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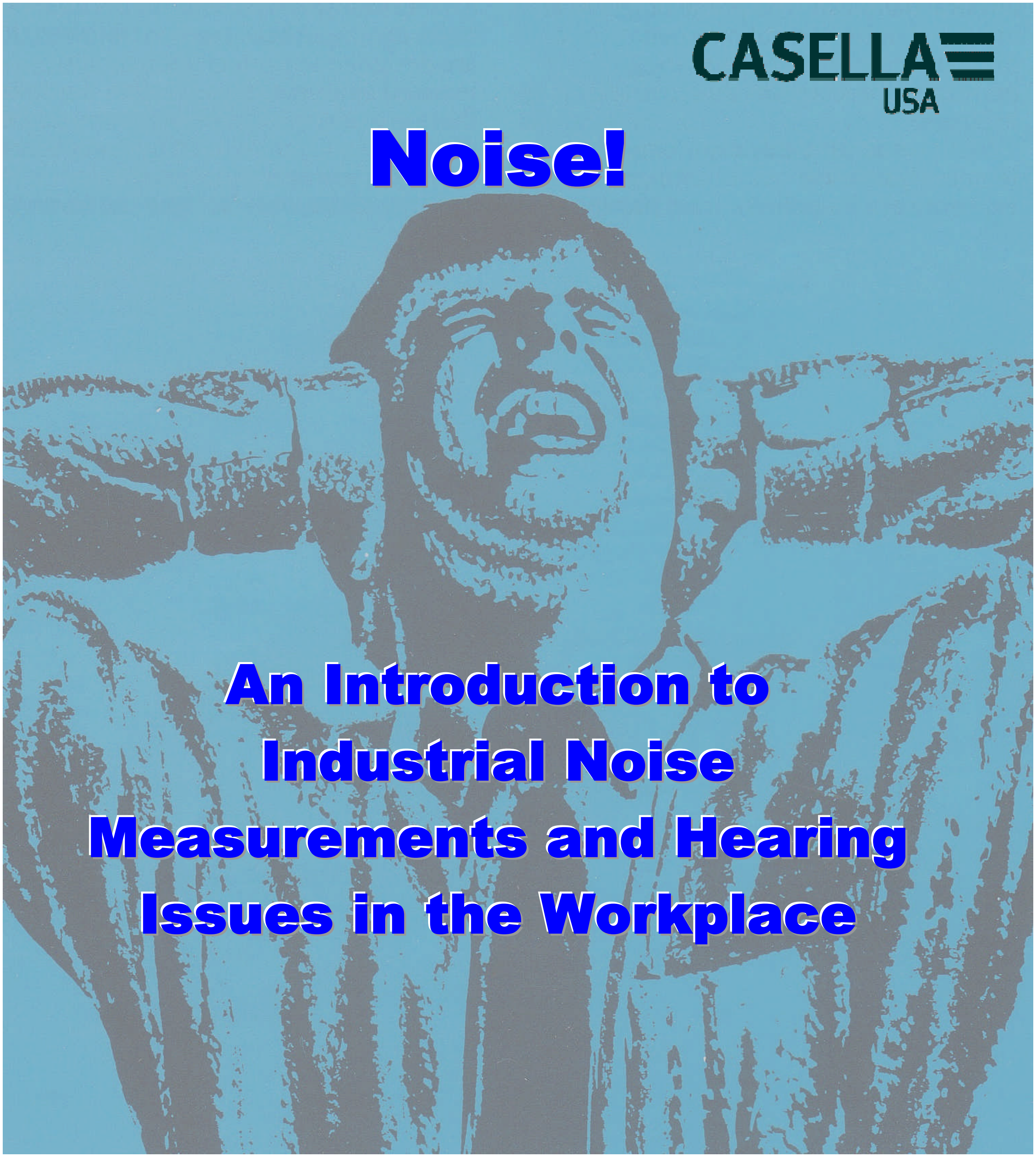


Noise!

An Introduction to Industrial Noise Measurements and Hearing Issues in the Workplace

Contents

Introduction

This booklet is about the protection of employees and visitors from the effects of excessive noise in the workplace. Occupational noise can and does damage our hearing, resulting in serious social and physical handicap. The prime objective of an industrial noise control programme is to protect employees from suffering permanent hearing loss due to high noise exposure.

We have all probably experienced a temporary hearing loss following noise exposure at a loud disco, from hammer drilling of concrete for an extended period, shooting etc. However, our hearing soon returns to its normal state, with the time taken to recover depending on the exposure severity. This recovery appears to be total. However, repeated exposure to high levels will lead to a permanent hearing loss. Consequently, limits for occupational noise exposure have been established that are designed to protect the majority of the workforce against noise-induced deafness. As is so often the case, there is a relationship between the degree of protection and the costs of compliance.

Current limits protect the vast majority of the workforce but not everyone will be equally protected due to differing human susceptibility to noise induced-deafness. Like most human senses we judge sound in a subjective manner and so it makes quantitative assessments very difficult. Hence the correct measurement and analysis of the level is critical in deciding the degree of hazard that is present and what type of noise control measures are required for a particular situation.

Modern sound level meters and noise analysers or dosimeters have facilitated the accurate measurement of the noise levels provided that the instruments are properly used, calibrated and regularly re-certified. These measurements provide the basic data upon which the degree of hazard may be decided and the correct remedial measures prescribed.

Physical properties of sound

The passage of acoustic energy through air results in the instantaneous pressure at any point in space and time consisting of two components; namely the atmospheric pressure and the sound pressure. The atmospheric pressure only changes slowly as weather systems come and go with the standard atmospheric pressure (STP) at mean sea level and 20° Celsius (68° Fahrenheit) being 101,325 kiloPascals (29.9 in mercury, 1013 mbar). The symbol kPa is usually used for the air pressure and this unit replaces N/m^{-2} with which it is identical. Audible pressure fluctuations are a result of the passage of acoustical energy through the air and are normally much less than 1 Pa; they are tiny in comparison with atmospheric pressure. These tiny fluctuations are extremely important to our lives. An acoustic wave can therefore be quantified in terms of the amplitude and frequency of these pressure fluctuations. Even the most complex sound can be analysed into individual components at different specific frequencies and levels. Generally speaking frequency is interpreted as pitch and the amplitude of the pressure fluctuations as loudness. However, these two parameters are interdependent, as we will see later.

The audio frequency range is normally defined to be the range from 20 Hz to 20,000 Hz. (Hz = Hertz = cycles per second i.e. the speed of the variation of the fluctuations). However, tones that are below 25 Hz are not generally heard but are rather sensed by various parts of our body like our chest cavity that resonates at very low frequencies, typically below 10 Hz. Most adults are not able to hear tones whose frequency is greater than about 16,000 Hz (16 kHz, k = kilo = 1,000), particularly as they get older.

Human ears are most sensitive to sound in the mid-frequency range of 500Hz to 6,000Hz. The perceived loudness level of any given sound pressure will be less at the lower and higher frequency extremes than at these mid-frequencies.

The human ear responds to a very wide range of sound pressures from the painfully loud at around 20 Pa to the quietest sound that we can just hear at 0.00002 Pa. That is a scale range with 6 orders of magnitude (i.e. a range of pressures from 1,000,000 to 1). This range of numbers is not only inconveniently large to work with, but can be misleading because to the listener there is exactly the same change in perceived loudness between a pressure change from 10 to 100 micro Pa as there is between 100 and 1,000 micro Pa or between 10,000 and 100,000 micro Pa for similar tones.

The subjective reaction of the human hearing process is, therefore, proportional to the *ratio* of the pressure levels and hence lends itself to measurements on a logarithmic scale in decibels. Using such a measurement unit would give each of the ratios mentioned above the same increment and will also compress the million to one ratio of sound pressures to more manageable proportions. The decibel (dB) is such a unit.

The decibel (dB) Scale

The dB scale is widely used in electrical and telecommunications engineering and is defined as the logarithm of the ratio of two powers. In noise measurements by choosing the reference level as the quietest sound that can be perceived (0.000,020 Pa) we get a scale that expresses the measured level relative to the threshold of hearing. Zero dB would therefore be theoretical silence. 0 dB is not the absence of sound pressure, simply the point at which the average person begins to start "hearing". Sound level meters are able to make measurements in very quiet situations around 0 dB and sometimes into negative dBs that may be found in TV or radio studios, for example.

We are considering sound pressures and it must be remembered that sound power, (strictly speaking, intensity) is proportional to the square of sound pressure.

We need therefore to obtain the ratio of the measured level squared divided by the reference level squared (0.00002 Pa). This should give the result in Bels which is then made more manageable by use of the decibel, dB. There are 10 decibels in a Bel. The scale then goes from the inaudible at 0dB (0.000,020 Pa) to the painful at 120dB (20 Pa).

Mathematically, the instantaneous sound pressure level, L_P, is expressed as:

$$L_p = 10 \log \int (P / P_o)^2$$

where P is the instantaneous sound pressure in Pascals and P_o is the reference pressure (20 micro Pa) at a frequency of 1,000 Hz.

For convenience the square term is usually taken outside the bracket and applied to the logarithmic result to give:

$$L_P = 20\log\int(P/P_o)$$

Note:
A doubling (or halving) of sound pressure causes a positive (or negative) 6dB change in the sound pressure level, whilst a 3dB change in the sound pressure level would result from a doubling or halving of the *energy*.

This can be seen quite easily by considering a pressure P and a second one of 2P. The ratio 2P/P yields a result simply of 2 and the logarithm to the base 10 of 2 is 0.30103. Multiply this by 20 to convert to decibels and the answer will be 6.0206 i.e. for all intents and purposes, 6 dB.

For the situation where the second pressure is half the first then the ratio is ½ so the logarithm to the base 10 is now –0.30103. Multiplying by 20 to convert to decibels gives the result –6.0206 dB.

We can now investigate the interdependence of sound pressure and frequency in respect of how they are interpreted by a listener to form a subjective assessment of loudness. Figure l shows equal loudness contours, which are curves that link the various combinations of pressure and frequency that sound equally “loud” to the average person. These contours show that the way in which we respond to different sounds is very complex. We hear particularly well in the mid-frequency range of 500Hz to 6,000Hz, but we do not hear lower frequency sounds quite so well. In fact, a low frequency tone has to have a fairly high level for it to be audible at all. For example, a 60dB, 63Hz tone has the same subjective loudness as a 1,000Hz tone of 40dB.

This interdependence of frequency and sound pressure has to be taken into account by any measurement system that needs to correlate to the human reaction and for this purpose various correction curves and methods have been developed to try and apply a single number to the sensation of loudness of sounds. Some of the correction curves that have been used are the 'A', ‘B’ and ‘C’ frequency networks found in many sound measurement devices. These weightings have a fixed frequency correction response in which the same attenuation at a certain frequency is applied regardless of the actual noise level. Whereas a system such as the complex measurement of the loudness of a sound in sones is a better way to take account of the complex relationship between frequency and level seen in the equal loudness curve responses.

The ‘A’ weighting scale

The most commonly used loudness unit is the ‘A’ weighted decibel, (sometimes written as the dB(A)). The A-weighting network was originally based on the 40-phon curve of the 1938 Loudness contours of Stevens and Davis and was intended as a method of making broadband loudness measurements.

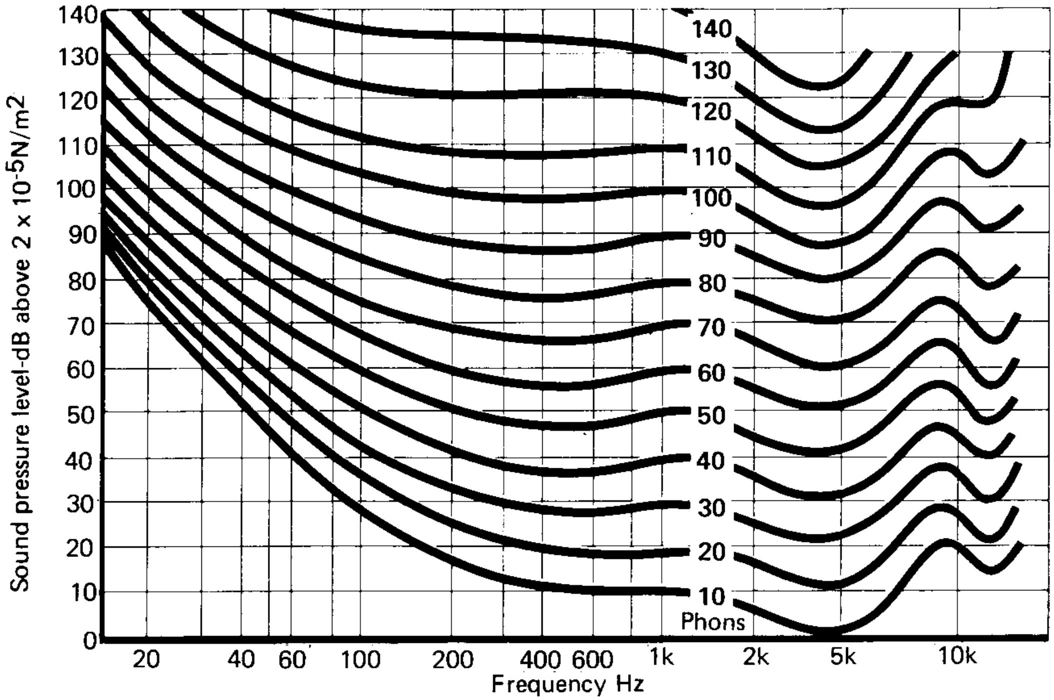


Figure 1. Equal loudness curves after Fletcher and Munson

The A-weighted sound pressure level (L_A) takes much less account of the low frequency components of the noise than the mid-frequency and hence corresponds more closely to the frequency response of the human ear. Subject research has shown that the A-weighting value also has a good correlation to the risk of noise-induced deafness and the annoyance rating of sound at all levels. Although it is not perfect, the A-weighted sound pressure level value is a very simple unit to measure and gives a good first approximation to the auditory sensation of the human hearing mechanism.

