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Review of diver noise exposure

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Divers are exposed to high levels of noise from a variety of sources both above and below water. The noise exposure should comply with 'The Control of Noise at Work Regulations 2005' (CoNaWR05). A detailed review of diver noise exposure is presented encompassing diver hearing, noise sources, exposure levels and control measures. Divers are routinely exposed to a range of noise sources of sufficiently high intensity to cause auditory damage and audiometric studies indicate that diver hearing is impaired by exposure to factors associated with diving. Human hearing underwater, in cases where the diver's ear is wet, is less sensitive than in air and should be assessed using an underwater-weighting scale. Manufacturers of diving equipment and employers of divers have a joint responsibility to ensure compliance with the exposure values in the CoNaWR05, although noise is only one hazard to a diver, and a balanced risk assessment must be applied to the whole diving operation. A diver noise reduction strategy is proposed and a health surveillance programme, involving audiometric tests for divers, should be established.

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Executive summary

Divers are routinely exposed to high levels of noise arising from their ambient environment. The noise exposure should comply with 'The Control of Noise at Work Regulations 2005' (CoNaWR05). There is evidence that divers are exposed to noise levels that exceed the requirements of the CoNaWR05.

The Health and Safety Executive (HSE) tasked QinetiQ at Alverstoke (Contract JN3983) to carry out a review of the available information on diver noise exposure, to enable a clear position to be presented to the commercial diving industry. The review identified sources of noise exposure experienced by commercial divers and related these to the requirement to achieve noise levels that are as low as reasonably practical (ALARP) and in accordance with the CoNaWR05.

Hearing underwater differs from hearing in air as the acoustic properties of water and air are different. Unlike sound in air, sound in water can propagate relatively freely through the human body. Although underwater hearing is not fully understood, it is likely that both bone conduction and tympanic sound conduction combine to produce hearing underwater. Bone conduction would appear to play a much greater role in hearing underwater than it does in air.

Human hearing underwater, with a 'wet' ear (*i.e.* where the external ear canal is filled with water, and water is in direct contact with the tympanic membrane), is less sensitive than it is in air, and so noise underwater is believed to produce less hearing damage than airborne noise. Due to the reduced hearing sensitivity of the ear immersed in water, the noise exposure of a diver with 'wet' ears, as may occur when using a band mask, should be adjusted using an underwater (UW) weighting scale rather than the (A) weighting scale used in air.

However, if the diver's ears are 'dry', *i.e.* when wearing a diving helmet, the noise exposure is the same as for airborne noise. The available evidence indicates that hearing sensitivity in hyperbaric environments, and in different breathing gases (heliox, nitrox or trimix), is similar to that in air at atmospheric pressure. Thus the exposure values, as identified in the CoNaWR05, should be applied to hyperbaric conditions and all breathing gas mixtures.

The review identified fifteen studies that have investigated hearing loss in divers; most of these studies used a combination of audiometric testing, medical examination for ear pathology and questionnaires. Twelve of the fifteen studies are consistent with diver hearing being impaired by exposure to factors associated with diving. Of these, several studies also suggest that divers' hearing deteriorated faster than non-divers *i.e.* increased the age-related deficit.

These hearing deficits are likely to be due to the combined effects of noise, pressure including barotraumas and decompression illness (DCI), although it is difficult to separate out the individual influences of these factors. In particular, it is difficult to establish, from the audiometric data, that the hearing impairments are due to noise *per se*.

A range of noise sources influence a diver's hearing, *e.g.* ambient underwater noise, dive site noise, self-generated breathing and helmet noise, tool noise and noise in compression chambers. When combined it is likely that these noises will result in a daily noise dose exceeding the exposure action values of the

CoNaWR05. However, on the surface divers are able to wear surface hearing protectors and to seek a quiet refuge.

Underwater tools generate very high noise levels, and some tools identified, if used for a typical diving work period, would result in noise doses that exceed the upper exposure action value. During compression and decompression, compression chambers typically generate high noise intensities that would rapidly exceed exposure values.

Divers produce a high level of breathing noise generated by gas flow through the regulator demand valve and self-generated breathing noise is a major contributor to divers' noise exposure when wearing diving helmets. The noise levels in diving helmets increase with increasing diver ventilation rate, with helmets producing exhaust bubbles presenting higher noise levels than those that did not. Communications (and flushing through) also create high noise levels. The noise levels depend on the helmet design, with some models leading to exposures that, for typical commercial dive durations, would exceed the exposure action and limit values of the CoNaWR05

As a consequence of exposure to these various noise sources, the total noise dose received by divers can potentially be very high. Noise control measures are required to reduce the noise hazard to ALARP and to comply with the requirements of the CoNaWR05.

Manufacturers of diving equipment and employers of divers have a joint responsibility to ensure compliance with the Supply of Machinery (Safety) Regulations 1992 (SM(S)R92) and the exposure values in the CoNaWR05. Compliance with CoNaWR05 requires calculation of a diver's total daily or weekly dose, *i.e.* taking into account all activities above and below water.

Manufacturers of diving plant and equipment are responsible, SM(S)R92 and BS EN 15333 parts 1 and 2, for ensuring that noise levels of diving equipment are as low as can be achieved technically, and to provide data on the noise produced by their systems.

Employers are responsible for ensuring that diver's noise exposure is reduced to ALARP and that it does not exceed the exposure limit value. Where the CoNaWR05 action values are exceeded noise reduction strategies should be implemented to limit exposure.

As noise is only one hazard to a diver, a balanced risk assessment must be applied to the whole diving operation; fully mitigating against one risk may exacerbate others.

It is proposed that a diver noise reduction strategy should employ the following hierarchy:

- Eliminate or reduce noise at source, *e.g.* by redesigning the equipment generating noise
- Provide noise attenuation at the divers head/ear, *e.g.* by noise insulating materials or Active Noise Reduction (ANR)
- Restrict the exposure time of the diver to the noise
- Provide hearing protection *e.g.* appropriate ear-plugs or ear-muffs.

Given the potentially high levels of noise that divers are exposed to, management of noise exposure risk for divers should include establishing a comprehensive health surveillance programme, involving audiometric tests for divers.

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1 Introduction

1.1 Background

Divers are routinely exposed to high levels of noise arising from the ambient environment, self-generated breathing noise, communications, the operation of underwater tools, and the dive site above and below water. Audiometric studies on divers have identified some concerns in respect of accelerated/excessive hearing loss [1] [2].

To meet the requirements of the European Economic Community (EEC) Directive 2003/10/EC, new noise exposure regulations were introduced in April 2006. These were implemented in the United Kingdom (UK) by “The Control of Noise at Work Regulations 2005” (CoNaWR05) (Statutory Instrument 2005 No. 1643) [3] [4]. These require employers to prevent or reduce risks to health and safety from exposure to noise at work and to:

- assess the risk to all employees including divers from noise at work;
- take action to reduce the noise exposure that produces these risks;
- provide hearing protection if the noise risk cannot be reduced sufficiently by other methods;
- ensure legal limits on noise exposure are not exceeded;
- provide employees with information, instruction and training;
- conduct health surveillance where there is a risk to health.

The CoNaWR05 require employers to take specific action at certain noise action values. These relate to the levels of exposure to noise of divers averaged over a working day or week and the maximum noise (peak sound pressure) to which they may be exposed. These values have been reduced by 5 dB from previous regulations and are:

- lower exposure action values:
  - Daily or weekly exposure of 80 dB(A) re. 20 µPa.
  - Peak sound pressure of 135 dB(C) re. 20 µPa.
- upper exposure action values:
  - Daily or weekly exposure of 85 dB(A) re. 20 µPa.
  - Peak sound pressure of 137 dB(C) re. 20 µPa.
- exposure limit values:
  - Daily or weekly exposure of 87 dB(A) re. 20 µPa.
  - Peak sound pressure of 140 dB(C) re. 20 µPa.

Although an employee may work or be exposed to noise for a range of working times during the day or week, the average noise exposures are normalized to the equivalent of a nominal 8 hour working day and 5 working days per week.

Where action can be taken to reduce noise risk, then this should be done, relative to the level of risk. This is the principle of reducing risk to a level as low as reasonably practical (ALARP).

There is a growing body of evidence that divers are exposed to noise levels that put them at risk of hearing damage [5] [6] [7]. Compliance with the CoNaWR05 requires a complete noise risk assessment of a diver's working environment, and may require changes to diving practices and equipment as well as the wearing of hearing protection. Design modification of diving equipment to produce less breathing noise, use of noise cancellation techniques to reduce incident noise at the ear and the provision of hearing protection for divers are all technically feasible.

The Health and Safety Executive have tasked QinetiQ at Alverstoke (Contract JN3983) to carry out a review of the available information on diver noise exposure, to enable a clear position to be presented to the commercial diving industry.

1.2 Objectives

The purpose of this review is to identify sources of noise exposure experienced by commercial divers and to relate these to the requirements and exposure values of the CoNaWR05. The evidence from audiometric studies for hearing loss in divers will also be assessed in respect of the identified noise exposures. The responsibilities of diving equipment manufacturers and employers will be identified, and guidance provided on ways to achieve compliance with current noise regulations.

1.3 Scope of work

The review identifies studies on the noise exposure of commercial divers and covers:

- diver hearing underwater and at pressure
- ambient underwater noise
- self-generated breathing noise and helmet noise
- diving site noise and hearing protection
- underwater tool noise
- diver audiometric surveys.

A search of published articles from the scientific literature, reports by the UK, US and other military organisations and the HSE has formed the basis of the study.

The information is reviewed and discussed in the light of the requirements of the EEC Directive 2003/10/EC, the CoNaWR05 and the Supply of Machinery (Safety) Regulations 1992 (SM(S)R92) (Statutory Instrument 1992 No. 3073). Manufacturers' and employers' responsibilities are identified, and guidance provided on ways that compliance with the regulations may be achieved.

1.4 Information search strategy

Searches were carried out using Scopus, Medline, Google, Google Scholar, with the following keywords:

- diver noise
- diver noise exposure

- diver hearing
- underwater noise
- ambient underwater noise
- barotraumas and diver (diving) helmet noise
- diving site noise.

The journals scanned for relevant information were:

- Undersea and Hyperbaric Medicine Journal
- Undersea Biomedical Research (1974-1992)
- The Journal of the Acoustical Society of America.

The articles found using these searches also contained references that were not identified in the initial search and, where relevant, these were obtained for potential inclusion in the review. In total, 143 articles were located, and these were scanned for relevant and reliable information and included in the review, where appropriate.

1.5 Specification of noise levels

Sound may be defined as vibration that is transmitted through a solid, liquid, or gas (*i.e.* a sound wave). In respect of hearing, audible sound relates to the frequency components of the vibrations that can be detected by the human ear.

Sound pressure is the local pressure change (from ambient) caused by the vibration. Sound pressure can be measured using a microphone in air and a hydrophone in water; the System International (SI) unit for sound pressure is the Pascal (symbol: Pa).

The traditional method of expressing noise is as a Sound Pressure Level (SPL) [3] where the ratio of the sound pressure to a given reference pressure is presented as a logarithm (Equation 1). The unit for SPL is the decibel (dB) and should be presented together with the reference pressure.

$$L_p(SPL) = 20\log_{10}\left(\frac{P_{RMS}}{P_0}\right) \qquad \text{Equation 1}$$

Where: L_p = Sound Pressure Level (dB)

P_{RMS} = Root Mean Square (RMS) Sound Pressure (Pa)

P_0 = Sound Reference Pressure (Pa)

When noise is propagating in air, the noise level in dB is referenced to 20 μPa (the average human threshold of hearing at 1 kHz), and so noise levels are written as:

dB re. 20 μPa

Measurements expressed in this way describe the dB level of the sound above human hearing threshold. To account for the sensitivity of the human ear in air at different frequencies, an A weighted scale, denoted by dB(A) is used, and indicates the way in which airborne noise is related to the human perception of sound. Thus the presentation for noise in air related to human hearing is:

dB(A) re. 20 μPa

Noise underwater is very different than in air and, by convention, underwater noise measurements are typically referenced to a pressure of 1 μPa [8]. Underwater sound is therefore expressed using the form:

dB re. 1 μPa

However, dB is only a ratio of the level of sound above a reference pressure. As the fundamental SI unit of sound is the Pascal, airborne and underwater sound levels can be converted by adding or subtracting 26 dB; *e.g.* a 1 Pa root mean square (RMS) sound pressure wave in air can be expressed as a noise of 94 dB re. 20 μPa, whereas the same 1 Pa pressure wave in water is expressed as 120 dB re. 1 μPa.

To be repeatable and reliable, measurement of noise radiation from a source must be undertaken in the far field of that source [8]. This often requires measurement at a range of tens or hundreds of metres. As the level of noise varies with range, measurements are typically normalised to allow direct comparison of levels. The convention is to specify the apparent noise at 1 m from the source; known as the Source Level. Thus, the noise from a ship measured at several kilometres range, may be expressed as an estimated Source Level at 1 m in the form:

dB re. 1 μPa @ 1 m

Where a reference source has used a range other than one metre, the level at one metre from the source may be estimated using an acoustic propagation model. In this report spherical spreading has been assumed [8].

The conventions presented here have, wherever possible, been adhered to throughout the report by converting the levels, where a different reference pressure has been used.

1.6 Specification of noise dose

The potential noise hazard from an airborne noise exposure is a function of the average A-weighted level of the noise (L_{Aeq}) and the period of exposure, leading to an overall daily noise dose ($L_{EP,d}$) [4]. The noise is A-weighted to transform the linear response of the measuring instrument (be that a hydrophone or microphone) into a form that is representative of the human non-linear response to noise. The noise assessment terms are defined as:

Equivalent continuous sound level (L_{Aeq})

L_{Aeq} is the A-weighted energy mean of the noise level, averaged over the measurement period. It can be considered as the continuous steady state noise level that would have the same total A-weighted acoustic energy as the real fluctuating noise measured over the same period.

Daily noise dose ($L_{EP,d}$)

The CoNaWR05 sets duties triggered by values of the 'noise dose' incurred that day. The noise dose is the sum of the total A-weighted noise energy, expressed as a level normalised to an 8 hour period (*i.e.* an equivalent steady state level for a period of 8 hours).

1.7 Specification of pressure (diver depth)

Several units for pressure are used in this report. The default unit for pressure is the 'System International' (SI) unit of Pascal (Pa). However, it is common to use metres (m) to describe the pressure a diver is exposed to; *i.e.* depth below the water surface. Throughout the work carried out to produce this report, it has been assumed that a pressure change of 100 kPa = 10 metres (m) = 1 bar (assuming a density of seawater of 1.01972 $kg \cdot l^{-1}$ at 4 °C) and that the air pressure at sea level = 0 m = 101.3 kPa (one standard atmosphere). Where depth has been expressed in feet of sea water (fsw) a general conversion of 10 m = 33.33 fsw has been applied.

2 Diver hearing underwater and at pressure

2.1 Hearing in humans

In air the human ear responds to sound frequencies in the range 20 Hz to 20 kHz, and has a dynamic range in excess of 100 dB. The ear has a resonance which makes hearing most sensitive to frequencies between 1 and 6 kHz, with maximum sensitivity around 4 kHz. The sensitivity deteriorates rapidly at higher frequencies and at frequencies below 100 Hz.

The ear comprises three sections: the outer, middle and inner ear (Figure 2.1). The outer ear consists of the pinna, the visible fleshy part of the ear, responsible for focusing sound into the auditory canal and along to the eardrum. The middle ear is an air-filled cavity, and is separated from the outer ear by the eardrum, a taut membrane also known as the tympanic membrane.

