typical residential homes, and the waking thresholds typically associated with the signal in the general population.

2.1 Requirements

Since 1996, NFPA 72, *National Fire Alarm Code*, has required the use of a three-pulse temporal pattern, or temporal-three (T-3), as an alarm signal for new buildings. This signal is intended to indicate that immediate evacuation of the building is required. Although this signal is a relatively recent requirement, it has been recommended by NFPA 72 (and its predecessors) since 1979. This signal has also been adopted as an American National Standard (ANSI S3.41,

Audible Emergency Evacuation Signal) and an International Standard (ISO 8201, *Audible Emergency Evacuation Signal*).

Identifying an optimal evacuation signal that will reach occupants and be heard and recognized can be difficult because of variations (e.g., loudness, frequency, pattern) in background noise among occupancies as well as various human factors. The T-3 standards only specify the on/off pattern of the signal. This approach allows manufacturers to select appropriate frequencies for an acoustic signal that may differ for given applications. This approach also allows visual and tactile signals to take advantage of the standard temporal-three pattern.

The T-3 pattern consists of a 0.5 second ON phase, followed by a 0.5 OFF phase. After the third ON phase, a 1.5 second OFF phase completes the cycle. The total time through one cycle of the signal is 4 seconds. Supplemental verbal instructions are allowed to be inserted in the 1.5 second OFF phase. There is also an exception made for single-stroke bells or chimes, which are allowed to chime at three consecutive one second intervals, followed by a two second OFF phase. Figure 2 illustrates several examples of the T-3 pattern; the topmost figure is typical of the signal used in residential smoke alarms.

Although not mandated as part of the requirements of ANSI S3.41 or ISO 8201, residential smoke alarms typically employ an alarm frequency of 3,000–4,000 Hz. In tests of one residential smoke alarm, the U.S. Consumer Product Safety Commission (CPSC) determined the operating frequency of the smoke alarm to be 3,200 Hz [Lee, 2005a]. The alarm signal in a smoke alarm is typically generated with a piezoelectric horn. These devices are used due to their ability to produce significant sound levels while using relatively little power, which is essential when relying on batteries as a power source.

The voluntary UL standard for single-station smoke alarms, UL 217, also provides requirements for the smoke alarm signal. These requirements include the use of the temporal-three pattern and also require that a minimum sound level of 85 dBA be produced at 10 feet from a smoke alarm operating in a room of a specific configuration (see Section 65 of UL 217 for details).

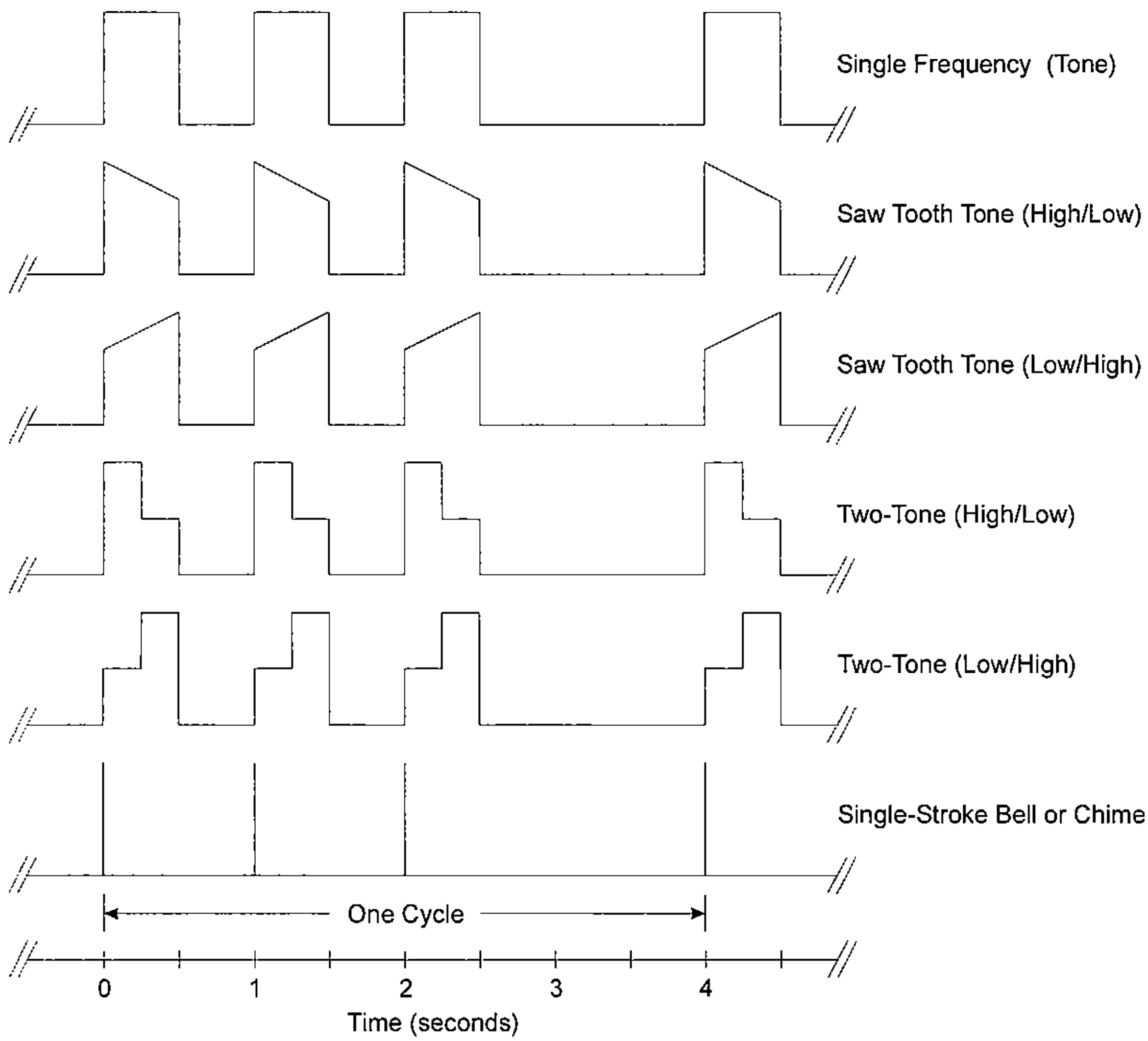


Figure 2 — Examples of the temporal-three (T-3) smoke alarm signal.

2.2 Waking Thresholds

Several studies have examined the response of adult occupants to the smoke alarm signal [Nober, et al., 1981; Kahn, 1984; Bruck and Horasan, 1995]. Bruck [2001] provides a summary of these and several other studies. In general, an unimpaired sleeping adult will awake quickly to a smoke alarm signal that reaches the occupants at a sound level of 55–60 dBA [Bruck, 2001]. Early work by Nober, et al. [1981] indicated that 18–29 year old adults could be aroused from sleep by a 55 dBA sound level in a relatively quiet environment. In a more noisy environment (window air conditioner running), a 70 dBA signal was required. Kahn [1984] obtained similar results when he presented male, college-age students (mean age 21.3) with alarm signals of 44, 54, and 78 dBA with background noise of 44 dBA. All participants awoke for the 78 dBA signal, 50 percent awoke for the 54 dBA signal, and 25 percent awoke for the 44 dBA signal. Bruck and Horasan [1995] found that 75–87 percent of the 18–24 year olds studied awoke to a

smoke alarm signal of 60 dBA with background noise of less than 30 dBA, depending on their sleep stage.

Data from the auditory arousal threshold (AAT) literature, such as Zepelin, et al. [1984] or that used in the review by Berry [1978], suggests occupants would be less responsive to a 55–60 dBA signal than was cited in the previous studies. However, the frequency of the sound used in the AAT studies was typically significantly different than that of a smoke alarm [Bruck, 2001]. Nevertheless, Berry [1978] concludes from a review of the literature that 75 dBA "can reasonably be expected to awaken a person under most circumstances."

Berry [1978] and Bruck [2001] both note numerous factors which can affect responsiveness and should be considered when applying AATs, including:

- Large individual variation in AAT,
- Hearing impairments,
- Sleep medication,
- Background noise levels,
- Drug/alcohol use,
- Sleep deprivation,
- Being a child/teenager, and
- Being an older adult.

2.3 Audibility in Typical Residential Dwellings

A study recently published by the Consumer Product Safety Commission (CPSC) examined sound levels from smoke alarms in several residential dwellings [Lee, 2005a]. Sound measurements were taken in three homes constructed from 1960 to 1989, ranging in size from approximately 1,100 to 3,300 ft^2.

The first home in which sound measurements were taken was a typical 1,100 ft^2 suburban ranch house built in 1960. Directly under operating smoke alarms, sound levels of approximately 90–105 dBA were recorded. Sound measurements taken in three bedrooms with a smoke alarm operating in the adjacent hallway ranged from 85–96 dBA with the door open and 71–88 dBA with the doors to the bedrooms closed. A smoke alarm operating in one of the bedrooms produced sound levels at the pillow of approximately 90 dBA, regardless of whether the door to the bedroom was open or closed. The sound level in the master bedroom of the ranch home was as low as 45 dBA (with the bedroom door closed) with a smoke alarm operating in the basement (at the bottom of the basement stairway on the ceiling, 5 feet from the stairs).

The second home in which sound measurements were taken was a 2,300 ft^2, two-story home (no basement) built in 1973. A smoke alarm operating in the first floor hallway produced sound levels as low as 42 dBA in the second floor bedrooms when the bedroom doors were closed. The final home in which smoke alarm measurements were taken was a 3,300 ft^2 two-story (plus a basement) Georgian colonial-style home. Sound levels measured in the second floor bedrooms with a smoke alarm operating on the first floor were as low as 61 dBA with the bedroom doors closed. The sound level in the master bedroom of the colonial home (on the second floor) was as

low as 34 dBA with the bedroom door closed and a smoke alarm operating in the basement (at the bottom of the basement stairway on the ceiling, 5 feet from the stairs).

Based on their measurements of sound levels in typical residential homes, the CPSC estimated that residential interior doors attenuate a smoke alarm signal approximately 10–20 dBA and that each level of the home through which the signal must travel attenuates an additional 20 dBA [Lee, 2005a]. From these results, the CPSC concluded that the signal from smoke alarms that are not interconnected may not be able to alert all occupants throughout two- or three-level homes. Therefore, interconnected smoke alarms or notification appliances on at least every level, and possibly in bedrooms as well, may be necessary to provide adequate protection throughout a dwelling.

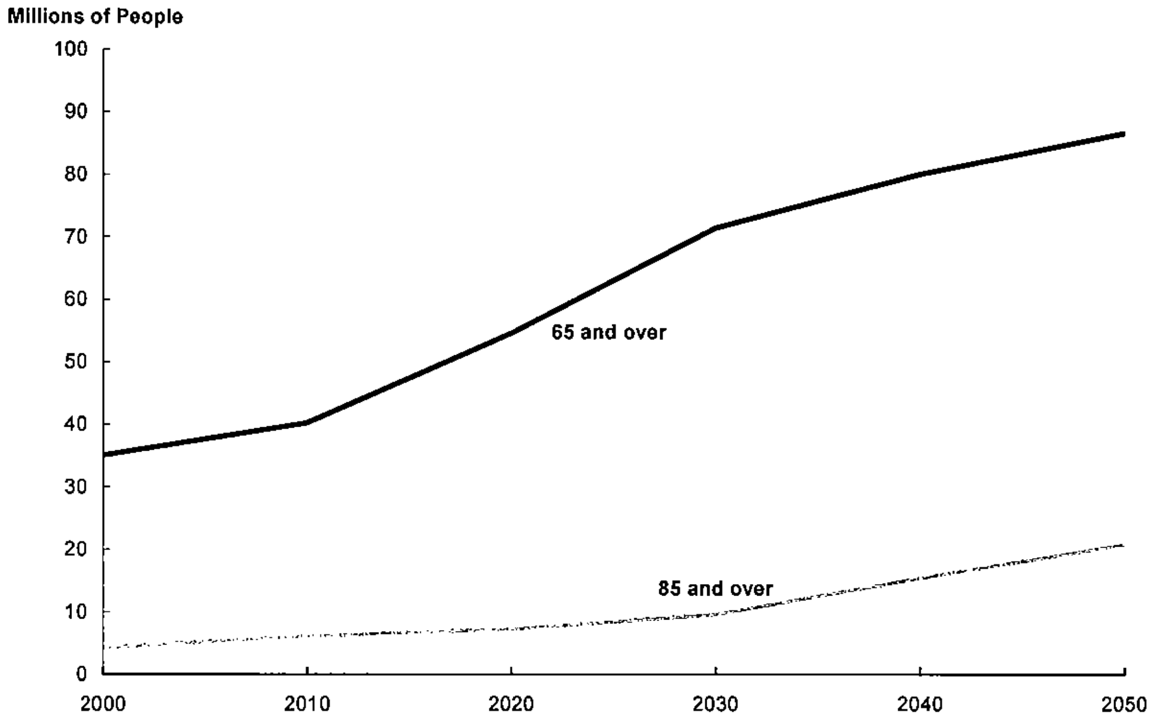
3.0 CHARACTERIZATION OF THE OLDER ADULT POPULATION

Several important distinctions can be made between older adults (65 years and older) and the overall population that are relevant to this analysis. Two recent reports highlight some of these differences [Smith, 2005; USFA, 2006]. The first report, published by the CPSC addresses age-related differences in the perceptual, cognitive, and physical abilities in adults and relates this understanding to improving product safety [Smith, 2005]. This CPSC report is based on an extensive literature review and serves as a valuable overview of characteristics of older adults in relation to safety. Similarly, the USFA published a report on fire and older adults, which contains a characterization of older adults and discusses several fire risk factors relevant to this population. This section provides a general characterization of the older adult population in terms of their population trends, impairments and disabilities, and housing conditions. For more detailed information on this topic, consult [Smith, 2005] and [USFA, 2006].

3.1 Population Trends

According to the U.S. Census Bureau, there were 35.0 million people 65 years of age and over in the United States in 2000 [Hetzel and Smith, 2001]. The older adult population represents 12.4 percent of the total population of the United States. Despite an increase in the number of the people in this age group, the proportion of the U.S. population in this age group declined slightly (from 12.6 percent in 1990 to 12.4 percent in 2000). This trend is expected to reverse as the "baby boomers" (those born 1946 to 1964) reach 65 years of age starting in 2011 [Federal Interagency Forum on Aging-Related Statistics, 2004]. Figure 3 shows population data from the most recent (2000) decennial U.S. Census, as well as projected population estimates for the next 50 years for people 65 years of age and over.

Over the last century, the older adult population in the U.S. grew from 3 million to 35 million, with the population age 85 and over growing from 100,000 to 4.2 million [Federal Interagency Forum on Aging-Related Statistics, 2004]. According to the U.S. Census Bureau, the number of older adults will increase dramatically during the 2010–2030 period. By 2030, the older adult population is expected to more than double its numbers from 2000, representing approximately 20 percent of the U.S. population. Rapid growth is expected in the population 85 years of age and over beyond 2030. This age group is projected to reach nearly 21 million people in 2050, representing nearly one quarter of older adults [Federal Interagency Forum on Aging-Related Statistics, 2004].



Source: U.S. Census Bureau [2004]

Figure 3 — Current and projected number of people age 65 and over in the U.S.

3.2 Impairments and Disabilities

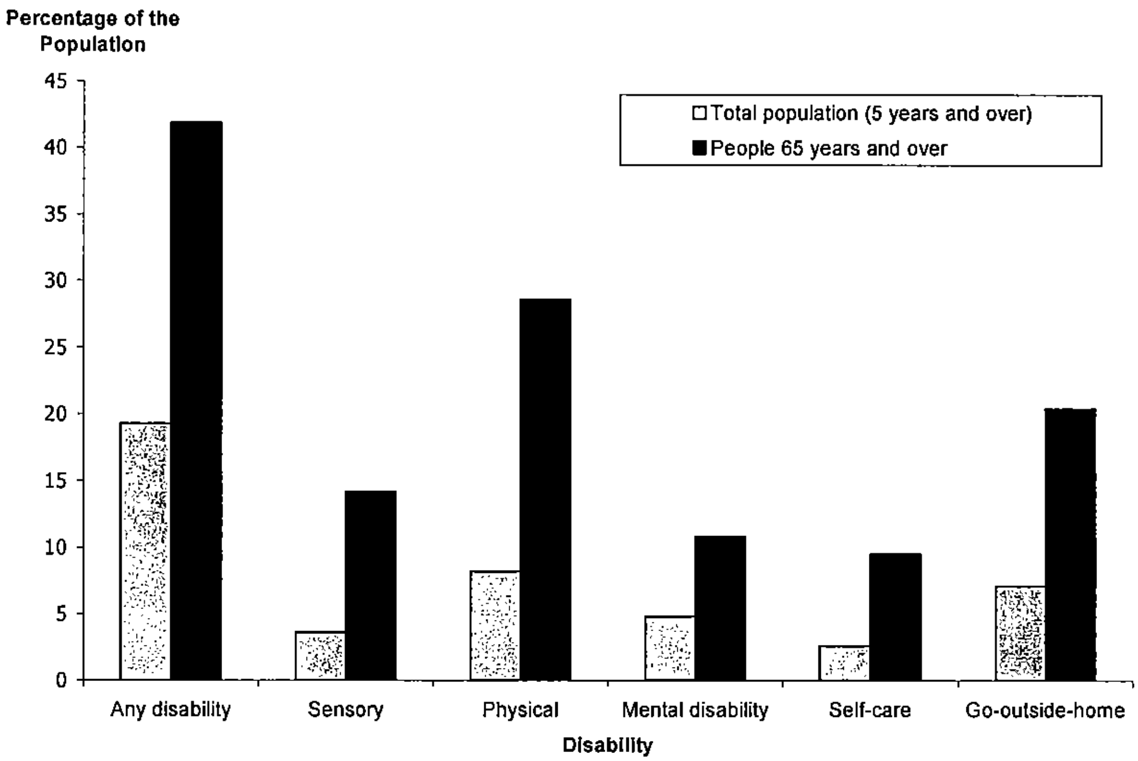
3.2.1 General

According to the U.S. Census Bureau, 42 percent of the population 65 years of age and over reported some type of long term condition or disability in 2000 [Gist and Hetzel, 2004]. Census 2000 showed disability rates rising with age for both sexes [Waldrop and Stern, 2003]. The Census provides information on five categories of disabilities [Gist and Hetzel, 2004]:

- Sensory—long-lasting blindness, deafness, or hearing impairment
- Physical—long-lasting, substantial limitation on one or more basic physical activities, such as walking, climbing stairs, reaching, lifting, or carrying
- Mental—Learning, remembering, or concentrating
- Self-care—Dressing, bathing, or getting around inside the home
- Difficulty going outside the home—Going outside the home alone to shop or visit a doctor's office

Figure 4 compares the percentages of older adults and the general population that report each of the five disability categories distinguished in Census 2000. For three of the five disabilities measured by Census 2000, the disability rate for those 65 years of age and over was at least triple

the rate of the total population [Gist and Hetzel, 2004]. Sensory disabilities, which include long lasting blindness, deafness, or hearing impairment, affect 14.2 percent of older adults. This is nearly four times the rate at which sensory disabilities affect the total population. Similarly, 28.6 percent of older adults are affected by physical disabilities, which are described as long lasting, substantial limitation on one or more basic physical activities such as walking, climbing stairs, reaching, lifting, or carrying. The rate of physical disability among the total population is only 8.2 percent. Due to long term physical, mental, or emotional conditions, 9.5 percent of older adults have difficulties providing self-care (dressing, bathing, or getting around inside the home). This is greater than three times the rate at which the total population has difficulty providing self-care (2.6 percent).



Source: U.S. Census Bureau [Waldrop and Stern, 2003]

Figure 4 — Disability status of older adults and overall U.S. population.

For the remaining two disabilities measured by Census 2000, the disability rate for those 65 years of age and over was at least double that of the total population. Mental difficulties, such as problems learning, remembering, or concentrating, were reported by 10.8 percent of older adults. This is over twice the rate at which these difficulties were reported by the total population. Over 20 percent of older adults reported difficulties going outside the home alone to shop or visit a doctor's office. The total population reported only 7.1 percent with this disability.

Over 50 percent of the population over the age of 85 reported a physical disability, with 47 percent indicating difficulties going outside the home [Gist and Hetzel, 2004]. For comparison, only 13 percent of people 65 to 74 years of age reported difficulties going outside the home. Similar trends were reported for sensory disabilities; nearly 35 percent of those 85 years and older reporting blindness, deafness, or hearing impairment, whereas only approximately 9 percent of those age 65 to 74 years reported similar difficulties.

The Census data on disabilities does not provide details regarding the extent of the disability. It is also possible, maybe even likely, that this data underestimates the magnitude of the problem since the information is based on the perception of the respondent. Regardless, since disabilities can affect people's ability to escape, this data suggests that the high rate of disabilities in older adults may contribute to their high risk of death in home fires.

