THE AUDIBILITY OF SMOKE ALARMS IN RESIDENTIAL HOMES

September 2005
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CPSC-ES-0503

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U.S. CONSUMER PRODUCT SAFETY COMMISSION
BETHESDA, MARYLAND 20814-4408

U.S. CONSUMER PRODUCT SAFETY COMMISSION

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

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

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This document contains corrections to the following page(s):

Page 20, Table 4. Test Home 2 – Sound Levels Measured, Smoke Alarm Outside the Master Bedroom

(Columns for *dB Loss* and *Bedroom Doors Closed* were transposed and corrected in January 2007)

EXECUTIVE SUMMARY

The U.S. Consumer Product Safety Commission (CPSC) staff initiated an evaluation in 2003 to review the audibility effectiveness of smoke alarms in residential homes. In this report, sound loss of a smoke alarm signal as it travels in a home is examined to determine the impact this may have on alerting occupants to a fire hazard. Sound loss measurements of smoke alarm signals in actual homes are compared to sound levels required to alert adults (without hearing or other impairment).

The CPSC staff conducted sound loss measurements in three different test homes using single station smoke alarms. The homes were built between 1960 and 1989. The sizes of the homes ranged from approximately 1,000 square feet to 3,300 square feet. The homes had either two or three levels. Measurements were taken with doors closed and opened.

The CPSC staff tests of sound loss measurements indicated that a single station smoke alarm installed in a small, single-level home may be sufficient to alert occupants, even if the bedroom doors are closed. The sound level effectiveness of an alarm in a single-level home with larger square footage may be reduced. For a two-level home, sound levels may not be sufficient to alert occupants in all areas of the home or cause a delay for some individuals to respond immediately. In CPSC staff tests, an alarm traveling from one level of a home to another and through a closed door produced sound levels around 50 dBA, which would be at the lowest level for awakening an unimpaired adult with no background noise present. Single station smoke alarms installed in a three level home may not be sufficient to alert occupants in all areas of the home. In CPSC staff tests, an alarm traveling from the basement to the second floor and through a door produced sound levels around 30 dBA, which would most likely not awaken an unimpaired adult, even with no background noise present.

Smoke alarms in homes are effective in alerting occupants only if the sound can be heard. The complexity of the path that the sound must travel plays an important role in the resultant sound level. A home with narrow hallways, turns, and multiple levels results in lower sound levels throughout the home compared to a home with an open floor plan and fewer turns.

In 1989, NFPA 74 *Standard for the Installation, Maintenance and Use of Household Fire Warning Equipment*, required newly constructed residential homes to have interconnected (hard-wired) smoke alarms on every level of the home and outside the sleeping areas. With interconnected smoke alarms, all the smoke alarms would sound if any individual smoke alarm detected smoke. If a fire occurred in a remote section of the home, the smoke alarm closest to the fire would sound and cause all the other smoke alarms to sound. NFPA 74 did not require existing homes to be retrofitted with interconnected smoke alarms, largely because of the financial burden this would place on homeowners. Most homes in the U.S. were constructed before interconnected smoke alarms were required.

- NFPA 74 *Standard for the Installation, Maintenance and Use of Household Fire Warning Equipment*, was renamed to NFPA 72, *National Fire Alarm Code* in 1993. NFPA 72-1993 included the installation of hardwired smoke alarms inside bedrooms or sleeping areas. Smoke alarms were required in bedrooms to address the concern associated with sound level losses when occupants sleep with the bedroom doors closed. The interconnected smoke alarm in the bedroom increased the assurance that the alarm sound level would be sufficient in the bedroom, and it also provided enhanced protection if the room of fire origin was the bedroom. Again, NFPA 72 did not require existing homes to be upgraded to these new requirements because of the financial burden this would place on homeowners.

The following conclusions, applicable to unimpaired adults, may be drawn from this report. For occupants with disabilities, or for young or older populations, the conclusions may be significantly different.

- Single station smoke alarms installed in two- or three-level homes may not be sufficient to alert occupants in all areas of the home or cause a delay for some individuals to respond immediately.
- The complexity of the path that the sound must travel determines the amount of attenuation (reduction) in the alarm signal.
- Closing a lightweight door attenuates a smoke alarm signal traveling from one room to another room between 10 to 20 dBA.
- Each (home) level that sound travels attenuates a smoke alarm signal about 20 dBA.
- Interconnected smoke alarms improve audibility effectiveness compared to single station smoke alarms.

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1.0 INTRODUCTION

The U.S. Consumer Product Safety Commission (CPSC) staff initiated an evaluation in 2003 to review the audibility effectiveness of smoke alarms in residential homes. This report describes the results of CPSC staff tests to quantify the reduction in smoke alarm sound level as the alarm travels through a home to determine the impact this may have on audibility effectiveness.

1.1 Fire Hazard

In 1999, there were an estimated 337,300 unintentional residential structure fires resulting in 2,390 civilian deaths, 14,550 civilian injuries, and $4.24 billion in property losses (Miller, et al., 2003). The National Fire Protection Association (NFPA) reported that, during the 25-year period from 1977 to 2001, home structure fires and home structure fire deaths both fell 47%, excluding the events of September 11, 2001. Home fire deaths fell 9% from 3,420 in 2000 to 3,110 in 2001 (excluding 9/11) (Ahrens, June 2003). The NFPA report for 2001 stated that four of every five fire deaths occurred in home structure fires.

1.1.1 Fire Hazard for Older Adults

There were an estimated 35 million people in the United States who were 65 years old or older in 2000 - almost 13% of the population. The number of people over the age of 65 is expected to double by the year 2030, growing to 70 million, or one in five people in the United States. It is estimated that the number of fire deaths for this age group will also increase significantly. The NFPA reported for 1999 that the fire death rate for people over 65 is 25.3 fire deaths per million, or more than twice the national average. The death rate increases for older age groups. For example, for those over the age of 75, the fire death rate (32.9 fire deaths per million) is about three times the national average.

Currently, residential smoke alarms operate at sound frequencies that may produce alarm sound characteristics poorly suited for the older population because of age-related hearing loss. A study by Davis (1995, UK) indicated that for study participants in the age range of 61-71 years, 51% had a hearing loss greater than 20 dB and 11% had a hearing loss greater than 40 dB. As the age range increased, the percentage with hearing loss also increased. For example, for study participants in the age range of 71-80 years, 74% had a hearing loss greater than 20 dB and 30% had a hearing loss greater than 40 dB.

1.2 Project Objectives

In this evaluation, sound loss of a smoke alarm signal as it travels in a home was examined to determine the impact this may have on alerting occupants to a fire hazard. Sound loss measurements of smoke alarm signals in actual homes were compared to sound levels required to alert adults (without hearing or other impairment).

2.0 SOUND LEVELS AND SOUND PERCEPTION

2.1 Human Response to Sound Pressure and Pitch

Sound is any disturbance of air (or fluid) that is perceptible to the ear. The way in which the human ear hears and interprets sound is very complex. Sound energy is transmitted through an air or fluid medium in pressure waves. Sound pressure is determined by the amplitude of the sound wave. The human ear can respond to sound pressures ranging from 20 μPascals (μPa*) to approximately 200 Pascals, although the response is not linear over this range. The ear may respond to sound pressures around 200 Pascals, but the threshold for pain is approximately 135 dBA (63 Pascals). Sound pitch is determined by the sound wave frequency, which is typically expressed as the number of cycles per second (measured in Hertz, Hz). Pitch increases as the frequency increases. The human ear can discern sounds ranging from 20 to 20,000 Hz. As with sound pressure, the response is not linear over this range; and hearing is typically optimal between 1000 and 4000 Hz. A sound with a frequency spectrum in the 1000 to 4000 Hz range will be perceived as being louder than a sound of equal sound pressure that is comprised predominantly of frequencies outside this range.

The decibel, or dB, is the unit of measure for sound levels. The decibel scale is a logarithmic scale representing the ratio of two numbers with a specific reference. Typically, the reference for acoustic signals is 20 μPa and corresponds closely to the lowest threshold of human hearing. Figure 1 shows an illustrated comparison between sound level and sound pressure.

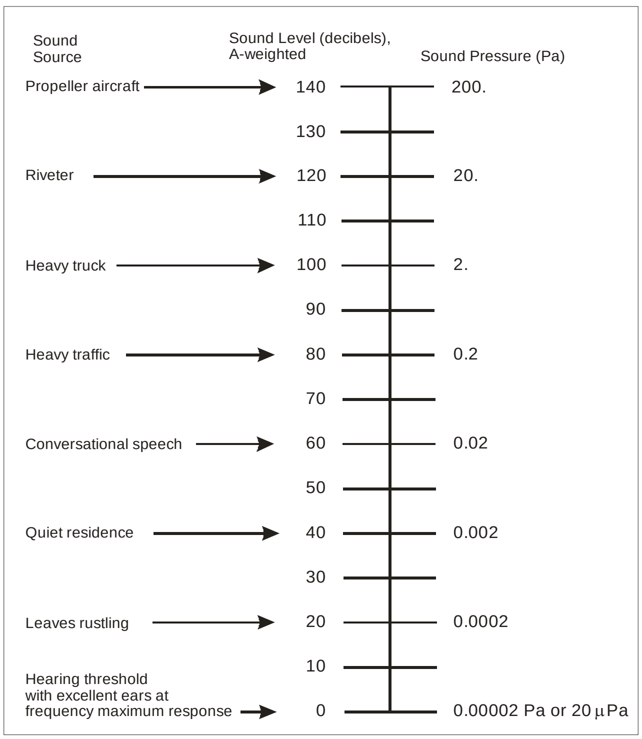

Figure 1. Sound Source Values for Sound Level and Pressure

* A Pascal is equal to a pressure of 1 Newton per square meter.

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

Figure 2 shows the different weighting scales and the no weighting scale case as applied to a recorded smoke alarm signature. The effects of the different weighting scales are most notable at lower frequencies, below 800 Hz. The signals for each of the weighting scales converge at 1 kHz; i.e., the sound level at 1 kHz is approximately the same regardless of the weighting scale used.

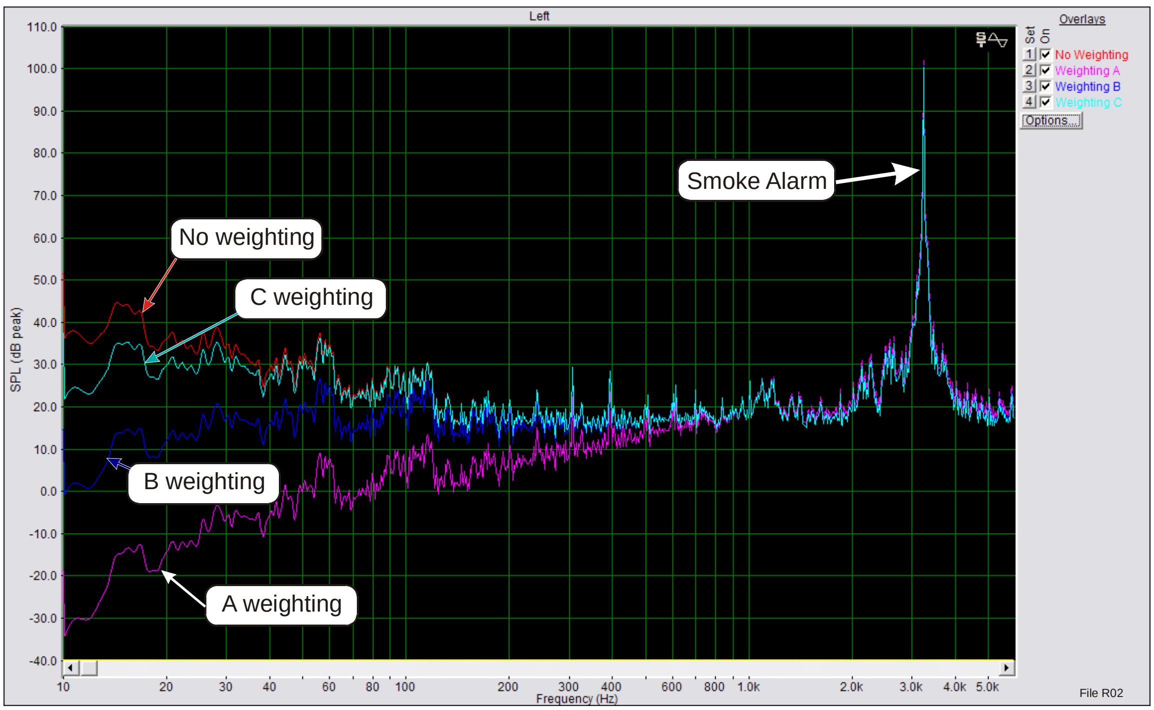

Figure 2. Weighting Scales for a Smoke Alarm Signature

Smoke alarms are designed to detect smoke and alert occupants of a fire – whether they are awake or sleeping. Most of the data quantifying thresholds required to alert individuals are from studies in which subjects were sleeping; many of these studies were conducted because most fire deaths occur when the victims are sleeping. Even though alerting thresholds need to be applied to both awake and sleeping individuals, the alerting thresholds used in this report are those obtained from studies attempting to awaken individuals.

2.2 Auditory Arousal from a Smoke Alarm

Some data suggest that a minimum of 70 dBA is required to wake most adults from sleep, although sound levels as low as 55-60 dBA can awaken some adults when the ambient noise levels are low (Bruck, 2001). Factors that affect auditory arousal from sleep include sound intensity and frequency, bedroom acoustics and background noise, time of night, current sleep stage, level of fatigue or sleep deprivation, the use of medication, alcohol or drugs, hearing loss, and whether or not the subject is primed to hear an alarm. Closed doors could also reduce audibility. A room air conditioner can have a sound level of 55 dBA; in this case, the smoke alarm sound level would need to be louder than the 55-60 dB to have the same effectiveness in alerting or awakening.

