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Lethal and physical injury of marine mammals, and requirements for Passive Acoustic Monitoring.

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1 Introduction.

This report has been prepared by Subacoustech Ltd., for the UK Department of Trade and Industry under programme RDCZ/011/00018 entitled 'A feasibility and demonstration study; active and passive detection of marine mammals'. This is the first report delivered as part of this programme aimed at 'estimating typical lethal range for marine mammals from anthropometric sources'. The overall aim of the project is to identify the limits of performance of methods of acoustically detecting marine mammals during offshore activity such as construction and seismic survey.

The value of the seas and seabed as a natural resource has increased greatly over recent years, and the number and scale of offshore activities has increased in proportion. Many of man's offshore activities cause underwater noise, from the noise created by ship movements through to the extreme levels of sound generated during the use of explosives underwater, for instance for decommissioning of unwanted oil and gas installations.

The noise from offshore activity has the capacity to directly cause disturbance to marine mammals such as seals, whales, dolphins and porpoises. The effects of noise can include death or lethal injury, physical injuries that can have longer term consequences for the animal such as deafness, and sub-lethal behavioural effects such as the avoidance of an area. All of these may have significant consequences for individuals or stocks of a species. In addition, secondary effects can occur, for instance by disturbance of the fish that are their food. Hence, it is generally a condition of consents issued for offshore activity that

- the likely level of noise created by various activities is estimated prior to an operation being undertaken,
- where the noise component of an activity may be significant, the noise levels are kept at the lowest reasonable level,
- and that where the noise of an activity is sufficient to create an adverse effect, mitigation measures are introduced.

Of the mitigation measures that might be used, a primary measure where sensitive species inhabit or may enter a proposed area of activity is the monitoring of the area for the presence of the species. This enables the activity to be terminated if there are marine animals present. Generally, use is made of Marine Mammal Observers (MMOs) in an attempt to visually detect marine mammals. However, this approach is ineffective, and in darkness or poor visibility detection is impossible. Under these circumstances acoustic detection offers significant advantages. There are three approaches for an Acoustic Detection System (ADS) that might be used, comprising

Passive Acoustic Monitoring (PAM). In this approach, a sonar-type system monitors for vocalisations or echolocation signals from the animals. The systems that have been fielded to date are of generally poor quality, have left-right ambiguity (i.e. cannot determine which side the signal is from) and have no range-finding ability.

Active Acoustic Monitoring (AAM). In this, a sonar "ping" is broadcast in the water and the system looks for a returning signal when it encounters a target. There are systems that have been well developed for military and other purposes, but they all suffer from the fact that they use a "beam" of sound and hence the area of water that is covered at any one time is small. In addition, the sonar may itself cause environmental effects, albeit at a low level.

Acoustic Daylight Monitoring (ADM). This class of sonar is new, and relies on detecting existing background noise being scattered from a target. It has significant potential advantages, including broad area coverage, lack of need for insonification and the ability to also act in PAM mode, but is “cutting edge” technology at the limits of achievability.

In order to specify the required performance of an acoustic detection system, it is necessary to know the range at which an animal may be affected by the noise. Most commonly, it is necessary to find the range at which injury will be caused. In order to calculate this, it is necessary to know the level of sound as a function of range that might be created, and the level of sound at which injury occurs. This report provides a technical review of current information related to the parameters that determine the lethal and physical injury range for marine mammals from acoustic energy in the underwater environment.

2 Range requirements for a passive acoustic monitoring system.

Figure 2-1 illustrates the use of a Passive Acoustic Monitoring (PAM) system to detect marine mammals within a zone around an underwater activity.

As a typical example of the use of a PAM system, an observer on a vessel may be used to detect marine mammals straying within the zone around an underwater blasting operation within which they may be injured. The aim is to ensure that the marine mammals are detected by their vocalisations prior to the blast being fired. The operator may listen on a hydrophone for the noises made by the marine mammal; if these are sufficiently above the level of background noise that they may be heard, a detection may be made by the operator. In this case, the activity may be halted until the marine mammal leaves the area, or other means are used to remove it, such as an acoustic harassment device.

It may be seen that for simple PAM systems sensing at one point, the detection range that is required is, at a minimum, equal to the lethal range. This will only be adequate, however, where the PAM system and the activity are co-located, which will not generally be possible. Therefore,, the required detection range will typically be at least twice the injury range.

