Foreword

Smoke alarm and signaling systems are a proven strategy for reduction of fire fatalities in the general population. However, studies have shown that at-risk populations such as the elderly, school age children, alcohol impaired, and those that are hard of hearing do not fully benefit from conventional smoke alarm systems, particularly during sleeping hours. Research has been conducted to develop performance requirements to optimize the waking effectiveness for alarm and signaling systems to meet the needs of these at-risk groups. This includes previous research from the Research Foundation on the waking effectiveness of alarms as well as other research.

The previous Foundation study involved several tasks including a risk assessment to estimate the potential impact 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. One of the main findings of this work is that the 520 Hz low-frequency harmonic tone, three-pulse temporal pattern was the most effective signal to awaken hard of hearing participants. Other studies have shown the same results for children and other at-risk populations.

Performance requirements for a sound pressure level of 85 dBA at 10 feet from the device for single- and multiple-station smoke alarms appear in multiple codes and standards, including UL 217, *Standard for Smoke Alarms*. The 85 dBA specification requires significantly more power, which makes the 520 Hz low-frequency harmonic tone signal a particular challenge for alarms operating on a battery/battery backup.

There was a need to review all existing data on this topic to clarify the sound pressure level(s) used in previous research and the background and technical basis for the required sound pressure levels in the codes and standards to determine the impact of a reduction in the sound pressure level when using a 520 Hz low-frequency harmonic tone signal.

Therefore, the Fire Protection Research Foundation initiated this project with the goal to assess the data on waking effectiveness to determine an acceptable reduction in the required sound pressure for sounders using a 520 Hz low-frequency harmonic tone signal that still provides superior waking effectiveness compared to high-frequency sounders.

The Fire Protection Research Foundation expresses gratitude to the report author Joshua B. Dinaburg, who is with Jensen Hughes located in Baltimore, MD, USA. The Research Foundation appreciates the guidance provided by the Project Technical Panelists, the funding provided by the project sponsors, and all others that contributed to this research effort.

The content, opinions and conclusions contained in this report are solely those of the authors and do not necessarily represent the views of the Fire Protection Research Foundation, NFPA, Technical Panel or Sponsors. The Foundation makes no guaranty or warranty as to the accuracy or completeness of any information published herein.

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About the Fire Protection Research Foundation

The Fire Protection Research Foundation plans, manages, and communicates research on a broad range of fire safety issues in collaboration with scientists and laboratories around the world. The Foundation is an affiliate of NFPA.

About the National Fire Protection Association (NFPA)

Founded in 1896, NFPA is a global, nonprofit organization devoted to eliminating death, injury, property and economic loss due to fire, electrical and related hazards. The association delivers information and knowledge through more than 300 consensus codes and standards, research, training, education, outreach and advocacy; and by partnering with others who share an interest in furthering the NFPA mission.

All NFPA codes and standards can be viewed online for free.

NFPA’s membership totals more than 65,000 individuals around the world.

Keywords: smoke alarm, waking effectiveness, at-risk population, low frequency smoke alarm, smoke alarm notification

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AUDIBLE ALARM SIGNAL WAKING EFFECTIVENESS

Low Frequency Sound Pressure Level Reduction: Literature Review

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List of Acronyms

**AAT** AUDIBLE ALARM THRESHOLD

**ANSI** AMERICAN NATIONAL STANDARDS INSTITUTE

**ASA** ACOUSTICAL SOCIETY OF AMERICA

**BAC** BLOOD ALCOHOL CONCENTRATION

**BOCA** BUILDING OFFICIALS CODE ADMINISTRATORS INTERNATIONAL (SEE UBC)

**BRANZ** BUILDING RESEARCH ASSOCIATION OF NEW ZEALAND

**BSI** BRITISH STANDARDS INSTITUTE

**BSRIA** BUILDING SERVICES RESEARCH AND INFORMATION ASSOCIATION

**CESARE** CENTER FOR ENVIRONMENTAL SAFETY AND RISK ENGINEERING

**CHABA** COMMITTEE ON HEARING, BIOACOUSTICS, AND BIOMECHANICS, OF THE ASSEMBLY OF BEHAVIORAL AND SOCIAL SCIENCES OF THE NATIONAL RESEARCH COUNCIL

**COTS** COMMERCIAL OFF THE SHELF

**CPSC** CONSUMER PRODUCT SAFETY COMMISSION

**CSE** COMBUSTION SCIENCE AND ENGINEERING

**DB** DECIBELS

**DBA** DECIBELS A-WEIGHTED

**EEG** ELECTROENCEPHALOGRAM

**FWS** FAST WAVE SLEEP (STAGE 2)

**HFA** HIGH FREQUENCY ALARM (TRADITIONAL SMOKE ALARM TONES)

**IAFSS** INTERNATIONAL ASSOCIATION OF FIRE SAFETY SCIENCE

**IBC** INTERNATIONAL BUILDING CODE

**ICBO** INTERNATIONAL CONGRESS OF BUILDING OFFICIALS

**ICC** INTERNATIONAL CODE COUNCIL

**ISO** INTERNATIONAL ORGANIZATION FOR STANDARDIZATION

**LFH** LOW FREQUENCY HARMONIC (ALARM TONE)

**NASA** NATIONAL AERONAUTICAL AND SPACE ADMINISTRATION

**NBC** NATIONAL BUILDING CODE (SEE BOCA)

**NBC-C** NATIONAL BUILDING CODE OF CANADA

**NBS** NATIONAL BUREAU OF STANDARDS (NOW NIST)

**NFPA** NATIONAL FIRE PROTECTION ASSOCIATION

**NIH** NATIONAL INSTITUTE OF HEALTH

**NIST** NATIONAL INSTITUTE OF STANDARDS AND TECHNOLOGY (FORMERLY NBS)

**NRCC** NATIONAL RESEARCH COUNCIL OF CANADA

**REM** RAPID EYE MOVEMENT (SLEEP STAGE)
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<thead>
<tr>
<th>Abbreviation</th>
<th>Full Form</th>
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<tbody>
<tr>
<td>RSO</td>
<td>ROOM OF SOUND ORIGIN</td>
</tr>
<tr>
<td>SBCCI</td>
<td>SOUTHERN BUILDING CODE CONGRESS INTERNATIONAL (SEE SBC)</td>
</tr>
<tr>
<td>SBC</td>
<td>STANDARD BUILDING CODE (SEE SBCCI)</td>
</tr>
<tr>
<td>SNR</td>
<td>SIGNAL TO NOISE RATIO</td>
</tr>
<tr>
<td>SPL</td>
<td>SOUND PRESSURE LEVEL</td>
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<td>SWS</td>
<td>SLOW WAVE SLEEP (STAGE 3-4)</td>
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<tr>
<td>UBC</td>
<td>UNIFORM BUILDING CODE (SEE ICBO)</td>
</tr>
<tr>
<td>UL</td>
<td>UNDERWRITER’S LABORATORIES</td>
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<td>USFA</td>
<td>UNITED STATES FIRE ADMINISTRATION</td>
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Executive Summary

Notification of sleeping occupants is a primary life safety function for residential smoke alarms. Sound, audibility, and human perception and cognition are all extremely complex and play a vital role in the effectiveness of this notification. Over 50 years of research and development of alarm tones have identified limitations of alarms, most notably for particular groups of the population at-risk for ineffective waking. A technology with the potential to reduce these limitations and improve waking effectiveness was identified in the last 20 years in the form of a low frequency harmonic tone. Testing primarily conducted by Dr. Dorothy Bruck at Victoria University in Australia has overwhelmingly indicated that this tone provides increased waking effectiveness over traditional high frequency alarms for at-risk populations. These groups include children, the hard of hearing and deaf, the intoxicated, and people on sleeping medication. This evidence led the NFPA to require the low frequency harmonic tone for notification devices in sleeping areas for devices connected to fire alarm control panels, to include the tone in voice notification systems, and to require the tone in installations for the hard of hearing. Current listing requirements from Underwriters’ Laboratories require the alarms to produce a tone of 85 dBA at a distance of 10 ft.

Increased electrical power is required to produce low frequency tones compared to high frequency tones. The sound pressure levels required by device listings have made development of battery-operated low frequency alarms challenging. At this time, there is not a single- or multiple-station battery operated low frequency alarm available. Despite evidence for improved performance, the NFPA does not require these alarms in single- and multiple-station devices in NFPA 72 Chapter 29. The purpose of this work was to determine if the experimental evidence is sufficient to allow a reduction in the required sound power for low frequency alarms to reduce the power consumption and aid in development of battery-operated devices without sacrificing the improved performance.

More than 50 years of experimental data on sound production, transport, interpretation, and actual waking of sleeping humans was reviewed and considered. Based on this research, the improved performance of the low frequency alarms is strongly evident for waking of at-risk populations. On average, equivalent waking to high frequency alarms is achieved for these groups at a reduced sound pressure levels of as much as 20 dBA. Proliferation of low frequency alarms, even at reduced sound level would likely have a significant impact for many groups including older adults, the hard of hearing, children, and people who have consumed drugs or alcohol. Evidence of improved performance is less overwhelming but still potentially observable when considering the entirety of the normal population (not at-risk). In experiments conducted with both high frequency and low frequency alarms, the low frequency alarms provide equivalent waking performance at an average reduced sound pressure of 6 dBA. When all waking studies conducted with any high frequency alarm are considered, this numerical effect is less evident, and the performance is closer to equivalent. There are a large number of test to test variables that can make cross-comparison very difficult (e.g., use of earpiece or speaker, testing at home or in lab, response used to indicate "waking", etc.) Overall, there is a drastic improvement of up to 20 dBA observed for at-risk groups and a 0-6 dBA impact for the normal population. Comparing a weighted average among all high and low frequency tests, the low frequency alarms provide an equivalent performance at a reduced sound of 9 dBA. Uncertainty of this value should be considered, as a single repeat experiment may vary by more than 15 dBA, but the trend in the improved response is observable.

In addition to improved waking effectiveness there are other potential benefits to the low frequency harmonic tones. Studies have shown that the sounds are transmitted through homes, walls and doors with greater efficiency. This results in an increase in resultant pillow sound pressure of 4-8 dBA for low frequency harmonic alarms installed outside the sleeping areas. Although interconnected alarms installed in each bedroom are required by code, many real installations do not comply with this level of protection. These non-compliant, worst case (other than no alarms) installations must be considered when weighing a potential reduction in SPL. A reduction in SPL of 4-8 dBA for low frequency alarms would still be expected to produce equivalent sound in closed bedrooms from high frequency devices installed in hallways.
The reasons explaining the improved waking to the low frequency alarms are not clearly defined but several potential reasons exist. In general, as we age, we tend to lose hearing in the high frequency ranges with the greatest severity. For this reason, high frequency alarms may often be completely ineffective to alert the elderly or others with hearing loss. Other limited studies have shown that when in deep sleep, the human brain may not interpret sounds in the same way as traditional hearing. The A-weighted scale for measuring sound is based on human interpretation, and the low frequency tones require greater total sound power to achieve “equal” A-weighted values. This increased total sound power may result in better waking effectiveness. This theory is based on very limited data and should be further studied for significance. The harmonic tone is also richer and can result in greater perceived loudness compared to single frequency tones.

Evidence indicates that low frequency harmonic tones can provide equivalent or improved waking performance over traditional high frequency alarms. A reduction in required sound pressure could potentially be justified in order to allow for design of battery-operated low frequency smoke alarms. There is not overwhelming evidence with low uncertainty to identify an exact threshold for reduction of sound. For alerting the previously discussed high risk groups, any reduction less than 20 dBA would likely provide improved performance over the existing high frequency devices. Among the normal population, a reduction of 4-6 dBA could likely be justified based on the improved transport of sound and/or the consideration of the limitations of A-weighing and perceived loudness. This level of improvement is supported by the waking effectiveness testing. A further reduction may be warranted if it is assumed that alarms will be interconnected and placed in all bedrooms per code. In general, the existing alarm design is effective for the normal population when in the bedroom. In fact, alarms producing a reduced 75 dBA at 10 ft were allowed by NFPA for installations in bedrooms until 1999 when the code was changed to reference the listing requirements, which did not specifically allow for such devices. A similar reduction in device sound pressure may be justified for bedroom installations.
1.0 Introduction

Early notification of a fire event is perhaps the most crucial factor in reducing the threat to life. Early notification provides occupants time to safely escape the home before life threatening conditions develop. The sensor performance of smoke alarms and detectors plays a crucial role in providing early notification but the signaling audibility and effectiveness are just as critical for affecting life-saving outcomes. The notification performance becomes especially critical when occupants are sleeping.

Requirements for smoke alarm signaling have existed since the first edition of NFPA 74, Standard for the Installation, Maintenance, and Use of a Household Fire Warning System, in 1967 [1]. This standard provides the first device-based performance requirement of 85 decibels at 10 ft (3.05 m) distance and that alarms “shall be audible in all bedrooms with intervening doors closed” in Section 2130 [2]. This requirement was changed to require 85 dBA at a distance of 10 ft in 1974 [3]. Over the subsequent decades, installation-based requirements have been clarified by requiring 75 dBA at the pillow as a definition of audibility in the bedrooms, requiring alarm locations on each floor, outside sleeping areas, and eventually in the bedrooms and with interconnections between alarms. Additional requirements were adopted requiring the use of a standardized temporal pattern for the alarm sounding and the need for low-frequency 520 Hz harmonic tones for sleeping areas and for the hard of hearing. A complete summation of the history and development of the codes and standards defining smoke alarm and notification requirements is summarized in Section 3.0 of this report.

Low power consumption and low cost with high sound output drove the commercial market toward the use of piezoelectric sounders during the early proliferation of residential smoke alarms. The piezoelectric sounders could produce the required 85 dBA sound pressure level (SPL) at 10 ft using a minimal amount of current from the batteries. Piezoelectric sounders produced tones with high frequency pitches over 2000-5000 Hz. Research conducted in the 1960s and 1970s on the various stages and depths of sleep, audible awakening thresholds (AAT) for various populations, and general notification (e.g., telephone rings, emergency sounders) attempted to quantify the minimal SPL required to awaken the general population, but also questioned and challenged the use of such a tone. Despite some concerns from various researchers, industry agreement was reached in the late 1970s that the 85 dBA piezoelectric sounders could provide 75 dBA of SPL in bedrooms when installed just outside the sleeping areas. General agreement was also reached that this 75 dBA level would be sufficient to awaken most occupants. Recommendations were made for pitch varying and whooping sounds, low frequency sounds, complex harmonic sounds, and even spoken voice messages, but little was done to modify the standard requirements based on these recommendations.

Over the subsequent three decades numerous researchers attempted to evaluate the real-world effectiveness of smoke alarm notification signals. Such studies confound numerous potential factors that impact the effectiveness of waking people. Such factors include the stage of sleep at the time of waking [4] and if it was measured, the length of sleep prior to waking, the age and gender of the subjects, the hearing capability of the subjects, the use of drugs, alcohol, or hypnotic sleeping aids, prior training or exposure to the alarm signals in the tests (naivety) of the subjects, the conduct of tests in laboratories or in homes, the criteria used to determine if the subject became “awake”, and the exposure frequencies (e.g. alarms per night, total number of nights, etc.) during the experimental period. These issues don’t even account for one of the most critical issues, the delivery, presentation, control, and definition of the test tone. Tested tones include single tones of various pitch, harmonic tones, white noise, or even voices, explosions, crackling, or footsteps. Tones have been presented at fixed SPL, or through stepped SPL increments with different length of tone presentation and intermittent quiet periods. Sounds have been presented by using real smoke alarms, recorded sounds played over speakers, or through ear-pieces. Most individual studies were able to draw comparative conclusions between their own data, but identification of definitive conclusions between studies has proven difficult.

Perhaps the most impactful research toward affecting modern requirements for smoke alarm signaling was conducted by Dr. Dorothy Bruck and colleagues at the Victoria University from 1995 through 2010. This work evaluated the performance of real smoke alarm sounds and other signals to wake various segments of the
population in controlled and repeated experiments. Multiple studies evaluated the populations at highest statistical risk for death in residential fires, including children, the elderly, and people affected by drugs, alcohol, or sleeping aids. Experiments identified serious shortcomings in the effectiveness of the existing high frequency piezoelectric sounders to affect positive waking outcomes for these segments of the population, even at higher audible thresholds than reasonably possible. Not limited to identifying a performance gap, the work of Bruck also identified a possible solution. A square-wave harmonic tone with principle frequency at 520 Hz was repeatedly more effective at waking at-risk and challenging populations as well as the general population of adults with normal hearing. In this case, effectiveness can be defined either by the number of subjects awoken at a given SPL or by waking the same number of subjects at a reduced SPL. These studies provided the basis for requirements that were adopted into NPFA 72, National Fire Alarm and Signaling Code, in 2010 for sleeping areas and the hard of hearing [5].

Despite demonstration of more effective waking performance, the implementation of 520 Hz sounders into battery operated smoke alarms for the consumer market has proven difficult. Low frequency alarms require up to 4 times the amount of power as high frequency sounders to meet the device specific requirements of Underwriter’s Laboratories (UL) Standard 217 and UL 268 (85 dBA at 10 ft). The extra current draw is a severe limitation to the design of battery operated, single- and multiple-station smoke alarms. For this reason, the 520 Hz sounder requirements have not been applied to single- and multiple-station alarms in sleeping areas in Chapter 29 of NFPA 72, but only for notification appliances in Chapter 18, Section 18.4.6, Sleeping Area Requirements. Chapter 29 does require the 520 Hz tones only for those with mild to severe hearing loss. Chapter 24 also requires the incorporation of the 520 Hz tone into voice notification and mass notification systems in sleeping areas. In the Appendix of NFPA 72, Section A.18.4.6.3 clearly indicates that the 520 Hz tone in sleeping areas is only applicable to notification appliances connected to fire alarm systems and does not address smoke alarms for dwelling units [6].

Although not currently required, it is desirable to provide sleeping areas in residential applications alarms with the more effective tones. With numerous states and local jurisdictions requiring residential smoke alarms with 10-year sealed batteries this has proven a potentially insurmountable technological hurdle to product design. For this reason, the smoke alarm community has questioned whether a reduction in SPL could be justified for low frequency sounders. Justification would require clear demonstration from test data that increased waking effectiveness is maintained compared to traditional high frequency sounders operating at the 85 dBA at 10 ft requirement.

This paper provides a detailed review of the historical research data that advised the creation of the existing device performance requirements. As previously noted, Section 4.0 of this report provides the historical timeline for development of the existing codes and standards. Section 5.0 of this report provides detailed summaries of literature reviews and experimental studies on waking effectiveness that guided the development of the codes and standards. Section 5.8 details experiments where the audibility of various alarm tones were measured or calculated. This section also includes details on the characterization of various alarm tones (frequency, sound power, etc.). This includes research used to justify the origins of the 85 dBA device and 75 dBA installation requirements as well as the research that identified the increased waking performance of the 520 Hz signal.

2.0 Scope

The primary scope of this paper is limited to summary and review of available data that may be used to justify a reduction in SPL for 520 Hz sounding appliances while maintaining increased waking performance to comparably installed high frequency sounding appliances. Analysis of the data provided in this report with respect to such a justification and to identify remaining knowledge gaps is provided in Section 7.0.

This report does not discuss in detail various other issues related to smoke alarm effectiveness in life safety. Such issues include: statistical data demonstrating how the proliferation of alarms resulted in reducing fire deaths in the general population; the detection/sensor effectiveness (location, sensor type, or fire source) of smoke alarm technologies; statistical evaluation to identify and quantify the at-risk populations and justify the
need for more effective than previous notification alarms; alternative, non-audible notification appliances such as strobes or shakers; or the likelihood of the population to maintain working smoke alarms, avoid nuisance alarms, or install them in locations as required by code. This research effort is devoted to determining whether existing data is available to justify a reduction in 520 Hz SPL while maintaining increased notification effectiveness.

It is recognized that the existing performance levels of 75 dBA at the pillow or 85 dBA at 10 ft may not be sufficient to wake at-risk and challenging populations, even when interconnected and installed in every sleeping area, outside every sleeping area, and on every floor of a dwelling. It is not the purpose of this effort to provide additional insight into more effective waking of children, the elderly, the hard of hearing, or the intoxicated. This analysis is not intended to challenge or define limitations of the existing device or installation criteria. Rather, the existing requirements are used as a baseline for comparison to determine a threshold for reduced SPL of low frequency sounders that could provide equivalent or improved waking performance. Where sufficient data are available this research effort will focus on determining SPL for low frequency sounders that may provide increased waking performance.

This literature survey is focused on data related to the evolution of codes and standards for performance and installation of notification appliances and the experimental research considered (or rejected) as the basis for those codes and standards. Justification of reduced SPL requires a thorough understanding of two specific topics; (1) what is the basis for the existing 85 dBA requirement? and (2) what factors contribute to the 520 Hz harmonic tone being more effective than high and/or single frequency alarm signals?

This review includes studies regarding waking effectiveness of audible signals and the attenuation of sound in homes. Using various installation and performance requirements as a baseline for “acceptable” performance, the research is summarized with a focus on what SPLs of low frequency sounders could be expected to be effective in various conditions. The range of potential installation conditions to be assessed include:

- Alarms installed in every bedroom and interconnected
- Alarms installed outside bedrooms with the door open
- Alarms installed outside bedrooms with the doors closed

This research summary includes a review of the existing and historical codes and standards. The timeline of requirements for alarm is presented in context with the research efforts used to justify the code requirements. The timeline is provided in Section 4.0.

This document only provides a summary of the historical research efforts. This document is intended to provide a synopsis of research data and alarm requirements to educate and refresh the smoke alarm community regarding the history of this topic. The purpose of the literature, experiments, and historical opinions cited in this report is to guide the reader to answer four critical questions:

1. What is the basis for existing audibility requirements and what justification exists for those requirements?
2. What is the baseline level of notification and waking performance provided by existing high frequency smoke alarms?
3. What quantified evidence exists to demonstrate the waking efficacy of low frequency harmonic alarms compared to the baseline?
4. Why does the low frequency harmonic alarm perform better than a high frequency alarm or other tone or signals at waking sleeping occupants?

3.0 Fundamentals

Comprehension of the data summarized in this report requires a basic knowledge about the production, transport, and interpretation of sound waves. In addition, a basic understanding of the human sleep cycles and
hearing, and the impacts of risk factors such as age or intoxication can provide needed context to the data presented and summarized.

3.1 BASICS OF SOUND AND HEARING

Humans are exposed to, sense, interpret, and respond to (or ignore) a constant hum of sounds throughout the day and night. Despite the commonality of the phenomenon, it is an extremely complex physical process. Sounds are periodic fluctuations in the atmospheric pressure moving through the air. The transport of these waves through the air in a room, colliding with walls, doors, objects, and around corners create complex patterns of absorption, reflection, modulation, and interference. When the pressure wave fluctuates with frequencies between 20-20,000 Hz, it can be sensed by the human ear and interpreted as sound. The interpretation of sound, sensitivities of the ear to various frequencies and the response of the brain add an entirely new layer of complexity to the understanding of sound.

Sound is a wave of atmospheric pressure fluctuations. The pressure of sound waves has been quantified using a relative scale based on the minimum threshold for human hearing (0.00002 Pascals). The human ear has been found to respond to changes in the intensity of sound power, and the power is proportional to the square of the sound pressure [7]. Using the minimum detectable pressure as a reference, a logarithmic scale has been developed for sound pressure level (SPL) based on the intensity of the sound power. This logarithmic scale is known as the Decibel (dB) and is calculated using Equation 1.

\[
SPL(dB) = 10 \log_{10} \left( \frac{\text{sound pressure}}{\text{reference pressure}} \right)^2 = 20 \log_{10} \left( \frac{\text{sound pressure}}{\text{reference pressure}} \right) \quad \text{Eq. (1)}
\]

When considering the intensity of sounds it is most valuable to describe the interpretation of the sound by humans, rather than the raw pressure or power of the wave. This interpretation is related to the frequencies of the sound waves. The ear is not equally sensitive to all frequencies, and weighting scales have been developed to transform raw sound pressures into sensible sound pressure. The A-weighting scale is used to describe the interpretation of sounds in the normal hearing range. The basis for this interpretation of sounds dates back to research conducted in the 1930s by Fletcher and Munson and has become standardized over the subsequent decades [8]. The A-, B-, and C- weighting scales as functions of frequency are shown in Figure 1 as defined by IEC 61672 Part 1, Sound Level Meters: Specifications.

![Figure 1 – Standard A-,B-, and C -Weighting Curves for Sound Pressure Levels in Decibels, Indicated delta between 520 Hz and 3200 Hz tones [9]](image-url)
Figure 1 also indicates the scaling factors applied by the weighting scales to sounds specifically occurring at 520 Hz and 3200 Hz frequencies. These frequencies are highlighted because they represent the required primary tone for current sleeping area notification appliances and a representative tone produced by a traditional piezoelectric smoke alarm sounder, respectively. When using an A-weighted scale to measure the resulting SPL from a smoke alarm, the measuring device (e.g. microphone) will automatically apply the scaling and a reduction of -3.0 dB to the 520 Hz signal and an increase of +1.2 dB for the 3200 Hz signal (pure tones). A-weighting of complex tones with multiple frequency components is achieved by arithmetically combining the octave or third-octave bands.

When measured in this way, the SPL of any sound can be reported as a single number in units of dBA, or A-weighted decibels. Standard methods for measuring the SPL of a smoke alarm all require use of the A-weighting scale. Therefore, most test series summarized report the measured SPL from alarms or the SPL subjected to sleeping test subject in units of dBA. This is appropriate based on the accepted standards for human hearing response, but it should be noted that a physical difference in the actual SPL of 4.2 dB is required to provide the same level of dBA for pure tone 520 Hz and 3200 Hz signals. A difference of 4.2 dB requires 1.5 times the amount of physical wave pressure, or 3 times the amount of wave power to achieve the same dBA rating for these two tones. The additional power necessary to produce an “equivalent” SPL for low frequency tones based on the A-weighted scale has implications for the current draw on batteries for sounders producing tones in this range.

One awakening study conducted in 1972 by Levere, Bartus, Morlock, and Hart concluded that waking a person from fast wave sleep is related to hearing, and therefore the A-weighting of tones is appropriate, but that waking a person from slow wave sleep is related to the physical sound pressure level [10]. This conclusion would imply that for deep sleep, when the person is most difficult to awaken, a 520 Hz tone may be as effective as a 3200 Hz tone with a 4 dBA reduction in SPL. The study by Levere et al. is discussed in more detail in Section 5.2.3. Detailed discussion of the stages of sleep is provided in Section 3.2.

The applicability of the A-weighting scale for interpretation of perceived loudness has been repeatedly questioned. A-weighting was originally based on the 40 dB threshold, or 40 phon, contour levels from the work of Fletcher and Munson [8]. Phons are a measure of the loudness of a sound based on a relative SPL in dB. For example, given a 40 dB sound at the standard frequency of 1000 Hz (the A-weighted threshold of ±0 dB), the dB, dBA, and phons would all be equal. A sound of the same loudness at 520 Hz, would have SPL of 43 dB, 40 dBA, or 40 phons.

The A-weighting scale was developed to be representative of the human perception of low level, barely audible sounds. The accuracy of the perception for sounds over 60 dB, as is the case for smoke alarms and waking, may be inaccurate. It may be argued that the B-weighting scale based on the 70 phon data and shown in Figure 1, may be more appropriate for alarm signaling. The B-weighted decibel scale actually applies a +0.2 dB benefit to the 520 Hz tone. The C-weighted scale, designed for very high-level sounds, applies a +0.5 dB benefit to the 520 Hz tone compared to 3200 Hz tones.

Many studies show at best a weak correlation between perceived loudness and the A-weighting scale. Research conducted by Zwicker has shown that complex tones and random noise are perceived as louder than single tones, despite having a lower overall SPL [11], [12]. Poulson and Mortinson determined that while A-weighting can be accurate for identifying low volume hearing levels it should not be used for “loudness” determination [13]. Hellman and Zwicker examined the processes involved in producing louder perceived tones with lower SPL using the A-weighting scale [12]. Numerous other studies have questioned A-weighting and have demonstrated variations in perceived loudness and the inadequacy of the A-weighting scale to represent it accurately (see Kuwano et al 1989 [14], Aarts 1992 [15], Quinlan 1994 [16], and Shomer et al 2001 [17]). Questioning the applicability of A-weighting for complex tones and random noise, the ISO 532 method for weighting, based on the Moore-Glasberg algorithm, was developed and some would argue is more representative of loudness for these tones [18]. An excellent analysis of this research was conducted by St.
Pierre and Maguire in 2004 [19]. Further analysis and justification for reducing the SPL of low frequency, harmonic tones may require some more in-depth analysis of the perception of loudness and the validity of the A-weighting scale as a metric.

Although the A-weighting scale is adopted as the international standard method of scaling sound for normal human hearing, all humans sense and perceive sounds differently. The Center for Disease Control and Prevention (CDC) estimates that 37.5 million Americans (~15% of population) are considered as “hard of hearing” or even deaf [20]. Even for a single individual, hearing changes drastically throughout life as we age. Presbycusis, or hearing loss with age is one of the most prevalent conditions resulting from age. Much like the A-weighting standard, this hearing loss does not occur uniformly over all frequencies. High frequency hearing loss is most prevalent with presbycusis. A comparison of hearing loss in older adults was conducted in 1998 by Cruickshanks et. al., based on the population of Beaverdam, Wisconsin [21]. This study compared the minimum threshold SPL of hearing sounds, in dBA, for various ages of the population at different frequencies. Although the region was limited, the study included 3,753 subjects evaluated with standard hearing threshold techniques. This data has been previously analyzed by Bruck [22] and her synthesis is shown in Figure 2. The difference in hearing threshold between the 500 Hz and 3000 Hz tones in that study ranged from 20 dBA for men aged 48-59 up to 33 dBA later in life.

![Figure 2 – Hearing threshold values for 3000 Hz and 500 Hz tones in males as a function of age (data from [21] and analysis from [22])](image)

The transport of sound from the source through a home to the human ear requires the complex interaction of many environmental and geometric factors. Sound is attenuated by distance and absorbed, reflected and transmitted by furnishings such as carpets, drapes, and beds, and objects like walls and doors. A well-defined set of rules for estimating the transport and attenuation of sound waves have been developed specifically for selecting optimal installation locations of smoke alarms. The development and basis of these guidelines are summarized in Section 5.8 of this report. The frequency and harmonic complexity of the sounds can increase the resulting loudness at the receiver location, for a range of source conditions (in room, closed doors, separate floors, etc.). In general, the lower frequency and more complex tones have greater transmission properties and often result in higher SPL at the receiver location for most residential conditions.

### 3.2 HUMAN SLEEP

Human sleep is also a complex subject. Numerous studies have evaluated human sleep cycles, depth, brain activity, and waking processes over the last century. The stages of sleep and other terminology were standardized and defined in 1968 by Rechtschaffen [4]. Sleep has been distinguished into Stage 1, 2, 3, 4 and rapid eye movement (REM) based on the measurement of delta wave activity in the brain using electroencephalogram (EEG). Stage 1 and 2 sleep, referred to as fast-wave sleep (FWS), would generally be considered as the lighter stages of sleep, where the subject is more easily aroused. Stage 3 and 4, slow-wave
sleep (SWS), is generally considered as deeper levels of sleep. Sleep stages throughout the night progress cyclically, with reduced amounts of slow-wave sleep occurring later in the night.