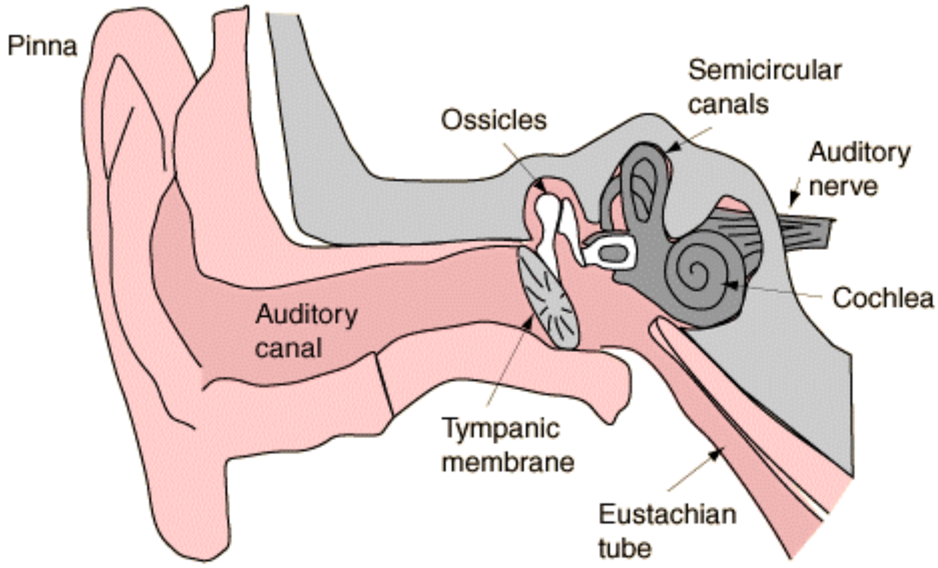
When sound waves reach the eardrum, they cause it to vibrate in synchrony. This results in the transmission of sound to the middle ear, and from there it is further propagated via three small bones called the ossicles (the malleus, incus, and stapes). The stapes is connected to another membrane known as the oval window which communicates with the cochlea within the liquid-filled inner ear.

The cochlea (Figure 2.1) is a narrow, fluid-filled tube, coiled up into a spiral horn with the diameter of the tube decreasing toward the top of the horn. It is where sound is converted, via pressure-induced movement of hair cells, into electrical activity in neurons of the auditory nerve producing hearing. Each sound frequency excites (resonates) a different region of the cochlea, resulting in sounds of differing pitch being heard. This is known as tympanic sound conduction.

A further mechanism for producing hearing is bone conduction, where sound is conducted to the inner ear through the bones of the skull. The presence of bone conduction explains why a person’s own voice sounds different to them when it is recorded - in this case, there is no bone conduction present. For airborne sound reception, the overall contribution of bone conduction to hearing is rather small, but it has an increasing contribution at low and high frequencies.

2.2 Hearing underwater

Hearing underwater differs from hearing in air as the acoustic properties of water and air are different. Unlike sound in air, where much of the incident sound energy is reflected by the skull, sound in water can propagate relatively freely through the human body, as the acoustic properties of human tissue and water are similar. As sound goes through the skull, it excites the cochlea and/or the ossicles, and sound is produced independently of the outer ear and eardrum.



|-----------------outer ----------------|-middle-|-inner ----|
ear ear ear

Figure 2.1: Diagram of the ear, showing outer, middle and inner ear

This so-called bone-conduction route was for many years considered to be the only way in which sound could be heard underwater [9] [10] [11].

However, evidence that tympanic conduction is also involved in hearing underwater has come from studies investigating the ability of divers to locate sound. In air, sound localisation occurs by detecting the delay between sounds arriving at each ear, and involves tympanic conduction of sound. If bone conduction is the only mechanism for hearing then localisation would not be possible because the sound at each ear would be similar. Several studies have, however, proved that sound localisation by divers is possible, although difficult, and so tympanic conduction may also contribute to hearing [12] [13] [14] [15].

Although underwater hearing is not fully understood, the likely explanation is that both bone conduction and tympanic sound conduction produce hearing underwater, the so-called dual path theory. At low frequencies tympanic conduction appears to predominate and this may explain why sound localization is more acute at these frequencies. At high frequencies, bone conduction is considered to be the dominant factor [10] [12] [15]. Bone conduction would appear to play a much greater role in hearing underwater than it does in air.

2.3 ‘Wet’ ear/‘Dry’ ear effect

When using Self Contained Underwater Breathing Apparatus (SCUBA) or a band-mask a diver’s head is surrounded by water and the ears are likely to be ‘wet’ (*i.e.* there is water in the auditory canal and in contact with the tympanic membrane). It should be recognized that in some circumstances the auditory canal may not be filled with water (*e.g.* with tight fitting hoods) and air or other gas may still be present. Where the external ear canal is filled with water, estimating the noise hazard requires use of an underwater weighting scale that adjusts for decreased hearing sensitivity underwater. The decreased sensitivity may be due to the movement of the tympanic membrane being damped by the mass of water, as opposed to air, that has to be moved.

However, for an enclosed helmet, the diver's head is surrounded by air or an alternative gas such as nitrox or heliox and the ears are 'dry'. In this case determining the noise hazard is achieved using the same method as for occupational noise hazard assessment on land based on the A-weighted scale for sound. All that is required is knowledge of the incident noise at the diver's ear.

Therefore, the type of headgear worn by a diver, *i.e.* diving helmet (dry ear) or hood (wet ear), is important in determining the noise hazard. As hearing is more sensitive in air than in water [13], it is assumed that a given noise level is more damaging to the 'dry' ear than the 'wet' ear.

2.4 Underwater auditory thresholds and frequency sensitivity

Early studies of underwater auditory thresholds produced results that tended to show a large degree of variability in threshold levels (*e.g.* [10] [16] [17]). These findings are likely to have resulted from a failure to control for relatively high background noise levels in water, along with inaccuracies in measurement of the sound intensity at the subject's head and failure to establish whether subjects had normal tympanic and bone conduction hearing [12].

The underwater auditory threshold curve has been determined by Parvin *et al.* [13] (Figure 2.2); both the underwater and airborne curves are displayed for comparison.

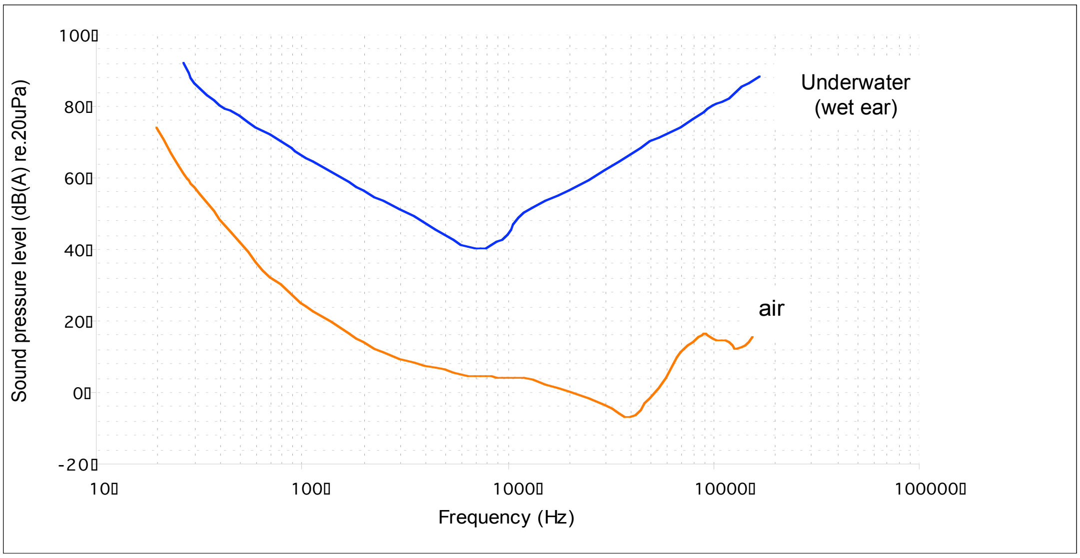


Figure 2.2: The threshold of hearing in air and in water [13]

Comparison of the air and underwater auditory threshold curves (Figure 2.2) shows the following:

- the human auditory system is most sensitive to waterborne sound at frequencies from 400 Hz to 1 kHz, with a peak at approximately 800 Hz. Hence, these frequencies have the greatest potential for damage;
- within this frequency band, underwater hearing is 35-40 dB less sensitive than in air;
- for airborne sound, hearing is most sensitive between 2 and 6 kHz, with a maximum sensitivity at approximately 4 kHz. However, underwater hearing is less sensitive at these frequencies, and so the noise hazard is reduced;

- above 6 kHz, there is again reduced hearing underwater compared with air, although hearing is still possible at frequencies as high as 16 kHz;
- below 400 Hz, the underwater hearing threshold drops off at a rate of approximately 35 dB per decade to 40 Hz. This is not as rapid as for air, and suggests that sound at frequencies below 100 Hz contributes to underwater sound perception to a far higher degree than in air, and so may be a greater hazard;
- for relatively high frequencies, a higher level of noise would be permissible underwater than would be in air, as a result of the reduced sensitivity of the ear underwater.

2.5 Underwater noise weighting scale

The exposure action values of 80 and 85 dB(A) in the CoNaWR05 are applicable to the air environment rather than underwater in those cases where the ear is 'wet'. In order to assess the noise hazard underwater, it is necessary to re-assess these values by taking into account the reduced sensitivity of the human ear underwater. A method for achieving this was developed by Parvin *et al.* [13] [18], who defined an 'underwater noise weighting scale', measured on the dB(UW) scale, by analogy to the A-weighted scale, dB(A).

The scale defines the relationship between waterborne sound incident upon a water-filled external ear and the resultant auditory perception, and is shown in Table 2.1. Use of the UW-weighting scale enables the allowable level of noise underwater to be assessed and directly compared to in air dB(A) levels.

Within Table 2.1, a method of converting underwater hearing thresholds into an underwater scale is presented, which can be used to assess the noise hazard to a diver from underwater sound. The UW-weighting curve is obtained using the following quantities:

- column (1) is the auditory threshold sound level underwater (Minimum Audible Field (MAF), *i.e.* the lowest sound that can be heard underwater at each frequency
- column (2) is the auditory threshold sound level in air
- column (3) is the difference between columns (1) and (2) giving the reduction in hearing sensitivity at each frequency
- column (4) is the A-weighted curve, *i.e.* an adjustment that takes into account the sensitivity of the human ear in air
- column (5) is the UW-weighting scale, which is calculated by adding the reduction in sensitivity of the ear underwater, column (3), to the A-weighted curve, column (4).

Centre Freq (Hz)	(1) MAF underwater dB SPL re.20µPa	(2) MAF Air dB SPL re.20µPa	(3) Difference [(2)−(1)] dB	(4) A weighting Factor dB	(5) UW weighting [(3)+(4)] dB(UW) re.20µPa
25	92	65	−27	−46	−73
31.5	87	56	−31	−39.4	−70.4
40	81	48	−33	−35	−68
50	77	42	−35	−30.2	−65.2
63	74	36	−38	−26.1	−64.1
80	70	29	−41	−22.3	−63.3
100	67	25	−42	−19.1	−61.1
125	64	21	−43	−16.2	−59.2
160	59	17	−42	−13.2	−55.2
200	56	14	−42	−10.8	−52.8
250	53	11	−42	−8	−50
315	49	9	−40	−6.5	−46.5
400	46	7.5	−38.5	−4.8	−43.3
500	44	6	−38	−3.3	−41.3
630	43	5	−38	−1.9	−39.9
800	41	5.5	−35.5	−0.8	−36.3
1 000	44	5	−39	0	−39
1 250	48	4	−44	0.5	−43.5
1 600	54	2.5	−51.5	1	−50.5
2 000	57	1	−56	1.2	−54.8
2 500	61	−1	−62	1.2	−60.8
3 100	64	−3	−67	1.2	−65.8
4 000	67	−4	−71	1	−70
5 000	70	0	−70	0.5	−69.5
6 300	73	6	−67	−0.2	−67.2
8 000	76	15	−61	−1.1	−62.1
10 000	80	15	−65	−2.5	−67.5
12 500	83	13	−70	−4	−74
16 000	86	25	−61	−7	−68

Table 2.1: The underwater weighting scale [13]

2.6 Example of the noise hazard underwater using the underwater weighting scale

The noise levels associated with a small compressed air rock drill are presented in Figure 2.3 and Table 2.2.

The output noise from the drill (*i.e.* underwater), as indicated in Figure 2.3 by the curve labeled ‘external hood noise’, is broadband, being high across the entire spectrum and varying between 120 and 140 dB.

However, due to attenuation by the neoprene of the diver’s band-mask, the level at the ear of a diver is reduced at frequencies above 200 Hz as indicated by the curve labeled ‘internal hood noise’.

It follows, therefore, that a diver’s foam neoprene hood can offer substantial protection from underwater noise, and that this will be greatest at shallower depths where the neoprene has not been compressed, reducing its noise attenuating properties.

When considering the use of a foam neoprene hood, it is also necessary to assess the risk of physical injury to the head; foam neoprene hoods do not provide adequate physical head protection for all situations.

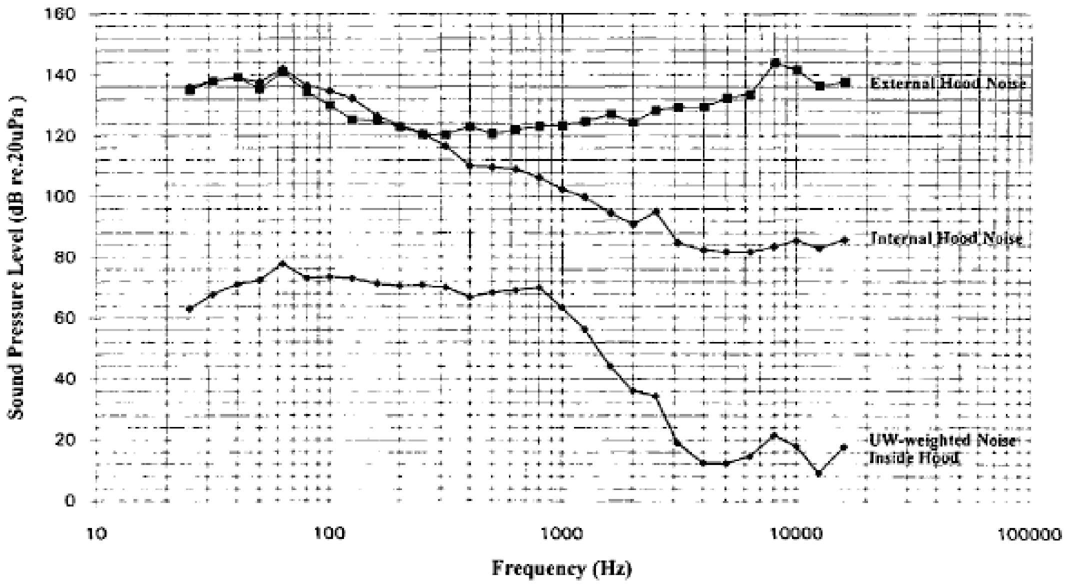


Figure 2.3: Sound levels inside and outside a diving band-mask hood while operating a rock drill together with the UW weighted noise exposure at [13]

Using the UW-weighting scale, the noise hazard of the rock drill can be calculated for a diver wearing a diving hood ('wet ear') [13]. The method is shown in Table 2.2 where column 2 represents the noise level of the drill inside the diver's hood, column 3 is the UW-weighting scale, and column 4 is the 'sensation level' at the ear underwater. The 'sensation level', obtained by adding columns 2 and 3 at each frequency (presented as the 'UW-weighted noise' curve on Figure 2.3) may be used to calculate the noise hazard.