As adults age, they may increasingly experience hearing loss in the frequency range at which smoke alarms sound. Adults experience hearing losses at most frequencies as they age, and the rate of hearing loss is greatest at higher frequencies (above 2 kHz). One-third of all persons 70 years of age and older have some form of hearing impairment. This number has remained constant for the period 1984 to 1995 (Desai, 2001). As the older population increases over the next 30 years, the number of older persons with hearing impairments is also expected to increase. Age-related hearing loss is more significant in men than women, and it is the upper frequency ranges that are most affected. At 65 years of age, there is typically a loss of approximately 30 dB with a sound source at a frequency of 3000 Hz.

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

3.0 SOUND SOURCE IN RESIDENTIAL SMOKE ALARMS

3.1 Piezoelectric Horns Used in Residential Smoke Alarms

Smoke alarms (both the ionization and photoelectric types) typically use a piezoelectric horn to indicate to an occupant that the smoke alarm has activated. Piezoelectric horns are popular in smoke alarms because they can output significant sound levels without using much power. Depending on the piezoelectric horn design, the maximum sound pressure level can vary but is typically rated at a minimum of 85 dBA at 10 feet away as specified in the Underwriters Laboratories' voluntary standard for smoke alarms, UL 217 *Single and Multiple Station Smoke Alarms*.

3.2 Smoke Alarm Signal

Residential smoke alarm signals are required to use a temporal-three pattern as specified in American National Standard ANSI S3.41, *Audible Emergency Evacuation Signal*. The temporal-three pattern was standardized to be used as an audible emergency evacuation signal. The temporal-three pattern does not limit the signal to one sound (such as a bell, horn, ring, chime, or electronic sound) but, rather, to a sound pattern. This also does not limit the frequency or combinations of sound types that can be used in the temporal-three pattern.

The frequency of the horn output for a residential smoke alarm was measured. For typical smoke alarms, it is between 3,000 to 4,000 Hz. As shown in Figure 3, the frequency of the signal for the tested smoke alarm was 3.2 kHz. In addition, UL 217 – *Single and Multiple Station Smoke Alarms*, requires an A-weighted sound pressure level of at least 85 decibels (dBA) when measured at a distance of 10 feet from the horn, in a room of a specific configuration and under specific conditions (UL, 1997). The sound pressure level of the tested alarm was slightly less than 85 dBA; however, it was not measured under the conditions specified in UL 217.

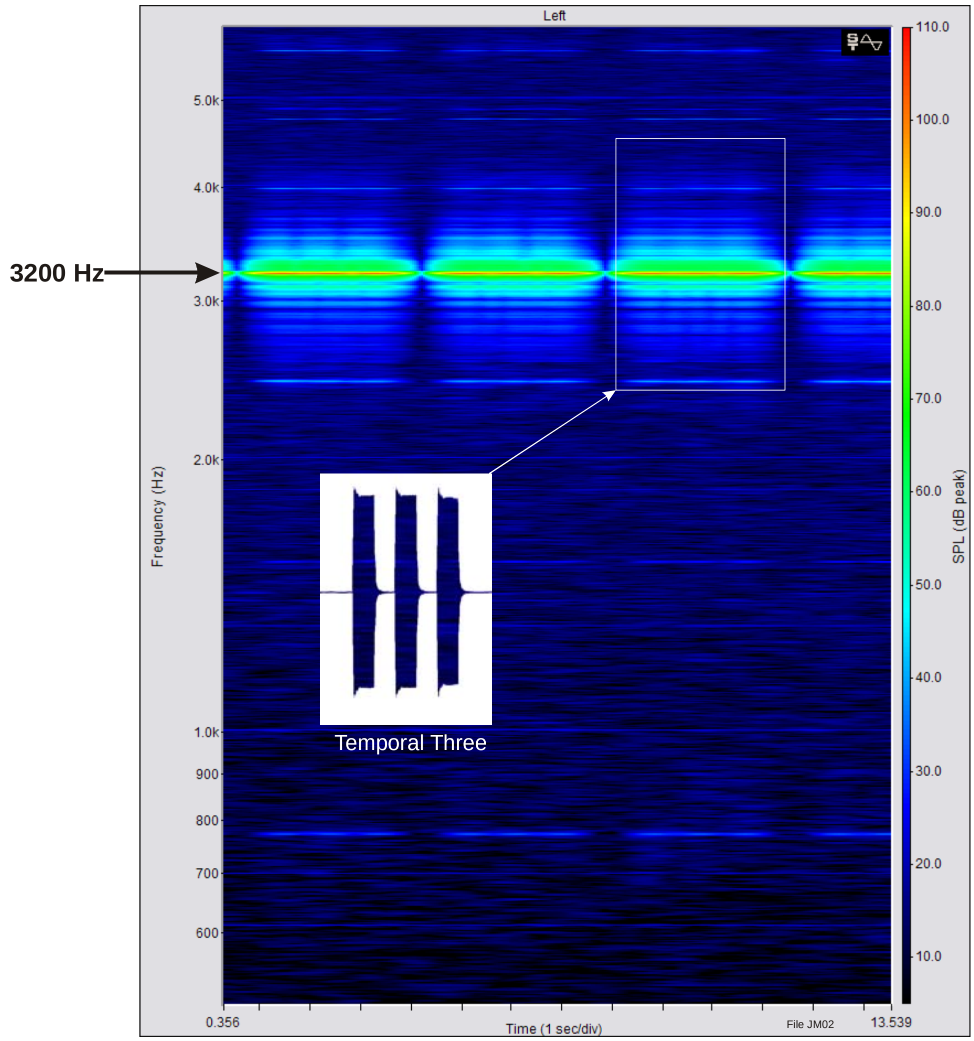

Figure 3. Smoke Alarm Signal – Temporal-Three Pattern (A-weighted)

4.0 FIRE ALARM CODE IN ONE- AND TWO-FAMILY DWELLINGS

The NFPA requirements for smoke alarms in newly constructed residential homes have changed over time.

Prior to 1989, existing homes typically installed single-station, battery-only-powered smoke alarms. With single-station smoke alarms, the smoke alarm closest to the fire would be expected to activate first. Depending on the size and layout of the home, if a fire occurred in a remote section of the home, as shown in Figure 4, the alarm might not be sufficiently audible to be heard by some occupants or to awaken sleeping occupants. If the fire progressed and smoke traveled to a smoke alarm closer to the occupants, this might result in a sound level sufficient to be heard or to awaken sleeping occupants. The delay before a closer smoke alarm notifies the occupants of the fire might dramatically reduce the amount of escape time and eliminate some of their egress options, perhaps leaving them with only seconds to exit the home.

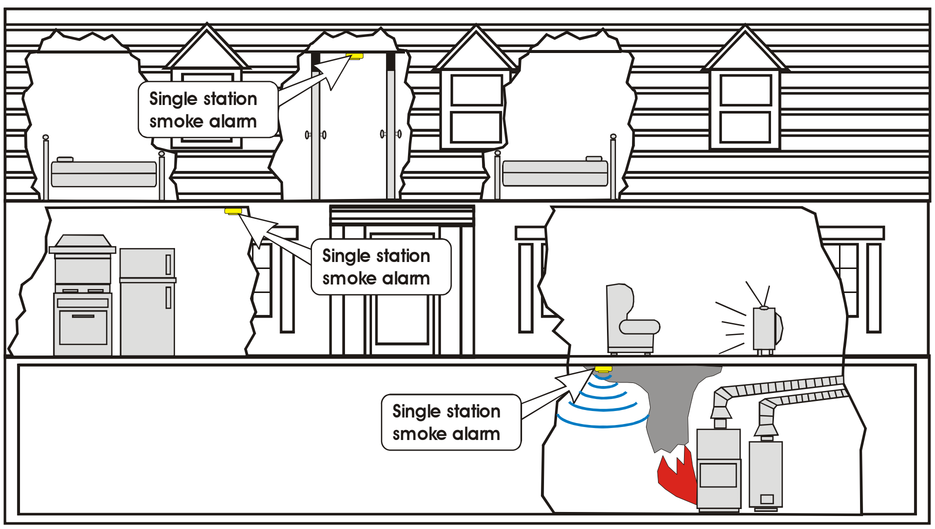

Figure 4. Single Station Smoke Alarms in Older Homes

In 1989, NFPA 74, *Standard for the Installation, Maintenance and Use of Household Fire Warning Equipment*, required interconnected smoke alarms on every level of the home and outside the sleeping areas in newly constructed homes. With interconnected smoke alarms, all the smoke alarms will sound if any individual smoke alarm detects smoke. If a fire occurs in a remote section of the home, the smoke alarm closest to the fire will sound and cause all the other smoke alarms to sound, as shown in Figure 5. NFPA 74 did not require existing homes to be retrofitted with interconnected smoke alarms, largely because of the financial burden this would place on homeowners. Most homes in the U.S. were constructed before interconnected smoke alarms were required.

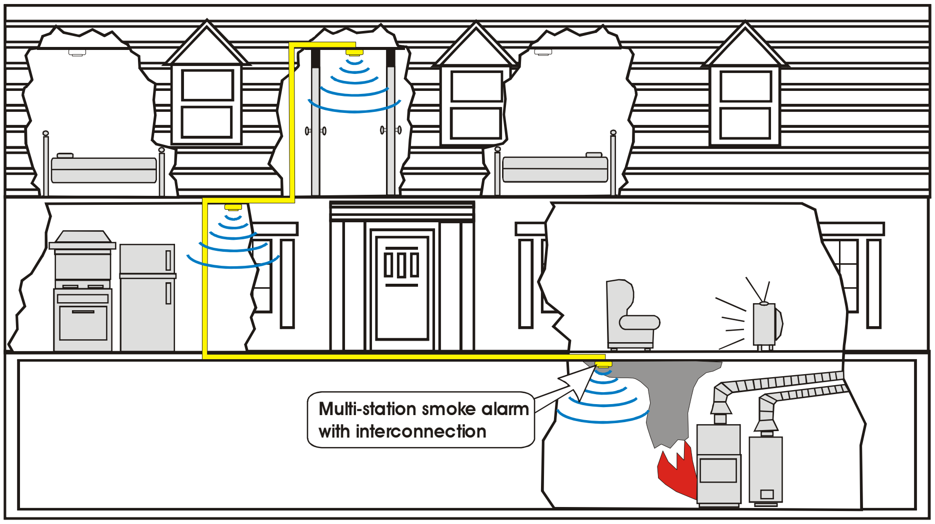

Figure 5. Interconnected Smoke Alarms on Every Level and Outside Sleeping Area

In 1993, NFPA 74 *Standard for the Installation, Maintenance and Use of Household Fire Warning Equipment* was renamed to NFPA 72 *National Fire Alarm Code*. NFPA 72-1993 edition included the requirement for newly constructed residential homes to have interconnected (hard wired) smoke alarms inside bedrooms or sleeping areas, in addition to hard wired smoke alarms on every level of the home and outside the sleeping area, as shown in Figure 6. Smoke alarms were required in bedrooms to address the concern associated with sound level losses when occupants sleep with the bedroom doors closed. The interconnected smoke alarm in the bedroom increased the assurance that the alarm sound level would be sufficient in the bedroom, and it also provided additional protection if the room of fire origin is the bedroom. This provided increased smoke alarm audibility, even if the bedroom doors were closed. Again, NFPA 72, 1993 edition, did not require existing homes to be upgraded to these new requirements because of the financial burden this would place on homeowners.

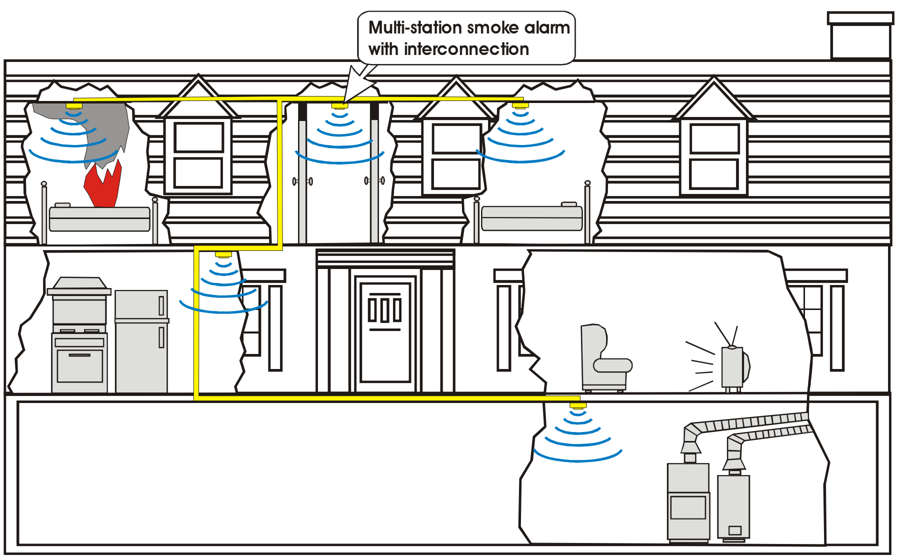

Figure 6. Smoke Alarms on Every Level, Outside and Inside Sleeping Rooms

Hardwired smoke alarms with battery back-up were not required until the 1996 edition of NFPA 72. In 1996, the requirement to have hardwired smoke alarms with battery back- up in new construction was to address non-operability during power outages.

