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A Method to Determine the Optimum Location for Fire Alarms in Residential Buildings

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ABSTRACT

Fire alarms can save lives in a fire emergency only if people hear them. If alarm sounding devices are to be used effectively, attention must be paid to where they are located in the building. A simple expression has been developed to calculate the attenuation of the alarm signal from a smoke detector as it propagates through a residential building, with the path viewed as a series of connected rooms. Attenuation depends on floor area and type of furnishings in each room. Corrections are applied if the house does not have forced air heating or if a number of doors are closed. The expression can be used to determine the optimum location for alarms.

SOMMAIRE

Les alarmes-incendie peuvent sauver des vies dans une situation critique à condition que les gens les entendent. Pour que les dispositifs d'alarme d'un bâtiment soient vraiment utiles, il faut veiller à les placer aux bons endroits. On a défini une expression simple permettant de calculer l'atténuation du signal d'alarme provenant d'un détecteur de fumée au cours de sa propagation dans un bâtiment d'habitation, le trajet suivi étant considéré comme une série de pièces communicantes. L'atténuation dépend de la surface de plancher et du type de meubles et accessoires que contient chaque pièce. On effectue des corrections si la maison n'est pas dotée de chauffage à air pulsé ou si un certain nombre de portes sont fermées. L'expression en question peut servir à déterminer le meilleur emplacement des alarmes.

Introduction

It is estimated[1] that 40 to 50% of the people killed in fires each year could be saved if adequate early-warning fire detection devices were installed. A study by Jones[2] of multiple death fires in the U.S. indicates that 81.4% of fires occur between 8:00 p.m. and 8:00 a.m., with the largest number (40.5%) between midnight and 4:00 a.m.

Smoke alarms are generally considered to be more effective than people in detecting fire aerosols, and because they can be used to monitor unfrequented areas they are effective early-warning devices for fire. It is important to remember that in many cases the sound of the alarm is the only means of alerting a sleeping person to the existence of a fire, but they can save lives only if people hear them.

The question of where to place smoke alarms in single family homes and fire alarms in highrise buildings so as to be assured that as many people as possible are alerted is really a two part question. First, how loud must it be to alert people, especially sleeping people, and second, how much is the sound attenuated as it propagates through the building?

The first part of the question is really the most difficult to answer. Since it requires a louder sound to awaken a sleeping person than to alert a person already awake, it follows that this should be the relevant criteria. But how loud must a sound be to be sure of wakening a sleeping person?

There have been a number of studies to determine the awakening threshold; this is the level which will cause awakening 50% of the time. The literature has been extensively reviewed by Pezoldt and Van Cott[3] who found measured values varying over a large range. Another reviewer, Berry,[4] concluded that 75 dBA at the ear was a minimum level to awaken "normal" people. Lukas[5] looked at a number of studies concerned with the sleep arousal effects of aircraft noise and produced a cumulative distribution curve. This curve indicates that to arouse or awaken 80% of the subjects a level of 80 dBA is needed. The problem is fourfold. There is a lack of unanimity with regard to what constitutes awakening, the noise signal used is often not properly identified, there are often other experimental artifacts which confound the application to fire alarms, and even within any one experiment there is a wide range of values reported.

These studies have all been concerned with specially selected people, and do not include the effects of medication or alcohol both of which can inhibit arousal. Children tend to sleep more deeply and require higher levels, whereas older people tend to sleep more lightly and are more easily aroused[3]. In the case of older people this is often offset by hearing impairment. Considering all of these factors, we feel that a level of 75 dBA at the ear is the minimum level required to provide adequate fire safety in most circumstances.

This paper is primarily concerned with the second part of the question, the propagation of the alarm within residential buildings. The paper is in two parts. The first is a study of propagation within single family dwellings and the development of a model to predict this attenuation. The second part has been included because it illustrates a situation typical to many highrise apartments of which designers and acoustical consultants should be made aware and is a case where the simple model developed in Part 1 can be used. It is similar to a study by Robinson[6] of the attenuation from the corridor into the sleeping rooms in a college dormitory, but in this case a selection of apartment buildings have been used. These include cases where the sound is attenuated by more than a single partition.

PART 1: Propagation of Smoke Alarms in Single Family Residences

The use of smoke alarms is now commonplace in homes, but information is not readily available as to where best to locate them. There are two basic concerns:

1) what is the best location with regard to fire detection?
2) what is the best location with respect to audibility?