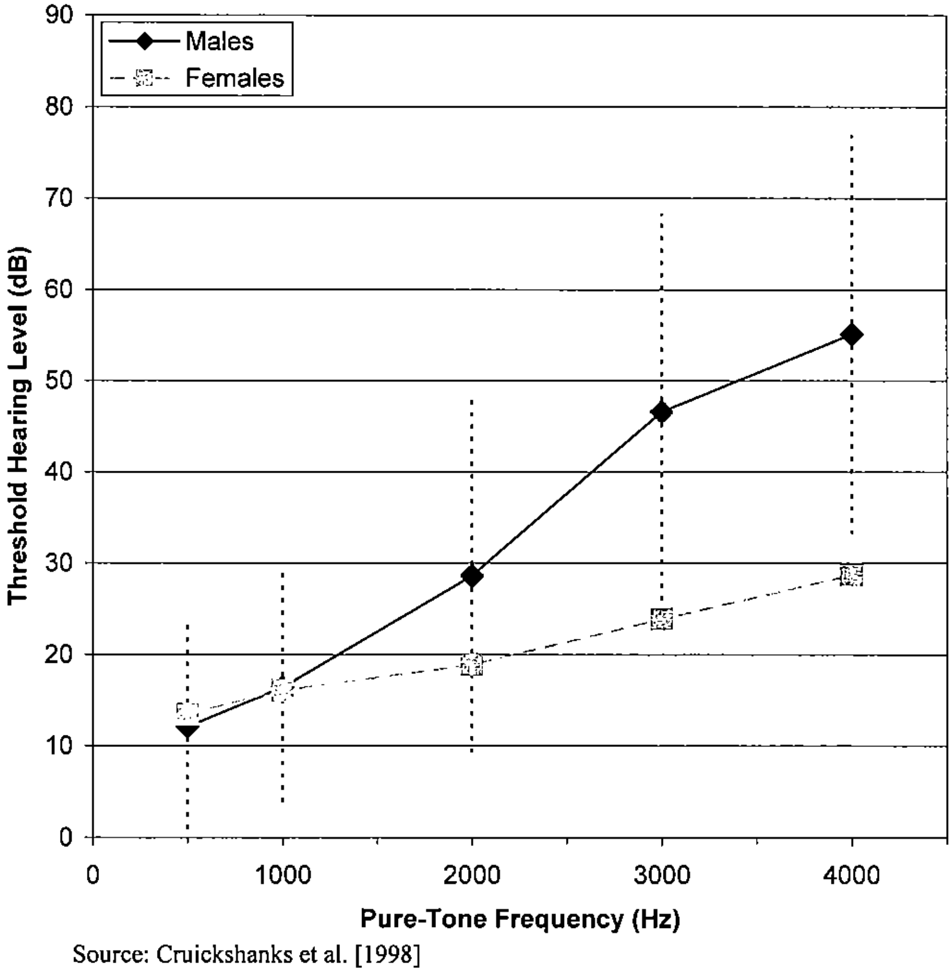
3.2.2 Hearing Impairment

The National Institute on Deafness and Other Communication Disorders (NIDCD), one of the institutes that comprise the National Institutes of Health (NIH), estimates that 28 million people in the U.S. are deaf or hard of hearing [NIDCD, 1996]. Hearing impairments affect a significant portion of the older adult population. Older adults comprise approximately 37 percent of all hearing-impaired individuals in the United States, despite representing only around 12 percent of the total U.S. population [Desai et al., 2001]. Around 30 percent of older adults are affected by presbycusis, gradual age-related hearing loss [Gates, et al., 1990]

Cruickshanks et al. [1998] conducted a large epidemiological study to measure the prevalence of hearing loss in older adults using standard audiometric testing. Study participants ranged in age from 48–92 years, with a mean age of about 66 years. Overall, 46 percent of the study participants had a hearing loss of at least 25 dB in the worse ear. They also found that the risk of hearing loss increases with age such that almost 90 percent of participants over 80 years of age experienced hearing loss. Figure 5 shows mean hearing threshold levels for men and women
60–69 years of age. The error bars in Figure 5 show one standard deviation and are only presented for males. Age-related hearing loss is primarily at the higher frequencies (greater than 2,000 Hz) and is greater for men than women, as shown in Figure 5. Hearing thresholds were slightly worse (higher) for left ears than right ears at frequencies above 250 Hz. The worse ear was used to determine the prevalence of hearing loss, so average hearing thresholds from the left ear are presented in Figure 5. As the number of older adults increases in the future, the number of older adults with hearing impairments will likely increase as well.

It is also important to recognize that many older adults may be unaware of their hearing difficulties. In the human behavior portion of this project [Bruck, et al., 2006], approximately 15 percent of the potential participants, who believed they had average or better hearing for their age, failed the hearing screening. Although this screening was fairly stringent, requiring each person to perform within one standard deviation of the mean threshold sound level for their age and sex at each frequency (500, 1000, 2000, 3000, and 4000 Hz) in both ears, these results highlight the prevalence and lack of awareness of hearing impairments among older adults.

A significant proportion of the older adult population with hearing impairments has not taken corrective action. In 1995, 76 percent of people age 70 and older with a hearing problem had seen a doctor for the problem; however, only 34 percent used a hearing aid [Desai, et al., 2001]. In contrast, over 98 percent of those age 70 or older with a visual problem had seen a doctor and 93 percent wore glasses. Similar statistics exist for the overall population of those with hearing loss. Of the 28 million Americans with hearing loss only about 25 percent currently use hearing aids [SHHH, 2006]. Thirty percent of those with hearing loss cannot afford hearing aids, 33 percent deny or hid their hearing loss and 7 percent are unaware of their hearing loss [SHHH, 2006]. Only around 5 percent of those with hearing loss require medical or surgical procedures to treat their hearing loss [SHHH, 2006]. In the context of this report, it is important to note that people that use hearing aids typically do not wear their hearing aids while sleeping.



Source: Cruickshanks et al. [1998]

Figure 5 — Hearing threshold levels among adults age 60–69 years.

3.3 Housing

Data from the 2000 U.S. Census can be used to characterize the types of housing that older adults occupy. Census data regarding housing is typically characterized according to households and householders. Households include all people who occupy a housing unit (i.e. a house, an apartment, a mobile home or trailer, a group of rooms, or a single room occupied as separate living quarters). A householder is the person, or one of the people, in whose name the home is owned, being bought, or rented [U.S. Census Bureau, 2006]. Previous versions of the Census used the term "head of household" rather than householder.

Table 1 shows that there were 35 million people age 65 years and over, which was 12 percent of the 281 million total U.S. population. Of the 35 million older adults, 33 million (94%) were in occupied households, as opposed to group living quarters. Consequently, the statistics related to occupied households represent the vast majority of the older adult population. As shown in Table 1, the rate of home ownership among those 65 years of age and over was higher than the general population. Seventy-eight percent of householders age 65 and over owned the home they occupied, whereas only 66 percent of all householders owned the home they occupied. However, the percentage owning their home declined with age within the 65 and over age group [Gist and Hetzel, 2004]. Table 2 provides further information on the types of homes that older adults occupy. Among householders 65 years of age and over who owned a home, 84 percent (around 15 million households), lived in single-unit attached or detached structures (i.e. single-family homes). When combined with renter-occupied structures, 71 percent (around 16 million households) of householders 65 years of age and older lived in single-unit structures.

Older adults are also more likely to live in older structures. As Table 3 shows the year in which the structure was built was relatively consistent for owner- and renter-occupied households. Only 5 percent of housing units with householders age 65 and over were built within the five years preceding Census 2000 (1995–2000). It is not surprising then that 90 percent of the housing units in which older adults live were built prior to 1990 and 60 percent were built prior to 1970.

Table 1 — Home ownership among older adults and overall U.S. populations.

	Total for All Ages		65 years and over	
	Number [1]	Percent	Number [1]	Percent [2]
Population	281.4	100%	35.0	12%
Occupied Households	105.5	100%	22.6	21%
Owner-Occupied Households	69.8	66%	17.6	78%
Renter-Occupied Households	35.7	34%	5.1	22%

1. Number in millions (people or households, as appropriate).
2. Percentages for population and occupied households are based on the total for all ages. Percentages of owner- and renter-occupied households are based on the number of occupied households in the age group specified.
Source: Census 2000, Summary File 3

Table 2 — Types of homes in which older adults live.

Units in Structure	Owner-occupied Million Households	Owner-occupied Percent	Renter-occupied Million Households	Renter-occupied Percent	Total Million Households	Total Percent
Single Unit (detached or attached)	14.8	84%	1.2	23%	16.0	71%
Multiple Units (apartments)	1.3	8%	3.7	73%	5.0	22%
Mobile home, boat, rv, van, etc.	1.4	8%	0.2	3%	1.6	7%
Total	17.6	100%	5.1	100%	22.6	100%

All values are based on the number of housing units in which the householder was 65 years of age or over.
Source: Census 2000, Summary File 4

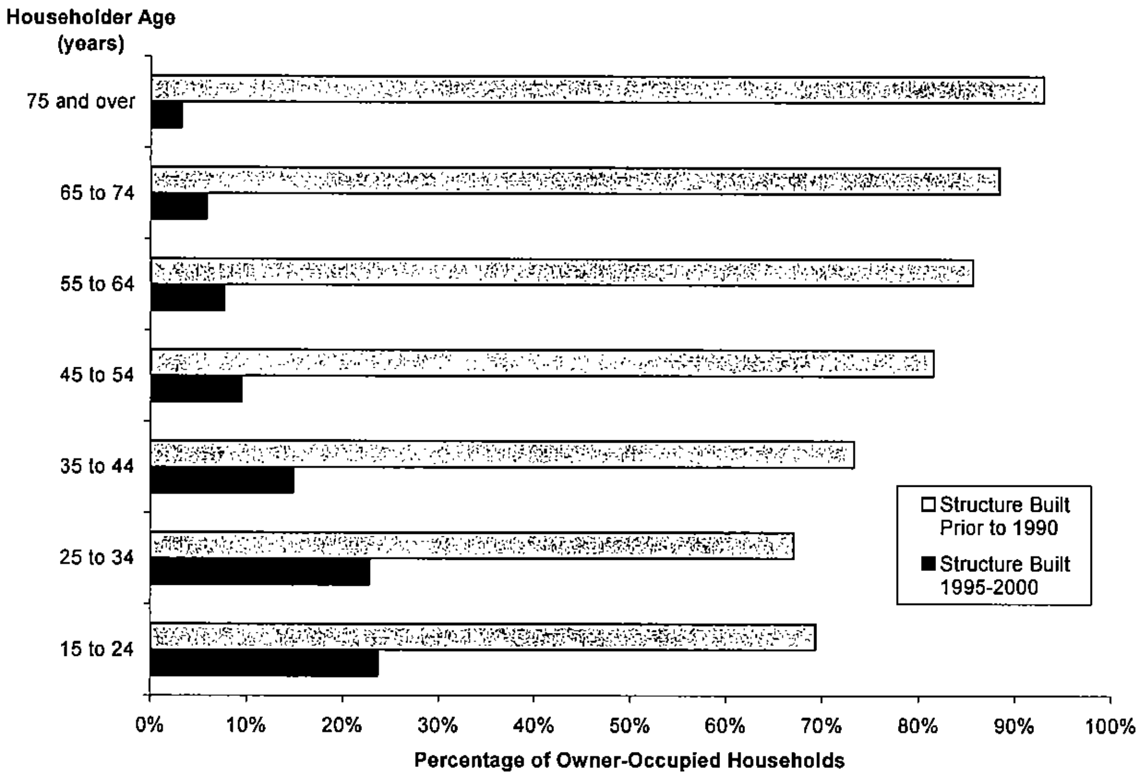
Table 3 — Age of structures in which older adults live.

Year Structure was Built	Owner-Occupied Households Million Households	Owner-Occupied Households Percent	Renter-Occupied Households Million Households	Renter-Occupied Households Percent	Total Households Million Households	Total Households Percent
Built 1995 to 2000	0.8	5%	0.3	6%	1.1	5%
Built prior to 1990	15.9	91%	4.5	88%	20.4	90%
Built prior to 1970	11.0	63%	2.6	51%	13.6	60%
Total	17.6	100%	5.1	100%	22.6	100%

Data for householders age 65 years and over.
Source: Census 2000, Summary File 3

According to Table 1, the vast majority of housing units in which the householder was age 65 and over were owner-occupied structures (78%). Therefore, the remainder of this discussion will focus on owner-occupied housing units. As Figure 6 shows, the percentage of owner-occupied households in which the structure was built prior to 1990 increased with age of the householder. Likewise, percentage of owner-occupied households in which the structure was built 1995–2000 decreased with age of the householder. In contrast to the housing units in which older adults live (see Table 3), nearly one in four owner-occupied structures with householders 34 years of age and younger were built 1995–2000.

Another distinction made in the Census data regarding housing is the type of household. There are a variety of different household types, but one type that is of interest is non-family households in which the householder lives alone. Table 4 summarizes statistics from Census 2000 regarding the number of people that live alone. In the overall population, approximately 10 percent of people live alone. However, nearly one in three people age 65 and over live alone. In addition, a significantly higher proportion of older adult women live alone (36 percent) compared to older adult men (17 percent).



Source: Census 2000, Summary File 3

Figure 6 — Percentages of households living in structures built prior to 1990 and built from 1995–2000 according to the age of the householder.

Table 4 — Older adult and overall U.S. populations by sex and the portion of those living alone.

	All Ages		65 years and over	
	Million People	Percent	Million People	Percent
Total Population	281.4	100%	35.0	100%
Total Males	138.1	49%	14.4	41%
Total Females	143.4	51%	20.6	59%
Total, living alone	**27.2**	**10%**	**9.7**	**28%**
Males, living alone	11.8	9%	2.4	17%
Females, living alone	15.5	11%	7.3	36%

Source: Census 2000, Summary File 1

4.0 STATUS OF FIRE SAFETY AMONG OLDER ADULTS

Older adults clearly face a higher risk of death in fires than other groups; this was established in Section 1.0. However, simply knowing that older adults are at high risk is not sufficient. This section aims to provide insights into why this high risk situation may exist for older adults. With the data currently available, it is not possible to positively identify the cause(s) of the elevated fire risk of older adults. Nevertheless, risk factors believed to be the most significant and relevant are identified and discussed. Smoke alarm usage among older adults is also analyzed, including examining the presence, operability, and locations of smoke alarms in older adult households. This section also analyses the potential benefits of smoke alarms that provide improved waking effectiveness for older adults.

4.1 Risk Factors

A number of studies have examined potential fire death risk factors, including many that are applicable to older adults. A series of studies by the USFA are particularly relevant to this discussion [USFA, 1999; USFA, 1999b; USFA, 1999c; USFA, 2006]. These reports address the fire risks of people that are blind or visually impaired, have mobility impairments, that are deaf or hard of hearing, and of older adults in general, respectively. Hall [2005] also discusses a variety of risk factors associated with fire deaths, although not specifically targeting the older adult population.

Figure 7 presents a list of potential fire death risk factors. This list is largely based off the discussion of risk factors by Hall [2005] and is not meant to be exhaustive, but rather to provide an idea of the characteristics that have been considered by previous studies. Many of these risk factors seem intuitive, but their statistical power as a risk indicator varies. For this study, the risk factors receiving the primary focus are the age of the victim (older adults versus other populations), whether or not the victims were sleeping, and the presence and operation of smoke alarms. However, several of the other factors shown in Figure 7 are also discussed, based on the limited data available.

One of the difficulties faced when trying to assess many of these risk factors is the limited amount of data and the disconnected nature of the available data. This problem was also noted in the USFA studies mentioned earlier:

> Neither of the two national sources for fire death data—the National Center for Health Statistics (NCHS) and the National Fire Incident Reporting System (NFIRS)—provides for data collection of ancillary information on the deceased.

For example, although NFIRS may have some general information on the condition of a fire victim, this information is often unreliable given that emergency personnel do not necessarily know the medical history of fire victims. Therefore, they are only able to report information that is readily observable at the fire scene. More reliable data on the condition of the victims may be available from medical reports, but the data is typically not linked to other fire statistics of interest (for example, the presence and operability of smoke alarms during the fire). In addition, there may be some reluctance to report intoxication or disabilities in fire victims.

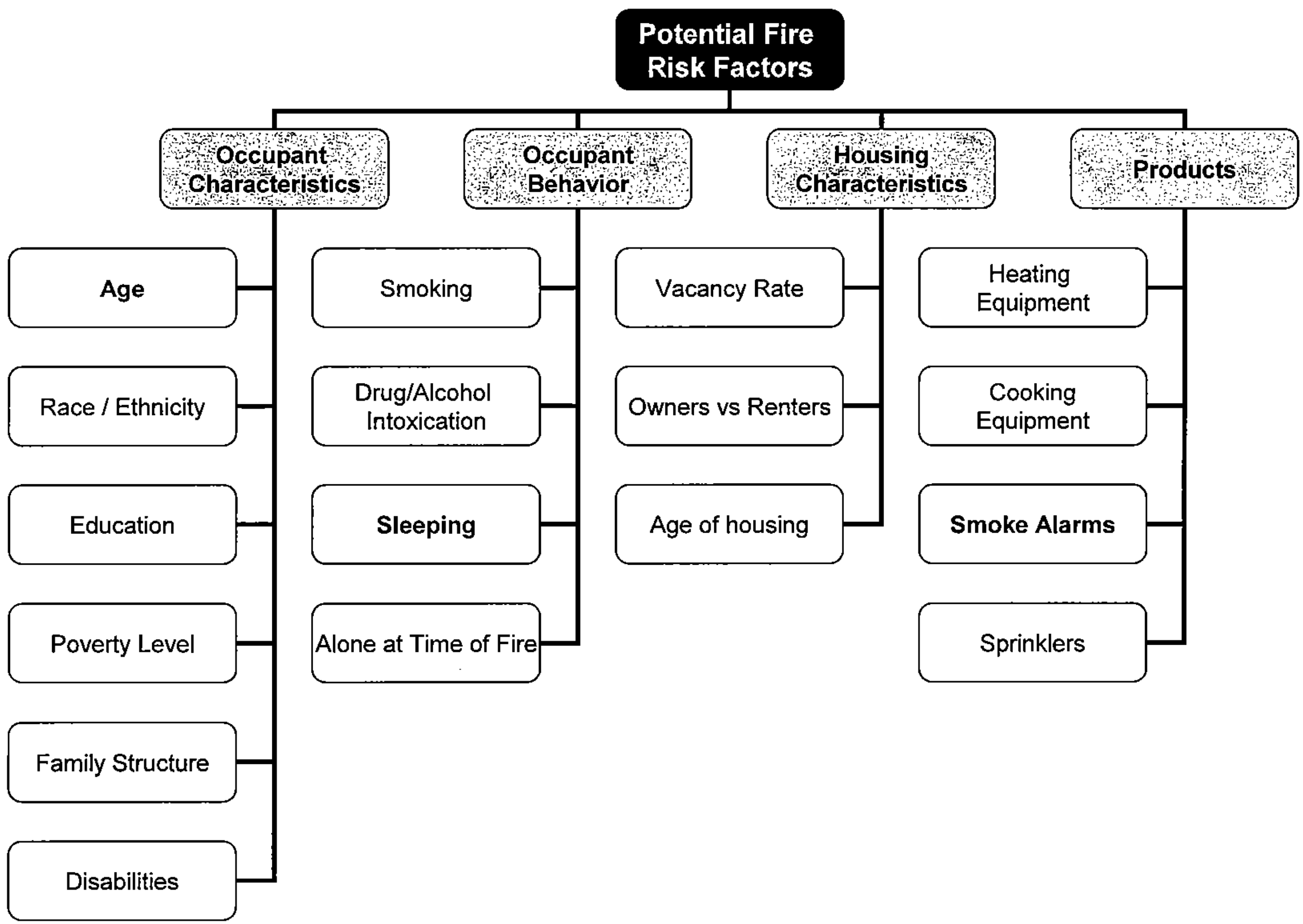


Figure 7 — Potential fire risk factors.

Some of the risk factors identified in Figure 7 seem to logically apply to older adults, but are not supported by the data. For example, given the prevalence of older housing among older adults, as discussed in Section 3.3, one might expect that the age of housing would be important. However, previous studies have shown that the age of a home is not a primary driver of fire risk [Hall, 2005]. Another example is the expectation of an increased risk of cooking-related fire deaths for older adults; however the data does not support this.