The A-weighted sound pressure level has now been standardised and adopted throughout the world in order to assess the hazards of noise to our hearing. All sound level meters conforming to the current international standards (as published by IEC and ANSI and other similar organizations) have an electrical filter built in to them that gives them an A-weighted response. This is shown over the audio range of frequencies in Figure 2. Noise measured in this way should be quoted in A-weighted dB (or dB(A), although this terminology is falling out of favour with many users) and when people often speak about decibels they almost invariably mean A-weighted dB.

A full definition of the instantaneous A-weighted sound pressure level, L_{pA} in decibels, is therefore:

$$L_{pA} = 20\log(P_A / P_o)$$

where P_A is the instantaneous A-weighted sound pressure and P_o is the reference pressure of 0.000,020 Pa, (20 µPa).

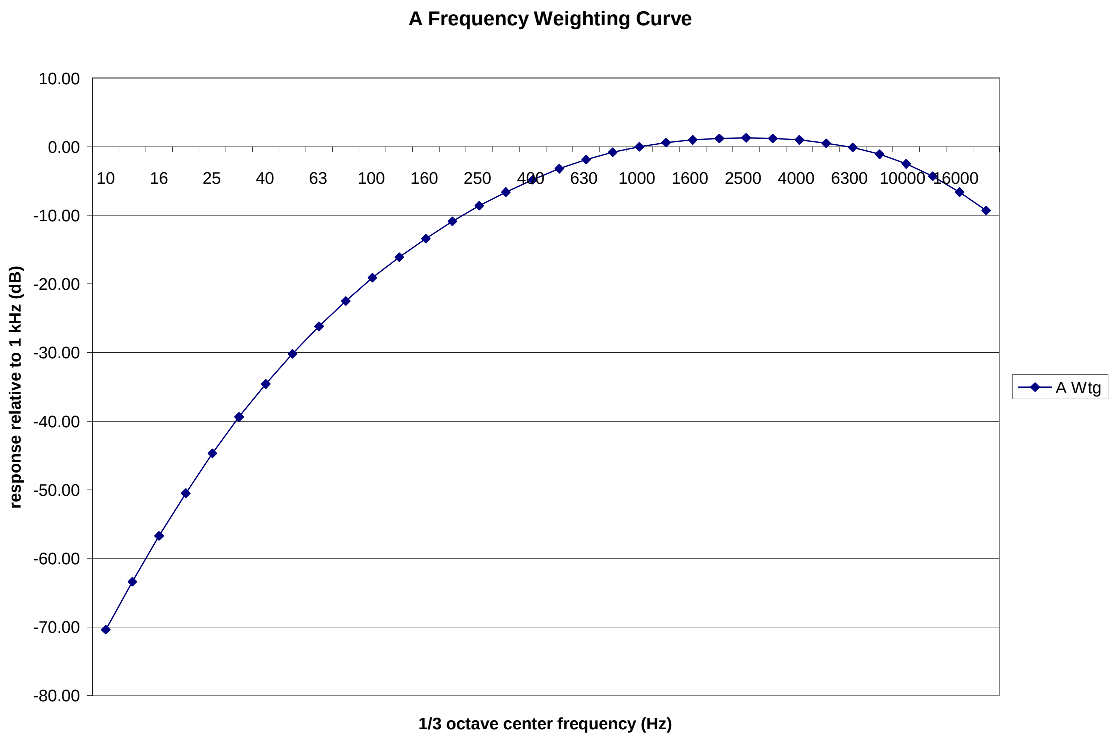


Figure 2. The ‘A’ frequency weighting curve used in sound level meters

Hence, it can be seen from Figure 2 that:

1 a 125Hz tone whose true linear level is 80dB has an A-weighted level of 64dB.
2 a 500Hz tone whose true linear level is 75dB has an A-weighted level of 72dB.
3 a 16,000Hz tone whose true linear level is 90dB has an A-weighted level of 83.4dB.

The decibel scale

A few useful things to remember about the dB scale are:

- An increase or reduction of a measured sound level of 3dB is a “just noticeable” change even though it represents a change in the energy level by a factor of 2, i.e. a doubling (or halving) of the energy of the sound.
- An increase of 10dB is approximately a doubling in the apparent “perceived” loudness.
- It follows from the logarithmic nature of the dB scale that adding and subtracting sound levels do not follow the rules of simple arithmetic. It is the fundamental units of energy that are summed, and <u>not</u> the dB levels.

Hence the effect of turning on a second identical broad band source will be to double the acoustic energy produced and hence the product of $(P_1^2 / P_2^2)^2$ will increase by a factor of 2 and 10 log 2 = 3dB.

Therefore, adding a second source of identical level to the first will increase the sum of the levels by 3dB[1] and it is the *intensities* that add and not the pressures or the dB levels. Quite definitely, 80 dB plus 80 dB does <u>not</u> equal 160 dB!

An interesting party trick arises here since it is now possible to prove that

2 + 2 = 5

at least as long as we are talking about decibel values!

[1] (* This is true for broad band sources but would be higher or lower if the sources were at the same frequency.)

In the past, many methods have been proposed using graphs or the difference between levels to simplify the addition or subtraction of levels but with the advent of pocket sized scientific calculators it is just as convenient to use the basic formulae.

$$L_p = 10\log[10^{(0.1L_{p1})} + 10^{(0.1L_{p2})} + 10^{(0.1L_{p3})} + ...10^{(0.1L_{pn})}]$$

where L_{p1} is the first sound pressure level in dB
L_{p2} is the second sound pressure level in dB
L_{p3} is the third sound pressure level in dB
L_{pn} is the nth sound pressure level in dB

The multiplication of the individual sound pressure levels by 0.1 is to convert the decibel values back into Bels. The antilog of each term is then calculated as shown by raising 10 to the power of the Bel value to obtain the absolute sound pressure represented by the individual parts and then these are all summed, logged and multiplied by 10 again to arrive at the overall decibel value.

It follows from this relationship that if a small sound source produces a sound pressure level of 80dB at a point in a typical factory then Figure 3 shows the effect of adding more similar sources.

Appendix C shows a tabular method for adding and subtracting decibel levels that may be more convenient to use where a pocket calculator is not available.

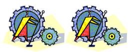
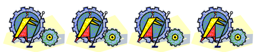
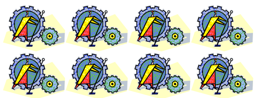
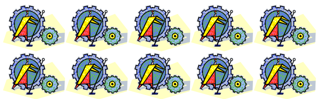
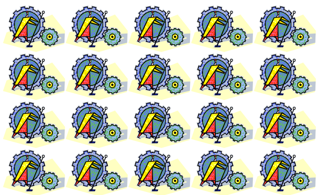
Number of sources	Energy received Per second	Resultant Level (dB)
	1E unit	80
	2E units	83
	3E units	84.8
	4E units	86
	8E units	89
	10E units	90
	20E units	93
etc.	40E units	96
etc.	80E units	99
etc.	100E units	100

Figure 3. Addition of identical noise sources.

That is, one hundred small noise sources will give, compared to a single noise source, an increase in level of 20 dB. This may not seem tremendously significant but exactly the same rules apply when a reduction in level is required. Consequently, if we seek a large reduction in level then, there has to be a very significant reduction in energy output. This can be achieved either by reducing the acoustic energy output of each source and/or by a dramatic curtailment of the number of sources.

For example, if a factory had 20 small similar machines in use, what would be the effect if; (a) one machine were removed, (b) if ten machines were removed, (c) if a 20dB reduction is required then how could this be achieved?

(a) The removal of one machine out of twenty gives a 5% drop in acoustic energy output. However, the corresponding reduction in level is a surprisingly small drop of only 0.2dB. That is, a minute reduction in level on removing one single machine. This change in level is not noticeable by the average human ear and is probably not a detectable change even with a sound level meter.

(b) Halving the number of machines by removing ten of them reduces the acoustic energy output by 50% and will result in a 3dB drop in level. This is a just noticeable change in noise level. It is not a significant reduction in acoustical level; it would, however, be a very significant reduction in work output!

(c) To achieve a 20dB reduction in level requires that the acoustical energy output be reduced to one hundredth of its original value. That is only two tenths of one machine can be on; however, in reality parts of a machine cannot usually be on by itself. To realise this reduction one machine must be on <u>and</u> it will require an additional 8dB of silencing to achieve the required reduction.

An important consequence of this is that to achieve a measurable and significant reduction in the overall noise level requires considerable attention to detail when an engineering solution is required.

Other frequency weightings or filters that are sometimes used for noise measurements have included the ‘B’ and ‘C’ curves. Of these two only the C curve is in common use nowadays for the measurement of impulsive or impact noise levels of relatively short duration. The B curve has very much fallen out of use in normal noise measurements and is only found in certain specialized noise protocols such as the assessment of the interior noise heard in automobiles when used to gauge the reaction of listeners to the quality of the sound. The curve representing the frequency response of the C weighting is shown in Figure 4. The ‘C’ curve is almost flat from 50 Hz to 10 kHz.

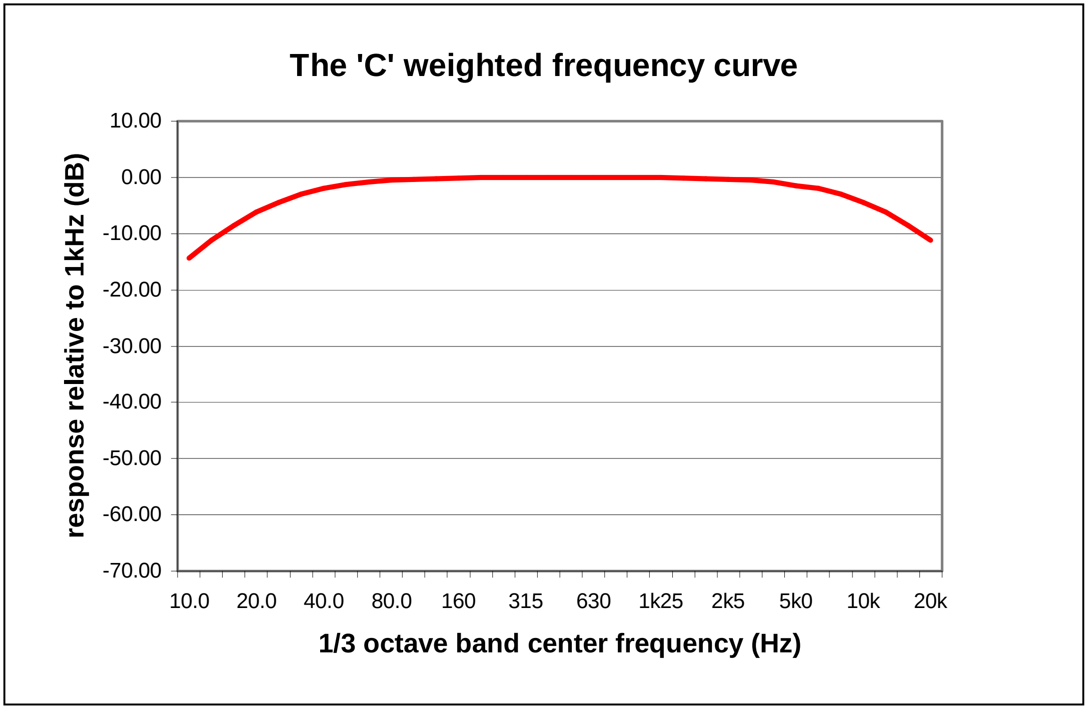


Figure 4. The ‘C’ frequency weighting curve used in sound level meters

The hearing process

The human ear essentially consists of three sections; the external, middle and inner ear and these are shown diagrammatically in Figure 5. The external ear extends from the pinna (external ear lobe) to the tympanic membrane (ear drum). The pinna's shape allows it to collect and funnel sound into the external ear canal and is particular effective at the higher frequencies.

The acoustic energy that flows down the ear canal eventually arrives at the eardrum forcing it to vibrate in sympathy with the incident energy. Energy is then introduced into the middle ear that comprises of three small bones called the hammer, anvil and stirrup. These are connected in a chain and transmit the motion of the eardrum through to the inner ear.

The middle ear acts as an amplifier having about a 25dB gain. The last bone in the chain is the smallest in the human body and it is in contact with a small flexible membrane of the inner ear called the oval window. The inner ear comprises the cochlea, a fluid filled snail shaped organ that converts the mechanical motion introduced via the oval window into nerve signals.

As the oval window moves it forces the perilymph, the fluid in the cochlea, into motion setting up a travelling wave. This wave propagates the energy along the scala vestibuli round the helicotrema and back towards the round window via the scala tympani. As the wave traverses the scala tympani it forces the flexible basilar membrane to move.

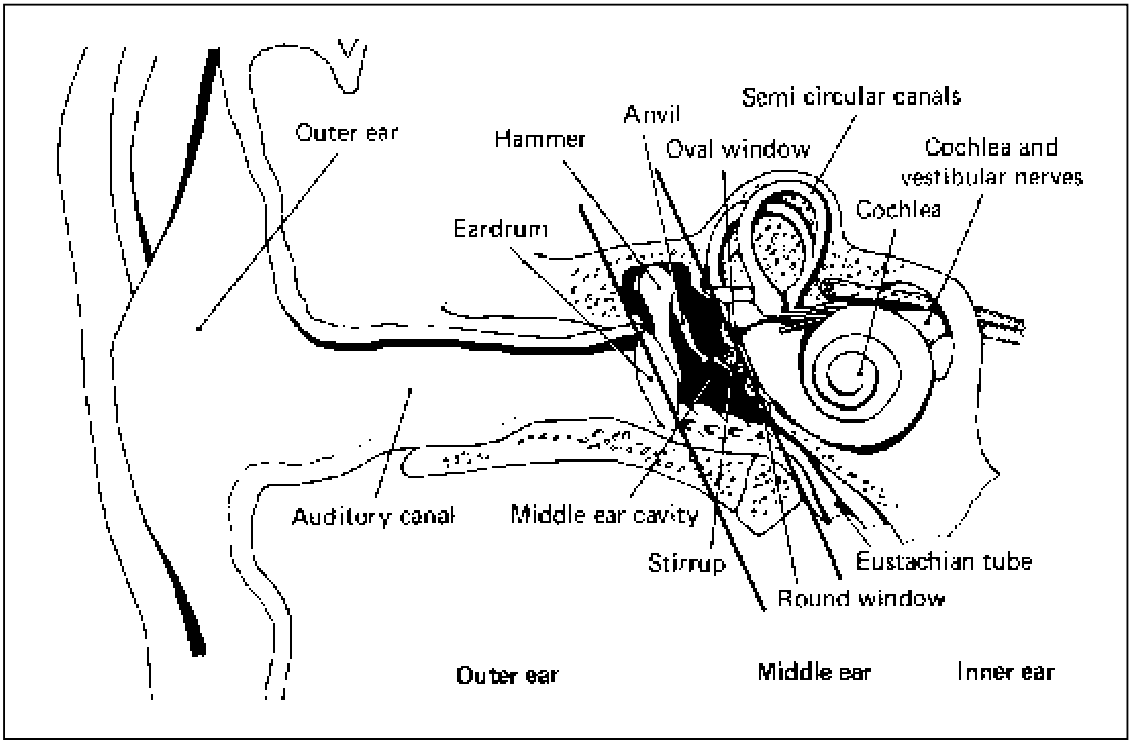


Figure 5. Simplified anatomical diagram of the ear.