In this study only the second question is addressed. After all, no matter how effective the detector is at determining that a fire exists, if the alarm is not heard then the system is not effective.

Once the alarm sound level has been established, there is still the question of where to locate an alarm so as to provide maximum benefit. The answer to this question requires a model that can be used to calculate the attenuation of the alarm signal as it propagates through the home . The model would permit one to determine the optimum location for an alarm to achieve the required signal level at any location in the home.

To assess the attenuation of the alarm signal from smoke detectors it was necessary to make measurements in a number of homes and from the data to develop a general model to be applied for any single family residence. Eleven buildings were studied, constituting a reasonable cross-section of the common types of dwelling: bungalows, split-level, and two-story houses. The study included both furnished and unfurnished homes.

Measurement Procedure

Measurements were made using a smoke alarm (modified to operate continuously) as a source of alarm signal. It was mounted on a stand 2.1 m in height so as to simulate a ceiling-mounted detector and placed in a number of locations in each dwelling: in the basement near the furnace room, in the main hallway near the kitchen, and in the hallway near the bedrooms. From each source location the attenuation of noise was measured to every other room. This was done first with all doors in the propagation path open, then with them closed successively until all doors in the path were closed.

To determine the attenuation along each path, the sound level was measured simultaneously near the source and in the receiving room. The source microphone was in a fixed position 1 m from the smoke detector, while the receiving room microphone was moved about the room to provide an average sound level for the room. A Hewlett-Packard model 3582A two-channel FFT analyzer was used to collect data from the two microphones simultaneously. Sixty-four spectra were averaged and the resultant spectra for each microphone were stored for subsequent analysis. A calibration signal was recorded on each microphone at the beginning and end of each measurement period.

As acoustical data are usually provided in third-octave bands, the narrow-band spectra provided by the FFT analyzer were converted to third-octave spectra by summing the energy within the standard third-octave bands. Rather than simply summing the energy in the spectral lines, a weighted sum was used so that a realistic filter shape could be realized. The overall level was then .and corrected using the calibration signal to obtain the absolute sound levels in third-octave bands. The attenuation was then calculated as the difference between source and receiver levels for each third-octave.

Discussion of Results

The reduction in sound level that is provided by walls, doors, etc., within a building increases with increasing frequency. To be most effective it would thus be reasonable for a smoke detector to have most of its acoustical output at low frequencies, say below 500 Hz. It is more economical, on the other hand, to produce an alarm operating in the 2000 to 5000 Hz range where the human ear is most sensitive. Since the attenuation of these alarms will be higher they must operate at a higher sound power if they are to be adequate as warning devices.

Sound power measurements on a number of smoke alarms are listed in Table 1, which shows that most smoke alarms only provide noise output in a few bands, the two dominant ones being the 3150 and 4000 Hz bands. For the purpose of this study only the 3150 Hz band has been used to develop a propagation model. The higher frequency band, which was not present for all smoke alarms, will tend to be attenuated more and thus will be less useful in alerting occupants. Where there is energy in lower frequency bands, the model will predict too little attenuation and thus provide an extra margin of safety.

Two different models were considered for predicting the attenuation of noise from the alarms. The first was based on a model proposed by Berry.[4] Its most attractive feature is its simplicity, the basic attenuation being assumed to be a function of the straight-line horizontal distance between source and the mid-point of the receiving room, without regard for changes in elevation. Added to this basic attenuation are three corrections, one for the number of floor changes in elevation, another for each closed door along the propagation path, and a third for each open doorway along the propagation path.

Figure 1 shows a histogram of the increase in attenuation provided by closing a single door in a propagation path. The wide range in attenuation is a result of the wide variation in fit among doors, from doors with large gaps beneath to those carefully weather-stripped. The mean value is 10 dB, and this was used in the model as the correction for closed doors.

Simple Model

The simple model proposed by Berry did not determine the attenuation of the smoke detector alarm, but rather determined a probability of awakening based on the assumptions that the alarm provides 85 dBA at 10 feet and that 75 dBA can be expected to awaken a person. Using the same basic structure for the model the best fit to the data was found with an attenuation of 1.77 dB per metre and the following corrections: 10 dB for each floor between the source and receiver, 3 dB for each open doorway along the path, and 10 dB more for each closed door along the path. Figure 2 shows the attenuation calculated using this model plotted against the measured attenuation. The solid line is a least square fit to the data, with a standard deviation of 14 dB and a correlation coefficient of 0.71.

