Smoke Detector Alert for the Deaf

Phase II SBIR

Final Report

NIH Grant No. 2R44 DC004254-2

Submitted to:

The National Institute on Deafness and Other Communication Disorders

Center for Scientific Review
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May 27, 2005

I. EXECUTIVE SUMMARY

This research study has led to the development of a device that first discerns the sound of a standard NFPA 72/ANSI S.341/ISO 8201* compliant smoke detector and then activates a vibratory device to awaken a sleeping individual who may not have or can not hear the audible alarm. The product is primarily directed towards deaf and hard of hearing persons whose hearing capacity prohibits them from responding to an activated smoke detector. The current research has indicated that there is a pervasive need for audible alarm alternatives for not only the deaf but also the hard of hearing and the hearing able elderly population.

Several intermediary tasks were performed in order to arrive at a prototype emergency notification device. The tasks were divided into two research directives that were pursued simultaneously. The first task developed the Phase I audio recognition algorithm to better detect the sound of an activated audible smoke detector, and the second task involved human subject testing performed in cooperation with a national sleep laboratory to identify which alerting methods work best to awaken sleepers of various hearing abilities. The tasks associated with the development of the sound recognition algorithm included characterizing the sound attenuation due to distance and acoustic barriers, refining the algorithm to recognize the smoke detector signal in the presence of different audible interferences including other smoke detectors, and incorporating some additional methods to guarantee positive activation for pre-1996 alarms. The tasks associated with sleep testing of human subjects included, recruitment of deaf, hard of hearing, and hearing able subjects; selection of commercially available alerting technologies assumed to have the greatest awakening reliability; and evaluation of the reliability of each device for each hearing classification of the volunteers.

The algorithm development culminated in the development of a LabView™ virtual instrument that regularly scans the background noise, performs a Fast Fourier Transform on the processed data, determines the spectral content of the aural data, and checks whether the temporal pattern of an NFPA 72 compliant smoke detector alarm is present. Rigorous testing of the algorithm in echoic and anechoic environments and in the presence of continuous and pulsed

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* The pulsed temporal pattern incorporated into the NFPA 72 fire code in 1996 has been adopted by the American National Standard ANSI S3.41 "Audible Emergency Evacuation" and the International Standard ISO 8201 "Audible Emergency Evacuation Signal" standards. NFPA 72, ISO 8201, and ANSI S3.41 will be used interchangeably throughout this document ONLY with respect to the temporal requirements of an audible alarm. The NFPA 72 code in Appendix A-2-2.2 further specifies that the decibel level of a manufactured audible alarm should have a rating of 85 dB at 10 feet, while the audibility of an alarm must minimally register 15 dB above ambient noise in a bedroom or 75 dB at pillow height.

interferences led to additional refinements of the algorithm's sensitivity. Likewise, a sleep mode was incorporated that reduces the data sampling interval from 30 seconds to 50 milliseconds when a 3200 Hz (+/- 10%) peak is not present in the background noise. This cuts down on the energy requirement of the device. Finally, a means of tuning the algorithm to detect pre-1996 alarms and industrial audible smoke detector signatures was arrived at to expand the range of applicability of the device. All of these features have been incorporated into the logic of the prototype device.

The sleep testing demonstrated that the audible smoke detector is 92% effective across all sleep stages for the hearing able population, 57% effective for the hard-of-hearing, and 0% effective for the deaf. The strobe effectiveness was 32% for hearing able, 34% for hard-of-hearing, and 57% for deaf persons. The vibratory bed shaker offered greater effectiveness: 82% for the partially hearing, and 93% for the deaf, while offering effectiveness comparable to the audible detector for the hearing able, namely 92%. Nonetheless, a bed shaker that made use of an intermittent vibratory signal similar to the three-pulse pattern of the audible smoke detector yielded 100% waking effectiveness for hearing able, hard of hearing, and deaf subjects across all sleep stages. As a result, the three-pulse bed shaker was rated the best actuation device to be coupled with the algorithm. Thus, the prototype contains the sensitivity of an algorithm that can be tuned to one's particular smoke detector with an effective tactile signal that can be easily distinguished as an emergency alarm.

II. INTRODUCTION

When it comes to meeting the general public's need for adequate fire emergency notification devices, one is forced to consider whether the standard off-the-shelf audible smoke detector provides the most appropriate stimulus to prompt a sleeping person to take life-preserving action when the alarm activates. A small fire that starts in a corner and spreads to adjacent home furnishings can render an entire bedroom untenable in less than five minutes. Therefore, selecting an alerting stimulus that can expediently reach a person's consciousness across all levels of sleep is paramount to reducing a person's awakening latency. More importantly, selecting a device that does not depend solely on one's hearing capacity (which can change imperceptibly over time) may have a broader applicability as an emergency notification and fire protection device. The most recent statistics from the National Center for Health Statistics indicate that 17% of Americans over the age of 18 (35 million people) have some form of hearing loss, and over 3% of those people are severely hearing impaired or profoundly deaf [1]. Thus, a significant portion of the American population is at a great disadvantage of not receiving timely notification of a fire event from an audible alarm alone. And as the population grows due to the influence of longer life expectancies, the public health risk associated with people's inability to respond to audible alarms will increase.

Legislation, such as the Americans with Disabilities Act (ADA) in conjunction with regulations imposed by local fire officials, has helped the public recognize the disadvantage that deaf and hard-of-hearing people have concerning notification of fire alarms. Likewise, legislative efforts have established government entities such as the Interagency Coordinating Council on Emergency Preparedness and Individuals with Disabilities very recently. Most residential automatic fire detection systems generally provide notification with an audible signal. Most residential alarm manufacturers recommend special purpose alarms with strobes for locations where persons with hearing loss may sleep or reside. Nonetheless, the effectiveness of combination audible/visual alarms drops for the hearing impaired when assistive listening devices are removed for sleep or if the individual is out of the line of sight of the visual alarm. Research to date shows that the effectiveness of flashing lights is limited to high intensity strobes that are placed at a range of 6 to 10 feet from the sleeping subject [2]. Waking persons from sleep is of significant importance because the majority of fire deaths in residential settings occur between the sleeping hours of 11:00 pm and 6:00 am. Although only 20% of fires are reported to have taken place during this temporal window, nearly 50% of fire fatalities occur during this time [3].

Thus for the purpose of improving fire safety for the deaf and hard of hearing, Combustion Science & Engineering, Inc. (CSE) requested this Small Business Innovative Research Grant to investigate the following objectives:

1) Which of a number of commercially available methods of awakening people may best serve the public independent of hearing ability?
2) Is the waking effectiveness of emergency alerting devices affected by the sleep stage from which one is awakened?

3) Can the algorithm developed in the Phase I proof of concept study be further developed to positively identify an audible smoke detector amid background noise and physical sound barriers?

4) Can a new technology/prototype be developed that will take advantage of the algorithm's aural discernment of an audible detector and provide a waking alert for the deaf and hard of hearing that is as effective as the standard audible alarm for the hearing able?

Research conducted by the Center for Fire Research at the National Institute of Standards and Technology (NIST) found that most deaf people are "fully capable of self-preservation [from fires] if they are informed of the danger"[4]. Therefore, the use of fire alerts specifically designed for deaf individuals that can provide a timely mechanism of warning across all sleep stages could significantly improve the chances of surviving a fire for a hearing impaired individual.

III. BACKGROUND

A. The Nature of Sleep

Normal adult sleep is cyclic in nature and consists of five distinct phases [5]. Stage 1 sleep is characterized by drowsiness and is the first stage of sleep in the sequence. During this initial 5 – 10 minute stage, the eyes are closed. In stage 2 (S2) sleep, the brain and body prepare to enter deep sleep. Muscles tense and relax, the heart rate slows, and the body temperature decreases. Stages 3 and 4 comprise the DELTA phase of sleep, the deepest sleep requiring the strongest stimuli to awaken from. Brain activity slows during this phase. Stage 5 or REM sleep is unique in that the level of brain activity increases and is similar to stage 1, yet the body's major voluntary muscle groups remain paralyzed. REM is an "active" sleep characterized by rapid eye movements. Muscles twitch, and the heart rate and respiration may accelerate and become erratic. As a person sleeps, he or she initially "descends" sequentially through stages 1 through 4, ascends sequentially through stages 4 to 2, and then enters REM sleep. The first occurrence of REM is 10 minutes in duration and occurs 90 minutes into the onset of sleep for most adults. From REM, the cycle of descending and ascending begins with S2 and continues with the depth of the cycle tending to become less with each sleep period [5]. The REM sleep phase tends to reappear every 90 – 100 minutes throughout the sleep cycle and increases in duration with each period to a maximum duration of an hour [6].

The time the brain spends in each sleep phase is not equally distributed throughout the night. Stage 4 occurs predominantly during the first third of the night, while REM sleep is most prevalent during the last third [5]. The distribution of sleep across each phase is also affected by age. Pezoldt found among numerous sleep study reports that young adults could spend up to 20% of their total sleep in DELTA, while 50-60 year old male subjects spend approximately 2.7%, and 64-87 subjects spend 1.4% of their total sleep in the DELTA phase. Pezoldt is careful to point out that because of his limited sample size of people between 64-87 years of age, his conclusions regarding the range of differences in sleep character between human subjects of different ages can not be generalized to the population as a whole. Nonetheless, the multiple studies he cites demonstrate that as one ages the amount of time spent in DELTA sleep decreases. And therefore, arousal thresholds will vary with each person studied.

Bonnett provided a comparison between sleep level and arousal threshold [7]. Twenty-six hearing able young adult males were exposed to two second 1000 Hz tones at varying decibel levels while sleeping. The arousal thresholds were determined to be 70 decibels above ambient noise (dBA) in stage 2, 92 dBA in stages 3 and 4, and 83 dBA in REM sleep. His second study found that subjects awoke one half of the time to 1000 Hz 75 dBA tones. The delta phase of sleep requires the most intense arousal; the arousal threshold differences between stages 1, 2 and REM are minimal [7]. The literature points to several other sleep tests that demonstrate that stages 3 and 4 are most difficult to awaken from. The implication of this notion is that any newly designed emergency notification device must be sufficiently intense to provoke a response when the sleeper is in DELTA sleep.

B. Literature Review

While several studies have investigated arousal to audible tones, only a limited number of those studies have examined the waking effectiveness of audible smoke detectors while taking into account sleep stage. Bruck and Horasan studied the awakening effectiveness of smoke detectors with twenty-four young adults in various stages of sleep [8]. The subjects were not informed that the investigators were observing arousal to sound, but rather that they were looking at dreams and the volunteers' performance of a task. The detector was located outside of the sleeping rooms and emitted a sound of 2000 – 4000 Hz at a volume of 60 decibels (dB) at the pillow. The sleep level of the subjects was monitored with scalp and facial surface electrodes. Each subject was awakened twice during the night while in sleep stages 2, 4 or REM. The alarm continued for ten minutes if the subject did not awaken and was repeated again once the subject returned to the specific sleep stage. The subjects who awakened to the alarm were monitored to see what actions they took. If no action was taken, the sleep technician entered the room, informed the subject of the true nature of the experiment, and then asked a series of questions to assess his or her mental activity or dreaming immediately prior to the alarm. The subjects were told that they would be awakened once more during the night and that they were to press the intercom button next to the bed to communicate with the sleep technician.

Of the twenty-four subjects studied by Bruck [8], five of them were not aroused by one or more of the alarm events. No significant difference was found in the time of arousal between the tests where the subjects were aware that an alarm was sounded to awaken them and those tests where the subjects were naïve to the true purpose of the alarm. Seventy-five percent of the awakenings occurred within 30 seconds of the alarm activation and 87% occurred within one minute. If the alarm did not wake the sleep test subject in one minute, the probability of awakening the subject dropped to less than 50%. Bruck found that the latency period to awaken from sleep was longer in stage 4 sleep than either stage 2 or REM, and that 23% of awakenings from stage 4 were longer than two minutes. Nonetheless, given the small sample size, these results were not found to be statistically significant [8].