4.1 Smoke Alarm Performance

In 2000, the U.S. Consumer Product Safety Commission (CPSC) staff coordinated the evaluation of current and emerging smoke alarm technology responses to common residential fire scenarios and nuisance alarm sources. CPSC staff worked with interested organizations in developing and funding a two-year project to evaluate smoke alarms in full-scale fire tests. The work, conducted by the National Institute of Standards and Technology (NIST), was completed in December 2002 (NIST, 2003). Tests were conducted in actual homes representing typical sizes and floor plans. The tests utilized actual furnishings and household items for fire sources and actual smoke alarms currently sold in retail stores. Smoke alarm performance was quantified in terms of the escape time provided by groups of alarms installed in accordance with typical code provisions.

The NIST testing showed that using alarms in the bedrooms, in addition to having alarms on every level, reduced the time to alarm for every fire scenario tested with most alarm technologies. The alarm in the bedroom provided an additional 3 to 923 seconds (15 minutes 23 seconds) of available egress time, depending on the fire scenario. As expected, alarm times for the bedroom fire scenarios were most affected by the additional alarms, since alarms were now included in the room of fire origin. The report states that the test data provides a basis for evaluating whether smoke alarms should be required in bedrooms of existing homes constructed prior to 1993.

5.0 MEASURING SOUND LOSS IN RESIDENTIAL HOMES

When sound travels in a home, it takes essentially the same path as a person who walks through the home. For example, a sound source originating in the living room may travel to the foyer, up the stairs, into the upper hallway, and then into the bedrooms. Sound also travels through the central air conditioning and heating ducts but to a lesser degree. Sound level decreases as the sound travels.

To determine the amount of sound loss in homes, a smoke alarm was used as an alarm source and sound levels were recorded throughout three test homes. Three different home types were used in the testing – ranch, contemporary, and colonial. The homes were built between 1960 and 1989, and they ranged in size from 1,120 to 3,371 square feet (s.f.), respectively. All homes are wood framing with ½-inch drywall.

5.1 Test Setup and Instrumentation

A UL listed, battery-powered smoke alarm was used as the sound source and was mounted to a ceiling for all tests. A new battery, with a minimum of 9 volts, was installed in the test smoke alarm before each test series.

A data acquisition system consisting of a microphone, digitizing unit, and a computer was used. The microphone was connected to a preamplifier and mounted to a tripod, which was adjusted so that the microphone/amplifier was 5 feet from the floor. Even though the microphone was omni-directional, it was mounted in a vertical orientation (pointing upward). A coaxial cable connected the microphone/amplifier to the digitizing unit. The digitizing unit was then connected to the computer. The test setup is shown in Figure 7. The test setup was moved to different locations in the home to record sound loss.

The microphone was calibrated before and after each test series. In all the testing, the home ventilation and air conditioning (HVAC) system was turned off. All the homes had a ducting system for air conditioning and/or heating.

Two-conductor wiring was soldered to the smoke alarm test connectors to allow the operator to activate the smoke alarm from a distance, to avoid sound propagation interference. Approximately 11 seconds of alarming (or three sets of temporal three patterns) were recorded for each test.

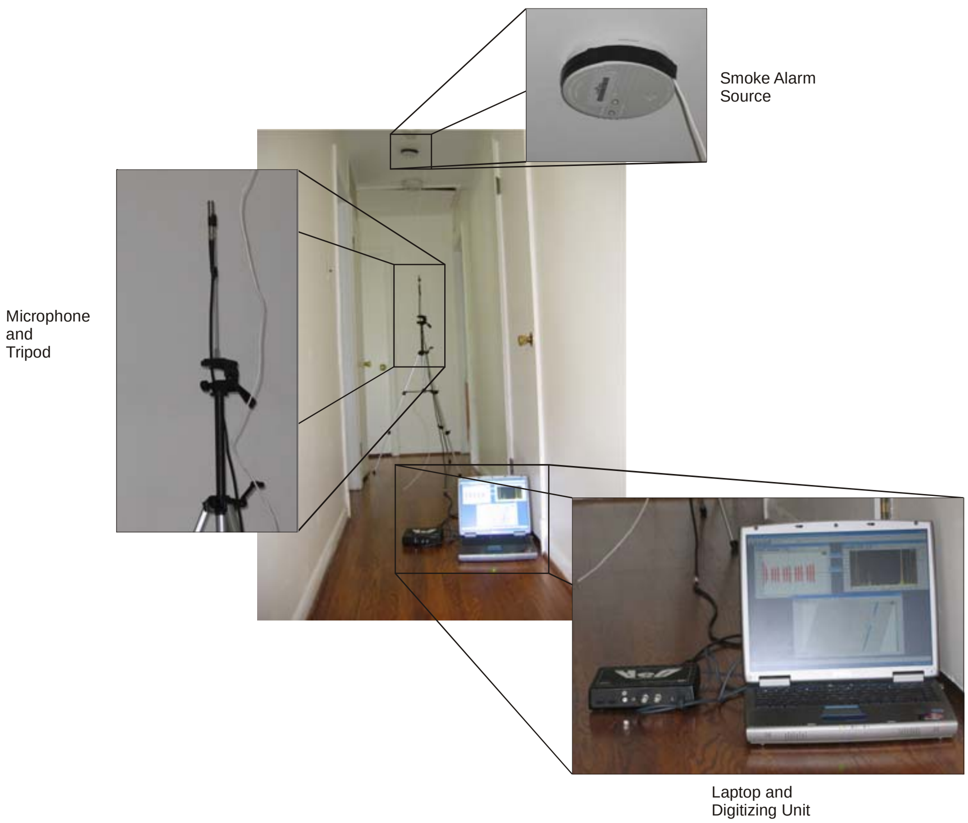

Figure 7. Test Setup

Below is a list of the equipment used in the testing. CPSC does not endorse the equipment and instrumentation used in the project nor state that the equipment or instrumentation used is the best or only for this application. The product and company names listed are trademark or trade names of their respective companies.

Alarm Source	Single Station Smoke Alarm 9-volt Battery Powered UL listed[1]
Microphone	G.R.A.S. Sound & Vibration Type 40AO Sensitivity 10.07 mV/Pa Frequency Response 5Hz-12.5kHz @ ±2 dB 3.15Hz-20kHz @ ±1 dB
ICP Preamplifier	G.R.A.S. Sound & Vibration Type 26CA Frequency Response 2Hz-100kHz @ ±2 dB
Digitizing System	Sound Technology, Inc Model ST191 32 bit PC link
Computer	Laptop 3GHz processor 1G RAM
Analysis Software	Sound Technology, Inc LAB432 Enterprise Edition Version 19
Audio Calibrator	Quest Technologies Model QC-20 Calibrated 30 March 2004

The data was analyzed by applying a power spectrum on the recorded signal. The spectrum graphs are a 2 dimensional plot of the spectrum. In the spectrum graphs, the horizontal axis shows the frequency in Hertz (Hz) and the vertical axis shows the amplitude of each frequency line. The amplitude scale was calibrated using the audio calibrator before each home was tested.

The total number of available spectral lines is equal to the FFT size / 2. The FFT size set for the tests was 65536; therefore, there will be 32768 spectral lines. The measurement starts at 0 Hz and extend to 1/2 of the selected sampling rate, which was 44.1 KHz, divided by the

[1] UL 217, *Single and Multiple Station Smoke Alarms*, requires a minimum sound pressure level of 85 dBA at 10 ft for a specific acoustic environment. The measurements in the test homes do not represent the same acoustic environment as that specified in UL 217.

Decimation Ratio of 1. The frequency limit was 22 KHz. The spectral line resolution is the frequency limit (22 KHz) divided by the number of spectral lines (32768) or 0.673 Hz.

The maximum displayed spectrum is limited on the low and high ends. The lowest 3 bins contain a DC component and are not displayed; the top 1% of the span often contains alias components and, therefore, is not displayed.

5.2 Test Home 1 – Built 1960

Test Home 1 was built in 1960 and is a classic suburban ranch house typical of many homes found in major U.S. cities. The house is approximately 1,120 s.f. and is illustrated in Figure 8. The house is located on a quiet secondary residential street and backs to woods. This house and the surrounding houses are situated on similar sized lots of about one quarter acre. The home has a first floor and a basement. The interior doors are hollow with an undercut of approximately 1/2 inch.

Figure 8. Illustration of Test Home 1 – Built 1960.

The first floor has three bedrooms, a living room, full bath, breakfast/dining room, and a kitchen, as shown in Figure 9. The dining room contains half walls that lead to the kitchen and living room. The first floor contains hardwood floors throughout with area rugs, except the kitchen which has linoleum flooring. The master bedroom is approximately 11’ x 10’. Bedroom 2 is used as an office and is approximately 14’ x 10’. Bedroom 3 is a guest bedroom and is approximately 9’ x 12’. The ceiling height for the first floor is 8’. The majority of the basement is finished into a small apartment with a separate rear entrance.

The test smoke alarm was placed in the following locations: the hallway, bedroom 3, and at the bottom of the basement stairs. Sound measurements were made with the microphone in the master bedroom, bedroom 2, bedroom 3, the hallway, and at the bottom of the basement stairs. The door to the bathroom was closed throughout the testing to provide the best case for sound propagation and allow improved consistency in testing.

Figure 9. Test Home 1 – Floor Plan

Testing was conducted during the day on a weekday. The temperature in the dining room was 80º F with 51% humidity. The humming sound of the refrigerator could be heard when standing in the kitchen or dining room. The home has central air conditioning, which was turned off during testing.

5.2.1 Smoke Alarm in the Hallway

In this series of tests, the smoke alarm was placed in the hallway outside the bedrooms. The door to the bathroom was closed for all the tests.

The sound level in the hallway under the smoke alarm was measured. The peak sound level measured with all the bedroom doors either opened or closed was nearly the same, 104 dBA. The peak sound level difference was not significant because of the close proximity of the sound source to the microphone.

Sound levels were also measured in each of the bedrooms with all the bedroom doors opened and with them closed. The sound levels measured in the master bedroom, bedroom 2, and bedroom 3 with all bedroom doors opened were 85 dBA, 85 dBA, and 96 dBA, respectively. Figure 10 shows the sound levels measured in each of the bedrooms. The sound levels in the master bedroom and in bedroom 2 were similar; the sound level in bedroom 3 was the highest.

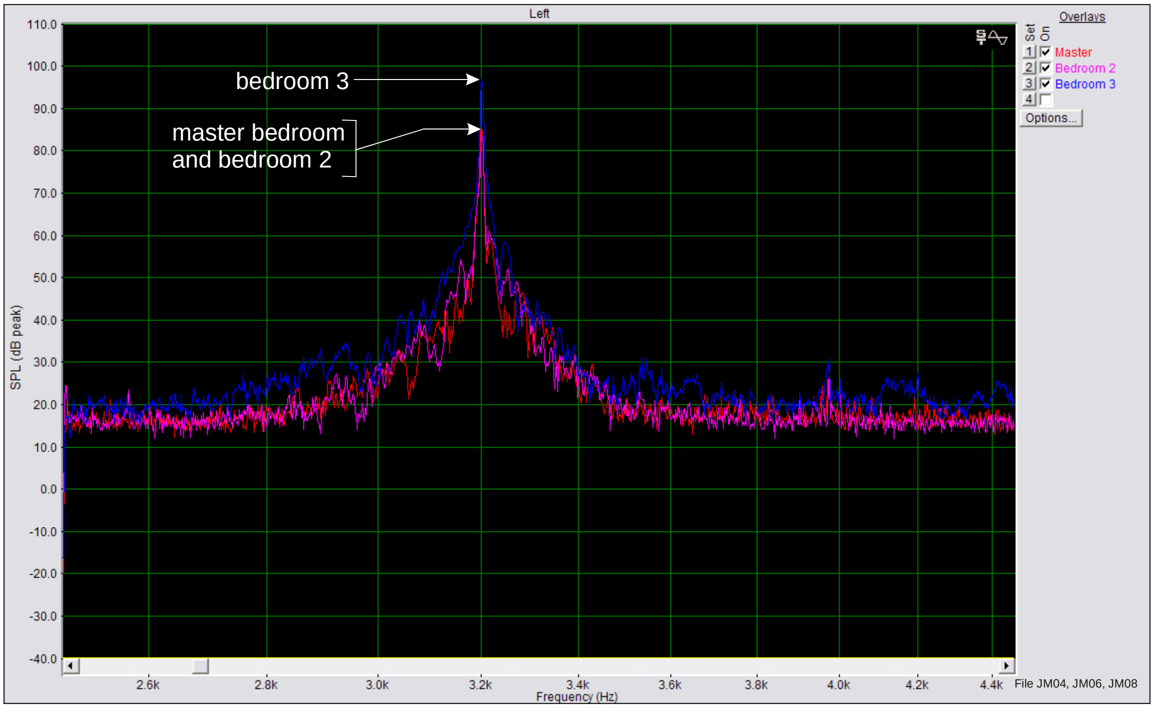

Figure 10. Smoke Alarm in Hallway – Sound Spectrum in Bedrooms with Bedroom Doors Opened

The sound levels measured in each of the bedrooms (master, 2, and 3) with all the bedroom doors closed were 77 dBA, 71 dBA, and 88 dBA, as shown in Figure 11. The sound level in bedroom 3 was again the highest.