In order to specify the required working range of a PAM system it is necessary to know the range for a given effect, such as injury, specified in terms of

- The level of sound emitted by the source,
- the level of sound above which injuries may be caused, and hence
- the range at which an animal may be injured.

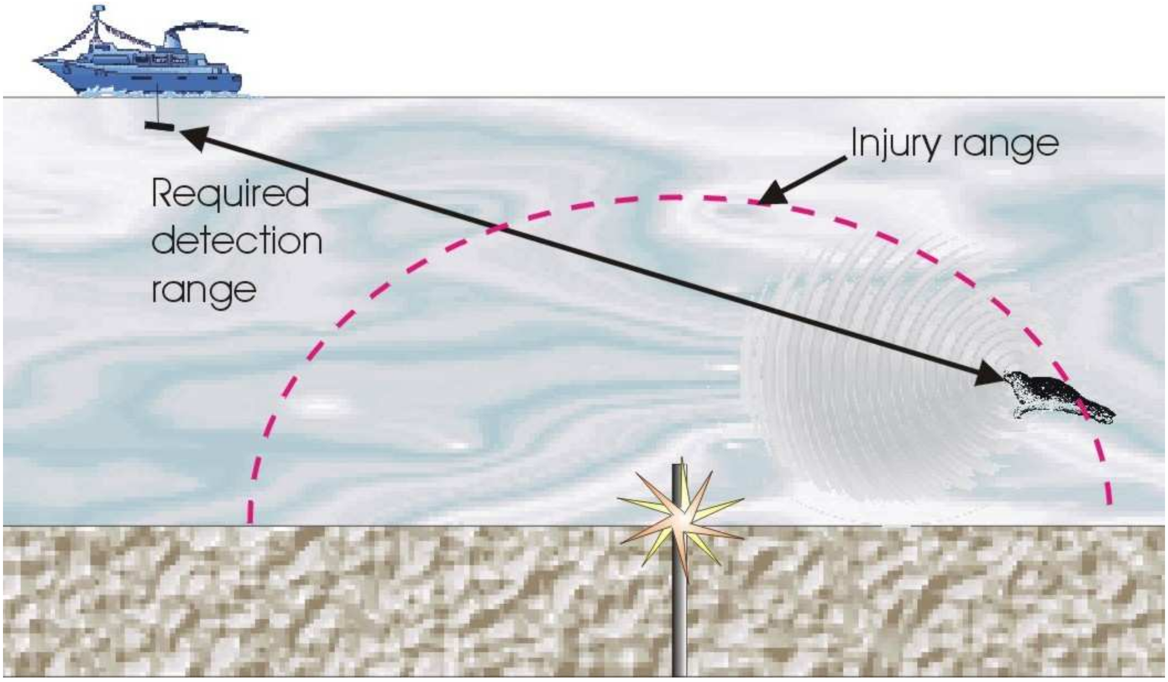

Figure 2-1. An illustration of the use of a PAM system.

In order to determine whether this required range of operation may in principle be achieved by a PAM system it is necessary to know

- The level of vocalisation by the animal,
- The level of background noise, and
- The detection threshold, or level above the background noise at which a reliable detection may be made.

It should be noted, however, that these considerations will indicate *in principle* whether a PAM system can work for a given application. The hardware used in actual PAM systems may not perform to the theoretical limit of performance, and tired operators in difficult conditions may not achieve the ideal detection thresholds cited herein.

This report considers the required performance for PAM systems for monitoring of several types of offshore activity involving high levels of noise, and indicates whether the successful use of such systems is fundamentally feasible in these operations.

3 Units for measuring impulsive noise.

3.1 Introduction.

If a PAM system is considered as a method of mitigating the effects of high levels of underwater noise, such as for a blasting operation, it is necessary to first determine the distance at which the noise may have an effect. To do this it is necessary to consider the units that must be used to measure the noise.

The noise sources that are of most concern are those that generate “transients”, or short powerful pulses of noise, such as blast, seismic surveying using airguns, and piling. Estimating the lethality or injury potential from such noises is a complex and inexact process. There are examples where apparently innocuous peak pressure levels can cause a severe effect at long range from a source, and examples of where peak pressure with a very low related level of impulse can cause injury or fatality at close range from a small source. Rawlins (1987) reports on six varying cases of exposure to humans of underwater transients from blast waves and indicates that both peak pressure and the duration over which the peak pressure acts on the body are important factors in determining the potential for injury and lethality.