Nober performed sleep tests to assess the alarm level needed to arouse subjects in their homes [9]. While aware of the importance of sleep stage, he was unable to incorporate sleep stage measurements into his experimental home testing protocol. Nober assessed sufficient alarm levels for waking on the basis of three sets of experiments. The first set measured the intensity frequencies of several smoke alarm signals and arrived at a mean smoke detector sound definition of 80 – 92 dB above ambient at 10 feet from the detector with the highest energy peaks between 3000-5000 Hz. The audibility of the smoke detector characteristic was found to drop to specific levels of 70, or 55 dBA depending on the position of the detector inside or outside of a bedroom door. The second set of experiments quantified the subjects' effective awakening to the mean detector signal against a number of variables: alarm sound level (85, 70, 55 dBA), background noise (63 dBA air conditioner), hours into sleep, gender, and night of the week. The final experiments looked at the behavior of a designated respondent in his or her home and the time for the entire household to evacuate. The respondent was the member of the household who when awakened was to deactivate the alarm and call the fire department. Nober looked at households with geriatric subjects, yet did not investigate age-related hearing loss as a specific factor affecting time to complete the required tasks.

Nober concluded that college age subjects are most effectively awakened by alarms with a sound level of 55 dB above ambient, if the subject is sensitized to the signal prior to the test. Regarding the household tests, audible alarms were found to be effective, and the egress time did not exceed two minutes for 75% of the cases investigated. The egress times for the elderly were found to be longer due to mobility issues rather than difficulty awakening from sleep.

A study by Khan investigated the alerting effects of not only sound but also other stimuli generally associated with fire, specifically heat and smoke odors [10]. The experiments were conducted on two groups of hearing able college-age male subjects. The first group of test subjects was exposed to a smoke detector at volume levels of 78, 54, and 44 dBA. The second group was exposed to a smoke odor generated by the illumination of a spray painted light bulb, a separate heat presentation produced by the activation of a radiant heater, and a smoke detector presentation at 54 dBA. Each presentation of the smoke detectors, smoke, or heat occurred at distinct times: 2, 4, and 6 hours after the person initially fell asleep. Test subjects were told that the environment in which they slept would likely change and they should contact the experimenter by intercom to describe any change that awakened them. Each subject received only three stimuli throughout the course of the evening. Specific sleep stage was not monitored; however, presenting the stimuli in the specific time blocks was geared towards examining whether elapsed time from onset of sleep would impact response latency.

Khan found that 100% of the presentations of the 75 dBA smoke alarm, 41.7% of the 54 dBA smoke alarm presentations, and 25% of the 44 dBA smoke alarm presentations were detected by the first group of test subjects. In the second group, 58.3% of the 54 dBA smoke alarm presentations, 25% of the smoke presentations, and 25% of the heat presentations were detected by the test subjects. Khan attributed the lack of response to many of the smoke alarm presentations as attributable to students' lack of familiarity with the tone produced by the smoke detector used. Likewise, he pointed to lack of familiarity with the risk of fire and fire cues to the poor response to heat and smoke presentations. Nonetheless, Khan found a mean latency of 83 seconds for the 78 dBA alarm presentation and was able to demonstrate with his results that test subjects respond most readily to audible stimuli which present at pillow height with a strong signal to noise ratio. In addition, he found response times to increase approximately 23 seconds/decibel as the signal-to-noise ratio of the alarm presentation dropped. While not statistically significant, Khan also noted reduced times to arousal during the 4 hour time band. The average times to alert to the 54 dBA detector, the smoke, and the heat presentations were 624, 974 seconds, and 1107 seconds, respectively, for the second group. Khan's work points to the importance of choosing stimuli that both hold significance to the population studied and are sufficiently different from everyday stimuli when designing fire-emergency notification systems.

Underwriters Laboratories' Subject 1971 "Report of Research on Emergency Signaling Devices for Use by the Hearing Impaired" is a cornerstone report in that the conclusions of the analysis have been instrumental in establishing the equivalency of 110-177 candela (cd) strobes in sleeping areas to the audible smoke detector[11,12]. The report looks at the efficacy of strobes under different lighting conditions. In addition, the impact of a person's activity level in these environments on strobe alerting efficacy was also evaluated. The influence on air movement and vibratory stimuli on a person's ability to awake from sleep were also investigated.

The first series of experiments in the UL test exposed 110 hearing able UL employees to flashing light from a tunable strobe placed behind them seven feet above the floor. To replicate the conditions of the individual at home, each volunteer was placed in a room with an illuminated television and two 100W lamps. The volunteer sat on a sofa in front of the television between the two lamps, and he or she was given headphones to simulate deafness and eliminate the impact of hearing on his or her response. The light intensity of the strobe was adjusted by swapping in differently rated charging capacitors. During this test, the efficacy of the strobes was compared when the subjects' eyes were open. 92.7% of volunteers were able to perceive a 1 Hz, 17 cd strobe when their eyes were open. Those who were not alerted to the strobe attributed their negative response to poor eyesight. 92% were able to perceive a 1 Hz 75 cd strobe while awake with their eyes closed. All of the volunteers were alerted to a 150 cd strobe when their eyes were closed. UL's demonstration of the differences between closed and open eyes was intended to gain insight into how much additional light intensity was required to penetrate the eyelids. Although the protocol did not represent a true sleep test, these recorded measurements are thought to correspond to the lowest perceptible strobe intensities for sleeping subjects.

The second set of tests investigated the time for seated individuals to find an object on a table across the room and return to their seat while a strobe activated. Strobe intensities were rated at 20 cd and 120 cd , and the flashing frequencies varied from 0.33 Hz to 3 Hz. At 0.33 Hz, 95% of the volunteers performed the task within 35 seconds when working with the 20 cd strobe. At the same flash frequency, the 120 cd strobe elicited slightly longer completion times: 95% of the volunteers exposed to the more intense strobe finished the task in 50 seconds. The brighter strobe induced longer episodes of temporary blindness; however, according to the report, it was the frequency of the flashing more so than intensity that had the greatest impact on the alacrity with which volunteers performed the task. The faster the flashing rate (3Hz), the more reflected light was available to sufficiently illuminate the room for the individual to perform the task. Results for task completion for the high frequency strobe cases are not provided within the UL report.

To establish strobe intensity thresholds that are perceptible in windowed daytime work areas, legally deaf junior high students of the Illinois School for the Deaf were observed in their classroom environment. A strobe alarm was placed in the rear of the classroom behind the students on 7 ft poles. This third test series was conducted randomly in three different classrooms over the course of almost three months. While engaged in normal classroom activities, the students were observed for any indications that they were aware of the onset of strobe activation. What observers looked for in terms of behavioral cues from the students is not mentioned. Likewise, whether a teacher was present directing classroom activity is not clear. If the teacher stood at the head of the classroom facing the strobe, he or she would have directly observed the strobe and could have influenced the responses of the students. The strobes were activated for 4 minutes. UL’s data indicates that within 60 seconds of activation, 12% of the 34 students exposed to the 5 cd strobe responded directly to the light and its reflections, while 6% were alerted by their peers, and 82% were unaware of the light after 4 minutes. When exposed to a 10 cd strobe, 76% of 76 students responded to the strobe light, while 4% were alerted by peers and 20% did not respond. At 15cd exposures, 92% of 27 students were alerted to the light within 30 seconds, and only 8% did not respond.

Next, UL engaged in tests to determine strobe-awakening intensities for sleeping deaf individuals during the night. One hundred one individuals between the ages of 10 – 65 were tested in their homes. A strobe with tunable intensity was placed in the subject's bedroom on a 7 ft pole at the end of the room opposite the head of the bed. The strobes were activated once a night between 1:00 – 4:00 am by timers for 4 minutes. Activation intervals varied from every other night to once a week. Volunteers were directed to record both the time they first perceived the alarm, and whether they were asleep at the time of the strobe activation. If the subject's reported time was within 4 minutes of the true activation time, the subject was said to have successfully awakened to the alarm. The test protocol indicates that volunteers are exposed to lights of decreasing intensity after positive tests. Negative tests were repeated once at the same intensity and then resumed at higher intensities until successful results were again achieved. Volunteers were not monitored to determine their sleep stage or whether in fact they were asleep. Overall, 88% of all of the study participants were able to perceive the 110 cd strobe. Those individuals who were taking medication were found to perceive the brightest strobe only 28% of the time. Younger unmedicated volunteers were less likely to perceive the alarm while asleep: high school age volunteers had 91% positive responses to the 110 cd strobe, while junior high age volunteers reacted 86% of the time. Of the 22 adult subjects not taking medications, 100% awakened to 110 cd strobes while 95% awakened to 40 cd strobes.

What is intriguing about this second result is that it contradicts the lowest light intensity threshold established in the first set of tests. According to those preliminary tests only 10% of the volunteers could perceive a 45 cd strobe when their eyes were closed. The sleep test results should not exceed the sensitivity of the awake-with-closed-eyelids test. Similarly, 77% of the adults awakened to a 2 cd strobe. None of the individuals in the closed eye test perceived strobes below 40 cd. Subject's testimony of whether they were awake or not at the onset of the strobe initiation is not included in the published report. The peculiarities of this portion of UL's testing protocol will be revisited later in this Phase II report.

Finally, UL investigated air movement and vibratory stimuli on test subjects sleeping in their own home environment. The protocol for the fan and vibratory activations was similar to that used in the previously mentioned home study. The fans were placed such that they directed air onto the sleeping individual. Two fans in oscillatory mode were utilized. In order to deliver 140, 270, 320, and 480 ft/min of air at the bed, both the high and low fan settings were utilized.

The vibratory device operating at 100Hz was placed either under the subject's pillow or under the mattress directly under the individual's torso. Whether the subject was asleep when the vibrator or fan activated can not be discerned. Of the 69 unmedicated test subjects ranging in age from 10-65, 55% responded to the 140 ft/min air speed while 81% responded to air velocities of 270 ft/min and higher. As in the strobe test, children reacted less frequently than adults: 78% of high school age volunteers, and 77% of junior high age volunteers responded to air flows of 270 ft/min or greater, while 100% of the 10 adults tested responded to the same air exposures. Regarding the vibratory devices, volunteers in general responded more aptly to the device under their pillow than under their mattress: 90% responded to the pillow shaker while 84% responded to the mattress shaker. The 21 adults in the study responded equally, 95% of the time to the device independent of its placement. To summarize, UL was able to measure waking effectiveness of 95% or greater for legally deaf adults exposed to 1) strobes of 75 cd or stronger, 2) air speeds of 270 ft/min, or 3) vibratory devices with a minimum displacement of 1/8 inch at 100 Hz.

IV. PROJECT DETAILS

A. Algorithm Development

Residential Smoke Alarm Signals Characterized

The majority of the residential smoke alarms sold in the United States manufactured after 1996 adhere to NFPA 72 requirements for audibility. The standard for the temporal pattern, later adopted by ANSI S3.41 and ISO 8201, requires that the temporal pattern consist of three tones of ½ second separated by a ½ second with a 1 ½ second pause after the third tone. The signal may deviate from these times by up to 10%. The sound power standard included in NFPA 72 states that the audible signal be no less than 75 dBA in sleeping areas when doors along the path of audio transmission are closed. In noisy environments, NFPA 72 includes a corollary suggestion wherein the power of the audible signal measure at least 10 dBA above ambient noise levels, except in sleeping areas where the signal should measure 15 dBA or above.

The signals from several smoke detectors manufactured both prior to and since 1996, were characterized based on temporal signal and spectral content. Smoke alarms, available as of April 2003, and produced by three different manufacturers were characterized. Three smoke alarms produced by different manufacturers prior to 1996 were also characterized. These audible smoke alarm signals were characterized in terms of pulse pattern, frequency, and strength of signal. The analysis took place in an anechoic environment in order to reduce interfering resonating signals. A unidirectional microphone with a flat frequency response was used to collect the audio signal. The signal was then recorded and processed by a dynamic signal analyzer using the data acquisition and analysis program Labview, developed by National Instruments.