It can be seen (Figure 2.3) that most of the noise hazard lies between 30 and 1000 Hz, and for a diver with a 'wet ear' (*e.g.* a diver wearing a band-mask) the noise hazard is reduced considerably, with a maximum level of less than 80 dB, due to the reduction in hearing sensitivity underwater.

The total noise hazard of the rock drill is obtained by calculating a logarithmic sum of the 'sensation level' noise values, giving a noise hazard of 83.8 dB(UW) re. 20 µPa. The dB(UW) noise level of this rock tool will contribute to a daily noise exposure that may require action to be undertaken.

Centre Freq (Hz)	Noise Level in $\frac{1}{3}$ octave band dB re.20µPa	UW weighting dB(UW) re.20µPa	Sensation level dB SPL re.20µPa
25	136	−73	63
31.5	138.1	−70.4	67.7
40	139.1	−68	71.1
50	137.7	−65.2	72.5
63	141.8	−64.1	77.7
80	136.4	−63.3	73.1
100	134.6	−61.1	73.5
125	132.2	−59.2	73
160	126.6	−55.2	71.4
200	123.4	−52.8	70.6
250	120.9	−50	70.9
315	116.5	−46.5	70
400	110.1	−43.3	66.8
500	109.6	−41.3	68.3
630	109	−39.9	69.1
800	106.3	−36.3	70
1 000	102.4	−39	63.4
1 250	99.9	−43.5	56.4
1 600	94.5	−50.5	44
2 000	90.8	−54.8	36
2 500	95.1	−60.8	34.3
3 100	84.8	−65.8	19
4 000	82.4	−70	12.4
5 000	81.8	−69.5	12.3
6 300	81.8	−67.2	14.6
8 000	83.5	−62.1	21.4
10 000	85.4	−67.5	17.9
12 500	83	−74	9
16 000	85.7	−68	17.7
		Overall level	83.8

Table 2.2: Assessment of diver noise exposure while operating a compressed air rock drill [13]

2.7 Sound localisation

In air, directional sound perception at low frequency is based on the use of phase information, *i.e.* differences in time of arrival of sound at each ear, and by intensity variation at each ear as a result of shadowing by the skull at high frequencies. However, in water, where sound velocity is increased by a factor of 4.5, the difference in time of arrival of sound at each ear is much smaller and difficult to detect than in air. A bare human head and surrounding water have similar acoustic impedances meaning that incident sound will pass through the skull without causing any shadowing [13]; although, if a neoprene hood or other attenuating garment is worn shadowing may occur.

Therefore sound localisation by divers is much more difficult than in air, and early studies suggested that it would not be possible (*e.g.* [17]). However, more recently many studies have indicated that divers can localise sound underwater, and to a much greater degree than expected by chance [13] [16].

2.8 Effects of the hyperbaric environment and different gases on hearing

Breathing gases used in diving other than air *i.e.* oxygen in nitrogen mixtures (nitrox - for use to a depth in the order of 40 m), oxygen in helium mixtures (heliox - used for greater depths) along with oxygen in nitrogen and helium (trimix) may also affect hearing sensitivity. Heliox and to a lesser extent trimix are used in saturation diving, where divers live and work at depths typically greater than 40 m for long periods of time, several days or weeks being possible, thus avoiding the repeated cycles of pressurisation and decompression along with lengthy decompression stops involved in bounce dives.

Hyperbaric environments for saturation diving have increased pressures and gas densities *e.g.* ranging from 200 kPa (density 0.6 $kg \cdot m^{-3}$) at 10 m to 2,100 kPa (density 3.6 $kg \cdot m^{-3}$) at 200 m (densities are typical values for heliox mixtures); for comparison air at the surface (100 kPa) has a density of 1.36 $kg \cdot m^{-3}$ and at 50 m (600 kPa) a density of 8.16 $kg \cdot m^{-3}$. In this environment many aspects of physiological function are affected, such as respiration, cardiovascular function and vision [19]. As the ear contains gas-filled cavities, changes in pressure and gas density associated with the hyperbaric environment might also be expected to affect hearing, either transiently or long-term.

Early studies suggested that hearing is impaired by saturation diving. Fluur and Adolfson [20] investigated the effects of hyperbaric air on hearing function and found reduced hearing sensitivity at around 500 Hz and at 3-5 kHz, with sensitivity reductions increasing with depth at all frequencies. Thomas *et al.* [21] [22] reported a similar pattern of reduced sensitivity with divers breathing heliox at 100 - 300 m, along with increases in hearing deficit with depth. There was also an increase in hearing sensitivity at 2 and 6 kHz when breathing heliox.

However, more recent studies have not confirmed these adverse effects on hearing. O'Reilly *et al.* [23] reported no changes in diver hearing following a saturation dive to 186 m (1,960 kPa) lasting 24 days. Mendel *et al.* [24] investigated United States Navy (USN) divers during saturation deep dives to 300 m (1,000 feet of sea water), and found that hearing function was similar under hyperbaric pressure and in heliox to hearing on the surface, and hearing sensitivity in fact improved at 6 and 8 kHz.

Studies have also investigated the effects of breathing different gases at normal air pressure *i.e.* not in a saturation environment and found that hearing sensitivity was unaffected, for example, while divers breathed a mixture of 20 % oxygen and 80 % helium [25].

Overall, recent audiometric studies have shown that hearing is unaffected by the increased pressure and gas density of hyperbaric environments, with the exception of hearing at high frequencies which may be improved slightly. Furthermore, breathing different gases (heliox and nitrox) in the absence of increased pressure, also, does not affect hearing. It therefore appears appropriate to directly apply the CoNaWR05 regulations to hyperbaric environments without modification when assessing diver noise exposure.

2.9 Summary

Human hearing underwater, with a 'wet' ear, is less sensitive than it is in air, and so sound underwater will produce less hearing damage, than airborne sound. This applies to divers where the auditory canal is filled with water, *e.g.* SCUBA divers and divers wearing band-masks.

A diver's 'neoprene' hood can provide substantial protection from underwater noise, particularly at shallow depths.

For a diver with 'wet' ears, assessing the noise hazard underwater requires the use of noise exposure values in the CoNaWR05 to be adjusted using an UW-weighting scale.

However, if the diver’s ears are ‘dry’, *i.e.* when wearing a diving helmet, the noise hazard is the same as for airborne sound. This is because the ears are surrounded by air, and so sound waves affect hearing in the same way as they do above water.

Hearing sensitivity in hyperbaric environments and in different breathing gases (heliox, nitrox or trimix) is similar to hearing in air at normal air pressure. The exposure values, as identified in the CoNaWR05, may be applied to hyperbaric conditions and all breathing gas mixtures.

3 Diver audiometric surveys

3.1 Introduction

Following exposure to elevated noise levels a temporary impairment of hearing may occur, known as a temporary threshold shift (TTS). With repeated exposure to these noise levels a permanent threshold shift (PTS) may occur, this is the basis of noise induced hearing loss (NIHL) and thus the requirement to control noise exposure and reduce the risk of long term damage. A study conducted by Curley and Knafelc [26] identified moderate TTS in divers using surface-supplied diving apparatus for dives of 120 min duration; they also reported that with the exception of one diver hearing returned to pre-dive levels within 24 hours of surfacing. It is, therefore possible, that divers experiencing a TTS may suffer long term hearing loss.

The review identified fifteen studies that have investigated hearing loss in divers and/or conducted audiometric surveys. Most of these studies use a combination of audiometric testing, medical examination for ear pathology and questionnaires to identify diving experience, history of barotrauma and noise exposure.

The majority of investigations are retrospective, that is, comparing divers' and non-divers' hearing at the time of the study and looking backwards in time at their diving history. Some are prospective studies, which are a more powerful experimental design because they identify a group of divers, assess their hearing and then re-test after a period of time, looking at before and after effects. The record of diving activities, noise exposure and other relevant events is also likely to be more accurate.

3.2 Studies showing no differences in hearing loss between divers and controls

Some early studies were unable to establish that divers' hearing was impaired. Brady *et al.* [27] investigated 97 US Navy divers and age-matched controls, taking into account diving experience, incidents involving barotrauma, type of diving equipment, and prior noise exposure. Although there was a significant relationship between noise exposure and hearing, the noise exposure was not always associated with diving or occupational noise. There were no significant differences in hearing acuity between divers and non-divers, and the study concluded that the factors investigated had only minimal effects on auditory sensitivity. These findings were consistent with those of Shilling and Everley [28] who examined divers and submarine personnel and found no differences between the hearing of divers and non-divers, after taking age into account. There was, however, significant hearing loss in those who showed evidence of ear disease or barotrauma, and this group's hearing was worse than the hearing of divers without ear trauma or infection.

Other evidence from Coles and Knight [29], who investigated 62 divers and submarine-escape instructors, suggested that minor occurrences of barotraumas associated with diving procedures did not result in permanent hearing loss. Among the problems with some of these retrospective studies is that separating the effects of age and experience on hearing loss, which are usually confounded, has not always been considered. Also, the groups selected as non-diving controls as well as the divers may have been exposed to noisy environments, and as a result it is not possible to discriminate hearing impairments solely due to diving.

3.3 Evidence for hearing loss in divers – from retrospective studies

In contrast with the studies described above, there is a substantial body of evidence indicating that the hearing of divers is impaired. Edmonds [1] investigated 28 professional abalone divers, who averaged six years of diving, and concluded that more than 70 % had high frequency hearing loss, to an extent that was eligible for compensation. Ear pathology and barotraumas were excluded as a cause and the group was not exposed to other occupational noise. Similarly Zannini *et al.* [2] investigated 123 professional divers and found that 76.9 % of divers had impaired hearing, a percentage that was significantly higher than non-divers.

Although Skogstad *et al.* [30] were unable to establish significant differences between the hearing thresholds of construction divers compared with age-matched controls (group size of 26 in both cases), the divers showed reduced hearing in the left ear compared with the right ear from 3 to 8 kHz. Both divers and controls in the study were occupationally exposed to relatively high levels of noise, and so both were likely to have impaired hearing. A study of RN divers' audiograms, conducted by the Institute of Naval Medicine (INM), compared the hearing thresholds with data for an otologically normal population and identified a reduced percentile of normal hearing at 500 Hz [31].

3.4 Evidence for hearing loss in divers – from prospective studies

Evidence for the presence of hearing impairment in divers has been strengthened by a number of prospective studies looking at groups of divers before and after a period of time, of the order of several years. Haraguchi *et al.* [32] conducted a prospective study with 18 professional fishery divers over 5 years. At the start they had normal hearing or some hearing loss, and changes were determined after eliminating the effect of age. The investigation concluded that the hearing of divers deteriorated faster than in non-divers, with a mean hearing deterioration of 6.6 dB (significant at specific frequencies). The authors hypothesized that the hearing deterioration was due to hair cell damage associated with repeated, long-term compression-decompression cycles in divers.

Further evidence for an increased rate of hearing deterioration in divers is seen in a study by Molvaer and Albrektsen [33]. They investigated 116 professional divers before and after an interval of approximately 6 years, and found that although the hearing thresholds of younger divers (less than 35) were lower than in unscreened (*i.e.* not visually or by other means (*e.g.* acoustic impedance) checked for damage to the auditory system) normal population at comparable age, the gap closed with increasing age; Figure 3.1 (Blue line higher than, but getting closer to or below red line with increasing age). The divers had higher hearing thresholds than screened non-divers of the same age; Figure 3.1 (Blue line always lower than green line). However, for the three older age groups, the divers (Figure 3.1 blue line) were more similar to the unscreened non-diver population (Figure 3.1 red line) for higher frequencies of hearing. This suggests that diver hearing deteriorates faster than for non-divers.

Skogstad *et al.* [34] [35] conducted two prospective studies and suggested that the number of years diving is significantly related to hearing loss, in a dose-response fashion. The investigation, in 2000, investigated 54 young occupational divers divided into high-exposure and low-exposure groups, tested at start of the study and after 3 further years diving. At the start of testing the hearing of the high-exposure group was reduced compared to that of the low-exposure group. During follow-up after 3 years the combined groups showed further reduced hearing ability at 4 kHz in the left ear only. There was an association between auditory function at 4 kHz and total number of years diving, suggesting a dose-response relationship. The second study by these authors in 2005 involving a six-year follow-up of 47 divers, indicated that the divers' hearing was reduced at 4 and 8 kHz. The study concluded that mild hearing impairment can occur in young professional divers, although divers' hearing acuity was better than in the general population.

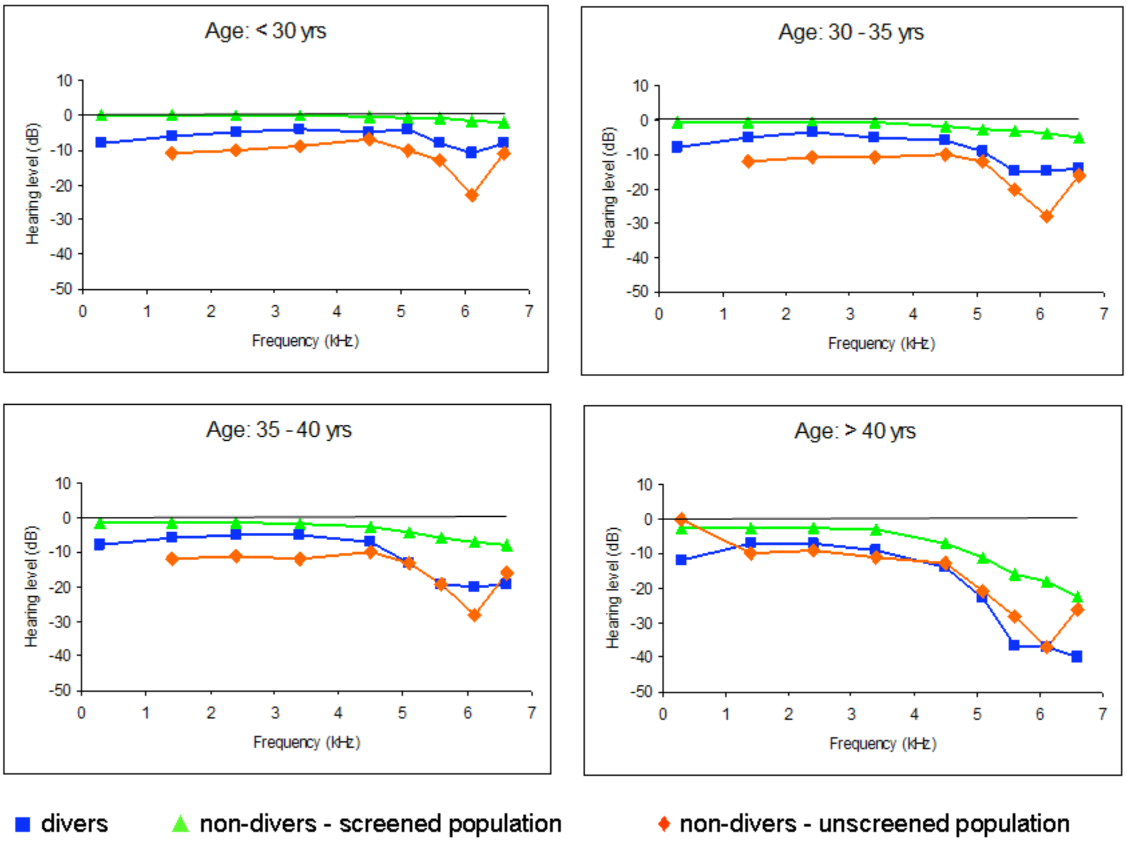


Figure 3.1: Increasing deterioration in hearing with age of divers compared to non divers - from Molvaer and Albreksten [33]

3.5 Evidence for increased rate of hearing loss with age in divers

Several studies have suggested that although divers initially seem to have better hearing than the general population, their hearing deteriorates faster than non-divers. Selection procedures mean that the hearing of young divers at the start of their careers is better than for the general population, which includes individuals with ear diseases and occupational damage. Further evidence for the increased rate of hearing deterioration in divers has come from two additional studies. Molvaer and Lehmann [36] investigated 160 professional divers and compared them with a standard population of non-divers, with age grouped according to decades between 20 and 60 years. As expected, hearing sensitivity decreased with age/diving experience, and also with smoking and subjectively assessed noise exposure. The study indicated that while hearing acuity in younger divers was better than an age-matched general population, hearing in the older age groups was the same as the non-diving population.