Hair-like nerve cells are "mounted" on the basilar membrane, some of which are the stiff cilia and are arranged in a regular pattern. They are not all of the same length. As these cilia move up and down in sympathy with the vibration of the basilar membrane they come into contact with the hard tectorial membrane and in doing so receive a sideways shearing force. This force, if sufficient, causes the hair cell to be “triggered” (stimulated) into sending an electrical impulse along the eighth nerve to the brain. The efficiency of the ears of any individual may be quantified by audiometric testing. These audiometric assessments are not only able to accurately determine the degree of loss but also to locate the cause of the problem.

Electron microscopy has shown that exposure to high levels of noise results in irreparable damage to the hair cells in as much as they appear to be “bent over”, and can no longer be capable of generating a nerve signal for the brain to interpret. This damage can be caused by a single very severe shearing force (a very loud noise) or much more likely by fatigue damage due to prolonged exposure to stress (more moderate levels). In fact even noise levels over 85dB will cause some hearing loss with some people being affected more seriously than others.

Three factors increase the degree of noise induced hearing loss:

- the higher the noise level,

- the longer the exposure time,

- the higher the personal susceptibility,

then the more likely a person will be to suffer from noise induced hearing loss.

Hearing problems

Hearing loss can be caused by:

(a) Obstructions in the external ear (abscesses, wax, growth or a foreign object).

(b) A perforation of the eardrum causes a few dB's loss resulting from the thickening of the drum as a result of scar tissue generated by the body's healing process. (Most of us suffer a perforation sometime in our lives and the ensuing hearing loss is hardly noticeable).

(c) A rupture of the eardrum is more serious because of the risk of infection occurring in the middle ear and is often associated with damage to the middle ear system. A rupture requires medical attention and normally results in moderate loss.

(d) Middle ear disorders such as missing or damaged ossicles, calcification or other effects such as the build-up of fluid in the cavity, that limits the mobility of the ossicular chain cause conductive hearing losses. All of these, and many other problems associated with hearing caused by problems with the outer or middle ear can be successfully treated using modern medical and surgical methods. Hearing aids can also be of great benefit to people who suffer from these conductive types of hearing loss.

(e) There are, however, other causes of deafness due to problems with the inner ear. These are perceptive in nature and result from the failure of the inner ear to generate nerve signals that the brain can interpret. Typical of these types of problem are damage to inner hair cells by ototoxic drugs (such as Quinine and Streptomycin). Failure of the hair cells following excessive noise energy immission (the product of noise level and the exposure duration) is the most common.

Once the nerve cells are destroyed, a hearing impairment is acquired for which there is no cure. The nerve cells will not regenerate and neither will medical or surgical attention be able to restore normal hearing. Similarly a hearing aid will be of no benefit as, no matter how much the sound is amplified, the brain will not be able to hear it. Hearing problems represent a serious handicap for the sufferers resulting in social isolation and can cause enormous strains on family and working life. The only treatment for noise induced hearing loss (occupational deafness) is prevention at the source, and it is to this end that industrial hearing conservation programmes have been initiated.

Many noise regulations is force around the world specify a hearing conservation program of various degrees of complexity to protect the hearing of workers. Examples of this include the US OSHA regulations that require regular audiometric testing of workers to identify deteriorations in the hearing acuity over time. The hearing conservation program (HCP) has other requirements to monitor the noise exposure, issue hearing protectors, train workers on the correct usage of them and so on.

Occupational deafness

There is a natural ageing effect, called presbycusis, which results in a loss in hearing acuity that is most marked at high frequencies. This effect on its own does not usually leave the subject at a social disadvantage even at quite an advanced age. However, losses due to noise exposure also affect the high frequency sounds first, starting at 4 kHz and then spreading out, and these effects are additive to those of presbycusis.

Quite quickly, therefore, the noise-exposed worker can acquire a hearing handicap. The problem is made worse by the fact that the relative response of hearing at different frequencies is affected; it is not just simply an overall reduction in volume that occurs. This will result in distortion of the received sound, sufferers are aware of a sound but find it difficult to comprehend.

Occupational deafness is a very common form of hearing loss, and the typical symptoms are:

- mis-hearing words, particularly those beginning with s, t, p, and f; for example, “pigeon” and “religion”; “seen and been” and “fight and right”. However, the mis-comprehension does not have to be at the beginning of the word, for example, “done” and “run” are frequently confused;
- difficulty in making telephone conversation;
- talking too loudly because you can't hear your own voice;
- it is more difficult to hear a conversation in the presence of high background noise levels on the shop floor or in a bar or restaurant;

- ‘tinnitus’ for most people results in a noise that sounds like a ringing in the ears which for a very few cases can become so loud that it makes sleep difficult. The cause of tinnitus is normally either an exposure to a loud bang or a “hit” on the ear that causes a slug of air to race down the ear canal and give the hearing process a “jolt”. In its worst form it makes sleep difficult because of the perpetual presence of the noise and some people can only find relief by drowning that noise (masking it) by listening to a more pleasurable sound such as a radio.

Another symptom is loudness recruitment where there is a very small range of levels between the inaudible and the intensely loud. The sufferer often asks for the television to be “turned up” then bitterly complains that you have made it deafeningly loud.

If you have one or more of these symptoms it does not necessarily mean that you have noise-induced loss but it would be wise to seek the advice of a medical professional.

Noise induced stress

In addition to the risk of occupational deafness, noise can also be a nuisance and can cause stress induced medical problems. Concentration is impaired and a further load is placed upon employees who are increasingly being asked to produce higher levels of productivity.

Stress results in increasing error rates and eventually leads to a wide range of social and medical problems. Such matters are beyond consideration here other than to draw attention to the fact that noise levels now proposed to control occupational deafness are purely those necessary to prevent or minimise actual physical damage to the ears. They are not pleasant conditions in which to work and for many skilled operations requiring close concentration by employees, considerably lower levels are desirable.

Damage risk criteria

Damage to the hair cells in the inner ear is proportional to the noise energy immission (that is the noise that a person is subjected to at their place of work). This is a dose concept that includes the product of both the noise level and the time of exposure. It follows, therefore, that the same amount of deafness will follow from the exposure to a very intense sound for a short period as to a lower sound for a proportionally longer period. The generally accepted daily noise exposure dose limit (or PEL) is 90 dB for an 8 hour working shift.

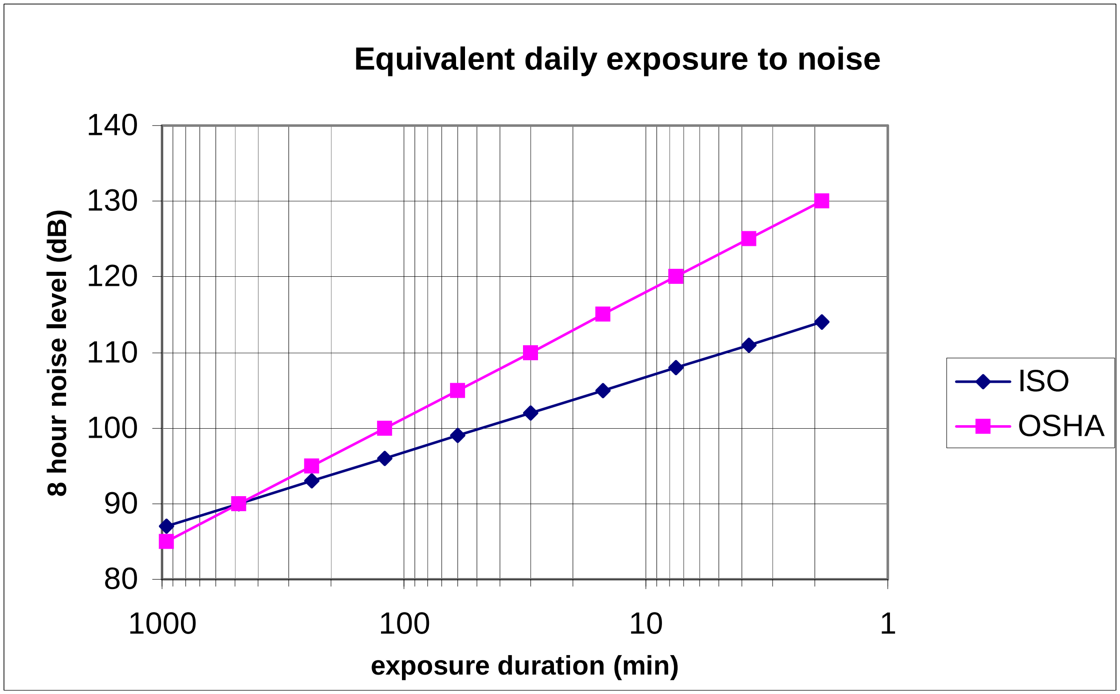


Figure 6. Noise and exposure duration (Noise Dose) Relationship

Figure 6 shows the relationship between different continuous sound levels (time average level) and exposure duration that equates to the same “dose”. It can be seen for the ISO rating (used in Europe and most of the rest of the world) that the exposure time has to be halved for each 3 dB increase in noise level to keep the same daily dose. Some country’s regulations use differing rates of risk increase as the noise level rises. In the USA, for example, a 5 dB increase in noise level is considered to “double” the risk factor (as specified in the OSHA 1910:95 regulations). Note that NIOSH and the ACGIH methods recommend a 3 dB exchange rate for the calculation of personal noise dose measurements in a similar manner to the ISO method.

As we saw earlier an increase of 3 dB represents a doubling of sound energy, hence this rule (specified by ISO) has become known as the equal energy damage risk criteria. It follows; therefore, that 93 dB for 4 hours is also 100% of the permitted exposure for a day. So 2 hours at 93 dB would be 50% of the permitted daily exposure. This is not true for noise measurements that follow other “exchange rate” rules such as 4 or 5 dB per doubling of risk. The 4 dB exchange rate is specified in the US Department of Defense regulations for some of the armed services in the USA.

Allowable exposure durations for other continuous equivalent noise values may be read from Figure 5. By converting noise exposures to % dose a simplified-method of calculating composite exposures can be realised. Expressing the actual exposure time as the numerator and the permitted exposure as the denominator for each exposure level and summing the fractions so produced will yield the composite dose.

If the resultant is less that 1 (i.e. a 100% noise dose) then it is a **“**safe” situation while a higher result indicates an over exposure.

For example, a process chemist working in a European company has a regular inspection tour that results in his exposure to the following noise levels for the given times.

90 dB for 5 hrs, 93dB for 2 hrs and 97.3dB for 6 minutes,

which gives:

= 5/8(h) + 2/4(h) + 6/64(m)
= 40/64 + 32/64 + 6/64
= 78/64
= 1.219

This produces an exposure of 121.9% and is therefore above the recommended daily dose.

For the same chemist working in a plant in the USA the assessment made against the OSHA regulations yield an alternative answer as shown below due to the different exchange rate stipulated at Q=5 dB.

90 dB for 5 hrs, 93dB for 2 hrs and 97.3dB for 6 minutes,

which gives:

= 5/8(h) + 2/5.3(h) + 6/2.8/60(m)
= 0.625 + 0.377 + 0.036
= 1.038

This produces a different exposure of 103.8% and is therefore also above the recommended daily dose but not by as much as the previous case. This is simply due to the fact that the Q=5 exchange rate specified by OSHA is more relaxed compared to the Q=3 rate adopted in the ISO/ACGIH standards.

For a more precise method the general mathematical formula for combining noise exposures L_T according to the ISO/ACGIH method is:

$$L_T = 10\log \frac{[t_1 10^{(0.1L_1)} + ... + t_n 10^{(0.1L_n)}]}{T}$$

where L_1 is the first continuous noise exposure for duration t_1
and L_n is the nth continuous noise exposure for duration t_n

then, for our example we have,

L_T = 10 log [5 x 10 ^ (0.1 x 90) +

2 x 10 ^ (0.1 x 93) +

0.1 x 10 ^ (0.1 x 97)]/7.1

= 91.3 dB

The permitted exposure under the damage risk criteria can be determined from the rating curves given in Figure 5. The general form for calculating the exposure time at any given sound level is:

$$T_L = T_c[2^{(L_T - L_C)/Q}]^{-1}$$

where

T_L = permitted exposure duration at a level of L_T.
T_C = allowable exposure at the criteria level of L_C.
Q = amplitude weighting function (or exchange rate factor)[2].

[2] (Q = 3 for equal energy damage risk criteria used in Europe and Q= 5 for the regulations that apply in the USA. Values of 4 & 6 are also occasionally found in some countries)

Then with a criteria of 90dB for 8 hrs that generally applies as the daily limit in our example given above (for the Q=3 ISO/ACGIH method),

$$T_L = 480[2^{(91.3-90)/3}]^{-1}$$

= 355.5 min.

= 5 hrs 55 min 30 sec

Hence, as the actual exposure was 7.1 hours (7 hr 6 min) it represents an unacceptable situation since this is longer than the allowable exposure time of 5 hrs 55 min 30 sec.