There is some data regarding risk factors associated with occupant behavior and product choices. Smoking materials are a significant contributor to fire risk—they "are the leading cause of home fire deaths, overall and for victims in every age group from age 35 up" [Hall, 2005]. For older adults (age 65 and over), smoking materials cause 32 percent of fatal home fires, which is consistent with the percentages of other age groups. The highest percentage of fire deaths attributed to smoking materials for any age group was for those 65–74 years of age, which had 37 percent of fire deaths caused by smoking materials. These statistics are somewhat surprising when the prevalence of smoking among older adults is considered. A study by the CDC in 2004 found that people age 65 and older have the lowest prevalence of current cigarette smoking (8.8 percent) among all adults [CDC, 2005]. In comparison, approximately 20.9 percent of U.S. adults were current smokers in 2004. Older adults appear to be at a disproportionately high risk of death in smoking-related fires, compared to the number of smokers in this age group.

Although alcohol intoxication certainly increases fire risk, it is not clear that the problem is sufficiently prevalent to significantly contribute to the high fire death risk of older adults. Studies from several states in which the blood alcohol levels of fire victims was examined found that 45–51 percent of adult fire victims had blood alcohol contents over 0.1 percent [Berl and Halpin, 1978; McGwin et al., 2000; Hall, 2005]. In the study on Maryland fire deaths [Berl and Halpin, 1978], 39 percent of fire victims age 60 and over were intoxicated compared to 51 percent of those age 20 and over. Similarly, a study of Minnesota fire deaths found that 21 percent of fire victims age 60 and over were intoxicated, compared to 46 percent of those age 20 and over (data from Minnesota Fire Marshal's Office in [Hall, 2005]). Older adults consume alcohol on more days each month than younger adults, but typically consume less in one sitting [USFA, 2006]. This may be significant given that Ball and Bruck [2004] found the greatest effect of alcohol on waking thresholds at only moderate levels of alcohol consumption (a blood alcohol content of 0.05).

Fahy and Molis [2004] conducted a study done in which they examined detailed narratives of fires from 1997–1998 where fatalities occurred in spite of smoke alarms operating. This work is of particular interest to the current discussion. Fahy and Molis examined 218 fires and 277 deaths, including 72 people over age 70. Forty-three percent of the older adult fire deaths in this study resulted from smoking-related fires; over a quarter of these older adults were smoking while on oxygen. The percentage of fire deaths associated with smoking for older adults is not significantly more than that of the overall population, in which 36 percent of deaths were from smoking-related fires. These statistics are consistent with the overall fire experience, discussed earlier. Fahy and Molis also found that 43 percent of the older adult fire victims in their study were believed to have some type of disability. This is significantly higher than the overall population (18 percent), but is relatively consistent with the disparity of disability rates between older adults and the overall population. Another risk factor that was examined by Fahy and

Molis was whether the victims were the only ones in the home at the time of the fire. Overall, 34 percent of victims age 16 and older were home alone at the time of the fire. For older adults, almost half (48 percent) of the victims examined were alone at the time of the fire. Given the large number of older adults living alone, this may be a contributing risk factor, particularly for those who have disabilities or difficulty hearing the alarm. Consistent with the previously presented data, a lower percentage of older adult fire victims (6 percent) were believed to be intoxicated than the overall population of adults 18 and over (23 percent). The determination of intoxication is based on the detailed narratives and not on tests of the blood alcohol content of the victims. Although the trend is similar to the previously presented results on alcohol intoxication and fire risk, it appears that the number of intoxicated victims may be under-reported. Regardless, intoxication does not appear to be as common for older adults. Although the data is not specific to older adults, Fahy and Molis found that 109 of the 154 victims (71 percent) with a known sleep status were asleep; the sleep status of 123 victims was undetermined. Clearly this indicates that in cases where smoke alarms do operate and there are still fatalities, the majority of these fire victims are sleeping. However, it is unclear from this data if the waking effectiveness of the alarm signal is the primary reason these victims were unable to escape. Other circumstances such as being intimate with ignition, alcohol or medication usage, or the inability to get out of bed may have contributed to some of these deaths.

4.2 Smoke Alarm Usage

An integral part of evaluating the fire safety of older adults is examining smoke alarm usage. Issues related to the usage of smoke alarms by older adults include whether or not smoke alarms are present, the operability of the smoke alarms during a fire, and the location of smoke alarms in the home. In general, there is limited data on smoke alarm usage, operability, and placement in homes. The information that is available is summarized below.

One source of general data on smoke alarm usage is the annual report published by NFPA titled *U.S. Experience with Smoke Alarms* [Ahrens, 2004]. In the most recent version of this report, NFPA estimates that 96 percent of homes (24 out of 25 homes) with a telephone have at least one smoke alarm [Ahrens, 2004]. However, there is relatively little information on the smoke alarm usage among older adults. The information that does exist suggests that households without smoke alarms are slightly more likely to be headed by an adult over 65 years old [Ahrens, 2004]. Other socioeconomic factors such as being poor or non-white had a similarly minor effect. More importantly, only around 60 percent of homes that reported fires have smoke alarms. This means that homes without smoke alarms report a disproportionate number of fires (4 percent of homes report around 40 percent of the fires). The reasons for this disparity are not obvious. However, two potential theories are that homes without smoke alarms are occupied by people who are less fire safe in general or that occupants of homes with alarms are alerted to fires earlier and are able to intervene before the fire reaches a size that necessitates contacting the fire department. NFPA has conducted an exploratory analysis of the latter explanation, and this analysis suggests that smoke alarms may reduce the number of fires reported to the fire department by 75 to 80 percent when compared to the number of fires that would be reported without smoke alarms [Ahrens, 2004].

It is also important to understand the source of power used by smoke alarms. NFIRS data from home fires in 1999–2001 indicates that around 72 percent of smoke alarms are battery-

powered [Ahrens, 2004]. Since there was no practical means to interconnect battery-operated smoke alarms until recently, these alarms are all expected to be single-station (i.e. not interconnected). Hardwired smoke alarms (i.e. those powered by AC power only) comprise 13 percent of the alarms found in home structure fires over this same period of time and smoke alarms that are hardwired with battery backup account for another 12 percent. Not all alarms that rely on AC power are interconnected. Therefore, it is unclear how many of these hardwired and hardwire with battery backup smoke alarms are multiple-station (interconnected) alarms. However, as an upper bound, no more than 25 percent of smoke alarms in home fires are interconnected. The power source used by alarms is also important in terms of the reliability and operability of smoke alarms. Generally, the operability of battery-operated smoke alarms is less than smoke alarms that are hardwired or hardwired with battery backup. Excluding fires that were deemed too small to operate a smoke alarm, NFIRS data from 1999–2001 shows battery-operated smoke alarms operated in 68 percent of home fires in which they were present; hardwired smoke alarms operated in 81 percent of fires in which they were present and hardwired smoke alarms with battery backup operated in 89 percent of fires in which they were present [Ahrens, 2004]. Missing, disconnected, or dead batteries account for the vast majority of battery-operated smoke alarm failures.

Although the data is not specific to older adults, the Smoke Detector Operability Survey conducted in 1992 by the Consumer Product Safety Commission (CPSC), as part of the National Smoke Detector Project, provides the primary source of data regarding the operability of smoke alarms [Smith, 1994]. Based on this survey, about 88 percent of households were estimated to have at least one installed smoke alarm. This means that around 12 percent of the households in the survey had no smoke alarms installed. The CPSC also found that 27 percent of smoke alarms tested did not work and that 20 percent of households with smoke alarms installed had no working smoke alarms. Furthermore, 46 percent of the households with no working smoke alarms thought that *all* their smoke alarms were in working condition prior to testing. In total, these survey results indicate that 32 percent of households did not have an operating smoke alarm.

As part of Fire Prevention Week in 1997, NFPA and several local organizations in Quincy, MA organized Project S.A.F.E. (Smoke Alarms for Elders) [Ahrens, 2004]. Residents of the community that were over 75 years of age or suffered mobility impairments were able to have new smoke alarms installed (as many as required to meet local codes) or to have their existing alarms tested. Over 80 percent of the participants lived in single-family homes. NFPA reported that 18 percent of the 139 homes had no smoke alarms and 39 percent of the 267 alarms tested did not operate [Ahrens & Gamache, 1997]. The project was repeated in subsequent years, and over the period 1997–1999, between 35–39 percent of smoke alarms in homes did not work [Ahrens, 2000]. Around half of the homes (46–52 percent) surveyed had at least one smoke alarm that was not working over this same three year period [Ahrens, 2000]. Over 80 percent of the non-working smoke alarms were due to dead, missing, or disconnected batteries [Ahrens & Gamache, 1997; Ahrens, 2000]. Around 20 percent of the alarms found in homes were believed to be over 10 years old, however this is likely an underestimate since people often do not know the age of their smoke alarms [Ahrens, 2000]. Although the size of the sample was small and self-selected (i.e. not a random sample of the older adult population), these results suggest that older adults may be more likely to have maintenance issues with their smoke alarms than the

general population. This assertion is based on the fact that the percent of inoperable alarms for the older population was 35–39 percent compared to 27 percent for the general population.

It is estimated that the majority of homes do not have smoke alarms in bedrooms, nor do they have interconnected alarms. Per NFPA 101, *Life Safety Code,* existing homes and apartment buildings do not require smoke alarms in bedrooms, and per NFPA 101 new apartment buildings do not require smoke alarms in bedrooms when there is a sprinkler system. No data was found that identified the number of homes that have interconnected smoke alarms or smoke alarms in all bedrooms, either for the general population or specifically for older adults. However, the age of the structure can be used to provide an assessment of how many homes have smoke alarms in bedrooms or have interconnected smoke alarms.

Requirements for interconnected smoke alarms and smoke alarms in bedrooms have continually evolved over the last two decades. The 1984 edition of NFPA 74, *Standard on the Installation, Maintenance, and Use of Household Fire Warning Equipment,* had no requirements for interconnected smoke alarms or smoke alarms in every bedroom. By 1989, NFPA 74 added requirements for interconnected smoke alarms in new construction. NFPA 74 and several other detection and alarm standards were eventually incorporated into a single consolidated standard—NFPA 72, *National Fire Alarm Code.* In the 1993 edition of NFPA 72, requirements for smoke alarms in every sleeping room were added for new construction.

NFPA 101 and the model building codes preceded NFPA 74, in some cases, in requiring interconnected smoke alarms. NFPA 101 added requirements for interconnected smoke alarms in 1988. Several of the model building codes required interconnected smoke alarms in new construction as early as the mid-1980's. NFPA 101 adopted requirements for smoke alarms in bedrooms in 1991 for new apartments and in 1994 for new one- and two-family dwellings. The model building codes generally added requirements for smoke alarms in all sleeping rooms in the early- to mid-1990s. Based on this brief review of the evolution of smoke alarm requirements, homes built prior to the early- to mid-1990s are not expected to have smoke alarms in bedrooms and homes built prior to the mid- to late-1980s are not expected to have interconnected smoke alarms. In reality, it typically takes several years or code cycles before model building code changes are incorporated into local codes. Therefore, it is likely that interconnected smoke alarms and smoke alarms in bedrooms were not routinely installed in new construction until the early- to mid-1990's.

The Census data on housing presented in Section 3.3 and the previous discussion of smoke alarm requirements can be used to estimate the number of households in which smoke alarms are installed in bedrooms or are interconnected. Per the 2000 Census data, 90 percent of older adult householders live in structures which were built prior to 1990. Therefore, with interconnected alarms and alarms in bedrooms not being required until around 1990, it can be estimated that up to 90 percent of older adult households do not have interconnected alarms and alarms in bedrooms.

4.3 Estimating the Impact of Improved Waking Effectiveness

This section provides a summary of an analysis by the NFPA Fire Analysis and Research Division that estimates the impact of improving the waking effectiveness of smoke alarms on the

fire death risk of older adults. The full report by NFPA is available in Appendix A of this report. The data used in this analysis is from the National Fire Incident Reporting System (NFIRS) and NFPA surveys. Data are generally shown for two sets of years—1980–1998 and 1999–2002—which are separated based on the major change in fire incident coding from NFIRS Version 4.1 to NFIRS Version 5.0. Long-term and more recent trends can be examined using these two data sets, which is important given the inherent variability of the data. The analysis also considers not only those age 65 and over, but also those under age 18 and those 18 to 64 years of age for comparison.

Table 5 provides a summary of the home fire death and injury risk for the three age groups examined. The fire death rate of older adults is two to three times that of those 18–64 years of age. The fire death rates for those under age 18 are slightly higher than those age 18–64, but still significantly less than those over 65 years of age. Comparing the data from the two sets of years examined, fire death and injury rates have decreased in the more recent data set. The fire death rate of those age 18–64 and those over age 65 has decreased by 30 percent from the 1980–1998 to the 1999–2002 data set. A 47 percent reduction in fire death rate for those under age 18 occurred for these same time periods. Injury rates for older adults are similar, but slightly less than those 18–64, while the under 18 age group had the lowest injury rates in both data sets.

Table 5 — Home fire death and injury risk by age group, 1980–1998 and 1999–2002

	Age 65 and over	**Age under 18**	**Age 18–64**
1999–2002 death rate	24.0	10.3	8.8
1999–2002 average deaths	845	746	1,539
1999–2002 average population (in millions)	35.2	72.4	175.6
1999–2002 injury rate	60.3	44.1	66.0
1980–1998 death rate	34.3	19.6	12.4
1980–1998 average deaths	1,048	1,283	1,884
1980–1998 average population (in millions)	30.5	65.3	152.5
1980–1998 injury rate	78.7	61.4	86.6

Notes: Death and injury rates are expressed per million population per year and exclude firefighters. These are national estimates of fires reported to U.S. municipal fire departments and so exclude fires reported only to Federal or state agencies or industrial fire brigades. National estimates are projections. Casualty projections can be heavily influenced by the inclusion or exclusion of one unusually serious fire. Home structure fires include one- and two-family dwellings, apartments, townhouses, flats, and manufactured homes, but exclude dormitories, barracks, hotels and motels, boarding or rooming houses, and assisted living facilities.

Source: NFIRS and NFPA survey, population figures from U.S. Census Bureau.

Before the impact of improving the waking effectiveness of smoke alarms can be determined, the activities of the fatally injured occupants need to be examined. Table 2 of Appendix A summarizes the percentages of fire deaths for the three age groups and the two year groups by

four groups of major activity when injured—sleeping, attempting to escape, attempting rescue or fire control, and unable to act or acting irrationally. Figure 8 provides a comparison between the three age groups of the activity when fatally injured for home fires from 1999–2002 (data taken from Table 2 of Appendix A). The percentage distributions of activity when fatally injured show very little variation between the two year groups, so the data shown in Figure 8 is also representative of the long term trends in the 1980–1998 data.

Overall, older adults had the lowest percentage of fire deaths in which the victim was sleeping (36–38 percent). In comparison, approximately 44–45 percent of the fire deaths in the 18–64 age group and nearly three out of five (57–58 percent) fire deaths among those under age 18 were sleeping when fatally injured. Although the reason for this trend is not entirely clear, it is well documented in the sleep literature that older adults have less deep sleep, more time awake after sleep onset and more fragmentary sleep, compared to other age groups. The percentage of fire deaths in which the victim was attempting escape and attempting fire control or rescue was similar for the age 65 and older and 18–64 age groups.

Fire victims age 65 and older were slightly more likely to be classified as unable to act or acting irrationally compared to the 18–64 year old age group. This difference is likely a result of the higher percentage of those age 65 and over with impairments that may render them unable to act.

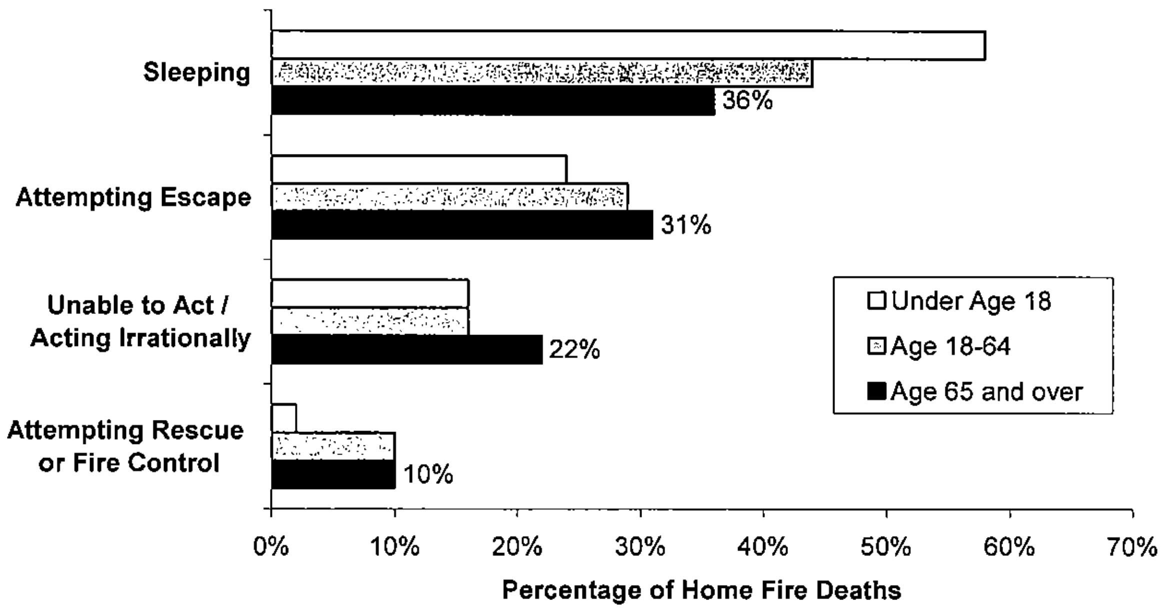


Figure 8 — Activity when fatally injured for home fire deaths (1999–2002)

4.3.1 Assumptions and Limitations

The fatal victims who were asleep when fatally injured are the focus of this analysis. A best-case estimate of the reduction in fire death risk can be made if the waking effectiveness of smoke alarms is changed such that all occupants for a given population are awakened. However,

successful waking of sleeping occupants is not enough to assure safe escape. Once awakened, some of the occupants would still be expected to die. There will be unsuccessful escape attempts, where the early warning from smoke alarms could not compensate in all cases for either limited time for escape or insufficient training and knowledge of effective escape routes and procedures. In addition, several other activities that the occupant may select once awake may involve indefinitely extended time in hazardous conditions and would therefore be expected to lead to death. On the other hand, changes that lead to successful waking of more occupants could also result in earlier alerting of occupants who were already awake. Earlier alerting could lead to more success in chosen activities and fewer deaths, but this effect is not considered in the analysis.

The analysis presented assumes that sleeping occupants, if awakened, will select activities in the same proportions as occupants who were not asleep when the fire began and will experience the same risks associated with those activities as did the occupants who were not asleep. For example, a newly awakened occupant is assumed to be just as likely to decide to fight the fire as an occupant who was never asleep and just as likely to be fatally injured while doing so. Further, the analysis assumes that a person newly awakened at one time of day will select activities and encounter risks associated with those activities in the same way as a person newly awakened at another time of day. For example, although a person is more likely to be asleep at 3 am than at 3 pm, once awakened, that person is as likely to choose escape rather than firefighting at 3 am as at 3 pm, and the risk of fatal injury for each activity chosen will be the same at 3 am as at 3 pm.

4.3.2 Risk Reduction

Using the assumptions stated in the previous section, a probabilistic model was developed to estimate the reduction in risk by waking all sleeping occupants. The details of this model and the values used to derive the model results are presented in Appendix A.

Using this model, the estimated fire death rate when asleep for those age 65 and over is 61.4 (deaths per million population per year) for 1999–2002. The fire death risk of older adults when sleeping is 3.4 times greater than when awake. Using the estimated fire death rates when asleep and awake, it can be shown that the estimated fire death risk to older adults is reduced by 27–32 percent if *all* sleeping older adults are awakened. This equates to an annual reduction in home fire deaths of 230–270 people age 65 and over, based on the annual average of older adult home fire deaths from 1999–2002. There are two primary reasons for the modest risk reduction found. First, even if all occupants were awakened, some of the occupants would still be expected to die as a result of unsuccessful escape attempts or because the occupant selects an activity, such as firefighting or attempting to rescue others, that may involve indefinitely extended time in hazardous conditions. Secondly, only 36–38 percent of older adult fire fatalities were reported to be sleeping when fatally injured. It should be noted that the percentage risk reduction for older adults was the lowest among the three age groups examined. The risk reduction for the under age 18 group was around 55 percent and the risk reduction for the 18–64 age group was around 45 percent. The primary driver of the larger risk reduction for these two age groups is that they have a greater percentage of occupants sleeping when fatally injured (56–58 percent for those under age 18 and 44–45 percent for those 18–64 years) compared to older adults (36–38 percent). Although the focus of this project is on older adults, it

is also instructive to consider the annual reduction in fire deaths for the entire population. If all occupants who were sleeping could be awakened, then the potential annual reduction in fire deaths would be 1320–1380.

The estimates of risk reduction and reduction in annual fire deaths discussed to this point have not considered the circumstances of the victims, such as their proximity to the fire and whether or not smoke alarms were present and operated. Clearly it is important to assess the impact these circumstances have on the expected reduction in risk.