The pattern of the signals of the smoke detectors produced after 1996 followed the temporal pattern prescribed by ISO 8201 within 10% of the times mandated. The smoke detectors manufactured prior to 1996, however, had varied time-domain signals. Some were continuous signals, while others were continuously pulsed. In the frequency domain, the signals from smoke detectors manufactured both before and after 1996 shared a common frequency peak between 3200 and 3400 Hz.

<u>Industrial Smoke Alarm Signals Characterized</u>

Several audible signals from industrial smoke alarms were characterized in the same way residential alarms were analyzed. These alarms had user-selectable audible signals such as chime, continuous horn, bell, siren, and whoop. Each of these settings had a unique temporal pattern. The spectral content of the signals were also varied, however they all produced the largest peak between 2500 and 4000 Hz.

<u>Interfering and Background Noises Characterized</u>

Numerous household noises were characterized using the same method as described above to characterize the smoke alarms. The audible signals from a blender, cell phone, hair dryer, watch alarm, alarm clock, radio, and carbon monoxide detector were evaluated. These signals were characterized in order to help design an algorithm that would be able to distinguish a smoke alarm signal from the background noise. The background noises included signals that had a wide range of peak frequencies and were both continuous and pulsed.

<u>Development of Signal Recognition Algorithm</u>

An algorithm was developed to recognize the audible signal from a residential smoke detector among background noise and interfering noises. The scope of this project was limited to the recognition of residential smoke alarms manufactured after 1996 due to the variety of alarm signals available from both smoke alarms made prior to 1996 and industrial alarms.

National Instrument's Labview was again used to develop this algorithm. The algorithm first requires the input of 12 audio data samples of 50 milliseconds spaced by 50 milliseconds. These samples were then processed using a Fast Fourier Transform routine to determine the spectral content. Based on the power of the signal and the temporal pattern present, the presence of an audible smoke alarm signal can be determined.

Further, because this constant scanning and analysis process would consume energy continuously, a routine was introduced to allow the recognition system to operate only when a smoke alarm signal may be present. The algorithm includes a "sleep mode", where a data scan is taken every 30 seconds, to determine if an audio signal containing a strong peak near 3200 Hz (+/- 10%) is present in the ambient noise. If this peak exists, the system will enter "scan mode", where it will begin collecting the 12, 50 millisecond samples required to determine if a smoke alarm signal is present. The system will run in "scan mode" for a maximum of 10 cycles or until it confirms the presence of a smoke alarm signal. If no signal is detected, the system reverts back to "sleep mode" where it will remain until a peak in the 3200 Hz range it detected.

The algorithm developed can be easily adapted to search for other patterns or signals with different spectral content. For instance, to enable to the system to detect the audible signal from smoke alarms produced prior to 1996, the pattern criteria could be eliminated and the target frequency peak would be widened.

Evaluation of Algorithm Performance

The performance of the signal recognition algorithm was then assessed in several different scenarios. Smoke detectors were activated with and without background noise including competing devices, with and without acoustic barriers, and in different acoustical environments. The algorithm was very successful in identifying a smoke detector alarm at varying distances in both echoic and anechoic environments. The algorithm was also able to identify the signal when walls and doors were placed between the smoke detector and the microphone of the audio acquisition system. Also, the detection algorithm was able to identify a smoke alarm amid competing background noises.

The most challenging scenario for the recognition system was that of multiple smoke alarms sounding simultaneously. The detection algorithm performed very well when there was one pre-1996 smoke alarm and one post-1996 smoke alarm sounding simultaneously. However, when there were multiple post-1996 smoke detectors sounding, the detection algorithm had difficulty distinguishing between the two and identifying the temporal pattern of either of the smoke alarms. Certain parameters in the detection algorithm were adjusted to improve the ability of the system to identify a smoke alarm in such a scenario. Due to slight differences in the alarming devices of smoke detectors and the differences in the power of the alarm at different distances, any two smoke alarms will produce two distinct power spectra. There is a routine in the detection algorithm which compares the power of all frequency peaks close to 3200 Hz. If these peaks have comparable power and occur in a certain temporal pattern, the detection algorithm has found a smoke alarm. By adjusting the amount by which these power peaks must match, two smoke alarm signals can be separated. This parameter was therefore fine tuned to improve the performance of the detection algorithm in this scenario.

B. Experimental Design

The major push of this Phase II SBIR was to move the preliminary “Proof of Concept” human subject testing into a realm of experimentation in which statistical relevancy of waking effectiveness could be determined. Phase I indicated that a vibrating device held under the bed was more effective than using a device that was physically attached to the body. To better understand the waking effectiveness of any device proposed for the deaf, the effectiveness of the standard smoke detector had to be ascertained for the hearing able population. Thus, the test population had to incorporate both deaf and fully hearing able people. Hard of hearing people were also entered as their own category to assess whether their waking frequency ever paralleled that of deaf or hearing able people. The sleep stages investigated were stage 2 (S2), DELTA, and REM.

<u>Population Selection and Recruitment</u>

The initial goal was to test 120 people: 40 deaf, 40 hearing able, and 40 hard of hearing. Sample sizes of 40 are consistent with a binomial distribution (either success or failure in awakening) with previous success rates near or greater than 80% and a sample error less than 10%. Attempts were made to identify individuals who would produce a sample population as racially and ethnically diverse as the current U.S. population. The sample was chosen as a probability sample using the method of judgment-stratified sampling. Sampling methods can be classified as either probability or non-probability. In a probability sample, each member of the population has a non-zero chance of being selected. Therefore, any member of the population may be called to serve as a sample population. In a non-probability sample, the degree to which the sample differs from the population is not known. Due to time and financial constraints, a true probability sample could not be attained for this study. However, the lack of such a sample did not affect the results.

The application for the study, the pre-trial questionnaire, required people considering enrollment for the study to indicate their name, contact information, race, age, hearing ability as they perceived it, and the manner in which they typically were awakened to emergency and non-emergency events. Each person accepted into the study was given a hearing test for the conduction of pure tones through both air and bone to validate each person's assessment of his or her hearing. The medical consultant on this project, Dr. John Biedlingmaier, interpreted the audiograms for each volunteer to assess which hearing category the subject should be placed in.

The study participants categorized as deaf on the basis of their audiograms were those with no hearing 90 dB or less over the range of 500 Hz to 8000 Hz. Fully hearing individuals had hearing of 20 dB or less across the frequency spectrum of 250-8000 Hz. Participants were said to be hard of hearing if their average hearing ability fell between 20 dB – 90 dB over the range of 250 Hz – 8000 Hz. It is important to note that while many of the hard of hearing participants in this study could fully understand speech, many of them were actually deaf at the 3100 Hz frequency of the smoke detector. Of the participants fifty years and older whose hearing loss was attributed exclusively to age (presbycusis), all experienced a rapid drop off of their hearing at 1000 Hz and above. The individual in this group with the best hearing ability at 3100 Hz could only perceive tones at 50 dB or louder. Assuming a closed door stood between that person and a sounding detector, he or she might not alert if asleep. This again points to the importance of rating the true reliability of the devices used by the public, and developing appropriate alternatives that can be used in conjunction with existing devices when the public is unaware of its risk-of-non-arousal to standard sounding devices.

Device Selection

Of the devices available for use as emergency alarms for the public, CSE selected three in addition to a standard audible smoke detector. The first device was an "off the shelf" strobe. The 1 Hz VA3 "Firewall M series" strobe was manufactured by SAE and rated at 110 cd. A light meter was used to quantify the effect of distance on luminosity, as shown in Fig. 1. Also selected was a pillow shaker, placed at the head of the bed in a pillowcase. The pillow shaker or "Motivator" was a Global Assistive Devices product with model number MV12. Lastly, a SonicAlert© Super Shaker Bed Vibrator (heretofore referred to as "bed shaker") was placed between the mattress and box spring in the center of the bed. An accelerometer was used to quantify the intensity of the vibration on the laboratory beds under the influence of the bed and pillow shakers. The root sum of each axis of acceleration squared (RSS) is shown in Figs. 2-3 for the pillow and bed shakers*.

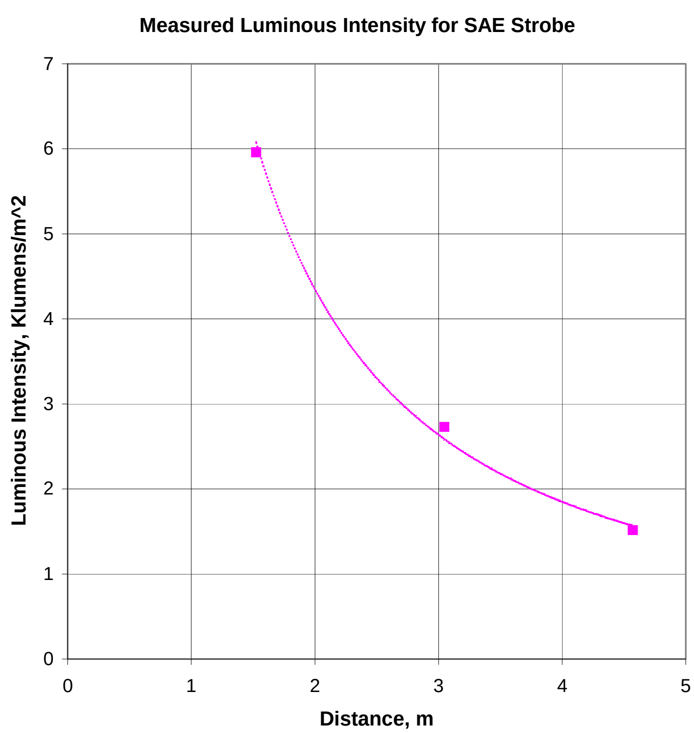

Figure 1: Luminous intensity characteristic for SAE 110 cd strobe

* See Appendix 1 for discussion of relationship between bed shaker acceleration and the force perceived by a person in contact with the device.

The audible detector chosen was a Firex Model CC smoke detector. The audible detector's presentation was adjusted, such that a presentation of 81 ± 4 dB at pillow height was attained. This rating was held fixed for all tests. Previous research by Khan[10], demonstrated that close to 100% of the hearing able would awaken to such a decibel level. Ambient noise at the testing facility measured approximately 45 dB. Thus, the 81 dBA rating exceeded both the 75 dB requirement and the 15 dB above ambient requirements of NFPA 72. By choosing this sound level, alarm salience was eliminated as a variable from the experimental test matrix.

A second smoke detector that operated in the frequency range of 400 – 500 Hz was introduced after the initial onset of sleep testing. This was done to determine whether a smoke detector with a lower tone would have a greater waking effectiveness for the hard of hearing specifically, and the entire population in general. The presentation of this alarm, a modified Darrow Company "Loudenlow", was 80 dB at pillow height.

Comments from deaf test subjects indicated that their likelihood of awakening to the bed shaker may be slow because they use the device as a non-emergency alarm clock when at home. As a result, Combustion Science & Engineering applied the innovation of the three-pulse standard temporal signal of the audible alarm to the vibration signature of the bed shaker. This yielded a secondary expression of the bed shaker as providing a tactile stimulus very different from the continuous pulse used by many as a non-emergency signal. Both the low frequency audible alarm and the "T3 bed shaker" were introduced after the initial onset of sleep testing.