Studies have found that the AAT of test subjects, or the intensity of sound required to awake them, increases noticeably for SWS cycles (stage 3 and 4) compared to FWS and REM [4], [23], [24]. Such effects should be considered when analyzing waking test data. If the sleep stage has been measured, lower SPL would be expected during FWS and should not be directly compared to SPL when sleep stages have not been measured during the test. The same is true for comparing SWS waking SPL values.

The proportion, depth, and duration of sleep cycles are impacted by the age and condition of test subjects. Children have been found to have a higher proportion of SWS than adults, while the elderly have higher proportions of FWS. These findings have correlated to data showing that children are generally "deep" sleepers and the elderly are relatively "light" sleepers. Other factors can mitigate these expectations. Hearing loss or slow physical response to stimuli in the elderly have often resulted in more difficulty achieving waking responses in testing. In addition, while intoxication reduces the amount of SWS, the intoxicated are more difficult to awaken than their sober peers.

Further discussion of the stages of sleep and potential psychological or physiological impacts are beyond the scope of this study. The reader should simply understand that human sleeping is a process characterized by lighter and deeper stages, and that various factors such as time of night, age, or sobriety of the subject can greatly change the SPL necessary to awaken even a single individual within a single, or repeated experiment.

3.3 FACTORS THAT IMPACT HUMAN AWAKENING STUDIES

Much of the data presented in this report details experiments in waking human subjects using various audible signals. There are many interrelated factors in the test methods that confound evaluation of test to test data. In general, the factors of the test methodology that can impact the results include:

+ The Test Signal
  - Tone, Pitch, Complexity
    - Single frequency
    - Harmonic
    - White noise
    - Words or name
    - Fire cues (crackling, explosion, etc.)
  - Presentation
    - Fixed intensity
    - Step increase in intensity
    - Duration of signal, time to step intensity, inclusion of off-cycle (quiet) periods
    - Sustained or periodic signal (beeping or steady tone)
    - Speakers, ear buds, or smoke alarm source

+ The Test Subjects
  - Age / Gender
  - Hearing Status
    - Normal / Impaired / Deaf
    - Self-reported or measured by standardized test
  - The sleep cycle at time of signaling
    - Measured by EEG during test
    - The time of night / prior duration of sleep
  - Mental Status
    - Intoxication during test
- Frequent user of intoxicants or sleeping aids
- Depression
- Self-reported light / heavy sleeper
- Hyperactivity, Insomnia, narcolepsy, other sleep disorder diagnosis
- Prior instructions and knowledge (naivety)
- Signal familiarity
- Purpose of test, knowledge of waking or smoke alarm

+ The Test Environment
  - Subjects’ homes
  - Test laboratory
  - Simulated home
  - Control or measurement of ambient noise conditions

+ Criteria to Determine Waking
  - EEG stimulation
  - Perform a simple task (e.g. push a button)
  - Perform a complex task (e.g., make phone call, complete questionnaire)
  - Evacuate the home

+ Duration of Testing
  - Number of nights tested
  - Number of audible presentations per test night
  - Nights included with no signaling (expectation)

When evaluating the quantitative data from any human waking experiment, it is important to consider these factors and how they may impact the results. This is especially important when attempting comparisons of AAT responses from one experiment to another. With so many factors, no distinct conclusions can be drawn from direct quantitative comparison between waking experiments. Direct application of AAT values obtained from sleeping experiments to real world signaling is equally without established basis. These confounding factors have contributed to the difficulties providing consensus prescriptive requirements for signaling.

### 4.0 Alarm and Signaling Performance Requirements

Most recent work on waking and alarms has been conducted by Dr. Dorothy Bruck and colleagues at Victoria University in Australia. This work has evaluated the relative effectiveness of various signaling methods and intensities to awaken the most challenging segments of the population, including the intoxicated, children, the hard of hearing, and the elderly. These studies have shown overwhelmingly that the 520 Hz harmonic was more effective across these populations compared to the historically traditional 2000-5000 piezo-electric type sounders. These studies directly led to requirements for 520 Hz notification in sleeping areas with fire alarm systems and for the hard of hearing in residential applications. Requirements are present in the most recent version of NFPA 72, National Fire Alarm and Signaling Code (2019) [6] for notification appliances in sleeping areas or areas that may reasonably be used for sleeping. The International Building Code (IBC) (2018) [25], and the International Fire Code (IFC) (2018) [26] do not reference the low frequency tone, but do require design of systems in accordance with NFPA 72. The low frequency harmonic tone is also defined in UL 217, Standard for Smoke Alarms (8th edition 2015) [27], UL 268, Standard for Smoke Detectors for Fire Alarm Systems (7th edition 2016) [28], and UL 464, Standard for Audible Signaling Devices for Fire Alarm and Signaling Systems, Including Accessories (10th edition 2016) [29], but the specific appliances that require this tone are not specified.

Modern requirements for the use of a specific frequency tone for alarm signaling resulted from years of targeted research and analysis. Consensus evolution of the codes and standards based on research and information are also reflected in changes to the alarm installation locations and the signaling pattern. The SPL requirements for
smoke alarms have remained essentially unchanged for over 50 years. Due to the large number of complicating factors in the production and transport of the actual sound waves in real world applications and the understanding of interpretations of sound, no major harmonization, justification, or update of these requirements have been addressed in decades to provide optimal waking effectiveness.

4.1 SOUND PRESSURE LEVELS

An 85-dB sound pressure measured at 3 m (10 ft) from the alarm has been required since the original version of NFPA 74, Standard for the Installation, Maintenance and Use of a Household Fire Warning System, in 1967 [1]:

2130. Sounding Devices:

2131. Every heat or smoke-detecting device shall cause the operation of alarm signaling device or devices which shall be clearly audible in all bedrooms with all intervening doors closed.

2132. All alarm sounding devices shall be rated not less than 85 decibels at 10 feet.

This requirement pre-dates the 1973 commission report to President Nixon, America Burning, that led to the creation of smoke detection installation requirements in NFPA 101 and the formation of the United States Fire Administration (USFA) [30]. Prior to 1967, the only guidelines for smoke alarm installation and performance remained essentially unchanged from the original 1927 version of the Building Exits Code (precursor to NFPA 101) [2]. This code required:

Sounding Devices.

1005. Required sounding devices shall be used for fire alarm purposes only.

1006. Alarm sounding devices shall be provided of such character and so distributed as to be effectively heard in every room above all other sounds.

1007. Alarm sounding devices shall be distinctive in pitch and quality from all other sounding devices.

The 1927 code also recommended that alarm signals should be standardized geographically to avoid confusion. No standardized signaling methods or sound level requirements were developed over the subsequent 40 years. The 1967 version of NFPA 74 provided the first quantified requirement for device performance to meet the previously unspecified audibility goal. In the 1974 edition of NFPA 74, the requirement for 85 decibels at 10 ft was changed to 85 dBA at 10 ft. The 85 dBA requirement later proliferated into the device listing requirements of Underwriters’ Laboratories (UL). The first editions of UL 217, Standard for Single and Multiple Station Smoke Alarms in 1976, and UL 268, Standard for Smoke Detectors for Fire Alarm Systems in 1979, also included the 85 dBA at 10 ft device performance requirement. This SPL requirement for single station smoke alarms and alarm sounding appliances integral with detectors remains unchanged into the 8th edition of UL 217, Standard for Smoke Alarms (2015) [27] and the 7th edition of UL 268 (2016) [28]. The 85 dBA at 10 ft requirement is also present in international standards in the United Kingdom (BS 5445-1), Australia (AS 2362.22) and Canada (CAN/ULC-S529).

UL 464, Standard for Audible Signaling Devices for Fire Alarm and Signaling Systems, Including Accessories (10th edition 2016) [29] is the standard for notification appliances separate from the detectors. This standard only requires a SPL of 75 dBA measured at 10 ft (3 m) from the device in the United States. In Canada (CAN/ULC S525) the 85 dBA requirement is enforced for these appliances. In general, many of these separate notification appliances are those applicable to the low frequency requirements in Chapter 18 of NFPA 72.

In the 1970s, low power piezo-electric sounders began to replace traditional mechanical buzzers. This created the "standard" 3 kHz sound we are familiar with today. This type of sounder was not necessarily selected due to proven waking effectiveness or sound transmission but rather due to power consumption, cost, total sound output, and other design requirements. It was around this time in 1978-1979 that research on waking
Audible Alarm Signal Waking Effectiveness

Low Frequency SPL Reduction

effectiveness was first conducted by Myles and Fidell at Bolt Baranek and Newman, Inc. for Edwards [31] and by Ernzen at Notre Dame [32]. This work first identified limitations of the existing 85 dBA requirements to provide effective waking. They reviewed SPL, sounder directionality, ambient background noise levels, and sound frequency and harmonic transmission through doors, around carpets, and drapes, etc. Despite the extensive nature of this research and the implications for potential performance, little was done to change any industry standards or device performance requirements. The complex nature of the problems made it difficult for the authors to develop well defined recommendations for change.

In the 1980 edition of NFPA 74, an exception was added allowing “an additional sounding appliance intended for use in the same room as the user, such as a bedroom, may have a sound pressure level as low as 75 dBA at 10 ft (3 m)” (§4-4.2) [33]. This provision recognized that when the sounder was inside a sleeping area, the device need not produce as intense of a sound to be effective. In addition, material was included in the Appendix of NFPA 74 (1980) in Section A-2-2 that addressed potential issues and failures for effective notification. This section identified that air conditioners may produce 55 dBA ambient noise, that test data indicates an 85 dBA at 10 ft alarm installed outside a bedroom produces 15 dBA above ambient noise at 55 dBA and that this should awaken people. Clearly the design goal in 1980 was to provide 70 dBA SPL at the pillow location, as was supported by the research data from the University of Massachusetts conducted in the same year [34] (See Section 5.3.8). The appendix also addresses the potential failure of distant alarms to awaken and recommends interconnection through wiring or radio frequency. These recommendations became requirements in later versions of the codes and standards as discussed in Section 4.2.

Concurrently in 1980, the British Standard BS-5839-1, Fire detection and fire alarm systems for buildings, Part 1: Code of practice for system design, installation, commissioning and maintenance was developed. Section 16 of this standard provides recommendations and commentary on audible alarm signals. This standard identified several acceptable audible performance levels, but provided the first standardized recommendation for a minimum installation SPL of 75 dBA at the “bedhead” location for sleeping locations [35]. The 75 dBA requirement may originate from waking research conducted by the U.S. Navy Medical Neuropsychiatric Research Unit in 1971 [36] (See Section 5.2). This requirement has since proliferated into almost all installation driven codes, such as NFPA 72 and ICC codes.

The NFPA Notification Subcommittee completed NFPA 72G, Guide for the Installation, Maintenance and use of Notification Appliances for Protective Signaling Systems in 1985. This guide recommended that audible signals in public mode have SPL not less than 75 dBA at 10 ft (or greater than 130 dBA). This guide also provided a summary of the average ambient sound levels for various occupancies to aid in design of audible systems, including a 35 dBA ambient noise level for residential occupancies [37]. This same year, NFPA 74F, Standard for the Installation, Maintenance, and use of Emergency Voice/Alarm Communication Systems included design guidance for a minimum SPL of 15 dBA over average ambient levels and 5 dBA over maximum ambient levels with 60 second or more duration [38]. The 15 and 5 dBA over ambient requirements remain present in ICC and NFPA codes today.

In 1990, NFPA 72 incorporated NFPA 72F, but did not include the 15 dBA over average SPL or 5 dBA above the maximum ambient sound of 60 second duration as requirements, but only as recommendations in the Appendix (A-2-4.9) [39]. In the same year, the Building Officials Code Administrators International (BOCA) adopted the requirements for 15 dBA above ambient sound levels, with 70 dBA in Groups R and I-1, 90 dBA in mechanical rooms, and 60 dBA otherwise in the National Building Code (NBC) (§1016.7.2) [40]. At this time, although alarms were required to produce 85 dBA at 10 ft, a SPL of 70 dBA in the bedroom was considered acceptable. The basis for the 70 dBA requirement was attributed to waking research conducted at the University of Massachusetts in 1980 (See Section 5.3.8). The 70 dBA requirement was also related to the 85 dBA device requirements and estimations of a reduction in SPL of approximately 15 dBA through a closed bedroom door.

In 1991, the Southern Building Code Congress International (SBCCI) matched the BOCA requirements for 15 dBA above ambient sound level, 70 dBA in Groups R and I-1, 90 dBA in mechanical rooms, and 60 dBA.
otherwise in the Southern Building Code (SBC) [41]. The International Conference of Building Officials (ICBO) never incorporated a requirement for minimum SPL into the Uniform Building Code (UBC) in the final version in 1997 prior to unification into ICC codes in 2000 [42].

In 1993, NFPA 72 incorporated the requirements of the final version of NFPA 74 (1989) and NFPA 72G, finally consolidating the alarm and signaling requirements in the National Fire Alarm Code. NFPA 72 (1993) included the 15 dBA and 5 dBA above ambient as requirements and included the first description of measuring the SPL at the “pillow”, requiring only 70 dBA in harmony with the BOCA NBC from 1990. Despite incorporating NFPA 72G it did not incorporate the 75 dBA at 10 ft requirement for public mode signaling. It did include the requirements for 85 dBA at 10 ft from NFPA 74 and the exception for alarms installed in a bedroom to provide as low as 75 dBA at 10 ft [43]. This requirement was removed in 1999 and NFPA 72 only required alarms listed to UL 217 or UL 268, both of which required 85 dBA at 10 ft device performance without the bedroom exception.

In 2000, the International Code Council (ICC) consolidated the NBC, SBC, and UBC codes. The original version of the International Building Code (IBC) included the BOCA NBC and SBC requirements for 70 dBA in the bedroom in 2000.

In 2002, NFPA 72 changed the requirements at the pillow installation from 70 dBA to 75 dBA. The requirements for SPL remain the same today [44]. This change was submitted by Bill Hopple from Simplex to remove a conflict between NFPA 72 and the National Building Code of Canada (NBC-C). The NFPA committee agreed that technical studies would substantiate a change from 70 to 75 dBA at the pillow. The 75 dBA requirement first appeared in the NBC-C in 1995 [45]. In 2009, the IBC changed the 70 dBA requirement to 75 dBA to harmonize with NFPA 72. In 2012, IBC took this requirement out completely and now defer only to the requirements of NFPA 72. This change in 2012 to the IBC directly references the 2010 version of NFPA 72, which includes the low frequency requirements. ICC codes do not specifically reference the low frequency alarms.


Device specific requirements during this time called for 85 dBA at 10 ft, originating in 1967 in NFPA 74 and proliferating into UL (1976 and 1979) and international standards and NFPA 72. It was believed that this could provide a minimum of 70 dBA in a bedroom with the door closed when the device was installed in the sleeping areas of a home. To provide a comparable level of protection, the 75 dBA at 10 ft exception for alarms installed inside bedrooms was present in various versions of NFPA 74 and NFPA 72 from 1980 through 1996. This exception was removed in 1999 and the device listing requirements were given precedent.

**4.2 INSTALLATION AND INTERCONNECTION**

In addition to the sounding requirements, the installation requirements for smoke alarms and detectors in residential applications have changed drastically over the past 5 decades. Over the years of 1980-2010 only minor changes were made to the SPL and device requirements. Overcoming waking limitations in alarms was affected over these three decades by evolving installation requirements. By requiring alarms in every bedroom and requiring interconnection of the alarms, solutions were focused on getting alarms closer to sleeping occupants, rather than on changing tones or loudness.

Initial requirements for smoke alarm sitting were included in NFPA 74 as early as 1967 and in regional model building codes in 1979. The requirements have been incorporated in numerous codes and standards and evolved over the decades, moving from requiring alarms on every floor to requiring alarms in every bedroom, and requiring interconnection of the alarms to produce simultaneous sounding. The evolution of these requirements has been tracked and evaluated.
In the first edition of NFPA 74 in 1967 [1], guidance is provided in the Appendix for specific citing requirements. It is noted, in Section 2421, that:

2421. A smoke detector shall be located in the immediate vicinity of but outside, the bedrooms. Other smoke detection placed in strategic locations around the household and in each bedroom are recommended.

In the basic design requirements for smoke alarms, i.e. 85 dBA at 10 ft, it was recognized that this was based on the alarms being present outside of the actual bedroom. This standard also based fire protection designs and best practices on sleeping with bedroom doors closed to prevent the spread of smoke and flame. NFPA 74 specifically noted that alarms “shall be clearly audible in all bedrooms with all intervening doors closed.” This may be the first guidance or assumption that bedroom doors should remain closed. This basic installation location was intended to provide approximately 70 dBA of SPL in the bedrooms.

In 1978, NFPA 74 increased the requirements from outside every sleeping area to include one on every level [46], and in 1989 required interconnection of alarms for new construction [33]. In 1993, NFPA 74 was incorporated into NFPA 72, and a new requirement was added to include alarms in every bedroom [43]. The requirements for hard-wired interconnection and alarms in every bedroom remained applicable only for new construction.

NFPA 101 contains requirements for installation of alarms and alarm systems in various occupancies. For the direct comparisons of this analysis, the requirements for one and two-family dwelling will be primarily considered. In such occupancies, the requirements of NFPA 101 have closely mirrored or even referred the reader to NFPA 74 or NFPA 72 (after 1993).

The various regional and international building codes have also included various provisions for required siting of smoke alarms. In general, the locations have closely mirrored those of NFPA requirements, with BOCA NBC, SBC, and UBC each requiring alarms in dwellings during the 1970s and 1980s, and advancing requirements through the 1990s for every floor, and inside each sleeping area. The ICC installation requirements have closely followed those of NFPA 72 and NFPA 101 throughout the past two decades. The primary differences in any of these codes generally relate to the minimum amount of construction requiring an upgrade to the new construction (hardwired, interconnected, battery backup requirements).

4.3 PATTERN AND TONE

During the 1970s, initial device and installation SPL requirements were developed. Minor changes in code requirements resulted in little change in device performance. To overcome this, installation locations and interconnections were increased. During this same time-period, research and standardization was introduced to define the pattern and sound frequencies of the smoke alarms to provide optimum alerting performance.

As previously discussed, the 1927 version of the Building Exits Code called for fire alarm signals to be “distinctive in pitch and quality.” The need for a geographically consistent alarm signal was needed to affect the proper evacuation response in occupants. Despite the recognition of the importance, little was done to standardize these requirements for nearly 40 years. From 1973-1975, the issue of the alarm signal gained noticeable traction. In 1972, W.Y. Humphreys, a Vice President at Federal Sign and Signal Corporation, began his campaign for the “slow whoop” with a slowly increasing frequency from approximately 600 – 1100 Hz over 4 seconds. He compared this signal to horn beeps or high-low frequency shifts favorably. In general, he favored any signal with “uniqueness, practicality, exclusiveness, generation, loudness, modulation, and frequency” characteristics [47]. In 1975, this effort was again taken up by Gosswiler, also from Federal Sign and Signal, in response to an upcoming vote on standardization at the NFPA Convention of 1975. He noted the benefits of the 500-700 Hz range because it fit the human ear responses, penetrated walls and doors, created resonance from room reflections, and even noted possible electrical designs for speakers [48]. Previous research work conducted by Levere et al. in 1972 also indicated improved waking effectiveness of lower frequency tones [10].
In the same year of 1975, a report was produced by the Committee on Hearing, Bioacoustics, and Biomechanics of the Assembly of Behavioral and Social Sciences of the National Research Council (CHABA). The CHABA report recommended a standardized temporal pattern over the slow whoop signal [49]. They recommended a pattern of two shorts and one long on cycle, because it could be adapted to numerous ambient environments, be adapted to touch or visual signals, and involve less effort to adapt existing systems because temporal interrupters could be installed without replacing existing notification appliances. Two shorts and one long are also the first three characters of the Morse Code letter F, intended to represent FIRE.

The CHABA work was summarized in a speech by the Chairman of the NFPA Sectional Committee on Protective Signaling Systems, Irving Mande at the NFPA convention in 1975. Despite a mild preference for the slow whoop sound based solely on the audibility, the temporal signal was supported in various committees 44 to 1 because of the ability to adapt nearly any sounder to meet the requirement [50]. Based on the criteria of detection, recognition, meaning, teachability, capability for tactile appliances, and cost, the temporal signal was selected over the slow whoop. The purpose of this selection was to maintain the flexibility of using various sounders, and to not exclude other applications from using similar sounding appliances (e.g., claim dominion over bells or horns). Current requirements for using a specific 520 harmonic in sleeping areas and the justification for such requirements, may highlight the potential limitations of this choice in 1975.

Despite some objections, during the committee sessions in 1975, NFPA 72A, Standard for the Installation, Maintenance, and Use of Local Protective Signaling Systems for Watchman, Fire alarm, and Supervisory Service (1975) included recommendations in the Appendix for the uniform Code 3 temporal pattern alarm [51]. Later codes and standards refer to this signal as the three-pulse temporal pattern or the temporal code 3. Colloquially, it is often referred to as the Temporal 3, T3 or T-3 pattern. The uniform code 3 temporal pattern (slightly different than modern three-pulse standard) was included in NFPA 72A without recommendation for tone, pitch, or volume. It was believed it was best left to a building owner or product manufacturer to determine the most appropriate tones to avoid masking by ambient noise or for electrical or mechanical design reasons.

A slightly modified version of the original pattern, the three-pulse temporal alarm pattern as defined by ISO 8201 in 1987 [52] and reaffirmed in 1990 by ANSI S3.41 [53] has become the standard fire signal in the United States. The three-pulse temporal pattern consists of a repeated pattern of three signal phases, (a) signal on for 0.5 ± 0.05 seconds, (b) signal off for 0.5 ± 0.05 seconds, and (c) the signal off for 1.5 ±0.15 seconds. The (a) and (b) phases alternate in an a-b-a-b-a pattern followed by the 1.5 second off cycle (c). The pattern is shown in Figure 3.

![Three-pulse temporal pattern alarm](image)

**Figure 3 – Standard three-pulse temporal pattern alarm signal [52], [53]**

In 1995, the National Building Code of Canada (NBC-C) required the use of the three-pulse temporal pattern signal [45]. In 1996, NFPA 72 also required the three-pulse temporal pattern as defined by ISO 8201 and ANSI
S3.41 [54]. This pattern, with no frequency or pitch requirements, remained the standard for over 10 years and is still valid for alarms outside of sleeping areas or when used for people without mild to severe hearing loss.

Over the subsequent 15 years after adopting the three-pulse temporal pattern, research by Bruck et al conducted both independently and for the Research Foundation identified the drastic improvement in waking effectiveness of the low frequency, 520 Hz, three-pulse temporal harmonic sounders compared to the industry "standard" 3 kHz sounders. Over multiple test series, this tone was demonstrated as more effective than existing high frequency sounders. Based on these data, NFPA 72 incorporated requirements for the 520 Hz harmonic tone in 2010 in Chapter 18 (Notification Appliances), Chapter 24 (Emergency Communications Systems (ECS)), and Chapter 29 (Single- and Multiple-Station Alarms and Household Fire Alarm Systems) [55]. This standard required:

18.4.5.3* Effective January 1, 2014, where audible appliances are provided to produce signals for sleeping areas, they shall produce a low frequency alarm signal that complies with the following:

(1) The alarm signal shall be a square wave or provide equivalent awakening ability.

(2) The wave shall have a fundamental frequency of 520 Hz± 10 percent.

24.4.1.2 Voice Evacuation Messages:

24.4.1.4.1 In occupancies where sleeping accommodations are provided, the pre-alert tone shall include a low frequency component of 520 Hz square wave range to accommodate the need of the hearing impaired for fire voice messages and emergency communication messages.

29.3.8.1 Mild to Severe Hearing Loss. Notification appliances provided for those with mild to severe hearing loss shall comply with the following:

(1) An audible notification appliance producing a low frequency alarm signal shall be installed in the following situations: (a) *Where required by governing laws, codes or standards for people with hearing loss (b) Where provided voluntarily for those with hearing loss

(2) *The low frequency alarm signal output shall comply with the following: (a) The alarm signal shall be a square wave or provide equivalent awakening ability. (b) *The wave shall have a fundamental frequency of 520 Hz+/−10 percent. (c) The minimum sound level at the pillow shall be 75 dBA, or 15 dB above the average ambient sound level, or 5 dBA above the maximum sound level having a duration of at least 60 seconds, whichever is greater.

The Appendix of NFPA 72 (2010) also includes definitions for the square wave harmonics, including the odd harmonics of the primary tone (e.g., 1560 Hz, 2600 Hz, 3640 Hz, and 4680 Hz) at intensities based on the Fourier series (i.e., 1/3, 1/5, 1/7, 1/9, respectively). In 2019, the “square wave” definition was removed from NFPA 72 and replaced with a requirement for a listed low frequency waveform. The waveform has been defined by UL 217 and UL 268, but the "square wave" terminology has been removed. Analysis determined that waking tests were conducted with a harmonic tone that was not exactly a square wave by definition. For this text, the tone is referred to as the low frequency harmonic or 520 Hz harmonic tone.

Further discussion about the construction of such a sound wave is not germane to this discussion, and the reader is referred to the references. NFPA 72 still requires the use of the 520 Hz harmonic signal for sleeping areas. These requirements only specifically apply to notification appliances connected to fire alarm systems, and not for single- or multiple-station smoke alarms. The low tone is only required for alarms for those with mild to severe hearing loss as of 2018. Voice evacuation systems used in sleeping areas must also produce the 520 Hz tones. In accordance with this change to NFPA 72 in 2010, the UL 217 and UL 268 standards for alarms...
included similar language defining the low frequency tone and measurement techniques. These standards do not define where low frequency alarms are required.

5.0 Waking Studies and Literature Reviews

Previous sections of this report provide context to review the research data presented in Section 5.0 and Section 5.8. The fundamentals of sound, sleep, sleep, and waking in Section 3.0 are provided so the reader can understand the complications and specific test methods used in each relevant study. The historical development of the codes and standards related to SPL (Section 4.1), Installation (Section 4.2), and pattern and tone (4.3) are provided so the reader can recognize how the various studies were interpreted and accepted into the fire alarm community at the time. To this end, the various studies are presented here in a chronological order, rather than organized by similarity of research method, subject group, or conclusion.

The purpose and context for evaluation of the various studies is to determine baseline performance levels for the effectiveness of audible smoke alarms and the potential for the 520 Hz three-pulse temporal harmonic to provide increased waking effectiveness to 3 kHz sounders at reduced sound pressure levels. The purpose of this report is to present the breadth of available data for review without judgement. Most of the work presented is credible and was conducted for government research laboratories, universities, and/or medical hospitals. Where data has been unpublished, is uncredited, unsubstantiated, or of a vague nature, the work has been included in the discussion and these limitations are also discussed. Recommendations and gap analysis based on this research has been included in Section 7.0 of this report to determine if justification exists to reduce sound pressure levels or alarm duration for low frequency tones.

The waking effectiveness of audible notification is affected by a broad range of factors. Factors include the installation locations of the alarms with respect to the location of occupants, the home construction and décor, the temporal, spectral, and intensity characteristics of the sound generated, and the condition of the persons requiring notification. With so many complex contributing factors, it has been difficult to create well defined performance requirements from first principles. Research efforts over the past 50 years have contributed to our understanding of the exacerbating and mitigating factors toward effective notification and optimal waking effectiveness. These factors should be considered when reviewing the data in this report.

Various experimental programs measuring the response of sleeping human subjects to audible notification have been summarized in the following sections. These reports have been organized chronologically so they can be reviewed in combination with the timeline of resulting codes and standards. This method of organization is intended to provide context to understanding the state of industry knowledge and understanding at the time of critical changes in standardization, application guidance, and prescriptive requirements. Notable changes to the codes and standards have been highlighted within the chronology to emphasize the impacts of the emergent data.

5.1 PRE-1970

5.1.1 Data and Experiments

Prior to 1970, waking of sleeping persons was not researched with the aim of improving or understanding alarm signaling. Rather, these studies focused primarily on psychological issues related to the depth and stage of sleep, prevalence of sleep disorders, and the physical levels of sound required to cause arousal [23], [56], [24] [57]. Most early work was conducted using a standardized 1000 Hz pure tone wave signal, selected because of its normal A-weighting (±0 dB), consistency, and repetition. Note that in subsequent experiments conducted with 1000 Hz pure tones, the units of dB and dBA can be used interchangeably. Research identified many of the bases for understanding waking performance, including the changes in AAT attributed to various sleep stages. Studies found wide disparity in the AAT needed to wake individuals between experiments due to numerous confounding factors (see Section 3.3).
This sleeping research had no focus on the actual tones used for alarms, no considerations for the conditions of alarm signal presentation, and no focus on the type or pattern of alarm, nor on the conditions of sleeping people or response to fire cues. For this reason, these studies are not discussed in further detail in this report. It is likely that much of this early work was used to inform the selection of 85 dB at 10 ft in the 1967 edition of NFPA 74. Direct influence or justification is unclear.

5.1.2 Code Status Update – 1967
The first edition of NFPA 74 was approved in 1967. The standard included the first requirement for 85 decibels at 10 ft distance from the alarms. This requirement is indicated in the timeline shown in Figure 4.

![Timeline Diagram](image)

**Figure 4 – Code Status Update – 1967 - NFPA 74 requires 85 dB at 10 ft with audible alarm in bedrooms with doors closed**

5.2 1970 - 1975

5.2.1 Zimmerman 1970 [57]
A series of waking experiments were conducted by William Zimmerman as part of a doctoral dissertation at the University of Chicago Department of Psychology. The AAT for 16 light and 16 deep sleepers were measured. This work was funded by a Public Health Service Grant from the National Institute of Mental Health and was overseen by Allen Rechtshaffen, one of the pioneers of the method of EEG sleep stage definition and testing.

Awakening tests were conducted over a single night with seven awakenings patterned throughout the night by sleep stage. Zimmerman used 800 Hz pure tones of 1 second duration with 5 dB increases with 8 seconds between presentations. Test data is reported in decibels, in weighted dBA values for 800 Hz should be reduced by approximately 1 dB. Subjects were judged as awakened when they spoke the phrase, “I am awake.” Zimmerman reported an AAT of 65 dB among all test subjects, but the “light” and “deep” sleep groups indicated drastically different responses. Median AAT for the light sleepers was 56.6 dB compared to 72.3 dB for the deep sleepers. The AAT values for the two groups measured as a function of sleep stage and awakening event are shown in Figure 5. In addition to the differences between light and deep sleepers, this work also showed for both groups that the AAT values from Stage 2 sleep decreased throughout the night with successive waking events. These data points and the steady decrease through successive Stage 2 awakenings is shown in Figure 6. The stages of sleep are shown as by shading the various vertical bars and represent a relative comparison of sleep stage depth throughout the 7 awakenings.
5.2.2 Keefe, Johnson, and Hunter 1971 [36]

In 1971 an experiment was conducted by F. Barry Keefe, Laverne Johnson, and Edna Hunter at the Navy Medical Neuropsychiatric Research Unit in San Diego. In this experiment, 35 adult males were subjected to 1000 Hz tones while awake and while asleep in various stages. For these tests conducted with 1000 Hz tones, units of dB and dBA are interchangeable. During the tests, the tone was presented as a 5 second tone with a 55 second off-cycle, with the tone increasing by 5 dBA increments in each cycle from dual speakers placed over the bed. Sleep cycles were measured by EEG. Various other potential response metrics were measured, including movement, heart rate, skin potential, skin resistance, and respiration rates. Waking responses were measured by pressing a button or by restoration of waking EEG. The AAT values reported indicate a response by 50% of the subjects. The AAT of response while awake and asleep from various groups are shown in Figure 7.
Figure 7 – Differences in AAT from subjects when awake and asleep during various stages of sleep [36]

For night-time sleepers, the difference between the waking and sleeping response thresholds are 35, 38, and 26 dB for REM, short wave, and fast wave (stage 2) sleep, respectively. For day sleepers, a delta of 36 dB was measured for fast wave (stage 2) sleep. It is possible that this estimation of an increase of 25-40 dB in SPL is needed to initiate response when sleeping compared to waking hearing thresholds.