TABLE 1. Maximum sound power output of smoke detectors.
(dB re: 10^{-12} W)

Detector[1]	Duty Cycle[2] (t)	500	630	800	1000	1250	1600	2000	2500	3150	4000	5000
		1/3 Octave Frequency Band, Hz										
A1	0.203	38	39	39	39	63	57	73	96	84	63	50
A2	0.230	37	38	38	38	44	56	70	98	92	67	56
B1	0.877	82	82	60	71	74	81	79	95	95	95	88
B2	0.870	79	81	66	72	76	81	77	93	94	96	92
C1	0.986	44	44	44	45	45	50	61	79	102	90	69
C2	0.989	44	44	44	45	45	50	62	79	102	91	70
D1	0.844	46	46	46	46	47	52	63	80	103	93	71
D2	0.845	44	44	44	45	45	50	62	80	102	88	68
E1	1.0	84	70	69	85	76	92	88	96	92	91	80
E2	1.0	76	83	63	69	80	87	85	97	100	91	89
F1	1.0	61	60	72	70	70	74	86	75	83	90	82
F2	1.0	58	61	69	70	72	77	90	81	82	89	82
G1	0.643	37	37	37	38	39	50	63	88	95	69	55
G2	0.667	38	38	38	38	39	48	61	84	95	71	56

[1]Detectors with the same letter designation are identical models.
[2]The duty cycle is the fraction of time during which the alarm is operating.
10 log(1/t) was added to the measured mean sound power level to give the maximum sound power level.

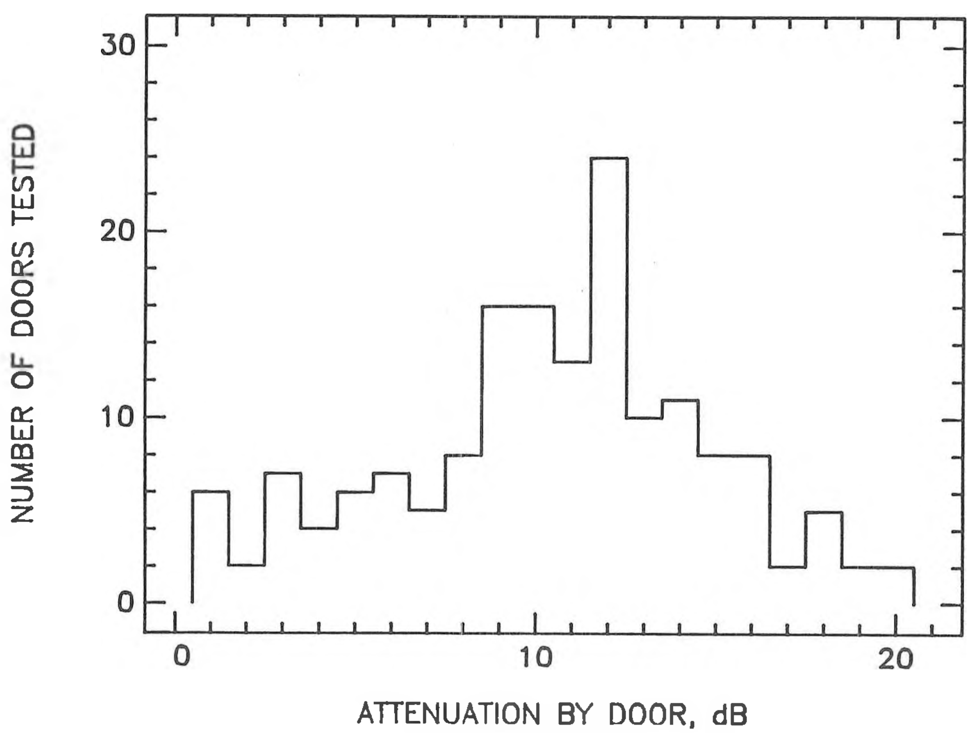

Figure 1. Histogram of sound attenuation due to closure of single door in propagation path.