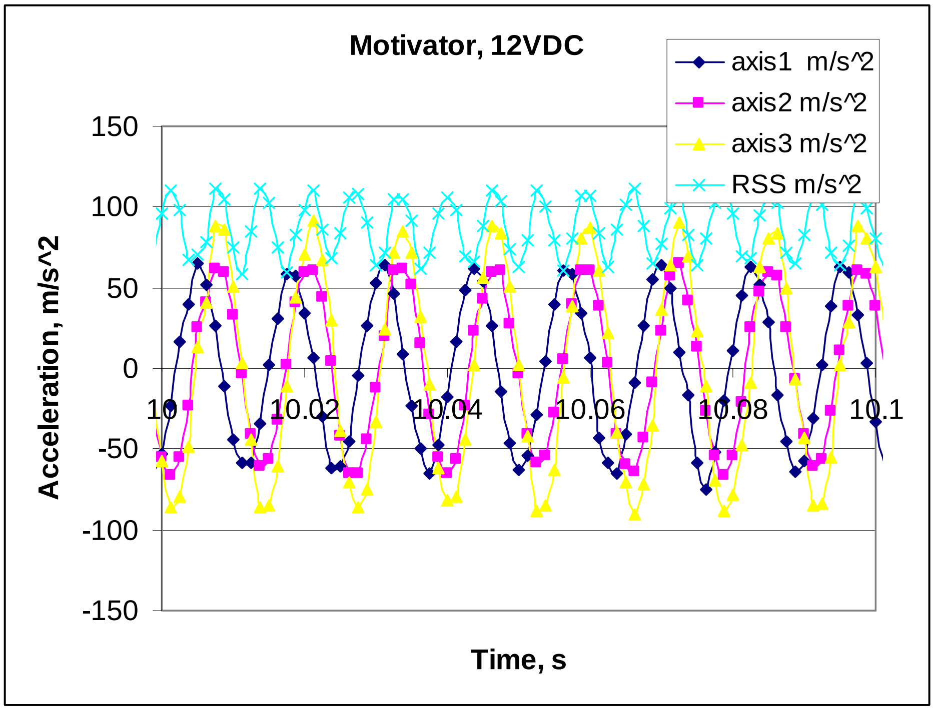

Figure 2: Global Assistive Devices "Motivator" (Pillow Shaker) Output

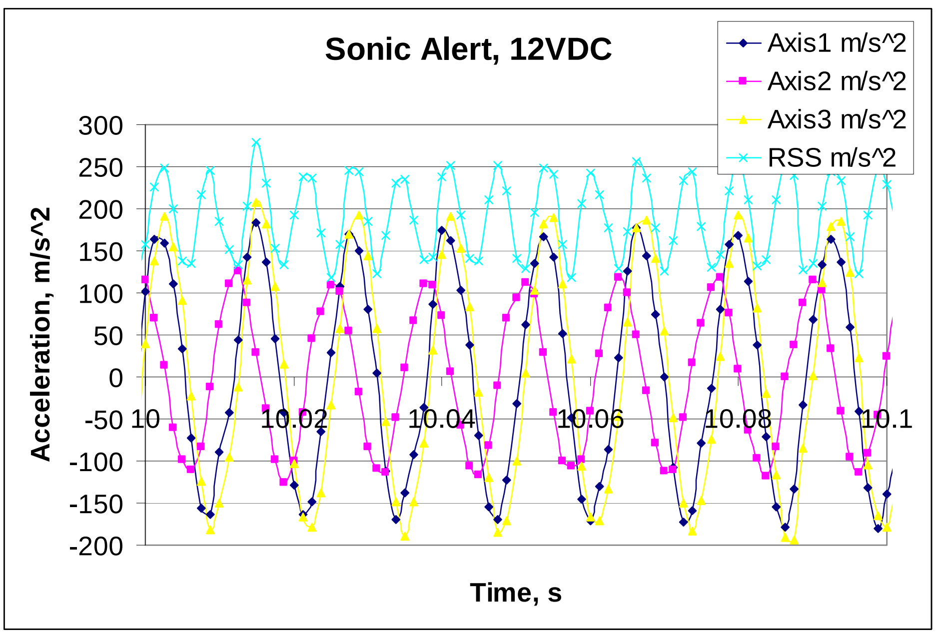

Figure 3: Sonic Alert "Super Shaker Bed Vibrator" (Bed Shaker) Output

Protocol

The decision to test the six devices across three distinct sleep phases for three subpopulations defined by hearing ability yielded at test matrix of eighteen device-sleep stage combinations for each hearing level. The following protocol was established in conjunction with Sleep Services of America to determine the waking effectiveness of each device in each sleep stage for each hearing subpopulation:

1. Each volunteer was introduced to the sleep laboratory staff and permitted to assess his/her experimentation room. The volunteer was shown how each awakening device in the room works unless they decline the demonstration. Consent forms were collected and the individual was prepared for the test.
2. Preparation of the subjects was performed by a Sleep Services of America technician. Electrodes were affixed to the subject's scalp to monitor brain activity(sleep stage), and a heart monitor was placed on the person's back to record heart activity. Once properly placed, calibrations were performed to facilitate tracking of the test patients' vital signs and brain activity while he or she slept. The test started when the patient fell asleep.
3. The strobe and both audible smoke detectors were placed 7 feet from the floor of the room, and 10-13 feet away from the head of the bed on the opposite wall. The pillow shaker was placed at the head of the bed in a pillow case. The bed shaker was placed in the center of the bed under the mattress.
4. The organization providing outside review of our testing protocol, Chesapeake Research Review, Inc., limited the number of awakenings per patient to three times per night. Likewise, a period of 4 hours of undisturbed sleep was required at the end of the testing. Thus, once the subject was asleep and in a particular sleep stage for at least two minutes, different awakening devices were activated for two minutes at a time until the person either awakened from the sleep phase or moved into a different level of sleep. This form of testing permitted more than one device to be tested for a single "awakening".
5. The time to awaken and the device used were recorded on data sheets by hand, and on the computer recordings of each person's brain waves. Times for awakening were compared and confirmed after testing has been completed.
6. Once the person was awakened they are asked a series of basic questions to help determine their level of coherence. The subject's answers were recorded on a data sheet.

Subjects reported to the sleep laboratory for one full night. The Sleep Services of America technicians monitored the subject throughout the night to ensure that the stage of sleep was known at the time of alarm activation. CSE engineers activated the alarms and recorded the subjects' responses.

V. RESULTS

The data reported here details 429 individual tests on subjects with varying levels of hearing ability. One hundred twenty four tests were conducted on subjects with normal hearing, 142 tests were completed for partially hearing subjects, and 163 tests were completed for deaf subjects. The results are presented in Figs. 4-5. A total of 111 subjects were tested, of whom, 32 were deaf, 45 were hard of hearing, and 34 were fully hearing able.

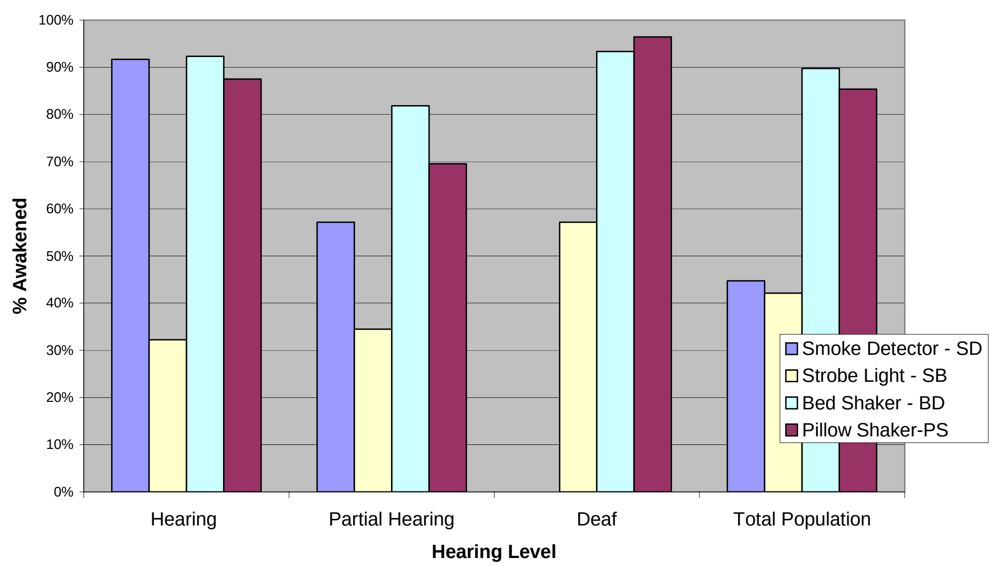

Figure 4: Awakening percentage based on hearing level and preliminary devices

Several significant results have been identified. For the hearing able subjects, the standard audible smoke detector was determined to be 92% effective across all sleep levels. The standard strobe, a device used in many hotel and boarding bedrooms, was only 32% effective across all sleep levels for hearing able subjects. The bed shaker with an average effectiveness of 92 % was comparable to the audible detector. The pillow shaker was somewhat less effective at 88%.

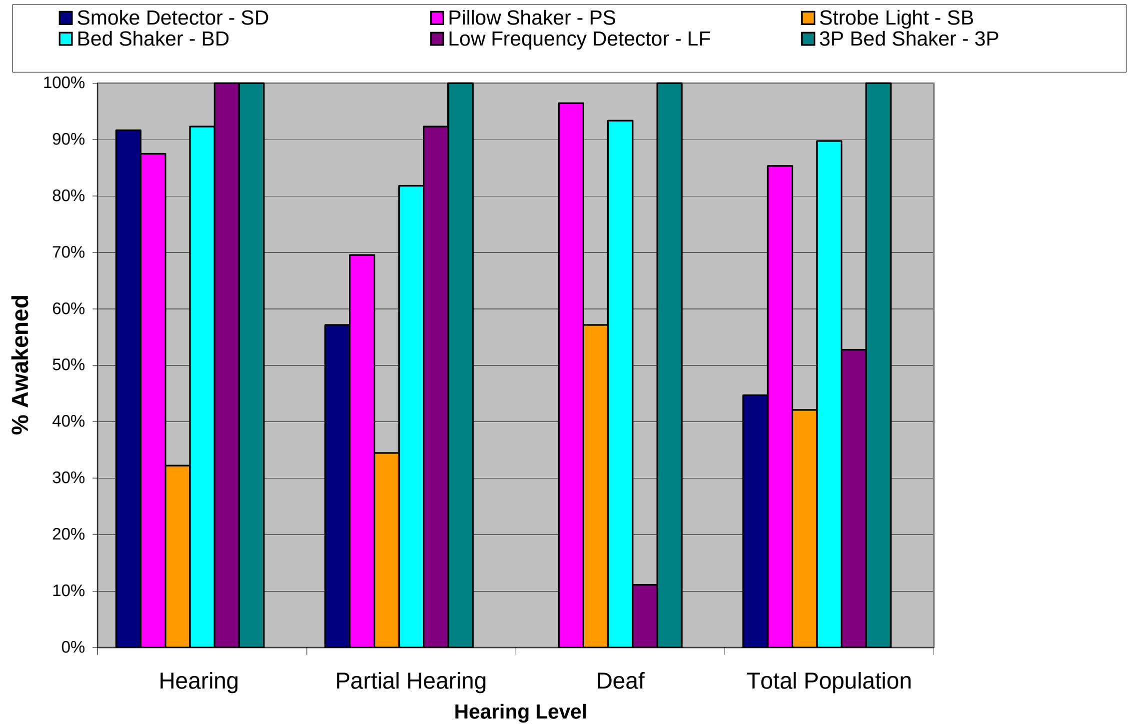

Figure 5: Awakening percentage based on hearing level and all devices

Among the partially hearing subgroup, the audible smoke detector was only 57% effective. The bed shaker was much more effective, eliciting a waking response of 82%. The response to the strobe for this group was similar to that of the hearing able subjects, namely 34% effective. The pillow shaker was 12% less effective than the bed shaker for this group.

The deaf subjects' responses differed drastically from the hearing able and partially hearing test subjects. The standard audible smoke detector did not awaken any of the deaf participants. The bed shaker and pillow shakers had comparable waking capacity, 93% and 96% respectively. And, the strobe was almost twice as effective for the deaf population as the other two populations with an awakening effectiveness of 57%.