Table 6 shows the percentage of home fire fatalities that were intimate with ignition for each age group, grouped by the victim's activity when fatally injured. Overall, a higher percentage of older adult fire victims were in close proximity to fires (either intimate with ignition or in room of fire origin) across all activities compared to other age groups. One in four older adult fire deaths (26 percent) that were sleeping when fatally injured were intimate with ignition. Furthermore, one of every two older adult fire deaths (50 percent) that were sleeping when fatally injured were in the room of fire origin (including intimate with ignition). Smoke alarms are not expected to be able to save those intimate with ignition. Victims that are in the room of fire origin, but not intimate with ignition, may or may not benefit from improvements to the waking effectiveness of smoke alarms.

Even though older adults had the lowest percentage of occupants fatally injured while sleeping among the three age groups examined, they had the highest percentage of fatalities while sleeping and being intimate with ignition or in the room of fire origin. This suggests that older adults may be less able to respond to and escape from fires in the rooms in which they are sleeping.

Examining reported smoke alarm presence and operability for fire fatalities provides insight into how many fire victims would realistically be able to take advantage of improved smoke alarm waking effectiveness. Due to changes in the fire incident coding regarding smoke alarm presence and operability, the recent data set (1999–2002) contains data reported in two different formats (NFIRS 4.1 and 5.0). Therefore, adjustments have to be made to combine the data from the two formats. To avoid this complication and still represent recent trends in smoke alarm usage a subset of data from the 1980 to 1998 data set was used. Table 7 presents statistics on smoke alarm presence and operability in fatal home fires, for each age group and activity when fatally injured during 1996–1998. Using this three year time frame is preferable to using the entire 1980–1998 dataset because the presence of smoke alarms has increased sharply since 1980. Only around 10 percent of home fire fatalities had smoke alarms present in 1980, compared to almost 50 percent in 1998 [Ahrens, 2004].

Only 44 percent of older adult fire victims that were sleeping when fatally injured were reported to have a smoke alarm present in 1996–1998. In other words, more than half of all older adult fire victims that died while sleeping did not have a smoke alarm present. Furthermore, only 24 percent of older adult fire victims who were sleeping when fatally injured had a smoke alarm present and operated (i.e. an operable smoke alarm). In essence, three out of four older adult fire victims that died while sleeping either did not have a smoke alarm or their smoke alarm did not operate.

The statistics on smoke alarm presence and operability for fire fatalities in the under 18 and 18–64 age groups were remarkably similar to those of the older adults. In order to realize the benefits of improved smoke alarm waking effectiveness, smoke alarms must be present and operate. This conclusion applies to older adults, as well as the general population.

Table 6 — Percentage of home fire fatalities who were intimate with ignition, by age group and activity when injured, 1980–1998.

	Age 65 and over	**Age under 18**	**Age 18–64**
Percent intimate with ignition			
Sleeping	26%	6%	20%
Attempting to escape	14%	6%	10%
Attempting rescue or fire control	20%	12%	12%
Unable to act or acting irrationally	44%	18%	36%
Percent in room of fire origin (including but not limited to intimate with ignition)			
Sleeping	50%	22%	38%
Attempting to escape	35%	21%	28%
Attempting rescue or fire control	48%	27%	30%
Unable to act or acting irrationally	66%	49%	60%

Notes: These are national estimates of fires reported to U.S. municipal fire departments and so exclude fires reported only to Federal or state agencies or industrial fire brigades. National estimates are projections. Casualty projections can be heavily influenced by the inclusion or exclusion of one unusually serious fire. Home structure fires include one- and two-family dwellings, apartments, townhouses, flats, and manufactured homes, but exclude dormitories, barracks, hotels and motels, boarding or rooming houses, and assisted living facilities.

Source: NFIRS and NFPA survey.

Table 7 — Percentage of home fire fatalities with smoke alarms present or present and operated by age group and activity when fatally injured, 1996–1998.

	Age 65 and over	Age under 18	Age 18–64
Percent smoke alarms present			
Sleeping	44%	45%	43%
Attempting to escape	43%	52%	45%
Attempting rescue or fire control	49%	42%	50%
Unable to act or acting irrationally	53%	38%	51%
Percent smoke alarms present and operated			
Sleeping	24%	20%	19%
Attempting to escape	27%	29%	21%
Attempting rescue or fire control	49%	17%	18%
Unable to act or acting irrationally	40%	18%	29%

Notes: These are national estimates of fires reported to U.S. municipal fire departments and so exclude fires reported only to Federal or state agencies or industrial fire brigades. National estimates are projections. Casualty projections can be heavily influenced by the inclusion or exclusion of one unusually serious fire. Home structure fires include one- and two-family dwellings, apartments, townhouses, flats, and manufactured homes, but exclude dormitories, barracks, hotels and motels, boarding or rooming houses, and assisted living facilities.

Source: NFIRS and NFPA survey.

5.0 RESPONSE OF OLDER ADULTS TO THE SMOKE ALARM SIGNAL

This section summarizes the work on quantifying the human behavior aspects of the response of older adults to smoke alarm signals. Full details on this work are provided in a separate companion report [Bruck, et al., 2006]. The goals of this portion of the project were to assess the auditory arousal thresholds (AATs) from sleep of older adults to various alarm signals and determine their performance abilities, in terms of cognitive functioning and physical mobility, after waking.

Four signals were examined in the sleep study, including a 3000 Hz high-frequency T-3 alarm signal (typical of that used in U.S. smoke alarms), a 500 Hz low-frequency T-3 alarm signal, a 500–2500 Hz mixed frequency T-3 alarm signal, and a male voice (200–2500Hz) alarm signal. The sleep study included a total of 42 participants who ranged in age from 65–85 years; however, not all participants completed all portions of the study. All participants were independently mobile, did not take medication affecting their sleep, and reported normal or better hearing for their age. The hearing of each participant was screened at 500, 1000, 2000, 3000, and 4000 Hz in both ears. In order to participate in the study, each person needed to

perform within, or better than, one standard deviation of the mean threshold sound level (for their age and sex) at each frequency in both ears, based on normative values established by Cruickshanks, et al. [1998]. In other words, older adults who performed in the lowest 16 percent for their age and sex at any of the frequencies tested in either ear were not included [Bruck, et al., 2006]. Approximately 15 percent of potential participants failed this screening procedure, despite having self-reported average or better hearing. Those that failed the hearing screening did so in one ear or both ears at a range of different frequencies (i.e. not just at the high frequencies). Across all frequencies tested, the participants of this study had mean thresholds less than the normative means used as a baseline. This indicates that study participants had better than average hearing compared to the general population (see Appendix E in Bruck, et al. [2006]).

The procedures used in the sleep study are not presented here; consult Bruck, et al. [2006] for details. The remainder of this section highlights the results from the companion report by Bruck, et al. [2006]. Table 8 summarizes the AATs of older adults to various signals. Table 9 summarizes the older adults that did not wake to various signals at two sound levels.

Based on Table 8, AATs in older adults were lower for the mixed frequency T-3 signal and the 500 Hz T-3 signal than to the male voice and the high-frequency T-3 alarm signal. In fact, examining the median AATs shows that the current high-frequency T-3 alarm signal used in smoke alarms required a 20 dBA greater volume to arouse the sleeping older adults in this study than the mixed T-3 alarm signal. There were no significant differences in AATs found between males and females. However, there were significant differences in AATs for the high frequency T-3 between older adults 65–74 years of age and those 75–85 years of age, with the older age group having higher AATs; no significant age-related differences in AATs were found with the other signals.

Table 8 — Summary of auditory arousal thresholds (AATs) of older adults to the four signals.

Signal	Auditory Arousal Thresholds (dBA)			
	Mean	Std. Dev.	Range	Median
Low Frequency T-3 (500 Hz)	52.6	18.1	35–Did Not Wake[1]	45
Mixed Frequency T-3 (500–2500 Hz)	48.0	13.3	35–85	45
High Frequency T-3 (3000 Hz)[2]	63.7	15.3	35–Did Not Wake[1]	65
Male Voice (200–2500 Hz)	55.9	19.2	35–Did Not Wake[1]	50

1. Did not wake to 95 dBA signal

2. Shaded row indicates the smoke alarm signal typically used in U.S. smoke alarms.

Table 9 — Summary of older adults that did not wake to the four signals at three sound levels.

Signal	Did Not Wake at 75 dBA		Did Not Wake at 85 dBA		Did Not Wake at 95 dBA	
	Number	Percent	Number	Percent	Number	Percent
Low Frequency T-3 (500 Hz)	7	16 %	3	7 %	1	2 %
Mixed Frequency T-3 (500–2500 Hz)	2	5 %	1	2 %	0	0 %
High Frequency T-3 (3000–4000 Hz)[1]	8	18 %	2	5 %	1	2 %
Male Voice (200–2500 Hz)	6	14 %	4	9 %	3	7 %

1. Shaded row indicates the smoke alarm signal typically used in U.S. smoke alarms.

The performance of the four signals examined in the sleep study is also shown in Figure 9, which shows the cumulative frequency of AATs for the four signals. The mixed frequency T-3 signal had the lowest percentages of participants that did not wake at each of the sound levels shown in Table 9. In fact, none of the older adults in the study slept through the mixed frequency T-3 alarm signal at 95 dBA, the loudest sound level used in the study. The male voice signal had the highest percentage (7 percent) of participants that did not wake at 95 dBA. At a sound level of 75 dBA, which is the recommended sound level in the U.S. to awaken sleeping occupants, only five percent of older adults studied did not wake to the mixed frequency T-3, while 18 percent did not wake to the high frequency signal used in current smoke alarms. As a result of the highly selected population and various methodological factors, the results of the sleep study are likely to significantly underestimate the proportion of older adults in the general population that will not awaken to an alarm under typical conditions in their homes. The older adult population examined in the sleep study did not include older adults with the poorest hearing, people taking medication that affects sleep, those with mobility or cognitive impairments, people impaired by alcohol, or people that reported difficulties falling asleep. The methodological issues include that the signals were not presented from silence, the participants were awakened from the deepest sleep stage, and they were primed (i.e. they were expecting to be awakened by a signal and they were familiar with the signal). Further research is required to determine the extent of the underestimation of older adults in the general population who will not awaken to an alarm in typical field conditions.

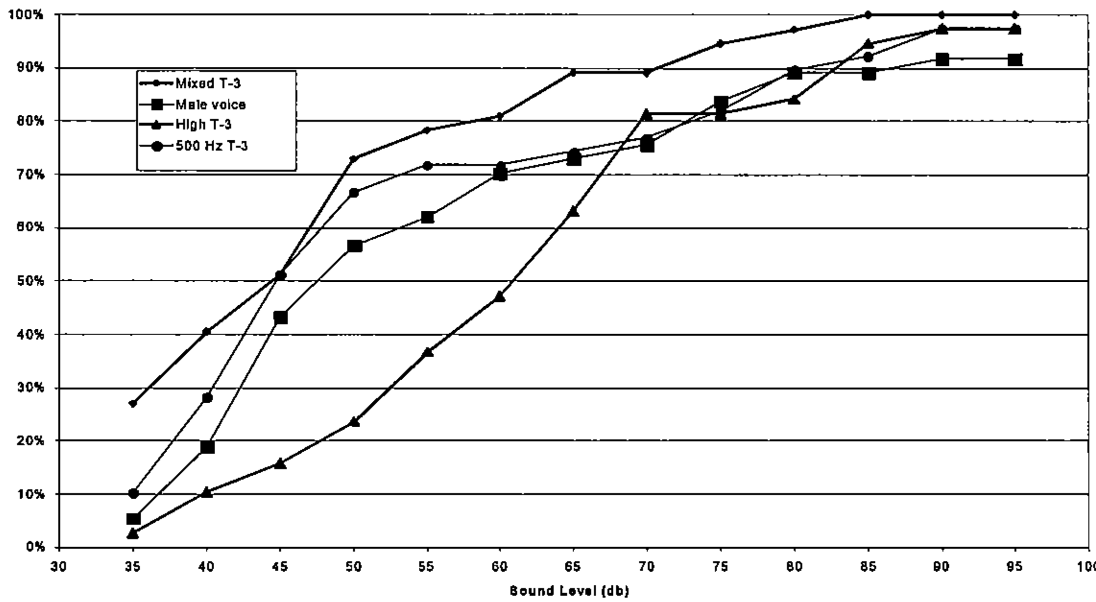


Figure 9 — Cumulative frequency of AATs for the four signals.

In terms of their physical and cognitive functioning once awakened, there was enormous individual variability in the results. In general, sleep inertia caused reductions in physical functioning, but did not have any important effects on cognitive functioning. Sleep inertia resulted in a 17 percent increase in time required to complete a psychomotor task of connecting numbers after waking compared to baseline conditions (prior to sleep). Likewise, sleep inertia increased the time required to get out of bed and walk 15 meters (about 50 ft) by 10 percent.

6.0 ANALYSIS

The sleep study results clearly show that the mixed frequency T-3 signal was more effective in waking the older adult participants than any of the other signals evaluated, especially the high frequency T-3, typical of most current alarms. Based on the results of the sleep study Bruck, et al. [2006] recommend that the high frequency alarm signal currently used in smoke alarms be replaced by an alternative signal that performs significantly better in awakening most of the adult population, once the nature of the best signal has been determined. Furthermore, a mixed frequency T-3 signal has performed significantly better than the high frequency signal in its ability to awaken sleepers in every sample group tested so far [Bruck, et al., 2006], including children, young adults (both sober and alcohol intoxicated), and older adults. However, several years of research may still be required to obtain the rigorous evidence needed to introduce a signal frequency recommendation.

The smoke alarm audibility study conducted by the CPSC [Lee, 2005a] found that a hallway smoke alarm produced a sound level as low as 70 dBA in a closed bedroom and a smoke alarm in the bedroom produced sound levels of approximately 90 dBA. All of the signals evaluated in the sleep study were more effective at greater sound levels, as is shown in Table 9 and Figure 9. To ensure that the maximum benefit of any alarm signal is provided to a sleeping occupant,

smoke alarms sounding within the bedroom are necessary. Furthermore, in order for a smoke alarm to sound in the bedroom when a fire is detected anywhere in the home, the alarms must be interconnected.

Although using the present sleep study to extrapolate to the general population of older adults and actual field conditions requires caution, this study is the only published source of data on the waking effectiveness of older adults currently available. Until data is available that addresses the general population of older adults in actual field conditions, estimates using the present sleep study are the best available. It is likely that these estimates *underestimate* the actual proportion of people who will not wake to an alarm, but the extent of this underestimation is unknown at this point.

The present sleep study is used as a case study to demonstrate the importance of having interconnected smoke alarms in bedrooms. Even for the high frequency T-3 signal, which was less effective than the mixed T-3 signal, the proportion of older adults in the study that did not wake was reduced to less than five percent (one or two participants) when sound levels consistent with a smoke alarm installed in the bedroom were used (greater than 85 dBA). This indicates that the vast majority of older adults examined in the sleep study would still be provided with an adequate level of protection from a smoke alarm with the current high frequency T-3 signal, if the smoke alarm was sounding in the room in which they were sleeping. This conclusion may not apply to the general population of older adults, which would include people with greater hearing loss and other factors that may reduce the likelihood that they wake to an alarm. In other words, the general population would likely have a lower waking rate to the same sound level. However, this study emphasizes the potential impact of having interconnected smoke alarms in bedrooms to achieve maximum sound levels to optimize the waking effectiveness of the alarm system.

As discussed in the risk analysis in Section 4.3, the vast majority of older adult fire victims that were sleeping when fatally injured did not have an operable smoke alarm. Therefore, improving the signal of an alarm without addressing concerns regarding the operability of smoke alarms would have limited impact on improving the safety of older adults. If all the older adult fire victims that were sleeping were awakened, the reduction in risk is 27–32 percent. In order to fully realize the benefits of smoke alarms that offer improved waking effectiveness, improvements in the proper use and maintenance of smoke alarms are required.

Section 7 discusses technologies that are currently available that address the issues highlighted in this section, including the use of alternative signals, technologies for the interconnection of smoke alarms and notification devices, and technologies that facilitate testing and maintenance of alarms.

7.0 REVIEW OF POTENTIAL TECHNICAL SOLUTIONS

One of the goals of this project is to not only identify and characterize the factors associated with the fire safety of older adults, but also to identify potential technical solutions for the fire safety challenges that older adults face. This section provides a review of current or promising technologies that may improve the waking effectiveness of smoke alarms for older adults and improve their fire safety. These alternative or assistive technologies aim to improve the

effectiveness of the smoke alarm signal and overall fire safety of older adults. Previous reviews of fire alarm technologies for the hearing impaired are discussed in DeVoss [1989], Vondrasek [1989], and more recently by the CPSC [Lee, 2005b], which focuses specifically on older adults. The potential technical solutions identified have been broadly categorized as those that provide alternative audible alarm signals, those that provide alternative sensory stimuli (visual, tactile, olfactory), those related to the interconnection of smoke alarms and notification devices, and those that facilitate testing and maintenance of alarms.

Within each of the broad technology categories, various aspects of the technology are discussed. First, the rationale and support for each technology is presented. Additional aspects of the technology that are considered are its availability/prevalence, features and functionality, applicability (i.e. who will benefit from the technology), practicality/ease-of-use, and estimated cost range.

This review represents a scan of available or promising technologies at the time of writing of this report. An attempt was made to address as many technologies and products as possible, however this review may not be all-inclusive due to rapid development of the marketplace in this area. In addition, the focus of this review is on technologies available in the United States. There has been similar interest throughout the world in developing accessible fire alarm technologies for older adults and for others with hearing loss, but these are not discussed. Mention of specific products or manufacturers is to provide specific examples and basis for the technologies discussed and does not constitute recommendation or endorsement by the authors or by the Fire Protection Research Foundation. Appendix B contains contact information for the manufacturers of the technologies mentioned in this section.

7.1 Alternative audible alarm signals

The focus of this project is on optimizing the audible alarm signal from a smoke alarm. The current alarm signal used by residential smoke alarms is described in Section 2.0. Alternative audible alarm signals may include variations in the pitch (frequency) or pattern of the alarm. Another alternative alarm signal is the human voice, which is also typically lower in frequency than the current alarm signal.

Increased signal speed, pitch, and repetition are the best parameters for urgent warnings when people are awake [Hellier and Edworthy, 1999]. The high-pitched T-3 signal currently used in smoke alarms is consistent with this approach. However, recent studies of the waking effectiveness of smoke alarms indicated that the high-pitched alarm signal currently used was the least effective signal at waking children when compared to a low-pitched T-3 signal, a female voice, and their mother's voice [Bruck and Ball, 2004a]. Similar studies with adults showed that mean arousal thresholds (i.e. the sound levels at which they awoke) were significantly higher for the high-pitched alarm, as compared to a female voice and a lower mixed-frequency T-3 (low/mixed T-3) [Ball and Bruck, 2004]. Another recent pilot study by Bruck found a male voice to be better than a female voice for waking adults. Research by Ashley, et al. [2005] indicated that a 3100 Hz T-3 audible alarm signal woke only 57 percent of hard of hearing subjects, while it woke 92 percent of hearing able subjects.

The results from the current sleep study, which are found in Section 5.0 and [Bruck, et al., 2006], indicated that the responsiveness of older adults to a mixed-frequency (500–2500 Hz) T-3 alarm signal was significantly better than the high frequency (3000 Hz) alarm signal currently used in most smoke alarms and a voice signal To date, no research has been done to systematically evaluate various frequencies and signal patterns to determine which provides the optimum waking effectiveness for smoke alarms.

There has been interest in technologies that provide alternative audible alarm signals to improve the effectiveness of smoke alarms in recent years, however only two commercial smoke alarms (one low-frequency smoke alarm and one smoke alarm using the human voice) were found that address this issue. No current smoke alarms were found that provide a mixed frequency alarm signal, similar to that used in the sleep study. Many combination carbon monoxide and smoke alarms now include a voice recording that identifies which alarm criteria (smoke or carbon monoxide) has been detected, and in some models, the location of the alarm. The primary purpose of the voice recording in these combination alarms is not to improve waking, but rather to provide additional contextual information to occupants once awake and to the fire service when they respond to the emergency. Therefore, only alarms utilizing alternative audible signals in an effort to improve the waking effectiveness of smoke alarms are considered here.

One possible contributing factor in the lack of prevalence of alternative audible alarm signals relates to the fact that the "piezoelectric horns used in current residential smoke alarms cannot produce a low frequency sound or output a voice message at the required dB level and still satisfy the battery requirements in UL 217, *Single and Multiple Station Smoke Alarms*" [Lee, 2005b]. Therefore, a significant technology change in terms of the design and hardware commonly used in smoke alarms is required to make this technology more prevalent in the marketplace.