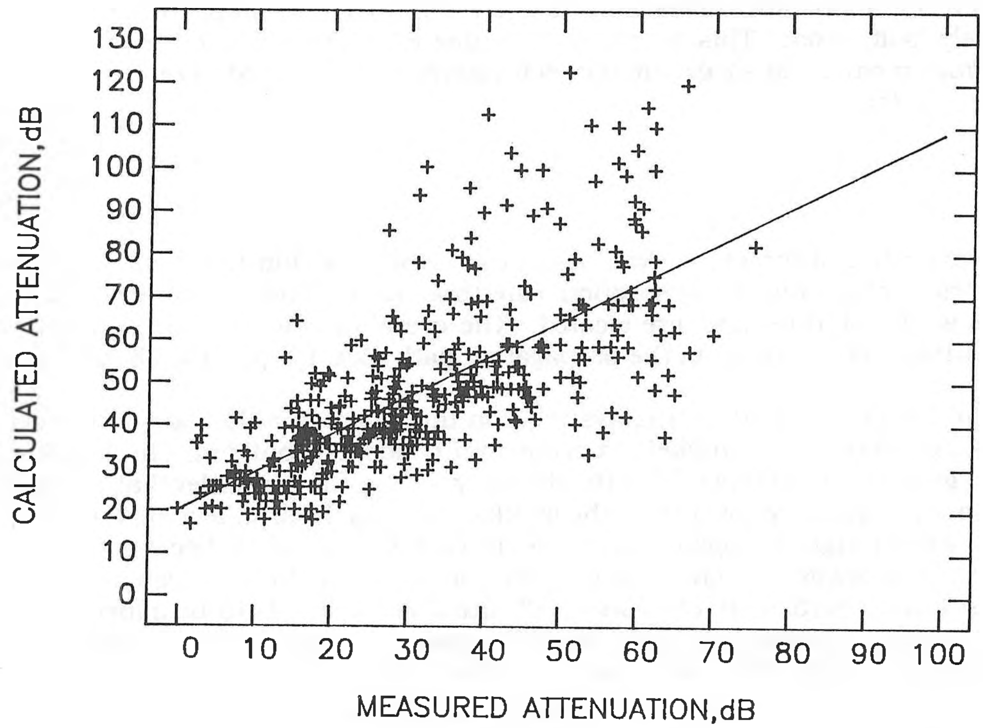

Figure 2. Simple Model: Comparison of calculated and measured attenuation.

Proposed Model

The second model considered takes a slightly different approach. In it, the propagation path is viewed as a series of linked rooms, each of which modifies the sound level. The path to be used is the most direct path as would be traversed by a person walking from the source to the receiver. Each space enclosed by walls or partitions, including hallways, is counted as a room provided that the opening leading from the previous room is a doorway or equivalent. For the purpose of this model, it is assumed that little, if any, sound is transmitted through the partitions or floors. From reverberation room theory, the sound level in a room due to transmission of sound through an opening or partition into the room is given by[7]

$$L_R = L_s - R + 10 \log \left[\frac{S\,T_{60}}{0.161\,V_R}\right] \qquad (1)$$

where R = transmission loss of partition,
L_s = sound pressure level in source room,
L_R = sound pressure level in receiving room,
S = area of partition (m^2),
T_{60} = reverberation time,
V_R = volume of receiving room (m^3).

It may be further simplified by assuming that sound enters the room only via an open doorway of area 2 m^2 with zero transmission loss, and that rooms are always 2.4 m high. A normally furnished room of average size, that is one with carpet and furniture, has a reverberation time of about 0.4 s at 3150 Hz.[8] The result is that the receiving room level is given by

$$L_R = L_s - 10 \log \left[\frac{\text{area}}{2.08}\right] + A \qquad (2)$$

where 'area' is the floor area of the receiving room and 'A' provides a means of adjusting this correction for instances in which reverberation time differs substantially from 0.4 s, as happens in a "hard," unfurnished room or in an extremely "soft" room. This would have a value of -2 dB for hard rooms such as bathrooms or kitchens, zero for normal rooms, and +2 dB for very soft rooms such as a bedroom with carpet, heavy drapes, and bedspread. Thus, the term

$$10 \log \left(\frac{\text{area}}{2.08}\right) + A \tag{3}$$

may be viewed as a correction to the sound level due to absorption within the room or, alternatively, as the room attenuation. Attenuation due to absorption can thus be calculated for each room in the house, independent of where source and receiver are located. The overall attenuation of the detector alarm is thus the sum of the attenuations for all rooms in the propagation path plus 10 dB for each closed door.

