NOISE: An appraisal of its measurement and of its effects.

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TASMANIA DEPARTMENT OF MINES 1976

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INTRODUCTION

Noise, as defined by the dictionary, is a loud or harsh sound of any kind.

Sound is that sensation produced in the organ of hearing when the surrounding air is set in motion in a manner so as to affect it.

The effect of sound on the ears of individuals varies greatly but can be classed into that which pleases or displeases.

Sounds that please can be broadly defined as music whilst those which displease are called noise. Alternatively, the combination of vibrations is either harmonious or discordant.

Harmonious sounds if amplified too much can have the same effect on the ears as noise.

There are other effects that should be noted and taken into account because of their possible influence on individuals.

Sounds, provided they consist of low frequencies and sufficiently muted, can have the effect of dulling the senses and quite possibly creating a state of languor or sleep.

Experiments have indicated that the driver or passenger in a car if subjected to vibrations having a frequency in the low tens can be affected in a manner similar to symptoms experienced by a sailor when he steps back on land after being at sea in a small boat for some time.

Noise can cause a person to become distressed by its loudness, particularly if tonal in character or by discordance.

There is a human reaction termed an arousal reaction which is generated by stress on the nervous system of individuals due to repeated loud impulse noises acting in a pin pricking manner. For a time the individual can recover from these repeated stresses but a situation will ultimately be reached when the individual gradually loses the ability to recover and so becomes over-stressed and will then become very irritable, probably prepared to quarrel and become violent. A very similar reaction occurs in animals: the reaction of a cat to a sudden loud noise will create three conditions called fright, fight and flight. The fright stage is when the hair becomes erect and the body stiffens whilst the fight is exhibited by the baring of the cat's claws, fangs and hissing and if the cat sees a chance to escape it will flee rapidly. These stages are part of the stress reaction and the human being is affected in a somewhat similar manner.

THE HUMAN EAR

How noise affects a person may be better understood by giving a brief description of how the ear operates.

The human ear may be divided into three main sections termed the outer, middle and inner ear. The structure of its various parts is shown in Figure 1.

Outer Ear

The outer ear consists of three parts, namely the pinna or that external form of the ear protruding outside the head, the auditory canal and

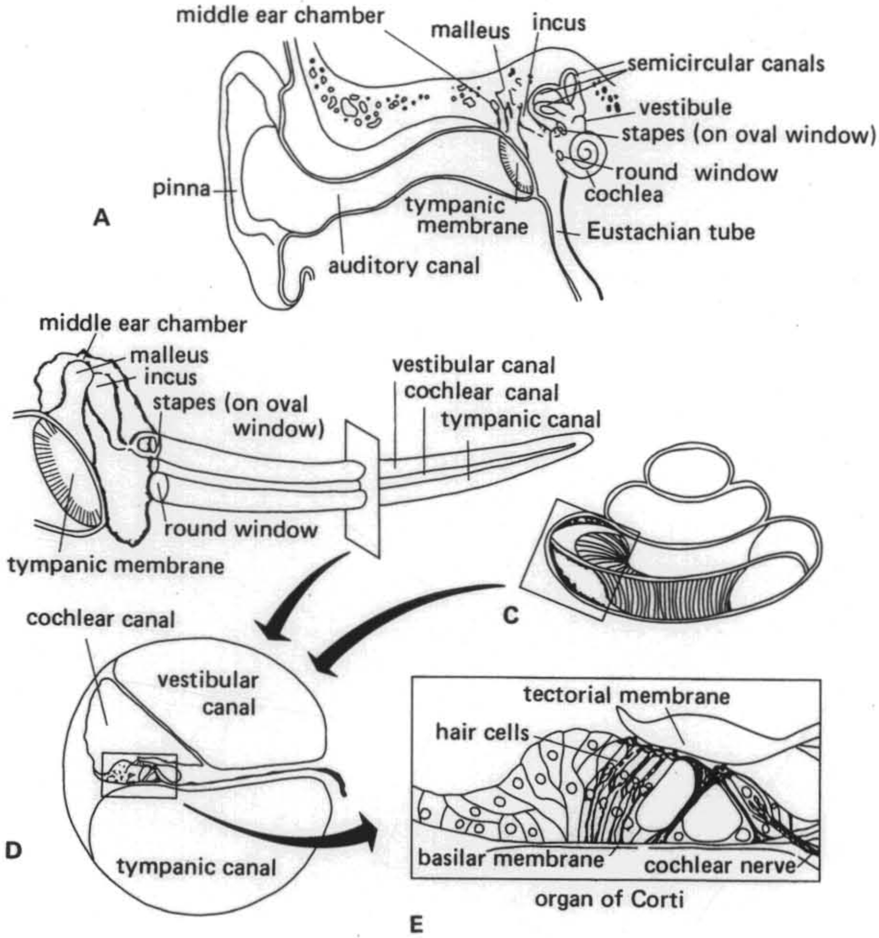


Figure 1. *The human ear. (a) Diagram showing major parts of the outer, middle and inner ear, (b) diagram showing relationship between the middle ear and the cochlea, which has here been uncoiled to show its canal system more clearly, (c) section through the cochlea in its normal coiled state, (d) enlarged cross section through one unit of the coil showing the relationship between the vestibular, cochlear and tympanic canals and the location of the organ of Corti and (e) enlarged diagram of the organ of Corti.*

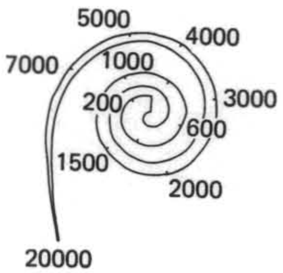


Figure 2. *Basilar membrane, showing positions of greatest response in the frequency range 200-20 000 Hz.*

the tympanic membrane or ear drum.

The pinna concentrates and conducts the sound waves to the auditory canal.

The auditory canal is a tube having a diameter of about 7.5 mm and a length of 25 mm. This tube conducts the sound waves to the tympanic membrane.

The tympanic membrane or ear drum is situated at the end of the auditory canal and vibrates in unison with the sound waves being conducted along the auditory canal.

Middle Ear

This part of the ear is that section between the outer and inner ear.

Contained in this part of the ear are the three bones called the malleus (hammer), incus (anvil) and the stapes (stirrup). The malleus is attached to the tympanic membrane, and the stapes to the oval window of the inner ear. The incus bone is the connecting link between the malleus and the stapes. This chain of bones enables the vibrations set up in the tympanic membrane to be transmitted to the oval window without distortion and in phase but having an amplification in the transmission of between 30 and 60 times.

The middle ear is also connected to the nasal passages of the nose, so that the air pressure is equalised on both sides of the tympanic membrane, by the Eustachian tube. If this tube becomes blocked the tympanic membrane can become distended and the ability of it to vibrate will be impaired and if the pressure difference becomes sufficient the loss will be great enough to prevent hearing.

Inner Ear

The inner ear consists of the oval and round windows, the cochlea and a fluid filling the chamber. The oval window is at one end of the cochlea and the round window at the other end.

Vibrations, in the oval window, create pressure waves in the fluid, contained in the cochlea, and these are transmitted finally to the round window which acts as a dampener.

These pressure waves distort the basilar membrane and this causes the basilar membrane to move and deform the hairs on the basilar membrane by pressing them against the tectorial membrane. This deformation of the sensory hairs produces a generator potential in the hair cells which triggers impulses in the sensory neurons running from the organ of corti to the brain.

If a simple harmonic wave is introduced into the cochlea fluid the basilar membrane is set into vibration over a large part of its length but with the maximum amplitude at a point which moves from the base to the apex as the frequency of the pressure waves increases.

The strength of the sound is interpreted by the number of impulses in the sensory neurons triggered by the basilar membrane whilst the sound frequency is judged, apparently, by the distribution of the activity among the many nerve fibres.

The position of the greatest response for the various sound frequencies is shown in Figure 2.

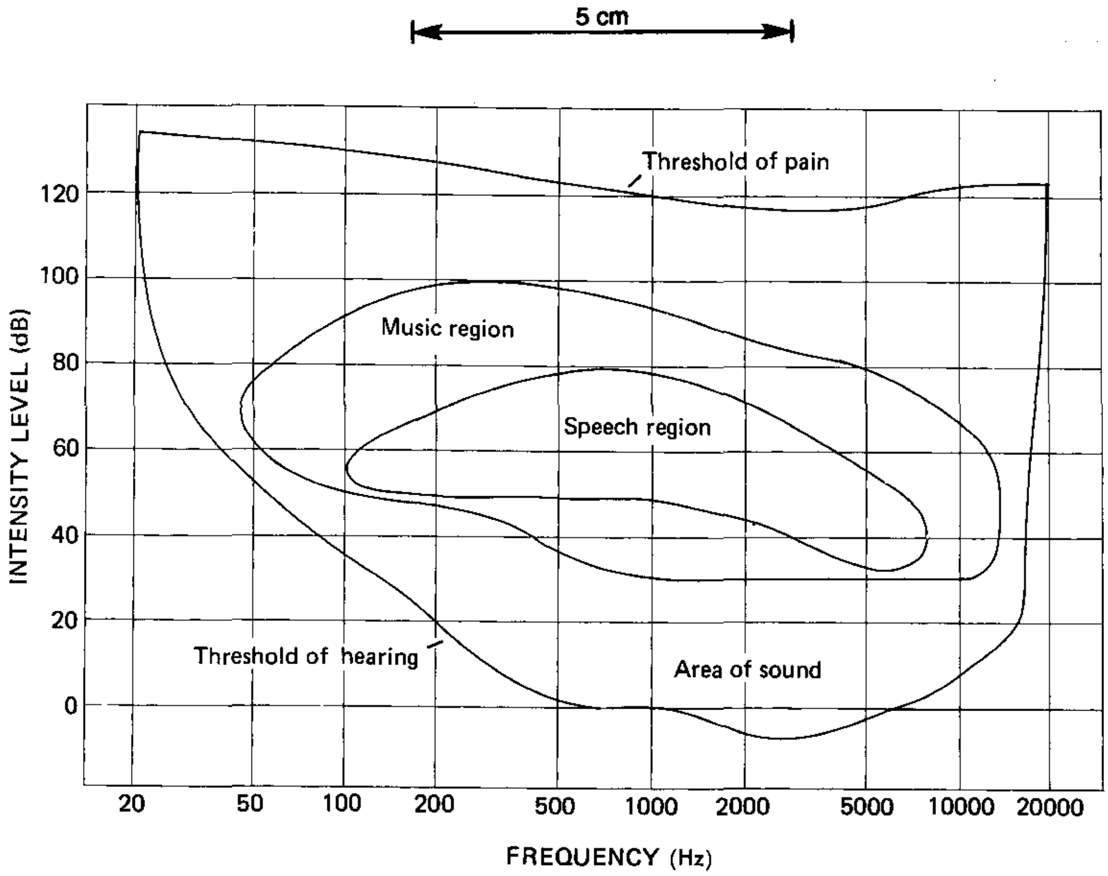


Figure 3. *The range of audibility of the human ear.*

The purpose of the round window is to vibrate in unison with the oval window and to stop pressure waves being reflected back to the oval window.

An individual not only hears sound waves transmitted through the air but also by conduction through the bone structure surrounding and enclosing the ear.

Sound frequencies below 20 Hz cannot be heard by most people and this is called the lower limit of audibility.

There is also an upper limit of audibility because the vibrations above this limit are so rapid that the auditory nerves do not respond to them. This upper limit for most people is about 20 kHz.

HEARING ABILITY

Tests carried out on many people have enabled the range of audibility of the human ear to be established and the results are depicted in the graphs shown in Figure 3.

The sound pressure level for the various frequencies at the threshold of hearing, is greatest at the upper and lower limits of audibility being 100 dB and 110 dB respectively decreasing rapidly to a very low pressure between frequencies of 500 and 5000 Hz (about 0 dB) with a minimum between 2 and 4 kHz.

If the sound pressure level is too high it can cause pain in the ear and this level is called the threshold of pain. The maximum sound pressure that can be tolerated is in the 20 Hz zone (140 dB) but decreasing to a minimum about the 4 kHz frequencies (115 dB) and only slightly increasing to the upper limit of audibility (122 dB).

The music region is much less than the area of sound having lower and upper limits of audibility of approximately 50 Hz - 12 kHz respectively with minimum sound pressure levels decreasing from the 50 Hz frequency to 1 kHz, and then maintaining that minimum to the end of the range. The sound pressure levels being 60 dB at 50 Hz, 30 dB at 1 kHz and 30 dB at 10 kHz. Maximum sound pressure levels for the various frequencies vary also being a minimum of 75 dB at 50 Hz rising to a maximum of 100 dB at 300 Hz and gradually decreasing to 60 dB at 12 kHz.

The speech region is further restricted having upper and lower limits of audibility of 8 kHz and 100 Hz respectively. Minimum sound pressure levels are 50 dB between 100 Hz and 1 kHz decreasing to about 35 dB at 5 kHz and then increasing again to 40 dB at 8 kHz. Maximum sound pressure levels are close to 60 dB at 100 Hz rising to 80 dB at 800 Hz and then decreasing to about 45 dB at 8 kHz.

Tests of the hearing of half a million people were conducted by the Bell Laboratories (U.S.A.) and the results of those tests are shown in Figure 4.

Due to variations in the hearing of people three curves are shown in Figure 4 showing the thresholds of hearing bettered by 5, 50 and 95% of the population.

It is again noted that the sound pressure levels are at a maximum for the upper and lower limit of audibility and a minimum between 2 and 4 kHz.

On the 5% curve the sound pressure level had decreased to a point just below 0.00002 Pa. The figure of 0.00002 Pa has been accepted as the base to which sound pressures for acoustics can be referred and accordingly 0 dB has a value of 0.00002 Pa. As a comparison and to indicate how soft a sound some people can hear is that the thermal noise due to random molecular motion amounts to 0.000005 Pa in the same frequency range so the threshold of hearing of people with acute hearing is very close to the ultimate limitation.

At about 120 dB, at all frequencies, there is a threshold of feeling which is like a tickle in the middle ear, due to the linked bones vibrating against the walls of the cavity containing them. This sensation occurs just before dangerously large vibrations may damage the structure of the inner ear and this threshold of feeling thus serves as a practical upper limit to the range of intensities which the ear can hear.

For most people, acuity of hearing drops steadily with age once a person reaches 20 years, particularly at higher frequencies and by the age of 60 years hearing is likely to be down 5-10 dB at voice frequencies and 25 dB at frequencies greater than 3 kHz.

When hearing tests are being made they should be conducted so that they are not influenced by extraneous sounds as they tend to mask the hearing ability of the person being tested.

Typical masking threshold curves due to noise are shown in Figure 5.

Sound pressure levels are decibel ratings of some of the common sounds are tabulated in Table 1.