Other observations included:

+ During slow wave sleep EEG responses were common but motor responses were less so
+ They found no difference in AAT by sleep stage
  - some difference in AAT between day and night sleepers
  - slow wave sleepers were more confused and uncoordinated
+ Day sleepers had higher AAT threshold than night and may be sleep deprived

Later review and recommendations by Berry in 1978 [58] specifically cite the work of Keefe et.al. and stress the fact that only 50% of participants awoke at an average of 75 dB. Berry did not think a 50% waking response was sufficient for emergency signaling. Further discussion of the criticisms and recommendations of Berry is provided in Section 5.3.5.

5.2.3 Levere, Bartus, Morlock, and Hart 1972 [10]

A waking experiment was conducted by T.E. Levere, Bartus, Morlock, and Hart at North Carolina State University in 1972. In this study, 8 college aged males with no disabilities slept for four nights in a mock bedroom inside the laboratory. The test room was furnished with carpets and drywall and found to have approximately 45 dBA ambient noise conditions. Subjects were monitored for sleep stage using EEG. Signals were presented as pure tones at 1/3 octave bands from 1000 Hz using an acoustic speaker 10 ft from the head at 80 dBA. Based on the A-weighting curves, the actual SPL in dB were 93 dB for 125 Hz, 87 dB for 250 Hz, and 80 dB for 1000 Hz. All these signals represent equivalent “loudness” of 80 dBA using the A-weighting scale.

During these experiments, subjects were provided 20 presentations of one band evenly spaced over 6 hours with a 15 second duration. This included 10 presentations during fast wave sleep, 10 during slow wave sleep, and none during REM. The relative “wakeness” of the test subjects, as a function of the EEG measured cortical desynchronization, is shown in Figure 8. In this figure, the heavy black line on top indicates the fully awakened EEG measures. The 1-minute epochs indicate the EEG measures immediately prior to and immediately following the 15 second sound presentation.
As indicated, the brief 15 second sound response did not bring the subjects to full wakefulness, and the EEG responses gradually receded back towards sleep. The comparison between the response to various tones is of note. During FWS, there is approximately no difference in response between the 125, 250, and 1000 Hz tones. This indicates that during FWS, response is related to subjective loudness (A-weighting).

During SWS the relative response is increased for the low frequency tones. The researchers concluded that during SWS, response is related to the physical intensity of signal, and not A-weighted SPL. In the unweighted dB scale, the 125 Hz (93 dB) and 250 Hz (87 dB) have more intense sound waves than the 80 dB (=80dBA) for the 1000 Hz tone. The magnitude of EEG response is related to the dB, not the equal dBA of the three signals. The authors concluded that the laws that govern auditory response (A-weighting) during wakefulness do not apply during SWS but may apply during FWS. Such a finding could be a significant issue related to the improved performance of low frequency alarms. This may be especially true for various at-risk groups or groups with greater proportions of SWS, such as children and adolescents.

This study was conducted with a limited number of subjects (8) and without fully waking subjects. The results are compelling and could provide reasons why the lower frequency tones have provided noticeably improved responses in later testing. Further experiments evaluating this exact phenomenon have not been identified.

5.2.4 Code Status Update -1974

The third edition of NFPA 74 was approved in 1974. In this edition, the requirements for household alarms to produce 85 dB at 10 ft were changed to 85 dBA. The specification of the alarm SPL in dBA resides in all codes and standards to the ay. This change is summarized in Figure 9.
In 1975, a literature review on arousal from sleep in emergencies was conducted by Edward Bixler of Pennsylvania State University for the Fire Detection for Life Safety Symposium for the Committee on Fire Research Commission on Sociotechnical Systems for the National Research Council. In this report he summarized observations from various other studies on arousal from sleep. This research summarizes the various stages of sleep as a function of EEG responses, the rates of the various stages of sleep throughout the night, and the relative proportion of the stages of sleep as a function of age.

This work may have been one of the first to enlighten the fire protection community about concepts such as children having more SWS, and thus being more difficult to awaken, that the prevalence of SWS is greatest early in the night, that waking from REM sleep is not the most difficult in humans, and that waking intoxicated or sleep deprived occupants requires greater signal intensity.

In 1975 significant discussion occurred at the NFPA Annual Meeting regarding the standardization of a smoke alarm signal. The benefits of standardization were universally recognized, but competing recommendations were presented in the form of a “slow whoop” signal with time varying tone frequency and a temporal pattern with no defined frequency requirements (See Section 4.3, [47], [48], [50]). In the end, the committee selected a temporal pattern similar to the standard now referred to as three-pulse temporal pattern and codified in ISO 8201 [52] and ANSI S3.41 [53]. This pattern description was included in the Appendix of NFPA 72A in 1975 as shown in the timeline in Figure 10.
5.3 1975 - 1980

5.3.1 Weir 1976 and 1979 [60], [61]

In 1976 an analysis was conducted by Catherine Weir from the Department of Psychology at the University College of London [60] of previous auditory response data collected by Hutt, Hutt, Lenard, Bernuth and Mentiwewrff in 1968 from the University Hospital at Oxford [62]. These tests evaluated the waking response of infants to various sine and square wave tones at 70, 125, 250, 500, 1000, and 2000 Hz, and recordings of male and female voices saying the word “baby”. In the analysis by Weir, she concludes that critical frequencies for waking response were closest to those of the human voice. This analysis recommended tones in the range of 125-250 Hz as the most effective for waking responses in the infants. Weir identified a significant cubic response in the sensitivity over the 70 – 2000 Hz range from the 1968 data from Hutt et. al. The conclusions of this analysis are questionable given that in subsequent work conducted by Weir in 1979, she identified a flat sensitivity response in infants to sinusoidal waves with fundamental frequencies from 125 – 4000 Hz. The SPL for 50% responses in these experiments are shown in Figure 11. It should be noted that the original review of the data by Weir indicated a flat response when scaled in dB, the pure sound wave power. When the data is transformed to dBA, a reduction is applied of 16.1 dBA at 125 Hz, 8.7 dBA at 250 Hz, and 3.2 dBA at 500 Hz, with an increase of 1.2 dBA at 2000 Hz and 1.0 dBA at 4000 Hz. When compared in dBA, it is apparent that the infants’ responses occurred at much lower SPL for the lower frequencies, ranging from 62-70 dBA below 500 Hz and 71-81 dBA above 2000 Hz. This analysis may provide more validity to the conclusion that the dB scale provides a better indication of SWS waking response than the dBA scale.

Figure 11 – Intensity in decibels SPL above ambient noise for infant subjects to response 50% of the time [61]

5.3.2 Code Status Update – 1976

In 1976 the first edition of UL 217, Standard for Smoke Alarms was adopted. This standard included the 85 dBA measured at 10 ft requirement first originating in NFPA 74 in 1974 (85 dB in 1967).
5.3.3 Code Status Update – May, 1978

In May of 1978 language was added to clarify requirements for audibility into Appendix A of NFPA 74 [46] Section A-2.2.4.1. This section indicates that alarms producing 85 dBA at 10 ft installed in the hallway outside closed bedrooms should produce sounds 15 dBA above ambient noise up to 55 dBA. It also claims that this (~70 dBA assumed) “should be sufficient to awaken the average sleeping person.” It is not clear or stated what basis was used to draw this conclusion in 1978. No reference was indicated in the standard.

5.3.4 Petzoldt and Van Cott 1978 [63]

In June of 1978, a literature review was conducted by Petzoldt and Van Cott at the National Bureau of Standards (NBS) (later National Institute of Standards and Technology (NIST)) on arousal from sleep by emergency alarms (NBS Report 78-1484). The purpose of this work was to examine the existing scientific literature, much of which had been conducted by psychologists and physicians and assess the results for emergency fire signaling. Much of this review detailed the various stages of sleep and increased AAT during SWS, the effects of alcohol and drugs, the importance of recognized signals with significance, and reiterated the conclusions from previous research.

This literature review work was the first of many research projects conducted by or funded by NBS to review the effectiveness of alarms over the next several years. This report leveraged several professional relationships, as it included data and conclusions from several unpublished studies and personal communications.
This report references an unpublished literature review conducted by Michael Bonnet from the University of Florida in 1975 [64]. In this review, Bonnet emphasizes the issues inherent with reviewing AAT data from sleep studies (see Section 3.3). Bonnet is quoted that “behavioral responsivity as a function of signal intensity is an intuitively obvious way to approach sleep and one that seems fairly simple. Unfortunately, it is not simple.” The confounding test factors complicate analysis and the qualitative value of such studies.

Petzoldt and Van Cott also review an unpublished analysis of over 90 studies focused on aircraft noise in residential environments by J.S. Lukas from the National Aeronautics and Space Administration (NASA) [65]. The review by Lukas indicated an expectation that 80% of people would awaken to 80 dBA sounds from aircraft. This was a much greater SPL than indicated by a study reviewed by Lukas and conducted by Steinicke in 1957 for the German Ministry of Economic Affairs and Transport. Lukas notes that Steinicke’s work used increasing SPL without an intermittent off cycle time. This greatly increased the duration of the test tones, greatly reducing the SPL needed to affect awakening. This is a key factor to consider when evaluating AAT data. The Lukas and Steinicke data are compared in Figure 14. It should be noted that the raw data, including subjects, number of tests, evaluated tone, and determination for waking are not indicated for this data. These results are rather a composite assembled by the author.

Figure 14 – Frequency of arousal or behavioral awakening as a function of noise level (Steinicke data does not include intermittent quiet periods between SPL increases) [65] [63]

Comparing the AAT for the 50% awakening threshold, the Lukas data indicates an average AAT of 75 dBA, while the Steinicke data indicates an AAT of 32 dBA. The 75 dBA determined by the analysis of Lukas is consistent with numerous other studies and later code requirements for 75 dBA at the pillow level for awakening. Both sets of curves are quite steep in response, indicating how strongly SPL increases on the decibel scale. For example, increasing the SPL from 70 dBA to 80 dBA increases the awakening from 40% to 80% based on Lukas’ analysis.

5.3.5 Berry 1978 [58]

In July of 1978 Charles H. Berry wrote a review article in the *Fire Journal* questioning the effectiveness of residential smoke alarms. Berry was a US Navy Lieutenant Commander for the Navy Strategic Systems Project. The article by Berry reviews previous test data and the existing codes and raises concerns about the ability of alarms to wake people effectively. This article is often cited and has been occasionally mis-referenced to include experimental test data. This is not the case, as Berry only references previous test data to make his case.

In the article, Berry notes that although audibility is required by NFPA 74 in all bedrooms over ambient noise with all doors closed, the explanation of audibility provided in the Appendix is potentially insufficient for fire safety. In Appendix A of NFPA 74 (1978) a section was added to clarify Section 2-2.4.1. This addition was
approved by the NFPA committee in May of the same year and released in June, only one month before the article was released by Berry. This section references “test data” that indicates that 85 dBA at 10 ft alarms installed in hallways outside closed bedrooms can produce sound 15 dBA above ambient noise of 55 dBA [46]. This statement implies a reduction in SPL from through the closed door of 15 dBA and that SPL of 70 dBA is sufficient to awaken occupants. The “test data” is not noted with any specific reference or source. Berry also references unpublished data from Bradley and Wheeler at the University of Maryland indicating a reduction in SPL of 16.4 dBA through closed doors [66].

Berry references the study of Keefe et. al. that indicated that 75 dBA was sufficient only to awaken 50% of test subjects using a 1000 Hz tone [36]. Berry concludes that 70 dBA in the bedroom, as is intended by the hallway installation of 85 dBA at 10 ft alarms by NFPA 74, is likely insufficient to awaken most people.

5.3.6 Bonnet, Johnson, and Webb 1978 [67]

Independent AAT experiments were conducted by Michael Bonnet and Laverne Johnson of the Naval Health Research Center in San Diego, CA and Wilse Webb at the University of Florida, Gainesville in September of 1978. Both studies measured the AAT of 1000 Hz tones in ascending SPL, but with some notably different methodologies. The drastically different results are indicative of the influences of the confounding test variables in waking experiments.

In the San Diego experiments, 26 men (17-37 years old) slept in the laboratory for 5 baseline and two test nights. Of the test subjects, 12 were good sleepers, confirmed by sleep latency and quality, 14 were self-reported poor sleepers, with several observed sleep issues during screening. The subjects were awakened on the 1st, 3rd, and 5th baseline nights with a speaker clamped to a headboard. Sounds were presented for 2 seconds in 30 second intervals with 5 dB increases. All subjects had passed tests for normal hearing, and the tone was always started at the subjects waking hearing threshold, measured for all subjects between 35-40 dB. Subjects were required to press a button 3 times and say “I’m awake” to indicate waking. EEG measurements were recorded and subjects were awakened 5 times, two in Stage 2, one stage 4, one REM, and one at the morning waking time.

In the Florida experiments, nine men (21-23 years old) were subjected to 1000 Hz tones every test night (1-4 nights) using an earphone insert. The sound was presented in 3 second on, 3 second off patterns increasing from the normal hearing threshold in 2-5 dB increments. The subjects were wakened 5 times during the night, all during stage 2 sleep as measured by EEG. A response button was taped into their hand and they were told to push the button when they heard the tones.

The measured AAT values during the Stage 2 sleep cycles from both experiments are compared in Figure 15. The figure also shows the Stage 4 and REM measurements from the San Diego study. It is immediately apparent that the Florida study resulted in drastically reduced SPL at awakening than San Diego, with average SPL of 49±18 dB and 69±17 dB, respectively. Even among the same test sites and sample groups the wide variance in AAT for each set is noticeable, with standard deviations ranging from 15-25 dB.
The authors attributed the differences between experiments to the methodology, specifically citing the use of the ear piece as known to cause a reduction in hearing threshold of 10-12 dB and the impacts of scheduling the arousal on each test night and pre-experimental practice on thresholds during the Florida tests. It may also be possible, though not noted by the authors, that the brief 2 second on/30 second off period in the San Diego study compared to the 3 second on/off period in the Florida study can drastically increase the AAT measurements. It is worth noting that the more effective 3 second on/off cycle is more representative of smoke alarm signals (without the SPL increase) and may indicate an improved performance compared to AAT measured with brief tones.

5.3.7 Myles [68] and Fidell 1979 [31]

In June of 1979, two papers were presented by Mark Myles and Sandford Fidell from Bolt, Beranek, and Newman, Inc. (later BBN Technologies, later part of Raytheon) at the NFPA annual meeting detailing previous research conducted together. In these reports, Myles and Fidell are critical of the requirements for smoke alarm sounding, claiming that 85 dBA measured at 10 ft per the UL 217 method would be insufficient for awakening most of the population.

Their criticisms are based on several factors. First, the installation of alarms in hallways outside closed bedrooms creates a severe attenuation condition, and they do not believe 70 dBA is sufficient for awakening a majority of people. Second, they discuss the fact that there are no frequency or spectral requirements for the sounds. This means that in many realistic applications, in homes with various furnishings, geometries or ambient sounds, certain tones will be attenuated, and fully compliant installations would be insufficient. They further criticize the requirement for the temporal alarm pattern, which they believe provides no benefit in awakening or alerting effectiveness. Thirdly, they criticize the application of waking test data based on 50% awakening thresholds as insufficient. The requirements for a true emergency alert must be effective on 100% of the population. They recognize that this statement leads one to no practical answer and continue by referencing several confounding factors involved in assessing AAT data.

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*Figure 15 – AAT values measured from San Diego and Florida experiments by Bonnet et al. [67]*

The graph shows the AAT values measured from San Diego and Florida experiments by Bonnet et al. [67]. The authors attributed the differences between experiments to the methodology, specifically citing the use of the ear piece as known to cause a reduction in hearing threshold of 10-12 dB and the impacts of scheduling the arousal on each test night and pre-experimental practice on thresholds during the Florida tests. It may also be possible, though not noted by the authors, that the brief 2 second on/30 second off period in the San Diego study compared to the 3 second on/off period in the Florida study can drastically increase the AAT measurements. It is worth noting that the more effective 3 second on/off cycle is more representative of smoke alarm signals (without the SPL increase) and may indicate an improved performance compared to AAT measured with brief tones.

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The report by Myles includes physical test data of the spectral and SPL characteristics of a real electromechanical DC buzzer sounder in a real home. In these tests, the device produced 88 dBA at a distance of 10 ft. Installed in the hallway with the bedroom door closed, only 72 dBA was measured in the center of the room with SPL as low as 69 dBA near the walls. Based on plots of worst-case background noise, Myles predicted that this alarm may not even exceed ambient sounds. Analysis of another alarm with a pure tone signal indicated significant standing waves with null points throughout the room. The authors expressed concern over the number of realistic household variables that would result in failures of smoke alarms to properly notify sleeping occupants.

5.3.8 Code Status Update – 1979

In 1979 the first edition of *UL 268, Standard for Smoke Detectors for Fire Alarm Systems* was published. This standard also included the 85 dBA at 10 ft requirement from UL 217 and NFPA 74.

![Figure 16 – Code Status Update – 1979 – UL 268 1st edition](image)

5.3.9 Nober, Pierce, Well, Johnson, and Clifton 1980 [34], [69]

The first experimental waking test series to specifically evaluate fire alarm performance was published by Nober, Pierce, Well, Johnson, and Clifton at the University of Massachusetts, Amherst with a grant from NBS in 1980. A full report (NBS GCR 80-284 [34]) and an article in the *Fire Journal* in 1981 were produced [69]). This is one of the most highly referenced studies in the subsequent literature and was used as a basis for developing numerous future fire alarm codes and standards.

These experiments initially characterized the frequency and intensity of fire alarm signals at a distance of 10 ft. A mean output of 85 dBA (80-92 dBA) was found with peak energy at 4000 Hz and 2000-3000 Hz. This is consistent with the SPL requirements of NFPA 74 and UL 217/268 at the time. Additional detail on the spectral characteristics of the alarms is discussed in Section 6.4.

A second set of experiments then applied an alarm signal in waking performance tests. Thirty college aged subjects were subjected to a tape recording of an electromechanical horn alarm signal at various intensities. The alarm was presented at 85 dBA (10 ft distance), 70 dBA (estimated as in the hallway with the door open), and 55 dBA (estimated as in the hallway with the door closed). Each of the three signals were presented to ten of the test subjects. The subjects were preconditioned to the sounds prior to sleep testing. Waking responses were measured by requiring the participants to get up and place a phone call and fill out a questionnaire.

The levels of attenuation used in this study are rather conservative. They reference a 15 dB reduction in SPL when the door is closed as inferred by Berry from a review of NFPA 74 (1974 edition) [58] and a 16.4 dB attenuation measured by Bradley and Wheeler in unpublished results from the University of Maryland [66].
Despite these numbers, the authors use reductions in SPL of 15 dBA and 30 dBA for open and closed doors, respectively.

The researchers evaluated the responses of subjects at various hours into sleep, various nights of the week, both women and men, and with and without a 63 dBA air-conditioner operating. It was determined that effective waking of college aged students with the high frequency alarm was achieved even for 55 dBA signals, all ten subjects were awakened at this threshold. Even with the 63 dBA air-conditioner, all ten subjects were awakened, although additional notification time was required. They found a significant difference in response times for the 55 dBA and the louder presentations, but almost no difference between the 70 dBA and 85 dBA presentations. The authors recommended future studies evaluating real alarms in homes and exploring alternative alarm signals. Nober et. al. concluded that college-aged subjects could be awakened by smoke detector alarm levels as low as 55 dBA even with extraneous background noise when sufficiently sensitized to the signal and motivated to respond accordingly. This implied that 85 dBA alarms located in hallways would be sufficient, even with closed doors, to alert most normal hearing college-aged adults.

This work has been noted as the primary justification for the 70 dBA threshold requirements at the pillow level first appearing in BOCA NBS in 1990 and proliferating into NFPA and ICC. The 70 dBA threshold was also consistent with the guidance from NFPA 74 (1978) indicating that 85 dBA alarms installed outside bedrooms would be sufficient to provide 15 dBA over a 55 dBA ambient air conditioner [46]. NFPA 72 changed the 70 dBA requirement to 75 dBA at the pillow in 2002 [44], and ICC codes followed suit in 2009.

5.3.10 Code Status Update – 1980

In 1980 the new edition of NFPA 74 included an exception in performance for alarms installed inside of bedrooms. This exception allowed for alarms specifically installed in bedrooms to produce SPL of 75 dBA at a 10 ft distance. This exception was never included in the alarm listing standards of UL, but remained in the text of NFPA 74 and NFPA 72 until 1999 when it was removed.

Also in 1980, the British Standard BS 5839-1, *Fire detection and fire alarm systems for buildings, Part 1: Code of practice for system design, installation, commissioning and maintenance* was published. Section 16 of this standard provides recommendations and commentary on audible alarm signals. This standard identified several acceptable audible performance levels, but provides the first standardized recommendation for a minimum installation SPL of 75 dBA at the “bedhead” location for sleeping locations [35]. The 75 dBA requirement may originate from waking research conducted by Keefe et. al. at the U.S. Navy Medical Neuropsychiatric Research Unit in 1971 [36] (See Section 5.2.2). These experiments showed a waking effectiveness of 50% at 75 dBA. This requirement has since proliferated into almost all installation driven codes, such as NFPA 72 and ICC codes.
5.4 1981 - 1989

5.4.1 Kahn 1983 [70]

A further study supported by NBS was conducted in 1983 by Michael Kahn at North Carolina State University. In this study, 24 college aged males were exposed to various stimuli during a single night experiment. Half of the subjects were presented with smoke alarm signals of various SPL three times during the night, while the other half were subjected to smoke, heat and one smoke alarm warning at the same intervals. Tests were conducted in a mock bedroom in the laboratory. Sounds were produced using an actual smoke alarm with a bi-periodic signal at 2000 and 4000 Hz. The location of the smoke alarm was varied to produce three different SPL for testing. In these tests, the alarm just outside the closed bedroom door resulted in a 78 dBA signal. When the alarm was mounted on the outside of the outer hall wall it produced 54 dBA at the pillow. Finally, when the alarm was stuffed under a couch cushion it produced a 44 dBA signal. All alarms were presented against at 44 dBA air-conditioner ambient noise. It was noted, but not tested, that with the bedroom door open, the alarm produced 85 dBA at the pillow location when installed just outside the door.

This work was based off the assessment from previous data that waking response was not an immediate or binary function. Rather, the authors proposed, and supported by reviewing the Nober et al. data [69], that waking response time is a function of the signal to noise ratio (SNR) of the alarm and ambient conditions. When comparing their mean response times as a function of SNR, this was generally observed and agreed with the results of Nober. The general observation from these tests was that many students did not awaken to the signals at all. The percentage of students awoken to the 78, 55, and 44 dBA signals in various amounts of time are shown in Figure 18. The estimated SPL for various waking percentages, given certain time thresholds (30, 60, 120, and 600 seconds are also shown. An estimated (interpolated) 50% waking threshold for a 30 second response time is 65 dBA. The 50% waking threshold given 600 seconds to respond is 54 dBA.

Even when awoken, the students were not able to identify what the signals were or respond appropriately. Despite response limitations in the subjects, a review of the data indicates that a 78 dBA signal presented over a 44 dBA background was able to awaken all test subjects.

5.4.2 Zepelin, McDonald, and Zammit 1984 [71]

In 1984 a waking research study was conducted by Harold Zepelin from Oakland University and McDonald and Zammit from the Henry Ford Hospital in Detroit, MI. In this study 9 men and 9 women from each of three age
groups (18-25, 40-48, 52-71) were evaluated for AAT using a tape recorded, 800 Hz tone of 5 second duration through an ear-piece. All participants had normal hearing as measured by a standardized test, with some decline due to age observed. Testing included sleeping in the laboratory with one night for conditioning and another night for testing. Based on results, the tones were increased or decreased by 10 dB. Sleep stages were measured and used for comparison of AAT results. All awakenings were monitored by pressing a button located next to the bed.

This work indicated that average AAT levels decrease with age. This appeared to be independent of the amount of stage 2 or stage 4 sleep, but rather AAT decreased within those stages as well. It should be noted that among the youngest age group, even sounds presented at 120-130 dB did not result in awakening. The AAT data as a function of age for all participants is shown in Figure 19. Note that the data is presented in units of dB, in units of dBA an 800 Hz tone would be reduced by approximately 1-1.5 dB.

![Figure 19 – AATs averaged across Stages 2, 4 and REM for 48 sleepers plotted as a function of age [71]](image)

When broken down by sex and sleep stage, the reduction in AAT as a function of age is even more apparent. These data for men and women are shown in Figure 20.

![Figure 20 – Mean AATs for men (left) and women (right) at three age levels [71]](image)
In the deepest stages of sleep, AAT for waking during this study ranged from 105 dB for young men to 72 dB for older men, and from 98 dB for young women to 70 dB for older women. These values tend to run on the high side of many AAT experiments, especially for younger age groups and for tests conducted with ear-piece sources, and it is possible the brief 5 second presentation of the sounds may shift the AAT values higher than may be expected for persistant smoke alarms.

### 5.4.3 Busby and Pivik 1985 [72]

An experiment conducted by Busby from the University of Ottawa and Pivik from the Ottawa General Hospital in 1985 is one of the first studies to evaluate AAT specifically from a potentially at-risk subject group. Tests were conducted to evaluate the AAT from medicated and non-medicated hyperkinetic and normal male prepubescent children. Twenty-four male subjects 8-12 years old included 8 medicated hyperkinetic children 8 non-medicated hyperkinetic children, and 8 control children. The children spent four nights in a sleep laboratory with 2 nights of adaptation and 2 nights of AAT testing. Tones were delivered through ear inserts at 1,500 Hz in 3 second on/off cycles, in increasing intensity of 2-5 dB. EEG measurements indicated the stage of sleep, and AAT was tested in various stages on average 9 times per test night. Subjects pressed a button and said “im awake” to indicate arousal.

Tests were conducted with ascending AAT to levels upwards of 123 dB. The primary conclusion of the authors was there was an inability to awaken children of all three test groups, even at 123 dB. The total numbers of tests conducted resulted in arousal and non-arousal for the three test groups in various stages of sleep and the mean dB at arousal are shown in Figure 21.

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**Figure 21 – Proportions (arousals/attempt) and mean dB levels of behavioral arousal [72]**
The lowest proportions of arousal occurred during SWS, with only 3 awakenings in all test groups. Highest percentage of arousal occurred during REM sleep for all groups, ranging from 42.9% (medicated) to 55.3% (control). No distinction was observed among the three test groups by total percentage, as 33.1%, 35.9%, and 34% of all tests aroused the medicated, non-medicated, and control groups, respectively.

The average dB level at arousal during the tests is even more drastic than the low numbers of responses. Average dB ranged from 99.7 dB to 115.3 dB, with no responses occurring at less than 80 dB. This work proved extremely enlightening and alarming to the fire protection community, indicating the severe disparity between awakening children and adults with smoke alarms.

5.4.4 Johnson, Spinweber, Webb, and Muzet 1987 [73]

Waking of another at risk group was reported in 1987 by Johnson et. al. in the Journal *Psychopharmacology*. In these experiments, 36 adult males subjects with insomnia were tested with placebos and 0.25 and 0.5 mg doses of triazolam, a common hypnotic sleeping drug used at the time. Subjects were tested over 5 nights and exposed to a standard home smoke alarm on nights 1 and 4 of the experiment. The alarm was installed to provide 78 dB SPL at the pillow location. The alarm was played in 1-minute intervals during stage 2, SWS, and at morning awakening. After 3 1-minute presentations, the subject was determined to be non-responsive.

The subjects in this experiment taking triazolam failed to awaken to 50% of the presentations during SWS. The placebo group were awakened in 100% of the experiments. The use of hypnotics was noted to reduce waking effectiveness by approximately half.

5.4.5 Code Status Update – 1989

In 1989 the final version of NFPA 74 was approved before it was adopted into NFPA 72 in 1993. This version of NFPA 74 included requirements for interconnection of smoke alarms for the first time, for new construction only as shown in Figure 22. Research up to this time had raised concerns in the fire protection community that alarms throughout the home may be insufficient to awaken occupants of bedrooms. Much of this concern was driven by research on the transport and attenuation of sound conducted between 1981 and 1988 by Butler, Bowyer, and Kew [7], Halliwell and Sultan [74], Robinson [75] [76], and Schifiliti [77]. This research is discussed in more detail in Sections 6.5 through 6.10. A thorough accounting of the smoke alarm sound transport and attenuation research and guidance is provided throughout Section 5.8.

![Figure 22 – Code Status Update – 1989 – NFPA 74 Requires interconnection in new construction](image)

5.5 1990 - 1999

5.5.1 Sultan and Halliwell 1990 [78]

In 1990, after NFPA 74 included interconnection requirements and after writing the *Guide to Most Effective Locations for Smoke Detectors in Residential Buildings* in 1986, based on the attenuation of sound [74], Sultan and Halliwell of the National Research Council of Canada (NRCC) conducted a literature review published in *Fire Technology* focused on locating alarms in apartments and including evaluation how loud alarms are required to awaken occupants [78].
The authors noted the common practice of installing alarms outside apartments in the corridors as a common practice at the time with concern. They also reference the article by Berry in 1978 (See Section 5.3.5), and incorrectly conclude that he found 75 dBA as a minimum at the ear would awaken normal people. Quite conversely, Berry was concerned by the data of Keefe et. al. (see Section 5.2.2) that 75 dBA only awakened 50% of normal people, a number he found insufficient.

The authors reference the British Standard BS 5389 Part 1 as the only standard requiring a minimum of 75 dBA “at the bedhead” [35]. They reference the unpublished work of Lukas, described in the review of Petzoldt and Van Cott in 1978 (see Section 5.3.4) and conclude that 80% of normal adults would awaken to 80 dBA. Using the 75 dBA pillow threshold estimated, Sultan and Halliwell conducted an analysis of sound transmission as a function of frequency and location. This analysis is discussed in detail in Section 6.11.