The Darrow Company produces a smoke alarm called Loudenlow that provides a low-frequency (250–300 Hz) alarm signal. The low-frequency sound is delivered via a six inch dynamic speaker that is attached to an ionization smoke alarm. Based on the research discussed previously, the low-frequency alarm technology used in this product potentially benefits not only older adults, but also those with high frequency hearing loss and possibly children. However, there are several important points regarding the practicality and ease-of-use of this technology. Producing low frequency sounds at a high volume requires significantly different hardware than is currently used for smoke alarms. To house the six-inch speaker, amplifier, and power source used in the Loudenlow smoke alarm, an enclosure measuring 6.5 x 8 x 2 inches deep is used. The ionization smoke alarm that is mounted on top of the enclosure occupies another 1.5 inches of depth. The large size required by the current technology may affect the location/placement of the smoke alarm, as well raise concerns with homeowners regarding aesthetics. Another possible concern with regards to the practicality of this technology is power consumption. The Loudenlow smoke alarm is battery operated and draws 1 A (9 watts) of power when in alarm mode. For comparison, the power draw of a typical smoke alarm is 20 to 60 mA (0.15 to 0.5 W) when the alarm is sounding [NAEEEC, 2004]. Six AA batteries are required to power the Loudenlow, with a battery life of one year. The cost of one of these units is approximately $140. Since these smoke alarms are hand-built in small volumes, some reduction in cost may occur if

these were mass-produced. Also, note that the Loudenlow is not listed to UL 217, *Standard for Single- and Multiple-Station Alarms.*

SignalONE Safety, Inc. produces the KidSmart Vocal Smoke Alarm, a smoke alarm that incorporates a voice recording that alternates with the typical T-3 smoke alarm signal. The technology used in this alarm allows for personalized escape instructions to be provided in a familiar voice. Although the use of a voice signal is no longer recommended for adults, based on the results of the sleep study, this technology may benefit other population groups, such as children. The limited technical data available has indicated that voice warnings may benefit children; however, the data also indicate that the voice may be equivalent or less effective than low frequency signals. Additional technical data is needed to fully understand and quantify the effectiveness of a voice alarm for children. In terms of practicality and ease of use, this technology is similar to a typical smoke alarm. However, in order to use the voice feature of the KidSmart alarm, the voice message needs to be recorded by a user prior to installation. Recording the vocal warning is a relatively straightforward process. Unlike most smoke alarms that require a single nine volt battery, four AA batteries are required to power the KidSmart vocal smoke alarm. The cost of these smoke alarms is approximately $70. Although the currently available KidSmart smoke alarms are not UL-listed, UL-listed vocal smoke alarms from SignalONE Safety are expected in retail stores by summer 2006. As with any safety product, alarms with alternative signals should be tested with the intended audience to assure they produce the desired result.

7.2 Alternative alarm stimuli

Many older adults do not fully benefit from the audible alarm signals emitted from smoke alarms. In fact, nearly one in five participants in the sleep study, who had average or better hearing for their age, did not respond to the current high frequency (3000 Hz) alarm signal presented at 75 dBA. This effect is expected to be even greater in the overall population of older adults (i.e. those of all hearing abilities) since the tested population did not include older adults with the poorest hearing (see Section 5). Considering the prevalence of hearing loss among older adults, particularly in higher frequencies, smoke alarms that provide alternative means of notification need to be examined. This section examines visual, tactile (vibratory), and olfactory stimuli as alternatives to the audible smoke alarm signal.

7.2.1 Visual

High-intensity light sources, such as strobe lights, are used to provide emergency alarm signaling to the hearing impaired. The Americans with Disabilities Act (ADA) recommends the use of visual notification (strobes) for the sleeping areas of people with hearing impairments [ADA, 1994]. Requirements for this technology are outlined in UL 1971, *Signaling Devices for the Hearing Impaired.* Underwriters Laboratories (UL) conducted a research project as part of the development of UL 1971 that evaluated various signaling technologies, including strobe lights, to determine appropriate requirements [De Voss, 1991]. This study found that over 92 percent of the deaf subjects tested (adults and children) who were not taking medication were awakened by a 110 candela strobe. The response rate of those taking medication, who all were children 10 to 19 years of age, was significantly lower to the same visual stimuli. Only 28

percent (two out of seven) children who were taking medication awoke to the 110 candela strobe. All 22 adults in this study, none of whom were taking medication, awoke to the 110 candela visual signal. Strobes were slightly less effective for children not taking medication, 91 percent of those 13 to 19 years old and 86 percent of those 10 to 12 years old awoke to the 110 candela strobe. These results were consistent with work by Nober, et al. [1990] that concluded that deaf people could receive about the same levels of protection from visual smoke alarm signals that the hearing able receive from audible smoke alarms. However, more recent research by Ashley, et al. [2005], suggests that strobes may be less effective at waking occupants than the previous research indicated. In her research, Ashley examined the waking effectiveness of a 110 candela strobe for subjects of varying hearing abilities (hearing able, hard of hearing, and deaf). Ashley's research suggests that those with hearing loss may not benefit from visual alarms to the same extent as deaf occupants, possibly due to the increased familiarization of deaf occupants to visual stimuli as a means of alerting.

Compared to the other technologies examined in this review, smoke alarms capable of providing a visual alarm signal are relatively prevalent. In fact, most major smoke alarm manufacturers offer smoke alarm models with strobe lights, including First Alert, Gentex Corporation, and Kidde. Strobe lights may either be integrated into the smoke alarm or may be an accessory that connects to the alarm. For this review, the focus of the discussion will be on single- and multiple-station alarms with an integrated strobe intended for residential use. To assist people with hearing impairments, NFPA's Center for High Risk Outreach also provides a list of smoke alarms that include strobes on their website [NFPA, 2006].

The features available on smoke alarms with strobes are fairly consistent across manufacturers. These alarms generally feature a 177 candela strobe, in addition to a piezoelectric audible alarm yielding 85–90 dB at 10 feet. Most of the units are AC (hardwired) or AC with battery backup. Single-station units (i.e. not interconnected) are also available that are powered with an AC receptacle via a cord and plug. Alarms powered by battery only are not practical due to the typical power requirements of the strobes. As discussed earlier, technology that provides visual stimuli to alert occupants may not only be useful for older adults, but is also useful to others that are deaf or hearing impaired, regardless of age. However, the overall waking effectiveness of strobes for those that are not deaf may be limited. People that purchase alarms with strobes, should test the units with the intended occupants to determine if they will produce the desired result. These units generally cost in the range of $100–$160, but some cost up to $270.

7.2.2 Tactile

The sense of touch may also serve as a useful alarm signal. Vibratory devices such as bed shakers are the primary means of tactile stimulation commonly used; however the use of air movement as a means of alerting has also been discussed. Tactile stimulation, including vibratory alarms and air movement, as a means of emergency alerting was studied by UL during the development of UL 1971 [De Voss, 1991]. This research indicated that an air movement system, using a household oscillating fan with peak flows of 270–480 ft/min near the occupants head, awoke 82 percent of the deaf subjects in the study. However, there were concerns regarding the practicality of the installation and implementation of air movement systems, along with concerns that people accustomed to using fans for comfort would not be effectively alerted,

particularly when these comfort fans were in operation. There seems to have been little interest in air movement emergency alerting systems since then. However, interest in vibratory alarms has continued. The research by UL showed that 90 percent of the sleeping deaf subjects awoke to the vibratory alarm when placed under the pillow and 84 percent awoke when the alarm was placed under the mattress [De Voss, 1991]. The vibratory alarm used by UL was the smallest available unit at the time and it provided a displacement of one-eighth of an inch at a frequency of 100 Hz. UL noted that the effectiveness of larger vibratory alarms would be at least that of the unit they tested. Research by Ashley, et al. [2005] found vibratory alarms to be similarly effective. The vibratory bed shaker used in her study, which provided a vibration of 0.14–0.19 m^2/s, awoke 92 percent of the hearing able, 82 percent of the hard of hearing, and 93 percent of the deaf when placed under the mattress. Ashley found that the bed shaker was more effective than a 110 candela strobe at waking those with hearing impairments and was the most effective signal across the range of hearing abilities examined. Further work needs to be done to compare available bed shakers to the standard 177 candela strobes used with alarms. Overall, the performance of the vibratory bed shaker was comparable to that of the audible smoke alarm signal for the hearing able.

UL 1971 provides requirements for tactile signaling devices. Vibratory devices (that are not worn) must produce a displacement of one-eighth of an inch at a frequency of 60–120 Hz and have a cross-sectional area of at least 6 in^2. Air movement systems are required to produce a minimum peak air velocity of 270 feet/min at a distance of 5 ft. The air velocity must vary from zero to the peak velocity 15 to 20 cycles per minute.

Although not yet prevalent as part of smoke alarm systems, vibratory alarms in the form of bed shakers and portable pagers are readily available to address the needs of the hearing impaired. These products are used to alert the hearing impaired to common occurrences such as the telephone or door bell ringing, a baby crying, to wake up in the morning (an alarm clock). Generally, the vibratory device is just a component that attaches to the alarm clock or alerting system. Since the smoke alarm needs to be placed on or near the ceiling and the vibratory alarm needs to be in contact with a person being alerted, some means of communication is necessary to allow the vibratory device to know when a smoke alarm is activated. With the recent introduction of technologies that allow wireless interconnection of battery-operated smoke alarms, vibratory stimuli for emergency alerting will likely become more prevalent. The existing and new wireless technology associated with connecting smoke alarms to supplemental notification appliances, such as bed shakers, is discussed in Section 7.3.

Several manufacturers such as Clarity, ClearSounds, Sonic Alert, and Silent Call, produce vibrating pads (bed shakers) that incorporate with their other products such as telephones, alarm clocks, or alerting systems. The vibrating pads generally are powered by either 12 volts DC or 120 volts AC and typically cost around $30–$40.

7.2.3 Olfactory

There is a small body of research that has investigated the use of odors to stimulate the olfactory system and wake individuals in emergency situations. Although anecdotal evidence suggests that the olfactory system is able to detect the smell of burning materials quite well when

awake, the literature that is available on sleeping occupants provides consistent evidence that olfactory stimuli cannot reliably wake individuals [Kahn,1984; Lynch, 1997; Bruck and Brennan , 2001; Carskadon and Herz, 2004]. In addition to a lack of research supporting the use of olfactory stimuli for fire alarm signaling, no technology has been developed for this purpose.

7.3 Interconnection of Smoke Alarms and Notification Devices

The placement of smoke alarms is critically important to the waking effectiveness of smoke alarms and their life safety potential in general. The sound level produced by a smoke alarm must be sufficient to wake sleeping occupants in order to be effective. In order to achieve such conditions, it may be necessary to have a smoke alarm located in the same room as the occupant, particularly for older adults. Current requirements for new construction specify that smoke alarms are required on every level and in all sleeping areas. For new one- and two-family dwellings, these alarms are also required to be interconnected, so when one smoke alarm sounds an alarm, all the alarms sound. Historically, smoke alarms were interconnected via a third conductor run with the AC power cable. Therefore, for existing structures that had only battery-powered alarms or had non-interconnected AC power alarms, to interconnect the smoke alarms required the residence to be re-wired. Due to the practical and economic issues of upgrading wiring, interconnected alarms have not been required in existing construction. The difficulties associated with interconnecting alarms has also impeded the use of supplemental notification devices.

Figure 10 illustrates a typical smoke alarm installation in an existing two-story home with a basement, where only single-station (non-interconnected) smoke alarms are used. This figure shows a fire occurring in the basement of the home—the other smoke alarms in the home do not operate when the smoke alarm in the basement goes into alarm. Figure 11 illustrates the same scenario, but in this case hardwired multiple station (interconnected) smoke alarms are present. Once the smoke alarm in the basement alarms, all the smoke alarms that are connected also go into alarm.

Within the past few years, there has been a concentrated effort in developing interconnected smoke alarms suitable for installation in existing structures. In 2003, the Naval Research Laboratory (NRL) conducted a feasibility study for the CPSC regarding incorporating wireless communication capabilities into battery-powered smoke alarms [Street and Williams, 2003a; Street and Williams, 2003b]. Prototype devices were developed in this project that demonstrated the feasibility of the concept. The prototypes developed by NRL included radio frequency (RF) transmitter and receiver circuitry in each smoke alarm that allowed the alarms to be interconnected. The estimated additional material cost of the RF wireless technology (transmitter and receiver) was approximately $20 per smoke alarm, not including any cost recovery by the manufacturer for research and development [Street and Williams, 2003b].

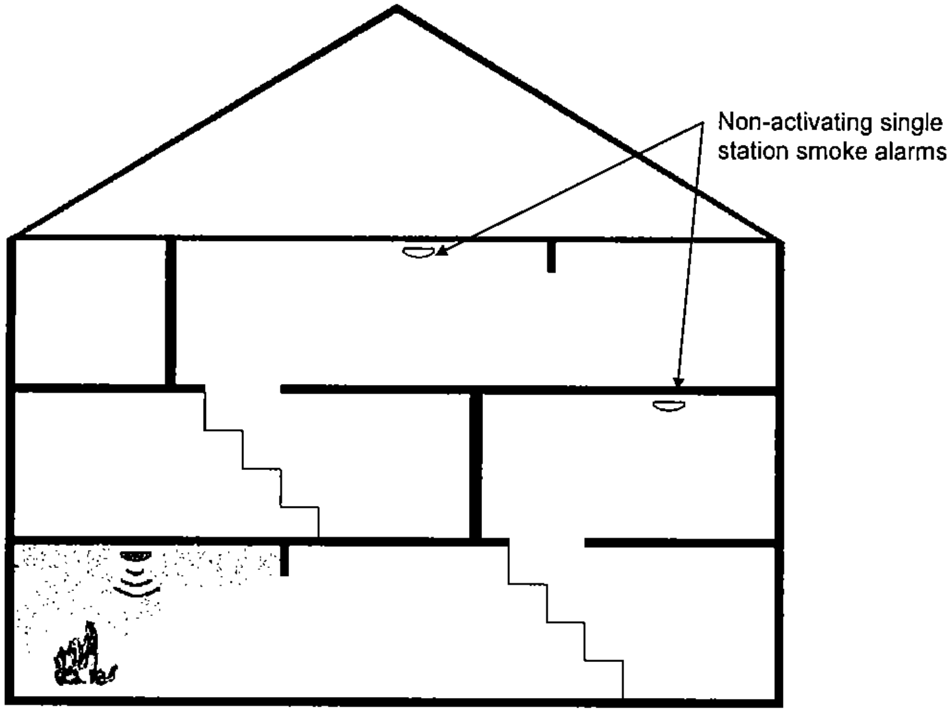


Figure 10 — Single-station smoke alarms.

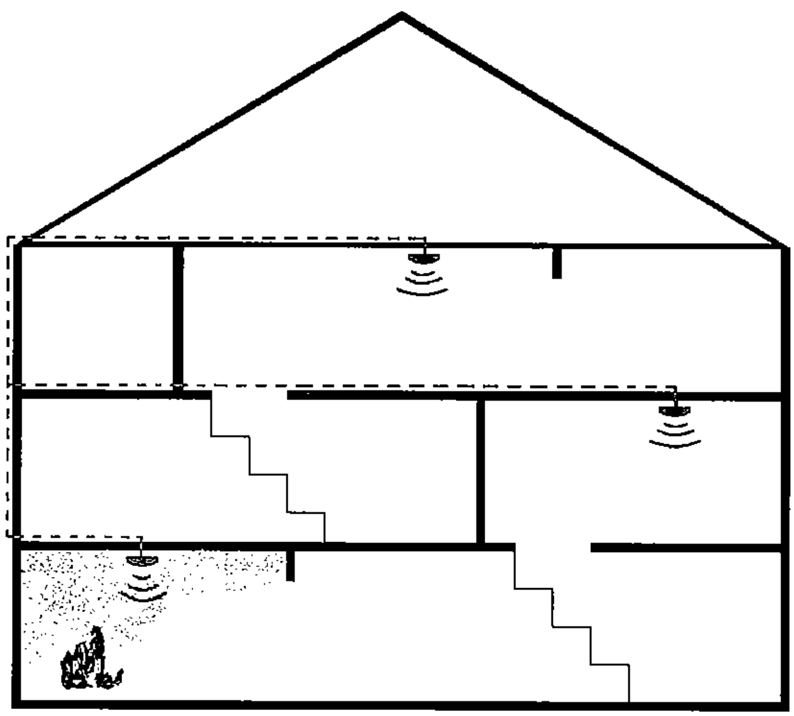


Figure 11 — Hardwired multiple-station (interconnected) smoke alarms.

Within the last year, products have become commercially available that incorporate wireless technology that enables battery-operated smoke alarms to be interconnected. Figure 12 illustrates the concept of wireless multiple-station (interconnected) smoke alarms. Similar to Figure 10 no wires are required between the smoke alarms. However, unlike Figure 10, when one of the wireless interconnected smoke alarms goes into alarm it signals all of the alarms in the home to alarm. In other words, wireless interconnected smoke alarms provide the benefit of hardwired interconnected smoke alarms (Figure 11) without the wires.

Wireless interconnected smoke alarms are available in home improvement stores and large retailers in many areas. Two of the primary manufacturers of residential smoke alarms, Kidde and First Alert, now offer smoke alarms with wireless technology. The features available in these alarms are similar to those typically available in traditional smoke alarms, but the number of different alarm models is relatively small. Units are available as battery- or AC-powered. The AC-powered units can supplement an existing hardwired, interconnected (multi-station) alarm system with wireless technology such that additional battery-operated wireless alarms can be added to new locations that are not wired for alarms.

Wireless smoke alarms do require one additional installation step compared to single-station alarms. The wireless units must be programmed to work together (communicate) as a system; this reduces the likelihood of interference from other RF wireless devices that may be in the home. Programming the wireless smoke alarms is achieved either by setting a series of switches on the unit or by following a brief programming procedure that involves pressing the test button when the unit is first powered. These smoke alarms retain their programming, so the unit does not have to be reprogrammed each time the batteries are replaced. The required programming step for wireless smoke alarms slightly reduces their ease of installation compared to traditional smoke alarms; however, the benefits of wireless interconnected smoke alarms are significant.

Wireless interconnected smoke alarms benefit a wide range of potential users, including older adults. Occupants who are hearing able would benefit from an increased sound volume at pillow level, possibly alerting them to a fire sooner. Occupants with hearing impairments could benefit from this technology via the use of supplemental notification devices, which better address their needs. Supplemental notification devices will be discussed in more detail later in this section. To fully take advantage of the wireless interconnect technology requires replacement of all existing battery-operated smoke alarms with new alarms that incorporate the wireless feature. One potential hurdle to implementing this technology is that the retail cost of these alarms are around \$40–\$60 per alarm. Combination smoke and carbon monoxide alarms are also available for an additional cost. For a three bedroom, two-story house the cost of installing five (5) interconnected alarms (one per bedroom, plus one for each level) would be \$200–\$300. In comparison, the CPSC estimated the cost to retrofit the same hypothetical home in the Washington, DC area with hardwired, interconnected smoke alarms at \$800–\$1200, based on quotes from licensed electricians [Lee, 2005b]. Wireless technology clearly provides a more cost-effective means of interconnecting smoke alarms than hardwired interconnection.

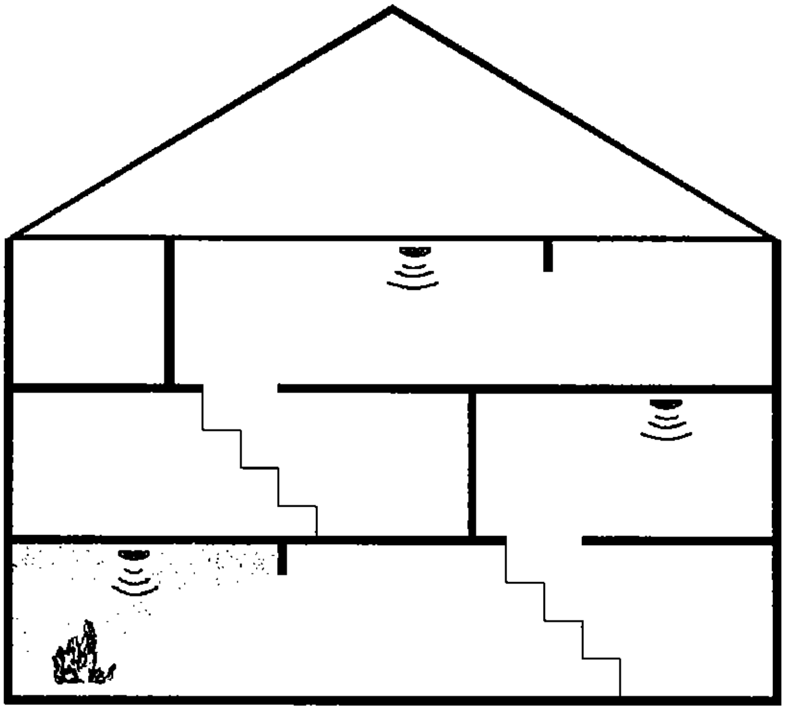


Figure 12 — Wireless multiple-station (interconnected) smoke alarms.