The pressure in a blast wave near to the explosive is so high that its waveform changes shape during propagation, forming a shock wave. At large distances from the source the propagation of the pressure wave usually approximates that of other sound waves. However, the high frequency energy is absorbed and scattered, and the waveform becomes extended in time. It is therefore common that the pressure wave from explosive at a distant point is dominated by low frequency components, and is perceived as a "rumble".

Historically, the peak pressure and the impulse are the units that have been used to describe the severity of transients such as blast.

3.2 Peak Pressure.

The peak pressure of a blast wave P_{max} is the maximum level of overpressure, that is, the pressure above the local ambient pressure caused by the shock wave. This is usually at the initial peak of the waveform, and is easily read from a recording of the blast wave. While the fundamental SI units of peak pressure are Pascal (Pa), in this report the subsidiary unit kPa has been extensively used, where 1 kPa = 1000 Pa, and the unit MPa = 1,000,000 Pa.

The peak pressure of the wave tends to be related to injuries caused by shearing of body tissues such as the “rib imprint” injuries to tissues in the chest wall.

3.3 Impulse.

The importance of impulse is that in many cases a wave acting for a given time will have the same effect as one of twice the pressure acting for half the time. The impulse of both these waves would be the same. The impulse I is defined as the integral of pressure over time and is given by

$$I = \int_0^\infty P(t)\delta t \qquad \textit{eqn. 3.1}$$

where I is the impulse in Pascal-seconds (Pa.s), P(t) is the acoustic pressure in Pa of the blast wave at time t and t is time. Expressed in this way the impulse might be considered to be the average level of the blast wave pressure multiplied by its duration. Physical considerations; however, indicate that in fact the impulse defined in this way will always be zero, since after the main blast front there is a period of relaxation in which the overpressure becomes negative. This introduces an equal and opposite contribution to the integral from that of the main pressure peak. Conventionally the impulse is estimated from the first peak of the blast wave, with the subsequent arrivals or relaxation being ignored. Expressed in this way, the impulse may be considered to be a measure of the low-frequency energy of the blast wave.

This low frequency component of blast tends to cause damage to the air containing structures in the body and is caused by their rapid compression and subsequent overexpansion. Impulse therefore correlates reasonably well with the severity of effects such as pulmonary injury.

3.4 Particle velocity.

For the sake of completeness, particle velocity should also be mentioned. In airborne blast, it is common to consider particle velocity as a measure of blast strength. The particle velocity of a shock wave is the instantaneous velocity of a particle of water as the shock wave passes. It should be noted that the particle velocity, which increases with increasing level, is not the same as the speed of sound, which is relatively constant. In air, the particle velocity is high as a result of its compressibility, leading to high transient air flows called "blast wind". However, water is relatively incompressible and hence the particle velocities are much lower. As a result, the particle velocity is not normally considered as a criterion for injury.

4 Physical injury and lethality in marine mammals.

4.1 Introduction.

This section of the report reviews current literature and examples of physical injuries in marine mammals, and uses these to suggest criteria for injury and death of marine mammals. In general, there is little information on the effects of high energy underwater sound on marine mammals of good quality. In particular, there are very few instances where the physical parameters of sound have been measured simultaneously with the impact upon the marine animal. This form of data is only likely to be provided from controlled, open water trials. In many cases, however, data arises as a result of accidental exposure which it may only be possible to interpret later in a limited way.

Studies have been conducted using submerged terrestrial animals and human divers: these are also reviewed here to provide quantitative data for the levels of the physical parameters likely to cause death or injury.

In many cases, the quantities quoted in the reports referenced herein are in non-SI units, such as psi, bar etc. Where this occurs, the convention has been adopted in this report of quoting the reference verbatim, including the use of the units as quoted by the authors of the report, followed by the appropriate SI conversion.

