# Attenuation of Smoke Detector Alarm Signals in Residential Buildings

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## ABSTRACT

The propagation of sound from smoke detector alarms through residential buildings has been investigated with respect to the effect of furnishings, type of heating system, and number of closed doors. A simple model representing the propagation path as a series of linked rooms, each modifying the sound level, is described and compared with measured attenuations in 11 houses. The model can be used to determine the optimum number and location of smoke detector alarms.

## 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 detectors 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 smoke detector is the only means of alerting a sleeping person to the existence of fire. Detectors can save lives only if people hear them.

The fire detector has two main components: a combustion aerosol detector that determines the existence of fire, and an alarm device to alert the occupants. A breakdown in either component will prevent a fire warning.

In the last two decades aerosol detection has received world-wide attention and is now reasonably well understood, but the problem of producing a sufficiently loud alarm signal has received scant consideration. Defining the alarm level distribution throughout a residential home is important, however, if the self-contained detector alarm is to be an effective warning device.

The sound power output of a smoke detector must be such that after attenuation as it propagates through a building the sound level is still sufficiently high to waken a sleeping occupant. The Underwriters Laboratories standard UL217[3] requires that such a device must provide an A-weighted sound pressure level of at least 85 dB at 3.05 m when mounted near to two reflecting surfaces. Nober et al.[4] concluded that an alarm level of 55 dBA at the ear position in a quiet background is adequate to waken a college-age person with normal hearing, but that 70 dB is required if a window air conditioner is operating in the bedroom. In another study, Kahn[5] suggested that 70 dB is the minimum level required at the ear in a quiet background to waken college-age persons with normal hearing. Clearly, the minimum level to waken people is not well defined and requires further study. Although it is beyond the scope of the present investigation, the question requires attention if the results of this study are to be used effectively.

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 a building. The model would permit one to determine the optimum location for an alarm to achieve the required signal level at any location in the building. It is the purpose of the present study to develop such a model.

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

## MEASUREMENT PROCEDURE

Measurements were made using a smoke detector (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 two-channel FFT analyser collected 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 analyser were converted to third-octave spectra by summing the energy within the standard third-octave bands. This was done by assuming a realistic filter shape 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.

Sound power measurements were made for two smoke detectors of each of seven models in accordance with ANSI S1.31-1980[6] in the reverberation chamber at the Division of Building Research, National Research Council of Canada.

## DISCUSSION OF RESULTS

The reduction in sound level that is provided by walls, doors, etc., within a building and the sound absorption provided by furnishings increase 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. The human ear, on the other hand, is most acute in the 2000- to 5000-Hz range. It is also more economical to produce an inexpensive alarm operating in a higher frequency range, but this means that such alarms must operate at a higher sound power if they are to be adequate as warning devices.

Sound power measurements on a number of smoke detectors are listed in Table 1, which shows that most smoke detectors 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 detectors, 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.[7] 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.

TABLE 1. Maximum sound power output of smoke detectors

| | | 1/3 Octave Frequency Band, Hz | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Detector[1] | Duty Cycle[2] (τ) | 500 | 630 | 800 | 1000 | 1250 | 1600 | 2000 | 2500 | 3150 | 4000 | 5000 |
| 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/τ) was added to the measured mean sound power level to give the maximum sound power level.

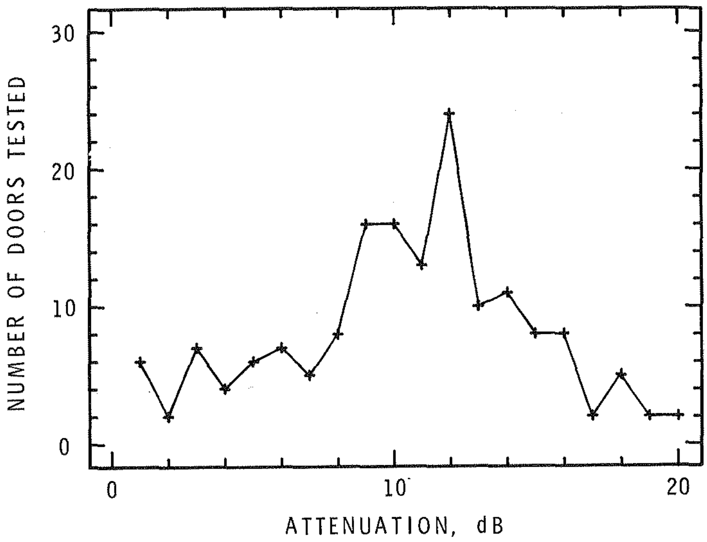

Figure 1. Histogram of sound attenuation due to closure of single door in propagation path.

Figure 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. At first glance this result appears to be in conflict with NFPA[8] work, which suggests 15 dB, and with that of Bradley and Wheeler[9] and of Nober,[4] who found 16.4 dB and 15 dB, respectively. This is, however, the change in attenuation with a door closure rather than an overall transmission loss of the wall-door system.

The best fit to the data was found with 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 measured attenuation minus the three corrections plotted as a function of distance from the source for the best fit values for these corrections. The slope of the least squares fit line drawn through the points gives the dependence on distance for this model. There is a very large range in the scatter, making this a less than satisfactory model for sound attenuation. Some of the scatter is a result of the range in measured attenuation of doors, but it is insufficient to explain all of the scatter. The major weakness of the model is its inability to make allowances for differing sound absorption in different rooms.