The secondary devices introduced later, namely the low frequency audible detector and the T3 bed shaker, yielded greater waking effectiveness than the standard audible detector and the bed shaker from which they were respectively derived. The hearing able subjects awakened to 100% of the low frequency alarm presentations. The 8% increase in effectiveness over the standard audible detector is statistically insignificant given the sampling error. The low frequency detector effectiveness was 92% for the hard of hearing: in two cases, deaf individuals awakened to the alarm presentations due to their residual hearing in the 450 Hz range, yielding an overall 11% effectiveness for the deaf. The bed shaker with the T3 pattern was 100% effective for all of the subjects tested, and exceeded the effectiveness of all other devices for all of the subjects tested.

Weighted Average

The results of this study were weighted against the population of the United States to account for the differences in demographics between the subpopulations of hearing able, hard of hearing, and deaf as shown in Fig 6. Assuming a total American population of 204 million adults, the National Health and Vital Statistics census data suggests 3% of the population is profoundly deaf and 14% is hard of hearing [1]. The effective awakening for each of the hearing sub-populations was multiplied by the percentage of the population that they represented in the United States. The following equation was utilized for this study:

A – Percentage of hearing able subjects awakening per device

B – Percentage of partially hearing subjects awakening per device

C – Percentage of deaf subjects awakening per device

3% - Percentage of US population who are profoundly deaf

14% - Percentage of US population who are partially hearing

83% - Percentage of US population who are hearing able

$$\text{Weighted Average Awakening Effectiveness} = (A \times 0.83 + B \times 0.14 + C \times 0.03)$$

The weighted average as compared to the raw data presented earlier is significant in that it specifically relates the waking effectiveness of each device for each hearing subgroup to the United States population as a whole instead of generalizing for all hearing levels. Again, it can be seen that the T3 bed shaker is the most effective across all hearing abilities at 100% effectiveness followed by the continuous bed shaker and low frequency audible detectors with 91% and 90% respectively. The standard audible detector is only 83% effective when taking into account the true demographics of the American population. The pillow shaker was comparable to the audible detector with 85% waking effectiveness. The least effective of all of the devices was the strobe which yielded only 33% waking effectiveness for the general population.

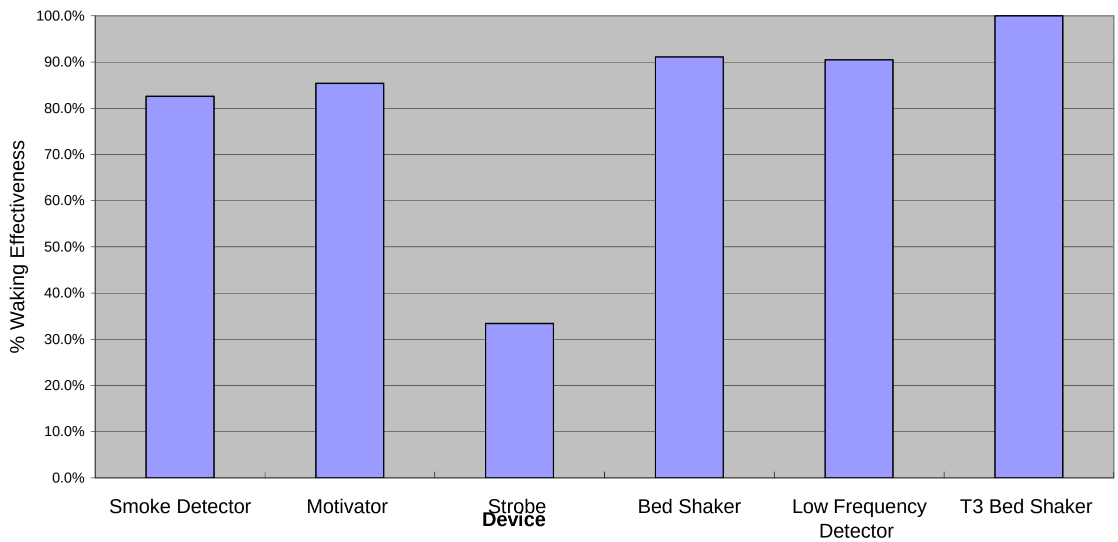

Figure 6: Awakening effectiveness weighted by US population hearing demographics

Sleep Level Results

The awakening effectiveness ratings of the devices tested followed the results found by Bonnett -- namely that the DELTA phase of sleep required the most intense arousal, but the differences between arousal thresholds for S2 and REM sleep were minimal. The results reported on the basis of sleep phase for each device and each hearing level are shown in Figs. 7 and 8.

The audible smoke detector was tested in each of the designated sleep stages with the most effective response of 50% in the S2 stage of sleep. The audible detector awoke 44% of the subjects in the DELTA phase. The bed shaker followed the same pattern, most effective in the S2 phase with a 96% success rate, and least effective in the DELTA phase with an 82% positive response. Similarly, the pillow shaker was least effective in DELTA measuring 81%; however,

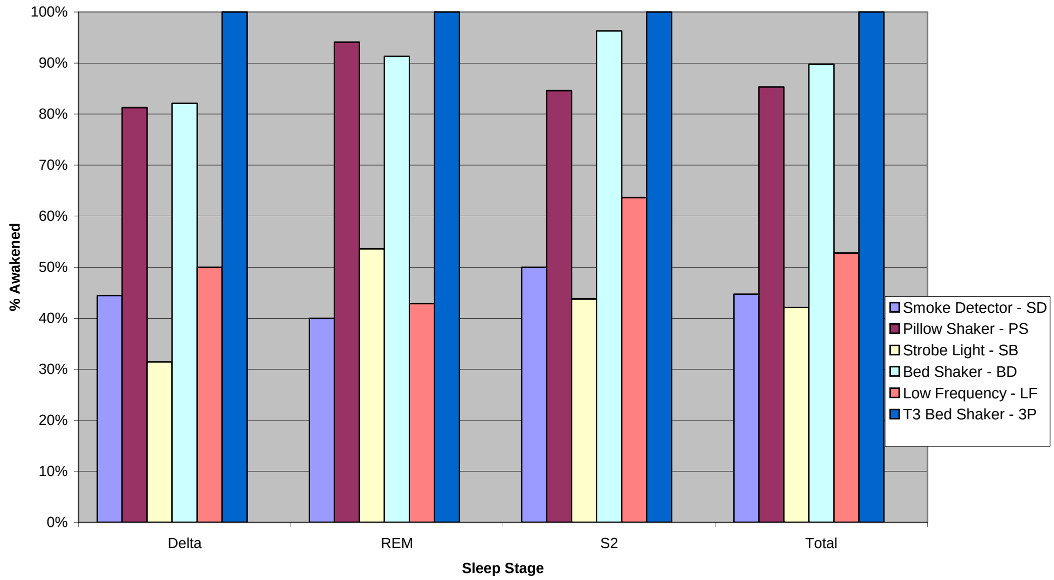

Figure 7: Awakening effectiveness based on device and sleep stage

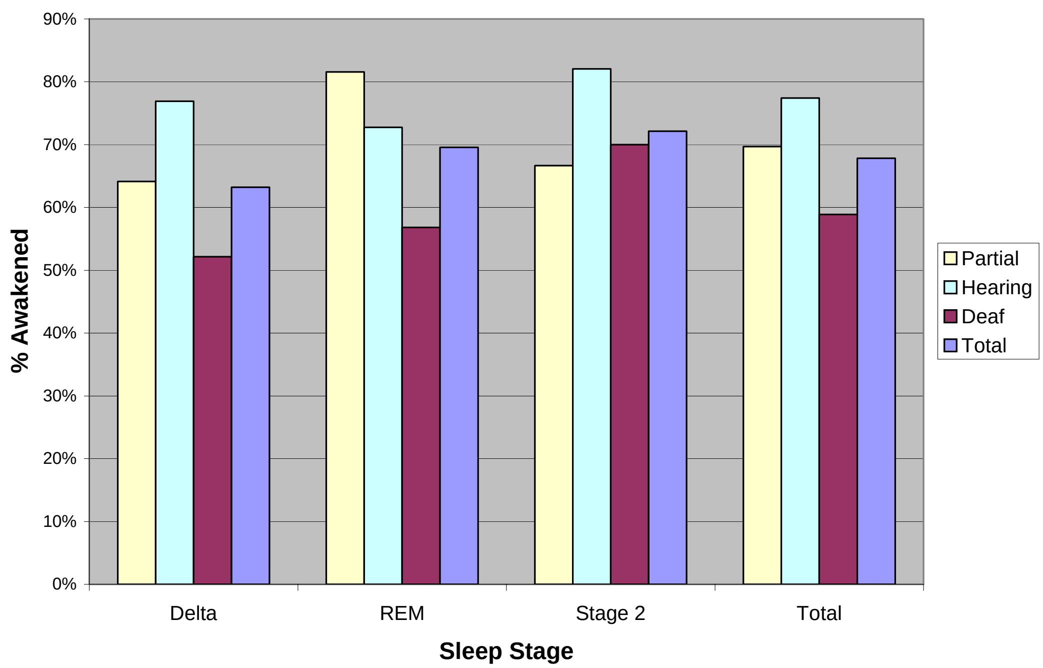

Figure 8: Awakening effectiveness based on sleep stage and hearing level

the REM effectiveness of 94% exceeded the S2 effectiveness by 9%. Nonetheless, it is the strobe results that were most remarkable. The strobe provided more than one and a half times the awakening effectiveness in the REM stage compared to the DELTA phase: 54% REM and only 31% in DELTA sleep. Only the low frequency audible detector and T3 bed shaker elicited different sleep stage response patterns in the population tested. The low frequency detector was 50% effective in DELTA. And while 64% effective in S2, the low frequency detector was the only device that was less effective in REM sleep at 43% than in DELTA. The T3 bed shaker measured 100% effectiveness across all sleep stages.

The distribution of awakening effectiveness as a function of sleep stage did not vary dramatically with respect to each hearing subgroup. The partially hearing subjects awoke, on average, approximately 15% more readily in the REM stage of sleep than in either DELTA or S2. The hearing and deaf subjects awoke approximately 10% more readily in S2 sleep.

Ethnicity Gender and Age

Ethnicity and gender were analyzed to account for any impact demographic differences may have on the awakening effectiveness of the devices tested. An attempt was made to have the ethnicity of the subjects tested mimic that of the United States. Fig. 9 compares the demographics of the United States population [13] with the demographics of the test subjects. No significant difference was found in the awakening effectiveness of various detectors when compared to ethnicity. Table 1 below details both the planned enrollment numbers and the number of human subjects that were ultimately included in the study. Our recruiting efforts were unable to attract the interest of all those targeted, specifically Hispanic males. The two Native American men initially recruited could not be retained to participate in the study. Nonetheless, as we accumulated our data, we found very clear trends in wakefulness and used this to justify curtailing the study before we had identified all 120 planned human subjects.

Table 1: Research study enrollment

	Targeted/Planned Enrollment			Inclusion Enrollment		
	Sex/ Gender			Sex/Gender		
Ethnic Category	Female	Male	Total	Female	Male	Total
Hispanic or Latino	9	8	17	8	3	11
Not Hispanic or Latino	52	51	103	53	47	100
Ethnic Category: Total of All Subjects	61	59	120	61	50	111
	Sex/ Gender			Sex/Gender		
Racial Categories	Female	Male	Total	Female	Male	Total
American Indian/ Alaska Native	2	2	4	2	0	2
Asian	4	4	8	5	4	9
Native Hawaiian or Other Pacific Islander	1	1	2	0	1	1
Black or African American	9	7	16	9	7	16
White	36	37	73	37	35	72
Other or Unknown	9	8	17	8	3	11
Racial Categories: Total of All Subjects	61	59	120	61	50	111

Two hundred forty two tests were performed on female subjects compared with one hundred and eighty seven tests performed on male subjects. Women awoke to 68% of the alarm presentations where men awoke to 67%. No significant difference was found regarding awakening effectiveness per device or sleep stage when based on gender.