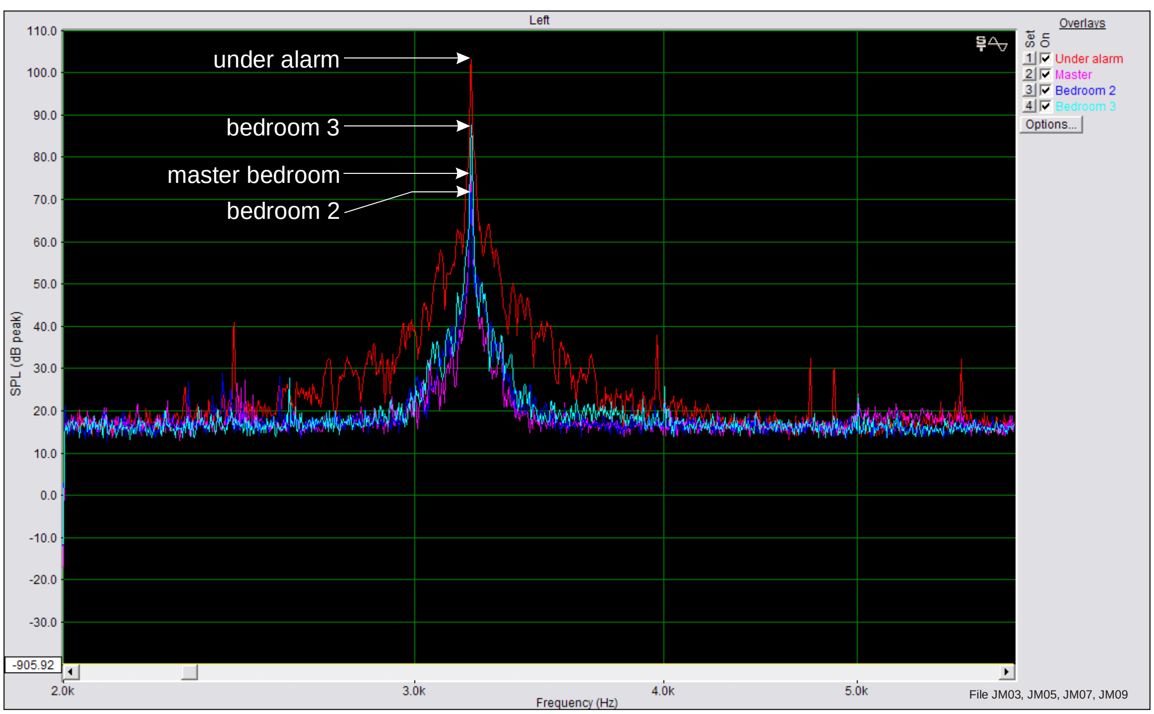

Figure 11. Smoke Alarm in Hallway – Sound Spectrum in Bedrooms with Bedroom Doors Closed

Sound levels were reduced by at least 8 dBA when the doors went from open to closed. Table 1 shows the comparisons of sound level measurements with the bedroom doors opened and closed.

Table 1. Test Home 1 – Sound Levels Measured, Smoke Alarm in Hallway

Microphone Location	Peak (dBA)		dB Loss
	Bedroom Doors Opened	Bedroom Doors Closed	
Under Smoke Alarm	104	104	N/A
Master Bedroom	85	77	8
Bedroom 2	85	71	14
Bedroom 3	96	88	8

5.2.2 Smoke Alarm in Bedroom 3

For this series of tests, the smoke alarm was mounted on the ceiling of bedroom 3, approximately 5 feet from the door. Sound levels were measured with the door to bedroom 3 opened and closed. The difference in sound level under the smoke alarm was 10 dBA – 90 dBA with the bedroom door opened and 100 dBA with it closed.

The sound level was measured at the pillow on the bed with the bedroom 3 door opened and with it closed. The bed was located against two walls, as shown in Figure 9. At the pillow, the position of the door did not affect the sound level. The peak sound level was measured at 93 dBA with the door opened or closed. The peak sound level measured at the pillow was higher than the peak sound level measured directly under the alarm itself (90 dBA), although sound levels for both locations were typically around 90 dBA.

Sound levels were measured in the other bedrooms with the doors opened and with them closed. The sound levels were lower when the bedroom doors were closed, as expected. With the doors closed, the sound level was 9 dBA lower in bedroom 2 and 16 dBA lower in the master bedroom. Compared to the sound level in the room of origin (bedroom 3), the sound levels in the other bedrooms with the doors closed were almost 40 dBA lower, as shown in Figure 12.

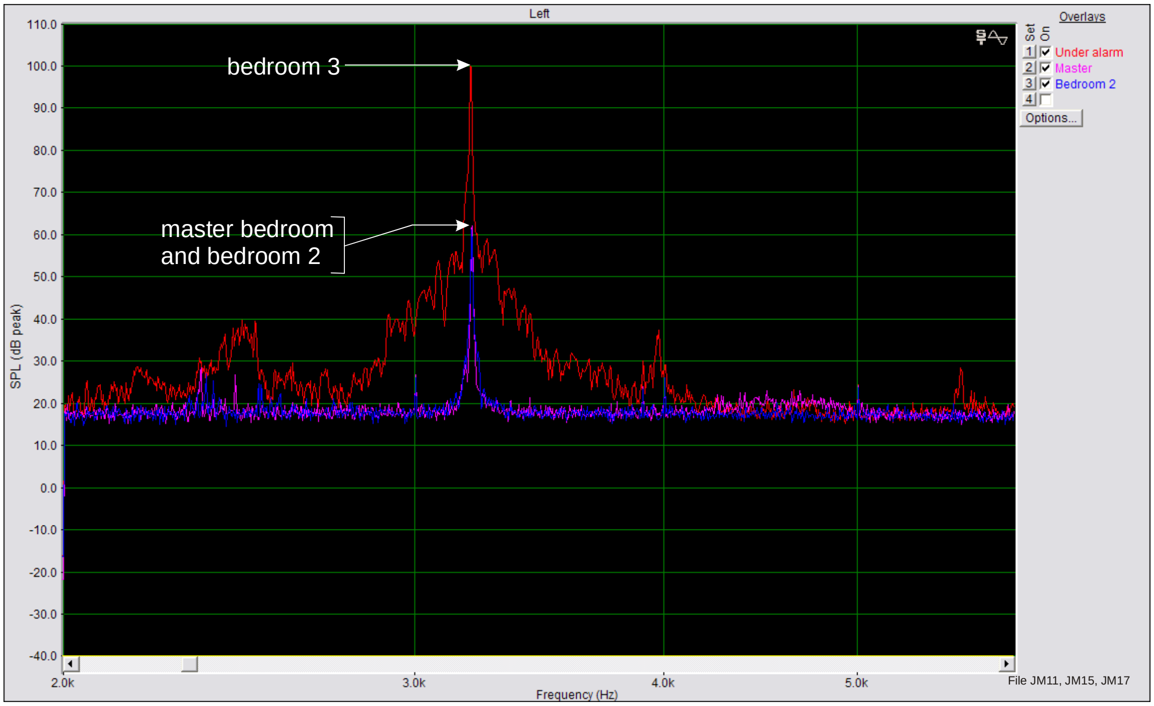

Figure 12. Smoke Alarm in Bedroom 3 - Sound Spectrum in Bedrooms with Bedroom Doors Closed

Table 2 lists the sound levels measured at the various locations.

Table 2. Test Home 1 – Sound Levels Measured, Smoke Alarm in Bedroom 3

Microphone Location	Peak (dBA)		dBA Loss
	Bedroom Doors Opened	Bedroom Doors Closed	
Under Smoke Alarm	90	100	N/A
At pillow, Bedroom 3	93*	93*	N/A
Master Bedroom	78	62	16
Bedroom 2	70	61	9

*Peak at 93 dBA, but was typically 90 dBA

5.2.3 Smoke Alarm in the Basement

For this series of tests, the smoke alarm was mounted on the ceiling at the bottom of the basement stairway, approximately 5 feet from the stairs. The peak sound level measured under the smoke alarm was 97 dBA. The sound level measured in the master bedroom with only the master bedroom door opened was 52 dBA; with the door closed, it was 45 dBA (a 52 dBA decrease, as shown in Figure 13).

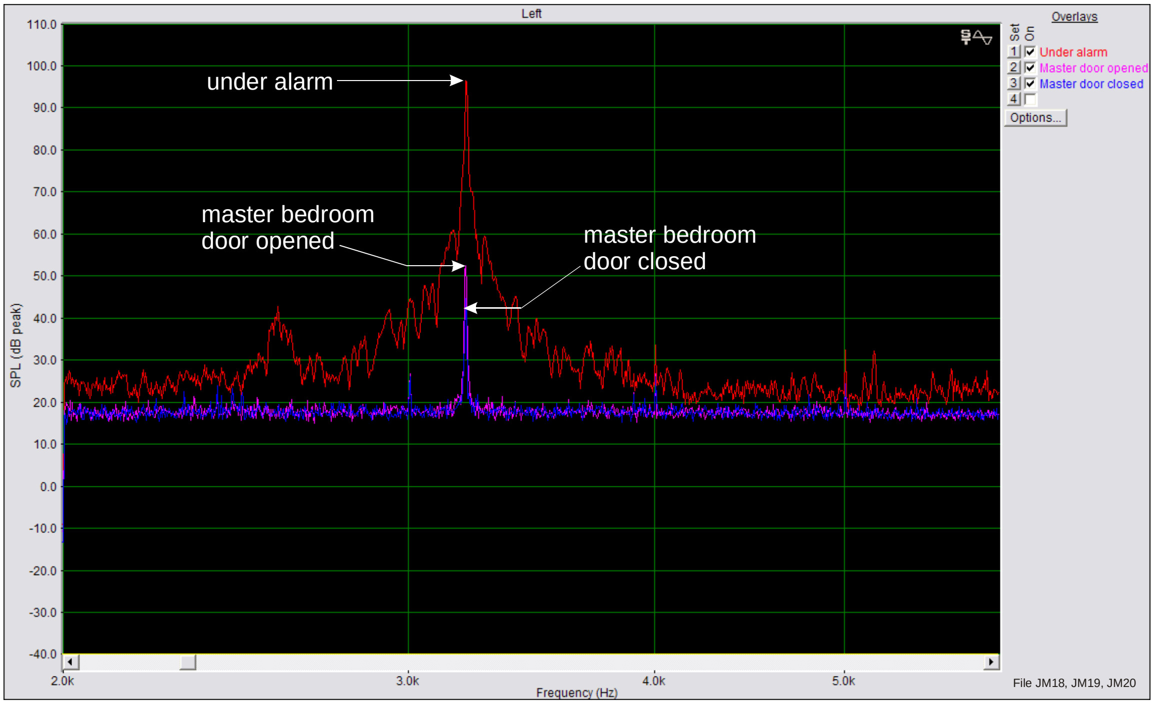

Figure 13. Smoke Alarm in Basement – Sound Levels in the Master Bedroom

5.3 Test Home 2 – Built 1973

Test Home 2 was built in 1973 and is a contemporary-style home. The house layout is the most unique of the three homes tested. The house is approximately 2,343 s.f. The house is located on a cul-de-sac in a quiet residential area that backs to other homes. This house and the surrounding homes are situated on large lots, approximately one acre, with mature trees. Figure 14 shows an illustration of the front of Test Home 2. The home has a first and second floor, but no basement. The house is built on a slab. The interior doors are hollow with an undercut of approximately 1 inch. The doors to the bathroom were closed throughout the testing to provide the best case for sound propagation and allow improved consistency in testing.

Figure 14. Illustration of Test Home 2 – Built 1973

The first floor has the master bedroom, living room, full bath, breakfast room, dining room, kitchen, family room, and laundry/mechanical room, as shown in Figure 15. The first floor contains hardwood floors throughout with area rugs, except the kitchen which has ceramic tiles and the master bedroom which has wall-to-wall carpet. The master bedroom is approximately 11' x 16'.

Open stairs lead to a loft on the second floor; one side of the loft is open to the living room below. The loft is used as a study and is approximately 12' x 13'. The second floor also contains three bedrooms (bedrooms 2, 3 and 4), and a full bath. Bedroom 2 is used as storage and is approximately 10' x 13'. Bedroom 3 is a guest bedroom and is approximately 10' x 13'. Bedroom 4 is a guest bedroom and is approximately 11' x 10'. The ceiling height of the first floor is 8', except in the living room where there is a vaulted ceiling to the second floor loft, and in the master bedroom, which also has a vaulted ceiling. The ceiling height for the second level is also 8'. The floor plan is shown in Figure 15.

The test smoke alarm was placed in the following locations: the first floor hallway between the kitchen and family room, and outside the master bedroom. Sound level measurements were made with the microphone placed under the smoke alarm, at the bottom of the stairs, at the top of the stairs, and inside each of the bedrooms.

Figure 15. Test Home 2 – Floor Plan

Testing was conducted during the day on a weekday. The temperature in the dining room was 75º F with 59% humidity.

5.3.1 Smoke Alarm in the Hallway Between the Kitchen and Family Room

In this series of tests, the smoke alarm source was placed in the hallway between the kitchen and the family room. The doors to the bathrooms were closed for all the tests. The peak sound level under the smoke alarm was measured at 102 dBA when the bedroom doors were opened. Since the smoke alarm was not in close proximity to the bedrooms, it was assumed that a similar peak sound level would occur with the bedrooms doors closed.

The peak sound levels at the bottom and top of the stairs were 80 dBA and 67 dBA, respectively. Sound levels were measured in each of the bedrooms with the bedroom doors opened and closed. The sound levels measured in each bedroom (master, 2, 3, and 4) with all bedroom doors opened were 68 dBA, 65 dBA, 64 dBA, and 60 dBA, respectively. The sound levels measured in each bedroom (master, 2, 3, and 4) when all the bedroom doors were closed were 55 dBA, 52 dBA, 42 dBA, and 49 dBA, respectively. Figure 16 shows a sound level comparison in the bedrooms with the bedroom doors closed. In comparison to the sound levels with the bedroom doors opened, the sound level was reduced between 11 dBA and 22 dBA.