A further investigation by Zulkaflay *et al*. [37] involving 120 Malaysian Navy divers and 166 non-diver naval personnel indicated that divers older than 30 years showed greater hearing loss at 4, 6 and 8 kHz than non-divers. The hearing damage was considered to be due to the combined effects of a high noise environment, decompression illness (DCI) and minor residual damage due to inner ear barotraumas. The study again concluded that divers' hearing deteriorated faster than non-divers, with the effects seen at higher frequencies (4-8 kHz).

3.6 Evidence for hearing loss in divers from an HSE-sponsored survey

The ELTHI (Examination of the long term health impact of diving) investigation reported by Ross *et al.* [38] involved a questionnaire study of lifestyle, occupation and health status on behalf of the UK Health and Safety Executive. The postal survey used included a large number of HSE-registered divers (2958) and a similar number of controls who were non-divers working in the diving industry. The divers were further divided into offshore (OSD) and non-offshore (NOSD). The OSD reported a higher incidence of hearing impairment (17%) compared with NOSD (11%) and controls (11%). Hence the study lends support to the investigations described above using audiometry where divers' hearing was impaired.

3.7 Summary

The majority of studies, 12 out of the 15 identified, are consistent with diver hearing being impaired by exposure to factors associated with diving. Of these, several studies also suggest that divers' hearing deteriorated faster than non-divers *i.e.* increased the age-related deficit.

All the prospective studies (*i.e.* examining before/after effects) provided evidence that the hearing of divers is impaired.

These hearing deficits are likely to be due to the combined effects of noise, pressure including barotraumas and decompression illness (DCI), although it is difficult to separate out the individual influences of these factors.

In particular, it is difficult to establish, from the audiometric data, that the hearing impairments are due to noise *per se*. This is partly because the effects are likely to be due to combinations of factors, and also because the noise levels they have been exposed to are essentially unknown.

In all the studies, noise exposure was only assessed subjectively, and may also be very variable within the diving group. This makes the link between noise and hearing loss difficult to establish in these investigations.

4 Sources of noise

4.1 Ambient underwater noise levels

Naturally occurring ambient noise in the ocean arises from turbulence and pressure fluctuations, and from wind-dependent noise such as bubbles, waves and spray from surface agitation. These sources contribute to the background level of 100 -140 dB re. 1 μPa and occur at frequencies from less than 10 Hz up to 20 kHz [39].

Man-made noise sources such as shipping and offshore oil exploration and production are so wide spread that they are effectively ambient. Shipping noise is the main source at frequencies below 500 Hz. Source levels radiated by super tankers and container ships lie in the range 188 -192 dB re. 1 μPa @ 1 m, while drill ship and dredging operations generate broadband source levels of 185 dB re. 1 μPa @ 1 m [40] [41]. Underwater source noise from boat and cruising traffic has been reported as 165 dB re. 1 μPa @ 1 m, in the frequency range 1-5 kHz for motorboats and lower frequencies for larger vessels [42].

Activities associated with the oil industry constitute a major source of underwater noise, and include oil and gas drilling and production operations and marine geophysical surveys. Seismic surveys are one of the strongest sources of noise, *e.g.* seismic survey air-gun source levels of 240 dB re. 1 μPa @ 1 m [43].

Figure 4.1: Exploratory oil rig with rig tender standing by [44]

Offshore oil and gas installations (Figure 4.1) are contributors to environmental noise. McCauley [44] measured noise levels on and near a drilling rig and identified three types of sources. The quietest period was with the rig working but not drilling, three types of sources. The quietest period was with the rig working but not drilling, with noise arising from mechanical plant, pumping systems and generators with a wellhead noise source level of 159 dB re. 1μPa @ 1 m. The second noise source involved the rig drilling and a rig tender on anchor, where noise source levels were 159-167 dB re. 1 μPa @ 1 m. The third and loudest source was a rig tender standing by for loading, producing broadband source noise of 189 dB re. 1 μPa @ 1 m, associated with continuous operation of the propellers and bow thrusters to maintain position. An overview of ambient noise levels is presented in Table 4.1.

Source of noise	Source noise level dB re. 1 μPa @ 1 m	Noise level dB re. 20 μPa @ 500 m	Noise level dB re. 20 μPa @ 1000 m
Seismic survey air guns	240	160	154
Heavy shipping	188 -192	108 -112	102 – 106
Oil rig tender operations	189	109	103
Dredging operations	185	105	99
Oil rig drilling	159 - 167	79 - 87	73 – 81
General boat traffic	165	85	79
Oil rig not drilling	159	79	73

Table 4.1: Ambient underwater noise levels

4.2 Ambient dive site noise levels

Diving sites are typically very noisy above water, and so divers are exposed to high levels of noise throughout the working day (Table 4.2). Wolgemuth [7] estimated the likely total noise dose received by a diver over 24 hours by combining in-air and in-water noise sources at a dive site. The diving operation was conducted from a salvage barge which accommodated equipment used to power underwater tools. These include a compressor producing in-air noise levels of 99.4 dB(A) re. 20 μPa at 10 feet from the source, and a hydraulic drill press compressor producing 100 dB(A) re. 20 μPa at 1-2 feet from the source and located near the operator. This required personnel to wear hearing protection which reduced the noise to 97 dB(A) re. 20 μPa. Measurements obtained for a life support buoy diesel generator and compressor were 105.6 and 94.6 dB(A) re. 20 μPa respectively, again requiring personnel to wear ear muff hearing protection, providing attenuation of 20-25 dB.

For comparison, a home living room may be 40 dB(A), typical office environment 65 dB(A), busy street noise 80 dB(A) and a road drill 100 dB(A).

Source of noise	Noise level dB(A) re. 20 μPa
Diesel generator	105.6
Diesel compressors	94 -100

Table 4.2: Example ambient dive site noise levels

4.3 Self-generated breathing noise and helmet noise

Divers produce a high level of breathing noise, generated by air flow through the regulator demand valve during inhalation. Bubble noise is also produced during exhalation and speech by air released from the regulator, leading to significant noise. For a diver wearing a free-flow helmet there is also the noise from the air flow.

The noise levels associated with breathing apparatus and wearing helmets may be considered as either the noise level that is transmitted into the water (*e.g.* as with SCUBA apparatus) or the noise incident at the diver's ear (*e.g.* as with diving helmets). Typical examples, under comparable sub-surface conditions, of breathing noise associated with an open-circuit demand diving helmet are presented in Figure 4.2 and for an open-circuit band-mask in Figure 4.3 [13].

A comparison between Figure 4.2 and Figure 4.3 (red lines) gives a clear indication of the comparative noise hazard from diving helmets and band-masks. Figure 4.2 gives the average internal helmet noise level (L_{eq}) at the diver's ear, 103 dB(A) re. 20 µPa and associated daily noise dose ($L_{ep,d}$), for a one hour exposure and no other exposure being considered, of 94.1 dB(A) re. 20 µPa, which exceeds the CoNaWR05 exposure limit value. Conversely, Figure 4.3 gives the average noise at the divers ear in a band-mask (*i.e.* a wet ear with the underwater weighting scale applied), (L_{eq}) 60.3 dB(UW) re. 20 µPa and associated daily noise dose ($L_{ep,d}$), for a one hour exposure and no other exposure being considered, of 56.1 dB(UW) re. 20 µPa, which is comfortably less than the CoNaWR05 lower exposure action value.

Radford *et al.* [45] measured the transmitted noise levels from three types of underwater breathing apparatus; these were a self-contained underwater breathing apparatus (SCUBA), semi-closed circuit re-breather (SCR), and a closed-circuit re-breather (CCR) systems. SCUBA produced the most noise, followed by SCR and CCR (161, 131 and 108 dB re. 1 µPa @ 1m respectively), with much of the noise occurring at low frequencies (<200 Hz). Note; these levels would be reduced by 26 dB when using the 20 µPa reference pressure for human hearing, and further attenuated if the diver was wearing a neoprene hood.

The noise levels of various types of diving helmet has been found to differ depending on the design characteristics, such as positioning of exhaust valves and supply hoses, and on the conditions under which the noise testing has been carried out, for example, whether the tests were manned or unmanned testing, and the type of environment (anechoic chamber versus open-water).

Evans *et al.* [5] conducted manned trials in an diving tank fitted with an underwater anechoic chamber to measure the noise levels in three different types of diving helmet, the Diving System International (DSI) Superlite (SL) 17B, SL-17K and Dirty Harry (Figure 4.4). During normal breathing the internal helmet noise levels at the divers' ear were 78.7, 88.0 and 91.1 dB(A) re. 20 µPa for Dirty Harry, SL-17K and SL-17B respectively, increasing to 93.4, 95.2 and 96.7 dB(A) re. 20 µPa for high ventilation rates. The differing noise levels were due to various design aspects: the Dirty Harry helmet system is part of a gas return line system that did not produce bubbles on exhalation, and the other two had different internal volumes and valve configurations. It is worth noting that the Dirty Harry system, and the associated noise levels, are comparable with return line systems being used for saturation diving. The data indicated that the primary source of noise for the diving helmets was exhaust bubbles formed on exhalation.

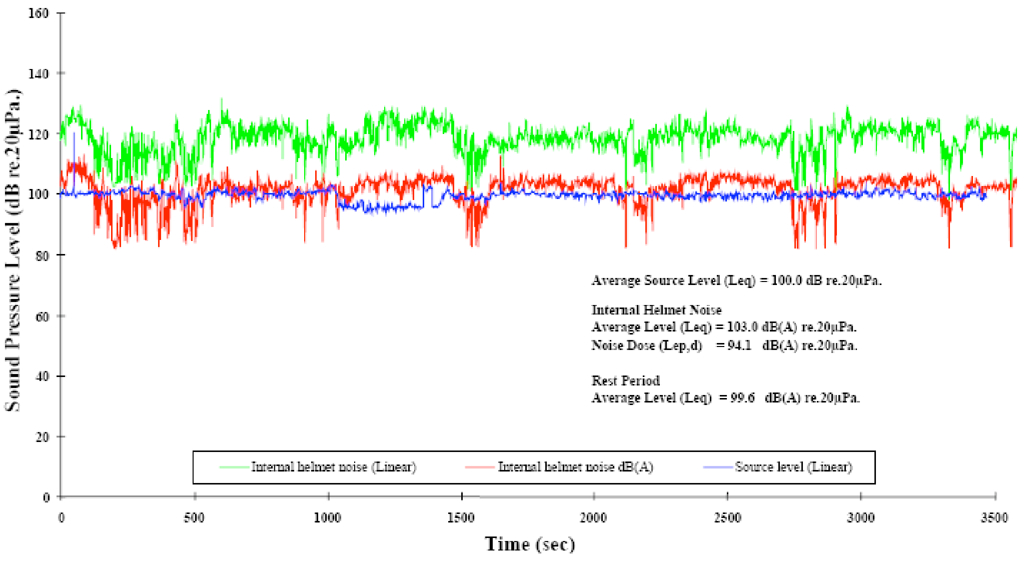


Figure 4.2: The breathing noise measured from an open-circuit demand diving helmet [13]

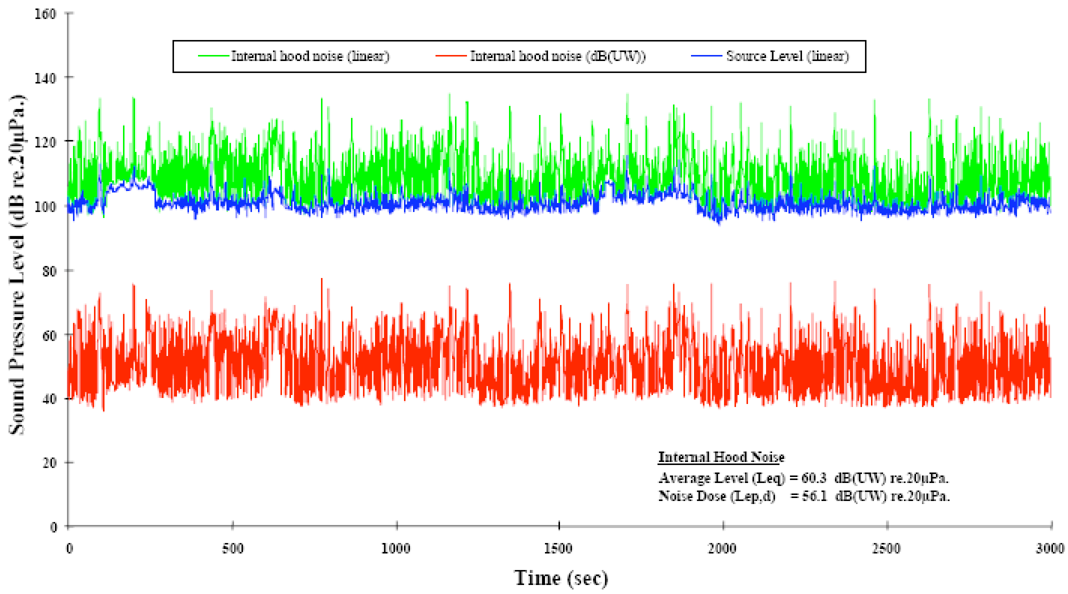


Figure 4.3: The breathing noise measured from an open-circuit demand band-mask hood breathing apparatus [13]

Figure 4.4: Diving helmets (SL-17B top left, SL-17K top right, Dirty Harry bottom row) tested by Evans et al. [5]

The study by Evans *et al.* [5] also measured the noise levels during communications and demisting for each of the helmets. Levels of 105.8, 102.4 and 101.6 dB(A) re. 20 µPa for communications and 104.1, 100.2 and 106.9 dB(A) re. 20 µPa for demisting were recorded for Dirty Harry, SL-17K and SL-17B respectively, indicating that use of the demist and communications should both be kept to a minimum.

A graphical illustration of the noise levels from the study by Evans *et al.* [5] is presented in Figure 4.5. It is apparent that:

- The noise levels in the helmets increased with increased diver ventilation rate;
- The helmets producing exhaust bubble had higher noise levels than those that did not;
- Communications (and flushing through) creates a high noise level;
- Communications requires a noise level in the order of 15 dB above background for the communications to be audible.