Sleep test subject data was also broken down according to the age of the participants. The study participants were predominantly young people under the age of 30; however, efforts were made to extend recruitment to the middle aged and elderly as shown in Fig. 10. Forty eight of the participants were between the ages of 18 – 30 years old, forty two were 31 – 60 years old, and twenty one subjects were 61 years of age or older. Fig. 11 is a hearing ability weighted

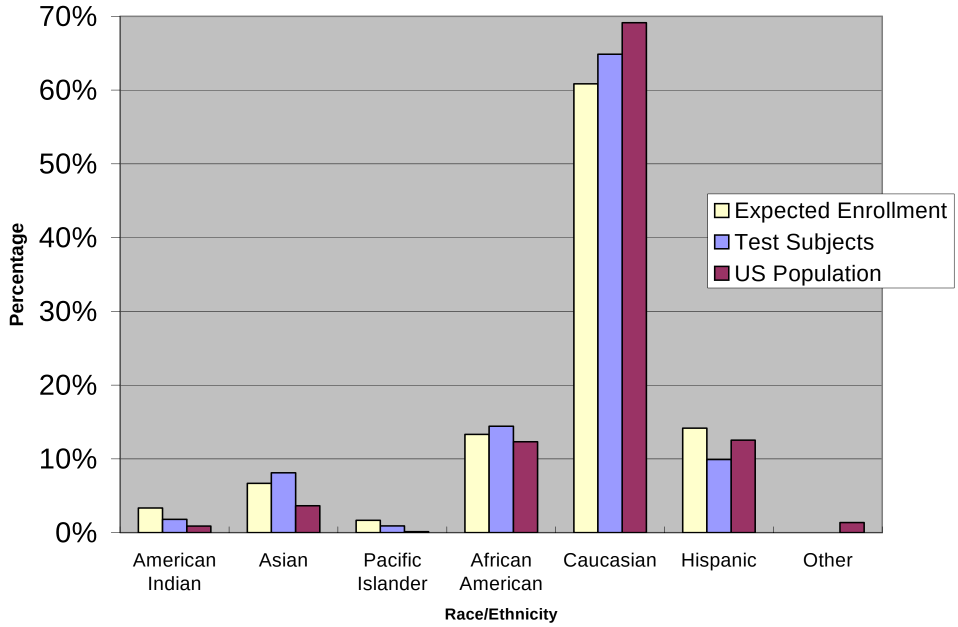

Figure 9: Test subject demographics relative to targeted enrollment and US population

profile that demonstrates that senior citizens are at a substantial risk of not awakening during the

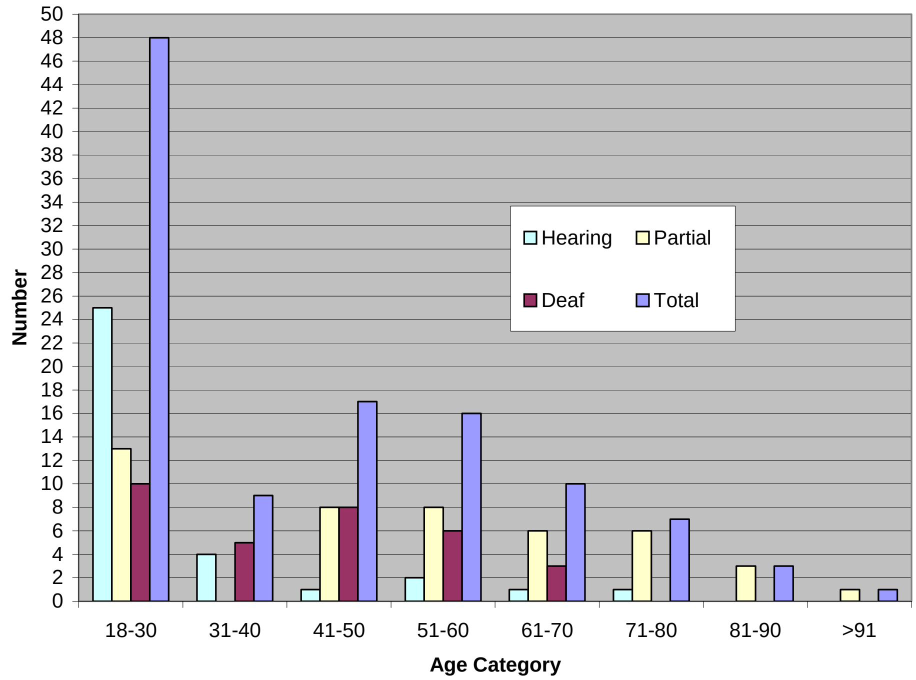

Figure 10: Test population hearing and age profile

deeper sleep stages. Waking effectiveness for subjects over 61 years of age was 58% in DELTA, and 12% in REM. Stage 2 waking effectiveness was however highest for this age range, namely 94%. The figure also shows that those individuals between the ages of 31 – 60 are comparably the most likely to awaken to any alarm presentation.

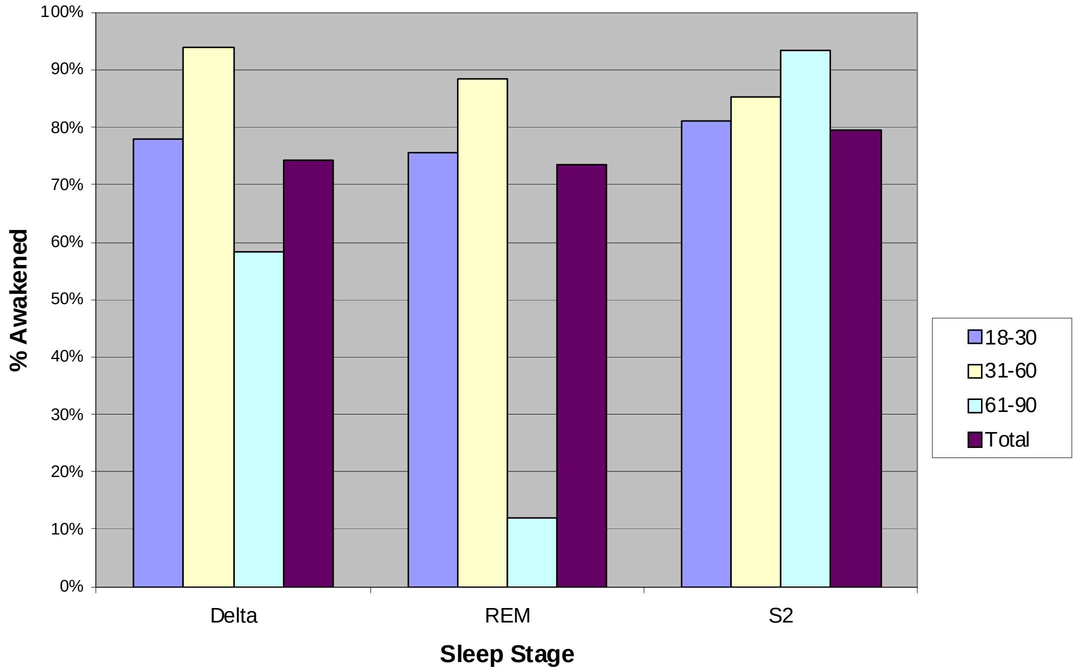

Figure 11: Awakening effectiveness based on sleep stage and age

VI. ANALYSIS

A. Devices

Several important points have been illuminated by this study. First, the standard audible smoke detector, which is installed in many homes throughout the United States, was found to be only 83% effective when weighted across the US population on the basis of hearing ability. This means that of the 204 million Americans over 18, thirty-five million might not awaken to the standard audible detector. Many smoke detector manufacturers have already come to accept this reality and now include a statement in their mounting instructions pertaining to the fact that a properly powered activated audible alarm may not be able to awaken a sleeper even when installed to meet the 75 dB at pillow height or 15 db above ambient requirements specified in the NFPA 72, national fire alarm code.

Nevertheless, the standard audible detector is required in most new residential construction and has been the standard for emergency smoke alerting devices for decades. This device has been promoted as an effective means of alerting individuals of residential fires. And, for the hearing able population, this is the case. Hearing able subjects awoke to the 92% of the audible smoke detector presentations. But the effectiveness of the standard audible detector must be brought into question when one’s hearing ability is even marginally compromised. The waking effectiveness of the standard audible detector was found to be approximately 57% for the hard of hearing population and completely ineffective for the profoundly deaf.

Concern for the lack of effectiveness of the audible detector is greatest for the hard of hearing population. Of the hard of hearing subjects studied, the test results indicated that one can not presume that those individuals with hearing in the range of the smoke detector will respond to the device while those with hearing only at 80 dB or louder in the 3000 Hz range will not. Subjects with hearing in the detector range responded to the 67% of the3000 Hz audible alarm presentations, while the fully hearing able responded with a waking effectiveness of 92%. Likewise, those hard of hearing subjects who did not have hearing in the range of the detector also responded differently than the profoundly deaf subjects. While one may expect that they would have a zero response rate, their residual hearing in the lower harmonics of the detector may be responsible for yielding the measured 50% waking effectiveness for this set of subjects. This latter group of hard of hearing subjects was particularly at risk in the DELTA stage: they awakened to only 40% of the alarm presentations in this particular sleep stage.

The risk for the elderly is also augmented for those who depend solely on an audible detector to awaken to a fire emergency. In the elderly population, hearing loss is more prevalent. And, the hearing loss is often unrecognized by the person experiencing it. Several studies have been performed which indicate that if a subject is greater than 65 years of age, their fatality rate in a residential fire can increase by 24%[14]. This increase in risk of death was initially thought to be an affect of the limited mobility of the elderly. However, this study, which does not require actual evacuation, indicates that decreased awakening effectiveness may be the cause.

The strobe has been marketed as an alternative to the audible smoke detector for deaf and hard of hearing. The Americans with Disability Act (ADA) recommends the strobe for use in both work and sleeping areas. Audible alarms with strobe attachments are required by most fire and building codes for sleeping areas in hotels. The assumption is that if a person is not awakened by the audible smoke detector, the strobe will provide the means for alerting the individual to the emergency. According to our test data, if the person is asleep, the strobe only has a weighted effective awakening of 33% across all hearing levels. The effective awakening is greater for the deaf community, 57%. Although comparably less effective for deaf people than the audible alarm is for the hearing able, the increased awakening effectiveness of the strobe on deaf people may be due to this subgroup's increased sensitivity to light as a means of alerting or awakening as mentioned above. Often, persons in the deaf community use a strong light or mild flashing strobe to signify non-emergency alarms such as telephone rings and doorbells. This constant use of light as a means of alerting may be the basis of their sensitization. Persons who have experienced a gradual loss of hearing over time might not be sensitized to light alerts. This would make the strobe less effective as demonstrated in our results for the hard of hearing: strobe effectiveness measured only 34 % for the hard of hearing. Nonetheless, these results show that many deaf people would be awakened by neither audible alarms, nor strobes while sleeping. This finding definitely calls into question the statement that the strobe is a device with a waking effectiveness for the deaf that is equivalent to the audible detector for the hearing able. Fully hearing able people responded to 32% of the strobe exposures.

The results collected here differ radically from those presented in UL's Subject 1971 report. According to the independent laboratory, "a light intensity of about 10 cd was needed to alert a majority [~61%] of the test subjects, and that the 110 cd signal alerted about 92% of the subjects not using medication" [11]. To gain insight on the discrepancies, inquiries were made to the author of the UL report, Ferdinand De Voss, Engineering Group Leader of the Burglary Protection and Signaling Department at Underwriters Laboratories, Inc. While the bedroom arrangements were similar in both the current study and the UL study, the human subjects' responses to the strobe light activation were quite different. Dr. De Voss indicated that some of the human subjects would sit upright in bed and wait for the strobe activation. Other subjects had been diagnosed with tunnel vision, sleep disorders, and sleep pattern disorders [15]. These abnormalities in conjunction with the expectation of a visual alert indicate that UL's positive strobe awakening results are as high as they are because the majority of test subjects were either not asleep at the moment of the strobe activation or they were in the lightest levels of sleep. CSE utilized EKG and EEG sensor technology to assure that 1) all subjects were asleep prior to activation of the alarms and 2) the exact sleep stage the subjects were experiencing was known.