5.5.2 Code Status Update – 1990-1993

A relative dearth of research was conducted or published on waking effectiveness or alarm performance from 1990-1995. The codes made some drastic steps toward improving performance in real buildings through installation-based requirements. In 1990, NFPA 72 incorporated the requirements of NFPA 74F, but did not include the previous requirements that alarms be 15 dBA above the ambient condition, or 5 dBA above the maximum ambient condition with 60 second durations. This is summarized in Figure 23.

![Figure 23 – Code Status Update – 1990 – NFPA 72 incorporates NFPA 74F](image)

The first building code in the U.S. adopted a minimum SPL requirement for residential smoke alarms and detectors in 1990. BOCA, responsible for the NBC, the building code covering most of the east coast and Midwest, required a minimum SPL of 70 dBA at the pillow in Group R (residential) occupancies. The origin of the 70 dBA minimum installation requirement was almost certainly based on the guidance of NFPA 74, which stated that 15 dBA above ambient is acceptable, and 55 dBA ambient is possible in residential. NFPA 74 also claimed that attenuation through closed doors was approximately 15 dBA, resulting in 70 dBA from alarms producing 85 dBA. BOCA also required a minimum SPL of 15 dBA over ambient and 5 dBA over maximum ambient conditions, the same threshold that NFPA 72 (1990) had not included from NFPA 74F. The next year, the SBCCI adopted the same SPL requirements in the SBC which applied to most southern states. The ICBO, covering much of the western states and Midwest, never adopted an SPL requirement before consolidation into the UBC. The building code changes are summarized in Figure 24.
In 1993, NFPA 72 fully incorporated the remaining NFPA 74 and NFPA 72G codes. This change included requirements for 85 dBA at 10 ft for alarms, but also included the 75 dBA exception for alarms installed in bedrooms. The 70 dBA pillow requirements were also included, mirroring the building codes. This version included not only interconnection in new construction, but also required an alarm in every bedroom in new construction for the first time. The 1993 NFPA 72 update is summarized in Figure 25.
5.5.3 Bruck and Horason 1995 [79]

Awakening research resumed in 1995 with the first experiments by Dorothy Bruck and Mahmut Horason from Victoria University of Technology in Melbourne. In these experiments twenty-four young adults were presented with a 60 dBA (±5 dBA) smoke alarm sound produced from a cassette recording with speakers placed in a cabinet in the bedroom in a sleep laboratory. Recorded alarm sounds were produced by a typical, approved Australian smoke alarm, with 85 dBA at 10 ft and 2000-4000 Hz tones. A 10-minute recording of the sound was played. Sleep stages were measured by EEG and alarms presented after Stage 4 sleep was reached.

These tests were conducted with the subjects naïve of the sound or the purpose of the tests. Bruck proposed that previous work conducted by Nober et. al. in 1980 (see 5.3.9) and Kahn in 1983 (see 5.4.1) had reported reduced AAT values due to the subjects knowledge of the sounds and tests.

The SPL of 60 dBA at the pillow was selected based on field studies of 8 rooms in 4 houses, where they measured pillow SPL of 51-68 dBA with bedroom doors closed from 85 dBA at 10 ft alarms in hallways. In addition, Bruck and Horason had evaluated the AAT values measured by Bonnet and Johnson in 1978 of 70 dBA in Stage 2, 92 dBA in Stage 4, and 83 dBA in REM (see 5.3.6), and Keefe, indicating that only 50% of subjects had awoken to 75 dBA (see 5.2.2). They also noted the concerns of Keefe regarding 4000 Hz tones with hearing loss, and the observations of Levere et. al. indicating improved sleep response to lower frequency tones (see Section 5.2.3).

Over all tests, five of the twenty-four subjects slept through at least one 10-minute alarm (21%). All five had noted some level of sleep deprivation from previous night. No significant differences were observed between the naïve and non-naïve presentations of the alarm, the primary hypothesis of the experiment. There were also no noted differences between sexes, and most who responded to alarms awoke quickly.

The actions of the subjects when awoken to the naïve alarm were slightly disconcerting. Only 1 of the 21 subjects that awoke to the naïve alarm took investigative action within 2 minutes, 2 others within 3 minutes. Subjects did not identify the sound as a smoke alarm. On the second presentation, subjects awoke and responded much more quickly. This highlights the importance of training and recognizing smoke alarm sounds, or perhaps a limitation of conducting a test in a laboratory, where subjects may not respond to unexpected emergency signals when a technician is known to be observing next door.
5.5.4 Code Status Update – 1995

In 1995 the NBC-C required a minimum SPL of 75 dBA at the pillow location and the ISO 8201 (ANSI S34.1) three-pulse temporal pattern for smoke notification appliances. The 75 dBA requirement that first appeared in the British Standard BS 5839 had proliferated into the Canadian codes. This change is summarized in Figure 26.

![Figure 26 – Code Status Update – 1995 – Canadian National Building Code 75 dBA at Pillow and three-pulse temporal Pattern](image)

5.5.5 Rosenthal et al 1996 [80]

A sleep study conducted by Rosenthal, Bishop, Helmus, Krstevska, Roehrs, and Roth at the Henry Ford Hospital was reported in the Journal *Sleep* in 1996. In this study, 27 healthy individuals, with no drug use, and prescreened for good hearing were tested for AAT response on 2 consecutive nights. Subjects were wearing headphones and presented with 988 Hz tones starting at 35 dB for 2 seconds, then increasing by 5 dB every 10 seconds until 80 dB was reached. If they did not awake at 80 dB, the subjects were still assigned the waking AAT of 80 dB for subsequent analysis and averaging. For these tests conducted with 988 Hz tones, units of dB and dBA are interchangeable.

In these experiments, the subjects were presented with sounds after only 5 minutes of sustained sleep as measured by the EEG, this resulted in most awakenings occurring during Stage 2, early onset sleep. Awakening was determined by an increase in the alpha waves on EEG for longer than 5 seconds, also a low threshold for defining awakening.

Subjects were separated into three categories based on their latency to fall asleep during screening trials, including a sleepy, alert, and alert but sleep deprived group. The AAT values for these three groups during the first half and second half of the test night are shown in Figure 27. Among all three groups the AAT values decreased later in the night, an effect generally agreed on throughout the sleep community. The early night AAT values among the three groups did not vary drastically, ranging from 59-63 dB on average with standard deviations of ±7-10 dB.
5.5.6 Grace 1997 [81]

In 1997 a thorough literature review of waking, alarms, and human sleep was conducted by Thomas Grace under the supervision of Dr. Charley Fleischmann at the University of Canterbury in New Zealand. This review included an extensive analysis of the human sleep cycles, EEG wave patterns, and smoke detection performance and placement throughout the home beyond the scope of this document. The review of Grace can be consulted for additional information on these topics.

In this research, Grace reiterated many of the conclusions of previous work discussed in this report. Grace raises some interesting new questions that gained traction in the fire industry over the next several years. He reviewed the work of Levere et. al. from 1972 that indicated low frequency tones were more effective at waking. Grace questioned of the value of the A-weighting scale and the impacts of greater total sound wave power in the lower frequency tones required to achieve equivalent loudness. This question still has not been quantified or evaluated further.

Grace also argues for the value of mid-frequency tones, closer to 1000 Hz. He notes that mid-frequencies are less attenuated by household walls and doors, and that they are most easily transmitted over electrical lines interconnecting between alarms. The conclusion regarding transmission is unclear because the 1000 Hz tone is not transmitted by electrical lines, only as a sound wave. Grace further notes that hearing aids provide the most gain at 1000 Hz, as this is among the most important frequencies for intelligibility of speech.

Grace makes several references to AAT measurements from previous work. He references the 1987 research of Johnson testing subjects for the effects of triazolam, in which all control subjects awoke at 78 dBA, but only 50% of the drugged subjects were awoken [73]. He also references 1966 work by Zung and Wilson where an AAT of 65 dBA was measured among normal adults [82]. He also references interesting work from Bradley and Meddis from 1974 which evaluated the effects of dream incorporation, who observed that subjects awoke at 70 dBA when they reported incorporating the sound into dreams, compared to 60 dBA for subjects reporting no dream incorporation [83].

5.5.7 Bruck 1998-1999 [84] [85]

In 1998 Dorothy Bruck produced a report for the Fire Code Reform Research Program in Australia evaluating waking effectiveness in adults and children [84]. This work was focused on determination of the effectiveness of 60 dBA alarm signals at the pillow to awaken both adults and children in their own home settings. Thirty-six subjects including 20 juniors 6-17 years old and 16 adults 30-59 years old with normal hearing and sleeping, with no drugs or alcohol or other impairments were evaluated.

Subjects slept in their own homes and were presented alarm signals from a smoke alarm mounted on a portable stand positioned to provide 60 ± 3 dBA at the pillow. The 60 dBA SPL was selected to represent an alarm outside a bedroom with the door open. Subjects wore Actigraph monitors to identify sleep and waking.
Actigraph is a motion sensitive wrist watch that measures relative motion of the wearer. Experiments were conducted over 4 nights, with alarms presented on the second and third nights only, approximately 1 hour before and 1 hour after the middle of the night (1-430 AM). Alarms remained signaling for 3 minutes before silencing. Subjects were instructed to move the Actigraph after waking and then fill out a questionnaire.

In these tests, all adults awoke effectively on both test nights. Among the juniors only 3 of 20 awoke on both nights, 6 of 20 awoke on one night only, and 11 of 20 slept through the alarm on both nights. Bruck conclude that 85% of the children were not reliably awakened by the 60 dBA alarm. Also noted is the fact that 2 of the 3 juniors that awoke both nights were the 16 and 17 year-old participants. This fact further strengthens the conclusion that children under 16 years old do not awaken to alarms at 60 dBA.

In a second article based on the same work and published in 1999 in the Fire Safety Journal Bruck makes several additional recommendations [85]. She supports the necessity of interconnecting alarms to awake the adults independent of the source of the initiating device. She questions the need for alarms in every bedroom, citing the 1985 work by Busby and Pivik indicating the children do not awaken even to 123 dBA alarms. She recommends conducting additional testing on children with alarm signals presented at 85 dBA.

5.5.8 Duncan 1999 [86]
Christine Duncan, under the supervision of Dr. Charley Fleischmann at the University of Canterbury, conducted waking effectiveness testing in 1999 as part of a degree thesis [86]. These experiments built on the literature review conducted two years earlier at Canterbury by Thomas Grace. In these experiments commercial off the shelf (COTS) ionization smoke alarms were purchased and modified to remove the detector and attached a computer-controlled actuator to the alarm sounder. The real alarm sounders were selected over recordings for authenticity of results. The alarms produced a maximum sound of 110 dBA at the source, produced 4 beeps per second, with a complex tone centered at 3000 Hz.

The modified sounders were installed in 40 homes, including those of 26 university students, 10 Maori, and 4 elderly subjects. Alarms were installed in the hallway outside the bedrooms, allowing all household members to participate. At the time in New Zealand, per the recommendations of the Building Research Association of New Zealand (BRANZ) and NZS 4514:1989 The Installation of Smoke Alarms standard, alarms were still only required outside bedrooms in the hallway.

A sound meter was used to determine the SPL at the pillows in the bedrooms. All alarms were initiated by a programmed date/time code on the alarms between 6PM and 6AM, and not based on sleep cycle or duration of sleep. After activation, alarms signaled for 255 seconds or if deactivated by occupants, whichever occurred first. Alarms were installed in homes for 2 weeks and alarmed 3 times, once in the evening (6-10 PM) and twice at night (10-2 AM and 2-6 AM). After hearing the alarm, subjects were to silence the device and call an answering machine to document which residents had awoken in the home.

The results were evaluated to determine the effectiveness of alarms in hallways and the effect of the alarm on various populations, including the elderly, children, or those under the influence of drugs or alcohol. The average SPL of the alarms varied from 75 dBA on average with the door open and 67 dBA with the doors closed. Measured SPL ranged from 61-93 dBA with doors open and 57-75 dBA with the doors closed.

Among the total test population, the alarms were found to be 85% effective, with only 35 of 229 possible test subjects sleeping through alarms. Even among the 35 sleeping subjects, 9 (26%) had indicated consuming alcohol and/or marijuana prior to sleep, and 18 (51%) were children under the age of 10. Only 8 of the 35 events involved adults who had not consumed an intoxicant. Among the adults that did not awaken, all occurred with bedroom doors closed with alarms ranging from 62-71 dBA.

During the testing, only one child under the age of 10 awoke, a 9 year-old girl sleeping with her bedroom door open and receiving an 81 dBA alarm signal. Another case study tested on the group evaluated a 3 year-old with
the alarm outside the bedroom (65 dBA) and inside the bedroom (91 dBA). This child did not awaken in any case tested.

Duncan also observed that the audibility (SPL) of the alarms did not correlate to the subject response time as expected. The response time as a function of the SPL is shown in Figure 28. Only a slight and poorly correlated decrease in response time was observed for louder alarms, although there were only 7 alarms over 75 dBA to evaluate which may impact drawing any real conclusion.

\[ y = -0.2962x + 49.956 \]
\[ R^2 = 0.0076 \]

**Figure 28 – Response time as a function of signal audibility (SPL) in Duncan testing [86]**

### 5.5.9 Code Status Update – 1999

NFPA 72 removed the language allowing the exception for smoke alarms installed in bedrooms to produce a reduced SPL of 75 dBA at 10 ft in 1999. This language was changed entirely, removing the 85 dBA at 10 ft statement and requiring compliance with UL 217 or UL 268. This harmonized the requirements and defaulted the device performance to the listing requirement of 85 dBA at 10 ft distance. This change is summarized in Figure 29.

**Figure 29 – Code Status Update – 1999 – NFPA 72 removes the 75 dBA at 10 ft exception for alarms intended for bedrooms**
5.6  2000 - 2009

5.6.1 Nakano 2000 [87]
In 2000 a waking study was reported by Mina Nakano and Ichiro Haiwara in the Proceedings of the Fourth Asia-Oceania Symposium on Fire Science and Technology in Tokyo Japan [87]. The test from this study is difficult to interpret from translation, but the authors measured the SPL at various locations throughout western and Japanese style homes and then measured the evacuation response times from 600 trainees sleeping at the Disaster Protection Center. They produced alarms from a 50-53 dBA hotel emergency bell, a 60-67 dBA siren, and a 48-55 dBA voice broadcast, in that order. Among the test subjects, 90% evacuated within 120 seconds of the alarms. Among those awoken, 74% awoke to the initial bell, 9% to the siren, 7% by other subjects, and 2% to the voice broadcast. Among the 600 subjects, 193 reported they drank very much and 70 claimed to be “dead drunk” without additional context. The authors did not notice differences in the initial response times or evacuation times as a factor of the alcohol consumption, the amount of previous sleep, or the depth of sleep of the subjects. The limited amount of data and analysis and subsequent translation of this document makes the conclusions or recommendations potentially suspect.

5.6.2 Bruck and Bliss [88] 2000
In 2000 Dorothy Bruck and Angela Bliss produced a report for the International Association of Fire Safety Science (IAFSS) to update her previous research on waking effectiveness of children in homes. In this work, the waking of 28 children, aged 6-15 years was evaluated with alarms placed inside of their bedrooms, with SPL of 89 ± 3 dBA at the pillow. Previous work by Bruck in 1998 had found that 60 dBA was insufficient to awaken children [85], this work intended to determine the effect of louder alarms.

A special portable mount was constructed to position an alarm at a ceiling and positioned to provide 89 dBA at the pillow. The alarms were placed inside the childrens’ homes and activated remotely 2 times during a 5 day period. Alarms were activated in the middle of the night, or the second third of the sleep night. Children were informed of the experiment and provided an Actigraph watch, which they were instructed to shake on awakening to record for data purposes.

Among the 28 children, 4 did not awake to either alarm (14.3%) and 10 did not awake on one of two nights (35.7%). Only 50% of the children awoke on both test nights. If the age group was reduced from 15 years old to only include 6-10 years, only 29% of children awoke both nights. Based on these test results, the authors indicate the importance of interconnected alarms, as the reliability of waking children alone is insufficient. They estimate that 31.3 – 68.7 % of the real population of children would not awaken to 89 dBA alarms in their bedrooms. Production and installation of alarms loud enough to wake children was not considered a reasonable option. Interconnected alarms would awaken the parents, who could then awaken the children, improving life safety outcomes.

5.6.3 Code Status Update – 2000
In 2000 the ICC consolidated the regional building codes including the BOCA NBC, SBC, and UBC codes. This included the existing NBC and SBC requirements for 70 dBA measured at the pillow and a minimum of 15 dBA over the ambient sound and 5 dBA above the maximum ambient sound with 60 second duration. This consolidation is summarized in Figure 30.
5.6.4 Bruck 2001 [89]

In 2001 Dorothy Bruck authored a literature review on waking effectiveness and AAT values for the *Fire Safety Journal*. She investigated the factors that affect responses in testing, the use of smoke alarms and other signals in AAT testing, fire fatality statistics that identified at risk populations, and compared AAT values from various studies [89].

Bruck reviews numerous studies and literature surveys and draws various conclusions. Several of the notable observations include:

+ A review of AAT data by Bonnet that indicates AAT is not affected when experiments are conducted with ascending or fixed SPL values
+ A review of data from Zepelin et. al. [71]
  - indicating that the difference between the waking and sleeping hearing thresholds are approximately 69 dBA for 18-25 year olds and 69 dBA for 52-71 year olds. This data is used to estimate that 25% of older adults will not awaken to 60 dBA at the pillow, and 10% would not awaken to 75 dBA among the older population.
  - Indicating higher AAT values than those found in smoke alarm studies. Bruck attributes this to the use of the 800 Hz tone rather than the 2000–4000 Hz alarms, but this conclusion contradicts later findings by Bruck indicating the effectiveness of lower tones. It is possible that the pure tone nature of the AAT studies compared to complex or harmonic tones in smoke alarm studies contributes to the higher AAT values.
+ Review of the 1976 work by Weir [60], concluding that humans would be most responsive to 150-250 Hz tones, those within the range of normal speech.
+ Review of the 1966 work by Zung and Wilson [82] which indicates that waking responses dropped from 90% to 25% when subjects were not pre-conditioned to the sound.
+ Reference to the sound attenuation work of Robinson from 1985 [75] which indicates that the transmission of sound in through partitions for tones above 500 Hz is approximately uniform (see Section 6.9)
+ Reference to the article by Berry in 1978 [58] which questions the validity of 75 dBA for awakening, as it was only proven effective for 50% of test subjects. This included discussion about at-risk populations and why 75 dBA as a minimum may be insufficient.

After her thorough review, Bruck concludes by emphasizing the importance of interconnected alarms placed in every bedroom. Most adults with normal hearing will awaken to existing alarms, but for remote fires the
interconnection is crucial. She raises concerns for at-risk populations which cannot be expected to awaken reliably even to alarms located in bedrooms.

5.6.5 Code Status Update – 2002

In 2002 NFPA 72 changed the installation-based requirement for a minimum of 70 dBA at the pillow to 75 dBA at the pillow. The 75 dBA requirement was more conservative and had been present in the British and Canadian Standards. At the time, this change was justified to the Technical Committee to harmonize the NFPA requirements with the Canadian requirements for SPL. This change is summarized in Figure 31.

![Figure 31 – Code Status Update – 2002 – NFPA 72 changes 70 dBA at the pillow to 75 dBA to harmonize with Canadian Standard](image)

5.6.6 News Media Reports 2002-2004

Beginning in 2002 the news media became interested by the failure of children to respond to smoke alarms and conducted series of local experiments. These experiments were conducted in homes with children by various fire departments or researchers. Often such experiments were not well controlled scientific explorations but rather were intended as evidence of the potential problem with waking of children. The goal of these experiments was not to quantify waking effectiveness, but to inform the public about the problem. The experiments were widely reported in the news media and resulted in significant public attention to the issue of waking children with smoke alarms. The voracity of these demonstrations have been questioned by the Consumer Product Safety Commission (CPSC) in a 2004 report by Arthur Lee et. al. [90] due to confounding variables such as camera crews, fake smoke, parents involvement, etc.

Several such experiments were summarized by Thomas Cunningham from the U.S. Naval Academy Fire Department [91]. He summarized the results of an 8 month fire industry study on sleeping children in two test families. In these tests, three boys, (6, 8, 10 years old) in a bedroom were exposed to an alarm outside their bedroom, only one child awoke, and it took over 4.5 minutes to wake his brothers and evacuate. In a second test with the alarm in the bedroom, none of the boys woke for over 10 minutes.

Another test on a family of 5 children required over 10 minutes to awaken the children, with the oldest 14 year-old waking twice but falling back to sleep. Four other children never woke up. In a repeated test, two children woke up within 2-minutes but others didn’t awake until the alarms were placed next to their heads.

Cunningham also summarized a large test study by the Stowe Fire Department on 600 children from 1997. These tests showed 70% of the children were not awakened. In a subsequent test of 76 children, they evaluated hallway and bedroom alarms, bedroom strobe alarms, and hallway and bedroom horns. Over 55% of the children did not awake to any signal. Only 11 children were alerted to hallway signals and 35 to bedroom signals.
Cunningham also cites smaller studies conducted by fire departments and local news organizations. This includes North Shores Fire Department in Wisconsin and WISN Milwaukee (10/25/02), Fishers Fire Department in Indiana, Arlington Fire Department in Texas with NBC Evening News with Tom Brokaw, the LA country Fire Inspector with NBC4 Los Angeles. All these tests affirmed and worried the public that children do not awaken to smoke alarms.

Cunningham notes that UL had never investigated the response of children to smoke alarms, and the device performance requirements did not account for this type of result. He indicated that UL would begin to investigate this issue and that the CPSC would conduct a two-year study to recommend changes to smoke alarm performance. CPSC published two subsequent reports and UL made changes to the UL 217 and UL 268 test standards after subsequent years of research.

5.6.7 Fahy 2003 [92]
At the NFPA Fire Suppression and Detection Symposium (SUPDET) in 2003, Rita Fahy from the NFPA addressed the recent media coverage of children and smoke alarms and conducted a literature review on the topic. She referenced more than 7 local news studies alarming the public about this topic. She carefully addressed the statistics surrounding smoke alarms to clearly indicate how their proliferation coincided with drastic reductions in fire deaths, including children. She reviews much of the work of Dorothy Bruck to evaluate the factors contributing to at risk populations and assesses the previous work of Nober et.al. and Busby and Pivik. Fahy also indicated the upcoming CPSC study on the topic and actions by UL to address the issue with manufacturers of smoke alarms.

5.6.8 Proulx and LaRoche 2003 [93]
In 2003 Guylène Proulx from the Fire Risk Management Program at NRCC and Chantal LaRoche from the Audiology and Speech Language Pathology at University of Ottawa published a paper in the Journal of Fire Protection Engineering assessing the ability of the public to recognize the three-pulse temporal pattern alarm. In a series of experiments they compared whether the Canadian public could recognize the three-pulse temporal pattern in comparison to a car horn, alarm bell, industrial buzzer, the slow whoop (see Section 4.3), and an institutional alarm bell. In these tests, the three-pulse temporal pattern was most often misidentified and considered the least urgent of all signals among the respondents. This frequent misidentification is concerning because education, motivation, and previous experience with alarm signals is considered a crucial factor in sleeping response. The authors recommended the need for wide public education on emergency alarm signals.

The three-pulse temporal pattern used for this work was a 505 Hz fundamental tone with odd harmonics (3rd, 5th, 7th, etc). The signal was recorded from the Simplex 1996, 4100 Fire Alarm Audio Demonstration CD. This signal has been referenced in the subsequent low frequency testing conducted by Dorothy Bruck and the signal that has become the basis for the 520 Hz harmonic tone required in sleeping environments today.

5.6.9 Ball and Bruck 2004 [94]
At the 2004 Human Behavior in Fire Symposium Michelle Ball and Dorothy Bruck presented experimental waking data assessing the effect of alcohol on young adults [94]. This study produced recorded alarm sounds from stereo speakers and a laptop computer. Several alarm sounds were evaluated, including the first waking study using the 505 Hz harmonic tone used by Proulx and LaRoche and recorded from the Simplex 1996 4100 Fire Alarm Audio [93].

The study was conducted with 12 adult subjects (18-25), self-reported deep sleepers, with normal hearing and no sleep disorders, and who reportedly drank alcohol occasionally. Subjects were tested while sleeping in their own homes and sounds of pre-measured SPL were played through stereo speakers on the bedside table, 1-2 meters from the pillow. Tests were conducted over 3 non-consecutive nights, with the subjects conditioned as sober and with blood alcohol concentration (BAC) = 0.05, and BAC = 0.08 over the three nights. BAC was controlled by administering vodka to the test subjects. During tests, subjects were played the sounds prior to sleep and monitored for sleep stages using EEG.
Tests were conducted using three distinctive sounds, a female voice warning of danger, a standard Australian Smoke Alarm with a modulating beep and 4000 and 5000 Hz primary tones, and the 505 Hz low frequency harmonic three-pulse temporal signal. Sounds were initiated when the subjects reached Stage 4 SWS sleep beginning at 35 dBA and increasing by 5 dBA every 30 seconds up to 95 dBA maximum. All three sounds were presented each test night to each subject in varying orders.

In these experiments the low frequency and voice notification awakened test subjects at overwhelmingly lower AAT than the 4000-5000 Hz smoke alarm. Among the three levels from sobriety, to 0.05 BAC, to 0.08 BAC, the low frequency tone awoke subjects at reduced AAT of 13.3 dBA, 6.8 dBA, and 4.6 dBA, respectively.

The AAT increased for all three tones as a function of alcohol consumption, although the greatest increase occurred between sober and 0.05 while relatively little difference was observed between 0.05 BAC and 0.08 BAC. The AAT from the low frequency alarm was also increased with increased alcohol consumption. Although a reduction of 4.6 dBA between the low frequency and the high frequency signals is significant, when the A-weighting scale is not applied to these signals, the actual powers of the sound waves are closer to equal. The mean AAT responses from this study are shown in Figure 32.

Figure 32 – Mean SPL needed to awaken young adults for various tones and levels of intoxication [94]

Ball and Bruck theorized that the reduced AAT from the low frequency and spoken alarms was due to both the frequency and the complexity of the tones. As previously discussed, complex tones have a greater perception of “loudness” than may be accounted for in the A-weighting scale. The authors were surprised by the result, expecting that the voice would perform best due to the emotional content and urgency. While voice did perform well, the low frequency tone arose as a welcome surprise in the data.

The relatively poor performance of the high-pitched alarm (4000-5000 Hz) is worthy of further note. When only the high-pitched alarm is considered, 2 of 12 (17%) test subjects did not awake to the standard alarm signal at 85 dBA when sober, 36% required 95 dBA or did not awaken with 0.05 BAC, and 47% required 95 dBA or did not awaken with 0.08 BAC.

5.6.10 Bruck et al 2004 [95]

Dorothy Bruck, Sharnie Reid, Jefoon Kouzma, and Michelle Ball also reported experimental waking data for children at the 2004 Symposium on Human Behavior in Fires [95]. In this study, a similar approach was taken for previous child waking tests by Bruck and Bliss in 2000 [88]. The same 89 ± 3 dBA alarm intensity was used with children wearing Actigraph watches to indicate awakening. This experiment varied by using a recording of
the mothers’ voice, an actors’ voice, and the low frequency T-3 alarm. The data was also compared to the 1999 data collected for the Australian standard smoke alarm by Bruck and Bliss [88].

Children aged 6-10 years were tested over several nights in their own homes. Each alarm signal was tested in different test series, and thus utilized slightly different schedules of alarms during the testing nights. All followed similar procedures for sleeping, alarm times, alteration of nights, and previous presentation of the sounds to the children. The test procedures for the various sounds are summarized in Table 1.

**Table 1 – Test methods for awakening of children by Bruck et. al. in 2004 [95]**

<table>
<thead>
<tr>
<th>Study 1</th>
<th>Study 2</th>
<th>Study 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Signals presented</td>
<td>mother's and actor's voice</td>
<td>low pitch T-3</td>
</tr>
<tr>
<td>dBA</td>
<td>89 +3 dBA</td>
<td>89 +3 dBA</td>
</tr>
<tr>
<td>Signal frequency</td>
<td>315-2,500 Hz</td>
<td>500-2,500 Hz</td>
</tr>
<tr>
<td>Time of signal</td>
<td>1 AM</td>
<td>1 AM and 3 AM</td>
</tr>
<tr>
<td>Participants(n)</td>
<td>N-20 (10M, 10F)</td>
<td>N-14 (8M, 6F)</td>
</tr>
<tr>
<td>Participants (age)</td>
<td>6-10 yrs</td>
<td>6-10 yrs</td>
</tr>
<tr>
<td>Signal delivery</td>
<td>Via speakers &amp; laptop</td>
<td>Via speakers &amp; laptop</td>
</tr>
<tr>
<td>Signal activation</td>
<td>2nd and 3rd nights</td>
<td>2nd and 3rd nights</td>
</tr>
<tr>
<td>Awake measurement</td>
<td>Actigraphy</td>
<td>Actigraphy</td>
</tr>
</tbody>
</table>

Significant differences were observed in the responses of the children between the low frequency and the high frequency alarm signals. All presentations were made at 89 dBA, so differences in AAT could not be determined, but the comparisons in the number of children awakened and the time to response among those who were awoken are considerable. The total number of children who awoke or did not awake to the four signals is shown in Figure 33.

**Figure 33 – total number of children who slept or awoke to various signals during testing by Bruck et. al. 2004 [95]**
Comparing different signals, all 19 children awoke to the mothers’ voice, 18 of 19 children awoke to the actors’ voice, 26 of 27 children awoke to the low frequency tone, and only 16 of 28 children awoke to the high frequency alarm. The time of responses were also notable, as responses were more often delayed to the high frequency alarms when awakening. The time to respond for each of the signals is shown in Figure 34. Most notable was that no other signal beside the high frequency alarm required longer than 1 minute, while only 73.4% of children awoke to the high frequency in this time. This data is also summarized in Table 2.

![Percent distribution of the time taken to awaken to different alarms](image)

**Figure 34 – Response time of awakened children by percentage in Bruck et. al. 2004 [95]**

**Table 2 – Percentage of children response times to various alarm tones [95]**

<table>
<thead>
<tr>
<th>Signal</th>
<th>0-30 secs</th>
<th>31-60 secs</th>
<th>Over 60 secs</th>
</tr>
</thead>
<tbody>
<tr>
<td>mother’s voice</td>
<td>15</td>
<td>78.9%</td>
<td>4</td>
</tr>
<tr>
<td>actor’s voice</td>
<td>12</td>
<td>70.6%</td>
<td>5</td>
</tr>
<tr>
<td>standard signal</td>
<td>10</td>
<td>66.7%</td>
<td>1</td>
</tr>
<tr>
<td>low pitch T-3</td>
<td>14</td>
<td>66.7%</td>
<td>7</td>
</tr>
</tbody>
</table>

5.6.11 Ball and Bruck 2004 #2 [96]

A third paper by Michelle Ball and Dorothy Bruck from the Human Behavior in Fire Symposium in 2004 detailed a survey and experiment conducted to assess the types of sounds people identified to elicit the greatest response. This paper included a broad discussion about brain functions and the interpretation of sound during sleep. It focused on the hypothesis, supported by previous data, that sounds that have urgency, emotion, or meaning would result in reduced AAT and initiate waking at lower SPL than generic beeping or other amorphous sounds. The authors introduced for the first time in testing the concept of a naturalistic sound for smoke awakening; or sounds that mimic the sounds of fire in a home. This included roaring, popping, crackling, and glass breaking.
This work included both a survey and experiment. A survey was conducted first to determine the sounds that people felt would illicit negative emotions, sounds that they thought would draw their attention when sleeping, and sounds they would investigate if they heard while sleeping. The survey was conducted among 163 people returning 1447 total responses. Among these results, human emotions, such as crying or screaming received the most responses for eliciting negative emotions and drawing your attention when sleeping. Naturalistic sounds received the most responses as sounds people would feel obligated to investigate in the night. Mechanical sounds generally received responses somewhere in the middle, generally below the emotional sounds. This data led the researchers to select three sounds for subsequent experiments, including naturalistic sounds of a fire, an actors’ voice conveying an emergency message, and a combination of the message and naturalistic sounds.