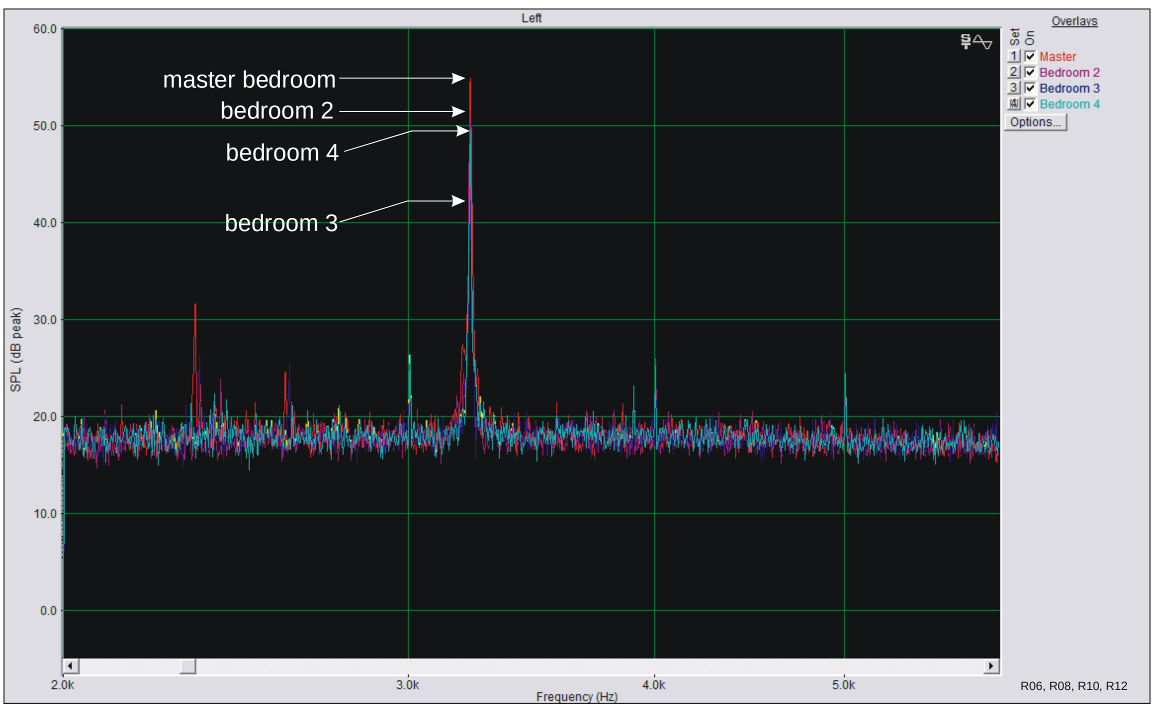

Figure 16. Smoke Alarm in Hallway – Sound Spectrum in the Bedrooms with Bedroom Doors Closed

Table 3 lists the peak sound levels measured in each bedroom with the doors opened and closed. It is not known why there was a larger difference in sound level associated with bedroom 3 (22 dBA). It was expected that the difference in sound levels would have been similar to those measured in bedrooms 2 (13 dBA) and 4 (11 dBA).

Table 3. Test Home 2 – Sound Levels Measured, Smoke Alarm in Hallway

Microphone Location	Peak (dBA)		dB Loss
	Bedroom Doors Opened	Bedroom Doors Closed	
Under Smoke Alarm	102	No measurement	N/A
Master Bedroom	68	55	13
Bedroom 2	65	52	13
Bedroom 3	64	42	22
Bedroom 4	60	49	11

5.3.2 Smoke Alarm Outside the Master Bedroom

For this series of tests, the smoke alarm was mounted on the ceiling outside the master bedroom, approximately 5 feet from the door. Sound levels were measured in the master bedroom and the bedroom doors on the second floor. The test bedrooms were tested with either the doors opened or closed. The other second level bedroom doors were closed during the testing. The sound level in the master bedroom decreased from 68 dBA to 53 dBA when the master bedroom door was closed. Sound levels were considerably lower when the bedroom doors were closed, especially for bedroom 2, as shown in Figure 18.

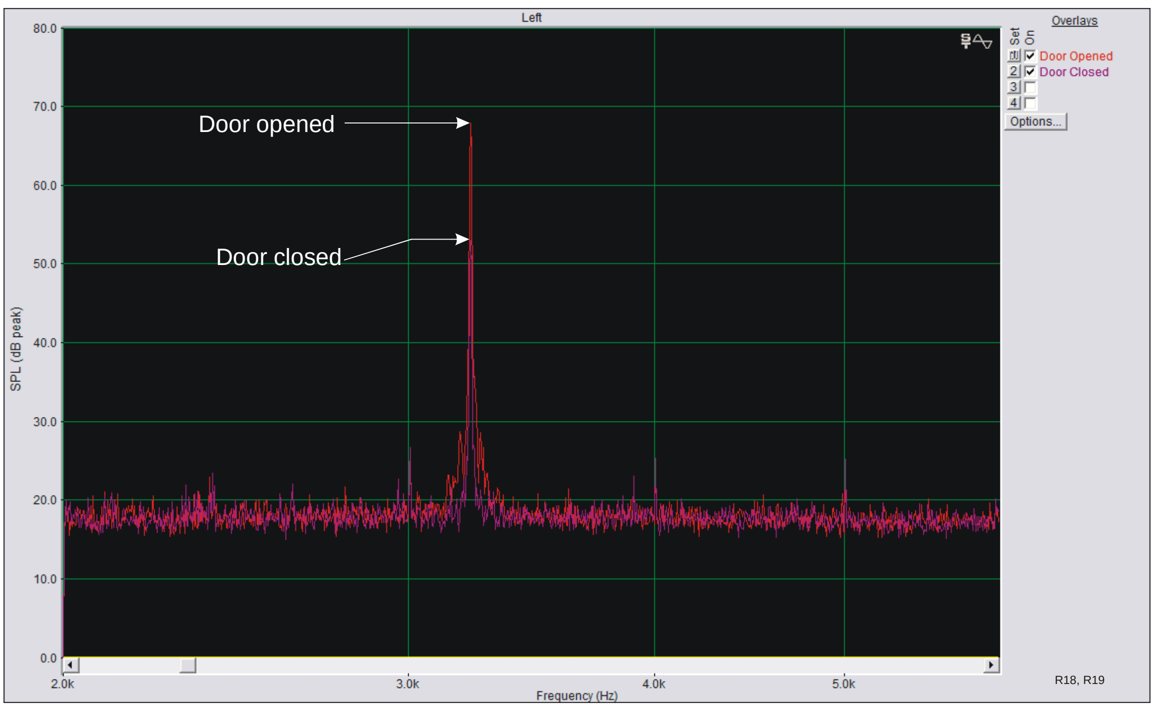

Figure 17. Smoke Alarm Outside Master Bedroom – Sound Spectrum in Master Bedroom with Bedroom Door Closed and Opened

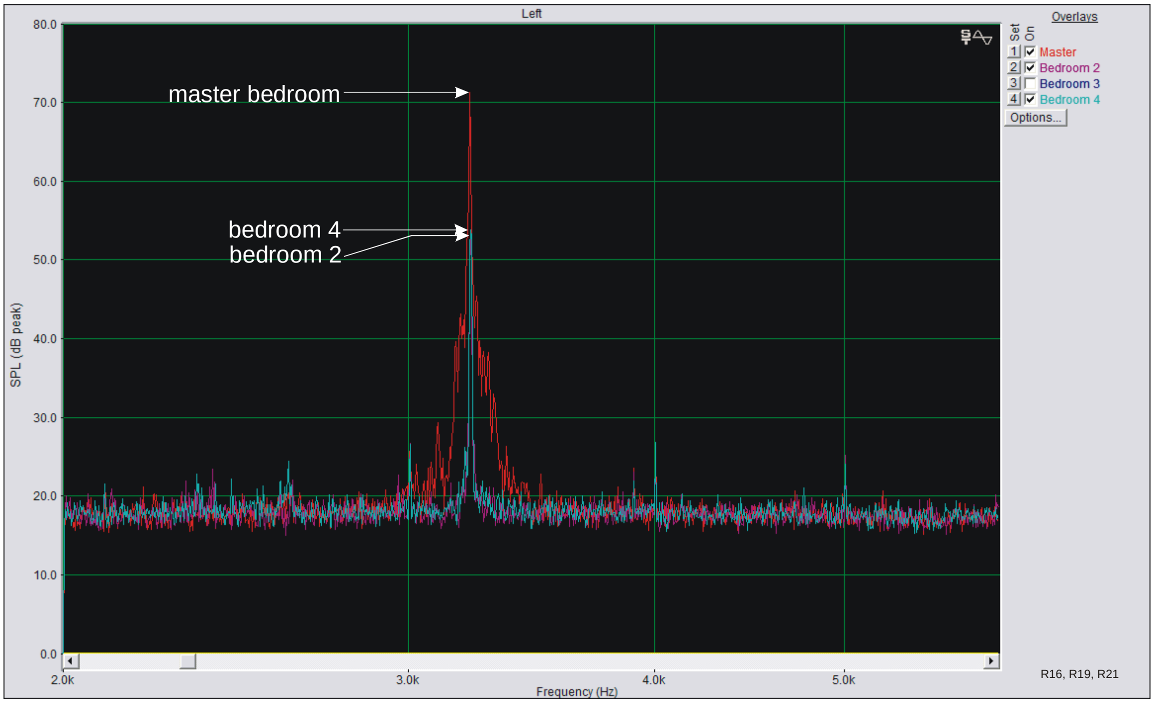

Figure 18. Smoke Alarm in Master Bedroom – Sound Spectrum in the Bedrooms (Master, 2, and 4) with Bedroom Doors Closed

Table 4 lists the sound levels measured at the various locations.

Table 4. Test Home 2 – Sound Levels Measured, Smoke Alarm Outside the Master Bedroom (Corrected 1/2007)

Microphone Location	Peak (dBA)		dB Loss	Comments
	Bedroom Doors Opened	Bedroom Doors Closed		
Under Smoke Alarm	96	92	4	
Master Bedroom	90	72	18	
Top of stairs	72	No measurement	N/A	
Bedroom 2	68	53	15	BD door 2 opened only, other 2nd level doors closed during testing
Bedroom 4	60	54	6	BD door 4 opened only, other 2nd level doors closed during testing

5.4 Test Home 3 – Built 1989

Test Home 3 was built in 1989 and is a typical Georgian colonial-style home. The house is approximately 3,371 s.f. and is illustrated in Figure 19. The house is located on a private, multi-home access road. This house and surrounding houses are situated on large lots, approximately 3 acres or more. The house backs to other homes on similar-sized lots. The home has a first floor, second floor, and basement. The interior doors are hollow with an undercut of approximately 1/2 inch. The doors to the bathroom were closed throughout the testing to provide the best case for sound propagation and allow improved consistency in testing.

Figure 19. Illustration of Test Home 3 – Built 1989

The first floor has a living room, dining room, family room, half bath, breakfast room, kitchen, and mud/laundry room, as shown in Figure 20. The kitchen and breakfast room have ceramic tiles; the remainder of the first floor contains hardwood floors, with area rugs in the family and dining rooms. The living room, which contains a pool table, is approximately 14' x 17'. The dining room is used as an office and is approximately 13' x 13'. Approximate dimensions for the other rooms are: family room 21' x 14', kitchen 22' x 15', breakfast room 10' x 12', and mud/laundry room 7.5' x 11'. The ceiling height of the first floor is 9'. There are two sets of stairs that lead to the second floor. The back stairs are accessed from the mud/laundry room and lead to the study and master bedroom/bath. The front or main stairs are in the entry foyer and lead to a small second floor hallway. The front stairs are hardwood, and the back stairs are carpeted. The basement is unfinished.

The second floor contains four bedrooms, a study, and two full baths. The master bedroom is approximately 14' x 22'. The upstairs study is accessed from the master bedroom/bath and is approximately 14' x 18'. Bedrooms 2, 3, and 4 are approximately 12' x 11.5', 14' x 11.5', and 14' x 15', respectively. All of these rooms are carpeted. The hallway bath is approximately 9.5' x 5' and has a ceramic tile floor.

There are two sets of stairs that lead to the basement. One set is accessed from the garage, and the other set is accessed from the family room. The unfinished basement is divided into two areas; the main area is approximately 36.5’ x 34.5’, and a smaller area is 15.5’ x 24’. The furnace and water heater are located in the basement.

The test smoke alarm was placed in the family room and in the basement. The microphone was placed in the following locations: under the smoke alarm, in each of the bedrooms, and at the top and bottom of the front stairs.

Testing was conducted during the day on a weekday. The temperature in the kitchen was 74º F with 54% humidity.