For the case in terms of the US OSHA regulations we need to use the 5 dB exchange rate and so the result comes out as,

$$T_L = 480[2^{(91.3-90)/5}]^{-1}$$

= 400.8 min.

= 6 hr 40 min 50 sec.

Again the actual exposure was 7.1 hours (7 hr 6 min) it also represents an unacceptable situation since this is longer than the allowable exposure time of 6 hrs 40 min 50 sec.

Dealing with the real world

So far we have only considered steady noise levels but it is soon apparent, when measurements are made in real situations noise levels are very rarely constant. They go up and down as a machine comes on and off load and product is moved about or processes change. This brings about the concept of equivalent continuous energy levels that can be used to express the time varying pattern as a steady level having the same duration and energy level as the actual measured levels. This is shown graphically in Figure 7 by the time history of a typical industrial noise climate.

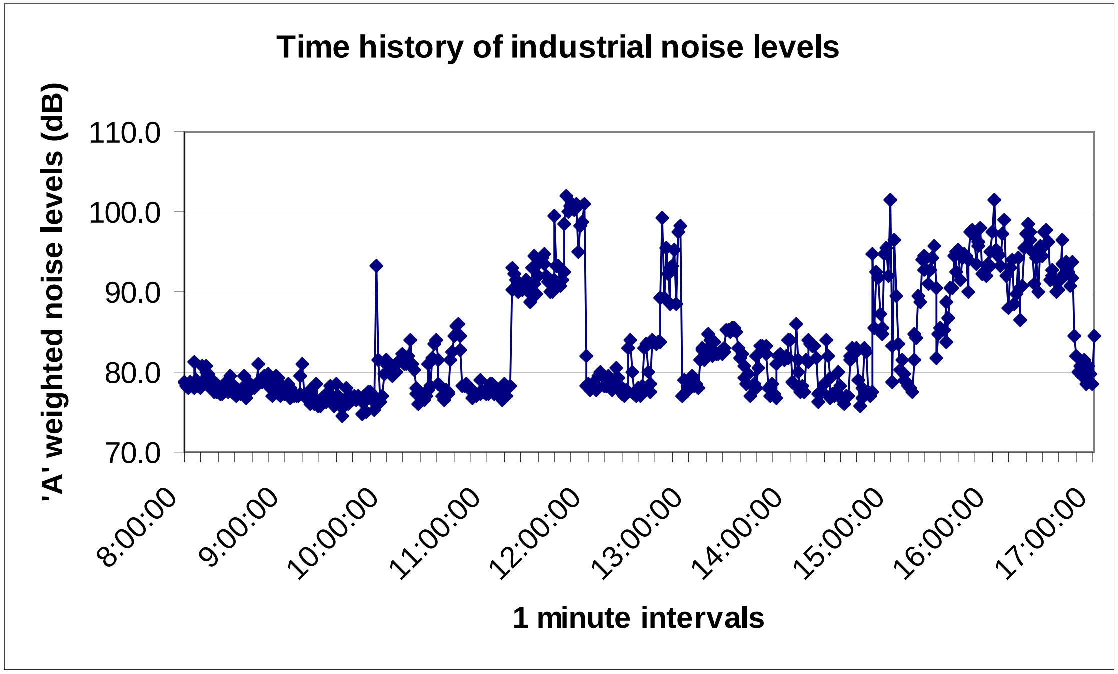


Figure 7. Typical time history variation of industrial noise levels

A measurement made over say a 2 hour period may have maximum value of 110dB and a minimum value of 75dB and take almost any value in between at successive moments in time, but its total energy content could equal say 92dB for a two hour period.

As this equivalent continuous value, L_{eqt}, is arrived at on an energy basis the L_{eqt} may be directly compared against the damage risk criteria by normalising it to a standard 8-hour working day to give an L_{eq8}. This is reflected in the ISO/ACGIH methodology and may be achieved by the relationship:

$$L_{eq8} = L_{eqt} - 10\log(8/t)$$

where t is the time over which the Leq was actually measured in hours and assumes the remainder of the period was at an insignificantly low level.

In the case of measurements according to the OSHA regulations a similar concept is applied. However, in this case it is the time average level Lavg that is used as the equivalent continuous level in calculations. This unit has to be measured in a different way from the more universal Leq unit since it requires the measuring instrument to be set to the Slow time weighting and to have the exchange rate factor (Q) set to a doubling rate of 5 dB. In comparison to the ISO/ACGIH method where the Leq is not affected by the selection of either the standardized Slow or Fast settings of a sound level meter and the Q value is essentially set at 3 dB according to the equal energy principle the US OSHA method is usually considered to be less conservative than for ISO/ACGIH measurements.

Although the equivalent continuous level L_{eq} (or the Lavg) is an average value over time its calculation is complicated by the logarithmic nature of the decibel scale. Being an energy average the ISO/ACGIH method fits in well with the equal energy damage risk criteria and it is therefore possible to use L_{eq} values in place of the steady values given on the sound level axis of Figure 6.

In the calculation of L_{eq} the higher levels have much greater effect on the resultant level than would at first appear. This is apparent from the rapid reduction in permitted exposure as the level increases. (see Appendix A). In the case of measurements in the US, where the OSHA regulations are mandated, more noise can be tolerated for a given period of time compared with the ISO/ACGIH method. There is continued discussions amongst those with a stake in the outcome that at some time in the future the US legislation will fall into line with the rest of the world but for the moment a different set of formulae must be used to calculate (or measure directly) the exposure of an American worker from noise in the workplace.

Among a typical population the spread of personal susceptibility to noise induced problems is quite wide and there will, therefore, be a variation in the degree of hearing loss observed following a fixed noise exposure. Even at the lower end of the recommended noise exposure scale it is, therefore, necessary to keep an eye open for the more noise sensitive subjects who could suffer a substantial injury that may well be actionable at common law even though the noise levels were within the statutory recommendations. Regular audiometric examinations are therefore an important part of a hearing conservation programme as they provide definitive proof as to the efficiency of the measures taken.

Compliance with a 90dB per day criteria (taken as a standard period of exactly 8 hours in both the US and the rest of the world) will result in approximately 25% of employees acquiring a noticeable hearing problem after a lifetime's employment of 40 working years. This gives a measure of the wide range of susceptibility among individuals to noise induced hearing problems. To protect this large minority proposals have recently been enacted in the EU to reduce the daily noise exposure to 85dB L_{eq8} per working day. Indeed some countries have already introduced even lower levels than this for some work places, and action levels of around 80dB L_{eq8} are commonly discussed.

There is, however, little evidence of significant noise induced loss at levels below 80dB L_{eq8}. In the USA the OSHA regulations require that the measurement instrument be constructed in such a way as to reject noise levels of less than 80 dB in the overall calculation of noise dose. This is the, so-called, Threshold level found typically in personal monitoring instruments used for making measurements according to the OSHA recommendations as far as assessments of individuals in a Hearing Conservation Program (HCP) are concerned.

In the ISO regulations all noise levels must be considered and usually it is the lower level of the measurement range (typically around 70 dB) in the instrument that provides a “threshold” below which no noise levels are included in the overall result. In any case, the affect of the noise levels below 80 dB is usually insignificant when there is a lot of noise between 80 and 90 dB as is typically found in many industrial situations.

For noise dose readings where the sound level is very high there is a risk that a single loud sound will cause instantaneous damage to the ears, i.e. rupturing the eardrum etc. There is, therefore, an upper limit normally placed upon the sound pressure levels to which employees may be exposed. In the ISO “world” this is currently set as 135dB (recently reduced from 140dB) and is a ‘C’ frequency weighted instantaneous peak value. (In the regulations this used to be referred to as a limit of 200 Pa, however, since most measurements are carried out with an instrument calibrated in decibels not Pascals the equivalent value of 140 dB is usually used).

In the US OSHA standards an un-weighted peak level is specified. This would be written as 140 dB (Lin) to signify that no frequency weighting is applied to the measured peak level. Since about the turn of the new century instrument standards now specify a new “Z” (or zero) frequency weighting rather than the Linear weighting so a L_{Zpk} limit is now measured and reported for any peaks that may occur. In any case, it is not recommended to use the normal ‘A’ weighting to measure the peak level of impulsive noise sources since this will seriously attenuate the low frequency content that may be present in the signal.

Hearing conservation programme

The first requirement of a hearing conservation programme is to establish who is at risk. This entails measuring the noise levels at various parts of the work place and calculating resultant personal noise exposures. Once the risk groups have been identified, action must be taken to reduce their exposure to safe levels. This should be by reduction of noise levels at source but where this is not practical then the exposure duration should be restricted, or personal protection equipment issued.

When a situation is reached where each individual employee is exposed to levels below the damage risk criteria in use, then from time to time monitoring checks need to be made to ensure noise levels have not increased. This should also be done so that the more noise susceptible employees are not being harmed by the so-called "permitted" levels.

The question to be considered is what do the various regulations actually require in terms of triggering actions to begin a hearing conservation program? On this topic there is general agreement on both sides of the Atlantic in that an 8-hour continuous noise level of 85 A-weighted dB acts as the point at which duties must be undertaken to protect workers hearing. In the ISO terminology this is called the "First Action Level". In OSHA terminology this represents the 50% daily dose level based on 90 dB for 8 hours as the primary noise criterion limit or Permitted Exposure Level (PEL). In this case the HCP action level is 85 dB(A).

It should be noted that noise dosimeters can often be set for a different criterion level to represent the 100% figure. If a dosimeter is set to measure with a criterion level of 85 dB for 8 hours then this will give a reading of exactly 100%. Caution should be exercised whenever dose% values are quoted since it is imperative to know to what value the 100% value is set in order to avoid potential confusion when quoting noise doses in percentage terms.

A good hearing conservation programme will have the following areas of attention:

- reduction of exposure limits to: $L_{Aeq\ (8h)}$ (or TWA) of 90dB or less;
- absolute maximum acoustic pressure of less than 135 dB peak for ISO or 140 for OSHA. This condition is unlikely to be exceeded if the A weighted peak level is not greater than 130dB if the meter does not have a linear peak capability;
- a periodic noise inspection of the whole site;
- regular noise surveys of all noise zones (areas over 85dB);
- noise reduction programme for any noisy machinery and processes;
- provision of adequate hearing protectors in zones where the noise cannot be controlled;
- keeping records of the noise exposure of all affected employees;
- individual audiometric monitoring of employees who use ear protection or are exposed to higher levels for any time during their working day;
- appointment of noise advisors;

An education programme must be introduced which would ensure that employees understand the following:

- risks of hearing damage;
- suitability of hearing protectors;
- warning signs and designation of high noise zones;
- correct fitting and maintenance of personal hearing protectors;
- how to get protectors repaired or replaced;
- what the implications are of partial compliance with the protection programme

Noise measurements

Having decided upon the damage risk criteria that apply in a given set of workplace regulations, it is then necessary to undertake on-site noise measurements to ensure that the limiting levels are not being exceeded. As with many other specialist functions that are being required of the modern Industrial Safety Officer or Occupational Hygienist (Industrial Hygienist), special techniques have to be learnt if the noise levels are to be accurately determined. However, these are soon mastered and will allow all of the front line survey measurements to be undertaken, and the hazardous situations to be identified. The information is then available to implement a hearing conservation programme (HCP) although it may be necessary to call upon the services of an Industrial Noise Control Consultant (or acoustic specialist) in order to determine the best method of reducing levels of noise emitted from machines or noisy processes if it is not immediately obvious.

One key fact that is often overlooked is that a high noise level in an area where nobody works or passes through is not going to cause a problem unless it can be heard by nearby workers. Therefore, it is necessary to determine the noise level actually entering the employee's ears and hence measurements must be made at the actual worker’s normal location in the employee’s hearing zone around their head.

The usual convention is that the subject is absent whilst the measurements are taken when using a hand held sound level meter. Alternatively, a personal noise dosimeter may be employed where members of staff are moving around from place to place. As soon as the first measurements are made it becomes apparent that the levels are probably never going to be constant. They vary as the production process moves through its cycle, with machines coming on and off load, exhausts venting and the movement of the actual product. In deciding what answers to write into the measurement report it is necessary to expand a little more on the actual damage risk criteria.

The limiting level is in fact an “average” level that expresses the continually varying time pattern of the noise level as a single number, i.e. an equivalent steady level that has the same energy level risk factor as the time varying pattern. This is the Time Weighted Average noise level TWA, and it must include all of the usual working time that a worker receives during his or her complete daily exposure to noise in the workplace and then expressed as an 8-hour equivalent value irrespective of the actual length of the working day.

Some examples of different noise climates that can typically be encountered in industrial situations include steady noises, noises with impulses included and completely randomly varying noise climates. These are shown in Figures 8a to c.

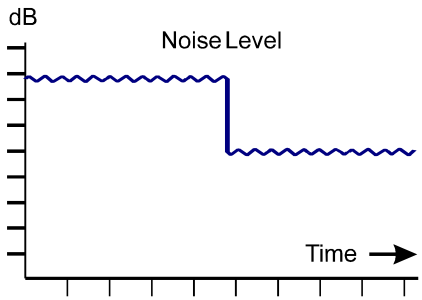


Figure 8a. Steady or stepwise noise climate

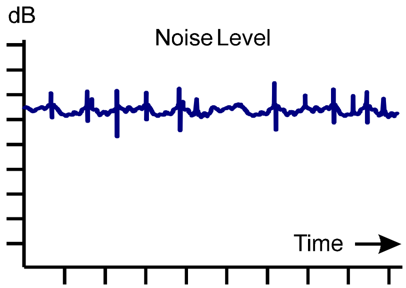


Figure 8b. Noise climate with impulses present

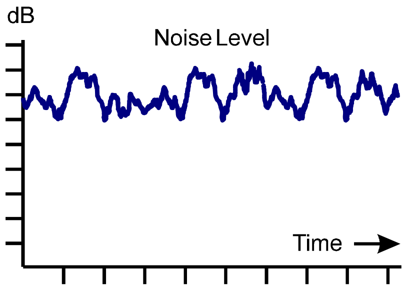


Figure 8c. Completely variable noise climate

Differences exist between the ISO/ACGIH and OSHA measurement methodologies as far as measuring the “time average level”. In ISO/ACGIH terms, the steady noise level is known as the equivalent continuous noise level L_{Aeq}, and was explained in the proceeding section. It is this L_{Aeq} value in dB that has to be measured. In OSHA terms the equivalent steady noise level is known as the Lavg.