Pilot testing was conducted to determine the AAT and response time to the signals. Similar to other experiments by Bruck, speakers were placed 1-2 m from the pillow and calibrated at the 60 dBA threshold. Subjects were monitored by EEG for sleeping cycle and the alarm was initiated at the start of Stage 4 sleep and increased incrementally from 35 dBA to 95 dBA in 30 second on / off cycles. Eight subjects were tested, six in their own homes and two in the laboratory environment. The mean response times and SPL during these pilot tests are shown in Table 3.

Table 3 – AAT response time and SPL to naturalistic and female voice tones pilot study [96]

<table>
<thead>
<tr>
<th></th>
<th>Naturalistic House Fire</th>
<th>Actor’s Voice</th>
<th>Signal Shift</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Response Time</strong></td>
<td>Mean</td>
<td>STD</td>
<td>Mean</td>
</tr>
<tr>
<td>(sec)</td>
<td>198.00</td>
<td>172.84</td>
<td>167.00</td>
</tr>
<tr>
<td><strong>SPL (dBA)</strong></td>
<td>50.00</td>
<td>14.39</td>
<td>47.50</td>
</tr>
</tbody>
</table>

Although the authors recognized that the actor’s voice resulted in the earliest response at the lowest average SPL, the differences in SPL between the signals were not drastic. All three signals produced a mean AAT below 52 dBA, indicating a likely improvement in response compared to other alarm signals, especially compared to the existing high frequency alarms. This work represented a small pilot study of only 8 subjects, and further work conducted by Bruck would build on these concepts and evaluate the waking performance of alternative signals.

5.6.12 Lee, Midgett, and White 2004 [90]

In December of 2004, a literature review was published by Lee, Midgett, and White from the CPSC to evaluate the waking of children and older adults by smoke alarms [90]. This work summarized the waking effectiveness measured in numerous previous studies, including work by Busby and Pivik and Bruck. The authors reviewed the potential for alternative alerting methods and tones and recommended further research to improve waking of children and older adults. Specifically, they recommended exploring alternative sound frequencies for smoke alarms.

This report included comprehensive review of the human responses to sounds, the detection of smoke, production of sound from common smoke alarm sounders, the attenuation of sound in homes, hearing loss and hearing in older populations, and fire loss statistics identifying at-risk populations. These details are beyond the scope of this report, but readers are referred to this text for in depth discussion.

Based on the evaluation of waking responses, human hearing, and existing smoke alarm technologies the authors made the following recommendations:

+ **Children:**
  - Have longer period of deep sleep than adults
  - Are not reliably woken by current smoke alarms
- Have a higher rate of death in fires, but no evidence indicates it is the result of the inability to wake to smoke alarms.

+ Current smoke alarms are effective at waking most adults:
  - Who do not have hearing impairments
  - Are not under the influence of drugs or alcohol
  - Are not sleep deprived

+ Interconnected alarms can provide earlier warning of fires:
  - Home configurations can limit the transmission of sound from remote alarms
  - Interconnected alarms in bedrooms could increase sensor response times when doors are closed

+ Alternative sounds and waking methods are worthy of further research due to the limitations of the existing technologies for at-risk populations.

Subsequent work conducted by Lee in 2005 evaluated the transmission of smoke alarm sounds throughout homes [97] (See Section 6.16).

5.6.13 Roby 2005 [98], Ashley et. al. [99] and Ashley and Milke 2007 [100]

Between 2005 and 2007 a series of papers were published by Richard Roby from Combustion Science and Engineering (CSE) and Erin Mack Ashley and Jim Milke at the University of Maryland. These papers detailed research conducted through funding from the National Institute of Health (NIH) to review alternative alarm signals for the hard of hearing and deaf. This work investigated the use of bed shakers and strobes, and even developed a sensor capable of responding to the sound of high frequency smoke alarms to initiate an alternative signal, such as the bed shaker. These topics are beyond the scope of this report. In addition to alternatives for the deaf, the studies evaluated audible signals, including developing a baseline performance for current smoke alarms and low frequency smoke alarm signals germane to this discussion.

An experiment was conducted with 111 total persons with normal hearing, hard of hearing, and deaf populations to determine waking effectiveness. The purpose of these experiments was to compare the baseline effectiveness of 3100 Hz three-pulse temporal alarms to the low frequency alarm (and other strobes and shakers). Subjects ranged from 18-80 years of age, but most were college aged students as shown in Figure 35.

![Figure 35 – Age demographics of the experiments of Roby, Ashley, and Milke [98] [99] [100]](image)
The high frequency alarm was a Firex Model CC. The low frequency alarm was a “Loudenlow” from Darrow Company, producing a tone of 400-500 Hz. The alarms were mounted to the ceiling approximately 10 ft from the bed and measured to produce 81 ± 4 dBA and 80 dBA at the pillow, for the high and low frequency alarms, respectively. All tests were maintained at this fixed SPL.

Tests were conducted in 1 night in a sleep laboratory and included EEG and heart rate data. Subjects were awoken a maximum of 3 times during the night at various sleep stages using various notification appliances. Subjects were classified as awake when the technician noted the EEG response and the subject raised their hand. Test data was reported and analyzed in all reports by Roby, Ashley et.al., and Ashley and Milke, but the analysis shown here is mostly based on the final 2007 analysis by Ashley and Milke.

Overall, the authors found that a standard high frequency alarm at 81 ±4 dBA effectively awoke 92% of hearing able, 57% of hard of hearing, and 0% of deaf subjects. Noticeably improved waking performance was observed for the low frequency alarm. At 80 dBA the low frequency alarm woke 100% of hearing, 92% of hard of hearing, and 11% of deaf subjects. These results are compared in Table 4.

### Table 4 – Waking effectiveness of high and low frequency alarms compared by Ashley [100]

<table>
<thead>
<tr>
<th></th>
<th>Hearing</th>
<th>Hard of Hearing</th>
<th>Deaf</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>High</td>
<td>Low</td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>24</td>
<td>5</td>
<td>28</td>
</tr>
<tr>
<td>Awakened</td>
<td>22</td>
<td>5</td>
<td>16</td>
</tr>
<tr>
<td>Not Awakened</td>
<td>2</td>
<td>0</td>
<td>12</td>
</tr>
<tr>
<td>% Awakened</td>
<td>92%</td>
<td>100%</td>
<td>57%</td>
</tr>
</tbody>
</table>

The waking effectiveness was compared as a function of the sleep stage during alerting. This data is shown for the entire test group and for the hard of hearing population only in Figure 36. The low frequency alarm was more effective across all sleep stages for both the general test population and the hard of hearing population. The impact was greatest for the hard of hearing group, because both alarms performed well with the hearing population and poorly among the deaf populations.

![Figure 36](image)

**Figure 36 – Waking effectiveness of high and low frequency alarms for all subjects and hard of hearing subjects [100]**

The authors performed an analysis by extrapolating the test data to the overall American population based on data from the National Health and Vital Statistics census from the Center for Disease Control. This data
indicated 83% of Americans having normal hearing, 14% are hard of hearing, and 3% are deaf. Based on this analysis, the low frequency alarm was estimated to be 90% effective overall while the high frequency alarm was estimated to be 83% effective.

5.6.14 Bruck and Ball 2005 [101]

In 2005 Dorothy Bruck and Michelle Ball published a paper summarizing and adding analysis to their previous research work. This paper broke down statistics of who dies in fires, highlighting the at-risk populations and then compared their test results based on these at-risk populations. Bruck and Ball emphasized that the low frequency alarm required a 13 dBA lower SPL to awaken sober adults and was twice as likely to waken children aged 6-10 at 89 dBA than the high frequency alarms tested. These conclusions were based on their previous research.

This paper included a tabular comparison of several of the most prominent waking studies, including Nober et al. [34], Kahn [70], Bruck and Horason [79], Bruck [85], Ball and Bruck [94], and Ashley [100]. This table has been reproduced in Table 5 in its entirety.

**Table 5 – Summary of details from articles on arousal to smoke alarms in adults by Bruck and Ball [101]**

<table>
<thead>
<tr>
<th>Authors and Year</th>
<th>Signal details</th>
<th>dBA at pillow</th>
<th>Background dBA</th>
<th>Time of night/ sleep stage</th>
<th>N</th>
<th>Age: years</th>
<th>Result: % awoke</th>
<th>Result: latencies of those who awoke</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nober et al 1981 [34]</td>
<td>3000-5000Hz</td>
<td>55</td>
<td>n/a</td>
<td>Varying</td>
<td>10</td>
<td>18-29</td>
<td>100%</td>
<td>within 21 sec</td>
</tr>
<tr>
<td></td>
<td>70</td>
<td>n/a</td>
<td>10</td>
<td>100%</td>
<td>within 16 sec</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>85</td>
<td>n/a</td>
<td>10</td>
<td>100%</td>
<td>within 11 sec</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>70</td>
<td>53</td>
<td>10</td>
<td>100%</td>
<td>within 85 sec</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>55</td>
<td>53</td>
<td>10</td>
<td>100%</td>
<td>within 75 sec</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Kahn 1984 [70]</td>
<td>2000-4000 Hz</td>
<td>44</td>
<td>44</td>
<td>2, 4 and 6 hrs after lights out</td>
<td>12</td>
<td>mean =21.3</td>
<td>25%</td>
<td>within 20 minutes</td>
</tr>
<tr>
<td></td>
<td>54</td>
<td></td>
<td>12</td>
<td>50%</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>78</td>
<td></td>
<td>12</td>
<td>100%</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Bruck and Horasan 1995 [79]</td>
<td>2000-4000 Hz</td>
<td>60</td>
<td>&lt;30</td>
<td>stage 4</td>
<td>8</td>
<td>18-24</td>
<td>87%&lt;sup&gt;a&lt;/sup&gt;</td>
<td>Mean = 79 sec</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>stage 2</td>
<td>8</td>
<td>75%&lt;sup&gt;a&lt;/sup&gt;</td>
<td>Mean = 12 sec</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>REM</td>
<td>8</td>
<td>75%&lt;sup&gt;a&lt;/sup&gt;</td>
<td>Mean = 20 sec</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Bruck 1999 [84]</td>
<td>2000-4000Hz</td>
<td>60</td>
<td>n/a</td>
<td>1 am-4.30 am</td>
<td>16</td>
<td>30-59</td>
<td>100% on both nights</td>
<td>within 32 sec</td>
</tr>
<tr>
<td>Ball and Bruck 2004 [94]</td>
<td>Female voice 300-2500Hz</td>
<td>B</td>
<td>n/a</td>
<td>stage 4</td>
<td>12</td>
<td>18-25</td>
<td>59.6 dBA (14.06)&lt;sup&gt;c&lt;/sup&gt;</td>
<td></td>
</tr>
<tr>
<td></td>
<td>4000-5000Hz</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>72.5 dBA (17.77)&lt;sup&gt;c&lt;/sup&gt;</td>
<td></td>
</tr>
<tr>
<td></td>
<td>T-3 500-2500Hz</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>59.2 dBA (15.64)&lt;sup&gt;c&lt;/sup&gt;</td>
<td></td>
</tr>
<tr>
<td>Ashley et al 2005 [100]</td>
<td>3100 Hz</td>
<td>&gt;75</td>
<td>n/a</td>
<td>stage 4</td>
<td>32</td>
<td>adult</td>
<td>96%</td>
<td>within 120 sec</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>stage 2</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>REM</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
The authors acknowledged that existing smoke alarms were generally effective for adults with normal hearing who are not intoxicated, sleep deprived, or in high background noise environments. They indicate that the low frequency alarms have not only performed better for the at-risk groups (children, the elderly, hard of hearing) but that it performed better for the normal adult population as well, by as much as 13 dBA AAT. They attribute this effect to the presence of the low frequency tones within the normal speaking ranges below 2500 Hz.

5.6.15 Bruck, Thomas, and Kritikos 2006 [22]

In 2006 Bruck, Thomas, and Kritikos reported data from another waking study on older adults. This study focused on adults aged 65-83 (73.1 ± 5.6). Tests were conducted using similar methods as previous Bruck studies. This included testing subjects in their own homes and playing pre-recording sounds from a set of speakers placed 1 meter from the pillow. The subjects were monitored for sleep stage by EEG and a tone was played 90 seconds after the subjects reached Stage 3 sleep, increasing from 35 dBA to 95 dBA in 5 dBA increments over 30 second intervals. The subjects indicated waking by calling from a phone located 15 meters from the bed. Tests were conducted over 2 nights separated by 1 week with two sounds tested per night.

This study included 45 older adults. Ambient background noise was measured during testing (39.4 dBA ±.46, 33.5-50.5 dBA Range). Tests were conducted using a high frequency alarm, a low frequency harmonic alarm (referred to as Mixed T3 in the report), a 500 Hz pure tone, and a recorded deep male voice. The authors note the origin of each sounds as:

+ Low frequency harmonic (mixed T3) from Simplex 1996 4100 Fire Alarm Audio CD
+ High frequency alarm recorded from a US smoke alarm (Kidde)
+ Male voice recorded from actor with a deep voice
+ Low 500 Hz tone generated by computer program

The cumulative waking effectiveness for each of the four signals among the test group is shown in Figure 37. The high frequency tone awoke 81% of the test subjects with 75 dBA at the pillow, but no additional subjects awoke from 70-75 dBA. To achieve an 81% cumulative effectiveness with the low frequency harmonic based on this data, a SPL of 61 dBA would be required. This is an overall reduction, at equal effectiveness, of 9-14 dBA. The male voice and pure 500 Hz tone show some initial response at low SPL, but as the SPL increases the cumulative waking approaches that of the high frequency tone.
A statistical analysis of the waking effectiveness for the various alarms is shown in Table 6. The low frequency harmonic alarm was effective at a reduced mean SPL of 15.7 dBA. The median SPL of the low frequency harmonic was 20 dBA more effective than the high frequency tone.

**Table 6 – Summary of waking responses for four alarm signals for older adult populations [22]**

<table>
<thead>
<tr>
<th></th>
<th>Low Frequency</th>
<th>Male Voice</th>
<th>High Frequency</th>
<th>500 Hz</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>AAT (dBA)</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mean</td>
<td>48.0</td>
<td>55.9</td>
<td>63.7</td>
<td>52.6</td>
</tr>
<tr>
<td>StDev</td>
<td>13.3</td>
<td>19.2</td>
<td>15.3</td>
<td>18.1</td>
</tr>
<tr>
<td>Range</td>
<td>35-85</td>
<td>35-105</td>
<td>35-105</td>
<td>35-105</td>
</tr>
<tr>
<td>Median</td>
<td>45</td>
<td>50</td>
<td>65</td>
<td>45</td>
</tr>
<tr>
<td><strong>N (%) slept</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>thru 75 dBA</td>
<td>2</td>
<td>6</td>
<td>8</td>
<td>7</td>
</tr>
<tr>
<td>(4.6%)</td>
<td>(14.0%)</td>
<td>(18.3%)</td>
<td>(15.5%)</td>
<td></td>
</tr>
<tr>
<td><strong>N (%) slept</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>thru 85 dBA</td>
<td>1</td>
<td>4</td>
<td>2</td>
<td>3</td>
</tr>
<tr>
<td>(2.3%)</td>
<td>(9.3%)</td>
<td>(4.6%)</td>
<td>(6.6%)</td>
<td></td>
</tr>
<tr>
<td><strong>N (%) slept</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>thru 95 dBA</td>
<td>0</td>
<td>3</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>(0%)</td>
<td>(7.0%)</td>
<td>(2.3%)</td>
<td>(2.3%)</td>
<td></td>
</tr>
<tr>
<td><strong>Behavioral Response Time</strong></td>
<td>Mean</td>
<td>93.3</td>
<td>153.9</td>
<td>192.1</td>
</tr>
<tr>
<td></td>
<td>StDev</td>
<td>77.9</td>
<td>147.7</td>
<td>105.2</td>
</tr>
<tr>
<td></td>
<td>Range</td>
<td>6-324</td>
<td>19-600</td>
<td>11-600</td>
</tr>
<tr>
<td></td>
<td>Median</td>
<td>75</td>
<td>91</td>
<td>197.5</td>
</tr>
</tbody>
</table>

Based on the analysis of this data, the authors recommended that the voice alarm should not be considered further for adult populations. The expected improvements due to emotional response from voice alarms did not manifest in the older adult population, and they expressed concerns about effectiveness for non-english speaking segments of the population.
Overall, the median AAT of the low frequency harmonic signal was better than the high frequency tone by 20 dB, 45 to 65 dBA, respectively. In total, 18% of subjects slept through the high frequency alarm at 75 dBA while only 5% slept through the low frequency harmonic at 75 dBA. There was minimal improvement from the pure tone 500 Hz or male voice over the high frequency alarm. The authors believed that the effectiveness of the harmonic may be due to the complexity of the tone (with harmonics), and not just the low primary frequency. The authors warn of generalizing these AAT levels to the overall population.

5.6.16 Bruck, Thomas, and Ball June 2007 [102]

In a June 2007 report for the NFPA Research Foundation Bruck, Thomas, and Ball reported on a new study of 32 adults to determine the effectiveness of various tones to awake individuals under the influence of alcohol. These tests were conducted using similar methods to the previous work of Bruck. Each subject received 6 alarm signals over the course of 2 test nights while sleeping in their own beds. Signals were presented after the subjects had reached Stage 4 sleep as indicated by an EEG. The subjects aged 18-26 and had consumed vodka in sufficient quantity to achieve BAC = 0.05 before going to sleep.

Testing included four distinct alarm tones; a 400 Hz harmonic, a 520 Hz harmonic, a 500 Hz pure tone signal, and a 3100 Hz tone recorded from a real smoke alarm. Tones were initiated at 55 dBA and increased in 10 dBA steps with 30 second on/off cycles until reaching 95 dBA. Tones were played through speakers placed 1 m from the pillow. The subjects were to push a bedside button after waking.

The authors developed a system to assign waking scores based on time / dBA at time of awakening to rank the results. Simply put, a score was issued based on the dBA level at the time of awakening. A range of 10 scores were given to account for subjects waking during the silent 30 seconds between alarm presentations. For example, if the subject awoke during the 75 dBA signal, a score of 5 was issued. If they awoke during the 30 second silence after 75 dBA, a score of 6 was issued. The benchmark for awakening was LEVEL 5, a 75 dBA presentation of the alarm signal. The waking score system, and SPL at the time of waking for each score, are summarized in Figure 38.

![Figure 38 - SPL for each waking score assigned by Bruck, Thomas and Ball [102]](image)

The cumulative percentages of people waking to each of the audible test tones are summarized in Figure 39. These percentages include subjects who awoke during the silence after a tone (e.g., waking score 6) as occurring at the SPL of the tone prior to the silence. This figure also shows a benchmark level of performance, based on a 75 dBA, 3100 Hz tone waking 61.5% of test subjects. Extrapolating against the 520 Hz harmonic tone, this would estimate a SPL of 58 dBA, or realistically somewhere between 55 dBA and 65 dBA. This result
agrees with other low frequency harmonic tests conducted by Bruck, which estimate between 10-20 dBA reduction in SPL to achieve equivalent waking performance to high frequency alarm tones. Even at a reduction of 10 dBA to 65 dBA, the 520 Hz tone was 93% effective at waking, more than 30% greater than the 3100 Hz tone at 75 dBA.

![Figure 39 – Cumulative waking effectiveness for each test tone as a function of SPL for subjects BAC = 0.05 [103]](image)

Overall analysis of the data indicates that 93-100% of subjects were awoken by the 400 and 520 Hz harmonic tones at 75 dBA at the pillow. At the same benchmark SPL, the recording of the 3100 Hz smoke alarm only awoke 61.5% of the subjects. Overall, both low frequency harmonic tones performed consistently and clearly better than the pure 500 Hz tone or the smoke alarm recording. Fundamentally, there were no differences observed between the 400 and 520 Hz harmonics.

The authors provide some commentary on possible reasons for the performance of the harmonics. They note the dissonant sound and the impression of fullness from harmonic tones. They note that humans respond best to sounds with ranges of frequencies during sleep, but that speech yielded inconsistent results in previous tests, so this is not the entire answer.

**5.6.17 Bruck and Ball August 2007 [103]**

In September of 2007, Bruck and Ball wrote a summary article in the Journal *Human Factors*. This article summarized some of the previous work and conclusions with a few clarified recommendations and references. After conducting several tests that identified the efficacy of the low frequency harmonics, the authors conducted an enhanced breakdown of the benefits of the low frequency tone, including attenuation through homes and human-based perceptions.

This report also included some analysis of how the low frequency signal could be generated in smoke alarms, having only tested previously using computer generated recordings through speakers. This is the first report where the ability to produce the low tone on a smoke alarm using batteries had been questioned. The authors directly referenced a comment by Robert Schifiliti on proposal 72-367 in 2005 (NFPA 72) that a smoke alarm with a 500 Hz tone signal was produced “within a week” using a 24 VDC audible alarm at 70 dB at 0.5 m with 110 mA current with strobe [104]. Despite this early optimism, the development of portable smoke alarms producing low frequency harmonic tones has proven a challenge over last decade.
5.6.18 **Bruck and Thomas 2008 [105] [106]**

In 2008, Dorothy Bruck and Ian Thomas co-wrote papers for IAFSS [105] and for *Fire Technology Journal* [106] detailing their previous literature and experimental work. The IAFSS paper summarized the problems with smoke alarm notification and summarized numerous studies detailing AAT experiments, sound transport, and human response. The journal article detailed the experiments conducted to evaluate the various tones on the older population, summarized already in Section 5.6.15.

5.6.19 **Bruck, Ball, Thomas, and Rouillard 2009 [107]**

In 2009 Bruck et. al. reported on another waking experiment intended to evaluate the AAT of various signals compared to the 520 Hz harmonic. Previous work had clearly demonstrated an improvement over high frequency alarms, but this work attempted to identify the best signal among a range of options. In this work, a direct comparison of the waking effectiveness of the high pitch and low frequency harmonic tones at fixed SPLs in various experiments was assessed and summarized in Table 7. As shown, the improvement in response ranges from mathematically infinite (100% woken by low frequency) to 4:1 for adults over 65 years of age. Improvements are observed across the test groups.

**Table 7 – Comparative effectiveness of 520 Hz harmonic and high frequency smoke alarm tones [107]**

<table>
<thead>
<tr>
<th>Participants</th>
<th>Alarm volume</th>
<th>% slept through</th>
<th>high pitched current alarm</th>
<th>520 Hz harmonic</th>
<th>Ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>children aged 6-10 yrs</td>
<td>89 dBA</td>
<td>43%</td>
<td>3.5%</td>
<td></td>
<td>12:1</td>
</tr>
<tr>
<td>deep sleeping young adults</td>
<td>75 dBA</td>
<td>43%</td>
<td>7%</td>
<td></td>
<td>6:1</td>
</tr>
<tr>
<td>older adults aged &gt; 65 yrs</td>
<td>75 dBA</td>
<td>18%</td>
<td>4.5%</td>
<td></td>
<td>4:1</td>
</tr>
<tr>
<td>hard of hearing adults</td>
<td>75 dBA</td>
<td>56%</td>
<td>8%</td>
<td></td>
<td>7:1</td>
</tr>
<tr>
<td>0.05 BAC young adults</td>
<td>75 dBA</td>
<td>38.5%</td>
<td>0%</td>
<td></td>
<td>n/a</td>
</tr>
<tr>
<td>sober young adults</td>
<td>75 dBA</td>
<td>21%</td>
<td>0%</td>
<td></td>
<td>n/a</td>
</tr>
</tbody>
</table>

A subsequent set of experiments were conducted on a group of 39 adults aged 18-27 years with no sleep disorders or medication. Subjects were pre-screened for normal hearing and ¾ slept at home while ¼ slept in the laboratory. Testing was conducted on 3 separate nights at least 1 week apart. Subjects were screened to ensure there was no sleep deprivation.

Tests were conducted in two parts. In Part A, nine signals, including low to mid-range short beeps, pure tones, frequency shifting whoops, and white noise were evaluated. In Part B, the effects of temporal manipulation were investigated by inserting silences between the beeps (12 seconds of beeps then 0, 10, or 21 second intervals). Part B was conducted with the best performing signal from Part A only, the 520 Hz harmonic tone. Subjects were told they would be awoken, but not played the tones before sleeping. Subjects indicated waking by pressing a button next to the bed.

Sleep was monitored by EEG during testing with tones initiated 90 seconds after reaching Stage 4 sleep. Tones were increased from 35 to 95 dBA in 5 dBA increments (Part A) or 10 dBA increments (Part B) in 30 or 66 second periods.
The 520 Hz harmonic tone awoke subjects at the lowest AAT as shown in Table 8. The various other signals were included to be certain the harmonic performed best, and this conclusion was evident from the data. All four harmonics produced the lowest AAT. White noise also produced AAT below the pure tone signals. A surprising result was that the frequency shifting signals, the “whoops” performed worst of all tones tested. This comparison was provided to indicate that the 520 Hz harmonic tone was not only superior to the high frequency alarms, but also to all other alternative tones evaluated.

Table 8 – Comparison of mean SPL to awaken for various tones across several test series [107]

<table>
<thead>
<tr>
<th>Number of Tests</th>
<th>Mean arousal threshold (dBA)</th>
<th>Standard Deviation</th>
<th>Min</th>
<th>Max</th>
</tr>
</thead>
<tbody>
<tr>
<td>520 Hz harmonic</td>
<td>45.5</td>
<td>6.9</td>
<td>35</td>
<td>65</td>
</tr>
<tr>
<td>400 Hz harmonic</td>
<td>46.2</td>
<td>7.0</td>
<td>35</td>
<td>65</td>
</tr>
<tr>
<td>800 Hz harmonic</td>
<td>51.8</td>
<td>10.1</td>
<td>35</td>
<td>70</td>
</tr>
<tr>
<td>1600 Hz harmonic</td>
<td>53.2</td>
<td>9.7</td>
<td>40</td>
<td>75</td>
</tr>
<tr>
<td>3 harmonics at 520, 800, 1200 Hz</td>
<td>54.6</td>
<td>10.8</td>
<td>35</td>
<td>70</td>
</tr>
<tr>
<td>White noise</td>
<td>59.6</td>
<td>18.1</td>
<td>35</td>
<td>(100)</td>
</tr>
<tr>
<td>3 pure tones at 400, 800, 1600 Hz</td>
<td>60.5</td>
<td>9.3</td>
<td>40</td>
<td>85</td>
</tr>
<tr>
<td>400 to 1600Hz whoop</td>
<td>61.3</td>
<td>16.7</td>
<td>35</td>
<td>95</td>
</tr>
<tr>
<td>400 to 800 Hz whoop</td>
<td>66.3</td>
<td>12.9</td>
<td>40</td>
<td>95</td>
</tr>
</tbody>
</table>

The authors referenced the theory of critical band widths by Zwicker as a possibility for the effectiveness of the 400 and 520 Hz harmonics. The apparent loudness of such tones is increased yet not quantified by the A-weighted sound meter. They also propose this as the reason why speech tones, which have broad spectra without clear peaks, is not as effective as the harmonic tones.

In Part B, the authors did not observe any significant advantage in using intermittent silence to the signals, although the 10 second break every 12 seconds showed some improvement over the other silence periods testing.

5.6.20 Code Status Update – 2009

In 2009 the ICC codes changed the 70 dBA pillow threshold to a 75 dBA threshold. This brought the ICC codes into harmonization with NFPA 72, and all other major building and design codes. This change is summarized in Figure 40.
5.7 2010 - 2019

5.7.1 Thomas and Bruck 2010 [108]

Thomas and Bruck published an article in *Fire Technology* in 2010 (written in 2008) summarizing the previous decade of research on waking effectiveness. Analysis and visualization of previous data was improved for this analysis. The presented results have been summarized here specifically to compare the effectiveness of 3100 Hz smoke alarms at 75 dBA, by percentage of subjects awoken, to the SPL of 520 Hz harmonic alarms to achieve equivalent waking effectiveness. Table 9 shows the cumulative number of test subjects awoken at or below SPL of 75 dBA for the 3100 Hz alarms and the SPL of the 520 Hz harmonic alarms to achieve the same number of woken subjects.

**Table 9 – Comparison of SPL of 520 Hz Harmonic to achieve equivalent waking effectiveness as 75 dBA 3100 Hz Alarm in decade of studies by Bruck et. al. [108]**

<table>
<thead>
<tr>
<th>Test Group</th>
<th>Number of Subjects</th>
<th>Waking Effectiveness of SPL ≤ 75 dBA – 3100 Hz Tones</th>
<th>SPL of 520 Hz tone to achieve equivalent effectiveness</th>
<th>Reduction in SPL for Equivalent Waking</th>
</tr>
</thead>
<tbody>
<tr>
<td>Older Adults 65-83</td>
<td>42</td>
<td>81%</td>
<td>61 dBA</td>
<td>-14 dBA</td>
</tr>
<tr>
<td>Adults with hearing loss</td>
<td>38</td>
<td>56%</td>
<td>&lt;55 dBA</td>
<td>&gt; -20 dBA</td>
</tr>
<tr>
<td>Sober young adults (18-26)</td>
<td>14</td>
<td>57%</td>
<td>61 dBA</td>
<td>-14 dBA</td>
</tr>
<tr>
<td>Young adults BAC = 0.05</td>
<td>14</td>
<td>36%</td>
<td>63 dBA</td>
<td>-12 dBA</td>
</tr>
<tr>
<td>Young adults BAC = 0.05</td>
<td>32</td>
<td>61%</td>
<td>55-65 dBA</td>
<td>-10 to -20 dBA</td>
</tr>
<tr>
<td>Young adults BAC = 0.08</td>
<td>14</td>
<td>36%</td>
<td>65 dBA</td>
<td>- 10 dBA</td>
</tr>
</tbody>
</table>

Overall, the 520 Hz harmonic was as effective as the 3100 Hz tone with a reduced SPL of 10-20 dBA among these various populations. The cumulative alarm thresholds for the various studies used to estimate the reduction in SPL are shown in Table 10.
Table 10 – Cumulative waking effectiveness of 3100 Hz and 520 Hz harmonic alarms in decade of studies by Bruck et. al. [108]

<table>
<thead>
<tr>
<th>Age Group</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Older adults (age 65–83 years, n = 42)</td>
<td>Data from [22]</td>
</tr>
<tr>
<td>Adults (age 18–77 years, n = 38)</td>
<td>With mild to moderately severe hearing loss as a function of sound level</td>
</tr>
<tr>
<td>Sober young adults (age 18–26 years, n = 14)</td>
<td>As a function of sound level [94]</td>
</tr>
</tbody>
</table>
### 5.7.2 Code Status Update – 2010

Based mostly on the numerous research studies and articles by Bruck et. al. at Victoria University, NFPA 72 was changed in 2010 to include requirements for low frequency tones for sleeping areas and the hard of hearing. Section 18.4.5.3 was written to include:

18.4.5.3* Effective January 1, 2014, where audible appliances are provided to produce signals for sleeping areas, they shall produce a low frequency alarm signal that complies with the following:

1. The alarm signal shall be a harmonic or provide equivalent awakening ability.
(2) The wave shall have a fundamental frequency of 520 Hz± 10 percent.