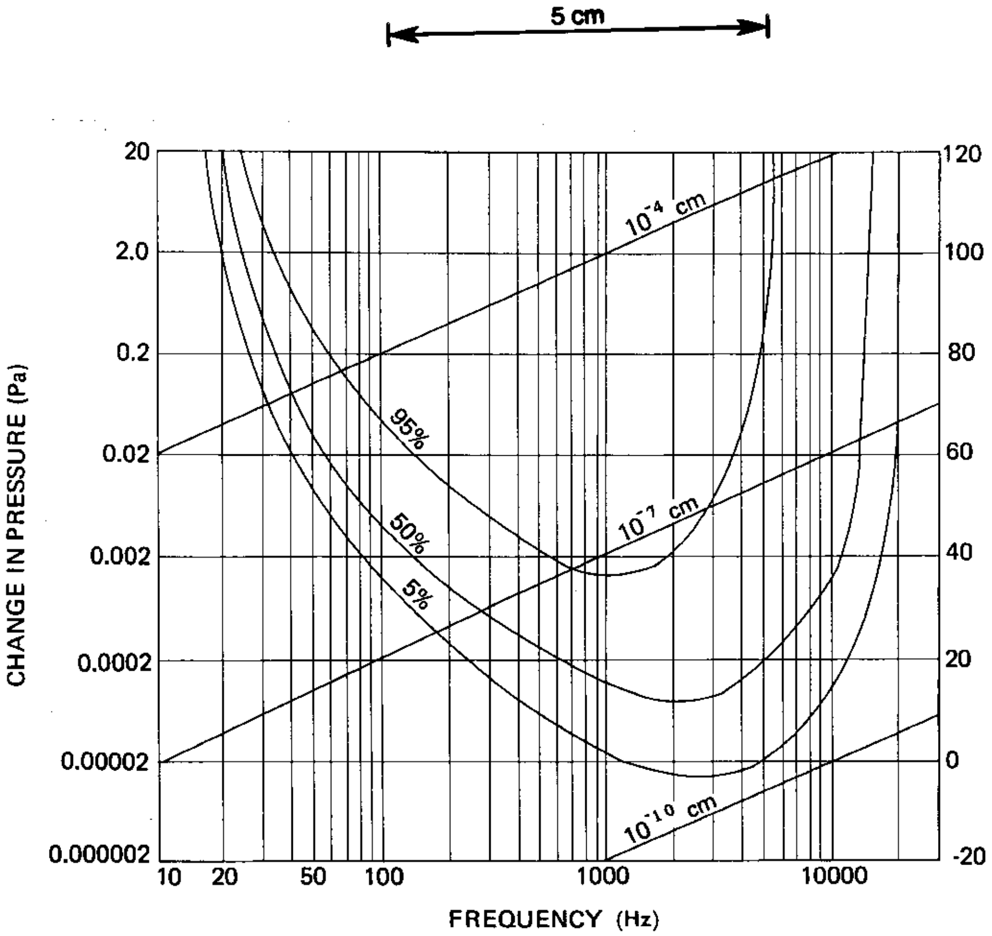


Figure 4. *Audibility diagram, showing thresholds of hearing bettered by 5%, 50%, and 95% of the population.*

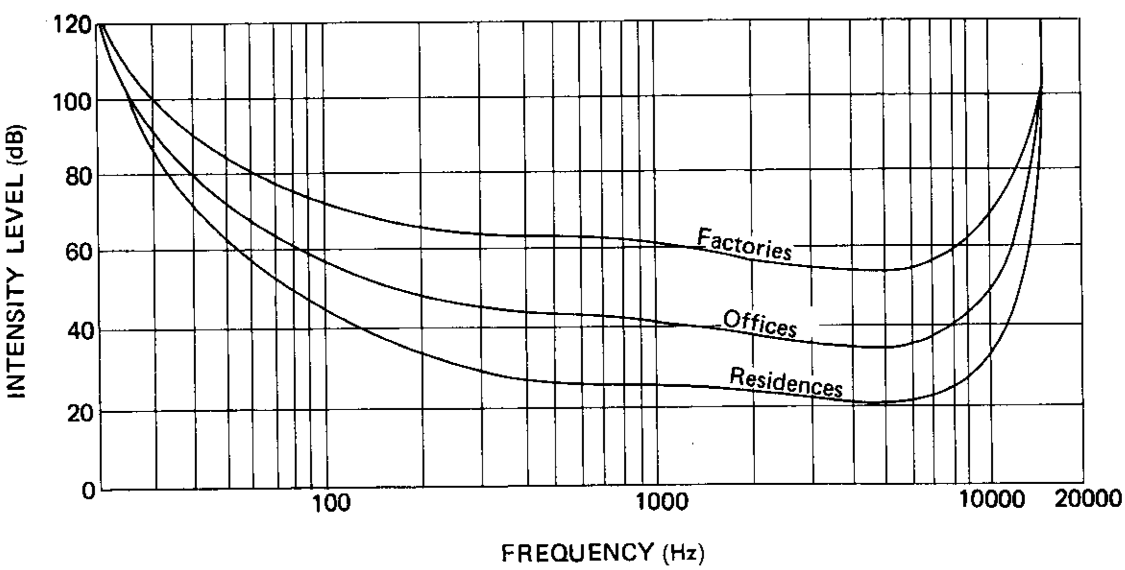


Figure 5. *Typical thresholds due to masking by noise.*

Table 1. *PRESSURE AND DECIBEL RATING OF SOME COMMON SOUNDS*

Sound pressure		S.P.L.	Remarks	
Pa	µbar	(dB)		
2 x 10^{-5}	2 x 10^{-4}	0	Threshold of hearing	
		10	Soundproof room	
2 x 10^{-4}	2 x 10^{-3}	20	Ticking of a watch	Very quiet
		30	Quiet garden	
2 x 10^{-3}	2 x 10^{-2}	40	Average living room	Quiet
		50	Ordinary conversation at one metre	
2 x 10^{-2}	2 x 10^{-1}	60	Car at 10 m	Noisy
		70	Very busy traffic	
2 x 10^{-1}	2	80	Tube train, loud radio music	
		90	Noisy factory, heavy lorry at 5 m	Very noisy
2	20	100	Steel riveter at 5 m	
		110	Thunder, artillery	
20	200	120	Threshold of feeling	INTOLERABLE
		130	Aeroplane propeller at 5 m	
200	2000	140	Threshold of pain	
		150	White noise causing immediate deafness	
200000	2000000		Atlas rocket launch (100 m away)	

Note: Each factor of 10 increase in sound pressure results in an increase of 20 dB in S.P.L.

A $\sqrt{10}$ fold increase in sound pressure corresponds to an increase of 10 dB in S.P.L.

HEARING LOSS AND ITS EFFECTS

It has been established that a person subjected to sound levels above 85 dB, when measured on the A scale network of a sound level meter, will suffer fatigue and temporary loss of function of the cochlea. These effects disappear if that person is not subjected to that intensity of sound for a period of time sufficient for the ear to recover. Permanent damage to the hearing can occur if a noise level above 85 dBA is persistently encountered and of sufficient duration. Once damage to hearing has occurred that loss is permanent.

Loss of hearing can occur essentially in three ways.

(1) Natural loss due to ageing.
(2) Medical loss due to disease or injury.
(3) Industrial loss.

Industrial noise can affect man in a number of ways, the five main effects are:

(1) Temporary loss of hearing.
(2) Communication problems.
(3) Performance difficulties.
(4) Annoyance.
(5) Physiological effects.

Temporary Hearing Loss

Exposure to loud continuous noise for short periods or to high impulse sounds such as rock drilling machines or gunfire will initially produce temporary deafness but this will gradually disappear if the man is withdrawn from those noisy conditions. It must be noted that there are considerable variations in susceptibility and recovery rates.

Communication problems

Noise increases the difficulty of communication and the additional effort needed to communicate will indirectly cause fatigue and irritation.

Conversely if the noise level can be reduced communication can become easier resulting in less fatigue and irritation increasing the ability of the person to hear warning sounds and to understand instructions.

Performance difficulties

Test data do not clearly indicate how noise affects the performance of an individual as a worker.

A worker has the ability to adapt to noisy conditions and this has an influence on his output but there is an initial period during which noise may cause irritation, increase absenteeism and decrease production. These effects may diminish if not disappear as the individual adapts.

Annoyance

It has been established that an operator is rarely disturbed by the noise generated by his machine.

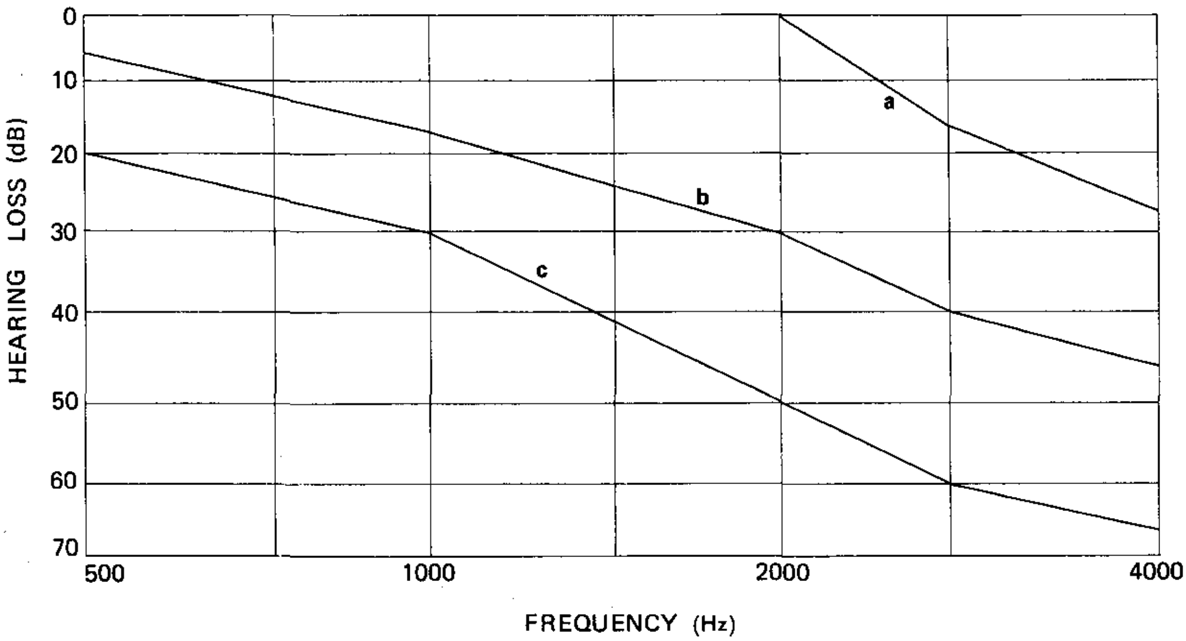


Figure 6. *Typical audiometric curves showing the progress of noise induced permanent hearing loss. (a) Early permanent hearing loss, (b) audiogram showing a hearing loss of 45 dB at 4 kHz and average hearing loss just over 15 dB and (c) severe permanent hearing loss.*

The degree of concentration required to perform his duties determines the amount of annoyance suffered by the worker due to the presence of extraneous noise.

Intermittent high pitched narrow band noise appears to cause the most distress.

Physiological effects

Noise levels of extreme intensity, in the order of 150 dB, have direct physiological effects. They cause:

(1) the skin to become heated,
(2) vibration of the thoracic and abdominal walls,
(3) pains in the ear,
(4) nausea,
(5) severe temporary or permanent loss of hearing or even total deafness.

Fortunately noise of this intensity generally falls outside the range of industrial noise (except for the aircraft or rocket industries).

Subsequent effects of over-exposure to a high intensity sound level are:

(1) Probable permanent hearing loss.
(2) Difficulties on the job.
(3) Social problems.

Permanent Hearing Loss

Continued exposure to noise which causes significant temporary hearing loss will eventually produce permanent hearing loss.

5 cm

The first evidence of permanent hearing loss occurs in the frequencies about 4 kHz for most people and continued over-exposure will increase the loss which will extend to the lower frequencies and it is at this stage of loss that a person begins to have difficulty in understanding normal speech. The effect of early permanent hearing loss is shown in Figure 6.

The ability of workmen to adapt to noise may mask the situation where, although there is no actual physical discomfort, a permanent hearing loss will accrue.

Test data have shown that employees working in noisy conditions, such as boilermakers exhibit a wide range of individual hearing loss. It is impossible to predict hearing loss from the known parameters such as employee's length of service, age and period of noise exposure. It is also found to be unreliable to try and predict the susceptibility of the employee to hearing loss by pre-exposure testing.

It has been found necessary to place emphasis on the noise exposure and hearing loss when conducting a hearing conservation programme. This will establish which employees are most susceptible to hearing loss. Their employer should then take steps to protect them from further hearing loss or transfer them to work in a quieter area where they are not exposed to dangerous levels of noise, or suggest that they seek employment in another industry where noise is less likely to affect them.

Difficulties on the job

A worker whose hearing is impaired may:

(1) Misinterpret verbal instructions and audible warnings.
(2) Suffer injury due to accident proneness.
(3) Possibly damage equipment or products.
(4) Be prone to absenteeism.
(5) Suffer monetary loss.
(6) Have limited promotion prospects due to
  (*a*) difficulty of using telephone etc.,
  (*b*) difficulty in following discussions either between groups of people or at conferences.
(7) Suffer an alteration of personality.

Social difficulties

Difficulties and problems of an employee's work; due to his hearing loss, often carry over into his private life.

Many factors create problems in the employee's private, or social life but the most important are as follows:

(1) The difficulty of communication with his family.
(2) Entertainment by television, radio, films, and theatre is restricted.
(3) The difference in the listening level of sound between the person whose hearing is impaired and his family when listening to television or radio can cause friction and irritation in the family.

(4) Communication at church, clubs and other organisations may become so difficult as to cause the loss of pleasure or satisfaction from participation in those activities.
(5) The above traumata have been recognised by industrial compensation laws when assessing the degree of hearing impairment suffered by the worker through industrial noise exposure and should be an important consideration when management is dealing with noise problems.

HEARING CONSERVATION PROGRAMME

A programme should not be haphazard but should follow definite guide lines covering the following facets:

(1) Evaluation of the noise problem.
(2) Reduction of noise exposure.
(3) Audiometric testing to detect workers who are susceptible to hearing loss due to noise.
(4) Provision and supervision of the use of personal protective devices.
(5) Monitary audiometry.
(6) Delegation of responsibility to those who are to implement and supervise the programme.

The aim of the programme should be to detect early permanent hearing loss and to maintain it below 15 dB, ranging over the speech frequencies, even at the end of the employee's working life.

There are two main reasons to justify why an employee's average hearing loss should not be allowed to exceed 15 dB during his normal working life:

(1) A person with an average hearing loss over the speech frequencies is first beginning to notice difficulties in normal conversation.
(2) This is the minimum hearing loss usually considered handicapping in legislation dealing with disability or compensation.

Curve *b* (fig. 6) shows a typical industrial type hearing loss. This curve shows that an average hearing loss of 15 dB occurs when the hearing loss, at a frequency of 4 kHz, is 45 dB. Using this criterion the application of a hearing conservation programme based on measuring the hearing loss at 4 kHz and ensuring that steps are taken to prevent this loss exceeding 45 dB will usually ensure that the average hearing loss at speech frequencies is kept below 15 dB.

To be successful, any hearing conservation programme must be properly organised and have the full co-operation and support of the management, unions, safety officers, medical personnel and the employees.

Noise which is of sufficient intensity to cause hearing loss should be fully investigated, and an attempt made to reduce its intensity.

Evaluation of the Noise Problem

A noise survey should be made in all noisy areas, the measurements being taken in the vicinity of the employee's ear. In areas where the employees move about, or where noisy machines of similar characteristics contribute to the general noise, readings should be taken at several points.