There are important differences between these two units if the measurements have to be made manually and these differences need to be taken into consideration carefully whenever “eyeball” averaging is carried out. This method can result in serious errors if the noise is too variable as explained in the following sections.

The simplest sound level meters typically available usually only indicate the momentary sound level in dB(A)’s and it is reasonable to deduce that if the momentary level never exceeds 90 dB then the average value must be less than 90 dB. If the initial survey shows no momentary levels above the limiting value, in practice a margin of safety of say 3dB would be taken, then the area can be considered safe, and no further action need be taken.

Even a simple sound level meter such as that shown in Figure 9 with a maximum hold feature can be used to “capture” the highest reading for ease of use in the case where the operator was not watching the display all the time during the measurement. Reference should, however, be made to the section dealing with impulsive and transient noises as these types of noises are not very accurately measured by simple instantaneous reading sound level meters.

Figure 9. The CEL-240 Simple sound level meter for spot checks

The effect of the sound within the working environment must be taken into account by considering the type of sound field that may be encountered when making measurements during a survey. Figure 10 below shows these effects.

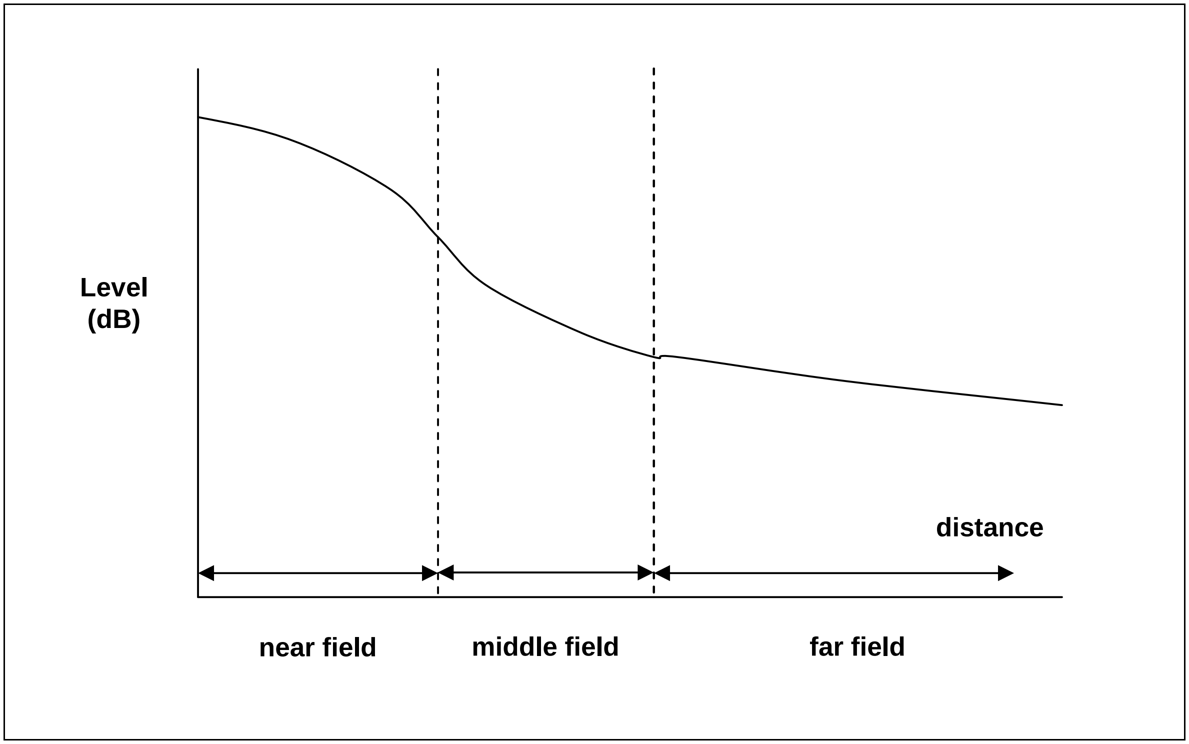


Figure 10. Free and random sound fields.

The type of sound field in which the subject is located can be acoustically free or reverberant conditions. In the open air or in large spaces, where the subject is close to the source, then free field conditions exist and the relative distances between the subject and the source affect the levels. In such situations the level has to be averaged in space and time as the subject moves about following their usual work pattern. It is necessary to pay particular attention to those occasions when he or she moves very close to the source, during an inspection procedure for example, as then small changes in distance between a worker and a noise source can result in large changes in the measured noise level.

Inside buildings away from the direct noise sources, reverberant conditions usually exist. This is where the sound field is made up from the multiple cross reflections between the walls and ceilings resulting in almost the same level at all points in the room. In these conditions noise measurements are more straightforward. When pure tones are present, however, it is necessary to watch carefully for standing waves that can develop causing clearly defined maxima and minima between opposing reflective surfaces.

In typical factory spaces free field conditions always exist close to the sources whilst reverberant conditions usually exist further away. The transition point between the areas where the direct sound dominates and that dominated by the reflected sound is known as the reverberation radius and this distance may be calculated from knowledge of the acoustic loss factor of the area. These sorts of details are beyond the scope of this booklet but are available in architectural acoustics textbooks.

Within the reverberation radius it is necessary to average in space and time making personal noise dose meters (or integrating sound level meters) the best choice, whilst at greater distances conventional sound level meters may be more convenient. It is often adequate to survey an area with a sound level meter to determine if the levels are constant at different positions.

After considering these results with general observations of the locations of the source and nearby reflective surfaces the type of sound field can be determined. In situations where the noise level is varying about or above the limiting value then the L_{Aeq} (or L_{avg}) value should be determined. This is best carried out using an integrating (or time averaging) sound level meter for ease of reading the result.

Figure 11. The CEL-320S Integrating Convertible sound level meter (left) and the CEL-244 Integrating sound level meter (right)

When the value indicated on the noise meter set to 'Slow' time constant varies over a span of less than +/-2 dB (or 4dB total) about a nominal value, the L_{Aeq} (or L_{avg}) may be determined by visually averaging the excursions of the meter. Due to the logarithmic base to the dB scale, large errors occur if visual averages are taken over wider spans than about 3 or 4 dB.

It may be that the noise source has a number of distinct modes, each producing a characteristic level. In these cases the meter may be visually averaged (for 4dB excursions) only for each mode and the duration at each level determined. These individual levels may then be combined using the formulae given in the ‘Damage Risk Criteria' section.

Sometimes it can be more difficult to know the actual duration of a noise exposure than it is to measure and estimate its level. Knowledge of standard times for certain tasks will assist in estimating the time factor to use for different parts of this “level x time” calculation.

It can soon be seen that where there are a number of individual steps in the noise profile or the noise continually varies by more than 4dB then more advanced methods must be used to determine the L_{Aeq} or L_{avg} value. Over the years a number of methods have been proposed based upon statistical analysis of the dynamic time history of the sound pressure.

Nowadays, thanks to microprocessor based instrumentation, simple, direct reading, 'integrating' sound level meters are available that indicate the L_{Aeq} (or L_{avg}) value directly. The instruments shown in Figure 11 are examples of low cost integrating sound level meters that can give an average result during the measurement. With these low cost instruments it is only necessary to monitor the work station long enough to allow the 'average' value to stabilise over a representative number of duty cycles of the noise source in question. The answer obtained may then be directly compared against the damage risk criterion.

Measurement of impulsive noise

Impulsive noise presents special measurement problems, firstly because the very rapid rates of change between widely spaced points are difficult for simple basic instruments to follow and secondly because the higher levels are very important in the calculation of the L_{Aeq} (or L_{avg}) value (permitted daily exposure at 130dB is only 2.72 seconds for the equal energy or Q = 3 exchange rate and only 112.5 seconds for the OSHA defined Q = 5 exchange rate). When impulsive noise is present it is necessary to use integrating meters complying with IEC-61672 or IEC-804 (or ANSI S1.43). These have significantly better performance than conventional sound revel meters (complying only with IEC-651 or ANSI S1.4) when it comes to handling impulsive noises.

There is some evidence to suggest that the damage risk is higher when the energy immission is delivered in an impulsive form and to take account of this several forms of impulse weighting of the measurements have been proposed. These include the impulse time weighting used to calculate the L_{Aim} average value that is in effect an impulse weighted $L_{Ieq.}$ Alternatively, the L_{tm} regulations found in West Germany are often used for the assessment of impulsive noises. This type of assessment is not as common as measuring the standard L_{Aeq} or the $L_{avg.}$

To date we have only considered workers who stay at the workstation throughout the working day, i.e. they are stationary in a varying noise field. In practice, however, often they move from place to place receiving a different noise level at each workstation. Here again, where there are clearly defined L_{Aeq} (or L_{avg}) levels at each point then a composite L_{Aeq} (or L_{avg}) exposure for the employee can be calculated from knowledge of each individual L_{Aeq} (or L_{avg}) value and by knowing the exposure duration at each noise level. Examples of this procedure are given in the section dealing with damage risk criteria.

Figure 12. The CEL-620 Integrating octave band sound level meter

A modern integrating sound level meter with a very wide dynamic range can be used to measure steady, variable and impulse type noise climates and will accurately capture all the variability in the noise source to give an easy to read answer. Additionally, some instruments such as that shown in Figure 12 can be used to collect the frequency based information in the form of octave band frequency values needed for the accurate determination of control measures or the prescription of the most appropriate hearing protectors.

In general, therefore, we can deal with the operator whose noise exposure varies in time and in space but it can be seen that where the work journey follows a complex route then a personal monitoring device (Personal Noise Dosimeter shown in Figure 13) such as a badge style dosimeter simplifies the measurement procedure and speeds up the collection of data. These personal noise dosimeters (or dose meters) also show considerable improvements in measurement accuracy when the subject is in an acoustically free field and moves close to the noise sources because in such conditions the noise level actually received is highly dependent upon the relative distance from the source.

Figure 13. The CEL-350 dBadge Logging personal noise dosimeter

In these conditions, noise dosimeters should be used to determine the employee's noise exposure. Use of personal noise dosimeters, and in fact all types of averaging instruments, have the effect of producing a single number rating because this is what is needed for comparison against the damage risk criteria. If only the single overall number is available from the instrument it can suppress a detailed understanding of the time pattern variation of complex noise levels. One way to overcome this limitation is to use a “logging” instrument that will save a record of the time history of the noise level that is so vital for understanding what has occurred and how to undertake any noise control operations. The data logging function can be found in many modern personal noise dosimeters and some sound level meters such as those shown in Figures 13 and 14.

Figure 14. The CEL-630 Logging Sound level meter

A basic rule in noise reduction is to go for the loudest sources first and the same is true with the control of personal exposure. If the noisy parts of the work cycle can be identified, then action can be taken to attenuate the source(s) or processes responsible. Data logging the time history profile of the measurements can achieve this in addition to simply obtaining the overall noise level.

In practice these noise profiles are usually short period L_{Aeq} (or L_{avg}) measurements stored every minute (for example) to give 480 separate results over the typical 8-hour working period. Other noise parameters may be collected at the same time for example the maximum noise level or the peak level to monitor the “worst case” conditions.

When better resolution is required to correlate the “noisy spikes” with events occurring in machinery operations many data logging instruments are able to store the time history profiles as fast as 1 second. This will obviously produce many more data points (up to 28,800 for an 8 hour measurement) but this is not usually a problem when results can be downloaded to computer software packages that can manipulate the data easily and quickly.

The topic of noise control is a complete subject in itself and there is no intention to give more than a passing mention in this short document to the many and varied techniques that can be used to reduce unwanted high noise levels. Please consult other more specialist books to review all the available techniques that can be called upon to solve a problem. Remember that the most obvious may not be the best method. Careful analysis should always be undertaken to fully understand the problem before spending any sum of money on a potentially costly solution. This will involve at least a sound level meter with an octave band analysis capability and maybe even third octaves or narrow band capabilities in addition to the measurement of the overall level.

From these individual samples the significantly noisy periods can be determined from the chronological order of the noise exposure and the necessary control actions initiated. An example of such data logged results is shown in Figure 15.