The derivation of Eq. (1) is based on the assumption that there is a diffuse sound field in both source and receiving rooms, a condition very unlikely to occur in a residential building. In actual rooms the sound level will decrease the greater the distance from the doorway. Thus the sound level at the doorway leading to the next room in the path is actually lower than the spatially averaged sound level. Similarly, the assumption of zero transmission loss through the open doorway is an over-simplification because it ignores any edge or interference effects of the doorway. A comparison of the sound attenuation predicted by this model with the measured attenuation indicates that an additional 5 dB attenuation needs to be added for each room in the propagation path. This may be looked upon as the attenuation of an open doorway and is consistent, albeit slightly higher, with the value of 3 dB found using the simpler model

It is well established from field studies of transmission loss of walls and floors that heating ducts can provide a flanking path that will short-circuit a partition and result in lower noise reductions than would otherwise be obtained. This was borne out in the present study; it was found that buildings that do not have forced-air heating provide an additional 6 dB attenuation for each room in the propagation path.

These corrections can all be summarized in the following expression:

$$\text{Atten} = \left[\sum_{r=1}^{n} \left\{10 \log \left(\frac{\text{area}_r}{2.08}\right) + 5 + A + K\right\}\right] + 10\,(\text{door}) \tag{4}$$

where area = floor area of room 'r' (m^2),
door = number of closed doors in path,
A = -2 for hard rooms (kitchen, bath),
= 0 for normal rooms,
= 2 for soft rooms (rugs, draperies),
K = 0 for forced air heating,
= 6 for electric or hot water heat,
n = number of rooms in path from smoke detector to point of interest, not counting room containing smoke detector.

Figure 3 shows the attenuation calculated using this model plotted against measured attenuations for all source-receiver configurations in the 11 houses studied. The solid line is the least-squares fit to the data, with a standard deviation of 7.5 dB and a correlation coefficient of 0.89.

Discussion of Models

The simple model badly over estimates the attenuation and must be considered as unsuitable as a method of determining the attenuation of smoke alarms. This method fails primarily because of its simplicity. Some of the large scatter is a result of the range in measured attenuation of doors, but it is insufficient to explain all of the scatter. The assumption that only the horizontal distance between the source and receiver is important ignores the fact that within rooms the sound field tends to be reverberant and that the primary

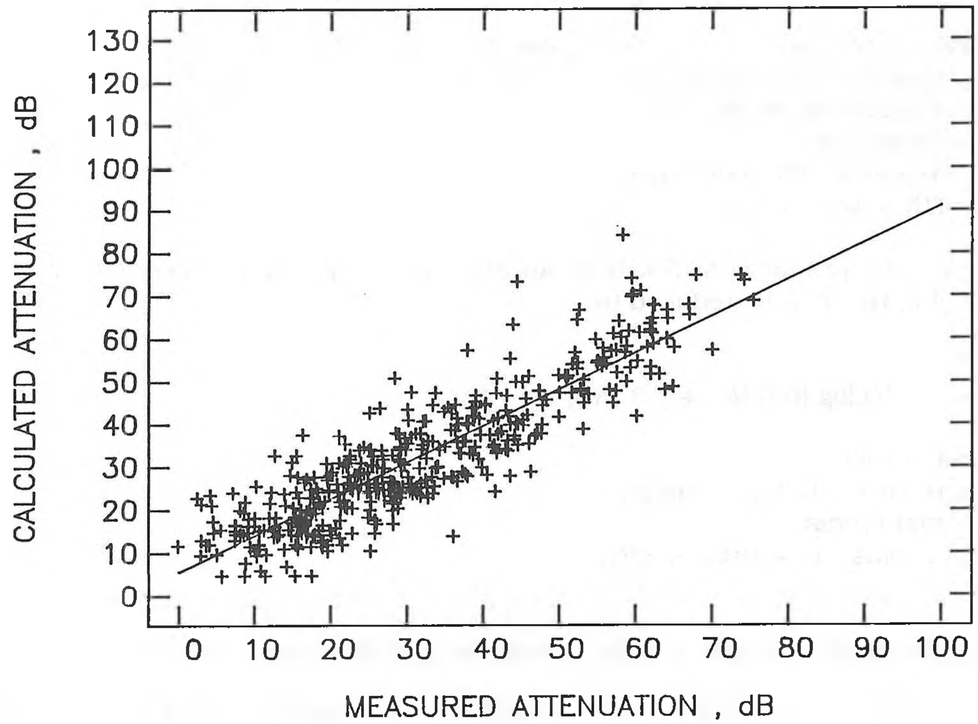

Figure 3. Proposed Model: Comparison of calculated and measured attenuations.