Chapter 18 is specifically applicable to notification appliances only. The Appendix (A.18.4.5.3) includes some commentary defining the 520 Hz harmonic signal. This section also makes clear that other sounds that demonstrate equivalent performance to the 520 Hz harmonic at the same SPL would be acceptable.

Chapter 24 was changed to require Emergency Voice notification systems to include a 520 Hz tone when used in sleeping areas.

Section 29.3.8.1 required 520 Hz harmonic tones for single and multiple station alarms for people with mild to severe hearing loss. Chapter 29 does not include any other requirements for low frequency alarms in dwellings with single and multiple station alarms. The changes to NFPA 72 2010 are summarized in Figure 41.

![Figure 41](image)

*Figure 41 – Code Status Update – 2010 – NFPA 72 includes requirements for 520 Hz Square Wave Sleeping Areas and for Hard of Hearing (effective Jan 2014)*

5.7.3 Pilon, Desautels, Montplaisir, and Zadra 2012 [109]

A 2012 journal article in *Sleep Medicine* by Pilon, Desautels, Montplaisir and Zadra details experiments evaluating whether sleepwalkers are more difficult to awaken than control groups. In the experiments, 10 adult sleepwalkers and 10 control adults were tested for waking response during normal sleep and during daytime recovery sleep following 25 hours of sleep deprivation. Sounds were presented during FWS, SWS, and REM using 1000 Hz tones for 3 seconds. After 57 seconds of silence, the tones were increased in 10 dB intervals from 40 through 90 dB. Tones were played through earphones after each sleep stage had been sustained for 1 minute. The mean SPL to induce either awakening or arousal (EEG response) for the sleepwalkers and controls are shown in Table 11.
Table 11 – Mean SPL that induced awakening or arousal during SWS, FWS, or REM sleep in sleepwalkers and controls during normal or recovery sleep (reproduced from [109])

<table>
<thead>
<tr>
<th>Mean AS intensity (in dB) that induced:</th>
<th>Normal sleep</th>
<th>Recovery sleep</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>SW</td>
<td>Controls</td>
</tr>
<tr>
<td>Awakenings during SWS</td>
<td>53.8 (11.1)</td>
<td>56.3 (13.5)</td>
</tr>
<tr>
<td>Arousal responses during SWS</td>
<td>52.3 (9.9)</td>
<td>53.6 (8.6)</td>
</tr>
<tr>
<td>Awakenings during FWS</td>
<td>55.3 (11.7)</td>
<td>63.0 (20.7)</td>
</tr>
<tr>
<td>Arousal responses during FWS</td>
<td>53.9 (9.6)</td>
<td>57.8 (21.0)</td>
</tr>
<tr>
<td>Awakenings during REM</td>
<td>94.1 (8.6)</td>
<td>70.0 (22.0)</td>
</tr>
<tr>
<td>Arousal responses during REM</td>
<td>80.4 (16.2)</td>
<td>64.0 (19.4)</td>
</tr>
<tr>
<td>Average</td>
<td>65.0</td>
<td>60.8</td>
</tr>
</tbody>
</table>

The AAT responses during FWS and SWS sleep did not differ between the sleepwalkers and control groups, but sleepwalkers required significantly higher AAT during REM sleep. Even for the control group, REM sleep AAT were higher than SWS, which is not in agreements with most other experimental studies. There is a distinctly higher AAT for the sleepwalkers in REM, requiring 87.3 dBA for normal sleep.

5.7.4 Code Status Update – 2012

In 2012, the UL standards for alarms, detectors, and notification appliances were changed to include reference to the 520 harmonic tones, including definitions of the frequency requirements for the tones. The ICC building codes do not include reference to low frequency sounders nor require their use in any specific application. The ICC codes from 2012 do reference meeting the requirements of NFPA 72 – 2010 edition. This edition of NFPA 72 requires the use of low frequency sounders in sleeping areas and for the hard of hearing as detailed in Section 5.7.2. The 2012 changes to UL and ICC as proliferated from the NFPA 72 changes are shown in Figure 42.

Figure 42 – Code Status Update – 2012 – Low frequency requirements into ICC and UL

5.7.5 Roberts 2013 [110]

In 2013 a summary of the history and status of technology in the smoke alarm industry was written by Richard Roberts from Honeywell Fire Safety. This document details the history of the technological changes that made smoke alarms available for residential use, reaching as far back to the development of reduced voltage alarms in the 1960s. This report also discusses the research work that led to and the resulting code requirements for low frequency alarms. As this report is written from the perspective of manufacturers, there is considerable discussion about the challenges for manufacturers to produce low frequency alarms because of the additional power compared to 2-4 kHz tones. Roberts notes that there are notification appliances for fire alarm systems
that can meet the sound production requirements, but that (as of 2013) there were no smoke or carbon monoxide alarms that could produce the 520 Hz tone.

5.7.6 Code Status Update – 2013

In 2013, a minor change was made to the appendix of NFPA 72 discussing the Chapter 18 requirements for low frequency sounders. In this edition, the appendix specifically notes that this requirement is only applicable for notification appliances connected to fire alarm or emergency communications systems and states that single- and multiple-station alarms in dwellings are not covered by this section of the code. It also clarifies that sleeping areas are meant to include any areas where people may reasonably sleep, such as in living rooms, but not hallways or lobbies.

Chapter 29, which includes the requirements for single- and multiple-station alarms, only requires low frequency alarms for people with hearing loss and does not include the requirement for all sleeping areas.

5.7.7 Lykiardopoulous 2014 [111]

In a 2014 Doctoral Thesis by Chris Lykiardopoulous at Victoria University, under the supervision of Bruck and Ball, a study was conducted to evaluate alarm signals for subjects taking hypnotic drugs. Hypnotics are drugs prescribed for treatment of insomnia. This study was undertaken because of the prevalence of hypnotic drugs among the adult population and the correlation to frequency of fire initiating accidents and a reduced responsiveness to alarms. In addition to the report of tests, this document includes details on discussion on human sleep and insomnia, the prevalence of hypnotic drug use, statistical analysis of fire data relating to at-risk populations, and an assessment of Australian smoke alarm and sounding requirements.

Lykiardopoulous notes that the only other study to evaluate hypnotics was conducted by Johnson et. al. in 1987 using triazolam. He expressed concerns with the limited methodology used for that study, including the inconsistent inclusion or exclusion of subjects, changes in modern hypnotics compared to triazolam from the 1980s, and the fact that all tests were conducted in a sleep laboratory on young adults.

A study was conducted to evaluate waking response of 11 women and two men aged 65-80 years. The subjects all took hypnotics (majority temazepam) and were compared to the control data set from Bruck and Thomas of similar aged subjects. Subjects were tested sleeping in their own homes using a remotely activated computer and speaker system. The speakers played recorded 3100 Hz and 520 Hz harmonic tones from 35-95 dBA in 5 dBA increments of 30 second duration with 10-20 second silences between (ascending method of limits). The subjects were judged awake after pressing a bedside button three times.

Participants were monitored over 11 nights. Sleep habits were monitored using a motion sensing Actigraph watch. Alarm presentations were selected for each subject to correspond to the likely peak hypnotic effects based on bedtime and consumption time.

The 520 Hz harmonic tone significantly outperformed the 3100 Hz sine wave in users of hypnotics. The percentage of subjects awoken at each SPL is shown in Figure 43. At 75 dBA, the 3100 Hz tone awoke 83% of subjects on hypnotics and 91% of subjects on no drugs. The 520 Hz harmonic tone achieved 91% waking at 52.4 dBA (interpolated from 83% at 50 dBA and 100% at 55 dBA) for subjects taking no drugs, a reduction in SPL of greater than 20 dBA. When the subjects had taken hypnotic drugs, the 520 Hz signal achieved an 83% waking effectiveness at a SPL of 58.7 dBA (interpolated from 58% at 55 dBA and 92% at 60 dBA), a reduction of over 16 dBA.
Figure 43 – Cumulative waking percentage for 520 Hz harmonics and 3100 Hz tones for subjects with and without hypnotic drugs [111]

A comparison of the AAT for the 520 Hz harmonic and 3100 Hz tones is shown in Figure 44. By average, the AAT for the 520 Hz harmonic was 12 dBA lower than the 3100 Hz tone when subjects were taking the hypnotics or not. This is greater than the effect of the hypnotics, which increase AAT by 9 dBA for both alarm signals.

Figure 44 – Mean AAT for 520 Hz harmonics and 3100 Hz tones for subjects taking hypnotics and subjects on no drugs [111]

5.7.8 Edwards Detection and Alarm 2015 [112]

In 2015 Edwards Detection and Alarm company released a handbook detailing the requirements for low frequency alarms. This document describes the requirements from the perspective of designers, manufacturers, or building code officials to understand how to enforce and implement low frequency alarms. This document stresses that the sleeping area requirements only apply to notification devices and not for single- and multiple-station alarms. It also details the requirements for the hard of hearing and emergency voice systems and note the exceptions for care homes or institutions where there are 24/7 staff monitoring. This document explains that
the low frequency requirements only apply to new construction and certain renovation projects. Concerns are also expressed that speakers for voice notification that can produce 520 Hz signals do not meet the requirements unless they have been listed by UL, i.e. just because they “can” doesn’t mean they are compliant.

Although NFPA 72 does not require 520 Hz for single- and multiple-station alarms in residential, the authors believe that building codes may require this in the future.

5.8 SUMMARY OF WAKING TEST DATA
A broad range of AAT tests have evaluated the most effective ways to awaken sleeping people for the last 50 years. These tests have produced some disparate quantified values for the SPL required to awaken people from different or similar populations. The trends of observed in the relative performance of alarm tones and signals, and the increased challenges in awakening at-risk populations are more consistent. A summary of various relevant waking experiments, including the sponsoring organizations, total number of tests, evaluated tones, and various findings is provided in Table 12.
## Table 12 - Summary of Waking Studies

<table>
<thead>
<tr>
<th>Authors</th>
<th>Year</th>
<th>Sponsor/Organization</th>
<th>Test Signal</th>
<th>Signal Presentation</th>
<th>Test Subjects</th>
<th>Total Number Tests</th>
<th>Test Environment</th>
<th>Waking Criteria</th>
<th>Takeaway</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>W. B. Zimmerman [57]</td>
<td>1970</td>
<td>University of Chicago, Department of Psychology National Institute of Mental Health</td>
<td>800 Hz Pure tones</td>
<td>1 sec ON/8 sec OFF 5 dB increases</td>
<td>16 light 16 deep sleepers</td>
<td>32</td>
<td>224</td>
<td>Lab</td>
<td>Spoken phrase</td>
<td>1 night 7 alerts</td>
</tr>
<tr>
<td>F. B. Keefe, L. C. Johnson and E. J. Hunter [36]</td>
<td>1971</td>
<td>Navy Medical Neuropsychiatric Research Unit</td>
<td>1000 Hz tones</td>
<td>5 sec ON/ 55 sec OFF 5 dBA increments Speakers over bed</td>
<td>Adult males 28 - day sleepers 7 - night sleepers</td>
<td>35</td>
<td>35</td>
<td>Lab</td>
<td>Pressing a button EEG response</td>
<td>7 nights</td>
</tr>
<tr>
<td>T. Levere, R. T. Bartus, G. W. Morlock and F. D. Hart [10]</td>
<td>1973</td>
<td>North Carolina State University</td>
<td>125 Hz 250 Hz 1000 Hz</td>
<td>Speaker 15 second alarms all 80 dBA</td>
<td>College aged males</td>
<td>8</td>
<td>160</td>
<td>Mock room in lab</td>
<td>EEG response</td>
<td>1 night of testing 4 total eval 20 alerts 10 SWS, 10 FWS</td>
</tr>
<tr>
<td>C. Bradley and R. Meddis [83]</td>
<td>1974</td>
<td>Bedford College University of London</td>
<td>White noise +4 dB every 5 seconds</td>
<td>8 young volunteers</td>
<td>8</td>
<td>39</td>
<td>Lab</td>
<td>Pressing a button</td>
<td>1 night</td>
<td>Dream incorporation raises AAT, subjects woke at 60 dBA if not incorporated slept until 70 dBA if they dream incorporated</td>
</tr>
<tr>
<td>J. S. Lukas [65]</td>
<td>1975</td>
<td>NASA</td>
<td>U</td>
<td>College aged men and women</td>
<td>U</td>
<td>U</td>
<td>U</td>
<td>U</td>
<td>U</td>
<td>80% would awaken to 80 dBA Slight increases in dBA can have large impact</td>
</tr>
</tbody>
</table>

Pre 1970s Data – AAT responses increase for SWS compared to FWS, presentation of signals matters, 65 dBA is effective for most populations, Ideal signals are complex and low frequency or resembling human voice tones.
<table>
<thead>
<tr>
<th>Authors</th>
<th>Year</th>
<th>Sponsor/Organization</th>
<th>Test Signal</th>
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<th>Waking Criteria</th>
<th>Duration of Testing</th>
<th>Takeaway</th>
<th>Notes</th>
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</thead>
<tbody>
<tr>
<td>M. H. Bonnet, L. C. Johnson and W. B. Webb</td>
<td>1978</td>
<td>Naval Health Research Center</td>
<td>1000 Hz speaker</td>
<td>2 sec on/28 OFF +5 db</td>
<td>26 men (12 good/14 poor sleepers)</td>
<td>26</td>
<td>390</td>
<td>Lab</td>
<td>Push button 3 times and say I’m awake</td>
<td>5 nights 3 awakenings night, 5 awakenings</td>
<td>69±17 dB AAT Presentation of tone, ear piece v. speaker can greatly impact AAT more rapid presentation reduces AAT</td>
<td></td>
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<tr>
<td></td>
<td></td>
<td>University of Florida Gainesville</td>
<td>Ear piece</td>
<td>3 on / 3 off +2-5 dB</td>
<td>9 men</td>
<td>9</td>
<td>approx 90</td>
<td>Lab</td>
<td>Push button taped to hand</td>
<td>1-4 nights FL, 5 awakenings</td>
<td>49±18 dB AAT Ear piece reduces AAT</td>
<td></td>
</tr>
<tr>
<td>C. Weir [61]</td>
<td>1979</td>
<td>Department of Psychology at the University College of London</td>
<td>125-4000 Hz sine waves</td>
<td>U</td>
<td>Infants</td>
<td>U</td>
<td>U</td>
<td>U</td>
<td>U</td>
<td>Flat response by infants over 125-4000 Hz, range from 70-80 dB Response is not flat when compared in dBA 10 dBA better at 500 to 2000 Hz</td>
<td></td>
<td></td>
</tr>
<tr>
<td>E. H. Nober, H. Peirce, A. Well, C. C. Johnson and C. Clifton [34]</td>
<td>1980</td>
<td>NBS University of Massachusetts Amherst</td>
<td>Alarm Horn</td>
<td>tape recording 85, 70, or 55 dBA</td>
<td>30 college aged women and men</td>
<td>30</td>
<td>70</td>
<td>Homes</td>
<td>turn off alarm phone call</td>
<td>1 night randomly out of 7 test nights</td>
<td>All respond to all alarms; even with 55 dBA AC unit 55 dBA was slower, 70 is the same as 85 dBA Primary justification for 70 dBA at pillow</td>
<td></td>
</tr>
<tr>
<td>M. Kahn [70]</td>
<td>1984</td>
<td>NBS North Carolina State University</td>
<td>2000/4000 Hz alarm</td>
<td>alarm in various locations</td>
<td>24 college aged males</td>
<td>24</td>
<td>288</td>
<td>Mock room in lab</td>
<td>Pressing a button</td>
<td>Single night 3 alarms</td>
<td>78 dBA over 44 ambient woke all subjects, 65 dBA to awaken 50% of subjects estimated many did not awake at all</td>
<td></td>
</tr>
</tbody>
</table>

**Test Signal:**
- 1000 Hz speaker
- 125-4000 Hz sine waves
- Alarm Horn
- 2000/4000 Hz alarm

**Signal Presentation:**
- 2 sec on/28 OFF +5 db
- 3 on / 3 off +2-5 dB
- Tape recording 85, 70, or 55 dBA
- Alarm in various locations

**Test Subjects:**
- 26 men (12 good/14 poor sleepers)
- 9 men
- 30 college aged women and men
- 24 college aged males

**Waking Criteria:**
- Push button 3 times and say I’m awake
- Push button taped to hand
- Turn off alarm phone call

**Takeaway:**
- 69±17 dB AAT
- 49±18 dB AAT
- Flat response by infants over 125-4000 Hz, range from 70-80 dB
- All respond to all alarms; even with 55 dBA AC unit 55 dBA was slower, 70 is the same as 85 dBA Primary justification for 70 dBA at pillow

**Notes:**
- Presentation of tone, ear piece v. speaker can greatly impact AAT more rapid presentation reduces AAT
- Ear piece reduces AAT
- Flat response by infants over 125-4000 Hz, range from 70-80 dB Response is not flat when compared in dBA 10 dBA better at 500 to 2000 Hz
- 78 dBA over 44 ambient woke all subjects, 65 dBA to awaken 50% of subjects estimated many did not awake at all
<table>
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<tr>
<th>Authors</th>
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</tr>
</thead>
<tbody>
<tr>
<td>H. Zepelin, C. S. McDonald and G. K. Zammit [71]</td>
<td>1984</td>
<td>Oakland University Henry Ford Hospital</td>
<td>800 Hz</td>
<td>Ear-piece 5 seconds 10 dB increases</td>
<td>9 men and women from 3 age groups normal hearing</td>
<td>54</td>
<td>54</td>
<td>Lab</td>
<td>Press button</td>
<td>One conditioning night one test night</td>
<td>AAT decreases with age over 100 dB didn’t waken (18-25)</td>
<td></td>
</tr>
<tr>
<td>K. Busby and R. T. Pivik [72]</td>
<td>1985</td>
<td>University of Ottawa Ottawa General Hospital</td>
<td>1500 Hz</td>
<td>Ear-piece 3 sec on/off +2-5 dB</td>
<td>Medicated and non-medicated hyperkinetic and normal boys</td>
<td>24</td>
<td>432</td>
<td>Lab</td>
<td>Press button and say “I’m awake”</td>
<td>4 days, 2 acclimation and 2 testing</td>
<td>Children do not awaken to sounds up to 123 dB for all three test groups</td>
<td></td>
</tr>
<tr>
<td>L. C. Johnson, C. L. Spinweber, S. C. Webb and A. G. Muzet [73]</td>
<td>1987</td>
<td>Naval Health Research Center Centre d'Etudes Bioclimatiques du CNRS</td>
<td>Smoke alarm</td>
<td>78 dBA at pillow 1 minute intervals, 3 times if non-responsive</td>
<td>Adult males with insomnia placebo, 0.25 and 0.5 mg triazolam</td>
<td>36</td>
<td>216</td>
<td>Lab</td>
<td>U</td>
<td>5 nights, alarm on nights 1 and 4</td>
<td>All placebo subjects were awoken, 50% of the subjects on triazolam did not</td>
<td></td>
</tr>
<tr>
<td>D. Bruck and M. Horasan [79]</td>
<td>1995</td>
<td>Victoria University</td>
<td>Smoke Alarm 2000-4000 Hz</td>
<td>60 dBA recording speakers 10 minutes</td>
<td>Young adults Stage 4 sleep Naive of alarm</td>
<td>24</td>
<td>48</td>
<td>Lab</td>
<td>EEG response and waking</td>
<td>1 night 2 alarms</td>
<td>5 of 24 subjects slept through 10-minute alarm only 1 subject did anything about it</td>
<td></td>
</tr>
<tr>
<td>Rosenthal, L., Bishop, C., Helmus, T., Krstevska, S., Roehrs, T., and Roth, T. [80]</td>
<td>1996</td>
<td>Henry Ford Hospital</td>
<td>988 Hz tone</td>
<td>Head-phones 2 sec on/ 8 sec off 35-90 dB +5 dB</td>
<td>Healthy adults</td>
<td>27</td>
<td>216</td>
<td>Lab</td>
<td>Increase in EEG alpha waves</td>
<td>2 test night, 5+ days apart, 4 alarm per night</td>
<td>59-63 dBA on average with standard deviations of ±7-10 dBA reduced AAT later in the night</td>
<td></td>
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<tr>
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<tr>
<td>D. Bruck [84]</td>
<td>1998</td>
<td>Victoria University Fire Code Reform Research Program in Australia</td>
<td>60 dBA alarms</td>
<td>Alarm mounted on stand 3 minute alarm</td>
<td>20 juniors and 16 adults</td>
<td>36</td>
<td>144</td>
<td>Home</td>
<td>Motion in wrist-watch</td>
<td>4 nights, alarms on 2nd and 3rd only, 2 times</td>
<td>All adults awoke, 11 of 20 children slept both nights, 6 of 20 one night, only 3 woke both nights and were older children</td>
<td></td>
</tr>
<tr>
<td>C. Duncan [86]</td>
<td>1999</td>
<td>University of Canterbury</td>
<td>3000 Hz smoke alarms</td>
<td>Placed in hallways 255 second alarm</td>
<td>40 homes, 26 students, 10 Maori, 4 elderly</td>
<td>40+</td>
<td>229</td>
<td>Homes</td>
<td>Alarm shutoff by occupant</td>
<td>2 weeks, 3 alarms, 2 during sleeping hours</td>
<td>85% awakened, 35 of 229 did not awaken, 9 had consumed intoxicant, 18 were under 10 years old, and remaining 8 all had door closed with SPL 62-71 dBA only 1 child under 10 woke at all waking did not correlate to SPL</td>
<td></td>
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<tr>
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<tr>
<td>M. Nakano and I. Hagiwara [87]</td>
<td>2000</td>
<td>Research Institute of Technology Konoike Construction Building Research Institute, Ministry of Construction Japan</td>
<td>50-53 dBA bell 60-67 dBA siren 48-55 dBA voice broadcast in that order</td>
<td>building alarm system speakers</td>
<td>Trainees at disaster protection center</td>
<td>600</td>
<td>600</td>
<td>Training facility</td>
<td>Evacuation</td>
<td>1 night, 1 event, 3 subsequent alarms</td>
<td>90% evacuation in 120 seconds, 74% awoke to the initial bell, 9% to the siren, 7% by other subjects, and 2% to the voice broadcast 193 drank a lot and 70 were &quot;dead drunk&quot;</td>
<td></td>
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<tr>
<td>D. Bruck and A. Bliss [88]</td>
<td>2000</td>
<td>Victoria University</td>
<td>Smoke alarm 89 dBA alarms in bedrooms</td>
<td>Children 6-15 years old</td>
<td>28</td>
<td>56</td>
<td>Homes</td>
<td>Motion in wrist-watch</td>
<td>5 nights, 2 alarms in 2nd half of the night</td>
<td>Alarms cannot wake children no matter how loud we can make them 31.3 – 68.7 % of the real population of children would not awaken to 89 dBA</td>
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<tr>
<td>M. Ball and D. Bruck [94]</td>
<td>2004</td>
<td>Victoria University</td>
<td>LFH and HFA</td>
<td>recordings from speakers 35-90 dBA +5 dBA 3 tones during the night</td>
<td>young adults with and without alcohol 0.05 and 0.08 BAC in stage 4 sleep</td>
<td>12</td>
<td>108</td>
<td>Home</td>
<td>Press a button</td>
<td>3 non-consecutive nights</td>
<td>sobriety, to 0.05 BAC, to 0.08 BAC, the low frequency tone awoke subjects at reduced AAT of 13.3 dBA, 6.8 dBA, and 4.6 dBA high frequency (72, 85, 88 dBA) baselines</td>
<td></td>
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<tr>
<td>D. Bruck, S. Reid, J. Kouszma and M. Ball [95]</td>
<td>2004</td>
<td>Victoria University</td>
<td>LFH mother voice, actor voice</td>
<td>89 dBA</td>
<td>Children 6-15 years old</td>
<td>48 (20 voice, 14 low frequency, 14 high frequency)</td>
<td>152</td>
<td>Homes</td>
<td>Motion in wrist-watch</td>
<td>5 nights, 2 nights with alarms, only low frequency and high frequency 2 tests per night</td>
<td>19 children awoke to the mothers’ voice, 18 of 19 children awoke to the actors’ voice, 26 of 27 children awoke to the low frequency alarm, and only 16 of 28 children awoke to the high frequency alarm.</td>
<td></td>
</tr>
<tr>
<td>M. Ball and D. Bruck [96]</td>
<td>2004</td>
<td>Victoria University Centre for Environmental Safety and Risk Engineering (CESARE) Australian Research Council</td>
<td>House fire sounds actors voice mixed house/fire voice</td>
<td>speaker 35 dBA to 95 dBA in 30 second on/off cycles</td>
<td>Deep sleepers, 18-25 yo, stage 4 sleep Non-naïve of tones</td>
<td>8</td>
<td>8</td>
<td>6 in homes, 2 in lab</td>
<td>Press button 3 times</td>
<td>1 night</td>
<td>little difference between signals, but all three signals produced responses at ≤52 dBA, which shows potential compared to other signals</td>
<td></td>
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<tr>
<td>Authors</td>
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<tr>
<td>E. Ashley, J. DuBois, Klassen, M. and R. Roby [99]</td>
<td>2005</td>
<td>Combustion Science and Engineering University of Maryland National Institute of Health</td>
<td>LFH and HFA</td>
<td>Normal hearing hard of hearing deaf</td>
<td>111</td>
<td>121 (51 LFH)</td>
<td>Lab</td>
<td>Raised hand</td>
<td>1 night, maximum 3 alarms</td>
<td>At about 80 dBA, low frequency woke 100% to 92% for high frequency, 92% v. 57% for hard of hearing, 11% v. 0% for deaf. Based on census, the low frequency alarm was estimated to be 90% effective overall while the high frequency alarm was estimated to be 83% effective.</td>
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</tr>
<tr>
<td>D. Bruck, I. Thomas and A. Kritikos [22]</td>
<td>2006</td>
<td>Victoria University CESARE</td>
<td>LFH HFA 500 Hz pure tone, and male voice</td>
<td>Speaker 35 to 90 dBA 5 dBA in 30 second increments</td>
<td>Adults 65-83 years old</td>
<td>45</td>
<td>180 Homes</td>
<td>Phone call</td>
<td>2 nights, 2 sounds per night</td>
<td>81% waking at 75 dBA for high frequency same 81% at 61 dBA for low frequency. Low frequency harmonic 20 dBA better by median AAT</td>
<td></td>
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<tr>
<td>D. Bruck, I. Thomas and M. Ball [102]</td>
<td>2007</td>
<td>Victoria University CESARE</td>
<td>400 Hz 500 Hz harmonic 500 Hz pure 3100 Hz pure</td>
<td>35-95 dBA 10 dBA increment 30 sec on/off speakers</td>
<td>18-26 adults sober and 0.05 BAC stage 4 sleep</td>
<td>32</td>
<td>384 Homes</td>
<td>Push a button</td>
<td>2 nights, 6 signals</td>
<td>75 dBA, 3100 Hz tone waking 61.5% of test subjects 55-65 dBA for 61.5% for low frequency. 65 dBA low frequency is 93% effective. Both 400 and 500 Hz complex tones equivalent</td>
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<tr>
<td>D. Bruck, M. Ball, I. Thomas and V. Rouillard [107]</td>
<td>2009</td>
<td>Victoria University CESARE</td>
<td>Beeps, white noise, harmonic tones</td>
<td>12 second beeps, 0,12,21 second intervals Varying delays</td>
<td>Adults 18-27 Stage 4 sleep</td>
<td>39</td>
<td>468</td>
<td>3/4 at home 1/4 in lab</td>
<td>Pressing a button</td>
<td>3 nights 1 week apart, 4 signals per night</td>
<td>Harmonics and white noise were the best performing pure tones and whoops were the worst intermittent silence did not affect results speech with broad spectrum are not as effective as harmonic tones</td>
<td></td>
</tr>
<tr>
<td>M. Pilon, A. Desautels, J. Montplaisir and A. Zadra [109]</td>
<td>2012</td>
<td>Center for Advanced Research in Sleep Medicine University of Montreal</td>
<td>1000 Hz</td>
<td>3 sec on/57 off 10 dB 40-90 dBA Earphones</td>
<td>10 adult sleep walkers 10 non sleep walkers 25 hr sleep deprivation /day time sleep</td>
<td>20</td>
<td>240</td>
<td>Laboratory</td>
<td>10 second EEG wakefulness</td>
<td>1 screening night, 2 tests, one night sleep one daytime recovery sleep</td>
<td>Sleep walkers higher in REM 87 dBA 54 -70 dBA in other experiments without distinction</td>
<td></td>
</tr>
<tr>
<td>C. Lykiardopoulos [111]</td>
<td>2014</td>
<td>Victoria University CESARE</td>
<td>LFH HFA</td>
<td>speakers 35-95 dBA, 5 dBA increments 30 second sound, 10-20 second silence</td>
<td>11 women and 2 men 65-80 years old all taking hypnotics (sleeping pills)</td>
<td>13</td>
<td>52 13 drugged 3100 Hz, 13 drugged 520 Hz, 13 non-drugged 3100, 13 non-drugged 520 Hz</td>
<td>Homes</td>
<td>pressing a button 3 times</td>
<td>11 nights, 4 alarm nights, 2 drugged and 2 non-drugged</td>
<td>20 dBA reduction in low frequency SPL with no drugs to match high frequency responses, 16 dBA with drugs hypnotics increase AAT by 9 dBA, low frequency median lower by 12 dBA</td>
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</table>
As previously discussed, there is great difficulty in comparing the AAT results among multiple tests due to the confounding variables. With this many sets of experiments over 50 years it is possible to form a composite AAT score by weighting the studies by the number of test subjects and alarm presentations and gain an overall impression of the average AAT for various tones. In general, the AAT is reported as the mean or of the waking results, implying 50% of subjects of the test subjects were awoken at the reported SPL. Reporting this value was questioned by various fire safety researchers, as 50% is not reliable for protection of life safety. This was specifically criticized by Berry in his analysis of the work of Keefe used to justify the original 75 dBA thresholds [58], [36]. The reported value of 50% effectiveness is a good metric for averaging and comparing among various data sets.