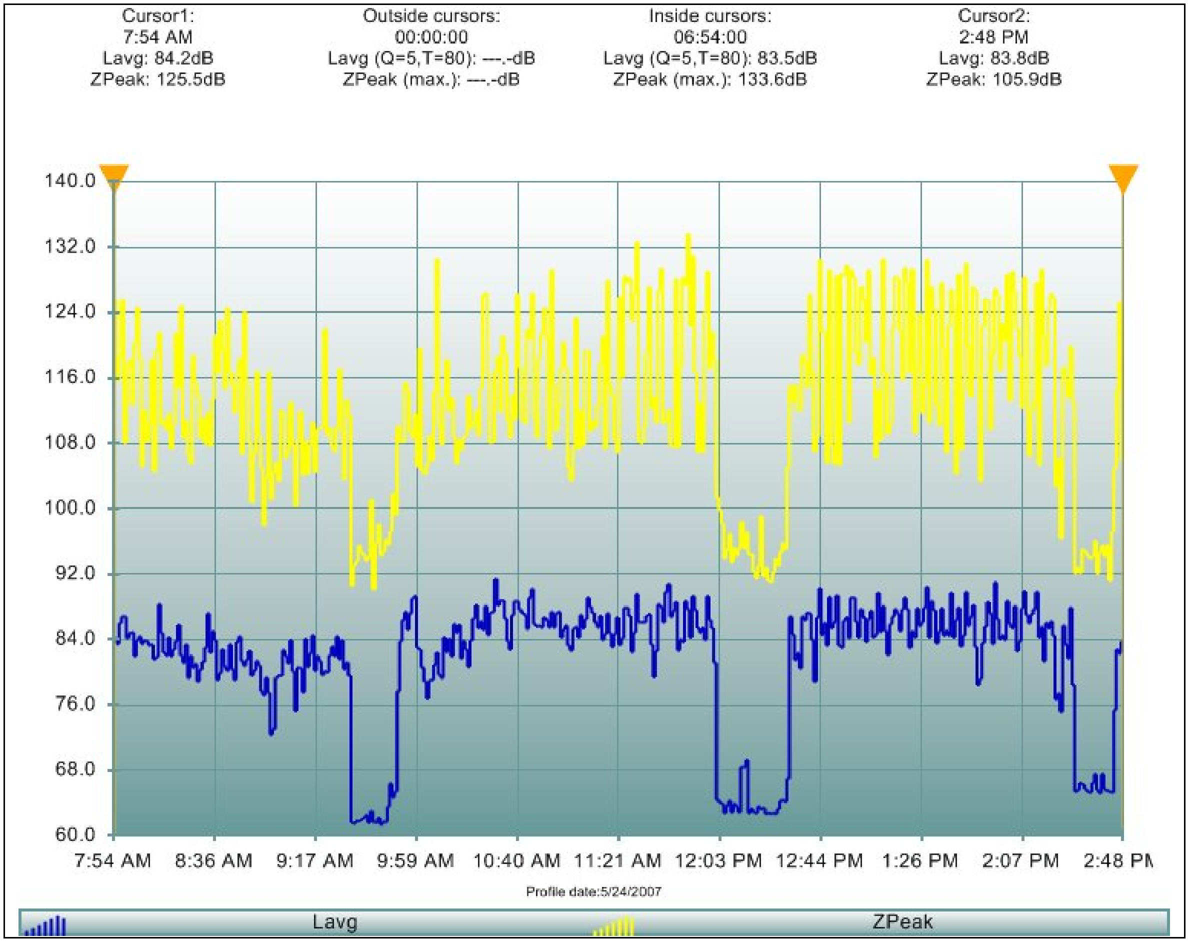


Figure 15. Time history profiles from CEL-350 dBadge logging noise dosimeter showing the average level (blue) and peak levels (yellow) every 1 minute

The cumulative (or overall) result may be calculated from the individual time history period intervals by the relationship;

$$L_T = 10\log[1/n\left[\sum_{1}^{N} 10^{(0.1L_N)}\right]]$$

where -

L_T = cumulative L_{Aeq} value and

L_N = noise level value for the Nth period when all periods are of equal duration.

A similar expression holds when the interval values represent the L_{avg} level calculated using the US OSHA method of data logging. Strictly speaking, in this situation only the values greater than the threshold level of 80 dB should be included in the result for the result according to the Hearing Conservation Amendment (HCA). Any measured L_{avg} intervals that are less than the 80 dB limit must be treated as if they were 0 dB but their time interval would still be used in the final overall calculation.

This relationship shown above can also be used to test the effects of noise control procedures on the total exposure by reducing certain of the controlled periods by the expected attenuation introduced and then reinserting them into the formula to obtain the new average.

To summarise, firstly the working environment has been classified into individual noise zones. Then the exposure of each employee who enters a zone classified at a level above the basic criteria has to be calculated from knowledge of the time spent in each zone. Then the composite noise exposure can be determined a separate assessment made for itinerant workers (foremen, fork truck drivers etc), who have very complex exposure patterns, or those in free field conditions using personal monitoring instruments.

From this information it is possible to identify both those at risk and the measures introduced to reduce their noise exposure and then to monitor their hearing acuity as a check on the effectiveness of the controls put into place.

It is, or course, necessary from time to time to repeat the noise measurement procedure on an audit basis to ensure that nothing has changed for the worse. This should be carried out whenever the job functions change or there is a change in any of the machinery or processes used in the work place. Remember to use the best instrument for the type of noise expected to be encountered i.e. either a sound level meter or a personal noise dosimeter depending on the expected method of worker activity.

Most regulations require that the instrument used for the workplace noise assessments should be calibrated before (and after) the actual measurement to verify that it is functioning correctly and to make sure that the sensitivity of the microphone circuit is correct for the ambient weather conditions. This is because the diaphragm on a microphone is a sensitive transducer and its output signal will vary depending on the local ambient air pressure, temperature and humidity.

The air pressure usually causes the largest variations of displayed level and so that is the reason for bringing the instrument back to its correct setting. Calibrating at the end of an important measurement gives the user confidence that the readings were the same (or within less than 1 dB) both before and after the measurement. It is then usually safe to conclude that no unforeseen drift has occurred while the measurement was taking place.

Noise control & ear protectors

Noise exposure is the product of the noise level and the exposure duration and hence may be controlled by reducing either one of these factors.

Reference to the noise level/exposure duration curve soon shows that it would just not be economically viable to use exposure time as the general variable, although in certain special situations it may be the only possibility. Limiting the noise level reaching the ears is a far more cost effective approach to controlling the hazard. However, the use of personal ear protectors is fraught with potential problems and it is always preferable that the noise should be reduced to the lowest level that is reasonably practicable by engineering methods.

Figure 16. Collecting octave band data around a machine

This objective may be achieved by a reduction of noise at source, obstructing the transmission path to the subject or by controlling the general environment of the receiving space. Noise reduction can provide a more economical solution when weighted against the costs and risks of administering a personal hearing protection programme, and the general principles are explained in more comprehensive work on industrial noise control procedures and need not therefore be explained here.

There are a few situations where control at source is just not possible and in temporary situations whilst engineering work is being undertaken then personal ear protection may be used. Such devices are readily available in many forms and are relatively inexpensive. However, there are problems associated with our reluctance to insert anything into or over our ears, coupled with the fact that the actual protection afforded is not readily apparent.

The actual amount of noise protection is a function of the construction of the defender, the frequency of the noise and the fit of the device to the subject and can differ widely from manufacturer to manufacturer. The attenuation quoted by the supplier is the average of the change in hearing threshold obtained on a number of subjects when the protector is “correctly” fitted. It follows, therefore, that some individuals will receive a lower degree of protection than the average.

The assumed protection that a hearing defender provides, therefore, is taken to be the mean attenuation less one standard deviation in order that due account is taken of these variations in fit. This assumed protection is also very frequency dependent: typically the attenuation provided goes from little or nothing at low frequencies up to potentially 35/40 dB at the higher frequencies.

Because of this variation in attenuation with frequency provided by a hearing protector there are changes in the frequency spectrum of the noise that eventually reaches the ear. It is not possible therefore to add up the various assumed attenuations and average them to provide a single number attenuation rating for the protector. This is because, as we have seen earlier, the ear is more sensitive to some frequencies than others. It is necessary, therefore, to consider each design of protection against the frequency spectrum of the noise in question in order to calculate the dB level inside the ear canal.

This may be achieved by a number of different standard methods. These include the Noise Reduction Rating (NRR), the High Medium Low (HML), the Single Number Rating (SNR) and the full octave band procedure. This last method with octave band information is the most accurate method and is described in more detail below.

First calculate the assumed protection by subtracting the standard deviation from the mean (or average) attenuation for each octave band. If the attenuation is not quoted at low frequencies then it must be assumed to be zero, whilst at high frequencies it is reasonably safe to assume that the attenuation is the same as that given for the highest frequency band quoted.

Hence, for a typical circumaural earmuff fitting around the outside of the ears we would have:

Octave band centre Frequency (Hz)	31	63	125	250	500	1k	2k	4k	8k	16k
Manufacturers data for Mean attenuation (dB)		5	12	19	31	33	35	37	41	41
Manufacturers data for Standard deviation (dB)		6	6	6	7	7	7	8	8	8
Assumed protection (dB)	0	0	6	13	25	26	28	29	33	33

Table 1. Typical manufacturer's data for a common hearing protector

In this case it can be seen that protection will range from 0 dB at 31 Hz to 33 dB at 16 kHz. The rules of statistics indicate that 84% of employees will receive at least this degree of protection. However, it should be realized that even if 84% of the workforce will be expected to receive this level of protection then that still means that 16% of workers will not gain that benefit.

There is a limiting value for attenuation around 50 dB that comes from the "bone conduction" path via the skull into the inner ear. That is sound waves hitting the head that are transmitted direct into the inner ear by vibration through the bones of the head and jaw. This path effectively bypasses the air conduction path and hence the ear defender. To better this level of performance, therefore, it is necessary to completely enclose the head.

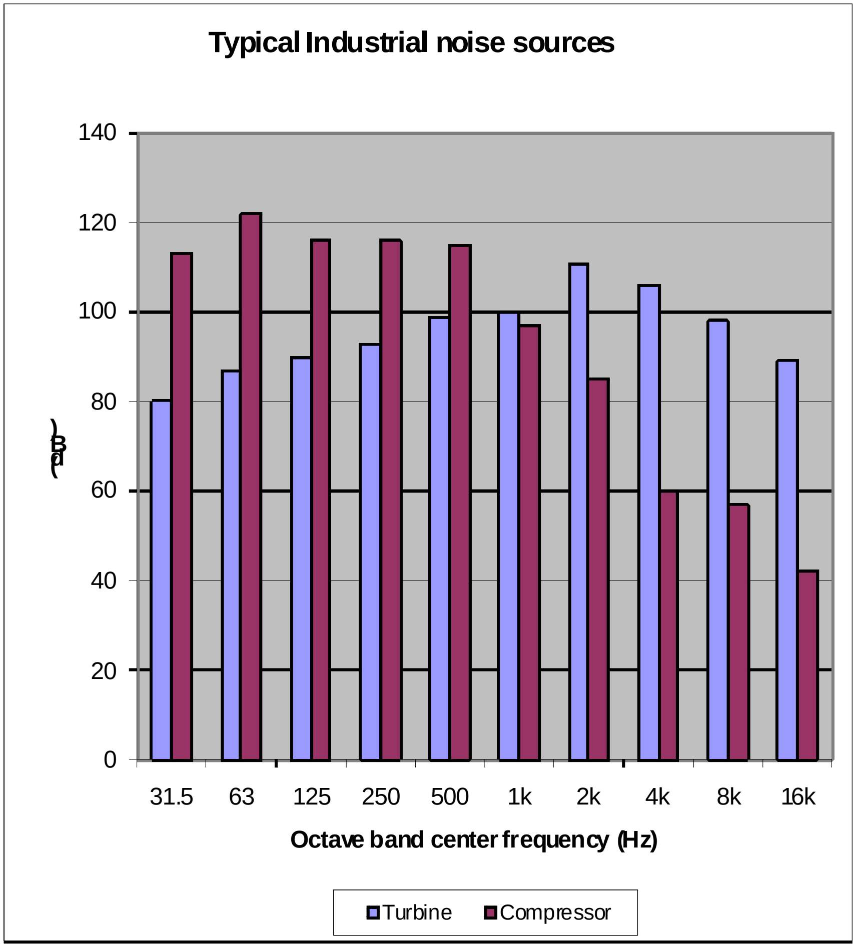


Figure 17. Typical industrial noise spectra from two different sources

Examples of the frequency spectra of a turbine and a compressor are shown in Figure 17. Both of these have a similar overall dB value of 113.6dB and the effect of the same ear protector in each environment is evaluated by way of an example of the procedure to be followed.

First subtract the calculated assumed protection from the measured band level to obtain the octave band levels actually at the ear. Then apply the A-weighting correction and recombine the levels. Hence for the protection afforded to turbine noise of 113.6dB proceeds as follows:

Frequency (Hz)	**31**	**63**	**125**	**250**	**500**	**1k**	**2k**	**4k**	**8k**	**16k**
Octave band levels (dB)	80	87	90	93	99	100	111	106	98	89
Assumed protection (dB)	0	0	6	13	25	26	28	29	33	33
Level at ear (dB)	80	87	84	80	*74*	74	83	77	65	59
A-W correction (dB)	-39	-26	-16	-9	-3	0	1	1	-1	-7
A-W level (dB)	41	61	68	71	71	74	84	78	64	52

Recombine the octave band levels in the last row to obtain the A weighted level at the ear in the form;

$$L_A = 10\log\sum_{1}^{n} 10^{(0.1L_b)}$$

Where L_b is the noise level in each octave band. This gives 85.4dB at the ear and hence the protection in this case is 113.6 - 85.4 = 28.2dB.

If we now consider an operator working near a compressor with the same overall level of 113.6dB but which has an entirely different spectrum then for the same protector a very different answer is obtained.

Frequency (Hz)	31	63	125	250	500	1k	2k	4k	8k	16k
Octave band levels (dB)	113	122	116	116	115	97	85	60	57	42
Assumed protection (dB)	0	0	6	13	25	26	28	29	33	33
Level at ear (dB)	113	122	110	103	90	71	57	31	24	9
A-W correction (dB)	-39	-26	-16	-9	-3	0	1	1	-1	-7
A-W level (dB)	74	96	94	94	87	71	58	32	23	2

Recombining the octave band levels in the last row for this noise source shows an A weighted noise level in the ear canal of 99.8dB. This means that the operator should not work a full shift at this level even when wearing defenders because the noise level will not have been limited sufficiently even when wearing this particular model of ear defender. The ear defenders in this case were providing only 13.8 dB attenuation that was not sufficient for the purpose of protecting the worker.

The important point to note here is that the *same* earmuff will afford different protection to the wearer according to the spectra of the noise being tackled.

Having calculated the effect of the ear protectors in any given noise climate we can now decide if they bring the noise level entering the employee’s ears down below the recommended limiting value. They will of course only do this if they are being worn! Consider the example with the turbine noise source. With the earmuffs on, the subject is exposed to 85dB and with them removed the level at the ear would be 113dB rounded to whole numbers.

Using the relationship given earlier for summing individual exposures the effect of removing the muffs for 6 minutes in an 8-hour measurement would be:

$$\frac{7.9}{24} + \frac{0.1}{0.04} = 2.83$$

***(NB**. 6 min = 0. l hour. Permitted exposure at 113dB = 0.04hr.)*

What was only a 33% exposure (8/24) has been increased to 283% by simply removing the protector for 1.25% (6/480) of the time. It was calculated earlier that the protector provided 28.2dB attenuation to the turbine noise but it can be shown that the effect of removing it for the short period mentioned above reduces this to a composite 19dB. There is, therefore, good scientific evidence for choosing a device with a lower performance if its comfort factor is such that its utilisation factor is significantly better than the heavy-duty types.