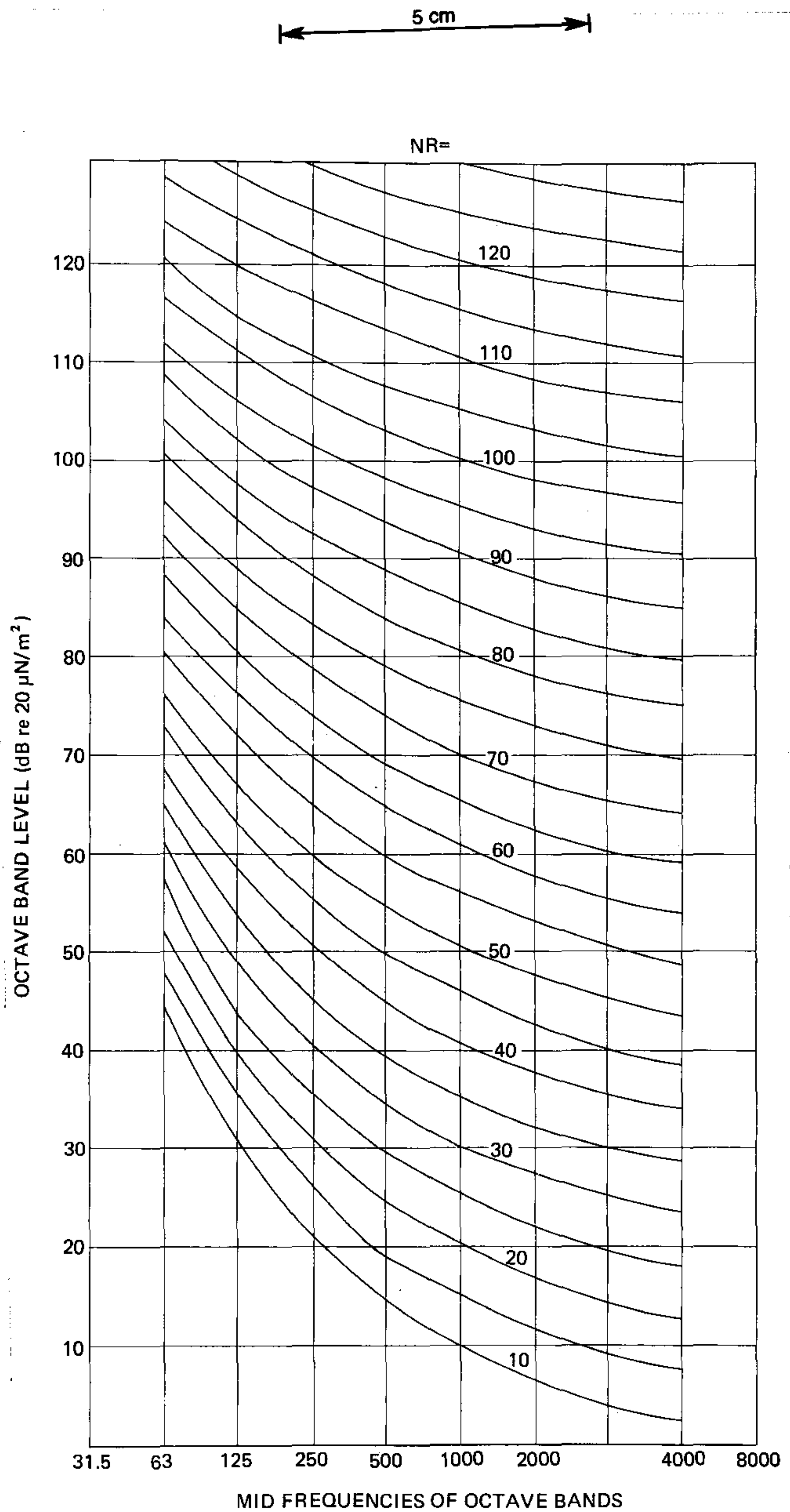


Figure 7. *Mid-frequencies of octave bands. Noise rating curves.*

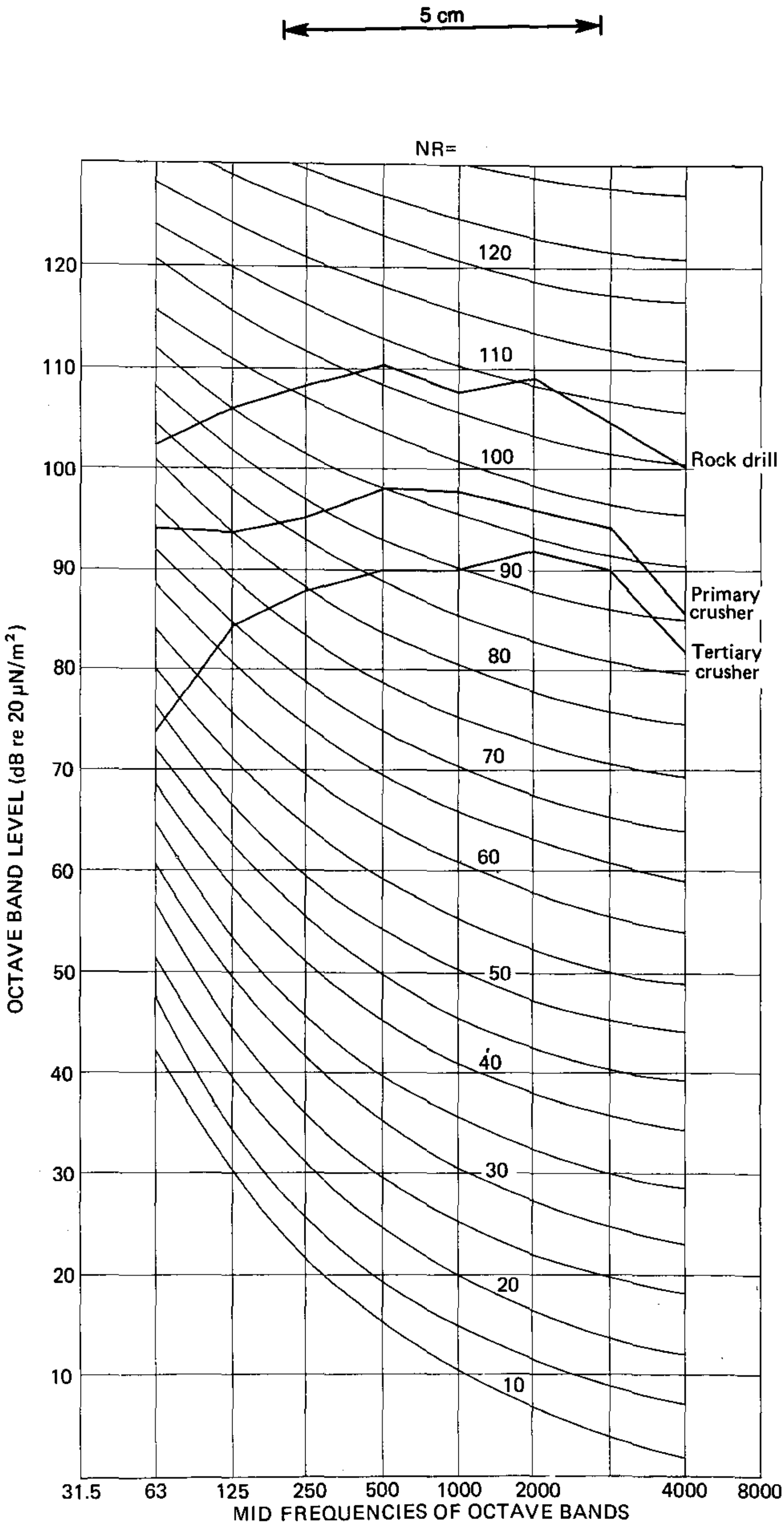


Figure 8. *Noise rating curves. Plot of octave readings for machines operating in a quarry (see Table 2).*

An accurately calibrated sound level meter should be used and on the location of a hazardous noise level the noise should be analysed by making use of an octave filter which can be attached to the sound level meter.

The level of sound or noise is expressed in decibels (dB) and it has been established that if the readings are taken on the A scale (dBA), then those readings are a measure of the possible hearing damage.

The Department of Mines has recognised that noise can create hearing damage and regulations concerning noise levels are contained in the Mines Inspection Regulations, 1969, and amendments thereto.

Regulation 9(5) states

> 'Every owner shall supply properly fitting hearing conservation equipment to every person who, during a normal working day in a mine, is subjected to a noise of a pressure level exceeding eighty-five decibels A scale, being a scale measured in accordance with the Standards Association of Australia Code for Sound Level Meters, Type 1 - General Purpose, (AS Z 37).'

Regulation 9(6) states

> 'No person shall knowingly or wilfully subject himself to a noise specified in sub regulation (5) of this regulation without wearing hearing conservation equipment.'

A reading taken on the A scale only gives a generalised idea of the noise problem and does not provide sufficient information for an engineer to devise means of controlling or alleviating the noise.

A noise can be more precisely defined if readings are taken at the mid-frequencies by using an octave filter in association with the sound level meter. The octave filter should comply with the bands as specified in the Australian Standard Z 33-1967. This enables an engineer to determine the frequency spectrum or the frequency distribution of the components of the noise.

The readings should then be plotted on a set of Noise Rating Curves which have been devised as a standard by the International Organisation for Standardisation.

These curves, which are commonly referred to as the noise of rating (NR) curves, are shown in Figure 7.

Sound pressure levels taken at the mid-frequencies of the octave bands of the noise generated by various machines operating in a quarry are shown in Table 2.

The number allocated to each NR Curve is the decibel reading of where the curve cuts the 1000 Hz line.

When each group of octave readings is plotted the NR number of that trace is the highest that any point of the trace reaches in the NR Curves. The NR number is 111 for the rock drill trace shown on Figure 8, 98 for the primary crusher, and 94 for the tertiary crusher.

If the trace of the plot follows the slope of the NR Curves and the NR number does not exceed 80 there should be no complaint but if there are peaks of significant magnitude, even though the NR number does not exceed 80 there may be complaints.

Table 2. SOUND PRESSURE LEVELS TAKEN AT MID-FREQUENCIES OF OCTAVE BANDS FOR VARIOUS MACHINES OPERATING IN A QUARRY.

Machine	Mid-Frequency (Hz)								NR	dBA
	63	125	250	500	1000	2000	4000	8000		
Primary Crusher	98	98	100	96	94	90	94	84	96	101
	94	94	96	98	98	96	94	84	98	103
Primary Screens	82	88	96	100	102	104	103	94	106	111
	90	94	98	102	102	102	102	90	104	109
Rock Drill	103	106	108	110	108	109	104	100	111	116
	105	105	107	108	104	101	101	99	106	111
Secondary Crusher	82	84	90	92	90	92	90	84	93	98
	82	86	94	99	100	100	98	86	102	107
Tertiary crusher	74	84	88	90	90	92	90	82	94	99

Plotting of some of the results shown in Table 2 on NR Curves is shown in Figure 8.

Complaints due to these peaks can be eliminated by:

(1) Finding the source or sources from which the frequency or frequencies causing the peak or peaks is coming and devise ways and means of reducing the sound level of those frequencies so that the NR trace is a smooth curve conforming to the slope of the NR Curves.
(2) Increasing the sound pressure in those frequencies which are below the NR Curve until a smooth curve is attained as in (1).

The trace for the rock drill shows a peak between 1000 and 2000 Hz but the difference is only about 5 dB and this would be difficult to reduce. The NR number for the primary crusher trace is 111 which is 31 dB above that set down in the Mines Inspection Regulation 1968 and amendments. The sound pressure level is considerably above the standard and accordingly the operator should wear hearing conservation equipment.

The trace for the primary crusher shows a peak between 1000 and 4000 Hz but this peak is more like a ridge with the top of the ridge following the NR 97 curve. The dBA rating of this crusher is 102 which is 17 dB above the standard as set out in the regulations and employees working in its vicinity should use hearing conservation equipment.

The comparison between readings on the A scale and the noise rating curves is that the decibel readings on the A scale (dBA) are 5 dB above the decibel number where the NR Curve crosses the 1000 Hz line.

Reduction of Noise Exposure

Control measures which reduce the noise level below the standards set out in legislation, are preferred as by doing this the following results are achieved:

(1) Hearing tests are then not needed.
(2) Hearing conservation equipment is no longer required.
(3) Communication becomes easier.
(4) Working becomes more comfortable with less fatigue and irritation.
(5) There will be no complaints from outsiders.

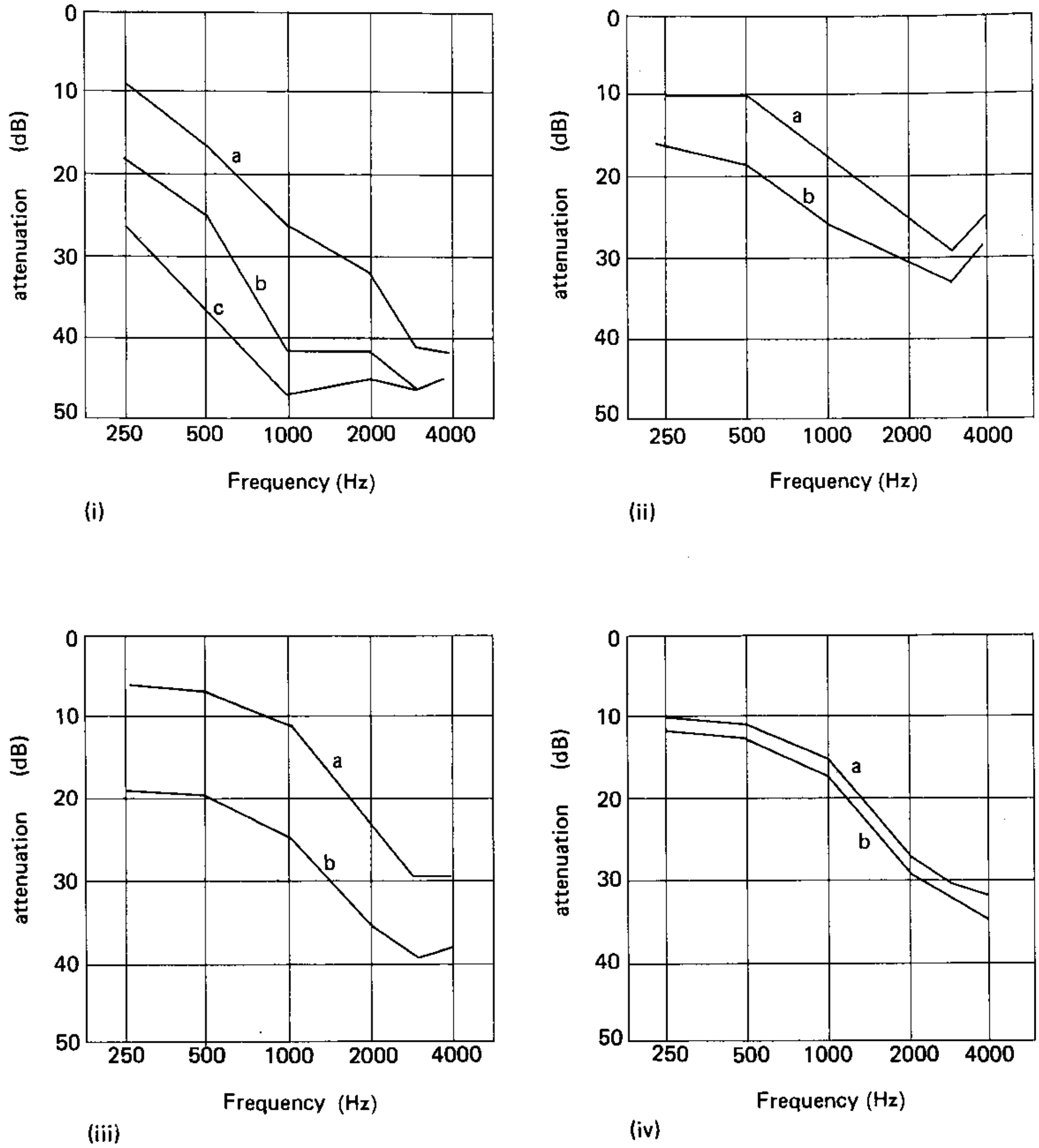


Figure 9. *Attenuation of hearing conservation equipment:*

(i) *a.* *Ear Muff, Light.*
b. *Ear Muff, Medium.*
c. *Ear Muff, Heavy.*

(ii) *a.* *Ear Plug, One Flange.*
b. *Ear Plug.*

(iii) *a.* *Silicone Rubber (Concha).*
b. *Silicone Rubber (Meatus).*

(iv) *a.* *Waxed Cotton Wool (Antinois).*
b. *Fibre Glass Wool.*

5 cm

The following is a resumé of the more important ways in which industrial noise may be reduced:

(1) Planning the siting of the equipment so that noisy machines are entirely removed from an area where the remainder of the machines are quiet and resiting them among other machinery which is noisier.
(2) Careful design or selection of new equipment and processes.
(3) Modification and, or, enclosure of existing equipment.
(4) Substitution of alternative quiet processes.
(5) Isolation of personnel from noisy surroundings.
(6) Reduction of reverberance by the use of absorbing material.