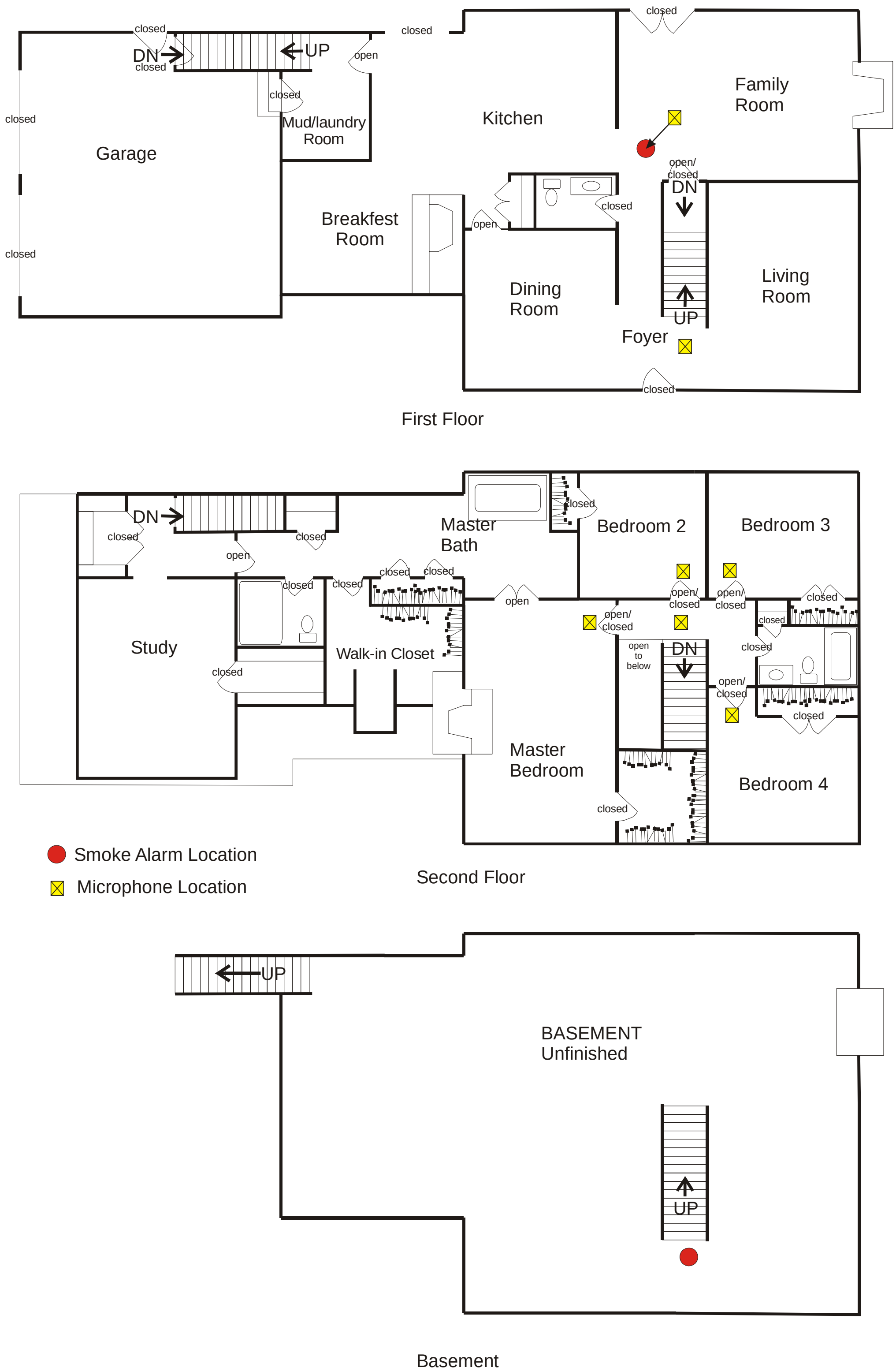

Figure 20. Test Home 3 – Floor Plan

5.4.1 Smoke Alarm in the Family Room

In this series of tests, the smoke alarm source was placed in the family room near the kitchen and hallway to the foyer. The door to the first-floor bathroom was closed for all the tests. The sound level measured in the family room beneath the smoke alarm measured 96 dBA.

Sound levels were measured at the top and bottom of the front stairs. The sound level at the bottom of the stairs measured 87 dBA. The sound level measured at the top of the stairs was 76 dBA (with the bedroom doors opened) and 89 dBA (with the doors closed). When the bedroom doors were closed, it created a confined space in the small upper hallway, which resulted in an increased sound level.

Sound levels were measured in the master bedroom and bedrooms 2, 3 and 4 with either the test bedroom doors opened or closed. The sound level measured in the master bedroom with the master bedroom door opened was 73 dBA. The other bedroom doors were closed. The sound levels measured in bedrooms 2, 3, and 4 with the test bedroom door opened were 74 dBA, 74 dBA, and 75 dBA, respectively. The doors were closed for the bedrooms without the microphone. The sound level measured in the master bedroom with all the bedroom doors closed was 63 dBA, as shown in Figure 21. The sound levels measured in bedrooms 2, 3, and 4 with the all the bedroom doors closed were 66 dBA, 67 dBA and 61 dBA, respectively. As expected, the sound levels decreased with the bedroom doors closed. Sound levels were reduced an average of approximately 10 dBA when the sound traveled through a closed doorway.

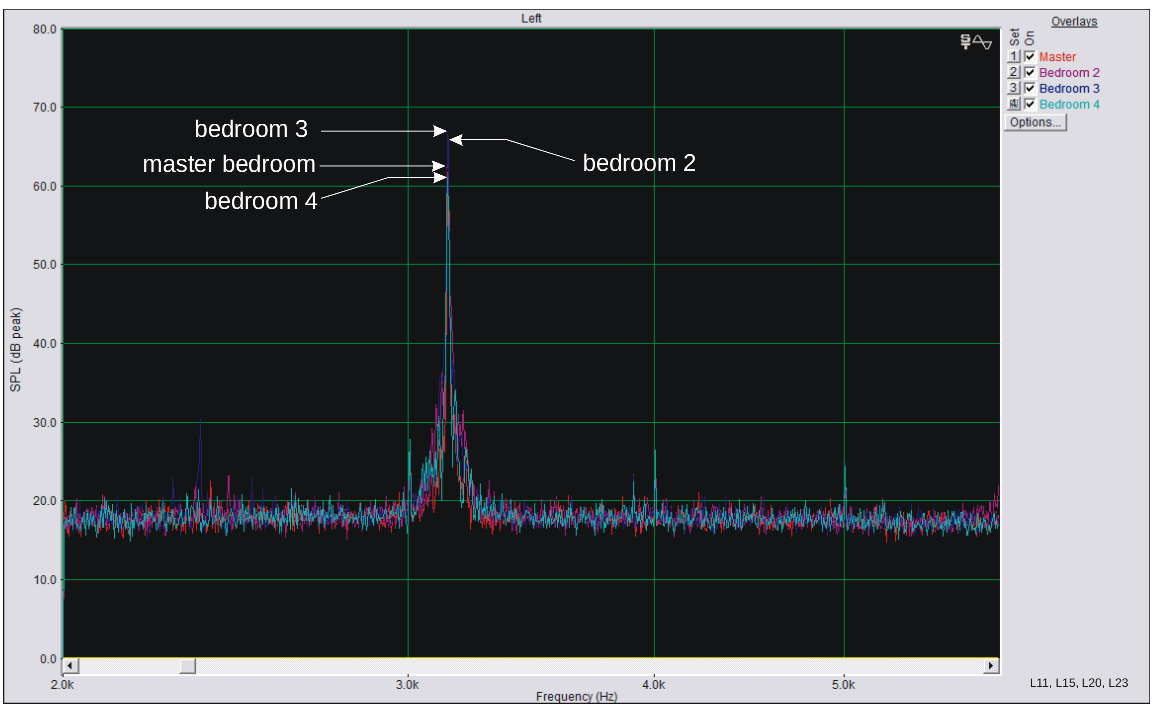

Figure 21. Test Home 3 – Sound Spectrum in the Bedrooms (Master, 2, 3, and 4) with Bedroom Doors Closed

Table 5. Test Home 3 – Sound Levels Measured, Smoke Alarm in Family Room

Microphone Location	Peak (dBA)		dBA Loss	Comments
	Bedroom Doors Open	Bedroom Doors Closed		
Under Smoke Alarm	96	No measurement	N/A	
Foyer	87	No measurement	N/A	
Top of foyer stairs	76	89	N/A	
Master Bedroom	73	63	10	Master bedroom door opened only, other 2nd level doors closed during testing
Bedroom 2	74	66	8	BD door 2 opened only, other 2nd level doors closed during testing
Bedroom 3	74	67	7	BD door 3 opened only, other 2nd level doors closed during testing
Bedroom 4	75	61	14	BD door 4 opened only, other 2nd level doors closed during testing

5.4.2 Smoke Alarm in the Basement

For this series of tests, the smoke alarm was mounted on the ceiling of the basement, approximately 5 feet from the stairs. The sound level in the master bedroom was measured with the bedroom and basement doors opened (55 dBA) and with them closed (34 dBA), as shown in Figure 22. The other bedroom doors were either closed or opened, similar to the master bedroom doors.

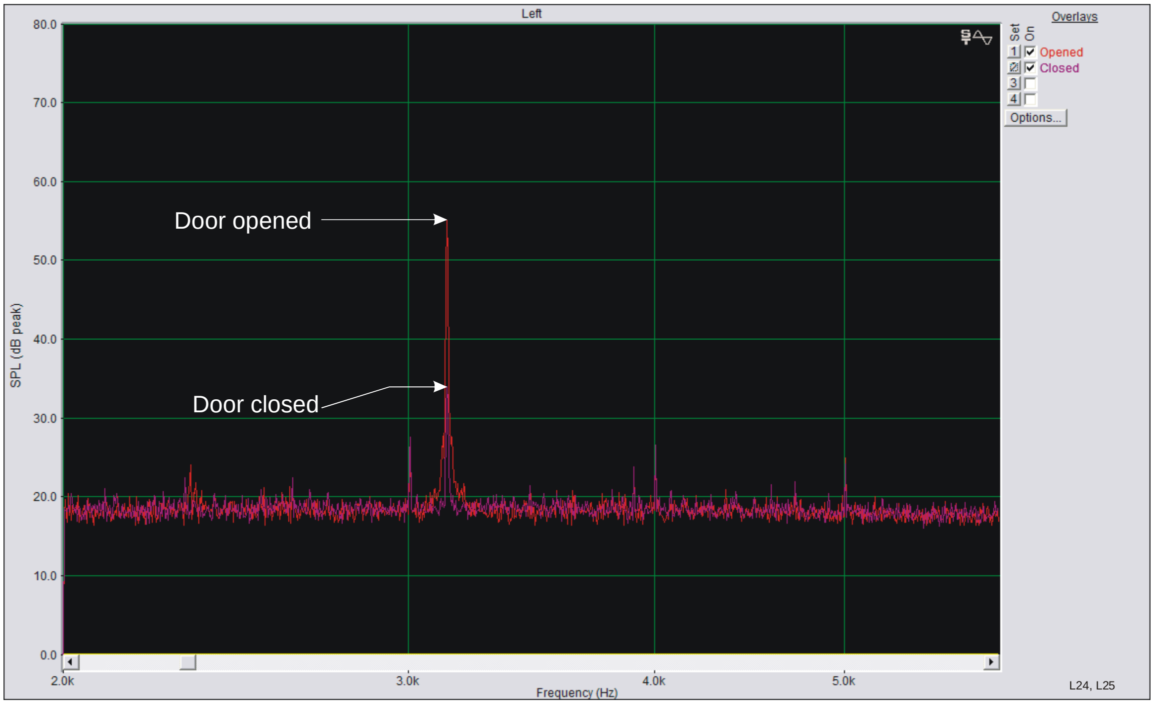

Figure 22. Smoke Alarm in Basement – Sound Spectrum in the Master Bedroom

6.0 ESTIMATING SOUND LOSS IN RESIDENTIAL HOMES

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

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

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

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

The data obtained from Test Home 1 was compared with calculations obtained using Sultan's *Guide* for estimating sound losses in a structure, as shown in Table 6. In Test Home 1, the smoke alarm was mounted in two different locations, the hallway and the basement. Sultan's *Guide* starts with a calculation at the room of origin, but since measurements were taken at the room of origin, the calculations begin in the adjacent room.

Table 6. Comparison Between Calculations Using Sultan's *Guide* and Data from Test Home 1

Sound Source - Hallway			Hallway Sound Level = 104 dBA (All bedroom doors closed)			
Room	*Area, ft² (m²)*	*Category*	*Attenuation (dBA)*	*Attenuation for door (dBA)*	*Sultan's Guide Calculation (dBA)*	*Measured (dBA)*
Master	109.8 (10.2)	Soft	-14	-10	104-14-10 = 80	77
Bedroom 2	139.9 (13.0)	Normal	-13	-10	104-13-10 = 81	71
Bedroom 3	107.6 (10.0)	Soft	-14	-10	104-14-10 = 80	88

Sound Source - Hallway			Hallway Sound Level = 104 dBA (All bedroom doors opened)			
Room	*Area, ft² (m²)*	*Category*	*Attenuation (dBA)*	*Attenuation for door (dBA)*	*Sultan's Guide Calculation (dBA)*	*Measured (dBA)*
Master	109.8 (10.2)	Soft	-14	0	104-14 = 90	85
Bedroom 2	139.9 (13.0)	Normal	-13	0	104-13 = 91	85
Bedroom 3	107.6 (10.0)	Soft	-14	0	104-14 = 90	96

Sound Source - Bedroom 3			Bedroom 3 Sound Level = 100 dBA (All bedroom doors closed)			
Room	*Area, ft² (m²)*	*Category*	*Attenuation (dBA)*	*Attenuation for door (dBA)*	*Sultan's Guide Calculation (dBA)*	*Measured (dBA)*
Hallway	45.2 (4.2)	Hard	-6	-10		
Master	109.8 (10.2)	Soft	-14	-10	100-6-10-14-10 = 60	62
Bedroom 2	139.9 (13.0)	Normal	-13	-10	100-6-10-13-10 = 61	61

Sound Source - Bedroom 3			Bedroom 3 Sound Level = 90 dBA (All bedroom doors opened)			
Room	*Area, ft² (m²)*	*Category*	*Attenuation (dBA)*	*Attenuation for door (dBA)*	*Sultan's Guide Calculation (dBA)*	*Measured (dBA)*
Hallway	45.2 (4.2)	Hard	-6	0		
Master	109.8 (10.2)	Soft	-14	0	90-6-14 = 70	78
Bedroom 2	139.9 (13.0)	Normal	-13	0	90-6-13 = 71	70

Sound Source - Basement			Basement Sound Level = 97 dBA (Basement doors to other areas of the basement were closed)			
Room	*Area, ft² (m²)*	*Category*	*Attenuation (dBA)*	*Attenuation for door (dBA)*	*Sultan's Guide Calculation (dBA)*	*Measured (dBA)*
Stairs	32.3 (3.0)	Hard	-5			
Kitchen	93.6 (8.7)	Hard	-9			
Dining	104.4 (9.7)	Hard	-10			
Living	226.0 (21.0)	Normal	-15			
Hallway	45.2 (4.2)	Hard	-6			
Master	109.8 (10.2)	Soft	-14	-10 (closed)	97-5-9-10-15-6-14-10=28	45
Master	109.8 (10.2)	Soft	-14	0 (opened)	97-5-9-10-15-6-14=38	52

In general, calculations using Sultan's *Guide* closely matched the measured sound levels when the distance between the sound source and location of sound measurement was very close. As the path between the sound source and the location of the microphone became more complex, the differences between the calculations and data increased. This is probably because the configuration of a home has an impact on sound level (either small or large). For example, if sound was traveling from one room to another, did it pass through a narrow doorway, or was the space open? If the sound traveled down a hallway, did the sound have to make turns, or was the hallway straight? The *Guide* does not take these circumstances into account. However, for simple calculations, such as from a hallway into a bedroom, the estimations are reasonably close to measured values.