The pillow and bed shakers are also devices that are often used by deaf and hard of hearing people as alarm clocks when used in conjunction with a clock or timer. The pillow shaker with an 85% weighted waking effectiveness was slightly less effective than the standard audible detector across all hearing levels. The bed shaker, which is a similar technology, measured a greater weighted effectiveness of 91% making it the most effective of the three devices for the US population when broken down according to hearing ability. The hearing population responded to 88% of the pillow shaker exposures and 92% of the bed shaker exposures. The hard of hearing awakened to only 70% of the pillow shaker presentations and 82% of the bed shaker presentations. A condition supporting the disparity between the pillow and bed shaker waking effectiveness, is that subjects often shifted while asleep. During several of the tests, the subject initially slept on the pillow with the vibrating device placed under it, but he or she switched pillows or rolled over during the night leaving the device on the opposite side of the bed. The deaf subjects awoke almost equally to the pillow and bed shaker: 96% for the pillow shaker and 93% for the bed shaker. The high effective awakening to the bed shaker for the hearing able may be attributed to the noise produced by the vibratory mechanism in addition to the actual vibration, as many people indicated that the sound of the alarm woke them. A review of follow-up questionnaires indicated that many deaf individuals using the bed shaker as a non-emergency alarm clock have reported sleeping through the alarm or activating a "snooze" option to temporarily arrest the alarm. This may account for the less than 100% effectiveness of the bed shaker among the deaf people tested.

The three-pulse (T3) bed shaker was introduced to see if a remarkable awakening distinction could be made between the conventional bed shaker continuous "alarm clock" signal and the international standard three pulse emergency signal. The test subject response was dramatic in that everyone awakened to the modified bed shaker yielding a 100% waking effectiveness for this device. These results indicate that the intermittent alarm is sufficiently salient to overcome the "snooze" tendency of individuals accustomed to the continuous alarm. Likewise, the central location of the device under the mattress eliminates the "shifting sleeper" problem that plagues the smaller pillow shaker. Whether the hearing able subjects heard or felt the alarm is irrelevant. What is important is that there is a device that is more effective for all hearing populations than the standard audible alarm.

The Loudenlow low frequency audible alarm was introduced to investigate methods to improve the audibility of alarms for the hard of hearing. As mentioned earlier, presbycusis is a condition brought on by age that is characterized by a decrease in auditory sensitivity to audible frequencies of 1000 Hz and above. The results of an epidemiology study conducted in Wisconsin, plotted in Fig. 12, show the rapidity of the drop off in mean perception thresholds above 1000 Hz [16]. While hearing in the higher frequencies is compromised, hearing in the lower frequencies is preserved. This trend was consistent with the results gleaned from the low frequency detector tests conducted by CSE. 92% of the presentations of this alarm to hard of hearing test subjects awakened them from sleep. 100% of the presentations of the low frequency alarm in the DELTA and S2 sleep stages effectively awakened the hard of hearing subjects. These results demonstrate that a low frequency alarm provides better waking effectiveness for the hard of hearing – including those senior citizens who may not perceive their own hearing loss – than either a strobe or a standard audible alarm. It is also interesting to note that the waking effectiveness of the low frequency alarm on the hearing able also exceeded the standard smoke detector. More tests would have to be performed on the hearing able population, specifically in REM, to determine the degree of benefit realized by the fully hearing from this device. The awakening of a deaf subject was recorded and attributed to the existence of residual hearing at frequencies less than 500 Hz in this individual.

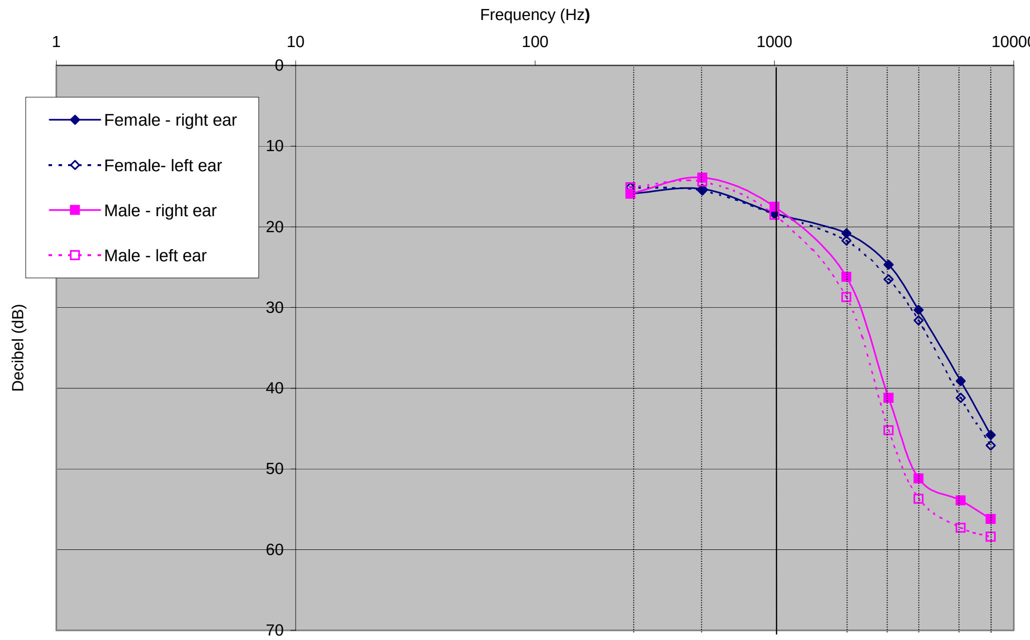

Figure 12: Age weighted hearing ability of Beaver Dam test subjects

B. Time to Awaken

There were no significant differences between sleep stage and time to awaken in the hearing able population. Ninety one percent of presentations made to hearing able subjects led to their awakening within thirty seconds, and 98% yielded awakenings within one minute. Of those awakening outside the 30-second window, individual subjects awoke within one minute to the standard audible alarm, the bed shaker, and the T3 bed shaker. Pairs of subjects awoke to the strobe and pillow shaker respectively within one minute. Two subjects awoke within ninety seconds to a visual strobe. If the subjects did not awaken to a device within thirty seconds, the chance that they would be aroused was reduced to only 9%.

Among the hard of hearing, 87% of alarm presentations yielded awakenings within the first 30 seconds and 97% yielded awakenings within one minute when all devices and sleep stages were taken into account. Of those awakening outside of thirty seconds, individual subjects awoke to the smoke detector and bed shaker, two subjects each awoke to the low frequency detector and T3 bed shaker, and 4 people awoke within one minute to the strobe. Beyond one minute, two additional awakenings were observed for the pillow shaker and one for the smoke detector. The most significant deviations regarding time to awakening occurred for the hard of hearing in the REM sleep stage. In the REM stage, only 68% of the awakenings occurred within 30 seconds, while 91% occurred in 30 seconds in DELTA and 100% occurred in S2. In contrast, the hearing able subjects experienced 100% awakening within 30 seconds in REM, followed by 88% in DELTA and S2.

Finally, the deaf population was found to have results similar to that of the hard of hearing population for awakening after the onset of the alarm signal. Again, taking into account all sleep phases and devices, a deaf individual's likelihood of awakening dropped to 13% after 30 seconds of exposure to an alarm. Of those awakening outside of the 30- second window, three awoke within 60 seconds to the strobe, individual subjects awakened to the T3 bed shaker and pillow shaker, and two subjects awoke to the bed shaker. Within 90 seconds, individual subjects awakened to the bed and pillow shakers. The increase in times to awaken to the bed and pillow shaker could be due to the test subjects' familiarity with the device as a non-emergency alarm as mentioned above. In the REM stage of sleep, deaf subjects' awakening patterns again mirrored those of the hard of hearing. In REM, 76% of the awakenings occurred within 30 seconds, while 92% occurred in DELTA and 89% occurred in S2.

Bruck reported that a subject's probability of awakening decreased significantly after 60 seconds [8]. Our results indicate the critical time to awaken from the alarm is within 30 seconds. If the subjects do not awaken within the 30-second window, the chance of awakening decreases to less than 14% for all hearing levels across all stages of sleep. In the field of fire safety, the amount of time required to awaken to a continuously activated alarm is significant because it is directly related to the amount of time one has to awaken before the alarming device is thermally deactivated and degraded by heat and also to the deterioration of tenable conditions within the room or along the exit path. Most smoke detectors activate when both the soot obscuration per foot reaches between 7 – 17% (as dictated by UL 217), <u>and</u> when a critical flow velocity of 15 cm/s is measured at the detector sensor [17,18]. Likewise, smoke detectors become thermally degraded when the surrounding air temperature reaches 92 ºC; and they are no longer able to produce sound at 114 ºC [19]. Based on a number of experiments, the time to thermal degradation after activation for a smoke detector mounted in the vicinity of flaming combustion can be as short as 45 seconds. Thus, awakening to the alarm within the first 30 seconds is crucial, especially if the alarm signal is terminated due to thermal degradation after that time. The time to awaken is also related to the amount of time one has to escape a building before the building or corridor becomes thermally untenable. Given the rate of the flame spread, once the alarm is activated, there may only be a limited time to escape by a given egress path before it becomes thermally untenable.

Under the circumstances that one has gone to sleep within four hours of the onset of a fire, one's likelihood of awakening to any alert is diminished. Reiterating an earlier finding of this study and data available in the literature, the DELTA phase requires the most intense stimuli for arousal, and the DELTA sleep stage dominates the first third to one-half of the average adult's sleep [5]. A review of National Fire Incident Reporting System (NFIRS) and NFPA survey data shows that fire fatalities peak between the hours of 11:00PM and 6:00AM [3]. Hypothesizing that the average adult sleeps for 8 hours, fire fatalities would most likely befall people while they were in the DELTA stage of sleep if they retired to sleep between 9:00 PM and 2:00 AM. Because most adults who work during the day do indeed retire between 9:00 PM and 2:00 AM, this hypothesis would suggest that all adults are desensitized to their sleeping environment during the early morning and, thus, have a heightened need for redundant alarm signals or devices that provide strong yet similar awakening effectiveness across all levels of consciousness.

C. Error Analysis

As mentioned earlier, the population of our sample was divided into three distinct strata: hearing able, hard of hearing, and deaf. Thirty-two of the subjects tested were determined to be deaf, forty-five were hard of hearing, and thirty-four subjects were hearing able. Based on statistics provided by the National Center of Health Statistics [1], the United States general population demographic is 83% hearing able, 14% hearing impaired and 3% deaf. Using the National Health Statistics population assessment of 204 million persons, the associated sample error for the study can be determined. With a 95% confidence interval, the variance and the standard deviation were computed for the devices of particular interest to CSE, namely the audible smoke detector, the strobe, the T3 bed shaker and the standard bed shaker. The associated sample errors of all devices are provided in Table 2.

Table 2: Associated sample error for stratus and device

Sample Error						
	Smoke Detector	T3 Bed Shaker	Strobe	Bed Shaker	Pillow Shaker	Low Frequency Detector
Total US Population	11%	22%	10%	11%	11%	16%
Hearing Able	20%	26%	18%	19%	20%	44%
Hard of Hearing	19%	19%	18%	21%	20%	27%
Deaf	17%	22%	17%	18%	19%	23%

In addition, visual representations of the associated upper and lower bounds for the waking effectiveness of the emergency alerting devices are shown in Figs 13 and 14.