propagation path between rooms is unlikely to be a straight line. For this data set most of the measurements were for distances less than 5 metres, despite the large range of attenuations found. Similarly the assumption that absorption can be ignored is suspect. While there is evidence that most rooms in residential homes tend to have the same amount of absorption,[8] there are sufficient differences between rooms such as kitchens and bedrooms to add significantly to the observed scatter.

The proposed model is more satisfactory with only a slight tendency to be conservative in cases of low attenuation. Some of the observed scatter will again be due to variation in the attenuation for closed doors (shown in Fig. 1), and some will be associated with measurement of the source room sound level. The source room sound pressure level was measured at a single position rather than with a moving microphone, as was done in the receiving room. The measured sound level will be more representative of the near field of the alarm, as modified by adjacent reflecting surfaces, rather than the mean sound level in the room. The smoke alarm used had a definite tonal quality to its output, thus one would expect that diffraction and other pure tone effects would also contribute to the scatter.

Obviously there are many other factors and transmission paths in real buildings which could be included in a more detailed calculation. The inclusion of such extra details would require extremely complicated calculations and is unlikely to provide a significantly better fit to the measured data than the empirical method described above.

The attenuation calculated by Eq. (4), when subtracted from the initial sound level provided by the alarm signal, gives the alarm signal level at the point of interest. The initial sound level provided by the alarm signal can be obtained in one of two ways. The most direct is to measure the mean sound level in the room containing the smoke alarm. This is not always practical, however, especially if one is trying to ascertain the best room in which to locate the alarm. Thus, the second method is to calculate the initial sound level from the sound power output of the alarm, using the expression[9]

$$L_s = P - 10 \log [(\frac{V_s}{T_{60}}) (1 + \frac{S_s l}{8 V_s})] + 14 \qquad (5)$$

where L_s = mean sound pressure level in source room,
P = sound power output of alarm (dB),
V_s = volume of source room (m^3),
T_{60} = reverberation time,
S_s = surface area of source room (m^2),
l = wave length of sound (m).

For an alarm operating primarily at 3 kHz in an approximately square room with 2.4 m ceiling and a reverberation time of 0.4 s, this can be reduced to

$$L_S = P + 14 - 10 \log [6.06A + .3 \sqrt{S}] - A \qquad (6)$$

where S = floor area of room,
A = -2 for hard rooms (kitchen, bath),
= 0 for normal rooms,
= 2 for soft rooms (rugs, drapes, etc.).

PART 2: Attenuation Between Corridor and Bedrooms in Highrise Apartments

It is common practice in buildings, such as highrise apartments, which have multiple apartments connected to a common corridor, to locate fire alarms in the corridor. There are a number of practical reasons for doing this, none of which really addresses the question of fire safety. Since the sound levels required to alert a sleeping person are higher, it was decided to look at the problem of attenuation between the bedrooms and the corridor of an apartment building and the ramifications that this would have on the alarm system.

Measurement Procedure

Measurements were made of the reduction in sound level between the corridor, immediately adjacent to the entrance door, and each of the bedrooms and the interior hallway, immediately outside the bedroom doors. The entrance door and the bedroom door were closed for all measurements.

A white noise source was used in the corridor, at least 3 m from the door of interest, rather than trying to simulate any particular alarm signal. This provided broad band results which can be applied to any source spectrum.

The corridor levels were measured in the centre of the corridor, immediately outside the apartment entrance, approximately 1.2 m above the floor.

The interior hallway level and the bedroom levels were spatially averaged by slowly moving the microphone about the space during the integration period. An Norwegian Electronics model 830 Real Time Analyser, using a 16 second integration time, was used to measure the equivalent sound level (Leq) simultaneously in the corridor and in the hallway or bedroom. For each measurement location the sound level was measured with the sound off and with it on.