Hearing Conservation

There is no difficulty in persuading employees to use hearing conservation equipment when working in high noise levels as the comfort the employee enjoys overcomes any reluctance he may have to adopt a new device. Persuasion becomes increasingly difficult as the noise level decreases, even though the noise level is still sufficiently high to ultimately cause a loss of hearing.

It is important to convince an employee that he should constantly wear hearing protection when working in noisy conditions and the employer should assist by providing suitable and comfortable hearing protection equipment.

If the employee is reluctant to wear the most effective type of hearing conservation equipment, but is willing to wear another, although less effective type, he should be allowed to do this. Once he is convinced of the benefits of this equipment he is then more likely to accept the more effective type.

One of the hurdles that the official in charge of the hearing conservation programme has to overcome is that the employee thinks that he will not be able to hear speech when wearing hearing conservation equipment, but once he begins to wear it consistently he will realise that this is not so.

The employee, provided he wears the hearing protection when, where and how it should be worn, will accrue a further benefit in that the periods of temporary loss of hearing will disappear.

Hearing Conservation Equipment

(1) Ear muffs.
(2) Ear plugs.
(3) Individually moulded plugs.
(4) Temporary plugs such as waxed cotton wool or fibre glass wool.

Any of the above equipment can be used in various noisy conditions but care must be used to select equipment which will attenuate the noise to a safe level. The attenuation of the various pieces of equipment at various frequencies are shown in Figure 9 whilst the overall attenuation is shown in Table 3.

Responsibilities

Programmes for hearing conservation cannot be successful, unless management, medical and safety officers, industrial unions and employees are all motivated towards prevention rather than compensation.

Table 3. OVERALL ATTENTUATION PROVIDED BY HEARING CONSERVATION EQUIPMENT.

Hearing Conservation Equipment	Noise Attenuation (dB)
Ear muffs:	
Heavy	40
Medium	35
Light	25
Ear plugs:	
Ear plug	25
Ear plug and flange	18
Individually moulded ear plugs:	
Silicone rubber (Meatus)	28
Silicone rubber (Concha)	14
Temporary ear plugs:	
Waxed cotton wool (Antinois)	20
Fibreglass wool	20

The programme is implemented as follows:

(1) Management

(*a*) The management is responsible for each part of the programme concerning the hearing conservation equipment.
(*b*) Evaluation of the noise problem.
(*c*) Completion of noise control procedures.
(*d*) Purchase of the hearing equipment.
(*e*) Issue and supervision of the equipment to the employees.

(2) Medical and Safety Officers

(*a*) Reference audiometry.
(*b*) Monitary audiometry.
(*c*) Advise as to who, from a noise level aspect only, should be employed where there is a noise problem.
(*d*) Surveillance, fitting and instruction in the use of hearing conservation equipment.

(3) Industrial Unions

It is necessary for the unions to adopt an attitude which recognises that the ultimate welfare of their members is best served by actual encouragement in the concept of protection rather than compensation.

SOUND MEASUREMENT

Sound Pressure and Sound Intensity

Absolute values of sound pressure and sound intensity can only be expressed in long and cumbersome numbers as is shown in Figure 10.

Power expressed in watts varies between 1×10^{-9} and 1×10^{5} a variation of 10^{14} or a hundred million million whereas if expressed in decibels the variation would be between 30 and 170 dB.

The doubling of the sound pressure level is equivalent to an increase of 3 dB *i.e.* if two machines are operating side by side and each creates a sound pressure level of 90 dB when operating alone, then the reading will be 93 dB when they operate together.

An increase of 10 dB in sound pressure level is equivalent to doubling the subjective loudness of the sound whilst an increase of 20 dB will appear to be four times as loud.

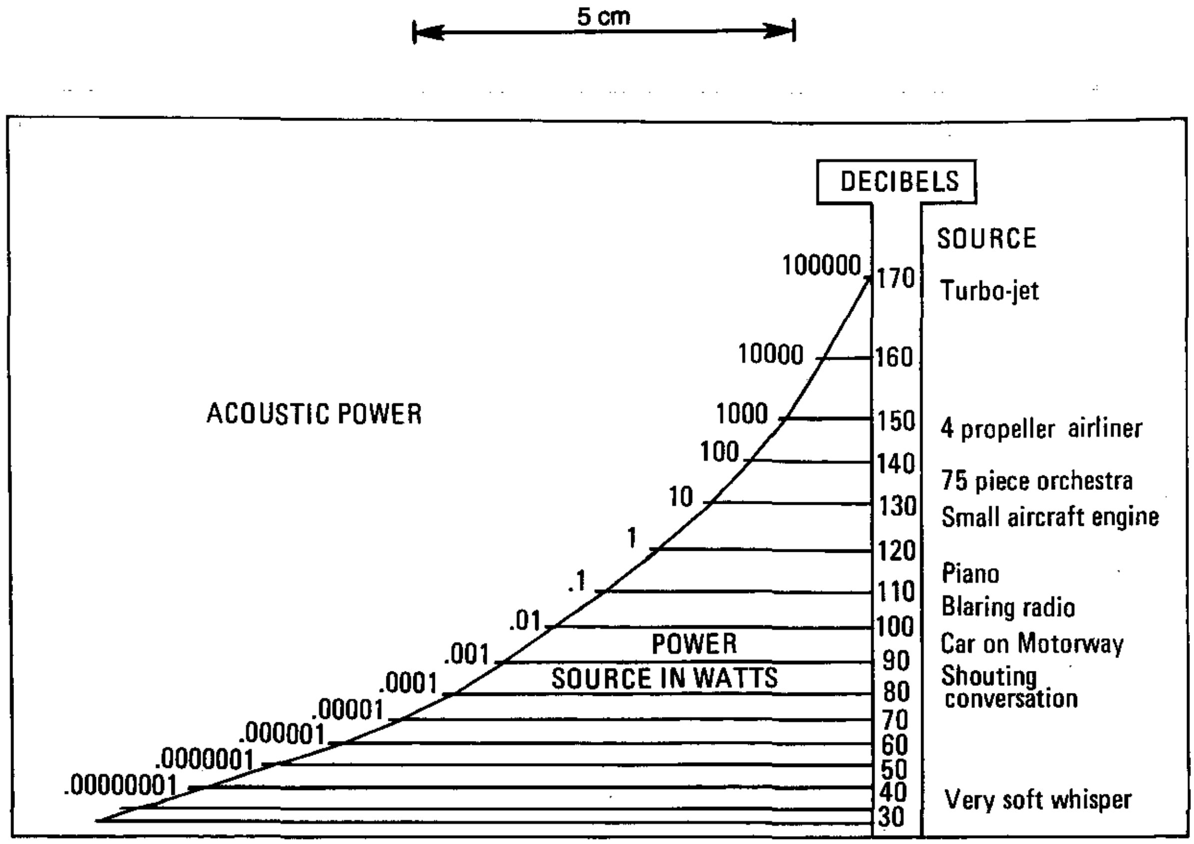


Figure 10. *Comparison between sound pressure level expressed in watts and decibels.*

In a free field out in the open air the loudness of a sound decreases with increasing distance according to the inverse square law and the effect of doubling the distance between the point of the test and the source of the sound will result in a decrease of 6 dB in the reading. In enclosed areas this does not always hold as reflected sounds affect the result.

A much easier and more convenient way to express the levels of sound is to use a logarithmic scale.

When using the logarithmic scale the unit of measurement on this scale is called the bel (after Alexander Graham Bell). In practice, the sound pressure level is expressed in decibels (dB) or one-tenths of a bel.

A decibel, by definition, is 10 times the logarithm, to the base of 10, of a ratio of two powers, and can be expressed as follows:

$10 \log (W_2/W_1)$ where W_1 and W_2 are expressed in watts
also $W_2/W_1 = (P_2/P_1)^2$ where P_1 and P_2 are pressures
i.e. $S.P.L. = 10 \log (P_2/P_1)^2 = 20 \log P_2/P_1$

where S.P.L. is sound pressure level in decibels
P_2 is sound pressure in pascals (Pa)
P_1 is the reference power, equal to 2×10^{-5} Pa

This can also be expressed $P_2 = 2.10^{((SPL/20)-5)}$
where P_2 = sound pressure level expressed as pascals.

Sound Pressure is the instantaneous pressure measured in a sound wave, that is, the variation from atmospheric pressure. A pressure of one atmosphere is approximately equal to one bar (b) or 10^5 Pa.

Sound Intensity in a specified direction is the average rate of sound energy transmitted in that direction through a unit area normal to the direction expressed in pascals (Pa). Sound intensity is proportional to the square of the sound pressure.

Sound Power of a source is the total sound energy radiated by the source per unit time.

Phon is a unit of loudness level and is defined as follows. Loudness level, in phons, is defined as a sound pressure level of a 1000 Hz tone that sounds as loud as the noise being rated.

Sone is a unit of loudness and by definition a sone is loudness produced by a 1000 Hz tone 40 decibels above the listener's threshold of hearing.

The loudness of any source that is judged by the listener to be *n* times that of the one sone source tone is *n* sones.

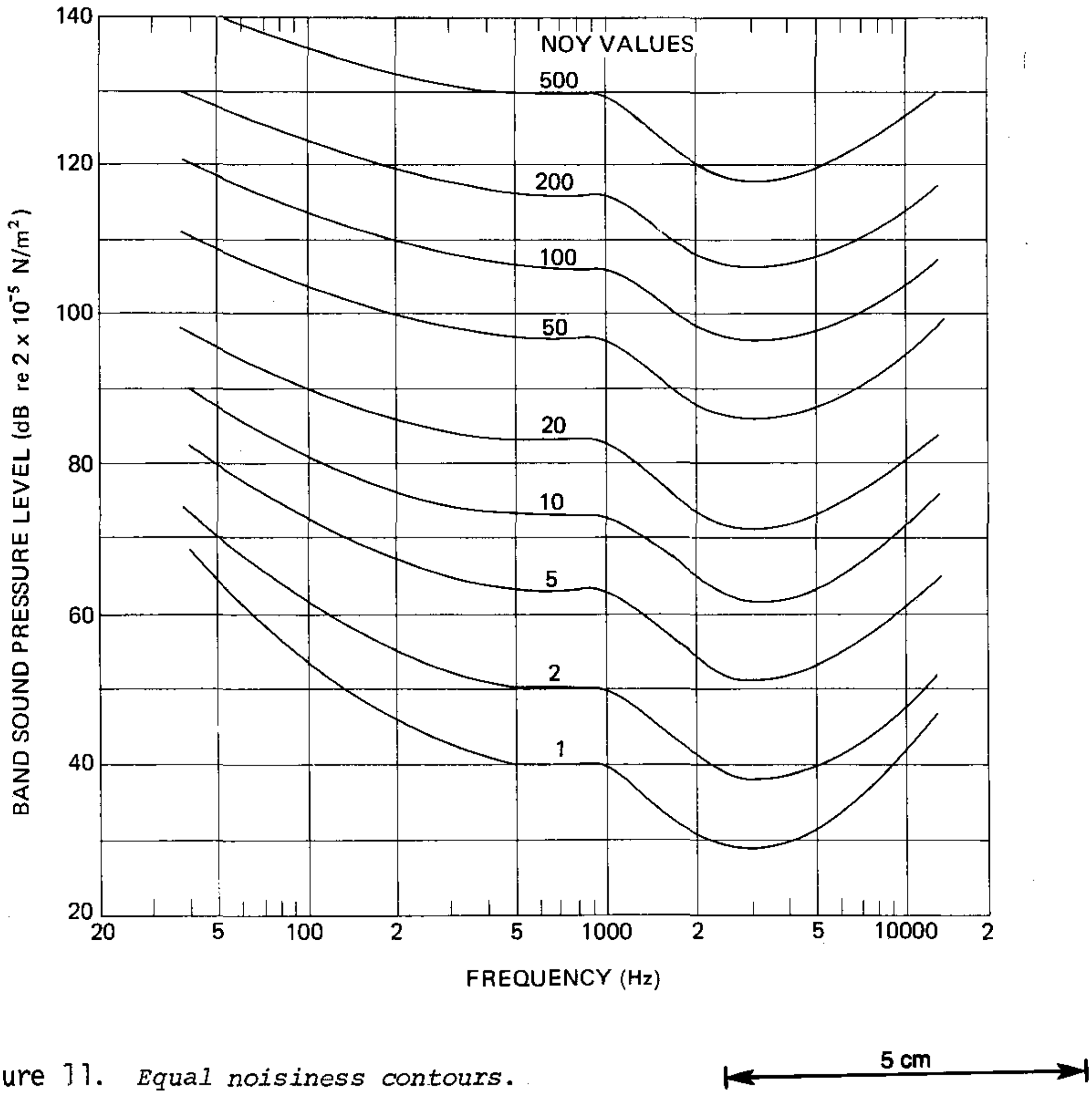


Figure 11. *Equal noisiness contours.*

Perceived Noise Level or PNdB is defined as the sound pressure level of a band of noise from 910 to 1090 Hz that sounds as noisy as the sound under comparison. It is used in a manner similar to phons, except that where phons are used in equal loudness contours, PNdB are used to obtain equal annoyance contours.

Noy is a unit of subjective noisiness and is defined as a unit of perceived noisiness by which equal noisiness contours replace equal loudness contours. Equal noisiness contours are shown in Figure 11.