Even if the most effective hearing protector is prescribed there will only be a maximum of 3 dB of attenuation afforded by wearing it if the employee removes it for 50% of the workday. Wearing it for 75% of the day gives only another 3 dB reduction to give 6 dB overall protection. This is illustrated vividly in the table below considering the example of a good 30 dB hearing protector.

% of time removed	100	90	80	70	60	50	40	30	20	10	5	1	0.1
minutes	480	432	384	336	288	240	192	144	96	48	24	4.8	0.5
Protection (dB)	0	0.5	1.0	1.5	2.2	3.0	4.0	5.2	7.0	10.0	13.0	20.0	30.0

Table 2. Effect of removing a hearing protection device for part of the workday

Thus, removing the hearing protector for only 4.8 minutes or 1% (less than 5 minutes in the whole day) only gives a maximum of 20 dB of potential protection for the other 99% of the time it is actually worn.

Types of hearing protector & their use

In typical industrial situations circumaural muffs will realistically provide about 15dB attenuation whilst ear inserts will provide 5 dB to 10 dB. Each has its own particular advantages and problems and must be properly prescribed, maintained and used throughout the noise exposure. Examples of both types are shown in Figures 18 and 19.

 Conforming foam ear plugs	 Ear plugs on a head band

Figure 18. Typical examples of earplugs fitted into the ear canal

Care is needed when recommending re-usable plugs for two reasons: firstly hygiene, as there is always a problem of keeping the plugs clean enough for frequent insertion; and secondly comfort. They can be uncomfortable to wear because the ear canal has to deform to their shape for them to be fully effective. In order to obtain the claimed attenuation they must make good contact with the skin of the ear canal and consequently they must be of the correct size to form an interference fit. They are produced in standard sizes and a trained person is required to ensure the correct fit. Disposable plastic foam plugs are more comfortable to wear as the foam expands to fill the ear canal. They should only be re-used with care and adequate supervision. Operators must be trained on to how to insert the plugs issued to them and on the necessity of good hygiene.

Figure 19. Typical circumaural ear muffs to fit around the outer ear

Earmuffs present different problems because as they are worn external to the ear canal they do not pose quite the same hygiene problems as plugs. The effectiveness is a function of the seal around the ears and this depends upon the cups being pressed against the head and there is, therefore, always a trading relationship between comfort and performance. The sprung headband achieves the seal to the head and the efficiency of the seal can be virtually destroyed by bending the band back to “loosen it” or by wearing certain types of safety glasses or long hairstyles.

The seal is generally made of plastic and this can cause sweating and sometimes more severe medical conditions can be set up particularly in dusty, oily conditions. Hygiene is still important to avoid complications. The issuing of all personal plugs, muffs and replacement parts like the seals for the cups should be recorded. Before muffs are issued for the first time relevant instruction on the importance of adjusting them for correct performance and their hygiene must be given.

Each muff should be checked for suitability for the noise climate and fit to the subject before issue. Earplugs must be fitted by the medical section and must be checked to be the correct size to provide adequate attenuation. The operator should check his own hearing protector for any defects. There should be a regular audit inspection by the issuing authority to ensure the predicted attenuation is being obtained. This may include regular audiometric tests by trained and qualified personnel.

Audiometric testing

Audiometric testing should be performed as part of a training program whenever a new worker joins a company where he is likely to be involved in noisy operations. This will establish the baseline hearing acuity of the individual prior to starting any noisy work and will allow the employer to know how much, if any, hearing loss can be directly attributed to the working pattern of the individual as a result of their exposure to high levels of workplace noise. This initial reference audiometric survey serves as a basis to compare later audiograms that may be obtained during the working lifetime of the employee.

Trained personnel in strictly controlled conditions should carry out an audiometric testing program. It is obvious that no useful information will be obtained by carrying out hearing tests on workers the day after they attended a noisy social event such as car racing or music concerts. At least 14 hours of quiet time should precede any testing to be certain that no temporary threshold shift exists for the subject as a result of exposure to high non-workplace noise levels.

Hearing tests should be carried out in quiet conditions in an environment where the background level will not cause erroneous results. Since testing is carried out over a range of audio frequencies the background noise levels in the booth or room must be assessed using an octave band sound level meter to ensure compliance with national limits where applicable.

The hearing tests consist of the subject sitting in a quiet room isolated from outside influences and disturbances wearing a pair of approved headphones over both ears. The technician in charge of the testing controls the audiometer such that different tones are presented to the subject for each ear separately. The level of the tone applied to each ear is reduced in steps until the subject indicates that it can no longer be heard in the headphone. Pure tones from at least 500 Hz to 6000 Hz are used at the following standard centre frequencies; 500 Hz, 1 kHz, 2 kHz, 3 kHz, 4 kHz, 6 kHz.

The subject receives a series of increasing and decreasing levels to establish a hearing sensitivity level in dB relative to the threshold of hearing at each test frequency for the right ear and the left ear independently. The difference in dB of the hearing level for every frequency of the test compared to the original baseline audiogram is established to determine if there is a shift in the threshold of hearing for the subject. Depending on the outcome of the results of an audiometric test the subject may need to be retested soon after the first test to prove a permanent threshold shift has actually occurred.

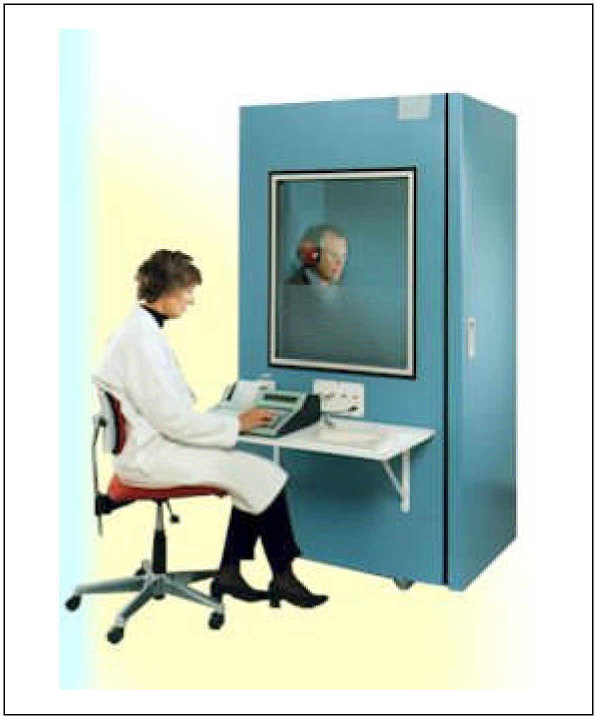


Figure 20. Testing a subject's hearing threshold levels in an audiometric booth

The audiometric assessment is carried out separately for each ear and reported as the amount of hearing loss from a notional norm based on the hearing of a healthy individual. An example of a typical audiogram is shown in Figure 21.

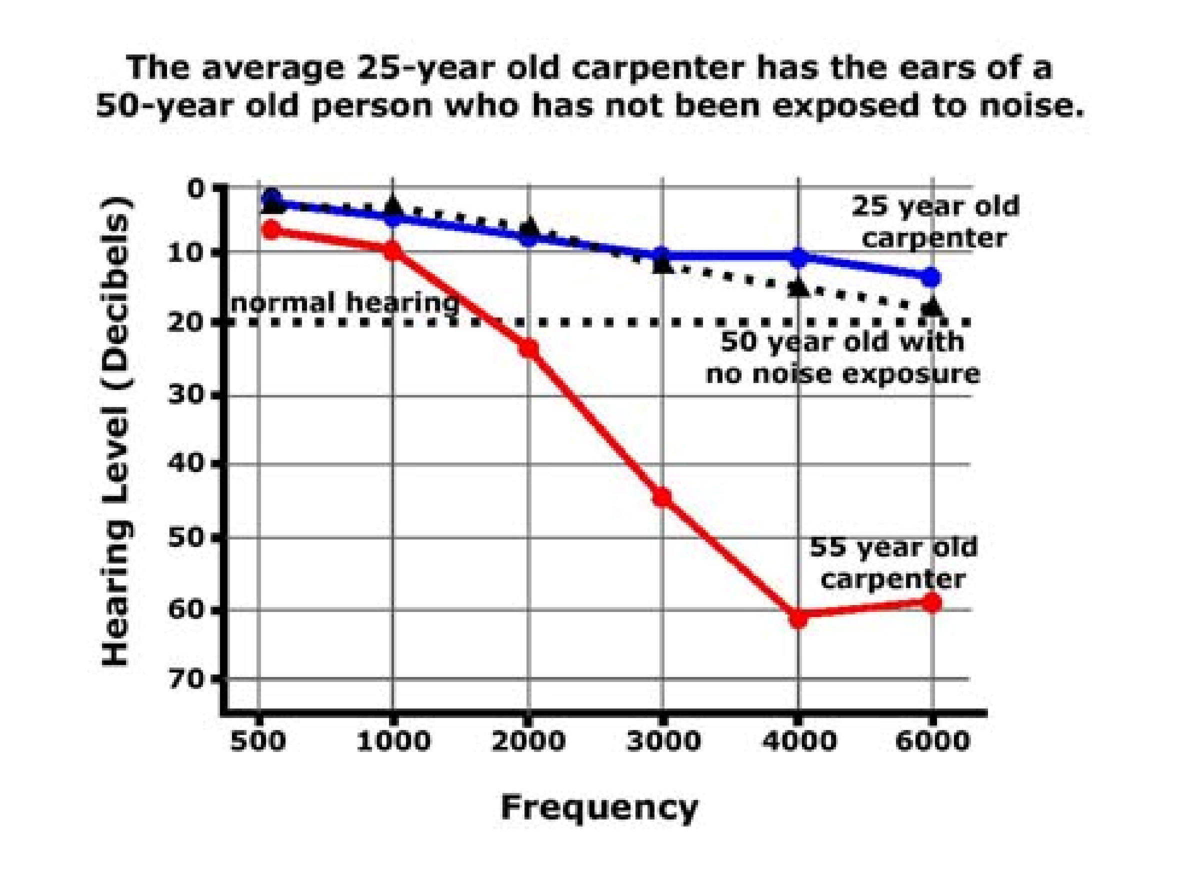


Figure 21. A typical audiometric chart showing the hearing loss of a carpenter

Account is taken of the fact that there will be a “normal” loss of hearing sensitivity that occurs as a result of the aging process. Statistical data exists showing what can be expected for an adult not exposed to high noise exposure in the workplace. This is used to find out how much of the loss of hearing is actually due to high noise levels at work.

Glossary of terms

Common acoustic terms used in this publication

L_{Aeq}	The equivalent continuous A weighted noise level that contains the same amount of noise energy as the actual noise level over the stated period of time where the exchange rate is 3 dB
L_{avg}	The generalised term for the continuous A-weighted noise level that expresses the result as a single number having the same effect as the varying noise over the stated period of time where the exchange rate can be 3, 4, 5 or 6 dB
L_{OSHA}	The generalised term for the continuous A-weighted noise level that expresses the result as a single number having the same effect as the varying noise over the stated period of time where the exchange rate is 5 dB as specified in CFR 1910:95
A weighting	Standardised correction to the frequency spectrum of a sound to mimic the human hear at most normal noise levels
Accuracy	The general term for the level of certainty in the measurements of noise levels by various monitoring instruments according to international standards, usually referred to as type 1 or type 2 under IEC and ANSI standards for noise meters
Action level	A decibel level at which certain duties are triggered in the workplace such as the issuance of hearing protectors to the workers or the marking of noisy areas in a workshop

Amplitude weighting	The number of decibels that a noise level must increase or decrease by to represent twice as much (or half as much) risk to hearing
ANSI	The American National Standards Institute that publish relevant national standards for instruments and procedures used the in measurement of noise
C weighting	Standardised correction to the frequency spectrum of a sound to mimic the human hear at higher noise levels
dB	Abbreviation for the decibel or the unit of amplitude of a certain noise level
Decibel	The unit for describing the sound pressure level of a sound in manageable units based on the ratio of the actual sound pressure to the reference sound pressure of 20 microPa
Dose	The percentage of the actual noise exposure based on an allowable maximum value of the steady 8 hour noise level
Dosimeter	A measurement instrument usually designed as a relatively small personal device that is light weight and can be worn by an individual worker to collect the noise exposure in the workplace
Doubling rate	The number of decibels that a noise level must increase or decrease by to represent twice as much (or half as much) risk to hearing – same as amplitude weighting
Ear muffs	A type of hearing protectors that fit on the sides of the head and completely encircle the outer ears
Ear plugs	A type of hearing protectors that fit inside the pinna of the outer ears usually made of deformable material for comfort and expand to block out the sound arriving at the ear

Exchange rate	The number of decibels that a noise level must increase or decrease by to represent twice as much (or half as much) risk to hearing – same as amplitude weighting
Fast	The time response of 125 milliseconds specified in sound level meter standards, used to more accurately follow rapidly fluctuating signals
Free field	The physical volume in 3 dimensional space where noise levels change according to the inverse square law such that a doubling of distance from a fixed source produces a 6 dB reduction in measured level
Frequency weighting	A correction curve applied to the tonal sounds of noises to take into account the normal human change of sensitivity over the complete audio range, usually A or C frequency weightings are specified
HCP	Hearing conservation program established to protect workers in the workplace from excessively high noise levels and the risk of deafness
Hertz	The unit of frequency expressed as the number of complete variations of a cyclic phenomenon that occur per second, where 1 variation per second is 1 Hz
IEC	The International Electrotechnical Committee
Impulse	The time response of 35 milliseconds for rising levels and 1500 milliseconds for falling levels originally specified in sound level meter standards, sometimes used to emphasise impact or impulsively fluctuating signals
kilo	Abbreviation for 1000 e.g. 1 kHz for 1000 Hz
LEP,d	The decibel equivalent of the total days worth of noise exposure expressed as an 8 hour value