In a second example, the data obtained from Test Home 2 were compared with calculations obtained using Sultan's *Guide*. Table 7 shows the comparison.

Table 7. Comparison Between Calculations Using Sultan's *Guide* and Data from Test Home 2

Sound Source – Hallway/Family Room			Family Room Sound Level = 102 dBA (Bedroom doors closed)			
Room	*Area, ft^2(m^2)*	*Category*	*Attenuation (dBA)*	*Attenuation for door (dBA)*	*Sultan's Guide Calculation (dBA)*	*Measured (dBA)*
Living room	242 (22.5)	Normal	-15			
Foyer/Hall	48 (4.5)	Hard	-6			
Loft	156 (14.5)	Normal	-13			
Master	176 (16.4)	Soft	-16	-10	102-15-6-16-10 = 61	55
Bedroom 2	130 (12.1)	Soft	-15	-10	102-15-13-15-10 = 49	52
Bedroom 3	130 (12.1)	Soft	-15	-10	102-15-13-15-10 = 49	42
Bedroom 4	110 (10.2)	Soft	-14	-10	102-15-13-14-10 = 50	49

Sound Source – Hallway/Family Room			Family Room Sound Level = 102 dBA (Bedroom doors opened)			
Room	*Area, ft^2 (m^2)*	*Category*	*Attenuation (dBA)*	*Attenuation for door (dBA)*	*Sultan's Guide Calculation (dBA)*	*Measured (dBA)*
Living room	242 (22.5)	Normal	-15			
Foyer/Hall	48 (4.5)	Hard	-6			
Loft	156 (14.5)	Normal	-13			
Master	176 (16.4)	Soft	-16	0	102-15-6-16 = 71	68
Bedroom 2	130 (12.1)	Soft	-15	0	102-15-13-15 = 59	65
Bedroom 3	130 (12.1)	Soft	-15	0	102-15-13-15 = 59	64
Bedroom 4	110 (10.2)	Soft	-14	0	102-15-13-14 = 60	60

Sound Source – Hallway Outside Master Bedroom			Hallway Outside Master Bedroom Sound Level = 92 dBA (Bedroom doors closed)			
Room	Area, ft^2 (m^2)	Category	Correction to sound power (dBA)	Correction for door position (closed) (dBA)	Sultan's Guide (dBA)	Measured (dBA)
Loft	156 (14.5)	Normal	-13			
Master	176 (16.4)	Soft	-16	-10	92-16-10 = 66	72
Bedroom 2	130 (12.1)	Soft	-15	-10	92-13-15-10 = 54	53
Bedroom 3	130 (12.1)	Soft	-15	-10		
Bedroom 4	110 (10.2)	Soft	-14	-10	92-13-14-10 = 55	54

Sound Source – Hallway Outside Master Bedroom			Hallway Outside Master Bedroom Sound Level = 96 dBA (Bedroom doors opened)			
Room	Area, ft^2 (m^2)	Category	Attenuation (dBA)	Attenuation for door position (dBA)	Sultan's Guide (dBA)	Measured (dBA)
Loft	156 (14.5)	Normal	-13			
Master	176 (16.4)	Soft	-16	0	96-16 = 80	90
Bedroom 2	130 (12.1)	Soft	-15	0	96-13-15 = 68	68
Bedroom 3	130 (12.1)	Soft	-15	0		
Bedroom 4	110 (10.2)	Soft	-14	0	96-13-14 = 69	60

In general, the calculations and the measured sound levels were similar. For this home, with the exception of the cathedral ceiling, the path between the sound source and the microphone was not very complex.

7.0 DISCUSSION

Smoke alarms are designed to detect smoke and alert occupants of a fire – whether they are awake or sleeping. Most of the data quantifying thresholds required to alert individuals are from studies in which subjects were sleeping; many of these studies were conducted because most fire deaths occur when the victims are sleeping. Even though alerting thresholds need to be applied to both awake and sleeping individuals, the alerting thresholds used in this report are those obtained from studies attempting to awaken individuals. The alerting thresholds used in this section are for comparison purposes; they do not necessarily represent an absolute number because many variables affect the dB threshold for alerting. These variables include but are not limited to whether the individual is asleep or awake, level of background noise, and the predisposition of the individual.

Some data suggest that a minimum of 70 dBA is required to awaken adults from sleep with significant background noises, although sound levels as low as 55-60 dBA can awaken some adults when the background noise levels are low (Bruck, 2001). Factors that affect auditory arousal from sleep include sound intensity and frequency, time of night, current sleep stage, level of fatigue or sleep deprivation, the use of medication, alcohol or drugs, hearing loss, and whether or not the subject is primed to hear an alarm. Closed doors and background noises, such as from a room air conditioner or fan, could also reduce audibility. A room air conditioner can have a sound level of 55 dBA; in this case, the smoke alarm sound level threshold would need to be louder to have the same effectiveness in alerting or awakening.

Since sounds in the home rarely occur in isolation, masking can occur for the audibility of smoke alarms. The threshold of audibility for the smoke alarm may be elevated by the presence of another (masking) sound. Masking sounds in homes can be air conditioners, televisions, small appliances, or outside traffic. Depending on the sound level and frequencies of the masking signal, the effectiveness in masking the smoke alarm sound will vary. Masking signals near the smoke alarm frequency typically are better at masking than frequencies lower or higher than the smoke alarm frequency.

A study conducted by Nober, Pierce, and Well examined the response time of sleeping subjects to a smoke alarm with and without air conditioner background noise. In the study, a window air conditioner noise in high fan mode was taped and amplified to 63 dBA at 12 inches from the speaker source. The speaker source was placed at a window in the room. Even though the air conditioner noise level was maintained at 63 dBA near the window, the sound levels at the pillow (ear) position were less, depending on the room acoustics, room size, bed distance, carpeting, furniture, etc. Smoke alarm sound levels at 55 dBA and 70 dBA were used.

Ten subjects were tested with the smoke alarm level at 55 dBA (near the pillow) and air conditioner noise. Two subjects nearly awakened and one subject required 433 seconds. The seven subjects that did awaken had a mean response time of 43.43 seconds, with a range from six seconds to 75 seconds. In comparison, in the unmasked condition (no air conditioner background noise), all 10 subjects awakened, with a mean response time of 13.60 seconds. The tests were also conducted with the smoke alarm level at 70 dBA (near the pillow) and air conditioner noise. The mean response time increased from 13.60 seconds to 18.80 seconds, which was not significant. The response times ranged from 6 seconds to 85 seconds.

Adults experience hearing losses at most frequencies as they age, and the magnitude of hearing loss is greatest at higher frequencies. At 65 years of age, there is typically a loss of approximately 30 dB with a sound source that has a frequency of 3000 Hz.

Using the data collected from each of the three test homes, "maps" of the sound levels throughout the homes were developed. (If measurement data was not available, calculations were made based upon Sultan's *Guide*.*) Maps were created as if the minimum requirements for installing single-station smoke alarms in locations as required by the National Fire Alarm Code (NFPA 72-2002) for existing construction. NFPA 72-2002 requires, for existing construction, smoke alarms outside each sleeping area and on each level, including the basement. For additional protection, additional single station smoke alarms are installed in the bedrooms. A threshold level of 60 to 70 dBA (minimum sound level required to wake an adult without impairment) was used to create the maps. Lower thresholds may be substituted for awake adults without impairment. Hearing or other impairment could change the threshold level needed for effective audibility.

Test Home 1 was the smallest of the three homes tested. If single-station smoke alarms were installed in locations currently required by NFPA 72, there would be one installed outside the bedrooms, one inside each bedroom, and one in the basement. (More alarms would be required in the basement if it was used as a rental space.) Figure 23 shows a map of the sound levels in Test Home 1 when the activated smoke alarm is in the hallway and the bedroom doors are closed. This and the following examples are assuming a smoke alarm sound level between 90 dBA and 100 dBA at the smoke alarm.

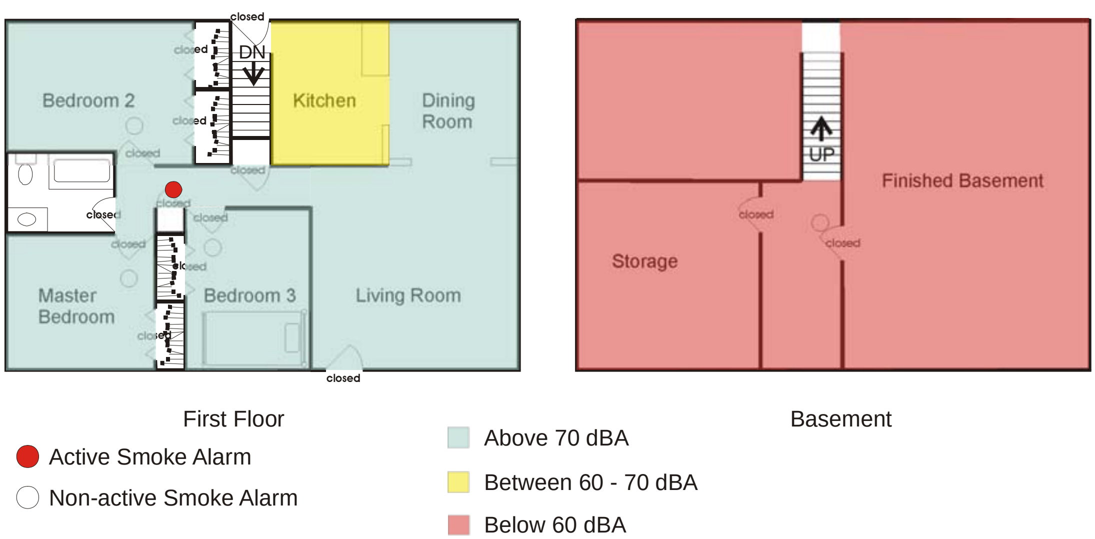

Figure 23. Test Home 1 – Sound Level with Alarm Source in Hallway

Alarm levels would probably be sufficient to wake occupants in the bedrooms. The sound level in the kitchen may also be sufficient to alert an individual; but if there was

* Calculations not shown.

background noise from running water or from an appliance, such as a dishwasher or cooking exhaust fan, the smoke alarm in the hallway may not be heard immediately. The sound level in the basement would be below 60 dBA and may not be sufficient to alert an individual or alert an individual in a timely manor.

Figure 24 shows a map of the sound levels when the activated smoke alarm is in bedroom 3 and all the bedroom doors are closed.

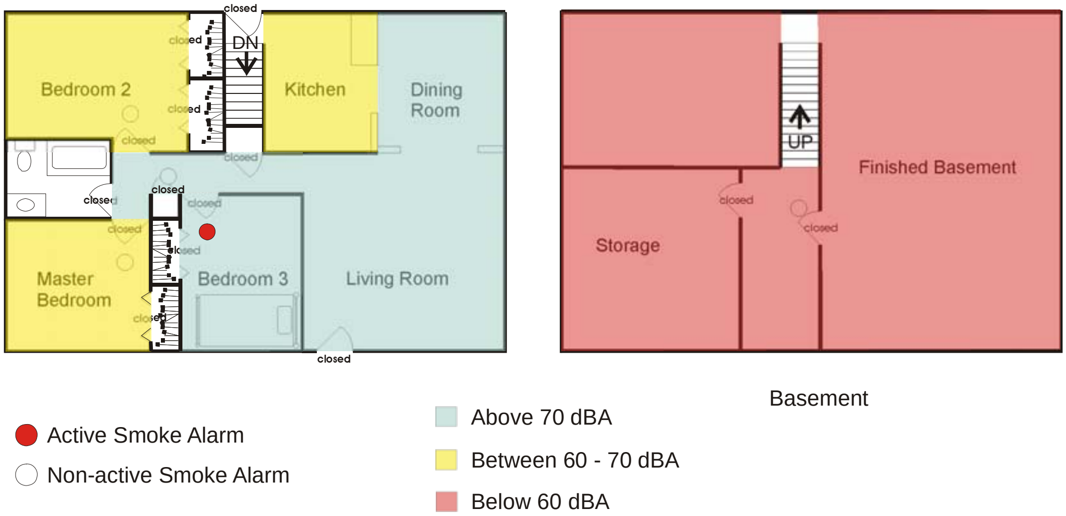

Figure 24. Test Home 1 – Sound Level with Alarm Source in Bedroom 3

The alarm level would be sufficient to wake the occupants of bedroom 3. The sound levels in the other bedrooms (master and bedroom 2), may also be sufficient to alert an individual if the background noise was low or cause a delayed response with background noise. The sound level in the kitchen most likely sufficient to alert an individual if other sound sources (e.g., appliances) were low. The sound level in the basement would be below 60 dBA and may not be sufficient to alert an individual or alert an individual in a timely manor. A smoke alarm sounding in one of the other bedrooms (with all the bedroom doors closed) would probably produce similar results, except that the sound level in the kitchen may fall below 60 dBA due to the added distance and the configuration of the rooms leading to the kitchen.