Measurements were made on a total of 73 apartment units in 9 different buildings. The buildings ranged from older, low cost housing for elderly people to new highrise luxury condominiums.

Results

In two of the buildings the apartments did not have separate bedrooms, but were bachelor apartments. For these cases the spatial average of the Leq in the area of the bed was used to calculate the attenuation which was treated as if it were an interior hallway attenuation since only one door separated the 'bedroom' from the corridor.

TABLE 2. Noise reduction from corridor in dB.

	Interior Hall		*Bedroom*	
Frequency Band Hz	*Attenuation*	*Standard Deviation*	*Attenuation*	*Standard Deviation*
100	22.5	5.2	34.8	6.4
125	24.8	4.6	37.3	6.4
160	27.4	4.4	41.9	6.2
200	26.9	3.9	43.6	6.2
250	29.0	4.4	46.0	6.7
315	28.9	4.6	47.8	6.8
400	30.8	4.8	51.0	7.2
500	31.7	4.9	53.7	7.9
630	32.2	4.4	55.6	7.9
800	32.5	4.4	57.1	8.2
1000	32.8	4.7	58.2	8.6
1250	33.7	4.8	59.1	8.5
1600	33.2	5.0	59.2	8.5
2000	30.6	4.8	55.6	8.1
2500	29.3	4.6	52.7	7.9
3150	30.8	4.7	53.9	7.9
4000	32.6	4.7	57.7	8.4
5000	29.2	4.8	56.3	8.5
A-wt	31.4	4.2	54.9	7.5

Discussion of Results

The results in Table 2 were obtained using a white noise source. There are several advantages in using white noise rather than any particular type of fire alarm. The most obvious is that the entire noise reduction spectrum is obtained. This makes it possible to calculate the expected noise reduction for any alarm system which produces broad band noise provided that the source spectrum is known. It should be noted that in most cases the attenuation of the alarm signal will actually be greater than that shown in Table 2. Few if any alarm systems provide much acoustical energy below 500 Hz, whereas the white noise source used provided a reasonable flat spectrum down to 100 Hz. When this is coupled with the transmission characteristics of partitions, which transmit more energy at low frequencies, one finds that the received spectrum for white noise has a strong low frequency component. This results in a higher A-weighted received level and thus a lower overall A-weighted noise reduction.

The mean A-weighted level difference between the corridor and the interior hallway for the nine buildings was 31.4 dB measured with the doors shut. The level difference between the corridor and the bedrooms was found to average 54.9 dB, again with the doors closed. If the door were open the level difference would only be 10 dB less as was shown in the previous study of single family residences.

What does this mean in terms of fire alarm systems? Although there is no clear minimum level required to awaken sleeping people, a level of 75 dBA as suggested by Berry is probably as reasonable a level as any. The mean background level found in the buildings studied was 36.5 dBA giving a healthy signal to noise ratio of 38.5 dB, but this is still not guaranteed to awaken everybody. Using 75 dBA means that the level in the corridor outside the apartment door must be 130 dBA. This is not a reasonable level. Not only is this above the threshold for permanent hearing damage , but it is quite difficult to achieve. The noise reduction between the bedroom and the adjacent hallway within the apartment is only 23.5 dB, so assuming a bedroom level of 75 dBA means that the hallway level need only be 98.5 dBA. This is not an unreasonable level and is easily achieved with existing alarm systems. Thus adequate fire safety protection for sleeping residents would require that an alarm be located within each apartment.

Whether one alarm within the apartment is sufficient will depend on the floor layout. Certainly in two level units which are found in some luxury apartments buildings it may be necessary to install two or more alarms. The optimum location for these alarms can be determined using the model developed for single family homes in Part 1.

Conclusion

A simple expression has been developed to calculate the attenuation of the alarm signal from a smoke detector as it propagates through a residential building, with the path viewed as a series of connected rooms. Attenuation depends on floor area and type of furnishings in each room. Corrections are applied if the house does not have forced air heating or if a number of doors are closed. The expression can be used to determine the optimum location for alarms. As the best location for an alarm is not necessarily the best location for a smoke detector, it is recommended that interconnected multiple detector/alarm systems be used or that detector and alarm be separated.

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