Loudness	The perception of a sound based on its level and frequency content, usually expressed in Sones
Maximum level	The highest sound level measured with a stated time weighting and a stated frequency weighting over a given observation interval
micro	1 millionth of a stated unit of measurement, e.g. 1 microsecond
Minimum level	The lowest sound level measured with a stated time weighting and a stated frequency weighting over a given observation interval
NIHL	Noise induced hearing level of an individual in dB at a specified frequency within the audio range
Octave band	A range of frequencies passed by a filter such that the ratio of the highest to the lowest frequency is 2:1 the audio range is covered by 10 complete octave bands from 31.5 Hz to 16 kHz center frequencies
Pa	Abbreviation of Pascal or N/m^2 the unit of sound pressure
Pascal	The unit of pressure equal to 1 Newton per square metre
Peak	The absolute highest sound pressure of the acoustic wave, can be from the positive or negative part of the input signal waveform
Peak level	The absolute highest reading of the acoustic signal without passing through the r.m.s. averaging circuit, typically an equivalent response time of less than 100 microseconds
PEL	The permitted exposure level for noise that represents the single number equivalent level of hazard for the day
Presbycusis	The natural loss of the hearing acuity as a result of aging

Projected dose	The estimate of the total noise dose at the end of a standard working day based on the actual measured level accumulated so far, usually projected for a standard 8 hour day
Reverberant field	The behaviour of an acoustic field where the sound is reflected by obstacles such as floors and walls such that the dissipation of the measured level is prevented from following the normal spreading out from the source that occurs in a free field
Slow	The time response of 1 second specified in sound level meter standards, used to facilitate visual averaging of relatively steady signals
Sound exposure	The single number noise energy that represents the total noise measured in terms of the product of the square of the instantaneous sound pressure and time of exposure (Pa^2sec)
Sound exposure level	The decibel equivalent of the sound exposure expressed as the noise level that would exist for only 1 second to produce the same amount of energy as the actual varying noise
Sound level meter	A measurement device with accuracy specified by the relevant IEC or ANSI standards for the correct measurement of noise levels
Threshold of hearing	A sound pressure level of 0 dB at a frequency of 1 kHz
Time weighting	The averaging time or response of a sound level meter usually specified as Slow, Fast, Impulse or Peak

TTS	Temporary threshold shift, the short term loss of hearing usually caused to workers who are exposed to high noise levels at the workplace when the hearing can recover to previous sensitivity once the high noise levels are removed
TWA	The time weighted average level in 'A' weighted dB that represents the same equivalent 8 hour continuous noise level as the actual fluctuating noise during the complete work day

Appendices

Appendix A

Sound levels and reference duration for equivalent noise dose

'A' weighted sound level	US OSHA - Lavg based Reference Duration			ISO - Leq based Reference Duration		
dB	*Hour*	*min*	*sec*	*Hour*	*min*	*sec*
80	32.000	1920.000	115200.000	80.635	4838.097	290285.810
81	27.858	1671.457	100287.425	64.000	3840.000	230400.000
82	24.251	1455.088	87305.274	50.797	3047.810	182868.601
83	21.112	1266.728	76003.656	40.317	2419.048	145142.905
84	18.379	1102.750	66165.025	32.000	1920.000	115200.000
85	16.000	960.000	57600.000	25.398	1523.905	91434.301
86	13.929	835.729	50143.712	20.159	1209.524	72571.452
87	12.126	727.544	43652.637	16.000	960.000	57600.000
88	10.556	633.364	38001.828	12.699	761.953	45717.150
89	9.190	551.375	33082.513	10.079	604.762	36285.726
90	8.000	480.000	28800.000	8.000	480.000	28800.000
91	6.964	417.864	25071.856	6.350	380.976	22858.575
92	6.063	363.772	21826.319	5.040	302.381	18142.863
93	5.278	316.682	19000.914	4.000	240.000	14400.000
94	4.595	275.688	16541.256	3.175	190.488	11429.288
95	4.000	240.000	14400.000	2.520	151.191	9071.432
96	3.482	208.932	12535.928	2.000	120.000	7200.000
97	3.031	181.886	10913.159	1.587	95.244	5714.644
98	2.639	158.341	9500.457	1.260	75.595	4535.716
99	2.297	137.844	8270.628	1.000	60.000	3600.000
100	2.000	120.000	7200.000	0.794	47.622	2857.322
101	1.741	104.466	6267.964	0.630	37.798	2267.858
102	1.516	90.943	5456.580	0.500	30.000	1800.000
103	1.320	79.170	4750.228	0.397	23.811	1428.661

'A' weighted	US OSHA - Lavg based			ISO - Leq based		
sound level	Reference Duration			Reference Duration		
dB	*Hour*	*min*	*sec*	*Hour*	*min*	*sec*
104	1.149	68.922	4135.314	0.315	18.899	1133.929
105	1.000	60.000	3600.000	0.250	15.000	900.000
106	0.871	52.233	3133.982	0.198	11.906	714.330
107	0.758	45.471	2728.290	0.157	9.449	566.964
108	0.660	39.585	2375.114	0.125	7.500	450.000
109	0.574	34.461	2067.657	0.099	5.953	357.165
110	0.500	30.000	1800.000	0.079	4.725	283.482
111	0.435	26.117	1566.991	0.063	3.750	225.000
112	0.379	22.736	1364.145	0.050	2.976	178.583
113	0.330	19.793	1187.557	0.039	2.362	141.741
114	0.287	17.230	1033.829	0.031	1.875	112.500
115	0.250	15.000	900.000	0.025	1.488	89.291
116	0.218	13.058	783.496	0.020	1.181	70.871
117	0.189	11.368	682.072	0.016	0.938	56.250
118	0.165	9.896	593.779	0.012	0.744	44.646
119	0.144	8.615	516.914	0.010	0.591	35.435
120	0.125	7.500	450.000	0.008	0.469	28.125
121	0.109	6.529	391.748	0.006	0.372	22.323
122	0.095	5.684	341.036	0.005	0.295	17.718
123	0.082	4.948	296.889	0.004	0.234	14.063
124	0.072	4.308	258.457	0.003	0.186	11.161
125	0.063	3.750	225.000	0.002	0.148	8.859
126	0.054	3.265	195.874	0.002	0.117	7.031
127	0.047	2.842	170.518	0.002	0.093	5.581
128	0.041	2.474	148.445	0.001	0.074	4.429
129	0.036	2.154	129.229	0.001	0.059	3.516
130	0.031	1.875	112.500	0.001	0.047	2.790
131	0.027	1.632	97.937	0.001	0.037	2.215
132	0.024	1.421	85.259	0.000	0.029	1.758
133	0.021	1.237	74.222	0.000	0.023	1.395
134	0.018	1.077	64.614	0.000	0.018	1.107

'A' weighted	US OSHA - Lavg based			ISO - Leq based		
sound level	**Reference Duration**			**Reference Duration**		
dB	*Hour*	*min*	*sec*	*Hour*	*min*	*sec*
135	0.016	0.938	56.250	0.000	0.015	0.879
136	0.014	0.816	48.968	0.000	0.012	0.698
137	0.012	0.710	42.630	0.000	0.009	0.554
138	0.010	0.619	37.111	0.000	0.007	0.439
139	0.009	0.538	32.307	0.000	0.006	0.349
140	0.008	0.469	28.125	0.000	0.005	0.277

Notes –

The OSHA – Lavg calculations are based on an exchange rate (Q factor) of 5 dB for the doubling of risk and the ISO – Leq calculations are based on an exchange rate (Q factor) of 3 dB for the doubling of risk. In the USA NIOSH recommends using the 3 dB doubling rate for noise exposure assessments and calculations.

Appendix B

Conversion from 8 hour Projected Noise Dose % to 8 hour TWA and LEP,d equivalent continuous sound levels

8 hour projected	US OSHA	ISO
noise dose	TWA (Q=5)	LEP,d (Q=3)
%	*dB*	*dB*
10	73.4	80.0
15	76.3	81.8
20	78.4	83.0
25	80.0	84.0
30	81.3	84.8
35	82.4	85.4
40	83.4	86.0
45	84.2	86.5
50	85.0	87.0
55	85.7	87.4
60	86.3	87.8
65	86.9	88.1
70	87.4	88.5
75	87.9	88.8
80	88.4	89.0
81	88.5	89.1
82	88.6	89.1
83	88.7	89.2
84	88.7	89.2
85	88.8	89.3
86	88.9	89.3
87	89.0	89.4
88	89.1	89.4
89	89.2	89.5
90	89.2	89.5
91	89.3	89.6
92	89.4	89.6

8 hour projected	US OSHA	ISO
noise dose	TWA (Q=5)	LEP,d (Q=3)
%	*dB*	*dB*
93	89.5	89.7
94	89.6	89.7
95	89.6	89.8
96	89.7	89.8
97	89.8	89.9
98	89.9	89.9
99	89.9	90.0
100	90	90
101	90.1	90.0
102	90.1	90.1
103	90.2	90.1
104	90.3	90.2
105	90.4	90.2
106	90.4	90.3
107	90.5	90.3
108	90.6	90.3
109	90.6	90.4
110	90.7	90.4
111	90.8	90.5
112	90.8	90.5
113	90.9	90.5
114	90.9	90.6
115	91.0	90.6
116	91.1	90.6
117	91.1	90.7
118	91.2	90.7
119	91.3	90.8

8 hour projected noise dose	US OSHA TWA (Q=5)	ISO LEP,d (Q=3)
%	*dB*	*dB*
120	91.3	90.8
125	91.6	91.0
130	91.9	91.1
135	92.2	91.3
140	92.4	91.5
145	92.7	91.6
150	92.9	91.8
155	93.2	91.9
160	93.4	92.0
165	93.6	92.2
170	93.8	92.3
175	94.0	92.4
180	94.2	92.6
185	94.4	92.7
190	94.6	92.8
195	94.8	92.9
200	95.0	93.0
210	95.4	93.2
220	95.7	93.4
230	96.0	93.6
240	96.3	93.8
250	96.6	94.0
260	96.9	94.1
270	97.2	94.3
280	97.4	94.5
290	97.7	94.6
300	97.9	94.8
310	98.2	94.9
320	98.4	95.1
330	98.6	95.2
340	98.8	95.3

8 hour projected noise dose	US OSHA TWA (Q=5)	ISO LEP,d (Q=3)
%	*dB*	*dB*
350	99.0	95.4
360	99.2	95.6
370	99.4	95.7
380	99.6	95.8
390	99.8	95.9
400	100.0	96.0
410	100.2	96.1
420	100.4	96.2
430	100.5	96.3
440	100.7	96.4
450	100.8	96.5
460	101.0	96.6
470	101.2	96.7
480	101.3	96.8
490	101.5	96.9
500	101.6	97.0
510	101.8	97.1
520	101.9	97.2
530	102.0	97.2
540	102.2	97.3
550	102.3	97.4
560	102.4	97.5
570	102.6	97.6
580	102.7	97.6
590	102.8	97.7
600	102.9	97.8
610	103.0	97.9
620	103.2	97.9
630	103.3	98.0
640	103.4	98.1
650	103.5	98.1

8 hour projected noise dose	US OSHA TWA (Q=5)	ISO LEP,d (Q=3)
%	*dB*	*dB*
660	103.6	98.2
670	103.7	98.3
680	103.8	98.3
690	103.9	98.4
700	104.0	98.5
710	104.1	98.5
720	104.2	98.6
730	104.3	98.6
740	104.4	98.7
750	104.5	98.8
760	104.6	98.8
770	104.7	98.9
780	104.8	98.9
790	104.9	99.0
800	105.0	99.0
810	105.1	99.1
820	105.2	99.1
830	105.3	99.2

8 hour projected noise dose	US OSHA TWA (Q=5)	ISO LEP,d (Q=3)
%	*dB*	*dB*
840	105.4	99.2
850	105.4	99.3
860	105.5	99.3
870	105.6	99.4
880	105.7	99.4
890	105.8	99.5
900	105.8	99.5
910	105.9	99.6
920	106.0	99.6
930	106.1	99.7
940	106.2	99.7
950	106.2	99.8
960	106.3	99.8
970	106.4	99.9
980	106.5	99.9
990	106.5	100.0
1000	106.6	100.0

Notes –

For noise dose readings outside of the range shown in the table above the relationship between the measured noise dose and the corresponding continuous noise level is given by the following equations;

For 3 dB exchange rate (ISO, NIOSH, ACGIH protocols)

$$LEP,d = 10\log(D/100) + 90$$

For 5 dB exchange rate (OSHA, MSHA protocols)

$$TWA = 16.61\log(D/100) + 90$$

where LEP,d and TWA are in A-weighted dB and D is the measured 8 hour total (or projected) noise dose in % based on the criterion level of 90 dB.

Appendix C

Addition and subtraction of decibels

Two separate decibel values can either be added together using logarithmic calculators or by the use this table of corrections as described below. For noises that are more than 10 dB apart the addition of the lower level to the higher one will have a negligible effect on the resultant level so it can usually be ignored. Corrections are shown for two noises up to 15 dB apart in the table below.

	Addition	**Subtraction**
Difference between the two noise levels (dB)	**Add this correction to the higher noise level (dB)**	**Correction to be subtracted from higher of the levels (dB)**
0	3.0	At least 10
1	2.5	6.9
2	2.1	4.3
3	1.8	3.0
4	1.5	2.2
5	1.2	1.7
6	1.0	1.3
7	0.8	1.0
8	0.6	0.7
9	0.5	0.6
10	0.4	0.5
11	0.3	0.4
12	0.3	0.3
13	0.2	0.2
14	0.2	0.2
15	0.1	0.1

Addition of noise levels (Use the second column)

Example

One machine on its own measures 84 dB at a certain position. At the same position a second machine measures 79 dB on its own. What will the effect be of measuring the effect of both machines operating at the same time?

Method

Difference between the two noise levels is 5 dB so the correction from the table above is 1.2 dB. Add this to the higher noise level so the overall measured level for both machines running at the same time will be 85.2 dB.

Subtraction of noise levels (Use the third column)

Example

When trying to establish what the level is of a piece of noisy equipment it is difficult to measure it without all the background being present. A solution is to measure the noise levels with the background only and then with the background and the noise source switched on and running. Subtracting the background level from the total level will give the level of the noisy piece of equipment on its own. Total noise level is 85 dB and the background alone is 78 dB.

Method

The difference between the total noise level and the background noise level alone is 7 dB. Therefore, the difference to be subtracted from the higher total noise is 1 dB, which makes the true noise of the equipment to be 84 dB on its own.

Other Information

Casella CEL also produces quality instruments for the measurement of

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