Often in the collection and reporting of data the 50% threshold cannot be directly reported. For example, if a test is only conducted at one SPL, e.g. 65 dBA, and some percentage of the subjects were awoken, e.g. 80%. Direct comparison or inclusion of these results in the global assessment can be challenging. In order to overcome these limitations a method for estimating the 50% threshold from arbitrary SPL and waking percentages has been developed. This method estimates that the response to alarms generally follows a normal sigmoid function, or an “S” shaped curve as a function of the SPL. The sigmoid function, including a scaling factor to allow for calculation based on changes in SPL, is shown in Equation 1.

\[
Waking\text{Percentage} = \frac{e^x}{e^x + 1}
\]

where:
\[
x = Scaling\ Factor(\text{SF})(AAT_{50\%} - AAT_{\text{experiment}})
\]

Equation (1)

If the AAT\text{experiment} and the Waking Percentage from the experiment are known, the equation can be solved recursively to determine the AAT\text{50\%} for comparison between data sets. The sigmoid function, when compared to various known waking percentage / SPL distributions in the test data provides a relatively accurate representation of the data, with a strong reliance on the scaling factor (SF). Through inspection, a scaling factor of 0.24 was found to provide the most representative curves, while some sets favored 0.15 ≤ SF ≤ 0.30. Several representative real SPL and waking percentage plots are shown with representative sigmoid functions in Figure 45.
Using the sigmoid function with scaling factors of 0.15, 0.24, and 0.30, the average SPL to achieve 50% was determined from numerous data sets. These data sets were then compared to determine the average SPL for various test conditions, including pure tone signals (generally 800-1000 Hz), standard high frequency alarms (HFA) (2000/4000 Hz bimodal or 3100 Hz pure tone), and low frequency harmonic (LFH) alarms. These data sets could be further refined to compare the effectiveness of the HFA and LFH alarms to normal at risk populations. The data has been weighted by the number of alarming tests/subjects and is provided in Table 13.

**Table 13 – Comparison of weighted average 50% AAT (dBA) among all tests separated by alarm tone and tested populations**

<table>
<thead>
<tr>
<th></th>
<th>High Frequency Alarms (HFA)</th>
<th>Low Frequency Alarms (LFH)</th>
<th>Improvement of LFH over HFA (dBA)</th>
</tr>
</thead>
<tbody>
<tr>
<td>All tests and subjects</td>
<td>67.2 (n=1324.0)</td>
<td>All tests and subjects</td>
<td>58.2 (n=207.0)</td>
</tr>
<tr>
<td>Normal Population (no risk factors)</td>
<td>60.9 (n=866.0)</td>
<td>Normal Population (no risk factors)</td>
<td>63.2 (n=17.0)</td>
</tr>
<tr>
<td>Normal Population (only tests with LFH)</td>
<td>69.6 (n=36.0)</td>
<td>At-Risk Population</td>
<td>57.7 (n=190.0)</td>
</tr>
<tr>
<td>At-Risk populations</td>
<td>79.3 (n=458.0)</td>
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</tbody>
</table>

Although there are several assumptions made in the analysis (scaling factor estimates), the SPL levels for 50% waking effectiveness agree well with the bulk of research and industry accepted values. The values range from 59 dBA for the LFH to 79 dBA for the HFA for at-risk populations (including older adults, those with hearing loss, children, the intoxicated, and people on drugs). Among this group, the LFH alarm displays the greatest improvement over the HFA, with a reduction in average SPL of 21.6 dBA. The observed improvement is...
drastically reduced for the normal populations. When comparing only among tests where both HFA and LFH were included with the same methods/subjects, etc., the LFH tones were as effective with a 6.4 dBA reduction in SPL. When comparing across all HFA alarm tests, including those ranging back to the early 1980s, long before LFH tones were being evaluated, the average 50% SPL for the HFA is 2.3 dBA lower than the LFH for only normal populations. It should be noted that the LFH tests for normal populations only includes a total of 17 experiments, compared to 866 experiments considered for all HFA tests with varying methodologies and so this comparison is made with widely disparate data sets. In addition, this analysis does not consider any bias in older data, when human sensitivity to electronic beeps, loud tones, or other noise may have been drastically different.

This simplified comparison does not account for a one to one evaluation of the statistical variance or comparison of data sets. In fact, among individual data sets the uncertainty and variance in the AAT values are often greater than the 15-20 dBA improvements observed for LFH alarms. In order to fully quantify these uncertainties and determine numerical significance, the full data sets from each considered experiment would be required and an exhaustive statistical evaluation would be needed. This expanse of full data is not available, and the scope of analysis is beyond the scope of this report.

6.0 Alarm Sounds and Transport

The previous section compares the intensity of sounds needed to awaken various test subjects. Many of these experiments included characterization of the alarm tones used or measurement of the attenuation of those alarm tones in homes or buildings. Several other non-awakening studies also address these two issues. The studies that include characterization or attenuation of alarm signals are detailed in this section.

6.1 BRADLEY AND WHEELER 1977 [66]
A 1977 unpublished report written by Bradley and Wheeler for an engineering course at the University of Maryland has been widely cited in audibility literature over the last 40 years. This report indicated 16.4 dB for alarm sounds to penetrate closed bedroom doors. No further details of the methods, experiments, or data are available.

6.2 MYLES AND FIDELL 1978 [113]
In June of 1979, two papers were presented by Mark Myles and Sandford Fidell from Bolt Beranek and Newman, Inc. (later BBN Technologies, later part of Raytheon) and submitted to Edwards Company that measured the acoustic signals of select residential fire detectors. Their findings indicate that 85 dBA measured at 10 ft per the UL 217 methods is not adequate for awakening most of the population in an actual residence due to sound attenuation.

The authors considered the attenuation of a door between an alarm in the hallway and the bedrooms, as was the required installation method at the time. The authors note absorption, spreading loss, and transmission through doors and walls as prevailing issues. The location of the alarms, the distances between the units and listeners, and the absorption from carpets, drapes, furniture and construction are all critical to assessing the real-world performance of smoke alarms.

Myles and Fidell broadly criticized the piezoelectric transducer common to smoke alarms at the time. The transducer has a single tone, which can create null zones from standing waves and not alert the listener. The single-frequency signal was also compared to electromechanical and AC buzzers and did not have comparable directionality patterns or on-axis measurements. Myles and Fidell recommended harmonic tones to produce a more even distribution of sound level throughout a space.

Myles and Fidell were also concerned with the attenuation of a space dependent on several factors; the location of the alarm unit, the distance between the alarm and the listener, the amount of acoustic absorption and details
of the construction. These factors can vary greatly between different residencies and rooms but Myles and Fidell were able to draw general conclusions. They concluded that doors could change the level of the alarm by 20 dB and estimated a 10 dB absorption from soft surfaces. They were concerned that the basic smoke alarm would perform very differently in realistic homes, and an acceptable expectation of success could not be determined.

Measurements were taken of SPL in a residence with alarm on the ceiling and measurements in adjacent bedroom (70 year old house, stud wall with plaster on lath, solid and ungasketed doors, carpeted hallways with pile runner, all doors closed). The test setup created a simulated reverberant source room. The measurement bedroom was acoustically dead with thick pile wall to wall carpeting and two beds with wool blankets. Transmission data as a function of tone frequency is shown in Figure 46.

![Figure 46](image-url)  

**Figure 46 – Transmission loss of typical residential doors and stud walls as a function of 1/3rd octave band center frequency in Hz [113] [114]**

In general, fiat transmission profiles are expected for open or ungasketed doors from 500 to 3000 Hz. For the gasketed doors, the attenuation increases linearly with an increase of over 8 dB from 500 to 3000 Hz. The stud wall construction has a dip in attenuation at approximately 300 Hz that results in only a 5 dB difference between 500 and 3000 Hz.

Myles and Fidell also tested the sound output from 3 types of alarm transducers including a 9 VDC electromechanical unit, a 12 VDC piezoelectric prototype, and a 110 VAC buzzer. The spectral outputs from the three sources are shown in Figure 47.
Figure 47 – Spectral sound power output of three alarms tested by Myles and Fidell [113]

In general, the electromechanical transducer exceeded 85 dBA at 10 ft with a rich harmonic tone that peaked at 3000 Hz. The piezoelectric transducer did not exceed 85 dBA at 10 ft and produced a pure tone at about 3150 Hz. The AC Buzzer exceeded 85 dBA at 10 ft and produced a rich harmonic tone with a peak at 3150 Hz.

The directionality of the alarms were also tested. The electromechanical transducer and AC buzzers displayed a difference of 10 dBA between the maximum and minimum SPL. The piezoelectric transducer actually produced the minimum SPL at the on-axis angle, with 7-10 dBA higher measured at 45° off-axis.

Myles and Fidell considered the alarm sounds with respect to the thresholds of human hearing and potential levels of background noise. Based on analysis of ambient noise, three levels for background noise were produced, best case, intermediate, and worst-case conditions. The three alarm signals, the threshold of human hearing, and the ambient noise levels are shown in Figure 48.
In 1979, a report was published that characterized existing alarms and compared alarm effectiveness. Factors such as directivity of the alarm, spacing between alarms, background noise level and the acoustical properties of the structure can all impact sound attenuation. This report evaluated sound power, directivity and frequency spectrum, and noted that building construction goals would directly compete with alarm notification goals.

One of the issues that was addressed was the lack of diffuseness when utilizing low frequencies, which creates the existence of standing waves. The author was concerned that sounds with long wavelengths would produce very few cycles in small bedrooms. For larger rooms Ernzen was concerned with inconsistencies of air absorption for frequencies over 1000 Hz, where absorption would vary with temperature and humidity.

Three microphone positions were used to determine SPL as a function of frequency and compared to the calculated SPL and Ernzen was able to determine the relative response of the room based on diffusion. The room responses were also evaluated as a function of reverberation time, which was independent from handbook-based calculation and subject only to experimental error. It was recommended that these calculations were verified using existing buildings data.

Overall, four alarms on the market were chosen to be tested. Two vibrating electric horns (Pyrotronics, and Edwards), a 10” vibrating bell, and a residential smoke alarm were also tested. The measured sound power levels and frequency spectra are shown in Figure 49.
As part of the waking experiments conducted by Nobe r et. al. in 1980, an assessment was made of the sound properties for various smoke alarms. They assessed the intensity-frequency characteristics of several smoke alarms by measuring acoustic signals at 10 and 15 ft distances from the source in an anechoic chamber and reverberant chamber. Tests were conducted in both chambers because of discussion at UL at the time about revising the sound pressure measurements for UL 464 (see UL Report of April 25 1979, Industry Advisory Conference for Audible Signal Appliances). It was believed that differences between the anechoic measurement (no reflections) and reverb measurements (highly reflective room) would vary greatly and that reverb measurements would be more indicative of realistic alarm performance. It was noted that the average value from a reverb measurement should correlate to the peak free field anechoic measurement.

Testing of the alarms found a mean of 85 dBA at 10 ft with 80-92 range, but a high range of variability in spectral and directional sound output, even from alarms among the same manufacturers. Conducting tests with 5 smoke alarms measured band peaks at 4000 Hz with second energy clusters at 2000-3000 Hz, directional variability up to 10 dBA in anechoic chamber (or 3.5 dBA in reverb chamber). The spectral intensity of alarms, even from the same manufacturers also varied. The spectral sound output from the 5 tested alarm is shown in Figure 50.
The waking tests conducted by Nober et. al. utilized SPL of three levels based on installation locations of the alarms. These levels were defined as 85 dBA - installed in the bedroom with no obstructions, 70 dBA – alarm in hallway with door open, and 55 dBA – alarm in hallway with door closed. These levels were selected based on measurements of alarm SPL in homes.

6.5 BUTLER, BOWYER, AND KEW 1981 [7]

In 1980, BSI included the first requirements for SPL in installations, requiring 65 dBA and 75 dBA for public areas and sleeping areas, respectively. In response, Butler, Bowyer, and Kew at the Building Services Research and Information Association (BSRIA) developed engineering design equations to calculate the transport of SPL throughout buildings. These equations were simplified versions of first principles, creating simple linear combinations of factors based on the properties of the sound and the building geometry and design. Calculations can be performed separately to evaluate the propagation of a sound down a corridor and then through a door opening (or closed door). Coefficients include:

- Solution to determine the sound power from a source based on SPL at a distance (e.g., 85 dBA at 10 ft)
- \( C_1 \) – Adjustment for the mounting position of the source
- \( C_2 \) – Adjustment for the distance from the source
- \( C_3 \) – Adjustment dependent on the number of directions of sound propagation
- \( C_4 \) – Adjustment dependent on the finishes in a corridor
- \( C_5 \) – Adjustment for distance from source to center of partition or door or window
- \( C_6 \) – Adjustment for the area of the partition
- \( C_7 \) – Adjustment for the frequency of the sounder
- \( R \) – Sound reduction index for partition (or sum of multiple partitions)

Tables are provided for the values of each of these factors, with examples and solutions for complex wall structures with air gaps and insulation, transport through multiple rooms, and combinations of sounds from adjacent alarms. For this analysis, the primary factor of interest is \( C_7 \), the adjustment for the frequency of the sounder. Based on both empirical and theoretical evidence, Butler, Bowyer, and Kew included Table VII to account for the peak frequency output of alarm sounders, shown in Table 14.

Table 14 – Adjustments for frequency of maximum output of sounders (Table VII, \( C_7 \) values from Butler et. al.) [7]

<table>
<thead>
<tr>
<th>Frequency of Sounder</th>
<th>( C_7 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>500 Hz</td>
<td>0</td>
</tr>
<tr>
<td>1000 Hz</td>
<td>-3 dB</td>
</tr>
<tr>
<td>2000 Hz</td>
<td>-5 dB</td>
</tr>
<tr>
<td>3000 Hz</td>
<td>-7 dB</td>
</tr>
<tr>
<td>4000 Hz</td>
<td>-9 dB</td>
</tr>
</tbody>
</table>

An immediate quantified takeaway is that a 520 hz signal is calculated with no additional attenuation, but a 2000 Hz signal is estimated with a -5 dB reduction (and -7 dB at 3000 Hz). This estimate is based on the transmission of sounds through partitions as a function of the frequency. The attenuation is based on several physical mechanisms, with low frequencies being affected by the stiffness, resonance, and damping of the partition. Intermediate frequencies, below a critical frequency are attenuated by a mass-controlled effect, with the attenuation increasing linearly with frequency. Above the critical frequency, the attenuation is reduced by the
coincidence dip, where the partition vibrates in unison with the frequency of the incident sound pressure waves. The relative attenuation and regions of attenuation are shown in Figure 51.

![Figure 51 - Characteristic transmission losses of partitions as a function of frequency [7]](image)

Higher frequencies result in increased attenuation, while lower frequencies transmit more readily. A 520 Hz tone likely approaches the resonance-controlled region of this curve. The resonance/mass transition is evident to anyone who has clearly heard the bass from music played in an adjacent room causing the wall to vibrate, while the treble, or higher tones, are almost completely blocked out.

The calculation methods developed by Butler, Bowyer, and Kew were reported and adapted by Robert Schifiliti in his 1988 article for Fire Technology [77], and later became the basis for audibility calculations in his chapter in the SFPE Handbook [115]. These simplified calculations are still used today as the basis for engineering design of alarm audibility.

6.6 KAHN 1983 [70]

During waking testing, the location of the 2000-4000 Hz bi-periodic smoke alarm was varied to produce three different SPL. Placing the alarm just outside the closed bedroom door resulted in a 78 dBA signal at the pillow. When the alarm was mounted on the outside of the outer hall wall it produced 54 dBA at the pillow. Finally, when the alarm was stuffed under a couch cushion it produced a 44 dBA signal. With the bedroom door open, the alarm produced 85 dBA at the pillow location when installed just outside the door.

6.7 NFPA 72G 1985 [37]

The NFPA Notification Subcommittee completed NFPA 72G, Guide for the Installation, Maintenance and use of Notification Appliances for Protective Signaling Systems in 1985. This guide recommended that audible signals in public mode have SPL not less than 75 dBA at 10 ft (or greater than 130 dBA). This guide also provided a summary of the average ambient sound levels for various occupancies to aid in design of audible systems, including a 35 dBA ambient noise level for residential occupancies [37].
6.8 HALLIWell AND SULTAN 1986 [74] [116]

In 1986 R.E. Halliwell and M.A. Sultan from NRCC developed an alternative method to Butler, Bowyer, and Kew for calculating sound propagation and attenuation in buildings. Halliwell and Sultan discussed the estimation of the sound level from a smoke alarm based on room size and furnishings and categorized rooms as hard (having no carpet and upholstered furnishings), normal (having carpeting, drapes and upholstery) and soft (having thick carpeting and drapes and soft furnishings).

Correction factors were implemented to determine sound attenuation between rooms. Smaller rooms would require a lower correction factor than larger rooms, while a soft room would have a higher attenuation factor than a hard room of a similar size. Halliwell and Sultan also determined that the correction factors from an adjacent room would be less than the room of origin. Two other factors considered were the positions of doors and air heating or cooling systems. They determined that the presence of a door would attenuation a signal by 5 dBA, while the closed door would result in a reduction of 10 dBA to the sound level, while the absence of an air heating/cooling system would reduce the sound level by 6 dBA. The number of doors and the reduction in SPL is shown in Figure 52.

![Figure 52 – Measured SPL attenuation from doors [116]](image)

The Halliwell and Sultan model is based on propagation from room to room through a series of linked paths. Each room in the path is modeled separately, accounting for room volume, reverberation times, area of partitions, and the speed of sound. The major limitation of the method of Halliwell and Sultan, has been the estimate that distances are accounted for by the room to room attenuation, the building materials and furnishings, and no further inclusion of distances from source to receiver are considered. For this reason, the method of Halliwell and Sultan are not used as the industry standard method but are widely recognized and often considered in conjunction with other methods (see Butler et. al. and Shifiliti).

The propagation model of Halliwell and Sultan is based on measurements of typical smoke alarms having a peak energy at 3150 Hz. The authors note that some of the higher frequency alarms, with 4000 Hz tones, would have increased attenuation and may not effectively alert occupants. They also note that lower frequency alarms would have reduced attenuation, and thus their calculation would provide a conservative estimate. No further calculation or adjustment for frequency is provided. The measured sound power levels for various tested smoke alarms are shown in Figure 53.
Figure 53 – Sound power as a function of frequency measured by Halliwell and Sultan for 14 smoke alarms (7 models) [116]

The Halliwell and Sultan calculations are based on a comparison to real attenuation data. The comparison between the calculations and the measurements are shown in Figure 54. On average, the calculation overpredicts the attenuation by approximately 1 dB, a conservative average. Overall, the average absolute error between the calculation and the measured data is 7.5 dB.

Figure 54 – Comparison of the Halliwell and Sultan calculated attenuation to experimental data [116]
6.9  ROBINSON 1986 [75] AND 1988 ARTICLE [76]

Two articles published in 1986 and 1988 by Donald Robinson from University of Massachusetts Amherst examined the attenuation of sound in a corridor. The 1986 study measured the loss of sound from corridors in a dormitory building using white noise. The author notes the conflicts between alarm design and building design. The goal of alarm designers is to reach 10 dB above ambient noise in rooms from alarms in corridors, while the main goal in construction is to reduce noise transmission between corridors and rooms.

Robinson references the 1975 CHABA recommendations for the standard temporal profile rather than implementation of a specific signaling device or standard spectrum (see Section 4.3). Even in 1975 this recommendation was not universally supported, and several other studies and recommendations were made. Gosswiller advocated a slow whoop signal with a base frequency of 500 to 700 Hz, while Humphreys recommended a 600 Hz slow ascending whoop signal. NFPA 72A recommends a code 3 temporal pattern and NFPA 72F recommends signals to be at least 15 dBA above SPL or at least 5 dBA above the maximum sound level and have a duration of at least 60 seconds. NFPA 74 required alarms at that time to have a sound pressure rating of 85 dBA at 10 ft outside bedrooms and to produce about 15 dBA over ambient levels of 55 dBA in bedrooms and UL 464 requires 75 dBA at 10 ft. Robinson considered these factors in design of his experiments.

Robinson also discusses a report from 1963 by H.J. Oyer and E.J. Hardick discussing the response of a population to an optimum warning signal finding four characteristics of optimizing alerting signals; a frequency in the range of 700-4,000 Hz, complex rather than pure tones, a frequency modulation between 5 and 10 percent, and that perceived loudness is the major determinant in judging the alerting potential of the signal with the best result being 80-100 Hz. This research also determined that a rhythmically interrupted signal is not necessary [117].

Robinson discussed the finding that the sounds loss performance of partitions can be divided into three regions; the stiffness-resonance region, the mass law region, and the stiffness-coincidence region. There was a predicted 5-6 dB loss per octave in the mass loss region and a 5-6 dB loss when wall mass doubles (see Figure 51 in Section 6.5).

Robinson’s study included sounds transmitted from the hallway to bedrooms in two college dormitories at Amherst. Robinson used white noise (broad spectrum) and measured the SPL in the bedrooms as a function of frequency. This allowed him to quantify the transmission of sounds though the corridor and through partitions and quantify the attenuation of separate frequencies simultaneously. These experiments verified the frequency dependent nature of audible sound transmission loss.

Robinson found that propagation losses in the corridor increase with increasing frequency, ranging for 0.17 dB per ft at 500 Hz to 0.23 dB per ft at 2000 Hz [75]. Over a 21 ft corridor (the distance for hallway alarms outside bedrooms per NFPA 72), this results in additional attenuation of 1.3 dB for 2000 Hz tones compared to 500 Hz.
Typical loss from the corridor to the room was 12 dB at frequencies over 500 Hz. An additional 15 dB was lost when the door was closed, and the reduction increased to 20 dB when the door edge was sealed. These losses were consistent over all the frequencies. The overall reduction from the corridor to the room with the door closed and the edge sealed was 30 dB, which would require the corridor sound level to be 105 dB to reach 75 dB in the room. Robinson also discussed there being little difference in attenuation at 500 Hz compared to 2000-4000 Hz, but there was increased attenuation above 1000 Hz.

In a follow-up article in 1988, Robinson stated that diffraction and reflection of sound waves generally act to improve fire alarm signals, but sound absorption and sound insulation must be considered based on the material of a corridor or similar barrier. In this report, Robinson also notes that all sounders tested inside bedrooms exceeded SPL of 80 dBA [76]. If alarms were installed in the bedrooms, the SPL exceeded design goals for the 85 dBA at 10 ft listed alarms.
6.10 SCHIFILITI 1988 [77]
In 1988 Robert Schifiliti published an article in *Fire Technology* detailing the sound attenuation calculation produced by Butler, Bowyer, and Kew in 1981 and using it to develop a framework for calculation of audibility in fire protection engineering design. Schifiliti discusses the different factors of the transmission of sound such as humidity, signal frequency, temperature, and the construction and furnishings of the area. He references the studies conducted by Nober [34] and Kahn [70] that indicate an SPL of 55-70 dBA would be required to wake a college-aged person with normal hearing. Schifiliti notes that U.S. codes only require a signal to be audible in all occupiable spaces in a building, while the British standards require signals to produce an SPL of 65 dBA or 5 dBA above ambient where people are not sleeping and 75 dBA at the head of the bed in areas where people are sleeping.

Schifiliti details the calculation methods of Butler, Bowyer, and Kew and applies them to several real-world examples. He performs a cost benefit analysis to justify installation of speakers inside bedrooms rather than in corridors only, because the total power consumption is drastically reduced and the potential for damaging SPL in the corridors is also reduced. This paper ultimately formed the basis for the SFPE handbook chapter on audibility by Schifiliti, in which the methods and examples remain nearly identical in the 5th edition of the handbook over 30 years later [115].

6.11 SULTAN AND HALLIWELL 1990 [78]
In 1990, after NFPA 74 included interconnection requirements and after writing the Guide to Most Effective Locations for Smoke Detectors in Residential Buildings in 1986, based on the attenuation of sound [74], Sultan and Halliwell of the National Research Council of Canada (NRCC) conducted a literature review published in *Fire Technology* focused on locating alarms in apartments and including evaluation how loud alarms are required to awaken occupants [78].

The authors noted the common practice of installing alarms outside apartments in the corridors as a common practice at the time with concern, referencing the attenuation work of Robinson. The authors reference the British Standard BS 5389 Part 1 as the only standard requiring a minimum of 75 dBA “at the bedhead” [35]. Sultan and Halliwell conducted an analysis of sound transmission as a function of frequency and location using the 75 dBA pillow threshold as a basis.

The attenuation of sound from corridor horns (building 1) and bells (building 2) were assessed experimentally in the first two apartment buildings. The spectral characteristics of the sources were measured in the corridors and inside the apartment’s interior foyer and the remote bedrooms. The spectral characteristics of the horns (left) and bells (right) are shown in Figure 57. The measured SPL in the interior foyers and bedrooms and the ambient noise levels are also shown. The bottom figures show the attenuation of the sounds as a function of frequency into the apartment interior foyer and bedroom areas.
Figure 57 – The measured SPL (top) and attenuation of signal from corridor to apartment hall and bedroom (bottom) from horns (left) and bells (right) from Sultan and Halliwell experiment [78]
The horns peaked at frequencies of 800, 1600, and 3150 Hz. The bells peaked at frequencies of 500, 1600, and 2500 Hz. The horn was able to produce sounds about 7.6 dBA above ambient in the remote bedroom of the apartment, while the bells were barely able to exceed ambient noise in the apartment interior hallway. The horn was attenuated by 34.8 dBA through the apartment hallway door, and 59.2 dBA to the bedroom with both doors closed. The bell was attenuated by 32.1 dBA through the apartment hallway door and 40.8 dBA to the bedroom with the doors closed.

Comparing the measured attenuation at 500 Hz and 3150 Hz indicates greater transmission at lower frequencies. For the horn, the attenuation of the 500 Hz tone is 7.5 dB less than the 3150 Hz tone to the apartment interior, and 12.2 dB into the bedroom. For the bell, the effect is even more pronounced. The 500 Hz component was attenuated by 13.2 dB less into the apartment, and by 20.3 dB less into the bedroom.

A second study was conducted in seventy-three apartments in nine buildings to determine attention and background noises with white noise source. The white noise provided broad spectral data that could be applied to any source type in the future. The level difference between common corridors and bedrooms was 54.9 dBA on average and opening the bedroom door only increased this to 65 dBA. Data on SPL in apartments and bedrooms showed that approximately 100 dBA in the main apartment should be enough to get 75 dBA at pillow in bedrooms. A compilation of the data from all buildings determined to provide an adequate awakening potential for residents, an alarm should be provided at a minimum within each apartment.

Spectrally, the white noise did not indicate the same reduced attenuation for 500 Hz tones compared to 3150 Hz tones as the horns and bells did in the first experiment. The attenuation of the white noise as a function of frequency is shown in Figure 58. The attenuation at 500 Hz was 31.7 dB and 53.7 dB for the interior and bedroom, respectively. At 3150 Hz, the attenuations were 30.8 and 53.9 dB, showing almost no difference. Inspection of the curves indicates the coincidence dip occurring between 2000-3000 Hz (see Figure 51 in Section 6.5), resulting in nearly equivalent attenuation at the two frequencies. The coincidence dip occurs at this frequency for the walls and doors tested but does not necessary occur at this frequency for other construction methods.

Figure 58 – Attenuation of white noise from a corridor into an apartment interior and bedroom through closed doors [78]
6.12 **BRUCK AND HORASON 1995 [79]**
Waking effectiveness testing was conducted using fixed alarm SPL of 60 dBA. This threshold was selected based on field studies of 8 rooms in 4 houses, where they measured pillow SPL of 51-68 dBA with bedroom doors closed from 85 dBA at 10 ft alarms in hallways.

6.13 **DUNCAN 1999 [86]**
As part of the waking study, the SPL from COTS (commercially available) ionization alarms was measured in multiple bedrooms with alarms installed in hallways in 40 total homes. The SPL of the alarms reduced from 75 dBA on average with the doors open and 67 dBA with the doors closed. Measured SPL ranged from 61 dBA to 93 dBA with doors open and 57-75 dBA with the doors closed.

6.14 **BALL AND BRUCK 2004 [94]**
In a 2004 study on waking of young adults under the influence of alcohol, Ball and Bruck characterized the spectral characteristics of the three tested alarm signals. These signals included a female voice message, a standard Australian smoke alarm, and the low frequency harmonic tone utilized in the 2003 study by Proulx and Laroche [93] (Simplex 1996, 4100 Fire Alarm Audio Demonstration CD). The spectral sound power levels of the three signals are shown in Figure 59.

![Figure 59 – Spectral sound power levels of alarm tones tested by Ball and Bruck [94]](image)

As indicated in the figure, the female voice was a complex tone with dominant peaks across the 315 Hz to 2500 Hz region. The low frequency harmonic was also complex, with peaks at 500, 1600, and 2500 Hz. Both performed better in the waking effectiveness tests than the Australian standard smoke alarm, which was a nearly pure tone with higher peak frequencies of 4000 and 5000 Hz.

6.15 **LEE, MIDGETT, AND WHITE 2004 [90]**
In the preliminary 2004 research study by Lee et. al. at CPSC, the basic characteristics and tones from various fire alarm notification appliances were summarized and assessed. A list of non-residential type sounders was produced. The various tones considered by Lee et. al. are shown in Table 15.
In addition, the report by Lee et. al. includes a description of the operation of the typical residential piezoelectric smoke alarm sounder. The piezoelectric sounder consists of a diaphragm on a ceramic plate with electrodes mounted on either side. When AC voltage is applied to the electrodes, the diaphragm contracts and expands, producing sound waves.

The report by Lee et. al. also includes a description of the sound attenuation calculation methods proposed by Halliwell and Sultan in 1985. A basic example calculation is provided along with some discussion of the application of the method.

### 6.16 LEE 2005 [97]

The 2005 study from Arthur Lee continued from the initial review of the 2004 study. This effort included experiments to assess the sound loss measurements using 3200 Hz, single station smoke alarms. Three test homes were used, each with a different home type and square footage, but all were wood framing with 1-2 inch drywall. The measured sound attenuation was compared to calculations for each home based on the methods of Halliwell and Sultan [74]. In general, the measurements agreed well with the calculations, especially for close source (alarm) /receiver (sound meter) positions. Errors were minimal for short distance sound transmission. As the distance between the source and receiver increased, and the complexity of the path increased, the error increased accordingly.

The alarm was listed to UL 217, but was noted to produce slightly lower than 85 dBA at 10 ft. It was noted that this measurement was not conducted in accordance with the requirements for SPL in UL 217, and so the listing of the alarm is not necessary in question. In addition, the spectral and temporal characteristics of the alarm were measured and show a single strong frequency peak at 3200 Hz.

Sound attenuation and alarm performance was evaluated based on the various installation requirements from previous decades. This included evaluations of the alarms on every level, outside the bedrooms in the hallways, and installed in each bedroom and interconnected.

Test Home 1 was a 1,120 square foot suburban ranch house with a first floor and basement. The peak sound measured in the hallways with the bedroom doors opened or closed was 104 dBA, while the sound levels in the bedrooms ranged from 85 to 96 dBA with open doors and 71 to 88 dBA with the doors closed. When the alarm was placed in one of the bedrooms, the sound levels in the other bedrooms with the doors closed was almost 40 dBA lower than when the alarm was in the hallway.