Figure 25 shows a map of the sound levels when the activated smoke alarm is in the basement, at the bottom of the stairway, and all bedroom doors are closed.

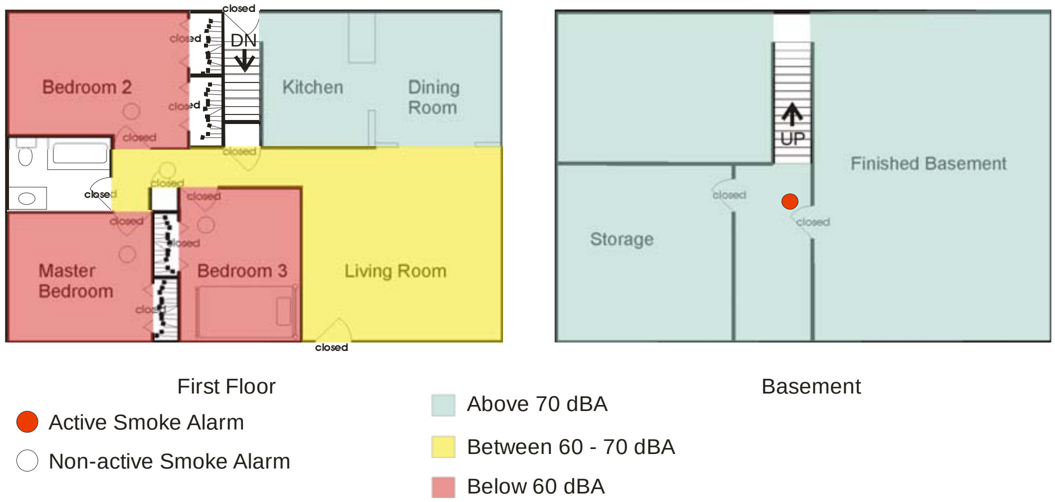

Figure 25. Test Home 1 – Sound Level with Alarm Source in Basement

Alarm levels in the bedrooms would be below 60 dBA and probably would not be sufficient to wake or alert occupants or significantly cause a delayed response for the occupants. Even if the bedroom doors were opened, the sound levels in the bedrooms would still be below 60 dBA and may still have the same result.

Test Home 2 was built in the 1970s and, of the three homes tested, was the second largest. If single-station smoke alarms were installed in locations currently required by NFPA 72, there would be one installed outside the master bedroom, outside the second level loft, and one inside each bedroom. An alarm near the family room or kitchen would not be required since the smoke alarm outside the master bedroom would satisfy the “every level” requirement.

Figure 26 shows a map of the sound levels in Test Home 2 when the activated smoke alarm is outside the master bedroom with all the bedroom doors closed. In this example, a smoke alarm sound level between 90 dBA and 100 dBA at the smoke alarm is assumed.

Figure 26. Test Home 2 – Sound Level with Alarm Source Outside Master Bedroom

The alarm should be sufficient to wake occupants in the master bedroom. The sound level in the kitchen should also be sufficient to alert an individual if other sound sources (e.g., appliances) were not present or very low. If background noises are high enough, the smoke alarm may not be heard immediately. The sound level in the upstairs bedrooms would be below 60 dBA with the bedroom doors closed. A smoke alarm sounding in the master bedroom would probably produce similar results, except that the sound level in the second level loft may drop to between 60 and 70 dBA. In addition, the sound level in distant rooms on the first floor may also drop below 60 dBA.

Figure 27 shows a map of the sound levels when the activated smoke alarm is in the second level loft, outside the bedrooms, with all the bedroom doors closed.

Figure 27. Test Home 2 – Sound Level with Alarm Source in Second Level Loft

The alarm would probably be sufficient to wake occupants in the second level bedrooms. The sound level in the master bedroom would be below 60 dBA and may not be sufficient to awaken or cause a delay for the individual to respond. The sound level on the first floor at the front of the house (living and dining rooms) would probably be sufficient to alert occupants. However, for the rooms at the rear of the house, the narrow doorways and distance away from the smoke alarm would cause a reduction in sound levels that may not be sufficient to alert occupants immediately.

A smoke alarm sounding in any of the upstairs bedrooms, with the bedroom doors closed, would probably produce similar results except the sound level in the rear rooms of the first level may drop below 60 dBA. Similarly, the distant rooms on the first floor may also drop in sound level below 60 dBA. The sound level in the master bedroom would still be below 60 dBA.

Test Home 3 was built in 1989 and was the largest home tested. As in the earlier examples, if single-station smoke alarms were installed in locations currently required by NFPA 72, smoke alarms would be installed outside the bedrooms in the upper hallway, inside each bedroom, with one on the first floor, and one in the basement.

Figure 28 shows a map of the sound levels in Test Home 3 in which the activated smoke alarm was in the family room on the first floor. In this example, a smoke alarm sound level between 90 dBA and 100 dBA at the smoke alarm is assumed, and the doors to the bedrooms and basement are closed.

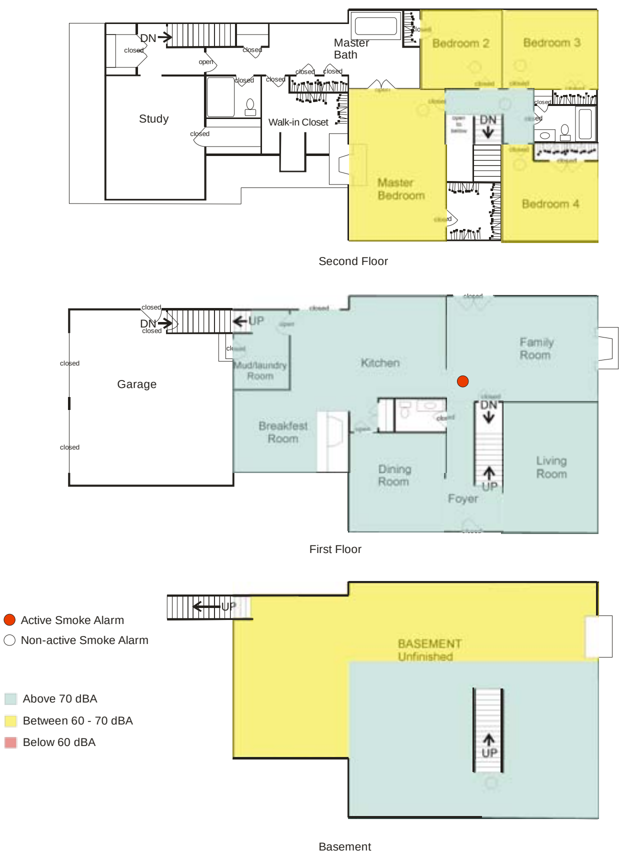

Figure 28. Test Home 3 – Sound Level with Alarm Source in Family Room

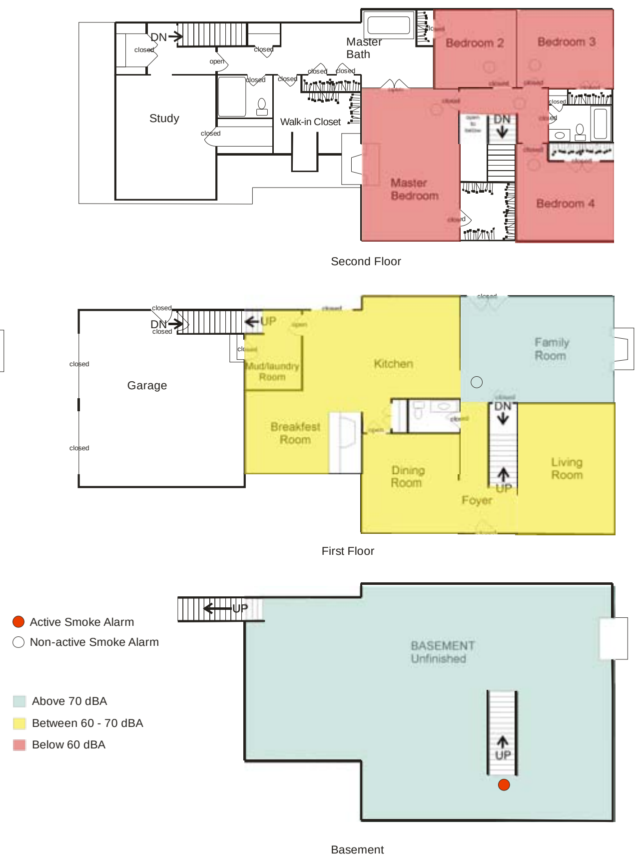

Figure 29. Test Home 3 – Sound Level with Alarm Source in Basement

In Figure 28, the sound level in the bedrooms, with the bedroom doors closed, would be between 60 and 70 dBA, which may be sufficient to wake an individual. If there was a high background noise, such as a room air conditioner or room humidifier, the sound level may not be sufficient to wake a sleeping occupant immediately. The sound levels in the remainder of the home should be sufficient to alert the occupants in different areas of the home.

A smoke alarm sounding outside the bedrooms or inside any of the bedrooms would probably produce sound levels above 70 dBA in the other bedrooms. The sound level on the first floor may be between 60 and 70 dBA and would probably be sufficient to alert an individual. The sound level in the basement would be below 60 dBA and may not alert an individual in that area or cause a delay for the individual to respond.

In Figure 29, a smoke alarm sounding in the basement, with the bedroom doors closed, would produce sound levels below 60 dBA and may not be sufficient to wake or alert occupants in any of the bedrooms. If the bedroom doors were opened, the sound level in the bedrooms would still be below 60 dBA.

In general, if an alarm source is nearby, the sound level is most likely sufficient to alert an occupant. As an alarm sound passes through a door, the sound level is attenuated between 10 dBA to 20 dBA, depending on the construction of the door and gaps around the door. An alarm sound traveling from one floor level to another is attenuated by about 20 dBA. As an example, an alarm sound with an initial level of 100 dBA (directly below the alarm) would be around 50 dBA after traveling two levels and through a door. Depending on the distance and the complexity of the sound travel path, such as around corners or through narrow doorways, sound levels may be reduced further.

8.0 CONCLUSIONS

Sound loss of a smoke alarm signal as it travels in a home was examined to determine the impact this may have on alerting occupants to a fire hazard. Sound loss measurements of smoke alarm signals in actual homes were compared to sound levels required to wake sleeping adults (without hearing or other impairment).

Some data suggest that a minimum of 70 dBA is required to wake most adults from sleep, although sound levels as low as 55-60 dBA can awaken some adults when the ambient noise levels are low. Factors that affect auditory arousal from sleep include sound intensity and frequency, bedroom acoustics and background noise, time of night, current sleep stage, level of fatigue or sleep deprivation, the use of medication, alcohol or drugs, hearing loss, and whether or not the subject is primed to hear an alarm. Closed doors could also reduce audibility.

Single station smoke alarms in homes are effective in alerting an individual only if the sound can be heard. The complexity of the sound travel path is an important factor in resultant sound levels. A home with narrow hallways, turns, and multiple levels would be expected to produce lower sound levels throughout the home compared to a home with an open floor plan and few turns.

The CPSC staff tests of sound loss measurements indicated that a single station smoke alarm installed in a small, single-level home may be sufficient to alert occupants, even if the bedroom doors are closed. The sound level effectiveness of an alarm in a single-level home with larger square footage may be reduced. For a two-level home, sound levels may not be sufficient to alert occupants in all areas of the home or cause a delay for some individuals to respond immediately. In CPSC staff tests, an alarm traveling from one level of a home to another and through a closed door produced sound levels around 50 dBA. Single station smoke alarms installed in a three level home may not be sufficient to alert occupants in all areas of the home or cause a significant delay for some individuals to respond immediately. In CPSC staff tests, an alarm traveling from the basement to the second floor and through a door produced sound levels around 30 dBA.

In 1989, the NFPA required newly constructed residential homes to have interconnected (hard wired) smoke alarms on every level of the home and outside the sleeping area. With interconnected smoke alarms, all the smoke alarms would sound if any individual smoke alarm detected smoke. If a fire occurred in a remote section of the home, the smoke alarm closest to the fire would sound and cause all the other smoke alarms to sound. NFPA did not require existing homes to be retrofitted with interconnected smoke alarms, largely because of the financial burden this would place on homeowners. Most homes in the U.S. were constructed before interconnected smoke alarms were required.

The following conclusions can be drawn from this report and are applicable to unimpaired adults. For occupants with disabilities, or for young or older populations, the conclusions may be significantly different.

- Smoke alarms are effective in alerting occupants only if the sound can be heard.
- Single station smoke alarms installed in two- or three-level homes may not be sufficient to alert occupants in all areas of the home or may cause a delay for some individuals to respond immediately.
- The complexity of the path that the sound must travel determines the amount of attenuation in the alarm signal.
- Closing a lightweight door attenuates a smoke alarm signal from one room to another room between 10 to 20 dBA.
- Each (home) level that sound travels attenuates a smoke alarm signal about 20 dBA.
- Interconnected smoke alarms improve audibility effectiveness compared to single station smoke alarms.

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