The relationship between sones and phons are expressed in the following formula:

$$\log 10S = 0.03 (P - 40)$$

where S = unit of loudness
P = unit of loudness level

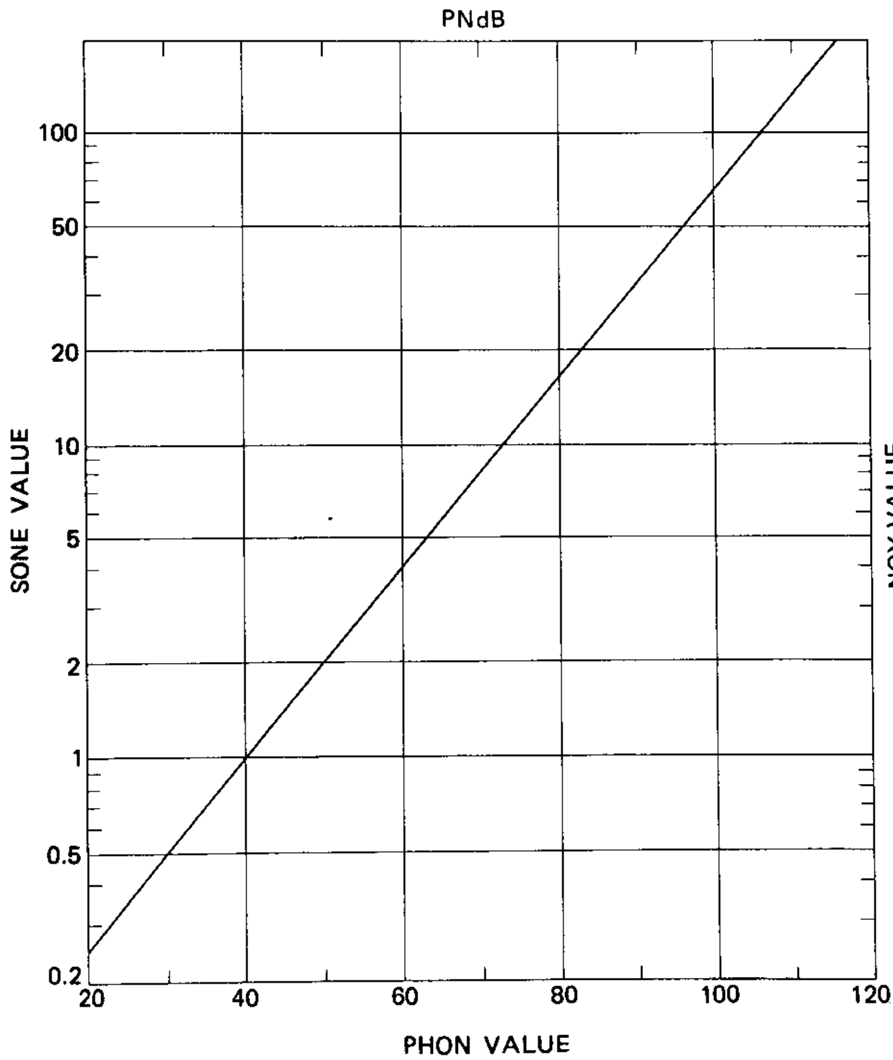


Figure 12. *The relationship between loudness in sones and loudness level in phons, and between annoyance in noys and perceived noise level (PNdB).*

5 cm

The relationship between PNdB and noy is expressed in the formula:

$$\log 10N = 0.03\ (PNdB - 40)$$

where N = unit of noisiness
PNdB = unit of noisiness level

The relationship between sones and phons also noys and PNdB is shown graphically in Figure 12.

Readings taken on the sound level meter are expressed in decibels (dB) together with whatever scale or network they have been recorded, an example being that a reading of 60 decibels on the A scale is shown as 60 dBA or if it had been on the C scale 60 dBC.

Velocity of Sound

The velocity of sound in air can be approximately calculated by the formula:

$$V = 20.03\ K^{\frac{1}{2}}$$

where V = speed of sound in air in metres
K = temperature of air in kelvins

Sound travels at different speeds in different media (Table 4).

Table 4. SOUND SPEED IN VARIOUS MEDIA

Medium		Approximate sound velocity (m/s)
Distilled water at 25°C		1498
Sea water at 25°C		1531
Metal:	aluminium	6420
	copper	5010
	lead	1960
	steel	5960
Wood:	ash	4670
	beech	3340
	oak	3850
Air at 25°C		350

Sound Level Meters

Instruments for the measurement of sound pressure levels must comply with certain standards. In Australia these standards are contained in Australian Standard Z 37-1967. Sound Level Meters Type 1 - General Purposes, and Z 38-1967 Sound Level Meters Type 2 - Precision.

The sound level meter illustrated in Figure 13 is one of the instruments which comply with those standards.

The reference sound pressure has been established as 2×10^{-5} Pa.

Scales or weighting networks are often used when sound level measurements are to be measured.

These networks modify the frequency response of the instrument so as to conform with curves known as the A, B, C and D weighting curves.

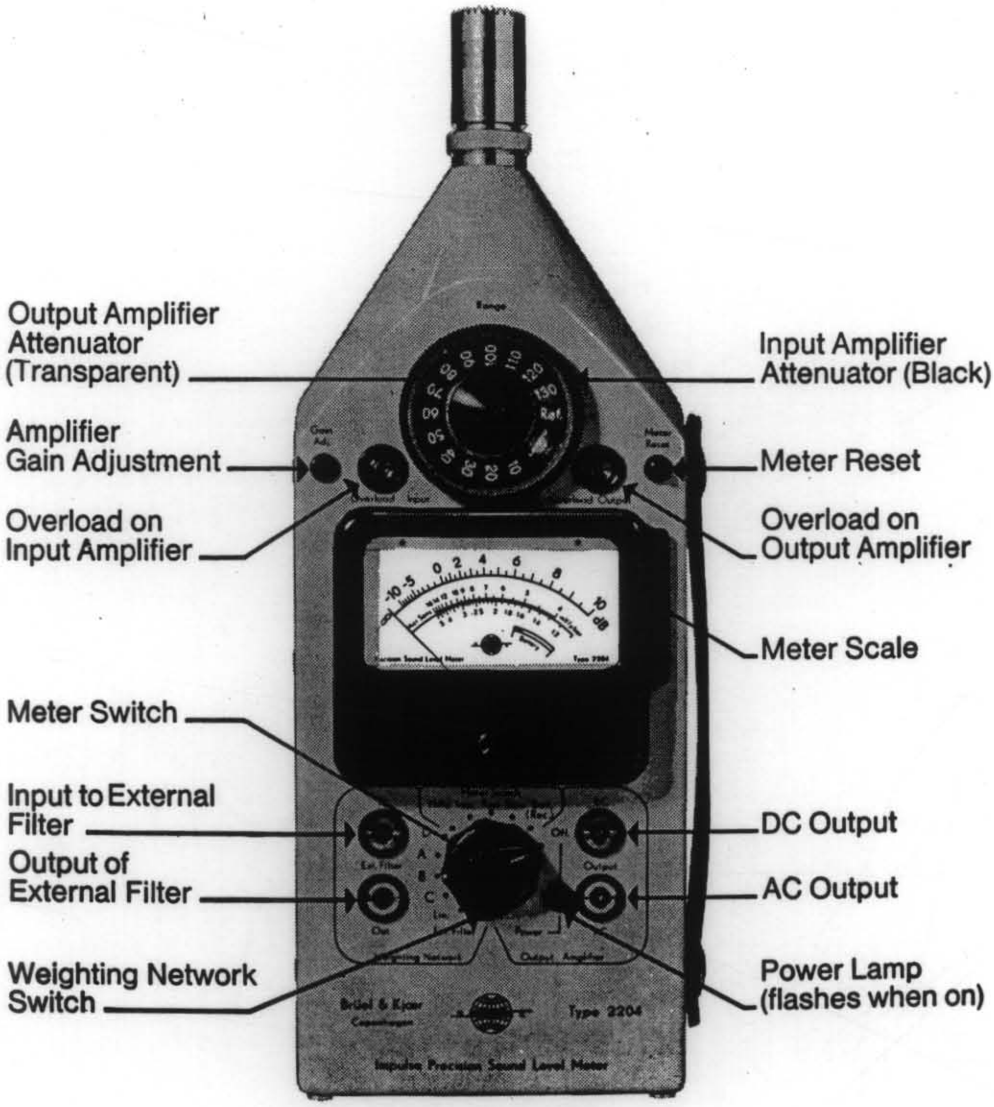


Figure 13. *Sound level meter*

The A scale enables the meter to conform approximately to the 40 phon equal loudness contour whilst the B and C scales follow the 70 and 100 phon contours respectively.

The D scale enables the meter to conform to a curve which is an approximation to the inverted 40 noy contour.

The trace of the effect of each network on the measurements for sound level readings is shown in Figure 14.

Cumulative Effect when Sounds are Combined

When combining the effects of two or more sound pressure levels, the sound pressure level of a source has to be expressed as antilog dB/10 and when sounds are combined the effect is the sum of the antilog of the decibel reading divided by ten. The logarithm of this sum can then be expressed as decibels. The following is an example of how this may be done.

Assume that three sounds are to be combined namely a portable air compressor and two rock drills having a sound pressure level of 112 dB, 114 dB and 110 dB respectively.

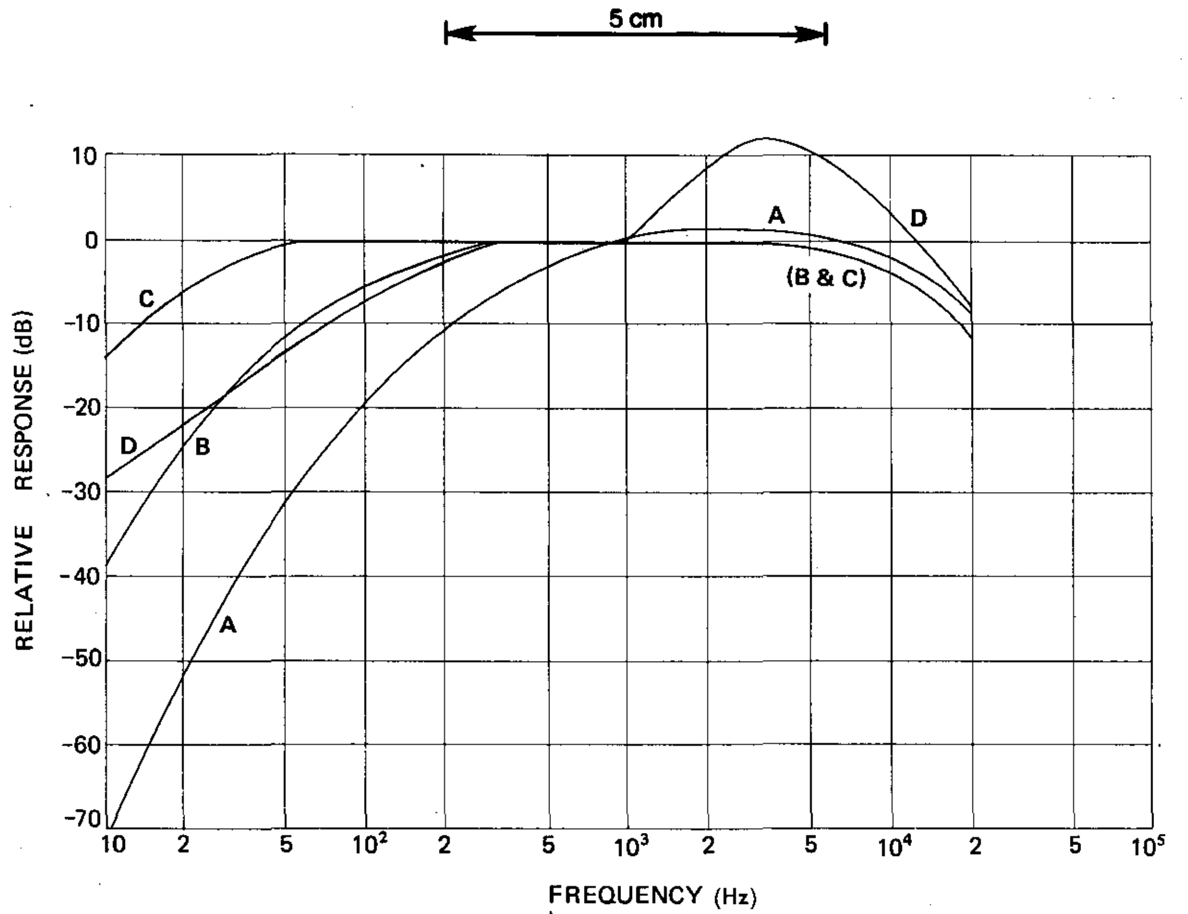


Figure 14. *A, B, C and D weighting networks*

Before the sound pressures can be added the antilog of each has to be established.

Air compressor	antilog $\frac{112}{10}$	$= 1.59 \times 10^{11}$
Rock drill A	antilog $\frac{114}{10}$	$= 2.51 \times 10^{11}$
Rock drill B	antilog $\frac{110}{10}$	$= \frac{1.00 \times 10^{11}}{5.10 \times 10^{11}}$

The total sound pressure level is equal to:

$$10 \log 5.10 \times 10^{11} = 10 \times 11.707$$
$$= 117.1 \text{ dB}$$

The sound pressure level of two sounds can be quickly compounded by reference to Figure 15. This figure can also be used to compound more than two sound pressure levels by compounding the two highest and then compounding this value with the next highest, and so on.

To establish the true sound pressure level of the noise from one machine it is necessary to deduct the sound pressure due to background noise and this can be quickly done by reference to Figure 16.

The sound level meters have large size 1.5 V batteries and it is always necessary to test to see that the voltage is within the limits shown on the machine to ensure that accuracy is maintained.

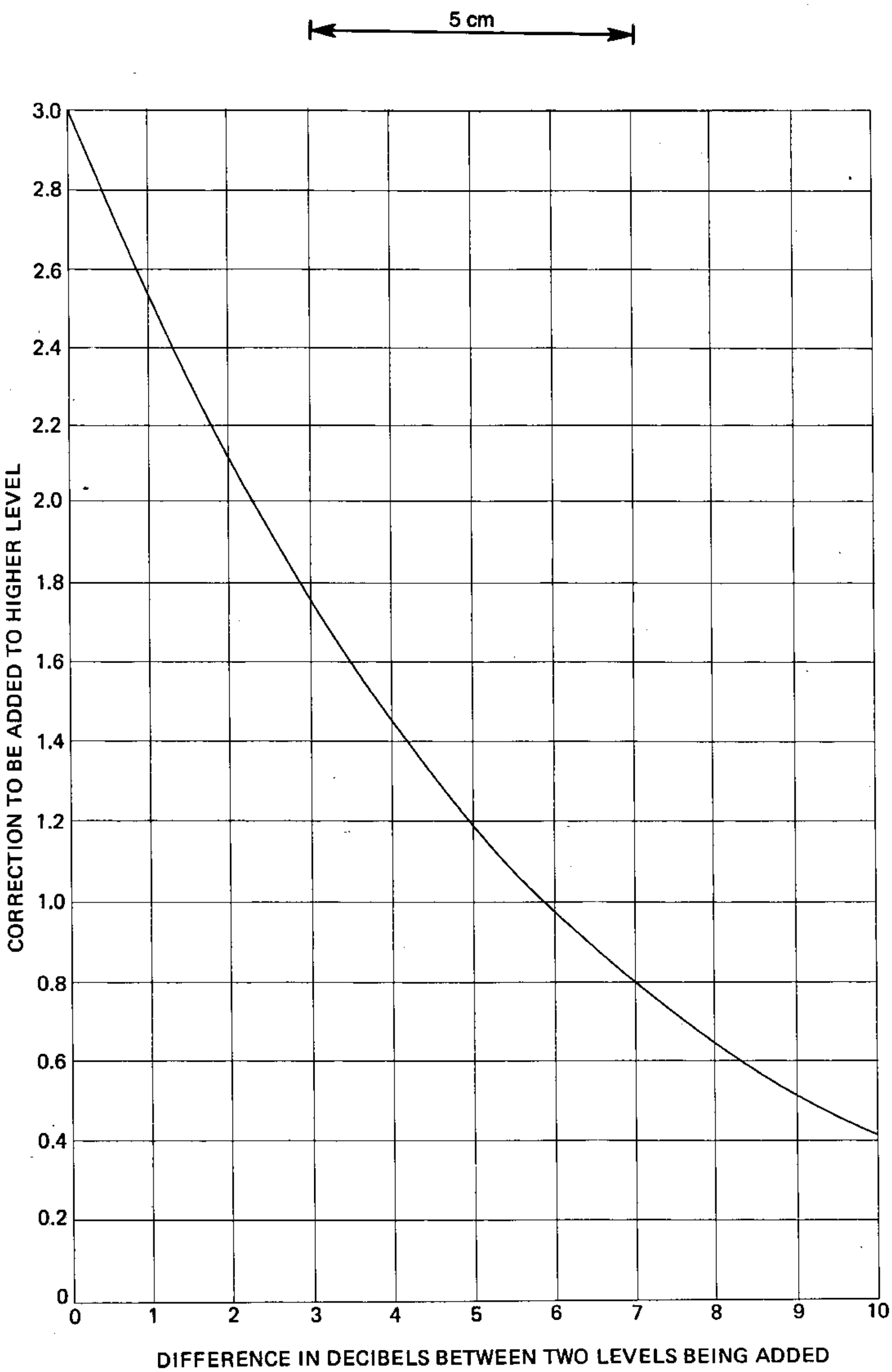


Figure 15. *Compounding of decibel levels*

Sound level meters must have their calibration checked immediately before being used and must be tested again after use.