Test Home 2 was a 2,343 square foot contemporary style house with a first and second floor, with the alarm source being placed in the hall between the kitchen and family room. The peak sound measured in the hallway under the alarm was 102 dBA, and the peak sound levels at the top and bottom of the stairs was 80 dBA and 67 dBA.

### Table 15 – Alarm tones from commercial fire alarms (non-residential) [90]

<table>
<thead>
<tr>
<th>Tone</th>
<th>Pattern Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Horn</td>
<td>Broadband Horn (continuous)</td>
</tr>
<tr>
<td>Bell</td>
<td>1560 Hz Modulated (0.07 second ON/Repeats)</td>
</tr>
<tr>
<td>March Time Horn</td>
<td>Horn (0.25 second ON/0.25 seconds OFF/Repeats)</td>
</tr>
<tr>
<td>Code 3 Horn</td>
<td>Horn (ANSI S3.41 Temporal Pattern)</td>
</tr>
<tr>
<td>Code 3 Tone</td>
<td>500 Hz (ANSI S3.41 Temporal Pattern)</td>
</tr>
<tr>
<td>Slow Whoop</td>
<td>500-1200 Hz Sweep (4.0 seconds ON/0.5 seconds OFF/Repeats)</td>
</tr>
<tr>
<td>Siren</td>
<td>600-1200 Hz Sweep (1.0 Seconds ON/Repeats)</td>
</tr>
<tr>
<td>High/Low</td>
<td>1000/800 Hz (0.25 Seconds ON/0.25 Seconds OFF)</td>
</tr>
</tbody>
</table>
dBA, respectively. The sound levels in the bedrooms with the doors open were between 60 and 68 dBA and 42 to 55 dBA with the bedroom doors closed. Another test was conducted with the smoke alarm outside the master bedroom, and the sound level decreased from 68 dBA to 53 dBA when the door was closed.

Test Home 3 was a 3,371 square foot colonial style home with a basement, first and second floor with the alarm source being placed in the family room. The peak sound measured under the alarm was 96 dBA, the sound level at the bottom of the stairs was 87 dBA and the sound level at the top of the stairs was 76 dBA with the bedroom doors open and 89 dBA with the bedroom doors closed. The sound levels in the bedrooms were between 73 to 75 dBA with the doors open and between 61 to 67 dBA with the doors closed. A third test was conducted where the alarm was mounted in the basement. The sound level in the master bedroom with the bedroom and basement doors open was 55 dBA and 34 dBA with the doors closed.

Four general conclusions were made based on the tests in the three houses. First, single station smoke alarms in two or three level homes are not sufficient to alert all occupants in the home. Second, the complexity of the path determines attenuation, and calculations lose accuracy as this complexity increases. Third, a closed, lightweight door attenuates the signal by 10-20 dBA, and fourth, each home level attenuates signal by approximately 20 dBA. These conclusions were all based on 3200 Hz alarms and no estimates nor comparisons to low frequency tones were considered.

6.17 ROBY 2005 [98]

In the 2005 work conducted by CSE a sensor was constructed to monitor for activation of smoke alarms and then activate secondary notification appliances for the hard of hearing and deaf. The sensor was built to look for alarms having a peak frequency output at 3200 Hz ± 10%. An evaluation of alarms was conducted comparing the pre-1996 alarms (pre three-pulse temporal requirement) and post-1996 alarms. Although the temporal pattern of the alarms had changed, it is noted that both types of alarms had peak frequencies between 3200-3400 Hz. The spectral patterns of industrial smoke alarms were also evaluated, including selectable signals such as chimes, horns, bells, sirens, and whoops. In this sense, industrial alarms include sounding appliances with selectable tones. The authors indicate that all these signals produced peak energy between 2500 and 4000 Hz.

Many of these tests were conducted for hard of hearing or deaf persons, and the authors note that many of the subjects were completely deaf to the 3150 Hz tones of the standard smoke alarm signals, with significant losses above 1000 Hz. To accommodate such subjects, the sensor was used to actuate a second alarm at 400-500 Hz to alert the hard of hearing and deaf test subjects. This alarm was able to awaken 11% of the deaf test subjects, compared to 0% for the 3150 Hz tone.

6.18 BRUCK, THOMAS, AND KRITISOS 2006 [22]

As part of a 2006 waking study, Bruck et. al. characterized the spectral intensity of three evaluated alarm signals. This included the 3100 Hz and 520 Hz harmonic tones used for nearly all subsequent tests and comparisons. A 500 Hz pure tone was also characterized. The three tones are shown in Figure 60.
In 2010, Thomas and Bruck reported an experimental study of alarm sounds in a home for the Australian Building Codes Board. This work was conducted to assess the status of Australian smoke alarm requirements at the time. In 2010 the Building Code of Australia (BCA) did not require alarms in bedrooms or interconnection, rather they were only required on floors with bedrooms and on each other floor. The Australian standard for smoke alarms AS 1670.1 (2004) required 75 dBA at the pillow level, in agreement with other international standards. The authors intended to assess whether standard alarms outside bedrooms could achieve the 75 dBA requirements.

Sound levels were measured in each room of 5 real houses with various doors open and closed. Sounds were produced from recordings of real alarm tones emitted at either 85 or 105 dBA near the ceiling in various locations (measured 1 m from speaker SPL). Identical tests were conducted with the 3100 Hz pure tone and 520 Hz harmonic signals. Sounds in bedrooms were measured diagonally opposite the doors to rooms at about pillow height. Measurements were all conducted during the day with unoccupied homes and 35-40 dBA background noise.

Overall, the 85 dBA alarms were not sufficient to produce 75 dBA in bedrooms. Even with all doors open, the 3100 Hz alarm only exceeded 75 dBA in the bedrooms 18.2% of the time, compared with 31.8% of 520 Hz harmonic signals exceeding this threshold. The reduction between rooms was about 6 dBA greater for the 3100 Hz tone than the 520 Hz tone.

Despite testing 105 dBA alarms and the improved sound transmission of the 520 Hz signals, the installation outside bedrooms is insufficient to consistently achieve 75 dBA at the pillow. Smoke alarms in hallways are unlikely to be loud enough for all bedrooms with open doors and will not be loud enough with doors closed. This provides further evidence that even for 520 Hz signals, with increased waking effectiveness and sound transport, interconnected alarms in all bedrooms are critical to fire safety.
The authors of the report conducted an overall analysis of the reduced SPL in homes. The purpose of this report is to quantify directly the differences between low frequency and high frequency tones. The complete set of data provided in Appendix B of the report has been further analyzed. The reduction in SPL as analyzed by Thomas and Bruck and as further analyzed for this report is provided in Table 16.

**Table 16 – Analysis of measured SPL in multiple homes for 3100 Hz and 520 Hz tones [118]**

<table>
<thead>
<tr>
<th>Doors</th>
<th>Signal type/level (Hz/dBA)</th>
<th>N (number of tests)</th>
<th>Maximum reading (dBA)</th>
<th>Median reading (dBA)</th>
<th>Minimum reading (dBA)</th>
<th>Mean (dBA)</th>
<th>% ≥75 dBA</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hallway to Bedroom Analysis by Thomas and Bruck [119]</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Closed</td>
<td>3100 85</td>
<td>42</td>
<td>55.9</td>
<td>44.8</td>
<td>37.4</td>
<td>45.5</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>520 85</td>
<td>42</td>
<td>67.5</td>
<td>52.7</td>
<td>39.2</td>
<td>51.8</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>3100 105</td>
<td>42</td>
<td>76.8</td>
<td>62.3</td>
<td>49.3</td>
<td>62.9</td>
<td>~5</td>
</tr>
<tr>
<td></td>
<td>520 105</td>
<td>42</td>
<td>86.9</td>
<td>72.4</td>
<td>55.7</td>
<td>71.1</td>
<td>~30</td>
</tr>
<tr>
<td>Open</td>
<td>3100 85</td>
<td>72</td>
<td>74.8</td>
<td>57.2</td>
<td>40.0</td>
<td>56.9</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>520 85</td>
<td>72</td>
<td>76.8</td>
<td>64.2</td>
<td>46.4</td>
<td>63.2</td>
<td>~5</td>
</tr>
<tr>
<td></td>
<td>3100 105</td>
<td>72</td>
<td>94.6</td>
<td>75.7</td>
<td>59.8</td>
<td>75.8</td>
<td>~55</td>
</tr>
<tr>
<td></td>
<td>520 105</td>
<td>72</td>
<td>104</td>
<td>84.0</td>
<td>64.4</td>
<td>83.7</td>
<td>~80</td>
</tr>
<tr>
<td>Hallway to Bedroom Only – 2019 Analysis</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>All</td>
<td>3100 All</td>
<td>88</td>
<td>91.6</td>
<td>61.3</td>
<td>37.6</td>
<td>60.0 ±13.1</td>
<td>14.8</td>
</tr>
<tr>
<td></td>
<td>520</td>
<td>88</td>
<td>95.1</td>
<td>68.7</td>
<td>41.6</td>
<td>67.5 ±13.1</td>
<td>33.0</td>
</tr>
<tr>
<td>Closed</td>
<td>3100 All</td>
<td>44</td>
<td>75.7</td>
<td>51.5</td>
<td>37.6</td>
<td>54.2 ±11.0</td>
<td>4.5</td>
</tr>
<tr>
<td></td>
<td>520</td>
<td>44</td>
<td>86.9</td>
<td>62.5</td>
<td>41.6</td>
<td>62.5 ±12.0</td>
<td>22.7</td>
</tr>
<tr>
<td>All Room of Origin and Measurement Locations – 2019 Analysis</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>All</td>
<td>3100 All</td>
<td>1085</td>
<td>99.4</td>
<td>49.6</td>
<td>34.2</td>
<td>52.8 ±12.9</td>
<td>6.8</td>
</tr>
<tr>
<td></td>
<td>520</td>
<td>926</td>
<td>97.8</td>
<td>56.8</td>
<td>33.1</td>
<td>58.5 ±14.8</td>
<td>15.4</td>
</tr>
<tr>
<td></td>
<td>3100 85</td>
<td>543</td>
<td>81.9</td>
<td>42.6</td>
<td>34.2</td>
<td>45.5 ±8.3</td>
<td>0.4</td>
</tr>
<tr>
<td></td>
<td>520</td>
<td>469</td>
<td>79.1</td>
<td>47.5</td>
<td>34.2</td>
<td>50.5 ±10.6</td>
<td>2.6</td>
</tr>
</tbody>
</table>

When the bedroom doors are closed, the 85 dBA tones did not produce greater than 75 dBA for either tone. Over all tests conducted with the alarm in the hallway outside of the bedroom, independent of door position, the 520 Hz tone measured an average increase of 7.5 dBA compared to the 3100 Hz tones. When only the closed-door tests are considered, this increased to 8.3 dBA. Considering only 85 dBA alarms, when all possible rooms and door positions are considered, the 520 Hz tones were on average 5 dBA louder than the 3100 Hz tones (45.5 v 50.5 dBA). The average resulting SPL in the homes was only 50.5 dBA, even for the 520 Hz alarms. While the low frequency harmonic consistently resulted in increased SPL of 4-9 dBA for various conditions, it was still rarely sufficient to produce 75 dBA in bedrooms when installed outside of the bedroom locations. In many tests the waking effectiveness of the low frequency harmonic is equal to high frequency at 10-20 dBA reductions, so overall a 65 dBA threshold in the bedroom may be closer to equivalent for comparison to the 75 dBA for high frequency alarms.

A further breakdown of the raw data used for comparison of several scenarios is provided in Figure 61 through Figure 68.
Figure 61 – Percentage of SPL measurements taken in bedrooms with sound originating in hallways for both open and closed doors (85 and 105 dBA sounds included) (raw data from [118] new analysis)

Figure 62 – Cumulative percentage of measurements exceeding given SPL taken in bedrooms with sound originating in hallways for both open and closed doors (85 and 105 dBA sounds included) (raw data from [118] new analysis)
Figure 63 – Percentage of SPL measurements taken in bedrooms with sound originating in hallways for closed doors only (85 and 105 dBA sounds included) (raw data from [118] new analysis)

Figure 64 – Cumulative percentage of measurements exceeding given SPL taken in bedrooms with sound originating in hallways for closed doors (85 and 105 dBA sounds included) (raw data from [118] new analysis)
Figure 65 – Percentage of SPL measurements taken in all rooms with sound originating in all rooms for open and closed doors (85 and 105 dBA sounds included) (raw data from [118] new analysis)

Figure 66 – Cumulative percentage of measurements exceeding given SPL taken in all rooms with sound originating in all rooms for open and closed doors (85 and 105 dBA sounds included) (raw data from [118] new analysis)
For the global average of all tests, independent of house, room, doors, or alarm intensity, the 520 Hz alarm was greater than or equal to 75 dBA in 15.4% of measurements, compared to 6.8% for the 3100 Hz alarm tone. This increase in SPL at 75 dBA or greater of 8.6% was not unique or biased by a single test condition or room but was observed over many origin rooms and door conditions. The increase in total SPL measured at or above a threshold for the 520 Hz compared to 3100 Hz are shown in Figure 69. The greatest difference was observed...
for all rooms and doors at a threshold of greater than 60 dBA, with the 520 Hz being 30% more likely to achieve this SPL than the 3100 Hz.

![Figure 69 – Percentage of additional alarms measured at SPL for 520 Hz alarms compared to 3100 Hz alarms (raw data from [118] new analysis)](image)

6.20 MOINUDDIN, BRUCK, AND SHI 2017 [120]

In a 2017 article for *Fire Safety Journal*, Moinuddin, Bruck and Shi again re-evaluate the SPL data taken in the 2010 experiment. In this analysis, Moinuddin et. al. further evaluate the likelihood of achieving 75 dBA for various alarm source locations, doors, and alarm intensities.

The authors note that AS 1670.1 requires SPL not less than 85 dBA and not more than 105 dBA, and that this standard drove the selection of the 85 and 105 dBA levels tested. The authors also reference UL 985, Standard for Household Fire Warning System Units, which requires residential sounders to be 85 dBA at 10 ft, which is 95 dBA at 1 m, the average of what they tested. This report also contains some additional analysis beyond the original report by Thomas and Bruck. The comparisons of average measured sound levels and comparison to the 75 dBA threshold in the rooms for various sound tones, intensities, and door positions as analyzed by Moinuddin et. al. are shown in Figure 70.
As indicated by this analysis, in few circumstances did the SPL exceed 75 dBA in the measurement room. The 520 Hz alarms were consistently greater than 5 dBA higher than the 3100 Hz tones for almost all conditions shown.

6.21 HAVEY, MUNOZ, KLASSEN, HOLTAN, AND OLENICK 2018 [121]

In 2018 an experiment was conducted to estimate the variability in measured SPL levels, even in repeated experiments. Havey et. al. specifically referenced the previous 2005 study conducted by Lee at the CPSC and note that only the peak SPL is reported with no discussion of variability. They also note the work of Halliwell and Sultan, which indicated that variability increased with distance and path complexity, but without quantification.

Multiple SPL tests were conducted on a 3 room with attached corridor. Tests were conducted in 12 variations based on door positions and were primarily driven toward determining the variability in the measurement techniques.
Figure 71 – Floor plan of the facility used for SPL measurements by Havey et. al. [121]

Tests were conducted using a standard high frequency smoke alarm 3100 Hz (UL listed -85 dBA at 10 ft). The interior of the space included thin commercial carpeting, gypsum board walls on metal studs, acoustic ceiling tiles, and solid core wooden doors. Ambient sounds were measured at 46.4 ± 1.9 dBA (42.8 – 49.8). The resulting SPL for the various receiving rooms (room containing sound meter) and door positions are shown in Table 17.

Table 17 – Measured SPL and variability in rooms in tests conducted by Havey et. al. [121]

<table>
<thead>
<tr>
<th>Receiver Room</th>
<th>Receiver Room Door</th>
<th>Position of Other Doors</th>
<th>Trial 1</th>
<th>Trial 2</th>
<th>Trial 3</th>
<th>Trial 4</th>
<th>Trial 5</th>
<th>Trial 6</th>
<th>Trial 7</th>
<th>Range (dB)</th>
<th>Avg SPL (STD)</th>
<th>Coeff of Var</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Closed</td>
<td>Open</td>
<td>61</td>
<td>60</td>
<td>69</td>
<td>68</td>
<td>61</td>
<td>67</td>
<td>61</td>
<td>9</td>
<td>64 (3.9)</td>
<td>6.2</td>
</tr>
<tr>
<td>1</td>
<td>Closed</td>
<td>Closed</td>
<td>68</td>
<td>63</td>
<td>68</td>
<td>68</td>
<td>64</td>
<td>60</td>
<td>64</td>
<td>8</td>
<td>65 (3.1)</td>
<td>4.9</td>
</tr>
<tr>
<td>2</td>
<td>Closed</td>
<td>Open</td>
<td>78</td>
<td>66</td>
<td>69</td>
<td>68</td>
<td>79</td>
<td>63</td>
<td>66</td>
<td>16</td>
<td>70 (6.2)</td>
<td>8.9</td>
</tr>
<tr>
<td>2</td>
<td>Closed</td>
<td>Closed</td>
<td>78</td>
<td>65</td>
<td>62</td>
<td>76</td>
<td>67</td>
<td>64</td>
<td>69</td>
<td>14</td>
<td>69 (6.1)</td>
<td>4.9</td>
</tr>
<tr>
<td>3</td>
<td>Closed</td>
<td>Open</td>
<td>81</td>
<td>66</td>
<td>79</td>
<td>78</td>
<td>64</td>
<td>79</td>
<td>78</td>
<td>17</td>
<td>75 (6.9)</td>
<td>9.2</td>
</tr>
<tr>
<td>3</td>
<td>Closed</td>
<td>Closed</td>
<td>64</td>
<td>80</td>
<td>64</td>
<td>78</td>
<td>79</td>
<td>75</td>
<td>63</td>
<td>17</td>
<td>72 (7.8)</td>
<td>10.9</td>
</tr>
<tr>
<td>1</td>
<td>Open</td>
<td>Open</td>
<td>81</td>
<td>84</td>
<td>79</td>
<td>86</td>
<td>80</td>
<td>81</td>
<td>83</td>
<td>7</td>
<td>82 (2.5)</td>
<td>3.0</td>
</tr>
<tr>
<td>1</td>
<td>Open</td>
<td>Closed</td>
<td>86</td>
<td>81</td>
<td>80</td>
<td>84</td>
<td>83</td>
<td>79</td>
<td>86</td>
<td>7</td>
<td>83 (2.8)</td>
<td>3.4</td>
</tr>
<tr>
<td>2</td>
<td>Open</td>
<td>Open</td>
<td>84</td>
<td>85</td>
<td>85</td>
<td>85</td>
<td>88</td>
<td>94</td>
<td>95</td>
<td>10</td>
<td>88 (4.6)</td>
<td>5.3</td>
</tr>
<tr>
<td>2</td>
<td>Open</td>
<td>Closed</td>
<td>89</td>
<td>95</td>
<td>96</td>
<td>86</td>
<td>87</td>
<td>83</td>
<td>87</td>
<td>13</td>
<td>89 (4.8)</td>
<td>5.4</td>
</tr>
<tr>
<td>3</td>
<td>Open</td>
<td>Open</td>
<td>88</td>
<td>85</td>
<td>85</td>
<td>87</td>
<td>89</td>
<td>89</td>
<td>100</td>
<td>15</td>
<td>89 (5.1)</td>
<td>5.8</td>
</tr>
<tr>
<td>3</td>
<td>Open</td>
<td>Closed</td>
<td>100</td>
<td>85</td>
<td>98</td>
<td>86</td>
<td>95</td>
<td>86</td>
<td>88</td>
<td>14</td>
<td>91 (6.3)</td>
<td>7.0</td>
</tr>
</tbody>
</table>

Overall, the closed door attenuated the SPL by 15-20 dB compared to open. The authors also noted that the position of the other doors had little impact on receiving room SPL. They noted variation between repeated tests ranging from 2.5 – 7.8 dBA. A comparison of the open and closed receiving room doors is provided in Table 18.
Table 18 – Comparison of closed and open door SPL for 3100 Hz alarms [121]

<table>
<thead>
<tr>
<th>Metric</th>
<th>Closed</th>
<th>Open</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean</td>
<td>69</td>
<td>87</td>
</tr>
<tr>
<td>STD</td>
<td>7</td>
<td>5</td>
</tr>
<tr>
<td>Minimum</td>
<td>60</td>
<td>79</td>
</tr>
<tr>
<td>Maximum</td>
<td>81</td>
<td>100</td>
</tr>
<tr>
<td>Median</td>
<td>68</td>
<td>86</td>
</tr>
</tbody>
</table>

In addition to experimental measurements, the authors compared their data to calculations based on the methods of Butler, Bowyer and Kew and Halliwell and Sultan. The authors note that their comparisons may be applicable to other alarm frequencies given the attenuation factors (C7) of Butler, Bowyer, and Kew or using the lambda term, the sound frequency divided by the speed of sound in the method of Halliwell and Sultan. It should be noted that the method of Butler, Bowyer, and Kew apply a reduction in SPL of -7 dBA for 3000 Hz alarms compared to 500 Hz tones. The method of Halliwell and Sultan actually favors higher frequencies through use of the lambda term, and do not account for differences in transmission of the sounds through partitions.

On average the method of Butler et. al. underpredicted SPL by 3.9%, while Halliwell and Sultan overpredicted SPL by 1.9%. The method of Butler et. al. always predicted low SPL (-6.8 - -0.9), while Halliwell and Sultan both under and overpredicted (-6.4 – 8.0%). The predictions of the two methods diverged with increasing distances, as the Butler method applies increased attenuation as a function of distance while the Halliwell and Sultan method does not.

Comparison of the SPL in the various rooms as function of the distance of the corridor indicates a consistent reduction in SPL as shown in Figure 72. Room 2 is 11 ft away from alarm, yet with door closed averages only 69 dBA and not 75 dBA as is required at pillows. With both the door open and closed, an average reduction in SPL was observed of -0.35 dBA per foot. With the door open, the average curve exceeds the 75 dBA requirements, but with the door closed even the intercept is below 75 dBA (0 ft distance). The SPL in the close bedrooms (8 ft, and 11 ft) did exceed the 75 dBA with variability, but in many repeated measurements did not. Even with hollow core doors, reducing the R from 18.5 to 14 and using the two calculation methods, Halliwell and Sultan predict 74.6 dBA and Butler predicts 70.4 dBA in room 2 11 ft from the alarm source, further indicating that alarms outside rooms are not adequate.

Figure 72 – Measured SPL in bedrooms of varying distance from hallway alarm (3100 Hz) with doors open and closed [121]
Based on the testing, the authors recommend making multiple measurements for audibility and expect errors as high as 20% and recommend applying at least a 10% safety factor to audibility measurements.

6.22 OLENICK 2019 [122]

In a 2019 research study for the research foundation, Olenick et. al. from Combustion Science Engineering (CSE) have evaluated the impacts of closed bedrooms doors on detection, fire spread, notification, and evacuation to determine if a “close your door” message from the NFPA is warranted in all cases. This report includes analysis of notification effectiveness in bedrooms with doors closed. The authors have utilized previous data and estimate the reduction in SPL from doors to be approximately 12.5-15 dBA.

This report utilizes the calculation method of Halliwell and Sultan and Butler, Bower and Kew to determine sound levels and audibility. They also reference the research of Bruck and Ball to estimate that sober young adults have an average awakening threshold of 72.5 dBA which can be extrapolated to assume 55% of occupants will awaken with a sound level of 75 dBA. Based on data from a study of fire statistics conducted by Ahrens in 2018, the authors estimate that 2.3-3.5% of all residential fires could have an adverse effect due to shutting the bedroom door due to notification issues.

7.0 Discussion

The purpose of this report was to determine if sufficient data existed to justify a reduction in SPL for low frequency sounders and to identify remaining knowledge gaps. A broad historical assessment was conducted to identify the full scope of this available data. To determine if a reduction in SPL can be justified, it is important to answer several questions.

- What was the original basis for 85 dBA at 10 ft for all alarms?
  - Is this basis still valid now that alarms are required in all bedrooms and with interconnection?
  - Why was the 75 dBA at 10 ft exception for alarms in bedrooms removed in 1999?
  - Given alarms outside of bedrooms, is the 85 dBA requirement even sufficient to alert most occupants?

- Why does the 520 Hz harmonic tone awaken more effectively than traditional alarms greater than 2000 Hz?
  - Is it because of the complex harmonic nature of the tone compared to pure tone alarms?
  - Is it because of the increased total sound power due to A-weighting of SPL?
  - Is it because the tone is unique and we are desensitized to the other beeps (electronics, dishwasher, microwave, etc) compared to 30 years ago?

- Can a reduction in SPL be predicated on the assumption that they will be installed in bedrooms?
  - Can we assume the public will install them correctly?
  - Can we justify a reduced SPL based on alarms installed in hallways outside closed bedrooms?

Based on the reviewed test data, several quantified effects become evident. In every test scenario conducted, the low frequency harmonic tones were able to awaken an equivalent number of test subjects across every population (children, hard of hearing, the elderly, the intoxicated, etc.) at reduced SPL between 10-20 dBA lower than high frequency pure tone alarms. A low frequency alarm with reduced SPL (dBA) installed in the same location as a high frequency alarm with 85 dBA at 10 ft SPL harmonic can achieve equivalent waking performance for most people and most scenarios. It should be noted that equivalent in this case may mean waking between 50-90% of test subjects, and this level of performance may not be considered adequate for emergency waking response. An equivalent performance to existing alarms for normal hearing adults, for whom existing high frequency tones are generally considered adequate, with an overall improvement for the at-risk groups would constitute a drastic improvement in overall fire safety performance.

A synthesized analysis of 50 years of waking performance data was conducted. This included average assessments of the 50% waking thresholds (as a comparison metric, not a performance target) among multiple data sets, populations, and alarm tones. The comparison of this data clearly indicated the improved
performance of the low frequency harmonic tone over traditional high frequency alarms. This effect was most apparent for at-risk populations, including children, older adults, people with hearing loss, the intoxicated, and subjects who took sleeping medication. Among this population, an average reduction in SPL up to 20 dBA was estimated to provide equivalent waking performance between low frequency harmonic alarms and high frequency alarms. Among the normal population, the effect was far less drastic. Depending on the way data was grouped, the improvement of low frequency alarms over high frequency alarms ranged from 6 dBA improvement to 2 dBA reduction in performance. It should be considered that the 6 dBA improvement was for test data compared when both alarm types were included in the same methodology. The 2 dBA reduction in average performance was estimated using a very limited set of low frequency data (n=17) and a very large set of high frequency data (n = 866) conducted with many different methodologies, alarm presentations, lab conditions, etc. that could easily bias this comparison. The high rate of variance even within single AAT experiments ( >15 dBA) and potential historical bias (desensitized modern population) lead one to uncertain quantification for the normal population.

In addition to waking performance, the sound transmission characteristics of the low frequency harmonics also result in higher SPL in bedrooms when installed outside the bedrooms. In multiple tested conditions, distances, door positions, and number of rooms, the low frequency harmonic tones consistently resulted in SPL 4-8 dBA higher than high frequency tones due to reduced signal attenuation. When installed inside bedrooms, the complex harmonic tone is less likely to produce destructive interference patterns and null zones or be masked by various ambient noises than pure tone alarms. In addition, complex harmonic tones give the impression of fullness with louder apparent sound that is not quantified by A-weighting measurement techniques.

Although test data is numerically strong indicating improved performance of low frequency alarms, the reasons for this improvement are less certain. The effectiveness of the low frequency tone may result from an increased total sound power level compared to high frequency tones. Due to the basis of the A-weighting scale on human hearing perception at low intensity (40 phon), the 520 Hz tone is measured with a 4.2 dBA reduction compared to 3100 Hz tones. This means that for the same dBA, the 520 Hz tone carries approximately 3 times the total wave power. It has been proposed, although with limited data, that humans do not perceive sound in deep sleep based on the A-weighting scale, and thus the low frequency tone has been artificially and unnecessarily penalized by 4.2 dBA compared to high frequency alarms. In sleep, it may be possible that sounds are not heard and interpreted the same as when during waking, and rather the sounds are felt more by the raw power than by traditional transformations of sound by the ear and brain. The primary data set indicating this effect was collected by Levere et. al in 1972 testing only 8 college aged males and measuring the magnitude of EEG responses and so should be considered as a theory that may explain the improved waking performance only. There is also no data clearly refuting or disproving this effect either.

Alternatively, the louder impression of the sound may have nothing to do with sleep but may be inherently related to the increased perceived loudness due to complexity and richness of tone. Several methods for quantifying perceived loudness have been proposed that indicate inadequacies in the A-weighted scale, including the method of Zwicker [11] and the Moore-Glasberg methods [18] recognized by ISO 532-2. These methods attempt to account for the cumulative effects of multiple harmonic frequencies and the increased perception of loud tones that the A-weighting scale does not. Regardless of why the low frequency tone is better, there is clear quantified numerical evidence that the tone provides equivalent performance at lower dBA values that traditional high frequency alarms.

8.0 Recommendations, Gaps and Next Steps

While a primary goal of this research was to identify gaps toward reducing the SPL requirements of low frequency alarms few gaps remain for research and study. There is compelling evidence of the potential of low frequency harmonic tones with reduced SPL for alarms located in the bedrooms and outside the bedrooms to maintain more effective waking performance for both normal and at-risk populations. Although demonstrated in controlled testing, it is not entirely clear how compounding effects (e.g., hard of hearing and taking sleeping
medication, etc.) could influence real world performance. The reasons why people respond to the alarm are not fully proven, but the improved performance is apparent in the conducted testing. A reduction in required SPL for low frequency alarms could be justified given the existing data. The recommended reduction should be minimized to meet the engineering design requirements due to power consumption and battery life to provide battery operated low frequency alarms in residential applications.

The remaining gaps include determining an acceptable magnitude for reduction. This decision would be based on weighing the increased performance for at-risk populations against the reduced or non-existent improvement for the normal population. A cursory comparison of the breadth of test data was conducted which indicates equivalent performance for at-risk populations at reduced SPL up to 20 dBA and for normal populations up to 6 dBA reduction. In order to fully reconcile these values statistically, access to the complete data sets for each considered experiment would be needed and a statistical analysis complete with uncertainty would be required.

In addition to considering measured waking performance, reduction in SPL could likely be justified if it is assumed that all alarms will be installed per code in every bedroom and interconnected. Even assuming alarms are only installed in hallways outside bedrooms in violation of requirements, there is also justification for a reduction in SPL of low frequency alarms due to the improved transmission of the tone through walls and doors. The next steps remain for the impacted parties, including manufacturers and life safety experts and authorities having jurisdiction, to review the data summarized in this report and determine if / how much of a reduction could be justified, and whether allowing reduced SPL low frequency alarms to exist is sufficient or if they should be required in all single- and multiple-station alarm installations.

The analysis of the existing research does not indicate a definitive, quantified number for allowable SPL reduction or a distinct code change. This has not been identified as a gap because no reasonable amount of further testing or study would provide such a clear and simple answer. The codes and standards governing the performance and installation of smoke alarms are based on consensus of committee and panels of experts and industry representatives. This report should provide sufficient data for members of those groups to review and understand and vet any potential proposal regarding this issue.

References


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