As discussed in Sections 6.1 and 6.2, a supplemental notification device could provide a lower frequency alarm sound, a voice alarm, a strobe light, and/or a bed shaker, whichever technology or technologies are most appropriate to wake the occupant. There are various means by which smoke alarms and notification devices can be connected in homes. One approach uses acoustic monitoring for the sound produced by a smoke alarm. This technology can be implemented either adjacent to the smoke alarm or remotely. For all implementations, a receiver with a microphone detects the sound of a smoke alarm signal and uses signal processing algorithms or circuitry to discriminate that sound from other noises. Detection of the sound of the alarm signal can then be used with additional electronics to sound other smoke alarms or to activate supplemental notification devices. Figure 13 illustrates how a supplemental notification device activated by an acoustic monitor that is located *remotely* from the smoke alarm would work. The acoustic monitor, which is directly connected to the supplemental notification device, senses the sound of an alarm and initiates notification. Figure 14 illustrates how a supplemental notification device that is activated by an acoustical monitor *adjacent* to the smoke alarm would work. In this case, the acoustic monitor is located near the smoke alarm and sends a wireless signal to the notification device when it determines that an alarm has occurred.

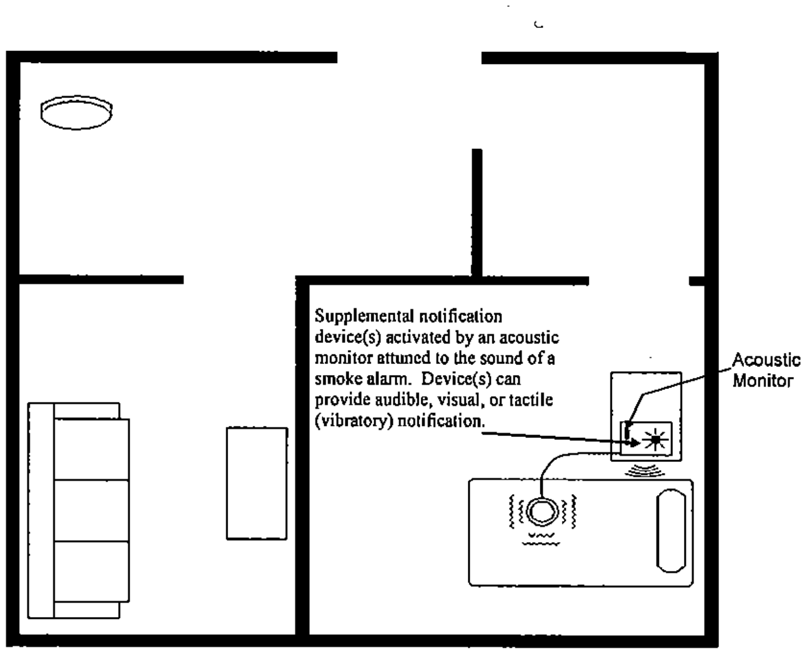


Figure 13 — Activation of supplemental notification devices by an acoustic monitor that is located remotely from the smoke alarm.

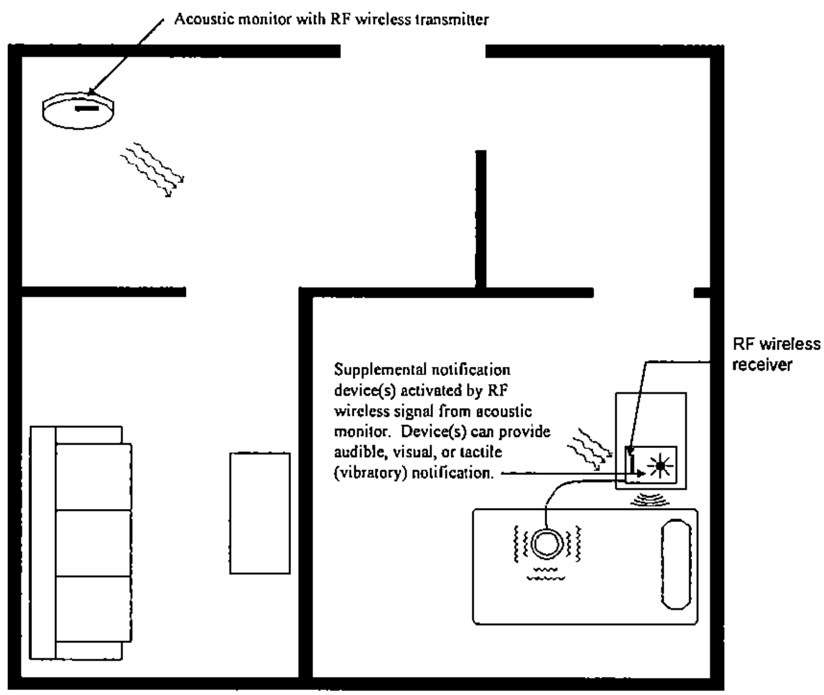


Figure 14 — Activation of supplemental notification devices by an acoustic monitor with wireless transmitter that is located adjacent to the smoke alarm.

Technology to detect the sound of a smoke alarm and initiate a supplemental notification device is being pursued by several manufacturers including Clarity (Ameriphone), Krown Manufacturing Inc., and InnovAlarm. Krown Manufacturing and Clarity both currently produce alerting systems for the deaf and hard of hearing that acoustically monitor existing audible alarms and transfer these alarms to supplemental notification devices via a wireless signal, as shown in Figure 14. InnovAlarm has developed similar technology and has several prototype devices, but none are yet commercially available [Crutcher, 2003; Morales, 2001; Albert, 2006]. The technology developed by InnovAlarm allows remote acoustic monitoring of the smoke alarm, with the supplemental notification device(s) attached directly to the remote device, as shown in Figure 13. One of the benefits of activating supplemental notification devices via acoustical monitoring is that existing smoke alarms do not need to be replaced. The transmitter units, which sense an audible alarm and transmit a wireless signal to the alerting system, are generally battery-powered, while the receiver units, which initiate the supplemental notification devices, are plugged into a household electrical outlet. The two commercially-available products mentioned are typically sold as systems (kits) that include a receiver unit and several supplemental notification devices (e.g. loud speakers, strobes, and/or bed shakers). The system from Krown Manufacturing includes one acoustic monitor, but the system from Clarity (Ameriphone) does not (it must be purchased separately). The systems cost \$200–\$300. Additional alarm transmitters, which acoustically monitor smoke alarms, cost in the range of \$40–\$50.

Just as a wireless signal from a smoke alarm can be used to activate other wireless smoke alarms (see Figure 12), it can also be used to activate supplemental notification devices. Figure 15 illustrates how a wireless smoke alarm can activate a supplemental notification device. Kidde produces a supplemental notification device that works with its RF wireless smoke alarms; the supplemental device provides both a voice alarm and a low frequency (1000 Hz) alarm signal when it receives a wireless alarm activation signal from a smoke alarm. Silent Call manufactures smoke alarms that incorporate the Silent Call wireless transmitter. This transmitter is not used to interconnect smoke alarms, but it is compatible with Silent Call wireless receivers that provide supplementary means of notification. Basically, the transmitter uses a relay contact on the smoke alarm to determine when an alarm occurs and sends a wireless signal to compatible supplementary notification devices. A wide range of notification devices are available that are compatible with the Silent Call transmitter, including strobes, bed shakers, and vibrating personal pagers. Power to the supplemental notification devices is generally delivered via an AC electrical outlet. The Silent Call wireless technologies are similar to the alerting systems discussed previously by Clarity and Krown Manufacturing, except that the wireless transmitter is integrated into special smoke alarms rather than relying on acoustic monitoring. The Kidde supplemental notification device retails for around \$60. The smoke alarms that include the Silent Call transmitter cost \$110–\$120, the supplementary notification device kits are \$150–\$175, and the personal pagers are \$120–\$130.

Additionally, interconnection of AC single-station alarms or supplemental notification devices could be achieved via a signal on the home's AC wiring (i.e. power line communication). A transmitter superimposes a high-frequency analog signal (20–200 kHz) over the standard 50 to 60 Hz household wiring. The superimposed signal does not affect the regular

operation of other devices on the AC power circuit. A receiver, which may be plugged into a household electrical outlet or hardwired to the household wiring, is required to detect and decode the superimposed signal. This technology is commonly used in home automation, but would require smoke alarms to be AC-powered and include a special transmitter to generate and apply the signal to the household wiring, as well as a supplemental notification device that could detect the signal on the AC wiring. Figure 16 illustrates how supplemental notification devices could be activated via power line communication. Despite being a feasible approach, there do not appear to be any current applications of this technology to activating supplemental notification devices from AC powered smoke alarms.

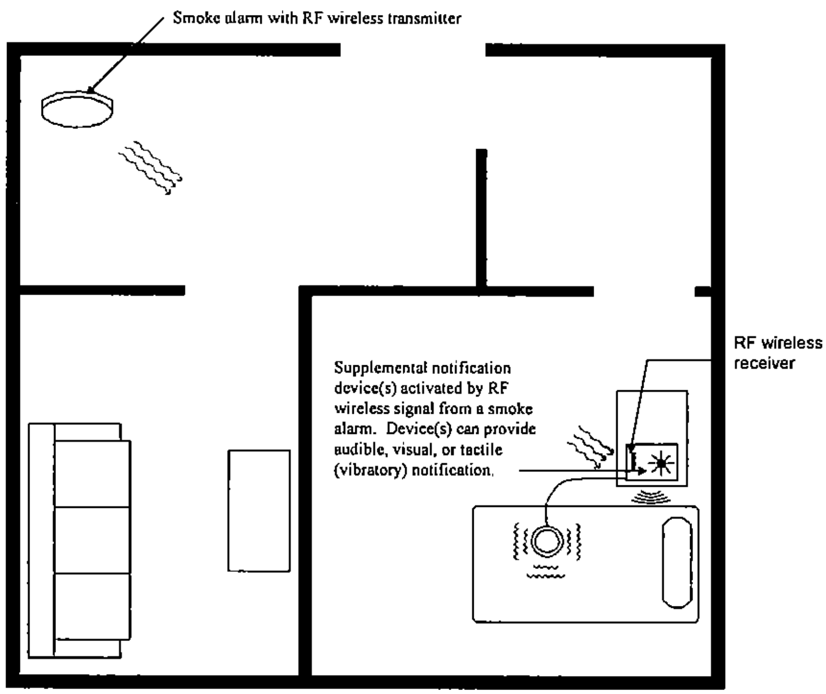


Figure 15 — Activation of supplemental notification devices by a wireless smoke alarm.

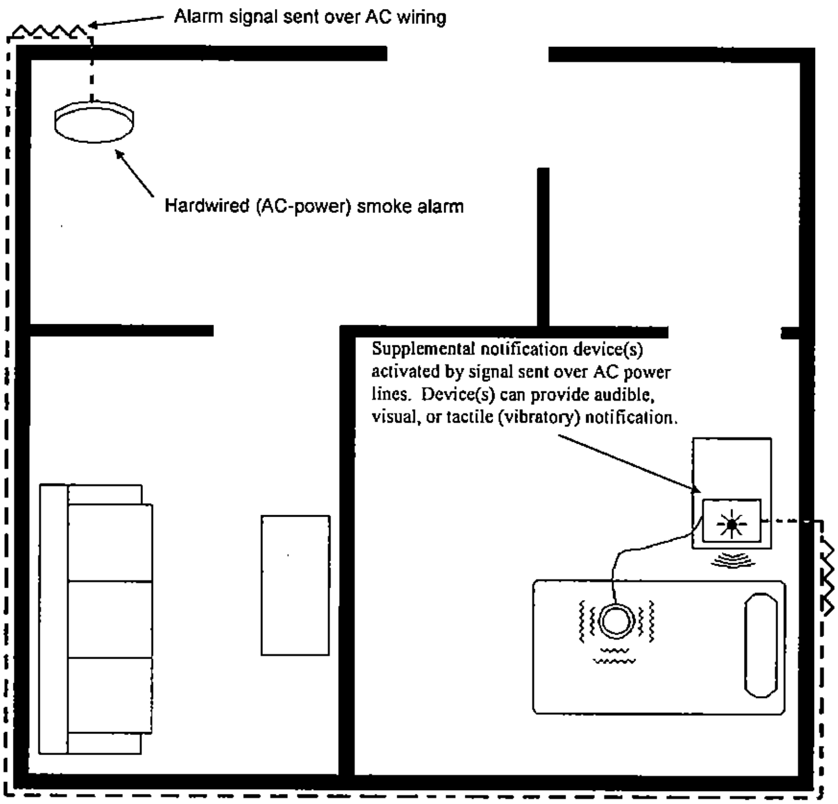


Figure 16 — Activation of supplemental notification devices by a smoke alarm via a signal on the AC wiring.

Several technologies were identified that facilitate the interconnection of smoke alarms with other smoke alarms, as well supplemental notification devices. These emerging technologies and products provide two important improvements to the fire safety of older adults and the entire population. First, they increase the sound levels of audible alarms throughout a home so occupants are aware of fires, even if they occur some distance from the current location of the occupant. Secondly, supplemental notification devices provide the opportunity to better meet the needs of populations that do not benefit from the typical high-frequency audible alarm signal. Delivery of alternative audible signals, visual signals, and vibratory alarm signals are all possible with supplemental notification devices. Interconnection of smoke alarms, and connecting smoke alarms with supplemental notification devices, can be achieved with RF wireless technologies, acoustic monitoring, and powerline communication. At present, the smoke alarm industry appears to be concentrating primarily on RF wireless technologies for interconnection with smoke alarms.

7.4 Testing and Maintenance

Estimates of smoke alarm operability indicate that approximately 27 percent of smoke alarms are not operational and that 20 percent of all households with smoke alarms have none that are working [Smith, 1994]. For older adults, studies have shown that 35 to 39 percent of alarms were not operational [Ahrens, 2004]. This data suggests that older adults may be more likely to

have inoperable smoke alarms than the general population. Technologies that facilitate testing and maintenance could increase the number of working smoke alarms and hopefully reduce the fire death risk for older adults. Although they are not in widespread use, various technologies currently exist that are aimed at improving the testing and maintenance of smoke alarms. The costs of these ancillary features will not be discussed since they are generally minimal and do not significantly impact the overall cost of the alarm. In addition, multiple features may be present on any alarm, therefore making it difficult to determine the cost of the individual feature.

Remote test and silence features are one example of a technology that could benefit older adults. This feature may be implemented in several ways. First Alert produces alarms that allow remote testing by pointing an infrared remote control (such as those used with a television) or a flashlight at the smoke alarm. A specific make or model infrared remote control is usually not required and no special programming of the detector or remote control is needed to use the remote test and silence features. DuPont manufactures another variation of this remote technology. In their product, test/silent features are activated by flipping a light switch several times. The alarm itself is principally powered via a rechargeable battery; however it is connected to a switched AC circuit (used to control household lighting) that recharges the battery each time the switch is turned on. Wireless interconnected smoke alarms, such as those by Kidde and First Alert mentioned in Section 7.3, incorporate another variation on remote test and silence features. With wireless interconnected smoke alarms, all connected smoke alarms can be tested or silenced from one wireless device.

Remote testing technologies allow for greater ease in testing the operation of smoke alarms. In fact, several do not even require users to physically push a test button on the device, which is typically mounted on the ceiling or upper part of the wall. Due to physical limitations, a large proportion of the older adult population may not physically be able to reach their smoke alarms and may require assistance to test and maintain the alarms. Even for those older adults who are physically able to test their smoke alarms, doing so could expose them to other risks such as falls. Remote testing technologies reduce or eliminate a possible barrier faced by older adults to testing and maintaining smoke alarms.

Another concern related to the testing and maintenance of smoke alarms is whether or not the alarms are actually powered. This is typically not a major concern with AC only (hardwired) smoke alarms. However, for battery-operated smoke alarms, which comprise over 70% of the smoke alarms in homes, missing, disconnected, or dead batteries are the most common cause of inoperable smoke alarms [Ahrens, 2004]. Numerous technologies have been advanced to facilitate battery replacement, to decrease the frequency of battery replacement, and to prevent the mounting of smoke alarms that do not have batteries. The previously mentioned smoke alarm by DuPont that allows remote testing via flipping the light switch includes a rechargeable battery; the battery automatically recharges whenever the light is switched on. Similarly, other smoke alarms feature non-replaceable long-life lithium batteries that are capable of providing power to the alarm for at least 10 years (often referred to as 10 year batteries). Manufacturers that produce smoke alarms with 10 year batteries include Dicon Global (American Sensor), First Alert, Kidde, Invensys (Firex), and Universal Security Instruments. Long life batteries eliminate the need to replace batteries in the smoke alarm during its 10 year recommended life. Once a smoke alarm in a one- or two-family dwelling has been in operation for 10 years, NFPA 72

requires that it be replaced with a new unit. Eliminating the need for changing batteries is expected to decrease the number of inoperable smoke alarms due to missing, disconnected, or dead batteries. With 10 year batteries, smoke alarm owners no longer have to remember to periodically change their smoke alarm batteries in order to ensure their protection. It should be noted that many smoke alarms come with a 10 year warranty, but this should not be confused with the battery life. Unless specifically stated that the alarm includes a 10 year battery, smoke alarm batteries should be replaced according to the manufacturer's recommendations, typically once a year.

There are also various other miscellaneous features that have been added to smoke alarms to improve the testing and maintenance of alarms. For instance, some smoke alarms now include doors or drawers that allow replacement of the smoke alarm battery without removing the unit from the ceiling. Removing smoke alarms from the ceiling often requires a significant level of manual dexterity, which may deter older adults and many other smoke alarm owners from performing necessary battery replacement. Battery drawers and doors facilitate battery replacement and hopefully improve the operability of smoke alarms. Also, as required by NFPA and UL standards, various visual and audible indicators have been added to smoke alarms that indicate when the battery is low, or when the alarm needs replacing (ten years after it is initially powered). These audible and visual indicators are intended to provide necessary reminders to ensure maximum operability and reliability of smoke alarms. In addition, some alarms now include a silence feature that allows the user to temporarily silence alarms without removing the batteries from the alarm. This feature addresses a common complaint of users and hopefully helps ensure smoke alarms are operable.

8.0 CONCLUSIONS

The objective of this project was to assess and optimize the performance requirements for alarm and signaling systems to meet the needs of an aging population. This project was separated into several tasks in order to achieve its objective. First, the older adult population was characterized relative to potential risk factors. Second, a risk assessment of older adults was performed to quantify the potential impact of improving the waking effectiveness of smoke alarms, in terms of the number of potential lives saved. This assessment was based on existing data regarding the characteristics of fire victims and fires. Third, the human behavior aspects of the problem were addressed; this work consisted of a sleep study of older adults and the details are presented in a companion report. Both the arousal thresholds from sleep for various frequencies and types of alarm signals, as well as the cognitive and physical abilities upon waking were examined in the sleep study. Fourth, a review was conducted of new and promising technologies that may improve the waking effectiveness of smoke alarms for older adults and improve their overall fire safety.

In an effort to understand the potential impact of improving the waking effectiveness of smoke alarms for older adults, a risk analysis was performed to determine the reduction in risk associated with such changes. Based on national estimates derived from the National Fire Incident Reporting System (NFIRS) and annual National Fire Protection Association (NFPA) surveys, smoke alarms that are improved to wake all sleeping occupants would reduce the estimated risk to older adults by 27–32 percent. This equates to an annual reduction in home fire

deaths of 230–270 people age 65 and over, based on the annual average fire deaths from 1999–2002.

However, less than one out of four older adult fire victims who were sleeping when fatally injured had an operable smoke alarm. The statistics on smoke alarm presence and operability for fire fatalities in the under 18 and 18–64 age groups were remarkably similar to those of older adult fire fatalities. The implication of these statistics is that although improving the waking effectiveness of smoke alarms is important, it is also necessary to increase the presence and operability of smoke alarms. In order to realize the benefits of improved smoke alarm waking effectiveness, smoke alarms must be present and operate. This conclusion applies to older adults, as well as the general population.

The sleep study portion of this project provided insights into the human behavior aspects of waking older adults exposed to varying types of signals and varying sound levels. Four signals were examined, including a 3000 Hz high-frequency T-3 alarm signal (typical of that used in U.S. smoke alarms), a 500 Hz low-frequency T-3 alarm signal, a 500–2500 Hz mixed frequency T-3 alarm signal, and a male voice (200–2500Hz) alarm signal. The results showed that the mixed frequency T-3 alarm signal provided the greatest waking effectiveness of the signals evaluated, including the high frequency T-3, typical of most current alarms. In fact, the high-frequency T-3 performed the most poorly of the alternative signals tested. There was a substantial difference in the median auditory arousal thresholds (20 dBA) between the high-frequency T-3 alarm signal and the mixed frequency T-3. The results also indicate that a male voice alarm is not suitable for older adults. In terms of the cognitive and physical abilities of older adults upon waking to an alarm, a decrement in physical functioning of around 10–17 percent was observed, with no important effects on simple or cognitive functioning.