Variations in atmospheric pressure affect the sound pressure level and this must be taken into account when calibrating.

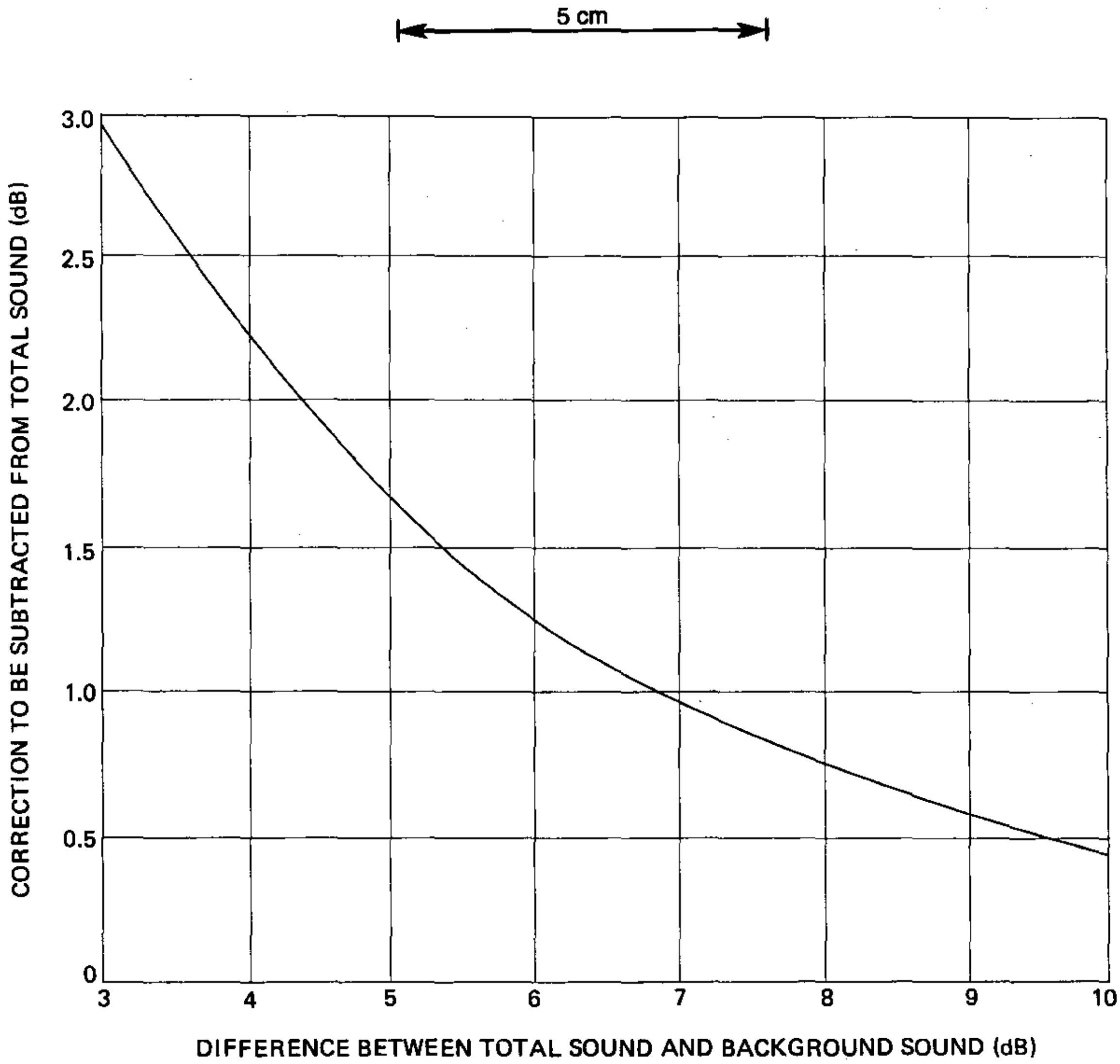


Figure 16. *Subtraction of decibel levels*

The barometer supplied with the machine indicates the atmospheric pressure in mm Hg and the correction in dB.

A pistonphone is used to calibrate the sound level meter and has a sound pressure level of 124 dB.

To calibrate the machine it is necessary to switch the network scale to linear and the other switch to fast response.

The reading on the machine should then be 124 dB plus the correction shown on the barometer. The gain adjustment screw should be used to ensure the correct reading is shown on the scale.

After the machine is calibrated the network switch is rotated to the desired network required for the recording.

The other switch is left at fast response or rotated to give the response required.

A period of preheating is necessary to ensure correct readings.

Machine overload is indicated by flashing lights and the meter scale must be altered to a higher scale. Each scale has a range of readings between -10 and +10 dB so that if set on a scale of 80 the instrument can indicate sound pressure level readings of between 70 and 90 dB. This instrument when fitted with a 25 mm microphone has an effective range of up to 140 dB.

In practice the A weighting scale has been found to closely approximate the response of the human ear.

Effects of Surroundings

A surface having an absorption coefficient of 0.1 means that 90% of the sound is reflected and 10% absorbed.

A square metre of material having a coefficient of absorption of unity is said to have an absorption of one sabin.

The number of sabins absorbed by a surface, material or object is established by the following expression:

$$S = A\alpha$$

where S = number of sabins
A = area in m^2
α = coefficient of absorption

A man wearing a coat will absorb 2.3 sabins at 128 Hz, 4.8 at 512 Hz and 7.0 at 4096 Hz.

It is fortunate that absorption of sound does occur at some solid surfaces, for otherwise sound energy released into the air of a closed room would remain in the air for a long period and the listener in the room would hear things spoken in the previous several seconds.

The quality of sound heard in a room can be varied by incorporating surfaces that have a high absorption or high reflectance, by the positioning of both types of surfaces, and by the type, shape and height of the ceiling and the shape of the room.

Noise in Residential Areas

To determine whether the extraneous noise is acceptable in residential areas it should be evaluated against noise level criteria applicable to those areas.

It may be derived from a basic value which is fixed for certain areas and which is corrected for the time of day and type of district. A situation may occur where the background noise level is less than the corrected basic noise level criterion and in this case the lower figure will be used.

It has been accepted that the basic noise level out of doors in residential sites shall be 40 dBA.

Corrections are applied to the basic noise level criterion for time of day and type of neighbourhood.

Time of day

Corrections to the base level for time are shown in Table 5.

Table 5. ADJUSTMENTS TO BASE LEVEL FOR DIFFERENT TIMES OF DAY WITH RESPECT TO RESIDENTIAL SITES.

Time of day	Adjustment to base level (dBA)
Day time, Monday to Friday (7 a.m. to 6 p.m.)	+5
Day time, Saturdays and Sundays and Public Holidays (7 a.m. to 6 p.m.)	0
Evening (6 p.m. to 10 p.m.)	-5
Night time, Monday to Friday (10 p.m. to 6 a.m.)	-10
Night time, Saturdays, Sundays and Public Holidays (10 p.m. to 7 a.m.)	-10
Early morning, Monday to Friday (6 a.m. to 7 a.m.)	-5

Zone corrections

Corrections to the base level for differing areas containing residences are shown in Table 6.

Table 6. ADJUSTMENTS TO BASE LEVEL FOR DIFFERING AREAS CONTAINING RESIDENCES

Noise area	Description of neighbourhood	Adjustment to base level (dBA)
R1	In rural and outer suburban areas with negligible transportation	0
R2	In general suburban areas with infrequent transportation	+5
R3	In general suburban areas with medium density transportation	+10
R4	In suburban areas with some commerce or industry or adjacent to dense transportation	+15
R5	In city or commercial areas or residences bordering industrial areas	+20
R6	Within predominantly industrial areas	+25

Background noise

The background noise level shall be the lowest noise level measured at a relevant place and time in the absence of the noise which is alleged to be offending. It shall be obtained by observing the pointer of the sound level meter set on fast response and by reading the lowest level which is repeated several times (mean minimum).

Outdoor readings

Noise levels should normally be measured out of doors at from 1.2 m to 1.5 m above the ground and at least 3.5 m from any walls, buildings or other reflecting surfaces. It is permissible to take a reading 0.5 m in front of an open window.

Indoor measurements

If it is necessary to take readings inside buildings because outside readings are not possible the readings shall be taken one metre from any walls, 1.2 to 1.5 m above the floor and 1.5 m from windows. Measurements should generally be made with windows open but if the circumstances are that the windows are regularly closed then the readings should be taken with the windows closed.

Guide to rating inside noise

General values for rating noises inside residential premises can be derived from those for outside noise by adding corrections as shown in Table 7.

Table 7. ADJUSTMENTS TO ACCEPTABLE NOISE LEVEL (CALCULATED) FOR ASSESSMENT OF ANNOYANCE, WHEN MEASURED INDOORS.

Window conditions	Adjustment (dBa)
Windows open	-10
For windows having a potential opening equal to:	
10% of the wall area	-10
20% of the wall area	-5
Single windows shut	-15
Double windows shut or non-openable windows, or single windows closed and sealed	-20

Notes:

(1) Where a window of known acoustic performance is used, the known value should be taken into consideration. Normally the acceptable noise level (indoors) should be fixed at not less than 20 dBA.
(2) This method is not applicable to noise arising within the same building.

Determination of noise level rating

In many cases corrections to the measured noise level are needed to obtain a better estimate of the degree of annoyance caused. These corrections are dependent on the character of the noise as regard impulse and spectrum character, duration and fluctuation. The sum of the measured noise level and the appropriate corrections, which are shown in Table 8, is the estimated noise level of an equally annoying steady state noise without impulsive character or pure tones.

The duration of the noise should also be considered in relation to the relevant time period. The typical noise on-time duration shall be determined as a percentage of the total time under consideration. Appropriate corrections in dBA shall be determined in accordance with Figure 17 for night-time and Figure 18 for other times and these corrections shall be applied to the measured noise level.