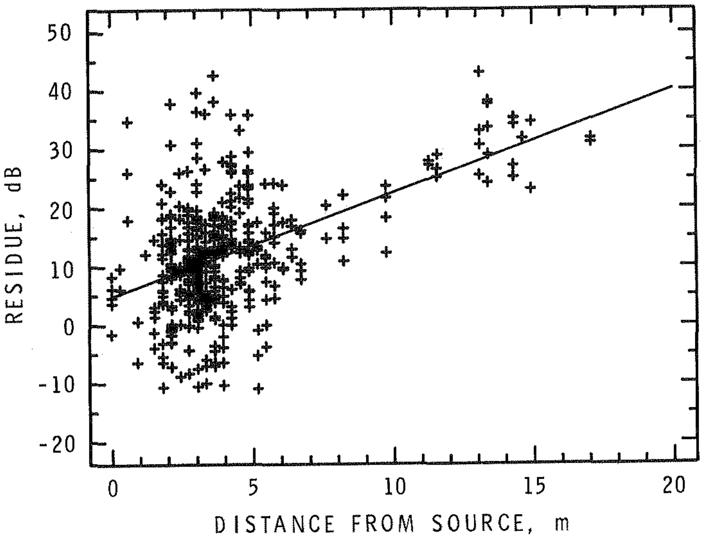

Figure 2. Measured attenuation minus corrections for open doors, closed doors, and number of floors between alarm and receiver.

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[10]

$$L_R = L_s - R + 10 \log \left[\frac{S\ T_{60}\ C\ (1.086)}{60\ V_R}\right] \qquad (1)$$

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,
$C$ = speed of sound (m/s),
$V_R$ = volume of receiving room ($m^3$).

At room temperature, this reduces to

$$L_R = L_s - R + 10 \log \left[\frac{S\ T_{60}}{0.161\ V_R}\right] \tag{2}$$

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.* The result is that the receiving room level is given by

$$L_R = L_s - \left[10 \log \left(\frac{\text{area}}{2.08}\right) + \text{corr}\right] \tag{3}$$

where 'area' is the floor area of the receiving room and 'corr' 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

$$10 \log \left(\frac{\text{area}}{2.08}\right) + \text{corr} \tag{4}$$

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. 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 viewed as the transmission loss associated with an open doorway. Note that the addition of transmission loss for the open doorway to the 10 dB insertion loss of the closed door gives a total attenuation of 15 dB, which compares favourably with values quoted by other workers.

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

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*J.S. Bradley. Unpublished data.

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:

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

where area = floor area of room 'r' ($m^2$),
door = number of closed doors in path,
corr = −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. Although some of this scatter will be due to variation in the attenuation for closed doors (shown in Fig. 1), much of it appears to 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

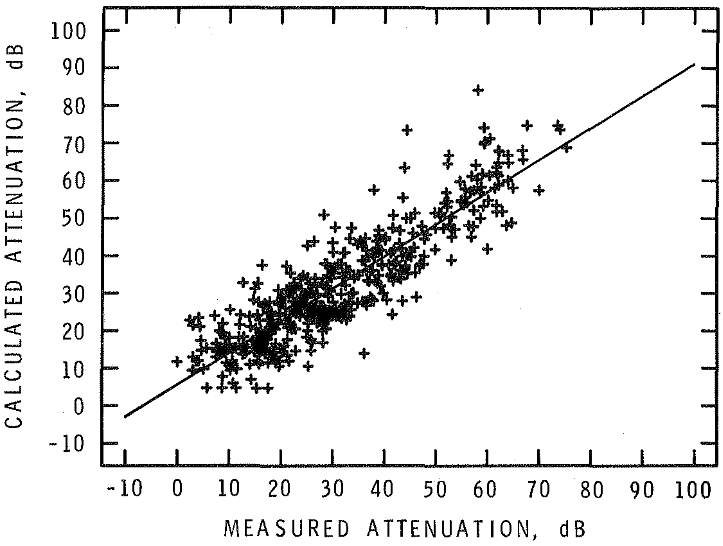

Figure 3. Comparison of calculated and measured attenuations.

more representative of the near field of the alarm, as modified by adjacent reflecting surfaces, rather than the mean sound level in the room.

Obviously there are many other 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 better fit to the measured data than the semi-empirical method described above.

The attenuation calculated by Eq. (5), 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 detector 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,[6] using the expression

$$L_s = P - 10 \log \left[ \left( \frac{V_s}{T_{60}} \right) \left( 1 + \frac{S_s}{8} \frac{\lambda}{V_s} \right) \right] + 14 \qquad (6)$$

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 ($m^2$),
$\lambda$ = wave length of sound (m).

For an alarm operating primarily at 3150 Hz in an approximately square room with 2.4-m ceiling and a reverberation time of 0.4 s, this can be reduced to

$$L_S = P + 14 - 10 \log \left[ 6.06A + .3\sqrt{A} \right] - \text{corr} \qquad (7)$$

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

## RECOMMENDATIONS

Of the seven smoke detectors considered during the study, not one provided any information about the sound power output of the alarm. It would seem to be desirable that either a minimum sound power output should be established for smoke detectors or that manufacturers should be required to indicate clearly the sound power output and the dominant frequency band.

One of the problems associated with these self-contained smoke detectors is that the optimum location for early detection of fires is not the same as the optimum location to ensure that the alarm is heard. This problem can be overcome in several ways, one being to make the alarms louder. It may increase the cost of the unit, and may also risk hearing damage for people close to the alarm when it is activated. Another is to have a number of smoke detectors interconnected so that detection of a fire by any one would trigger all the alarms. A third method would be to separate the detector and the alarm so that each could be placed in its optimum location. It is recommended that the last two options be incorporated in building regulations and practices for fire safety design.

## 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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