In summary, the sleep study concluded that the high frequency alarm signal that is typically used in current smoke alarms should be replaced by an alternative signal that offers significantly better waking effectiveness across the general population, once the nature of the best signal has been determined. While the research to determine such a signal is ongoing, it is imperative that the use of interconnected smoke alarms in bedrooms be encouraged to provide the maximum potential benefit of current and future alarms. Proper use and maintenance of smoke alarms is also critical to realizing the benefits of smoke alarms.

Numerous current and promising technologies are available that may improve the waking effectiveness of smoke alarms for older adults and improve their fire safety. These technologies can be broadly categorized as those that provide alternative audible alarm signals, those that provide alternative sensory stimuli (visual, tactile), those related to the interconnection of smoke alarms and notification devices, and those that facilitate testing and maintenance of alarms. Despite research, including the work done as part of this project, that shows alternative audible alarm signals may benefit smoke alarm users, including older adults, there are few products currently available that address this issue. The focus of the smoke alarm industry in terms of addressing the needs of the hearing impaired has largely been on technologies that provide visual stimuli (i.e. strobes) to supplement audible alarms. However, recent research has focused renewed interest on tactile (vibratory) stimuli as an effective means of waking occupants.

Although the technology is available, there has been only limited use and commercial development of tactile (vibratory) notification technology integrated with smoke alarms.

Recent technological advances have occurred that facilitate the interconnection of smoke alarms with other smoke alarms, as well as with supplemental notification devices. Interconnection of smoke alarms and connecting smoke alarms with supplemental notification devices can be achieved with RF wireless technologies, acoustic monitoring, and powerline communication. These emerging technologies and products provide two important improvements to the fire safety of older adults and the entire population. First, they readily enable increased sound levels of audible alarms throughout a home so occupants are aware of fires, even if the fire occurs remote from the current location of the occupant and the nearest smoke alarm. Secondly, the interconnection of supplemental notification devices provides the opportunity to better meet the needs of select populations. Delivery of alternative audible signals, visual signals, and vibratory alarm signals are all possible with supplemental notification devices that are wirelessly connected to smoke alarms.

Although technologies that facilitate testing and maintenance of smoke alarms do not influence the waking effectiveness of smoke alarms, they are expected to be able to impact the overall fire safety of older adults. Maintenance problems with battery-operated smoke alarms, such as difficulty testing alarms or missing, dead, and disconnected batteries, are being addressed by various smoke alarm technologies. Technologies are available that allow users to test the operation of smoke alarms remotely and that eliminate battery changes for the life of the smoke alarm. Designs of battery doors and drawers allow replacement of smoke alarm batteries without removing the alarm from the ceiling, and silence features allow the user to temporarily silence alarms without removing the batteries from the alarm.

9.0 RESEARCH NEEDS

Various research needs have been identified in this research program as a result of this study and the companion work by Bruck, et al. [2006]. Future research that would benefit the fire safety of older adults includes the following topics:

- The data currently available regarding the type and extent of disabilities of fire victims is extremely limited. Obtaining better data would enable more focused prevention and protection strategies to be targeted to those with disabilities that are at highest risk.

- A study of smoke alarm usage and operability in older adults, similar to Project S.A.F.E. (see Ahrens [2004] for an overview) but on a larger scale, would be beneficial in several ways. It would help quantify the extent of older adult homes that currently have smoke alarms in bedrooms and that have interconnected alarms. In addition, it would provide an assessment of the rate of inoperable alarms and the causes of inoperable alarms in older adult homes.

- Determine the optimal pitch and pattern of an alternative signal to wake people up. The option of a voice alarm should no longer be considered for adult populations. Alternative pitches and pitch patterns should be investigated within the T-3 temporal pattern.

- Test the signals found to have the lowest auditory arousal thresholds (AATs) in several high risk populations, including:
  - Children,
  - Older Adults (65 years and over),
  - Impaired Adults (e.g. alcohol or sleep medication),
  - Sleep Deprived People.

- Evaluate the effectiveness of alarms in more real-life scenarios, where priming of the participants is significantly reduced and other variables affecting responsiveness to alarms are uncontrolled (e.g. hearing impairments, alcohol intake, sleep deprivation, prior time in bed, and sleep stage). Such a study would need a large, random sample to yield population based estimates of waking effectiveness

- Study the spectral characteristics of typical background noises found in bedrooms to determine the extent to which masking of the smoke alarm signal may occur.

- A cost-benefit analysis of changing the smoke alarm signal would be useful, once the most effective signal has been identified for a range of population groups. Such a study would provide the developers of the relevant codes and standards the information needed to assess whether mandating a specific smoke alarm signal is warranted and if so, which signal will maximize improvements in fire safety for older adults and the general population.
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APPENDIX A—ESTIMATING THE IMPACT ON RISK OF FIRE DEATH FOR OLDER ADULTS FROM CHANGES IN WAKING EFFECTIVENESS OF SMOKE ALARMS

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Fire death risk by age group

Table 1 shows the fire death rates relative to population for three age groups – age 65 and older (the target population for this analysis) and ages 18-64 and 17 and younger (the two comparison populations for this analysis). Rates are shown for two sets of years – 1980-1998 and 1999-2002 – which are separated based on the major change in fire incident coding from NFIRS Version 4.1 to NFIRS Version 5.0. Some of the side analyses involve data values that are recorded in the later data.

Injury rates are also included, but because past analyses have shown no statistical impact of smoke alarms on injury rates, they are not analyzed further in this report.

Table 1. Home Fire Death and Injury Risk by Age Group, 1980-1998 and 1999-2002

	Age 65 and over	Age under 18	Age 18-64
1999-2002 death rate	24.0	10.3	8.8
1999-2002 average deaths	845	746	1,539
1999-2002 average population (in millions)	35.2	72.4	175.6
1999-2002 injury rate	60.3	44.1	66.0
1980-1998 death rate	34.3	19.6	12.4
1980-1998 average deaths	1,048	1,283	1,884
1980-1998 average population (in millions)	30.5	65.3	152.5
1980-1998 injury rate	78.7	61.4	86.6

Notes: Death and injury rates are expressed per million population and exclude firefighters. These are national estimates of fires reported to U.S. municipal fire departments and so exclude fires reported only to Federal or state agencies or industrial fire brigades. National estimates are projections. Casualty projections can be heavily influenced by the inclusion or exclusion of one unusually serious fire. Home structure fires include one- and two-family dwellings, apartments, townhouses, flats, and manufactured homes, but exclude dormitories, barracks, hotels and motels, boarding or rooming houses, and assisted living facilities.

Source: NFIRS and NFPA survey, population figures from U.S. Census Bureau.

Fire deaths by age group and activity when injured

Table 2 shows fire deaths for the three age groups and the two year groups by four major activity when injured groups – sleeping, attempting to escape, attempting rescue or fire control (including returning to the fire scene after having left), and unable to act or acting irrationally. (Occupants who were sleeping when injured are also identified under condition before injury, but some sleeping occupants may be hidden under other condition codes, such as impaired by drugs or alcohol, too old, too young, or handicapped.)

Other than escaping, the other activities would indefinitely prolong the person's presence in the fire area and so would be expected to involve some significant risk of injury.

Note that the percentage distributions show very little variation between the two year groups.

Table 2. Home Fire Deaths by Age Group and Activity When Injured, 1980-1998 and 1999-2002

	Age 65 and over	Age under 18	Age 18-64
1999-2002 percent sleeping	36%	58%	44%
1999-2002 percent attempting to escape	31%	24%	29%
1999-2002 percent attempting rescue or fire control	10%	2%	10%
1999-2002 percent unable to act or acting irrationally	22%	16%	16%
1980-1998 percent sleeping	38%	56%	45%
1980-1998 percent attempting to escape	31%	22%	31%
1980-1998 percent attempting rescue or fire control	8%	2%	8%
1980-1998 percent unable to act or acting irrationally	23%	20%	16%

Notes: These are national estimates of fires reported to U.S. municipal fire departments and so exclude fires reported only to Federal or state agencies or industrial fire brigades. National estimates are projections. Casualty projections can be heavily influenced by the inclusion or exclusion of one unusually serious fire. Home structure fires include one- and two-family dwellings, apartments, townhouses, flats, and manufactured homes, but exclude dormitories, barracks, hotels and motels, boarding or rooming houses, and assisted living facilities.

Source: NFIRS and NFPA survey.

Effects of improved waking effectiveness on fire risk

Successful waking of sleeping occupants is not enough to assure safe escape. Some of the wakened occupants would be expected to die. There will be unsuccessful escape attempts, where the early warning from smoke alarms could not compensate in all cases for either limited time for escape or insufficient training and knowledge of effective escape routes and procedures. Several of the activities involve indefinitely extended time in hazardous conditions and would be expected to lead to deaths. Some of the victims listed as sleeping when injured may have been awakened but returned to sleep; greater waking effectiveness might make no difference to these victims either.

On the other hand, changes that lead to successful waking of more occupants could also result in earlier alerting of occupants who were already awake. Earlier alerting could lead to more success in chosen activities and fewer deaths.

Also, the changes might not be sufficient to produce 100% waking effectiveness. For example, the changes might not address the reliability of operation of the home smoke alarm, currently estimated at 80% (based on a CPSC special study). Smoke alarms that do not activate cannot wake anyone.

Setting up the analysis

This paper will concern itself only with estimating the reduction in fire death rate if changes are made that are effective in waking all occupants for a given population. Hence, the percentage of fatal victims who were asleep when fatally injured are the focus of this analysis.

I will assume that sleeping occupants, if awakened, will select activities in the same proportions as did occupants who were not asleep when fire began and will experience the same risks associated with those activities as did the occupants who were not asleep. For example, a newly wakened occupant is assumed to be just as likely to decide to fight the fire as an occupant who was never asleep and just as likely to be fatally injured while doing so.

I will further assume that a person newly awakened at one time of day will select activities and encounter risks associated with those activities in the same way as a person newly awakened at another time of day. For example, although an older adult is more likely to be asleep at 3 am than at 3 pm, once awakened, that person is as likely to choose escape vs. firefighting at 3 am as at 3 pm, and the risk of fatal injury for each activity chosen will be the same at 3 am as at 3 pm.

The basic risk model

Equation (1) is a probabilistic model of the probability of dying in a fire (called p_{total}), distinguishing sleeping vs. all other activities. All probabilities are probabilities per year. Therefore, the best data-based estimate of p_{total} is the annual fire death rate (deaths per million persons, which is a dimensionless value suitable for use as a probability), for a specified population (e.g., older adults, children, adults other than older adults).

(1) $p_{asleep}\, p_{death,asleep} + p_{not}\, p_{death,not} = p_{total}$, where:

p_{asleep} = prob (asleep given age range) =
[prob (asleep and age range)]/[prob (age range)]

p_{not} = prob (not asleep given age range) =
[prob (not asleep and age range)]/[prob (age range)] = $1 - p_{asleep}$

$p_{death,asleep}$ = prob (death given age range and asleep) =
[prob (death, age range, and asleep)]/[prob (age range and asleep)]

$p_{death,not}$ = prob (death given age range and not asleep) =
[prob (death, age range, and not asleep)]/[prob (age range and not asleep)]

p_{total} = prob (death given age range) =
[prob (death and age range)]/[prob (age range)]

See Appendix A for a detailed derivation/substantiation of equation (1).

In equation (1), as noted, it is possible to use available data directly to estimate the right-side term (p_{total} is estimated as the annual fire death rate). It is not possible to directly estimate any of the other four terms from available data. Equation (2) introduces two new terms that can be estimated from available data:

(2) $q_{asleep} + q_{not} = 1$, where:

q_{asleep} = asleep share of age-range deaths

q_{not} = not-asleep share of age-range deaths

By dividing both sides of equation (1) by p_{total} and comparing the result to equation (2), it may be seen that:

(2A) $q_{asleep} = p_{asleep}\, p_{death,asleep} / p_{total}$

(2B) $q_{not} = p_{not}\, p_{death,not} / p_{total}$

Solving the model for reduction in risk through waking all older adults

Dividing equation (1) through by p_{total} and substituting $q_{asleep} = p_{asleep}\, p_{death,asleep} / p_{total}$ yields:

(3) $q_{asleep} + (1 - p_{asleep})\,(p_{death,not} / p_{total}) = 1$

If everyone has been wakened, then every occupant will face a probability of death equal to $p_{death,not}$. Therefore, the reduction in risk will be equal to $1 - p_{death,not} / p_{total}$. Solve equation (3) for the ratio:

(4) $p_{death,not}/p_{total} = [1 - q_{asleep}] / [1 - p_{asleep}] = [1 - q_{asleep}] / [1 - q_{asleep} (p_{total} / p_{death,asleep})]$

Equation (4) shows that the ratio of the new death probability (with complete waking effectiveness) to the old death probability is a function of three terms, two of which can be estimated from available data. The term that cannot be so estimated is $p_{death,asleep}$. It is easier to work in terms of the unknown ratio, i.e., $p_{total} / p_{death,asleep}$; call that ratio 1/A. See Appendix B for the derivation of the relationship between $p_{death,asleep} / p_{death,not}$, A, and the total risk reduction.

So, consider the sensitivity of the estimated risk reduction to A:

If q_{asleep} (sleeping share of fire deaths) = X		
And A =	Then % risk reduction in total fire deaths = X(A-1)/(A-X)	and $p_{death,asleep} / p_{death,not}$ =
1	0%	1
2	X/(2-X)	(2-X)/(1-X)
3	2X/(3-X)	(3-X)/(1-X)
5	4X/(5-X)	(5-X)/(1-X)
10	9X/(10-X)	(10-X)/(1-X)
50	49X/(50-X) or roughly X	(50-X)/(1-X)

Estimating A

It is possible to estimate the critical ratio of $A = 1/[p_{total} / p_{death,asleep}]$.

Start with this equation: (5) $p_{asleep,h} + p_{not,h} = 1$.

The subscript h refers to hour h, one of the 24 hour segments in the day.

Now rearrange terms in equations (2A) and (2B) to derive values for the two terms in equation (5), then rearrange terms again: (6) $q_{asleep,h} (1 / p_{death,asleep}) + q_{not,h} (1 / p_{death,not}) = 1 / p_{total,h}$

By the assumptions stated at the beginning, $p_{death,asleep}$ and $p_{death,not}$ will not change from hour to hour, but q_{asleep} and p_{total} may change, as will q_{not}.

The derived coefficients should be positive values. When they are estimated as negative, this means that the higher the estimated death rate is (and the closer the inverse of the death rate is to zero), the better the estimating equations fit. Fire statistics can be used to calculate, for each hour segment, values of $q_{asleep,h}$, $q_{not,h}$ and $p_{total,h}$. One can use least-squares estimation (same format as linear regression) to estimate $p_{death,asleep}$ and $p_{death,not}$. Table 3 provides the results.

Table 3. Estimated Reduction in Home Fire Deaths by Age Group Based on Statistical Linear Regression Parameter Estimation 1980-1998 and 1999-2002

	Age 65 and over	Age under 18	Age 18-64
1999-2002 coefficient for sleeping	0.01630	0.03883	-0.05137 (reset as 0)
1999-2002 estimated death rate (probability) when asleep (1/coefficient) ($p_{death, asleep}$)	61.4	25.8	NA
1999-2002 sleeping % of deaths ($X = q_{asleep}$)	36%	58%	44%
1999-2002 sleeping % of population (p_{asleep})	14%	23%	NA
1999-2002 value of A = $p_{death,asleep} / p_{total}$	2.56	2.50	NA
1999-2002 value of $p_{death,asleep} / p_{death,not}$	3.43	4.58	NA
1999-2002 % risk reduction	27%	55%	44%
1999-2002 reduction in annual deaths	230	410	680
1980-1998 coefficient for sleeping	0.006048	-0.01056 (reset as 0)	-0.21906 (reset as 0)
1980-1998 estimated death rate (probability) when asleep (1/coefficient) ($p_{death, asleep}$)	165.34	NA	NA
1980-1998 sleeping % of deaths ($X = q_{asleep}$)	38%	56%	45%
1980-1998 sleeping % of population (p_{asleep})	8%	NA	NA
1980-1998 value of A = $p_{death,asleep} / p_{total}$	4.82	NA	NA
1980-1998 value of $p_{death,asleep} / p_{death,not}$	7.16	NA	NA
1980-1998 % risk reduction	32%	56%	45%
1980-1998 reduction in annual deaths	340	720	850

NA: Not applicable because regression yields a negative estimate for coefficient. This means, the higher the ratio of death rate when sleeping to death rate when not sleeping, the better the fit to the hourly data used in the regression. And that means that the best estimate is that everyone who is wakened will survive.

Note: Death reduction is estimated to the nearest ten.

Source: NFIRS and NFPA survey, population figures from U.S. Census Bureau, regression analysis.

See Appendix C for the details of the derivation of the least-squares equations. See Appendix D for the statistics used in analysis for the three age groups and the two year groups.

Accounting for victims who are intimate with ignition

It may be appropriate to discount the life-saving potential by excluding fatal victims who were so close to the fire's origin that they are recorded as "intimate with ignition." This designation of extreme proximity to fire was discontinued in fire incident reporting after 1998. The percents shown below for sleeping victims can be applied to the Table 3 results to further reduce the estimated life-saving potential. The intimate percentages for other activities and the percentages of victims in the room of fire origin (including but not limited to those who were intimate with ignition) are shown to provide context.

Table 4. Percentage of Fatal Victims Who Were Intimate With Ignition, by Age Group and Activity When Injured, 1980-1998

	Age 65 and over	Age under 18	Age 18-64
Percent intimate with ignition			
Sleeping	26%	6%	20%
Attempting to escape	14%	6%	10%
Attempting rescue or fire control	20%	12%	12%
Unable to act or acting irrationally	44%	18%	36%
Percent in room of fire origin (including but not limited to intimate with ignition)			
Sleeping	50%	22%	38%
Attempting to escape	35%	21%	28%
Attempting rescue or fire control	48%	27%	30%
Unable to act or acting irrationally	66%	49%	60%

Notes: These are national estimates of fires reported to U.S. municipal fire departments and so exclude fires reported only to Federal or state agencies or industrial fire brigades. National estimates are projections. Casualty projections can be heavily influenced by the inclusion or exclusion of one unusually serious fire. Home structure fires include one- and two-family dwellings, apartments, townhouses, flats, and manufactured homes, but exclude dormitories, barracks, hotels and motels, boarding or rooming houses, and assisted living facilities.

Source: NFIRS and NFPA survey.

Smoke alarm performance by age group and activity when injured

It may be useful to see how reported smoke alarm performance varies by activity group and age group. This provides some perspective on how many victims would need smoke alarm presence and smoke alarm operability before they could be aided by improved smoke alarm waking effectiveness. Only 1996-1998 statistics are used because smoke alarm presence has increased sharply since 1980.

Table 5. Percentage of Fatal Victims by Smoke Alarm Performance, by Age Group and Activity When Injured, 1996-1998

	Age 65 and over	Age under 18	Age 18-64
Percent smoke alarms present			
Sleeping	44%	45%	43%
Attempting to escape	43%	52%	45%
Attempting rescue or fire control	49%	42%	50%
Unable to act or acting irrationally	53%	38%	51%
Percent smoke alarms present and operated			
Sleeping	24%	20%	19%
Attempting to escape	27%	29%	21%
Attempting rescue or fire control	49%	17%	18%
Unable to act or acting irrationally	40%	18%	29%

Notes: These are national estimates of fires reported to U.S. municipal fire departments and so exclude fires reported only to Federal or state agencies or industrial fire brigades. National estimates are projections. Casualty projections can be heavily influenced by the inclusion or exclusion of one unusually serious fire. Home structure fires include one- and two-family dwellings, apartments, townhouses, flats, and manufactured homes, but exclude dormitories, barracks, hotels and motels, boarding or rooming houses, and assisted living facilities.

Source: NFIRS and NFPA survey.