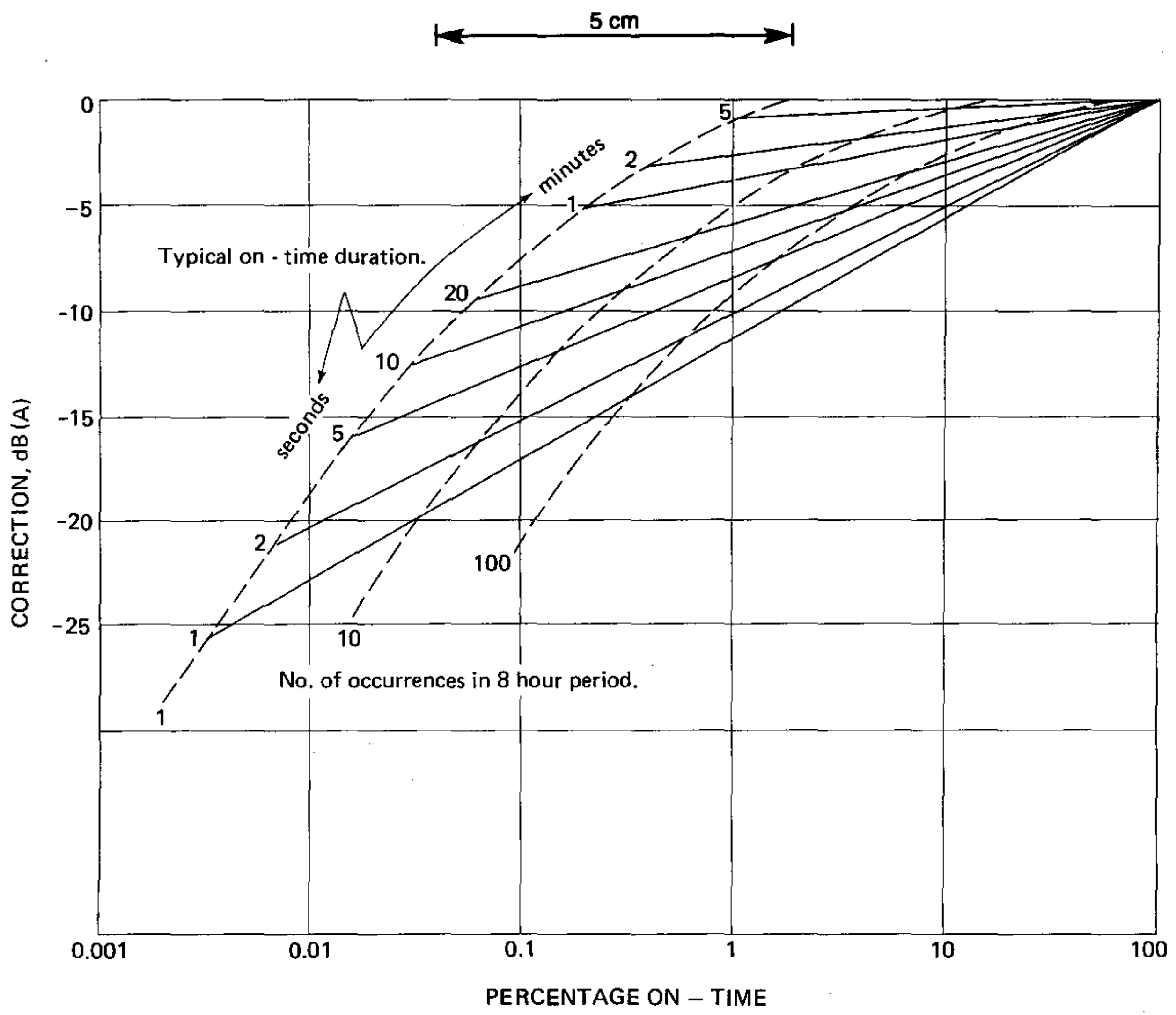


Figure 17. *Intermittency and duration adjusted for nighttime.*

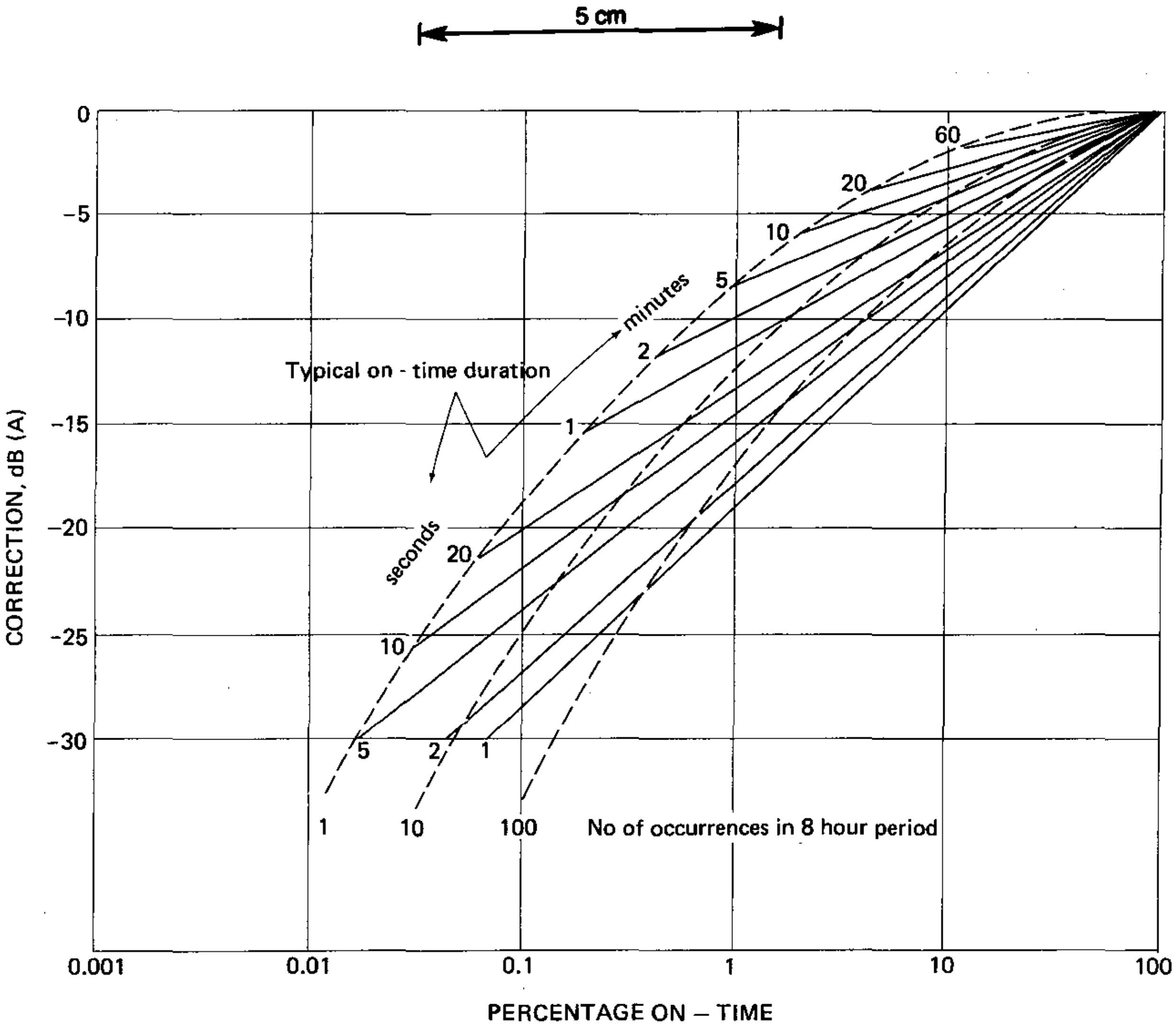


Figure 18. *Intermittency and duration adjusted for other than nighttime.*

Table 8. ADJUSTMENTS TO THE MEASURED NOISE LEVEL

Influencing factor	Possible conditions	Adjustments (dBA)
Impulsive	Hammering, bangs or thumps	+5
Noise spectrum	Prominent tonal components	+5
Noise spectrum	Beats, amplitude or frequency modulation	+5

Air blast

Most complaints are made because the complainants are convinced that the noise they hear from the detonation of explosives is damaging their property particularly if any windows rattle.

It has been determined that the number of complaints received is related to the noise produced.

A review of blasting complaints indicates that the noise propagation from some blasts was greater than others and the conclusion reached is that meteorological conditions were the cause. The findings of that review are as follows:

(1) Weather conditions can cause a variation in sound propagation.
(2) Weather conditions can be unfavourable to blasting from a sound propagation aspect.
(3) There is a reduction in the number of complaints by restricting blasting operations to those days having favourable weather conditions.

General rules can be established with regard to visible weather conditions and their effect on sound return.

These conditions can be interpreted as being favourable or unfavourable.

Favourable conditions:

(1) Clear to partly cloudy skies with fleecy clouds and relatively warm day temperatures.
(2) Cloudy days with rapidly changing winds, perhaps accompanied by brief showers.

Unfavourable conditions:

(1) The most unfavourable conditions occur when the air is relatively still. These days are usually foggy, hazy or smoky. An indication of unfavourable conditions may be drawn from the behaviour of smoke from a nearby smokestack. If the smoke fans out horizontally after the initial rise above the stack with little evidence of looping or vertical motion as the smoke moves away from the stack, then a poor dispersion condition exists and, very likely a temperature inversion.
(2) Clear, somewhat hazy days with fairly constant temperatures and possibly very light winds.

The difference in intensity of the noise from a blast is a function of the weather conditions at the time. These conditions determine the velocity of sound in different directions and at different altitudes. Noise from normal commercial blasting operations is not significantly affected by conditions at altitudes of more than 1500 m above ground level. The factors that influence sound propagation are wind velocity and temperature.

Normally air temperatures decrease with increasing altitude, the temperature drop being usually 1°C for 150 m.

Should the air temperature be constant over a range of altitudes then an isotherm is said to exist, but if the air becomes warmer with increasing altitude then an inversion occurs.

The following sets of conditions occur and are described below:

(1) Atmosphere perfectly still and isothermal.
(2) Sound speed increases with altitude.
(3) Sound speed decreases with altitude.
(4) Temperature and sound speed variations with altitude.
 (*a*) increase and then decrease,
 (*b*) decrease, increase and then decrease,
 (*c*) increase, decrease, increase at a greater rate and finally decrease.
(5) Wind speed and sound speed.
 (*a*) increase with altitude,
 (*b*) decrease with altitude.

Atmosphere perfectly still and isothermal

In the event of the very rare circumstance of a blast occurring when the atmosphere is perfectly still and isothermal, then the velocity of the sound in all directions will be equal. The wave front will be hemispherical in shape with the sound waves extending radially from the blast site (fig. 19).

Sound speed increasing with altitude

If the weather conditions (temperature and wind velocity) are such that a greater sound velocity in any direction occurs above the surface of the earth, then a wound-speed inversion occurs. In this case, parts of the sound wave in the direction of the velocity increase may be returned to the ground by refraction and produce a louder noise at the points of return.

When weather conditions exist that prevent the sound waves from progressing with the same velocity in all directions, then the wave front can no longer be hemispherical in shape. Although the wave front must remain continuous, the shape changes with some parts accelerating and the remainder lagging. Since the direction of sound propagation is at right angles to the wave front this will cause the front to bend.

When the temperature increases with altitude (a resultant increase in sound velocity is also experienced) the wave front drags in the direction of the surface of the earth and the sound waves are bent back to earth (fig. 20). It can be seen that the points of loud disturbance may be adjacent to points of very little return, and where two or more rays meet (focus) then the noise is extremely loud.

Sound speed decreasing with altitude

If the air temperature decreases with altitude, then there is a corresponding decrease in sound velocity and the sound waves are bent upwards and