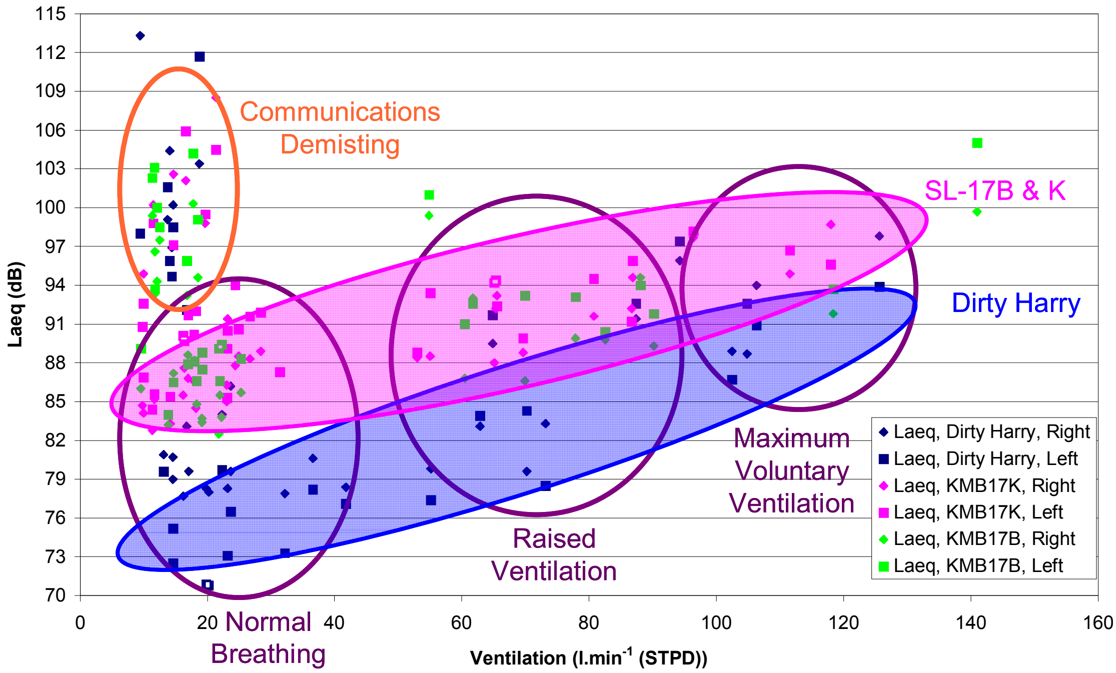


Figure 4.5: Graphical presentation of helmet noise levels with diver ventilation rate from data in Evans et al. [5]

Other studies also indicate that the high noise levels recorded are typical of those seen with many helmets. For example, Curley [46] assessed manned helmet noise (SL-17B) during oxygen-helium dives to simulated depths of 650 and 850 feet of seawater (195 and 255 m) in a simulated hyperbaric environment. The average noise inside the helmet was 97.9 dB(A) re. 20 µPa. Further manned evaluations of an AH3 free-flow diving helmet at simulated depths of 5, 30 and 50 m with divers carrying out graded exercise indicated noise levels ranging from 100.0 to 104.1 dB(A) re. 20 µPa depending on the air flow rate [47].

Noise levels inside the US Navy Mk V and commercial diving helmets (models unspecified) revealed levels up to 113 dB(A) re. 20 µPa, limiting allowable dive durations to approximately half an hour, by US Navy standards in 1971, when the study was carried out [48]. Further measurements by these authors with two standard US Navy diving helmets, the Mk V Air helmet and the Mk V oxygen-helium helmet, indicated levels of 106 dB and 103-116 dB re. 20 µPa respectively [49].

Curley and Knafelc [26] assessed noise within the US Navy MK 12 Surface Supplied Diving System (SSDS) helmet and investigated its effect on divers' hearing while breathing air at simulated in-water depths between 1.8 to 30.5 m, with dive durations of 40 to 120 min and the divers exercising. Noise levels were 95.8 - 97.8 dB re. 20 µPa depending on depth. Moderate hearing threshold shifts were observed at depths of 9.1 m or deeper after 120-min dives, although hearing returned to pre-dive levels within 24 hours with the exception of one diver.

Unmanned evaluation of Surface Supplied Diving Equipment (SSDE) using the SL-17K diving helmet indicated noise levels of 109.3 to 110.4 dB(A) re. 20 µPa inside the helmet at a depth of 10 m depending on breathing rate [50].

A summary of the self-generated breathing noise levels identified for diving helmets is presented in Table 4.3.

Source of noise	Internal helmet noise level $L_{A,eq}$ dB(A) re. 20 µPa	Comments
Open water testing of Surface Supplied diving apparatus with SL-17B, Figure 4.2 [13]	103.0	Diver exercising
Underwater anechoic chamber monitoring of 3 type of diving helmet [5]:		
Dirty Harry SL-17K SL-17B	78.7 88.0 91.1	Normal breathing
Dirty Harry SL-17K SL-17B	93.4 95.2 96.7	Maximum voluntary ventilation
Dirty Harry SL-17K SL-17B	105.8 102.4 101.6	During communication
Noise inside SL-17B helmet during oxygen-helium dives in a simulated hyperbaric environment (255 m, 850 fsw) [46]	97.9	
AH3 free-flow diving helmet at simulated depths of 5, 30 and 50 m [47]	100.0 104.1	At rest During exercise
US Navy Mk V and commercial diving helmets [48]	113	
US Navy Mk V with air US Navy Mk V with heliox [49]	106 116	
US Navy Mk12 SSDE at simulated depths to 30.5 m [26]	95.8 - 97.8	
SL-17 diving helmet during unmanned evaluation SSDE [50]	110.4	High ventilation rate

Table 4.3: Self-generated breathing noise within diving helmets

As the unmanned test data for the SL-17 [50] is in the order of 10 dB higher than all other SL-17 manned results there must be some doubt about the validity of unmanned testing of helmet noise, unless conducted under appropriate acoustic conditions [5].

It is clear from all the studies identified (Table 4.3) that these noise intensities (with the exception of the Dirty Harry helmet with the diver breathing normally) are an appreciable noise hazard to a diver. If used for typical working dive durations, the daily noise dose from these helmets is likely to exceed both the lower and upper exposure action values (80 and 85 dB(A) respectively) of the CoNaWR05.

It is, therefore, appropriate that control measures should be implemented to restrict a diver's noise dose. If the control measure is to restrict permissible dive durations, in some instances this will result in unrealistic dive times, in order to comply with the noise regulations. It is not the intent of the CoNaWR05 to restrict dive durations to unacceptable levels, but to use a range of control measures of which dive duration may be one. However, it is an unqualified duty for employers to reduce noise exposure to levels that comply with the CoNaWR05.

4.4 Tool noise

The operation of underwater tools by divers generates extremely high levels of noise. Although the divers' breathing apparatus can provide protection from external waterborne noise, the total noise dose from tools combined with helmet and self-generated breathing noise can be considerable.

Noise levels generated by underwater tools have been measured in a number of studies and indicate the potential for auditory damage in many cases. Goold and Fish [43] measured the broadband spectra of seismic survey air-gun emissions at ranges of 750 m, 1 km, 2.2 km, and 8 km range from the source. At 750 m the equivalent sound source level was 240 dB re. 1 μPa @ 1 m. Underwater broadband noise spectrum from a concrete island drilling structure in Alaska was recorded at a range of 1370 m as an equivalent source level of 175 dB re. 1 μPa @ 1 m [51], Molvaer and Gjestland [52] measured the noise generated by three underwater tools (a pneumatic rock drill and two different high-pressure water jet lances) and recorded levels up to 170.5 dB re. 1 μPa @ 1 m in the water close to divers' heads (presented here as source level @ 1 m).

The noise exposure from eight underwater tools was measured for divers wearing an open-circuit demand diving helmet and an open-circuit, band-mask hood, breathing apparatus, (Figure 4.6) [6]. The noise levels are shown in Table 4.4 and indicate the average source level at a range of 1 m and the noise levels at the diver's ear for the diving helmet (Figure 4.7) and band-mask.

For the open-circuit demand diving helmet, levels were 83 dB(A) re. 20 μPa for background noise (*i.e.* with the local ambient noise and breathing noise from the diver) and up to 112 dB(A) re. 20 μPa during tool operation, indicating a noise hazard both with and without tool operation. For the band-mask breathing apparatus, levels were 60 dB(UW) re. 20 μPa for background noise and up to 71 dB(UW) re. 20 μPa during tool operation, and therefore, a much lower noise hazard.

In the case of the diving helmet, the noise levels are high for all tools, *e.g.* the noise dose over one hour for the quietest tool, the oxy-arc cutter, is 91.7 dB(A) re. 20 μPa. For the band-mask hood, the levels are much lower due to the sound-attenuating effect of the hood and the reduced hearing sensitivity due to the diver having a 'wet' ear. In this case, all noise doses are below the lower exposure action value, with the noisiest tool, the rock breaker, resulting in a one-hour noise dose of 61.6 dB(UW) re. 20 μPa.

The noise hazard from three underwater bolt guns was assessed by firing each into concrete and measuring noise intensities at the divers' head [53]. Impulse noise produced by an underwater stud gun (a Ramset 200 HD gun-powder actuated tool) was recorded and the effect on the hearing of US Navy divers assessed. The average peak sound pressure level for a transient pressure wave of multiple consecutive shots underwater was 211.4 dB re. 1 μPa. These measurements conducted in an open-water, unconfined space did not demonstrate any acoustic injury [54].

Wolgemuth [7] measured noise generated by two underwater tools, a Butterworth 20 Kpsi hydroblaster and a hydraulic drill press, and calculated the allowable exposure time (as indicated by the US Navy Occupational Exposure Limit – NOEL, in 1971) of each for divers wearing a MK-21 helmet. The hydroblaster produced broadband noise, with a maximum intensity at 2 kHz of 152.2 dB(A) re. 20 µPa resulting in an overall in-helmet level of 98 dB(A) re. 20 µPa, limiting dive times according to the US Navy criterion to 42.5 minutes. For a hydraulic drill press, noise levels were 128.9 dB(A), and an overall in-helmet noise levels of 86.8 dB(A) re. 20 µPa, resulting in a maximum dive duration of 4 h 55 min. Noise levels for a further two construction tools, a hydraulic hammer drill and a hydraulic grinder, were 96.7 and 82.4 dB(A) re. 20 µPa overall in-helmet.

Noise levels typical of underwater tools are summarized in Table 4.4.

As with the self-generated helmet noise, it is clear from all the studies identified (Table 4.4) that for the divers wearing a helmet with a 'dry' ear these noise intensities are above the allowable levels for normalized eight hour working day exposures, as they exceed both the lower and upper exposure action values (80 and 85 dB(A)) respectively) of the CoNaWR05. It therefore seems appropriate that control measures should be implemented to restrict a diver's noise dose.

However, for divers wearing a band-mask with a 'wet' ear the levels comply within the requirements of the CoNaWR05. However, it should be noted that a band-mask does not offer physical head protection for a diver conducting underwater engineering and has an increased a risk of a diver developing an ear infection.

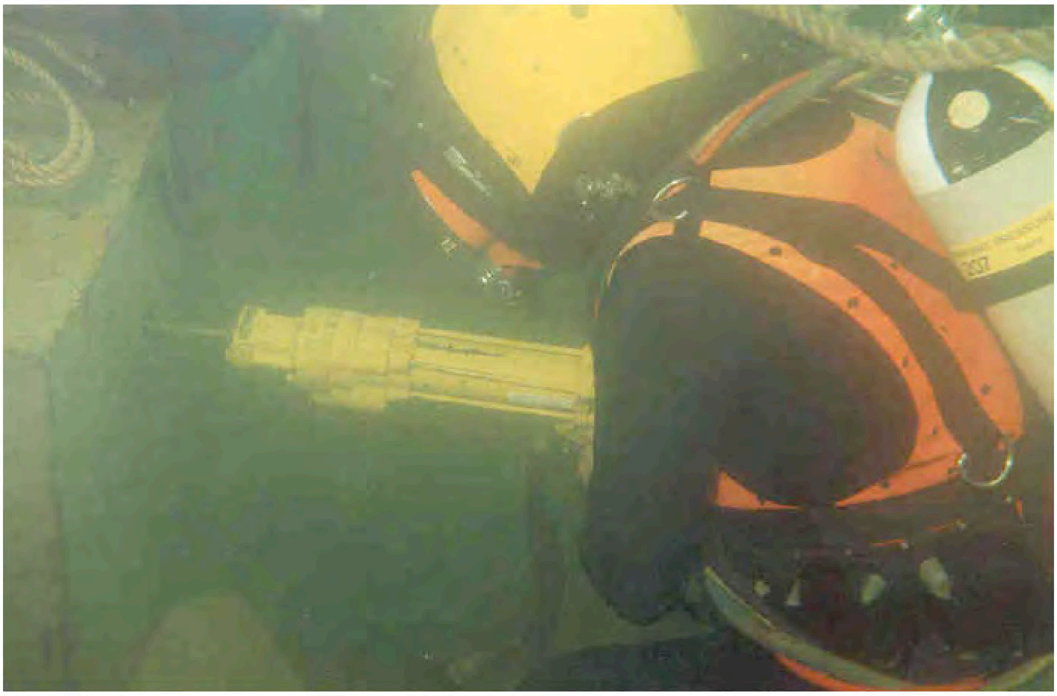


Figure 4.6: Photograph of a diver operating a hand drill during a survey of tool noise [6]

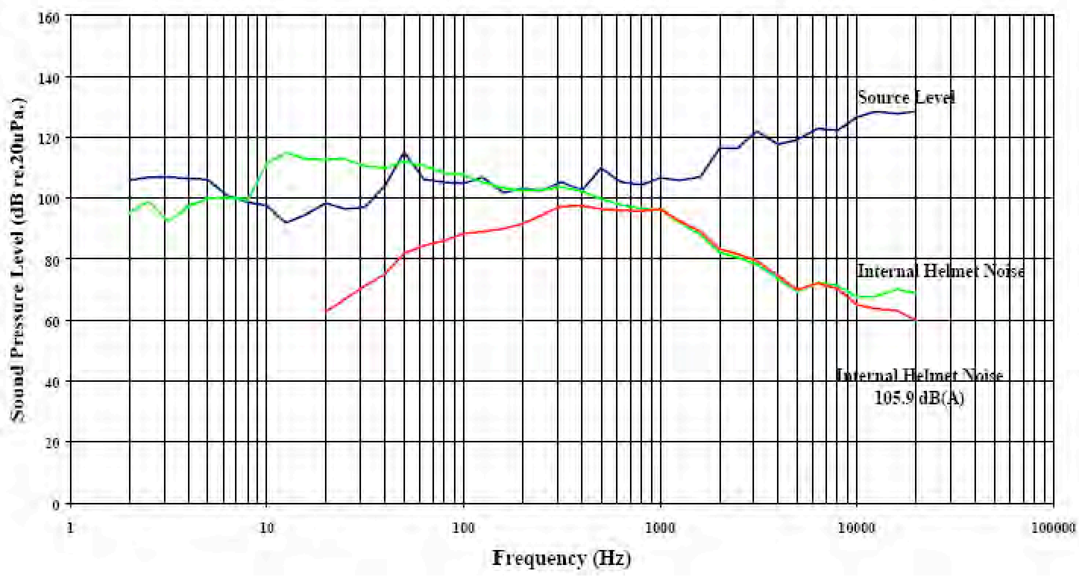


Figure 4.7: Typical noise levels generated by a hand drill for a diver wearing an open-circuit demand diving helmet (note: green line internal helmet noise dB, red line internal helmet noise dB(A), i.e. A weighted) [6]

Source of noise	Source noise level (in water) dB re. 1 µPa @ 1 m	In helmet noise level (at divers ear) $L_{A,eq}$ dB(A) re. 20 µPa	Inside band-mask noise level (at divers ear) L_{eq} dB(UW) re. 20 µPa
Seismic survey air-gun [42]	240		
Concrete island drilling structure [51]	175		
3 underwater tools: pneumatic rock drill two different high-pressure water jet lances) [52]	Up to 170.5		
Three underwater bolt guns [53] - Ramset 200 HD - Hilti UW10 - Beto Tornado	 206.7 209.1 208.6		
Underwater stud gun (a Ramset 200 HD gun-powder actuated tool) [54]	211.4		
Butterworth 20K psi hydroblaster Hydraulic drill press Hydraulic impact drill Hydraulic grinder [7]		98.0 86.8 96.7 82.4	
Chainsaw (Stanley CS11) [6]	162	101.5	66.4
Disk grinder (Stanley GR24) [6]	158	111.0	65.6
Rock breaker (Stanley B67) [6]	180	112.6	70.1
Rock chipper (Stanley CH18) [6]	163	111.5	71.3
Hand drill (Stanley DL08) [6]	159	109.5	65.6
Impact wrench (Stanley IW16) [6]	167	107.7	67.0
Clucas ‘Kerri cable’ cutter [6]	163	107.9	69.5
Clucas ‘oxy-arc’ cutter [6]	148	100.7	63.6
Background level [6]		83	60

Table 4.4: Noise levels generated by underwater tools

4.5 Compression chamber noise

Noise during compression and decompression cycles of a compression chamber reaches high intensities and can present an auditory hazard. Measurement of the internal chamber noise to obtain a hyperbaric noise dose estimate is required to determine whether the levels exceed the CoNaWR05 for personnel inside. Measurement of the external chamber noise is also required to assess the noise exposure of the chamber operator and support personnel. Noise levels typical of compression chambers are summarised in Table 4.5.