For the total United States population and subsequently the hearing able strata, the audible smoke detector and T3 bed shaker provide the same effective awakening when taking into account the sample error. The bed shaker is approximately 5% less effective than the strobe when comparing the upper bound effectiveness of the bed shaker to the lower bound effectiveness of the strobe. The sample size of hearing able and hard of hearing people exposed to the bed shaker was insufficient to provide error ratings that would enable the results to provide a significant statistical difference between the effectiveness of the two devices. For the hard of the hearing and the deaf populations, the T3 bed shaker provides significant improvement in the awakening tendencies of these subjects.

Overall, the error analysis illuminates the fact that the T3 bed shaker device shows statistically significant better results in awakening the deaf and hard of hearing than all of the other devices tested. The lower bound effectiveness of the T3 bed shaker is greater than the upper bound effectiveness of all other devices tested for the hard of hearing and deaf populations.

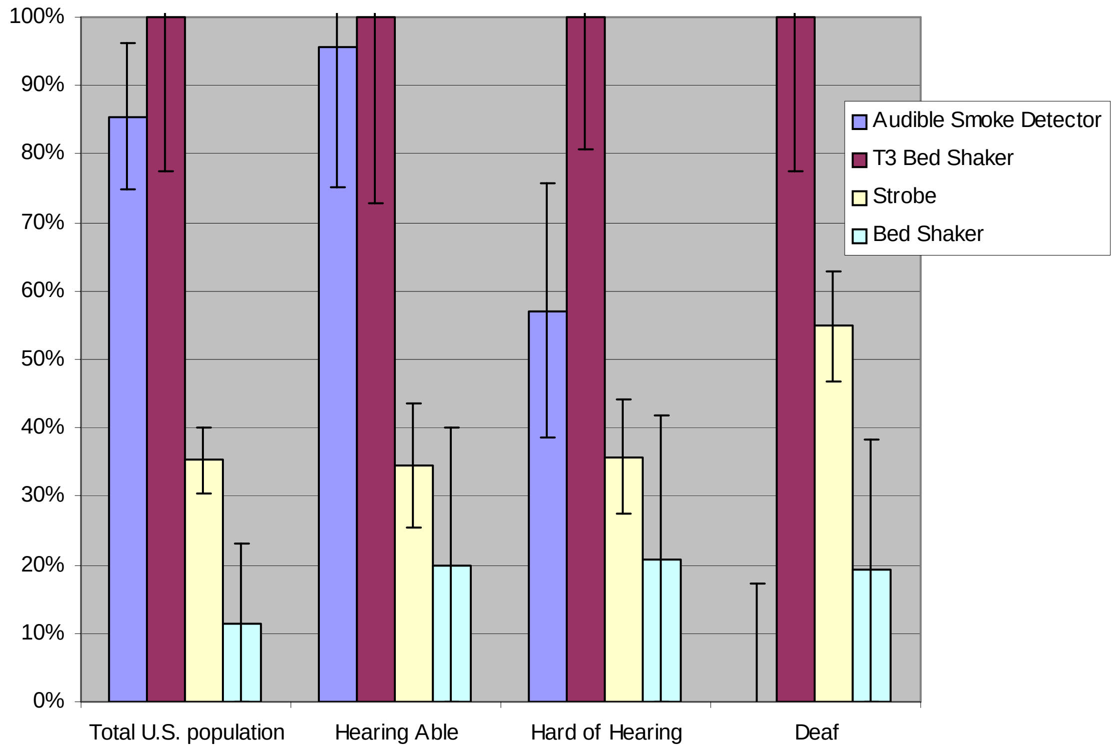

Figure 13: Upper and lower bounds of the effective awakening per device

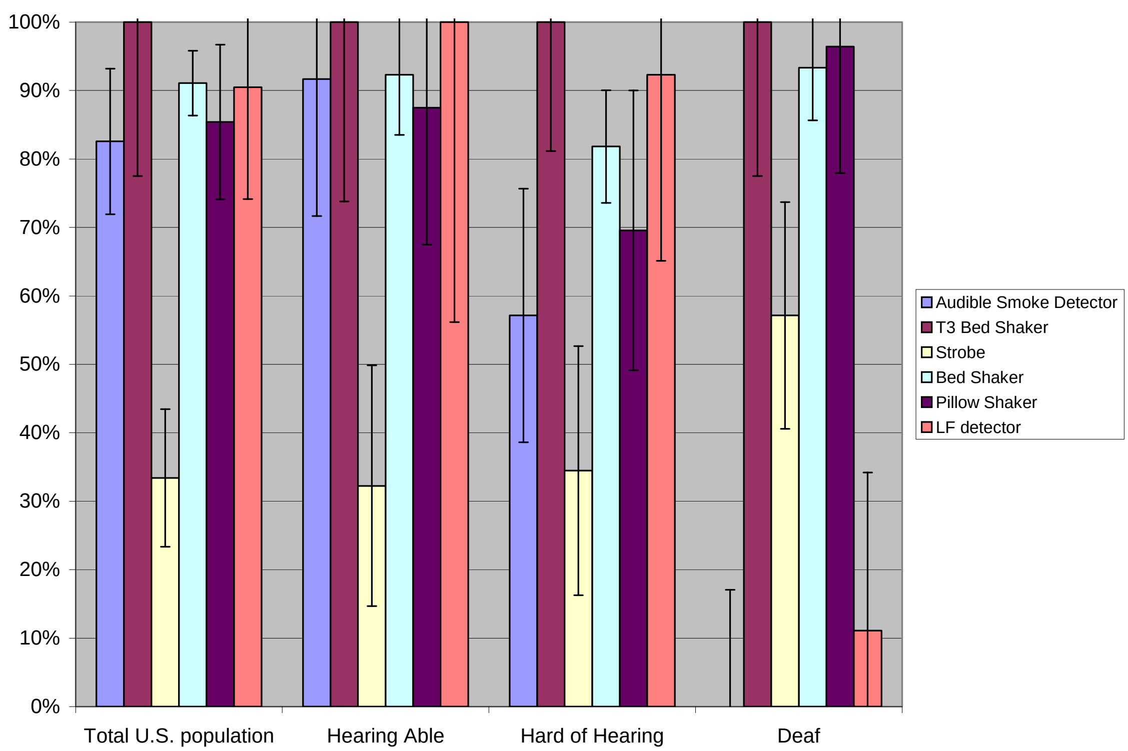

Figure 14: Upper and lower bounds of effective awakening for all devices

VI. PROTOTYPE DEVELOPMENT

A pre-production prototype has been designed and built following the human subject testing. It is currently being tested to assess the feasibility of implementing the LabView algorithm in a real world device. The prototype includes a custom multi-layer, integrated circuit board that makes use of surface-mount technology components and a MicroChip Digital Signal Controller. The digital signal controller combines the features of a microcontroller with the capabilities of a digital signal processor.

The circuit board is housed in a 5.5 inch wide by 3.5 inch long by1.5 inch high plastic housing. The housing contains a red light emitting diode to indicate when the device has detected an alarming smoke detector. The housing also includes a two-conductor jack into which the bed shaker is plugged, a two-conductor jack for the external power supply, and an eight-pin modular jack currently being used to program the device. Small holes are drilled in a portion of the housing for the internal microphone. The unit is powered by an external 12 volt wall transformer. Four AA lithium batteries mounted on the circuit board, provide backup power in case of loss of the external power. The detection algorithm includes a sleep mode, used in between detection periods. This significantly decreases the power consumption of the device, and concurrently ensures that the detection periods are sufficiently frequent to ensure prompt alarm detection. Patents have been filed to cover the algorithm and functioning of the device.

The algorithm generated and tested in LabView was translated as accurately as possible into the C programming language. The C program was then used to program the digital signal controller. A 512 byte window of data is processed in real-time by the integrated Fast Fourier Transform (FFT) algorithm, and the FFT spectrum is compared against the expected frequency spectrum for a smoke detector. The temporal pattern of the detected signal is also compared against the expected ISO 8201 pattern for an audible smoke detector. Upon successful detection, the digital signal controller generates the appropriate waveform to activate and drive the shaker.

At present, the prototype is being rigorously tested in echoic and anechoic environments and in the presence of continuous and pulsed interferences.

VII. CONCLUSION

Combustion Science & Engineering, Inc. has engaged in extensive research of both the aural characteristics of smoke detectors and the responses of human subjects to arrive at a piece of hardware that can be used by the deaf and hard of hearing as an extremely effective emergency awakening device. The technology developed makes use of an algorithm that can recognize and uses the conventional audible smoke detector with the ISO 8201 three pulse to trigger an intermittent tactile alert that is easily distinguishable to a sleeping person as an emergency signal. This research has taken into account the phasic nature of sleep on difficulty of awakening and compared the effectiveness of the dominant emergency alerting technologies on deaf and hard of hearing subjects. Fully hearing able subjects were used as both a control and a means of establishing a quantitative measure of the effectiveness of the audible alarm for sleeping fully hearing able people. This quantitative measure was then used to rate competing technologies and determine whether alerting systems of equivalent effectiveness exist for the deaf and hard of hearing.

Test results revealed the audible detector to be 96% effective for the hearing able across all sleep stages, while it was only 57% effective for the hard of hearing and 0% for the deaf. The strobe which has been accepted in the fire industry and established within the American with Disabilities Act legislation as the audible detector's awakening equivalent for the deaf and hard of hearing was found to be only 36% effective for the hard of hearing and 55% effective for the deaf. Despite the sensitivity of many deaf people to awakening devices that use light, the quantified awakening effectiveness for the strobe was much less than the baseline effectiveness of the hearing able to the audible detector. This result points to the need to not only provide a better alternative for the hearing disabled public, but also revisit the research that established the strobe as the smoke detector's equivalent. The data presented above also illuminates the heightened risk of injury that the deaf and hard of hearing face as a result of their reliance on inferior awakening technologies. Recasting the results in terms of weighted averages based on the United States demographics for hearing ability, the smoke detector rated 86% awakening effectiveness, and the strobe measured 35%. In sharp contrast, CSE's new technology measured a 100% awakening effectiveness.

The results were also assessed for the impact of age on outcome. The data addressed above agree with other data that demonstrate that the elderly are at a significant disadvantage of succumbing in fires given their failure to awaken in a timely manner. Across all of the categories of hearing ability, those people age 61 to 90 and above were the least likely to awaken to emergency stimuli presentations: their awakening effectiveness was quantified as 54%. This result supersedes mobility as the main cause of failure of the aged to escape from emergency situations. Nonetheless, time to awaken for all study subjects to the majority of alarm presentations (87%) was found to be 30 seconds. After one minute, the probability of awakening decreased to 4%.

With the prototype, CSE intends to engage in rigorous testing of the devices capabilities and effectiveness in real world environments. In addition, efforts will be made to improve the capability of the sound recognition algorithm to detector pre-1996 audible smoke detector signals. If additional funding is awarded, the monies would be used for the testing and to establish a new United Laboratories standard for vibratory awakening devices. Combustion Science & Engineering, Inc. will continue to oversee the development of the prototype device in order to uphold the rights of the hard of hearing and deaf to access to an effective and portable emergency awakening device.

VIII. ACKNOWLEDGEMENTS

This work was completed with funding provided by the National Institutes of Health through SBIR grant 2 R44 DC 004254. In particular, CSE would like to thank Dr. Lynn Luethke and Meigs Ranney of the National Institute on Deafness and Other Communication Disorders for providing guidance and the financial support required to pursue our development of an emergency alerting device for the deaf and hard of hearing. We thank the Chesapeake Research Review, Inc. for providing outside review of our research study and human subject protocols. Likewise, we acknowledge the contributions of John Mathias and Christine Magruder for providing a sleep test facility, staff, and clinical assistance during our human subject testing. Gretchen Paige at ENTAA Care, Debbie Schirico of Total Hearing Care Dallas, and Valerie McKenna of Overlook Hospital in New Jersey, Gallaudet University, and Dr. John Biedlingmaier of Maryland General are acknowledged for their assistance with the auditory classification of each test subject. Finally, we would like to thank Dorothy Bruck, Dana Mulvaney, Ester Kelly of The Deaf Action Center, and the Centralized Interpreter Referral Service for their immeasurable contributions.

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