5 cm

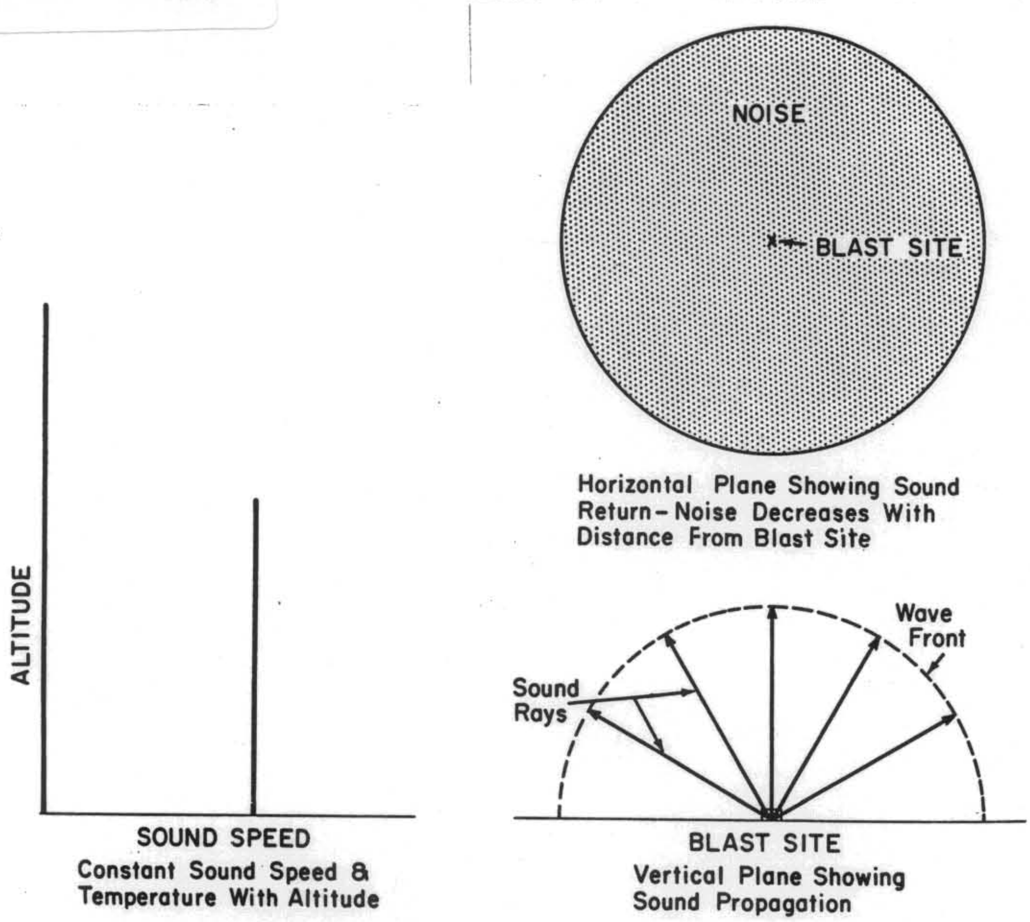


Figure 19. *Sound propagation from blast site.*

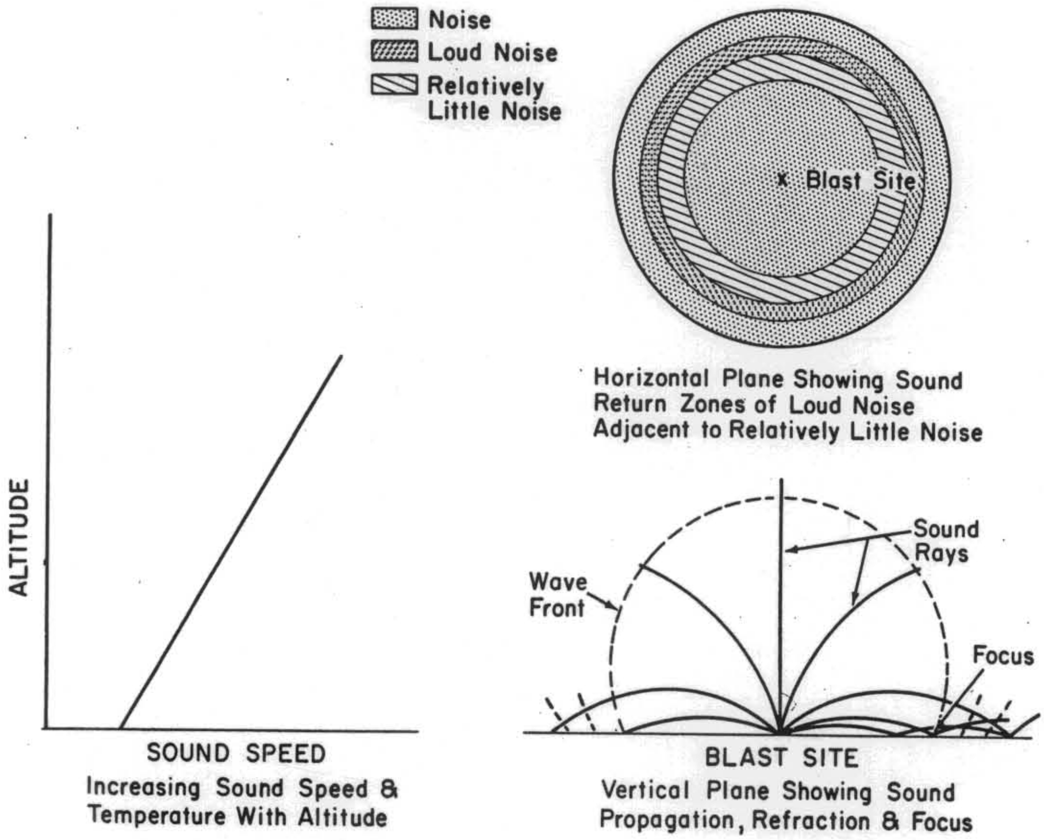


Figure 20. *Sound propagation from blast site.*

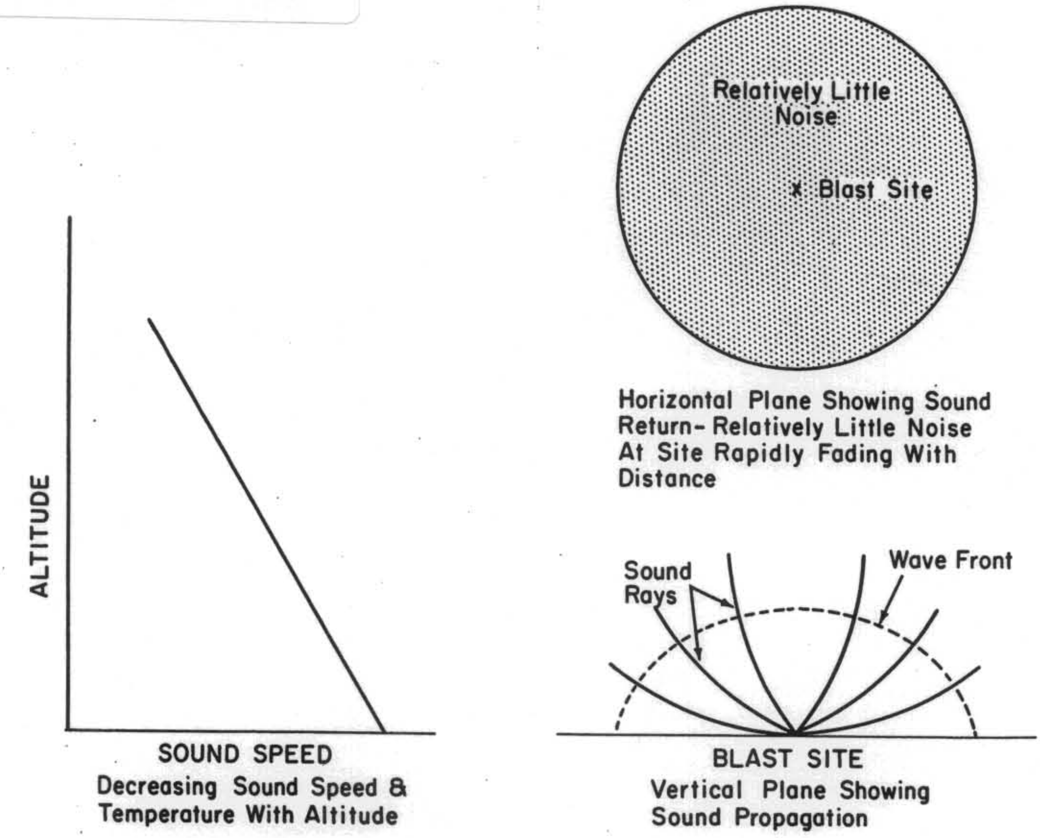


Figure 21. *Sound propagation from blast site.*

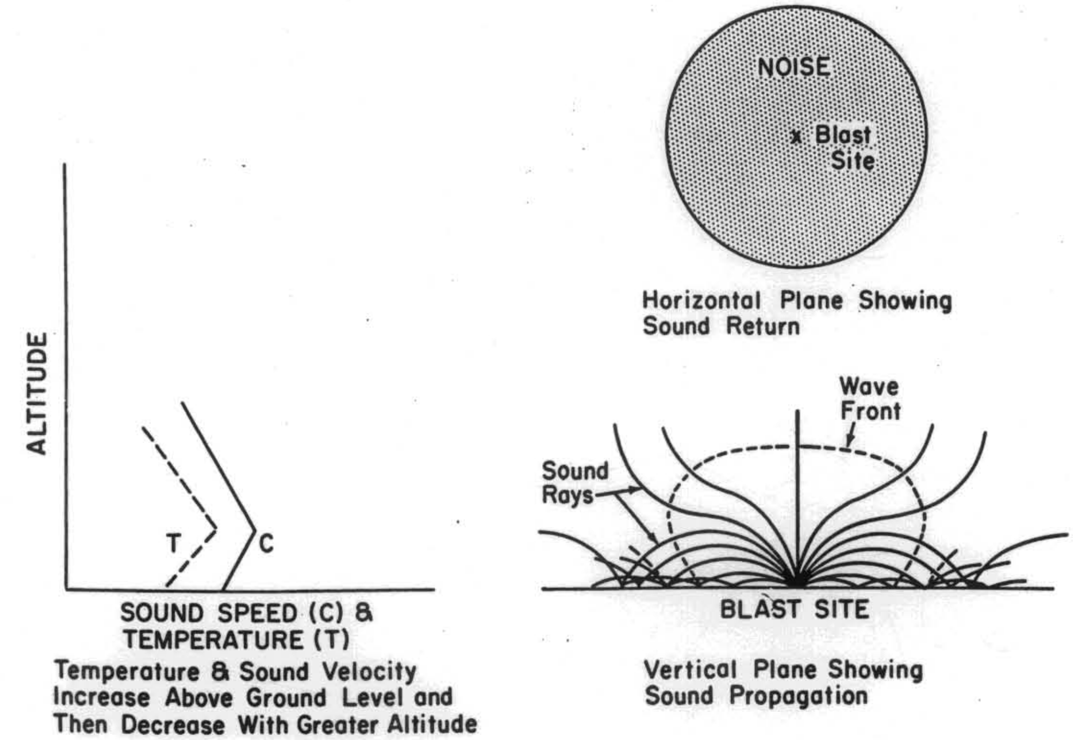


Figure 22. *Sound propagation from blast site.*

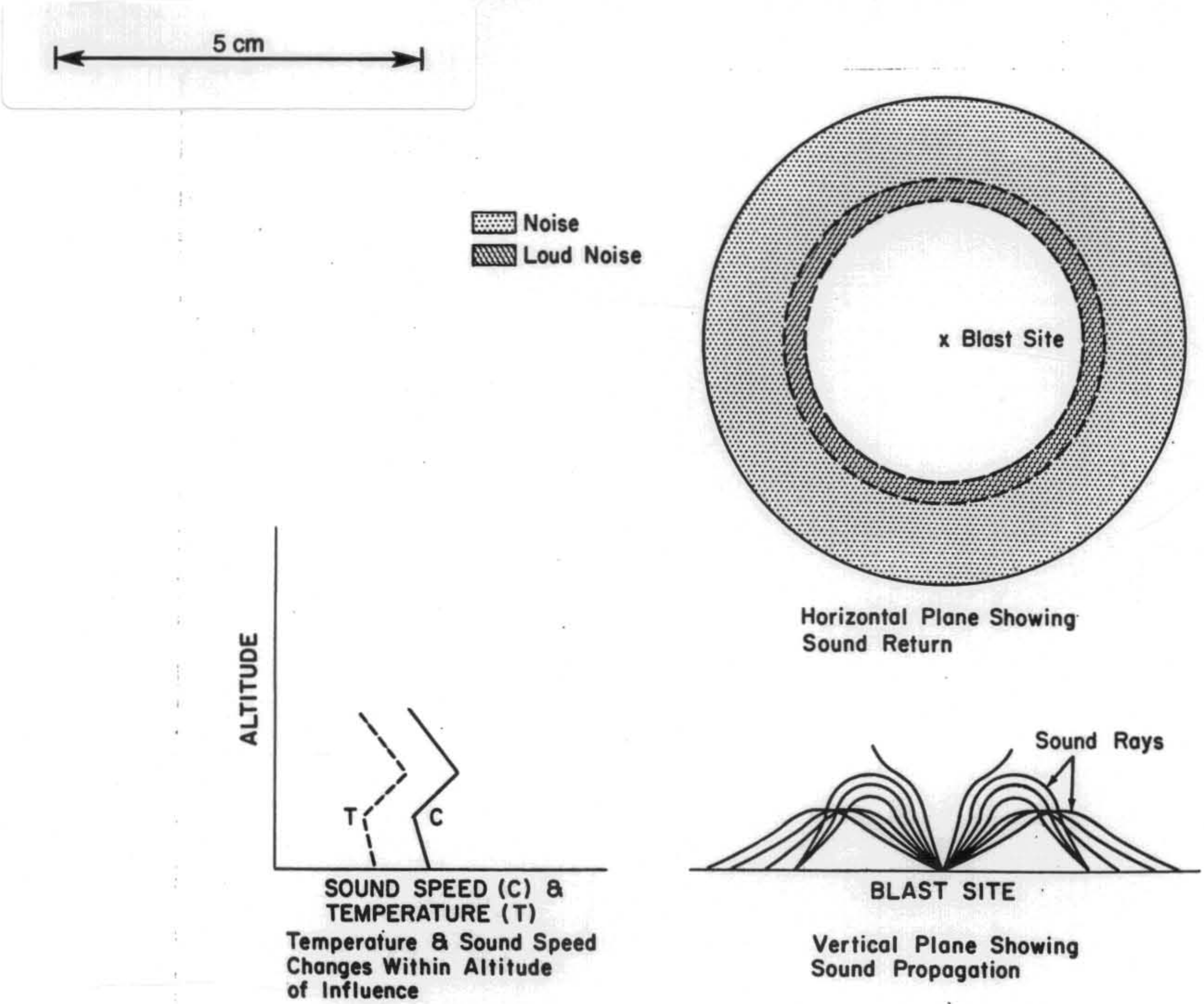


Figure 23. *Sound propagation from blast site.*

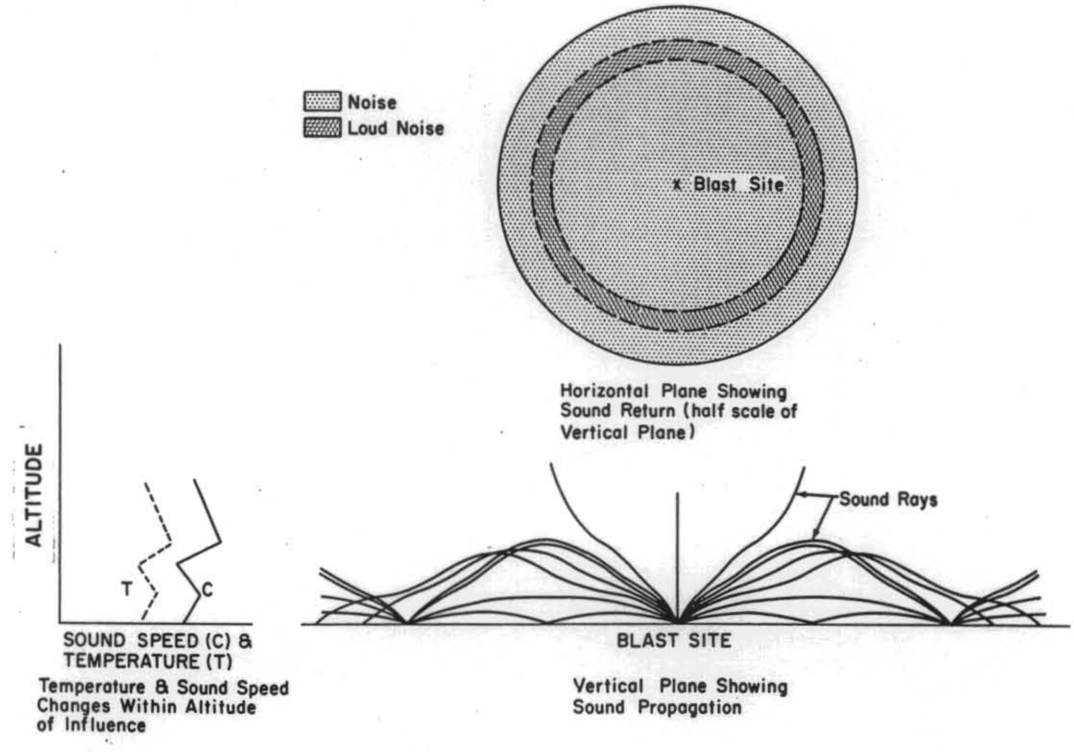
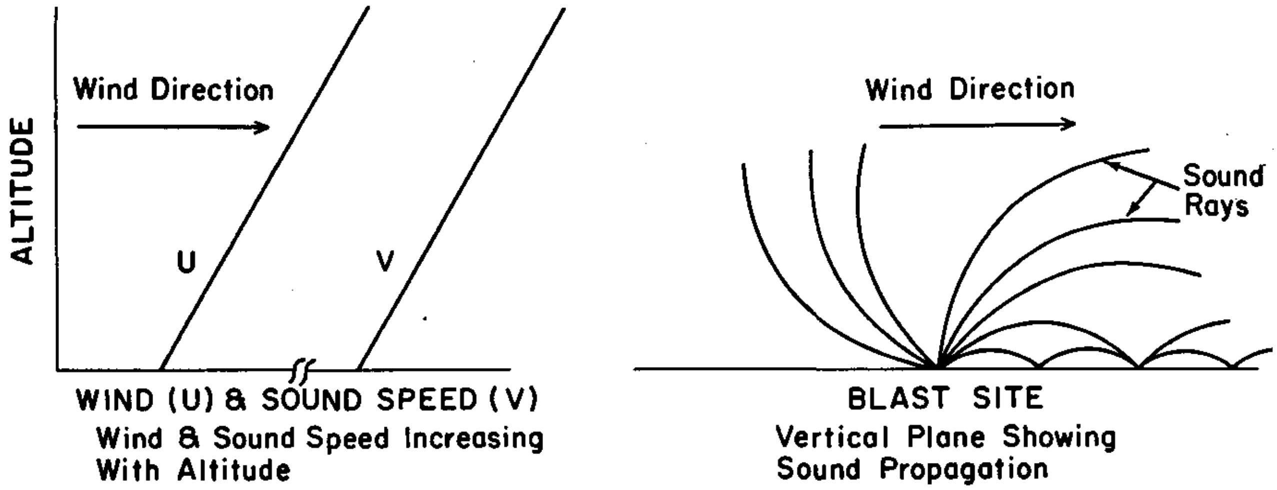


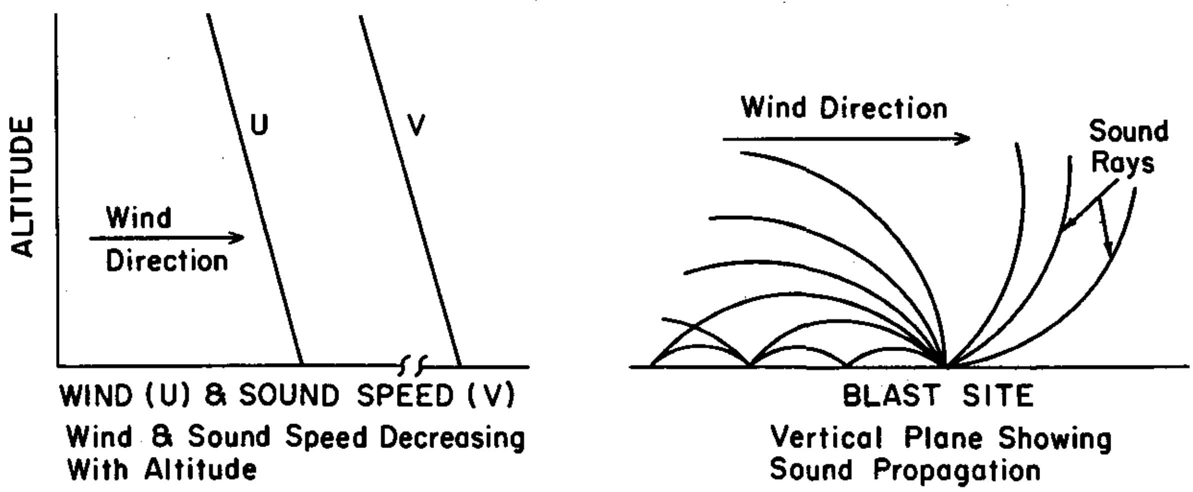
Figure 24. *Sound propagation from blast site.*

5 cm



Sound propagation from a positive wind gradient showing greatest sound return down wind from blast site.

Figure 25. *Sound propagation from blast site.*



Sound propagation from a negative wind gradient showing greatest return up wind from blast site.

Figure 26. *Sound propagation from blast site.*

do not return to ground. This effect is shown in Figure 21 and is obviously the most ideal condition for blasting as far as noise dispersion is concerned.

Temperature variations with altitude

Increase and then decrease. When the air temperature increases for a short distance upward and then decreases with increasing altitude no zones of silence will be present and the sound will be a rumble of relatively long duration. The duration of the sound is caused by the sound rays reaching the listener after a number of reflections and at different times since the reflection path length will be different for each ray (fig. 22).

Decrease, increase and then decrease. When the air temperature decreases in the lower altitudes, then increases for a similar distance and finally decreases again within the altitude of influence a zone of relatively little noise exists near the blasting location with loud noise disturbance at more distant locations. A narrow zone in which the sound return is especially loud and sharp and occurs outside the relatively quiet zone. This is the result of a bundle of rays returning to the ground at these points at exactly the same time. Beyond this zone of very loud noise, other sound rays are returning to the surface, but are lower in intensity and sharpness (fig. 23).

Increase, decrease, increase and then decrease. A third common speed inversion that may occur is one in which, with altitude, the temperature successively increases, decreases, increases again at a greater rate, and finally decreases. In this case there is a zone of noise surrounding the blasting site and proceeding in all directions. The noise in the zone nearest the blast will be a rumble of relatively long duration. This atmospheric condition also results in a zone of very loud noise. In this zone several sound rays return to the earth at the same time and are reinforced by rays that have travelled a shorter path and been reflected from the ground (returned by surface inversion); this is depicted in Figure 24.

Wind and sound speed

Increase or decrease with altitude. The effect of wind or noise disturbance is directional, either in a down wind or up wind direction depending on whether the wind velocity increases with altitude (positive wind gradient) or decreases (negative wind gradient). A positive wind gradient produces the greatest return down wind from the blast site and a negative wind gradient produces the greatest return up wind. These conditions are shown in Figures 25 and 26 and help to explain how a loud noise return can occur up wind from a blast on a day when the wind is relatively strong.

Generally winds tend to produce negative wind gradients and so prevent the formation of inversions. In normal confined blasting, the effect of wind cannot be discounted but temperature effects are felt to be more critical.

[25 June 1976]