A noise survey of the RN 'Type 1 non-TUP' compression chamber at HMS Nelson, Portsmouth during pressure profiles indicated maximum levels, typically during compression, of 145.3 dB(A) re. 20 µPa within the chamber [55] and concluded that hearing protectors would not provide adequate protection for personnel.

During pressure profiles to 18 and 50 m, internal sound levels for the Admiralty ‘Mk1’ compression chamber at HMS Dolphin, Gosport [56] were recorded at a maximum level of 110.5 dB(A) re. 20 µPa.

Searle and Parvin [57] recorded noise levels during pressure profiles to 18 and 50 m in the Duocom Holders Variant compression chamber onboard HMS Chiddingfold at Rosyth Dockyard, Dunfermline. The maximum noise level inside the chamber was 108 dB(A) re. 20 µPa.

Summitt and Reimers [48] recorded noise levels during periods of rapid compression or ventilation, at levels of 116 and 118 dB(A) re. 20 µPa respectively.

Murry [58] recorded hyperbaric chamber noise during a dive to 30 m (100 ft) at levels of 112 and 108 dB(A) re. 20 µPa for descent and ascent respectively, descent being completed in less than 2 min. The noise levels were highest in the frequency range between 300 and 4800 Hz.

The peak noise level in these chambers is in the same frequency range as for male speech and so ear protectors are not a viable option, indicating that noise should preferably be reduced at source if communication is to be unaffected [59]. However, it is thought that modern chambers have appreciably quieter noise levels than the reported levels identified for this review.

Source of noise	Noise level inside chamber $L_{A,eq}$ dB(A) re. 20 μPa
'Type 1 non-TUP' compression chamber at HMS NELSON, Portsmouth [55]	145.3
Admiralty 'Mk1' compression chamber at HMS Dolphin, Gosport [56]	110.5
Duocom Holders Variant compression chamber, HMS Chiddingfold [57]	108
Noise levels during [48]: - Rapid compression - Ventilation	 116 118
Hyperbaric chamber noise during a dive to 30 m [58] - Descent - Ascent	 112 108

Table 4.5: Compression chamber noise

4.6 Summary

Ambient noise in the ocean arises from both naturally occurring and man-made sources. Noise from shipping and offshore oil exploration constitutes an appreciable source, with seismic surveys and drilling generating high intensities.

Diving sites above water are typically very noisy leading to divers being exposed to high levels of noise between dives as well as when working underwater. The sources include generators and compressors for underwater tools. However, divers are able to wear surface hearing protectors and to seek a quiet refuge.

Self-generated breathing noise is a major contributor to divers' noise exposure when wearing diving helmets. The levels depend on the helmet design, with some models leading to exposures that for typical working dives, exceed the allowable daily noise dose.

Underwater tools generate very high noise intensities, and some tools identified resulted in noise doses that with use for only a few minutes would exceed the upper exposure action value by a substantial amount.

During compression and decompression compression chambers typically generate high noise intensities.

As a consequence of exposure to these various noise sources, the total noise dose received by divers can potentially be very high. Noise control measures are required to reduce the noise hazard to ALARP and to levels that comply with the CoNaWR05.

It appears that the only current noise control measure for diving is to restrict exposure time, and that this primarily occurs by default due to other constraints (*e.g.* gas supply, decompression and temperature limits).

5 Noise exposure values and guidance

5.1 Noise exposure values in air and underwater

5.1.1 Control of Noise at Work Regulations 2005 (CoNaWR05)

UK noise exposure legislation is based on the EEC Directive 2003/10/EC - The Control of Noise at Work Regulations 2005 (CoNaWR05) [3] - which define exposure values at which employers must take action to reduce noise hazard to their employees. The legislation is based on the average daily noise 'dose' of the 'A-weighted' noise energy received, normalized to an eight-hour working day, five days a week. The CoNaWR05 values are as presented in Para 1.1.

5.1.2 Noise energy and time dependence

Currently, the upper exposure action value noise dose is that incurred during continuous exposure of 85 dB(A) re. 20 µPa for a normalised eight hour period, each working day. By limiting the exposure time, a 'trade-off' may be achieved for exposure time against noise level, such that for each halving of exposure time a doubling (3 dB) of the sound energy is permissible. Therefore, under current legislation 88 dB(A) re. 20 µPa is permissible for 4 hours, 91 dB(A) re. 20 µPa for 2 hours, and so on. The noise energy and potential for hearing damage of each of these exposures is the same. The maximum peak level is 137 dB(C) re. 20 µPa.

It should be recognized that the principle of the CoNaWR05 is to reduce noise at source to a level that may be considered 'As Low As is Reasonably Practicable' (ALARP); thereafter, to apply further control measures. Purely limiting noise dose by exposure time does not follow this principle and relies on no further noise exposure occurring for the remainder of an eight hour working day. As illustrated, diving sites are noisy environments and this is not necessarily practical. Therefore, alternative noise control measures are also required.

5.1.3 Noise exposure underwater

The CoNaWR05 dB(A) values apply to noise in an air environment rather than underwater. It has been shown that the hearing threshold of the human ear is less sensitive in water (*i.e.* when the auditory canal is filled with water) than in air [13]. Due to the reduced hearing sensitivity of the ear immersed in water, the CoNaWR05 exposure values should use an appropriate dB weighting to determine the noise dose that divers are exposed to underwater.

Parvin *et al.* [13] have proposed a method to translate the criteria for assessing noise exposure in air to exposure underwater, using a knowledge of hearing sensitivity underwater to calculate an underwater weighting (UW-weighting) scale. The method assumes that any reduction in hearing sensitivity equates to an equivalent increase in allowable noise dose. Accordingly, since hearing is less sensitive underwater, a higher level of noise is tolerable.

5.1.4 'Wet' ear / 'Dry' ear effect, and other factors affecting the noise hazard

<u>'Dry' ear effect</u>

Where the diver is wearing a helmet, and the ears are 'dry', the noise hazard may be determined directly using the noise exposure values specified by the

CoNaWR05. All that is required is measurement of the sound level incident on the ears within the diving helmet. The 'dry' ear scenario is worst case in terms of noise hazard due to the greater sensitivity of hearing in air than underwater.

'Wet' ear effect

Where the diver's ears are 'wet', *e.g.* when wearing SCUBA or a band-mask, hearing sensitivity is reduced. The exposure values specified in CoNaWR05 cannot be applied directly and may be adjusted for the reduced hazard, for example, by using the method suggested by Parvin *et al* [13] using an UW-weighting scale. In this report the UW weighting scale has been applied where appropriate and it is proposed that this be formally adopted for assessment of underwater noise exposure.

Hooded divers

For divers with a wet ear wearing diving hoods (*e.g.* foam neoprene), hearing is further protected by the attenuation factor of the hood, found to be around 5 to 15 dB depending on the frequency of the noise [60]. It should also be noted that due to the compressible nature of foam neoprene the attenuation reduces appreciably with depth. When assessing underwater noise exposure the effect of any hood, linked with the depth of the dive, should be considered and the noise level within the hood and incident on the ear recorded; the UW weighting scale should then be applied.

Hyperbaric pressure and gases other than air

The evidence available from research reported in the open literature [24] has shown that hearing during saturation diving, where the ears are at hyperbaric pressure and exposed to gas mixtures other than air, is similar to hearing in air at surface pressure. The implication is that the noise hazard associated with hyperbaric and mixed gas diving can be determined by applying the CoNaWR05 values with no adjustment. In this report, this principle has been applied where appropriate and it is proposed it is formally adopted for assessment of hyperbaric and mixed gas noise exposure.

5.1.5 Saturation diving

The NORSOK U-100 Standard for manned underwater operations [61], published by the Norwegian petroleum industry, includes noise exposure limits applied to saturation diving.

The standard states that noise exposure shall be as low as practically possible. It further states that personnel exposed to harmful levels of noise (exceeding 83 dB(A) re. 20 μPa) shall use protective equipment, and that the use of noise protection equipment shall not reduce the quality of oral communication.

The following noise exposure limits from the standard are applicable to diving and hyperbaric operations, although they specifically exclude self-generated noise:

- Sleeping chambers 60 dB(A) re. 20 μPa
- Living chambers 65 dB(A) re. 20 μPa
- Control room 65 dB(A) re. 20 μPa
- Diving bell 65 dB(A) re. 20 μPa
- Habitats 65 dB(A) re. 20 μPa
- Diver in water 70 dB(A) re. 20 μPa

Given that divers live and work under these noise conditions for 24 hours per day, 7 days per week, it is expected that these limits would be adhered to by commercial diving operations in the Norwegian Sector of the North Sea, and adopted as best practice.

It should be noted that the CoNaWR05 identified exposure values averaged and normalized for an eight hour working day or weekly exposure values for nominally five working days per week. In saturation diving the divers are exposed continuously, this has been recognised for other occupational exposure limits and in EH75/2 the HSE have promulgated techniques for assessing continuous hyperbaric chemical exposure [62].

On the assumption that noise exposure should also be assessed for continuous exposure, combined with the principle such that for each doubling of exposure time a halving (-3 dB) of the sound energy is permissible, then if a 40 hour working week 80 dB value is extrapolated to a full 168 hour week it would require the average exposure to be 6.2 dB(A) (*i.e.* 10 log(168/40)) less than the normalized value.

For saturation exposure, and considering that no additional factors are required for pressure or gas mixture, an average continuous noise level of 73 dB(A) re. 20 μPa would provide the diver with a noise dose at the lower exposure action value of the CoNaWR05. However, the levels in the NORSOK U-100 standard would provide a more comfortable living environment.

5.2 Comparison of expected noise exposure with current noise regulations

5.2.1 Noise doses from various sources in the diving environment

The noise sources identified indicate that many sound intensities that a diver may be exposed to, could exceed both the lower and upper exposure action values of the CoNaWR05, depending upon the duration of exposure and the type of diving apparatus worn. In some instances, without other control measures being implemented, only unrealistically short dive or activity durations are possible in order to comply with the CoNaWR05.

Table 5.1 shows the noise dose received in one hour for various sources, along with the permissible exposure duration to comply with the requirements of the CoNaWR05 (lower action values).

<u>Diving workplace noise:</u>

Diving sites are inherently noisy, and divers are exposed to high levels of noise while above water in addition to those experienced underwater during dives. As an example, noise measurements conducted on a barge supporting diving operations [7] indicated high levels associated with compressors for powering underwater tools, *e.g.* for a hydroblaster and hydraulic drill press levels were 99.4 and 100 dB respectively; at these levels the 80 dB(A) lower exposure action value is reached within several minutes.

In practice divers may spend relatively long periods above water in between dives, the noise exposure during these periods must be taken into account when assessing the daily and weekly noise dose received. It should be noted that the divers' workplace is also required to comply with local noise policies and the CoNaWR05.

Sub-surface noise:

Divers are subject to high levels of noise exposure underwater arising from sources such as self generated breathing noise and the operation of underwater tools. It has been shown that diving in enclosed helmets is the prime contributor to underwater noise exposure, as the wet ear effect provides some mitigation against the noise hazard.

From the dive helmet noise exposures identified, a major source of noise appears to be associated with the release of exhaust breathing gas bubbles. Noise levels recorded inside diving helmets, examples of which are shown in Table 5.1, indicates that for typical working dive durations the levels do not comply with the CoNaWR05. Of those shown, only the Dirty Harry helmet, with the diver at rest and breathing normally, generated noise that for a typical dive duration was below the lower exposure action value of 80 dB(A). Even for the Dirty Harry helmet, physical exertion resulting in raised ventilation generated breathing noise that for normal dive durations would exceeding the allowable value, so dive durations would need to be reduced, *e.g.* to around 20 minutes for tasks with a high physical workload.

Communication devices used while diving also produce high noise levels, increasing the exposure by around 27 dB for the Dirty Harry helmet, and so noise exposure from use of communications needs to be reduced to a minimum.

Underwater tools generate very high levels of impulse noise. Even given that the tools are often operated for relatively short periods of time (30 minutes being typical) the levels are well in excess of the CoNaWR05 exposure values.

When diving the cumulative effect of background noise, self-generated breathing noise, communications and tool noise all need to be considered when assessing diver sub-surface noise exposure.

Compression chamber noise:

During saturation diving or if surface decompression is required a diver will additionally be exposed to noise, particularly during compression and decompression. These noise levels are typically high and frequently add to the noise hazard.

Noise source	L_{Aeq} (average over time recorded) dB(A) re. 20 µPa	One hour noise dose (calculated from L_{Aeq}) dB(A) re. 20 µPa	# Permissible exposure duration (Time to CoNaWR05 $L_{EP,d}$)
Diver workplace noise			
Example noise sources on deck:			
Hydroblaster compressor [7]	99.4	90.4	5 min
Hydraulic drill press compressor [7]	100.0	91.0	4 min
Diver sub-surface noise			
Example diving helmet noise:			
Dirty Harry diving helmet: [5] Normal breathing	78.7	69.7	10.7 h
Dirty Harry diving helmet: [5] Maximum ventilation	93.4	84.4	21 min
Dirty Harry diving helmet: [5] Communication	105.8	96.8	1 min 25 s
US Navy Mk V [47]	113.0	104.0	14 s
Superlite 17K diving helmet [50] with SSDE	110.4	101.4	25 s
Example underwater tool noise:			
Stud gun [54]	185.4	176.4	< 2 s
Hydroblaster [7]	98.0	89.0	7 min
Hydraulic drill press [7]	86.8	77.8	1 h 40 min
Rock chipper [6]	111.5	102.5	20 s
Compression chamber noise			
Example chamber noise:			
Type 1 non-TUP chamber: [55] (compression to 18 m)	138.6	129.6	< 2 s
Type 1 non-TUP chamber: [55] (decompression from 18 m)	107.1	98.1	56 s
Admiralty Mk1 chamber: [56] (compression to 18 m)	106.2	97.2	1 min 9 s
Admiralty Mk1 chamber: [56] (decompression from 50 m)	101.0	92.0	3 min 48 s
Duocom Holders Variant chamber: [57] (compression to 50 m)	103.0	94.0	2 min 24 s
Duocom Holders Variant chamber: [57] (decompression from 50 m)	103.5	94.5	2 min 8 s

Permissible exposure duration without hearing protection or other control measures to remain within CoNaWR05 lower exposure action value

Table 5.1: Example noise doses for sources commonly encountered by divers Estimation of divers' total daily/weekly noise exposure

The total daily noise exposure is required to be within the exposure limit, and estimating this requires the identification of all noise sources that the diver is exposed to, rather than only during diving. A complete daily exposure could comprise:

- Noise during transit to the dive site by boat or helicopter
- Ambient noise at the dive site
- Sub-surface noise during dive
    - Sub-surface ambient noise
    - Self-generated breathing noise
    - Tool noise
- Noise exposure in a compression chamber

Furthermore, the work patterns of divers are often highly variable, and so taking account of noise exposure both above and below water on an appropriate time frame is important. Estimating weekly noise dose may be a more appropriate measure, rather than daily.