Appendix A
Detailed Derivation of Basic Model

(1) $p_{asleep}\, p_{death,asleep} + p_{not}\, p_{death,not} = p_{total}$, where:

p_{asleep} = prob (asleep given age group) =
[prob (asleep and age group)]/[prob (age group)]

p_{not} = prob (not asleep given age group) =
[prob (not asleep and age group)]/[prob (age group)] = 1 - p_{asleep}

$p_{death,asleep}$ = prob (death given age group and asleep) =
[prob (death, age group, and asleep)]/[prob (age group and asleep)]

$p_{death,not}$ = prob (death given age group and not asleep) =
[prob (death, age group, and not asleep)]/[prob (age group and not asleep)]

p_{total} = prob (death given age group) =
[prob (death and age group)]/[prob (age group)]

Equation (1) can be substantiated as follows:

$p_{asleep}\, p_{death,asleep} + p_{not}\, p_{death,not}$ =

{[prob(asleep given age group)] x [prob(death given age group and asleep)]} +
{[prob(not asleep given age group] x [prob (death given age group and not asleep)]} =

{[prob(asleep, age group)]/[prob(age group)]} x
{[prob(death, age group, asleep)]/[prob(age group, asleep)]} +
{[prob(not, age group)]/[prob(age group)]} x
{[prob(death, age group, not asleep)]/[prob(not, age group)]} =

{[prob(death, age group, asleep)]/[prob(age group)]}+
{[prob(death, age group, not asleep)]/[prob(age group)]} =

{[prob(death, age group, asleep)] + [prob(death, age group, not asleep)]}/[prob(age group)] =

[prob(death, age group)]/[prob(age group)] = prob(death given age group) = p_{total}.

Appendix B
Relating Parameter A to $p_{death,asleep}$ / $p_{death,not}$

Start with these equations presented earlier:

$$p_{asleep}\ p_{death,asleep} + p_{not}\ p_{death,not} = p_{total}$$

$$p_{not} = 1 - p_{asleep}$$

$$A = 1/[p_{total} / p_{death,asleep}] = p_{death,asleep} / p_{total}$$

$$q_{asleep} = p_{asleep}\ p_{death,asleep} / p_{total}$$

Then: $q_{asleep} = A\ p_{asleep}$

and: $p_{death,asleep} = A\ p_{total}$

and: $p_{death,not} = [p_{total} - p_{total}\ q_{asleep}] / p_{not} = p_{total}\ (1 - q_{asleep}) / (1 - p_{asleep})$

Then the ratio we are trying to derive is $p_{death,asleep} / p_{death,not} =$

$$[A\ p_{total}] / [p_{total}\ (1 - q_{asleep}) / (1 - p_{asleep})] =$$

$$[A] / [(1 - q_{asleep}) / (1 - p_{asleep})] =$$

$$[A\ (1 - p_{asleep})] / (1 - q_{asleep}) =$$

$$[A - q_{asleep}] / (1 - q_{asleep}).$$

Let $q_{asleep} = X$. Then $p_{death,asleep} / p_{death,not} = (A-X) / (1-X)$.

As derived in the text, the percentage reduction in total deaths achieved by complete waking effectiveness is estimated as $1 - p_{death,not} / p_{total}$.

$$1 - p_{death,not} / p_{total} = 1 - [p_{death,asleep} / p_{total}] / [p_{death,asleep} / p_{death,not}]$$

$$= 1 - [A] / [(A-X) / (1-X)] = 1 - A\ [(1-X) / (A-X)]$$

$$= 1 - [(A-AX) / (A-X)] = X\ [(A-1) / (A-X)].$$

Appendix C
Estimation of Parameter A Using Least-Squares Methods Applied to Model of Risk as a Function of Hour of Day

First, the probability of being asleep and the probability of not being asleep add to one for each hour:

(C-1) $p_{asleep,h} + p_{not,h} = 1$, for h = 1, ..., 24;

Modify the equations (2A) and (2B), to provide hourly values of the parameters, as follows:

(C-2) $q_{asleep,h} = p_{asleep,h}\ p_{death,asleep} / p_{total,h}$, for h = 1, ..., 24; and

(C-3) $q_{not,h} = p_{not,h}\ p_{death,not} / p_{total,h}$, for h = 1, ..., 24.

Use equations (C-2) and (C-3) to solve for the two p values used in equation (C-1), then substitute in those derived expressions, which produces:

(C-4) $q_{asleep,h}\ p_{total,h} / p_{death,asleep} + q_{not,h}\ p_{total,h} / p_{death,not} = 1$, for h = 1, ..., 24.

Dividing through by $p_{total,,t}$ produces:

(C-5) $q_{asleep,h} / p_{death,asleep} + q_{not,h} / p_{death,not} = 1/ p_{total,h}$, for h = 1, ..., 24.

We now have a linear equation in two unknowns – $1/ p_{death,asleep}$ and $1/ p_{death,not}$ – with hourly values of the other three parameters, all of which can be derived from available data.

Appendix D
Parameter Values Used in Regression Analysis

The first column gives the time interval. The second and third columns give the shares of fire deaths for which victims were sleeping or not sleeping, respectively. The fourth column gives the inverse of the fire death rate (deaths per million population per year) for the hour interval.

Table D-1. Parameter Values for 1999-2002 Data and Age 65 and Older

Hour	$q_{asleep,h}$	$q_{not,h}$	$1 / p_{total,h}$
0:00-0:59	45%	55%	0.029164
1:00-1:59	60%	40%	0.030046
2:00-2:59	69%	31%	0.036001
3:00-3:59	54%	46%	0.029357
4:00-4:59	36%	64%	0.032358
5:00-5:59	44%	56%	0.034773
6:00-6:59	50%	50%	0.043490
7:00-7:59	44%	56%	0.032966
8:00-8:59	33%	67%	0.045890
9:00-9:59	19%	81%	0.055998
10:00-10:59	6%	94%	0.042841
11:00-11:59	12%	88%	0.038684
12:00-12:59	6%	94%	0.051380
13:00-13:59	17%	83%	0.040548
14:00-14:59	13%	87%	0.064566
15:00-15:59	11%	89%	0.054181
16:00-16:59	0%	100%	0.075833
17:00-17:59	16%	84%	0.044144
18:00-18:59	37%	63%	0.056180
19:00-19:59	41%	59%	0.039253
20:00-20:59	23%	77%	0.046479
21:00-21:59	44%	56%	0.041766
22:00-22:59	23%	77%	0.048012
23:00-23:59	41%	59%	0.047735

Notes: These are national estimates of fires reported to U.S. municipal fire departments and so exclude fires reported only to Federal or state agencies or industrial fire brigades. National estimates are projections. Casualty projections can be heavily influenced by the inclusion or exclusion of one unusually serious fire. Home structure fires include one- and two-family dwellings, apartments, townhouses, flats, and manufactured homes, but exclude dormitories, barracks, hotels and motels, boarding or rooming houses, and assisted living facilities.

Source: NFIRS and NFPA survey, population figures from U.S. Census Bureau.

Table D-2. Parameter Values for 1999-2002 Data and Age 17 or Younger

Hour	$q_{asleep,h}$	$q_{not,h}$	$1 / p_{total,h}$
0:00-0:59	64%	36%	0.053673
1:00-1:59	70%	30%	0.067737
2:00-2:59	66%	34%	0.054583
3:00-3:59	70%	30%	0.051163
4:00-4:59	65%	35%	0.046940
5:00-5:59	64%	36%	0.102768
6:00-6:59	57%	43%	0.076177
7:00-7:59	41%	59%	0.097365
8:00-8:59	71%	29%	0.090327
9:00-9:59	41%	59%	0.086074
10:00-10:59	55%	45%	0.131584
11:00-11:59	22%	78%	0.122762
12:00-12:59	0%	100%	0.224484
13:00-13:59	28%	72%	0.165746
14:00-14:59	58%	42%	0.212326
15:00-15:59	71%	29%	0.192415
16:00-16:59	0%	100%	0.200850
17:00-17:59	0%	100%	0.205518
18:00-18:59	0%	100%	0.227938
19:00-19:59	37%	63%	0.296473
20:00-20:59	44%	56%	0.206298
21:00-21:59	69%	31%	0.125215
22:00-22:59	82%	18%	0.086042
23:00-23:59	68%	32%	0.048281

Notes: These are national estimates of fires reported to U.S. municipal fire departments and so exclude fires reported only to Federal or state agencies or industrial fire brigades. National estimates are projections. Casualty projections can be heavily influenced by the inclusion or exclusion of one unusually serious fire. Home structure fires include one- and two-family dwellings, apartments, townhouses, flats, and manufactured homes, but exclude dormitories, barracks, hotels and motels, boarding or rooming houses, and assisted living facilities.

Source: NFIRS and NFPA survey, population figures from U.S. Census Bureau.

Table D-3. Parameter Values for 1999-2002 Data and Age 18-64

Hour	$q_{asleep,h}$	$q_{not,h}$	$1 / p_{total,h}$
0:00-0:59	46%	54%	0.076786
1:00-1:59	46%	54%	0.075327
2:00-2:59	57%	43%	0.053059
3:00-3:59	50%	50%	0.055190
4:00-4:59	55%	45%	0.058481
5:00-5:59	55%	45%	0.069844
6:00-6:59	53%	47%	0.099488
7:00-7:59	41%	59%	0.139691
8:00-8:59	48%	52%	0.119056
9:00-9:59	16%	84%	0.200084
10:00-10:59	60%	40%	0.224398
11:00-11:59	37%	63%	0.161235
12:00-12:59	46%	54%	0.230705
13:00-13:59	23%	77%	0.202471
14:00-14:59	22%	78%	0.180123
15:00-15:59	16%	84%	0.243607
16:00-16:59	21%	79%	0.313197
17:00-17:59	29%	71%	0.193073
18:00-18:59	25%	75%	0.176977
19:00-19:59	43%	57%	0.150057
20:00-20:59	23%	77%	0.200373
21:00-21:59	29%	71%	0.095513
22:00-22:59	40%	60%	0.126650
23:00-23:59	40%	60%	0.088376

Notes: These are national estimates of fires reported to U.S. municipal fire departments and so exclude fires reported only to Federal or state agencies or industrial fire brigades. National estimates are projections. Casualty projections can be heavily influenced by the inclusion or exclusion of one unusually serious fire. Home structure fires include one- and two-family dwellings, apartments, townhouses, flats, and manufactured homes, but exclude dormitories, barracks, hotels and motels, boarding or rooming houses, and assisted living facilities.

Source: NFIRS and NFPA survey, population figures from U.S. Census Bureau.

Table D-4. Parameter Values for 1980-1998 Data and Age 65 and Older

Hour	$q_{asleep,h}$	$q_{not,h}$	$1 / p_{total,h}$
0:00-0:59	46%	54%	0.023388
1:00-1:59	51%	49%	0.022329
2:00-2:59	53%	47%	0.022024
3:00-3:59	51%	49%	0.023142
4:00-4:59	49%	51%	0.024628
5:00-5:59	47%	53%	0.024603
6:00-6:59	47%	53%	0.026261
7:00-7:59	40%	60%	0.028558
8:00-8:59	29%	71%	0.027176
9:00-9:59	28%	72%	0.033837
10:00-10:59	17%	83%	0.032299
11:00-11:59	15%	85%	0.033462
12:00-12:59	32%	68%	0.036276
13:00-13:59	18%	82%	0.039477
14:00-14:59	27%	73%	0.038594
15:00-15:59	28%	72%	0.036885
16:00-16:59	26%	74%	0.034514
17:00-17:59	28%	72%	0.034172
18:00-18:59	27%	73%	0.035065
19:00-19:59	20%	80%	0.031054
20:00-20:59	38%	62%	0.031417
21:00-21:59	31%	69%	0.027706
22:00-22:59	43%	57%	0.029073
23:00-23:59	46%	54%	0.026579

Notes: These are national estimates of fires reported to U.S. municipal fire departments and so exclude fires reported only to Federal or state agencies or industrial fire brigades. National estimates are projections. Casualty projections can be heavily influenced by the inclusion or exclusion of one unusually serious fire. Home structure fires include one- and two-family dwellings, apartments, townhouses, flats, and manufactured homes, but exclude dormitories, barracks, hotels and motels, boarding or rooming houses, and assisted living facilities.

Source: NFIRS and NFPA survey, population figures from U.S. Census Bureau.

Table D-5. Parameter Values for 1980-1998 Data and Age 17 and Younger

Hour	$q_{asleep,h}$	$q_{not,h}$	$1 / p_{total,h}$
0:00-0:59	64%	36%	0.027597
1:00-1:59	62%	38%	0.029776
2:00-2:59	61%	39%	0.024909
3:00-3:59	70%	30%	0.031424
4:00-4:59	67%	33%	0.038099
5:00-5:59	69%	31%	0.055730
6:00-6:59	65%	35%	0.054843
7:00-7:59	61%	39%	0.047791
8:00-8:59	46%	54%	0.037274
9:00-9:59	43%	57%	0.038325
10:00-10:59	34%	66%	0.046085
11:00-11:59	23%	77%	0.059932
12:00-12:59	45%	55%	0.062544
13:00-13:59	27%	73%	0.078993
14:00-14:59	42%	58%	0.089072
15:00-15:59	42%	58%	0.094445
16:00-16:59	30%	70%	0.116618
17:00-17:59	31%	69%	0.126933
18:00-18:59	30%	70%	0.128832
19:00-19:59	29%	71%	0.122712
20:00-20:59	53%	47%	0.117680
21:00-21:59	49%	51%	0.071356
22:00-22:59	60%	40%	0.056093
23:00-23:59	62%	38%	0.031463

Notes: These are national estimates of fires reported to U.S. municipal fire departments and so exclude fires reported only to Federal or state agencies or industrial fire brigades. National estimates are projections. Casualty projections can be heavily influenced by the inclusion or exclusion of one unusually serious fire. Home structure fires include one- and two-family dwellings, apartments, townhouses, flats, and manufactured homes, but exclude dormitories, barracks, hotels and motels, boarding or rooming houses, and assisted living facilities.

Source: NFIRS and NFPA survey, population figures from U.S. Census Bureau.

Table D-6. Parameter Values for 1980-1998 Data and Age 18-64

Hour	$q_{asleep,h}$	$q_{not,h}$	$1 / p_{total,h}$
0:00-0:59	45%	55%	0.045202
1:00-1:59	52%	48%	0.040912
2:00-2:59	48%	52%	0.035770
3:00-3:59	52%	48%	0.037657
4:00-4:59	49%	51%	0.038375
5:00-5:59	53%	47%	0.049382
6:00-6:59	55%	45%	0.065062
7:00-7:59	41%	59%	0.091155
8:00-8:59	47%	53%	0.125587
9:00-9:59	36%	64%	0.140500
10:00-10:59	33%	67%	0.155728
11:00-11:59	36%	64%	0.149925
12:00-12:59	40%	60%	0.149553
13:00-13:59	26%	74%	0.167624
14:00-14:59	31%	69%	0.181761
15:00-15:59	31%	69%	0.166468
16:00-16:59	36%	64%	0.207727
17:00-17:59	31%	69%	0.180944
18:00-18:59	30%	70%	0.163536
19:00-19:59	34%	66%	0.129774
20:00-20:59	34%	66%	0.122777
21:00-21:59	33%	67%	0.117174
22:00-22:59	41%	59%	0.077069
23:00-23:59	41%	59%	0.060044

Notes: These are national estimates of fires reported to U.S. municipal fire departments and so exclude fires reported only to Federal or state agencies or industrial fire brigades. National estimates are projections. Casualty projections can be heavily influenced by the inclusion or exclusion of one unusually serious fire. Home structure fires include one- and two-family dwellings, apartments, townhouses, flats, and manufactured homes, but exclude dormitories, barracks, hotels and motels, boarding or rooming houses, and assisted living facilities.

Source: NFIRS and NFPA survey, population figures from U.S. Census Bureau.

APPENDIX B—CONTACT INFORMATION FOR PRODUCTS MENTIONED

This review represents a scan of available or promising technologies at the time of writing of this report. An attempt was made to address as many technologies and products as possible, however this review may not be all-inclusive due to rapid development of the marketplace in this area. In addition, the focus of this review is on technologies available in the United States. There has been similar interest throughout the world in developing accessible fire alarm technologies for older adults and for others with hearing loss, but these are not discussed. Mention of specific products or manufacturers is to provide specific examples and basis for the technologies discussed and does not constitute recommendation or endorsement by the authors or by the Fire Protection Research Foundation.

Smoke Alarms with Alternative Audible Alarms

The Darrow Company
9310 W 85th St.
Overland Park, KS 66212
http://www.loudenlow.com
Applicable Models: Original, Deluxe (SLF)

SignalONE Safety, Inc.
1050 Northfield Court, Suite 125
Roswell, GA 30076
Phone: (877) 543-7627
http://www.signalonesafety.com
Applicable Model: 012501, 012504 (Spring/Summer 2006), 012505 (available late 2006)

Smoke Alarms with Visual Notification

First Alert
3901 Liberty Street Rd.
Aurora, IL 60504-8122
Phone: (800) 323-9005
http://www.firstalert.com
Applicable Model: SA100B

Gentex Corporation
600 North Centennial St.
Zeeland, MI 49464
Phone: (616) 772-1800
http://www.gentex.com
Applicable Models: 713CS, 7139CS, 713LS, 7139LS

Kidde
1394 South 3rd St.
Mebane, NC 27302
Phone: (800) 880-6788
http://www.kiddeus.com
Applicable Models: 713CS, 7139CS, 713LS, 7139LS

Vibrating Pads for Tactile Notification

Note: These are not smoke alarms, but some of them may be used as part of alerting systems that include smoke alarms.

Clarity, a Division of Plantronics, Inc.
4289 Bonny Oaks Drive, Suite 106
Chattanooga, TN 37406
Phone: (800) 426-3738
http://www.clarityproducts.com
Applicable Model: C2210 (53334.000)

ClearSounds
8160 S. Madison Street
Burr Ridge, IL 60527
Phone: (800) 965-9043
http://www.clearsounds.com
Applicable Model: CS-SHK

Sonic Alert, Inc.
1050 East Maple Rd.
Troy, MI 48083
Phone: (248) 577-5400
http://www.sonicalert.com
Applicable Models: SS12V, SS120V

Silent Call Communications Corporation
5095 Williams Lake Road
Waterford, Michigan 48329
Phone: (800) 572 5227
http://www.silentcall.com
Applicable Model: VIB-PJ

Wireless Interconnected Smoke Alarms

First Alert
3901 Liberty Street Rd.
Aurora, IL 60504-8122
Phone: (800) 323-9005
http://www.firstalert.com
http://www.onelinkalarms.com
Applicable Models: SCO500CN, SA520CN, SA500CN, SA500CN2

Kidde
1394 South 3rd St.
Mebane, NC 27302
Phone: (800) 880-6788
http://www.kiddeus.com
http://www.kiddewireless.com
Applicable Models: RF-SM-DC, RF-SM-AC

Supplemental Notification Devices

Clarity, a Division of Plantronics, Inc.
4289 Bonny Oaks Drive, Suite 106
Chattanooga, TN 37406
Phone: (800) 426-3738
http://www.clarityproducts.com
Applicable Models: Ameriphone AM6000 (01865.000), Ameriphone AMAX (01880.00), Ameriphone AMPX (01885.000)

InnovAlarm
840 Research Parkway, Suite 225
Oklahoma City, Ok 73104
Phone: (405) 473-8117
http://www.innovalarm.com/

Kidde
1394 South 3rd St.
Mebane, NC 27302
Phone: (800) 880-6788
http://www.kiddeus.com
http://www.kiddewireless.com
Applicable Model: RF-SND

Krown Manufacturing, Inc.
3408 Indale Road
Fort Worth, TX 76116
Phone: (800) 366-9950
http://www.krownmfg.com
Applicable Models: KA300, KA300RX, KBS300RX, KA300TX

Silent Call Communications Corporation
5095 Williams Lake Road
Waterford, Michigan 48329
Phone: (800) 572 5227
http://www.silentcall.com
Applicable Models: 1008-3, SK09214, VIB-PJ, SU5001-S, SU5001-V, GV1097-1, VC4002-1

Smoke Alarms with Remote Test/Silence Features

DuPont
Phone: (888) 241-2780
http://www2.dupont.com/Fire_Safety/en_US/
Applicable Model: SC101

First Alert
3901 Liberty Street Rd.
Aurora, IL 60504-8122
Phone: (800) 323-9005
http://www.firstalert.com
Applicable Models: SA302

Smoke Alarms With Long-life (10-year) Sealed Batteries

Rechargeable

DuPont
Phone: (888) 241-2780
http://www2.dupont.com/Fire_Safety/en_US/
Applicable Model: SC101

Nonrechargeable

Dicon Global, Inc. (American Sensors)
20 Steelcase Road West, Unit 3
Markham, Ontario, Canada L3R 1B2
Phone: (800) 387-4219
http://www.nadidistribution.com
Applicable Model:

First Alert
3901 Liberty Street Rd.
Aurora, IL 60504-8122
Phone: (800) 323-9005
http://www.firstalert.com
Applicable Models: SA10YR

Invensys (Firex)
191 E. North Avenue
Carol Stream, IL 60188
Phone: (800) 951-5526
http://www.icca.invensys.com/firex
Applicable Models: 4671(C)

Kidde
1394 South 3rd St.
Mebane, NC 27302
Phone: (800) 880-6788
http://www.kiddeus.com
Applicable Model: 0910

Universal Security Instruments, Inc.
7-A Gwynns Mill Ct
Owings Mills, MD 21117
Phone: (410) 363-3000
http://www.universalsecurity.com
Applicable Model: SS-876-LRC