The noise dose received by a diver over a given time frame may be estimated from the average noise level (L_{Aeq}) for each component of an exposure and the duration of that exposure. This may be undertaken using:

- A tabular tool such the system developed by the HSE in 2007 and presented in Appendix A.1

or by using:

- The HSE 'on-line' system available at the following link: http://www.hse.gov.uk/noise/calculator.htm and illustrated in Appendix A.2.

Examples of the total noise exposure of divers are given below for:

- Completing a surface orientated air dive
- A saturation dive

and noise dose estimates of divers for:

- A nominal 12 h working day
- Dive with self-generated helmet noise

Example 1: Surface orientated dive total noise dose calculation

Table 5.2 provides an estimation of the noise dose during a dive to 40 m, including the use of an underwater tool [source data from 63]. The noise data included represent levels inside the diver's helmet. The overall noise dose is 83 dB, and exceeds the CoNaWR05 lower exposure action values.

Dive 1 Air Dive						
Depth 40 msw						
Dive time 40 mins						
Equipment Superlite helmet						
		Noise sources and typical SPLs at 4 kHz (dB)				
Dive activity	**Duration of exposure (mins)**	**Background noise**	**UBA**	**Comms**	**Tools**	**Sum (dB)**
Dressing	15	80				80
Descent	2		85	70		85
On bottom	5		85	70		85
Working with tool	30		-	70	90	88
On bottom	3		85	70		85
Ascent & in-water decompression	37		85	70		85
On surface	5		85	70		85
De-kit	15	80				80
	1.87 hours				**$L_{EP,d}$**	83 dB

NOTES
(i) Dive times are based on US Navy tables.
(ii) Background noise level on board a DSV derived from Nedwell[18], and Hicks[24].
(iii) UBA noise derived from Nedwell[18].
(iv) Tool noise received through the helmet at the diver's ear while using a water jet, derived from Molvaer[17].
(v) Communication noise level estimated.

Table 5.2: Noise dose for a dive to 40 m (UBA: Underwater Breathing Apparatus). Source data from reference [63].

Example 2: Saturation dive total noise dose estimation

For saturation diving, the total exposure includes noise exposure encountered during compression, decompression and while in the living habitat as well as during diving [64]. The total noise dose was estimated to be 88.4 dB(A) re. 20 µPa for a typical two-week tour of duty for a North Sea diver, and comprised exposure arising from representative sources as indicated in Table 5.3. Again the noise dose exceeds the lower and upper exposure action values of the CoNaWR05. However, it is also considerably greater than the levels in the NORSOK U-100 standard and the proposed continuous exposure level of 73 dB(A) re. 20 µPa (Para 5.1.5).

	Level dB(A)	No. of hours	Percentage of hours	Percentage of total dose
Compressing	95	1	0.3	3.0
Living Ch., active	80	112	33.3	1.0
Living Ch., asleep	70	112	33.3	10.5
Bell Duty	90	30	8.9	28.3
Diving	90	60	17.9	56.5
Bell checks etc.	75	21	6.2	0.6
TOTALS		336	100	100

Table 5.3: Noise dose for a typical North Sea diver's saturation dive [64]

Example 3: Total noise dose over a 12 h working day

The total noise exposure for a conceptual working day lasting 12 h is shown in Table 5.4. A 1.5 h fast transit is included along with two 2 h dives separated by a 4 h surface interval. The total exposure for the day is 89 dB(A), and so the upper exposure action value of 85 dB(A) and limit value of 87 dB(A) are exceeded.

Task/activity	**Noise Level L_{Aeq} dB(A)**	**Exposure duration (h)**	**Dose $L_{ep,d}$ (dB(A) for task**
Onshore travel	70	0.5	58
Fast transit	90	1.5	83
Dressing	80	0.25	65
Dive 1	89	2	83
Surface interval (4 h)	80	4	77
Dive 2	89	2	83
Fast transit	90	1.5	83
Onshore travel	70	0.5	58
		Duration of working day:	12 h 15 min
		Daily noise exposure ($L_{ep,d}$):	89 dB(A)

Table 5.4: Noise dose for a conceptual 12 h working day

Example 4: noise dose attributable to helmet noise

In order to comply with the requirements of the CoNaWR05, and if time of exposure is the only control measure implemented, many current diving helmets place severe restrictions on permissible dive durations, particularly when the physical workload is high and with appreciable use of communications. For example, the Dirty Harry helmet, the quietest tested by Evans *et al.* [5], produced acceptable noise when breathing rates were normal (78.7 dB(A) re. 20 μPa); high ventilation rates increased the noise output to 93.4 dB, and use of communications produced a further increase to 105.8 dB, requiring time limitations to be considered for these activities. A dive lasting one hour comprising more than approximately 15 minutes of high physical workload and 3 minutes of communication time would exceed the permissible daily noise dose.

5.3 Summary

Permissible noise exposure values are given by the CoNaWR05, and should be applied to divers in hyperbaric environments and when diving with a ‘dry’ ear’.

The noise hazard associated with hyperbaric and mixed gas diving can be determined by applying the CoNaWR05 with no adjustment. It is proposed that this principle be formally adopted for assessment of hyperbaric and mixed gas noise exposure.

For divers with a ‘wet’ ear, a correction may be applied to estimate the permissible noise dose. It is proposed that the method suggested by Parvin *et al.* [13], using an UW-weighting scale, be formally adopted for assessment of underwater noise exposure.

Divers with a wet ear wearing diving hoods are protected by the sound-absorptive properties of neoprene (approximately 5-15 dB at the surface, reducing with depth), and this further reduces their noise exposure.

For continuous hyperbaric exposure (*e.g.* saturation divers) the normalized, average daily and weekly noise dose values of the CoNaWR05 need to be appropriately applied to a full 168 hour week. It is proposed for saturation exposure that a maximum average noise level of 73 dB(A) re. 20 μPa is applied.

Noise doses from various types of diving equipment (helmets, underwater tools) and environments (on boat deck, inside compression chambers) have the potential to exceed the permissible values required by the CoNaWR05 by a substantial amount.

Compliance with CoNaWR05 requires calculation of a divers’ total daily or weekly dose, *i.e.* taking into account all activities above and below water. This may be undertaken using HSE calculation tools presented in Appendix A.

6 Control of noise exposure

6.1 Responsibilities arising from the CoNaWR05

6.1.1 Diver hearing

The evidence available from diver audiological studies suggests that diver hearing is impaired by exposure to factors associated with diving (12 out of the 15 studies identified). It is, therefore, appropriate, and as a requirement of CNRW05, that control measures are implemented to reduce divers' noise exposure and thereby reduce the risk of long term hearing deficit.

6.1.2 CoNaWR05 noise exposure

It has been shown that many aspects of the diving environment and equipment used, subject the diver to a noise dose that exceeds those defined by the CoNaWR05. The circumstances under which a diver is likely to be exposed to high noise levels have also been identified.

Once it has been established that a noise hazard exists, manufacturers and employers have a joint responsibility to reduce noise, so that divers are not exposed to a noise dose above the exposure values. In reducing the noise levels employers are required to demonstrate that the risk of noise hazard is ALARP and complies with the requirements of CoNaWR05.

6.1.3 Manufacturers' responsibilities

Designers and manufacturers of equipment are responsible for ensuring that noise levels are as low as can be reasonably achieved technically. This is embodied within UK law in that The SM(S)R92 requires that "Machinery must be so designed and constructed that risks resulting from the emission of airborne noise are reduced to the lowest level taking account of technical progress and the availability of means of reducing noise, in particular at source."

Manufacturers are also required to supply technical data specifying the noise output level of equipment, and the noise exposure characteristics (frequency spectra). Supporting data on the method of measurement used, including calibration certificates, is required. This data is essential for the assessment of total noise dose for diving operations.

Diving breathing apparatus is defined as personal protective equipment (PPE) and as such does not fall under the SM(S)R92. However, the European Norm for umbilical supplied diving apparatus BS EN 15333 parts 1 and 2, requires a manufacturer to identify the noise levels within diving helmets and provide the information to the user.

Thus the requirement to determine and supply data on noise levels applies to the provision of equipment for all aspects of diving operations including surface machinery (*e.g.* compressors), diving apparatus (*e.g.* diving helmets), diver tools and hyperbaric facilities (*e.g.* compression chambers).

6.1.4 Employers' responsibilities

Employers are responsible for ensuring that divers and all other employees are not exposed to noise that exceeds the values identified in the CoNaWR05.

Employers are also required to determine the level of noise that divers are exposed to and the duration of the exposure. The assessment must take into account all relevant factors including relevant working practices, and equipment, plant and other sources of noise not directly related to the diver's immediate task.

As part of this, there is a link with the manufacturers of equipment in that, employers have a responsibility under CoNaWR05 to include consideration of the choice of appropriate work equipment emitting the least possible noise:

http://www.hse.gov.uk/noise/goodpractice/lownoisemachines.htm.

If assessment indicates that the exposure values are likely to be exceeded, employers are responsible for eliminating or reducing noise at source to ALARP. If this is impractical, hearing protection must be provided.

6.2 Guidance for reducing diver noise exposure

6.2.1 Principle of noise control

An outcome of this review has been to highlight that the risk to divers' hearing is not simply due to the act of diving and using underwater breathing apparatus. The hazards are multi-faceted and embrace all aspects of a diver's working life and environment. Thus the solution and control principles invoked must also be multi-faceted.

There are three fundamental approaches to reducing noise exposure:

- elimination or reduction of noise at source
- reduction of environmental noise at the ear
- wearing hearing protection.

These are hierarchical with the control of noise at source being the optimum solution, and using hearing protection the least desirable.

However, diving and particularly commercial diving, where underwater engineering is undertaken, by its nature is a hazardous process. Noise is but one hazard of many that a diver faces. A balanced risk assessment must be applied to the whole operation, as fully mitigating against one risk may exacerbate the risk from another.

A significant example outlined in this review is the balance between the reduction in noise dose from a diver having a 'wet' ear compared to a 'dry' ear, and the physical head protection offered by a 'dry' helmet diving system compared to a wet SCUBA or band-mask system.

Whilst the ideal scenario is to both reduce noise dose to be fully compliant with CoNaWR05 and to provide full physical head protection; it is not achievable with equipment that is currently available in the diving industry. However, it should be a prime objective to achieve such. It is also not possible here to identify the balance between these two risks as it is highly dependent upon the nature of the task being undertaken. Thus the current principle for noise control must be a balanced risk assessment considering all factors linked with longer term action to reduce all risks including noise exposure.

6.2.2 Control of noise at source

The control of noise at source entails eliminating or reducing the noise output for each item of equipment that contributes to the noise dose. Self-generated breathing noise, dive site noise, tool noise and decompression chamber noise can each be addressed to reduce the total noise dose that divers receive.

Self-generated breathing noise and helmet noise

A significant contribution to a diver's noise exposure arises from diving helmet noise and specifically from exhaust bubbles generated during exhalation. Reducing or eliminating this source is likely to substantially reduce self-generated breathing noise. Diving breathing apparatus manufacturers, by addressing the noise from exhaust bubbles during exhalation (*e.g.* by eliminating exhaust bubbles or by moving exhaust bubbles away from the helmet), may be able to design helmets that have an appreciably reduced self-generated noise levels.

It has been recognized that audio communications are a major contributor to a diver's noise dose. As communications require a sound level in the order of 15 dB greater than the background, any reduction in internal helmet noise will have a proportional reduction in the noise dose from communications.

Dive site noise

Reduction of diving site noise produced by compressors, power generators and other equipment on a dive site, via engineering solutions is a viable approach to reducing total diver noise exposure. The principles of noise reduction are relatively well-established for these sources, and include:

- fitting exhaust mufflers on internal combustion engines
- fitting silencers to compressed air exhausts
- isolating (using rubber mounts and flexible connections) a vibrating noise source to separate it from the surface on which it is mounted
- fixing damping materials (such as rubber) or stiffening materials to panels to reduce their tendency to vibrate
- building enclosures or sound proof covers around noise sources
- fitting sound absorbing materials to hard reflective surfaces to reduce noise.

An additional approach is to provide 'quiet' areas on work and dive sites where divers may be protected from ambient noise during periods when they are not involved in a diving operation.

Tool noise

Many of the above engineering solutions may also be applicable to the reduction of tool noise, such as fitting exhaust mufflers and silencers. As with diving helmets, any pneumatically driven tool that is exhausting bubbles will be emitting a high noise level. Using tools that are hydraulically rather than pneumatically driven will reduce noise levels, as will moving exhaust bubbles away from the diver. The duty cycle of the tool may also be adjusted during use, as this would reduce the average noise exposure of the operator.

Compression chamber noise

A substantial amount of the noise during pressurisation arises from turbulence arising from high pressure gas merging with still air. Commercial silencers are available to reduce this noise [63] and are reported to achieve noise attenuation of around 10 dB at low frequencies rising to 20 dB at high frequencies. A further method to reduce noise inside chambers is to fit acoustic cladding to reflective surfaces. Chamber isolation to reduce the mechanical coupling of the steel structure of the chamber to the supporting surface is a further tried and tested method of reducing noise.

6.2.3 Reduction of environmental noise at the ear

Helmet soundproofing

Helmet noise may be further reduced by incorporating acoustic insulation in and around the diving helmet shell to provide soundproofing. This approach is currently being investigated by some manufacturers and may significantly reduce noise levels at the diver's ear.

Noise attenuation of diving hoods

Neoprene diving hoods either stand alone or as part of a band-mask provide protection by attenuating noise levels at the divers' ear [45] [54] [60] [65], and reduce noise intensities by approximately 5-15 dB depending on the thickness of the neoprene. As the thickness of the neoprene is reduced with depth the attenuation decreases with increasing depth.

As discussed previously divers with a 'wet' ear and diving hood have some protection from noise hazards due to the reduced sensitivity of the ear underwater, as well as noise protection by their diving hood, but may not have adequate physical head protection. However, also as previously indicated, this may not be a realistic single noise control option. Helmets are often preferred for many diving tasks as they provide physical head protection.

Active noise reduction (ANR)

ANR can be used in communications system earpieces to reduce the background noise transmitted by diver communication systems, in order to reduce overall noise levels generated during use of communications. This method has been successfully implemented to improve the intelligibility and noise reduction of aircrew communications headsets [66] [67]. ANR inside diving helmets to reduce environmental noise has been suggested to avoid the need for earplugs, an approach that has also been adopted in prototype helmet-integrated ANR systems for aircrew [68]. The application of ANR within vehicle cabins could also be applied to diving environments and transport to reduce diver noise exposure.

6.2.4 Reducing time of exposure to noise

When all practical measures have been undertaken to reduce the source of the noise, noise exposure may be controlled by administrative means such as limiting the time of exposure.

This principle may also be applied to voice communications limiting the communication with the diver. However, as communications are an essential safety and work function requirement, this is not a viable option.

Given the existing noise exposure levels and consequently the reduced allowable exposure (dive) times, this would also not be a practical approach because the work (dive) time would be too short. However, should noise levels be better controlled at source then this may become a more viable option in some circumstances.

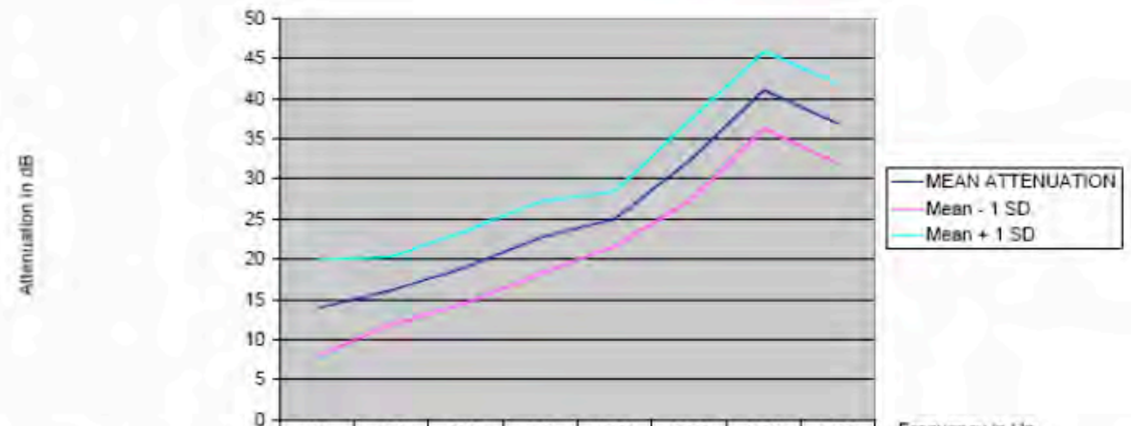
6.2.5 Hearing protection

Hearing protection should only be considered when all other noise control measures have been unable to reduce noise to an acceptable exposure. If when all other control measures have been applied the noise dose still exceeds 85 dB(A) re. 20 μPa then the CoNaWR05 mandates the use of hearing protection. If the noise level is between 80 and 85 dB(A) re. 20 μPa employers are required by the CoNaWR05 to inform any persons exposed to these levels and make hearing protection available on request.

Although 'earmuff' type hearing protectors are routinely used throughout industry, they are only suitable for use on surface on a diving site, or in compression chambers if they have been drilled (a small nominally 2 - 3 mm diameter hole in the centre of the earmuff shell). Drilling the earmuff allows gas to freely move between the inside and outside of the earmuff preventing any pressure differential and the associated risk of barotrauma.

Conventional earmuff hearing protectors cannot be used within current diving helmets as they simply will not fit within the space available. During the helmet noise trial conducted by Evans *et al.* [5], earplug hearing protection was successfully used and worn within diving helmets; the system also allowed viable audio communication. The 'Emtec' hearing protectors used provided attenuation ranging from 13.9 dB at 63 Hz to 41.1 dB at 4 kHz (Figures 6.2 and 6.3).

Figure 6.2: Emtec earplug hearing protectors fitted to a cutaway anatomical model and human ear



	63	125	250	500	1000	2000	4000	8000
MEAN ATTENUATION	13.9	16.1	19	22.7	25	32.2	41.1	36.9
Mean - 1 SD	7.9	11.9	14.5	18.2	21.6	27.2	36.3	31.9
Mean + 1 SD	19.9	20.3	23.5	27.2	28.4	37.2	45.9	41.9

Figure 6.3: Attenuation offered by Emtec earplug hearing protectors

Hagglin *et al.* [69] estimated similar attenuation (up to 40 dB between 500-3000 Hz) and highlighted difficulties with obtaining good attenuation at low frequencies. Murphy and Tubbs [70] and Du *et al.* [71] has suggested the use of double hearing protection, comprising earplugs and earmuffs, reporting that the combination added 15-20 dB of noise attenuation.

It is also understood that some commercial diving companies are now using pressure equalizing ear-plugs that include communications to reduce a diver's noise dose.

The characteristics of ear protection other than sound attenuation are an important consideration. Hagglin *et al.* [69] summarised some of these features as follows:

- earmuffs provide stable and reliable damping, and can be used when there is a risk of ear infection. They are, however, uncomfortable to wear for long periods, as they need to be close-fitting to provide hearing protection.
- earplugs, incorporating ventilated ducts for use by divers, are inexpensive and comfortable and can be used with both hoods and helmets. They cannot be used when there is a risk of ear infection and are easily contaminated with ear wax.

6.3 Health surveillance programme for noise exposure

As part of the CoNaWR05, if a risk assessment indicates there is a risk to the health of an employee who is exposed to noise, the employer shall ensure that such employees are placed under suitable health surveillance. Given the potentially high levels of noise that divers are exposed to, management of noise exposure risk for divers should include establishing a comprehensive health surveillance programme. This involves the following [4]:

- providing regular hearing checks in controlled conditions;
- telling employees about the results of their hearing checks;
- keeping health records;
- ensuring divers are examined by a doctor where hearing damage is identified.

6.4 Summary

Manufacturers and employers have a joint responsibility to reduce noise so that divers are not exposed to intensities above the exposure values defined by the CoNaWR05.

Manufacturers of diving equipment are responsible for ensuring that noise levels of diving equipment are as low as can be achieved technically, and to provide data on the noise produced by their systems.

Employers are responsible for ensuring that divers are not exposed to a noise dose that exceeds the exposure values, and for implementing noise reduction strategies to limit exposure where it is found to exceed allowable values.

A diver noise reduction strategy should employ the following hierarchy:

- Eliminate or reduce noise at source, *e.g.* by redesigning the equipment generating noise.
- Provide noise attenuation at the divers head/ear, *e.g.* by noise insulating materials or ANR
- Restrict the exposure time of the diver to the noise.
- Provide hearing protection *e.g.* appropriate ear-plugs or ear-muffs

A health surveillance programme involving audiometric tests for divers should be established as part of the management of noise exposure risk.

7 Conclusions

Audiometric studies (12 of 15 identified) indicate that diver hearing is impaired by exposure to factors associated with diving.

Several studies also suggest that divers' hearing deteriorates faster than non-divers *i.e.* increased age-related deficit.

Hearing sensitivity in hyperbaric environments and gases other than air is similar to hearing in air at normobaric pressure; human hearing underwater (*i.e.* with water in contact with the head and filling the auditory canal) is less sensitive than in air.

The noise hazard associated with hyperbaric and mixed gas diving, whilst the ear is dry, may be calculated using the A-weighted scale and the exposure levels in the CoNaWR05 applied without modification.

An UW weighting scale, as used in this review, should be formally adopted for assessment of underwater noise exposure where the ear is wet (*i.e.* with water filling the auditory canal).

For continuous noise exposure, an average noise level of 73 dB(A) re. 20 μPa will provide a noise dose at the lower exposure action value of the CoNaWR05.

Divers are routinely exposed to a range of noise sources of sufficiently high intensity to cause auditory damage; *i.e.* dive site noise, self-generated breathing noise, underwater tool noise and compression chamber noise.

Self-generated breathing noise and communications are major contributors to divers' noise exposure when wearing diving helmets.

Current noise control measures for divers are inadequate and additional control measures are required to reduce the noise hazard to within occupational exposure values.

Compliance with CoNaWR05 requires calculation of a divers' total daily or weekly dose taking into account all activities above and below water.

As noise is only one hazard to a diver, a balanced risk assessment must be applied to the whole diving operation; fully mitigating against one risk may exacerbate others.

Manufacturers of diving equipment and employers of divers have a joint responsibility to ensure compliance with SM(S)R 92 and the exposure values in CoNaWR05.

Manufacturers should supply technical data specifying the noise output level of their equipment.

A diver noise reduction strategy should employ the following hierarchy:

- Eliminate or reduce noise at source, *e.g.* by redesigning the equipment generating noise;
- Provide noise attenuation at the diver's head/ear, *e.g.* by noise insulating materials or ANR;
- Restrict the exposure time of the diver to the noise.
- Provide hearing protection *e.g.* appropriate ear-plugs or ear-muffs;

A health surveillance programme involving audiometric tests for divers should be established as part of the management of noise exposure risk.

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A Noise exposure calculator

A.1 Tool for estimating noise exposure (developed by HSE, 2007)

Sound pressure level, L_{Aeq} (dB)	*Duration of exposure (hours)*							
	¼	*½*	*1*	*2*	*4*	*8*	*10*	*12*
105	320	625	1250					
104	250	500	1000					
103	200	400	800					
102	160	320	630	1250				
101	125	250	500	1000				
100	100	200	400	800				
99	80	160	320	630	1250			
98	65	125	250	500	1000			
97	50	100	200	400	800			
96	40	80	160	320	630	1250		
95	32	65	125	250	500	1000		
94	25	50	100	200	400	800		
93	20	40	80	160	320	630		
92	16	32	65	125	250	500	625	
91	12	25	50	100	200	400	500	600
90	10	20	40	80	160	320	400	470
89	8	16	32	65	130	250	310	380
88	6	12	25	50	100	200	250	300
87	5	10	20	40	80	160	200	240
86	4	8	16	32	65	130	160	190
85		6	12	25	50	100	125	150
84		5	10	20	40	80	100	120
83		4	8	16	32	65	80	95
82			6	12	25	50	65	75
81			5	10	20	40	50	60
80			4	8	16	32	40	48
79				6	13	25	32	38
78				5	10	20	25	30
77					8	16	20	24
76					6	13	16	20
75					5	10	13	15

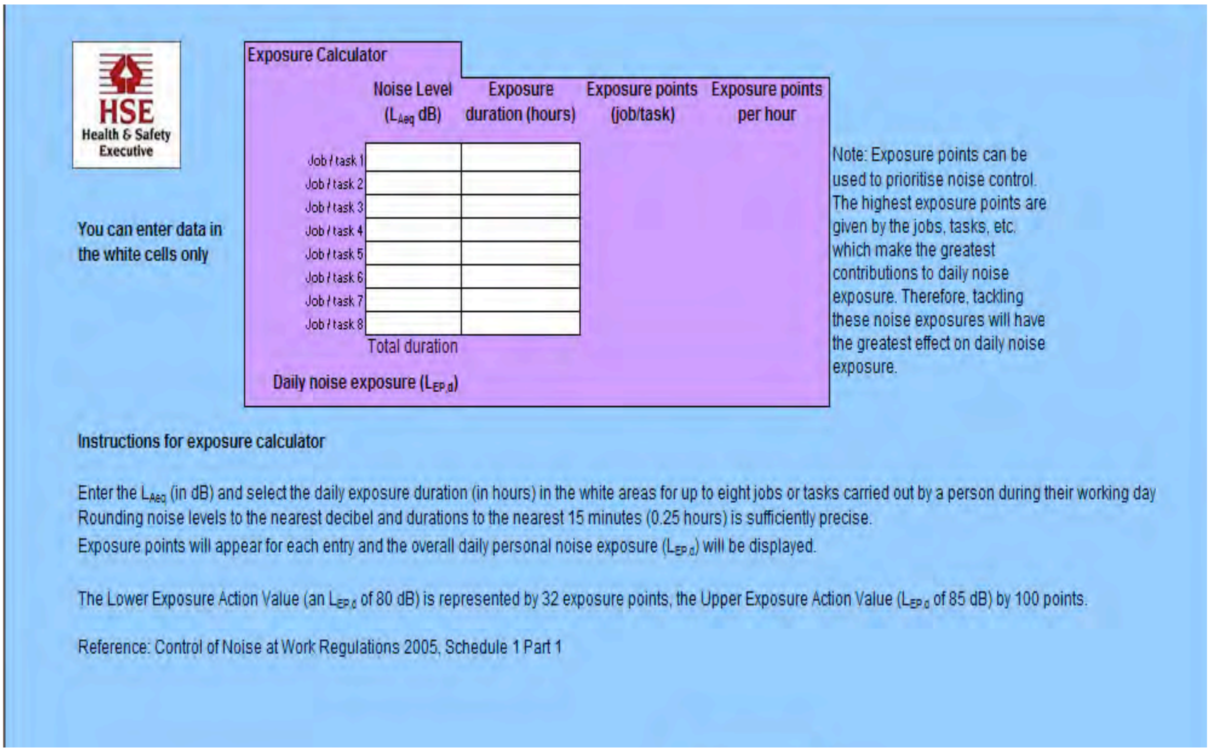
Total exposure points	*Noise exposure $L_{EP,d}$ (dB)*
3200	100
2500	99
2000	98
1600	97
1250	96
1000	95
800	94
630	93
500	92
400	91
320	90
250	89
200	88
160	87
130	86
100	85
80	84
65	83
50	82
40	81
32	80
25	79
20	78
16	77

Instructions:

- For each task or period of noise exposure in the working day look up in the table on the left the exposure points corresponding to the sound pressure level and duration (e.g. exposure to 93 dB for 1 hour gives 80 exposure points);
- Add up the points for each task or period to give total exposure points for the day;
- Look up in the table on the right the total exposure points to find the corresponding daily noise exposure (e.g. a total exposure points for the day of 280 points gives a daily noise exposure of between 89 and 90 dB).

A.2 Daily noise exposure calculator (developed by HSE, 2007)

Available at the following link: http://www.hse.gov.uk/noise/calculator.htm


HSE Health & Safety Executive

You can enter data in the white cells only

Exposure Calculator

	Noise Level (L_{Aeq} dB)	Exposure duration (hours)	Exposure points (job/task)	Exposure points per hour
Job / task 1				
Job / task 2				
Job / task 3				
Job / task 4				
Job / task 5				
Job / task 6				
Job / task 7				
Job / task 8				
	Total duration			

Daily noise exposure ($L_{EP,d}$)

Note: Exposure points can be used to prioritise noise control. The highest exposure points are given by the jobs, tasks, etc. which make the greatest contributions to daily noise exposure. Therefore, tackling these noise exposures will have the greatest effect on daily noise exposure.

Instructions for exposure calculator

Enter the L_{Aeq} (in dB) and select the daily exposure duration (in hours) in the white areas for up to eight jobs or tasks carried out by a person during their working day
Rounding noise levels to the nearest decibel and durations to the nearest 15 minutes (0.25 hours) is sufficiently precise.
Exposure points will appear for each entry and the overall daily personal noise exposure ($L_{EP,d}$) will be displayed.

The Lower Exposure Action Value (an $L_{EP,d}$ of 80 dB) is represented by 32 exposure points, the Upper Exposure Action Value ($L_{EP,d}$ of 85 dB) by 100 points.

Reference: Control of Noise at Work Regulations 2005, Schedule 1 Part 1

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Review of diver noise exposure

Divers are exposed to high levels of noise from a variety of sources both above and below water. The noise exposure should comply with 'The Control of Noise at Work Regulations 2005' (CoNaWR05). A detailed review of diver noise exposure is presented encompassing diver hearing, noise sources, exposure levels and control measures. Divers are routinely exposed to a range of noise sources of sufficiently high intensity to cause auditory damage and audiometric studies indicate that diver hearing is impaired by exposure to factors associated with diving. Human hearing underwater, in cases where the diver's ear is wet, is less sensitive than in air and should be assessed using an underwater-weighting scale. Manufacturers of diving equipment and employers of divers have a joint responsibility to ensure compliance with the exposure values in the CoNaWR05, although noise is only one hazard to a diver, and a balanced risk assessment must be applied to the whole diving operation. A diver noise reduction strategy is proposed and a health surveillance programme, involving audiometric tests for divers, should be established.

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