4.2 Levels of peak pressure that may cause lethal and physical injury.

4.2.1 Marine mammal data.

There are very few examples of observations of marine mammal mortality concurrently with the measurement of the physical parameters of the incident acoustic wave. Hanson (1954) recorded mortalities in fur seals at ranges of up to 23 m from an 11 kg submerged dynamite charge. Blast scaling laws indicate that the exposures were likely to have been at an incident peak pressure of up to approximately 530 psi (3.8 MPa or 252 dB re. 1µPa peak pressure). Wright (1971) reported that sea otters (*Enhydra lutris*) were injured by incident peak pressures of 100 psi (0.69 MPa or 236 dB re. 1µPa) and killed outright by 300 psi (2.07 MPa or 246 dB re. 1µPa).

4.2.2 Animal studies.

Cameron, Short and Wakely (1943) describe the effects of underwater explosions on submerged monkeys, dogs, goats and pigs, exposed to blast waves from a 320 lb (145 kg) TNT charge fired at a depth of 48 feet (15 m) in 90 feet (27 m) of water. The horizontal range from the charge to the submerged animals varied from 0 to 900 feet (274 m). At incident peak pressure levels from 13.7 MPa to 4.5 MPa, corresponding to impulse levels from 4480 Pa.s to 827 Pa.s, 11 out of 13 animals were killed instantaneously. At incident peak pressure levels of 4.0 and 3.6 MPa, and impulse levels of approximately 690 and 550 Pa.s, the animals were severely injured and would not have recovered. At incident peak pressure sound levels from 2.4 to 0.5 MPa, and at impulse levels from 276 to 14 Pa.s, lung damage was observed, and it was determined that the injury was such that the animal would have been expected to recover.

Wright (1951) reported on the pathological findings in a goat exposed just below the surface to a 2.5 lb TNT charge at a range of 10 feet (3 m). The exposure was estimated at a peak pressure level of 12.2 MPa (262 dB re. 1µPa) and an impulse of 620 Pa.s. The goat died 25 minutes after the exposure with extensive haemorrhage to both lungs and damage to the liver. Studies with submerged rats indicated that a peak pressure of 10.3 MPa (260 dB re. 1µPa) at an impulse of 165 Pa.s was lethal in 80% of cases causing extensive haemorrhage of the lungs together with severe bruising of the caecum (pouch at the beginning of the large intestine) and small intestine.

Rawlins (1974) reviews these injuries and suggests that for a submerged rat, 50% lethality (LD_{50}) might occur at an incident peak pressure of 800 psi (5.5 MPa or 255 dB re. 1µPa) and 95% lethality (LD_{95}) at an incident level of 1200 psi (83 MPa or 278 dB re. 1µPa).

Bennett (1955) provides a review of underwater blast impact on submerged rabbits and the use of materials to protect from the effects of the pressure wave. The rabbits were exposed to the pressure wave from three 1 g detonators, equivalent to 0.0066 lbs TNT, with the charge and rabbits at a depth of 3 feet (0.91 metres). At a peak pressure exposure of 2330 psi (16 000 kPa, or 264 dB re. 1µPa), with an associated impulse of 0.067 psi.sec (462 Pa.s), all five of the unprotected animals died, suffering severe injury to the lungs, stomach and bowel.

Bebb and Wright (1952, 1953, 1954a, and 1954b) made extensive use of animal models, primarily submerged sheep, to determine the effects of underwater blast. Studies were conducted at ranges from 8 ft (2.4 m) to 45 ft (13.5 m) from a 1.25 lb (0.57 kg) TNT charge. At the greatest range, with a peak pressure of 235 psi (1620 kPa or 234 dB re. 1µPa) and an impulse of 0.035 psi.sec (241 Pa.s) the injuries found at post mortem examination were 'hardly visible', but by contrast, at a range of 15ft (4.6 m), with a peak pressure of 900 psi (6200 kPa or 256 dB re. 1µPa) and an impulse of approximately 0.15 psi.sec (1034 Pa.s), the injuries were 'severe and extensive'. It was estimated that by a range of 8 ft (2.4 m), with a peak pressure of 1900 psi (13100 kPa or 262 dB re. 1µPa) and an impulse of 0.26 psi.sec (1790 Pa.s), instantaneous death would have resulted. As a result of these studies a formula to estimate the lethal range from an underwater charge of known weight was proposed. It was based on the conclusion that a peak pressure of 12,000 kPa and an impulse of 700 Pa.s would be lethal, as would a wave of 4300 kPa peak pressure with an impulse of 4900 Pa.s.

Based on the findings of Bebb and Wright, the impact of underwater blast in terms of its peak pressure impact on submerged animals is presented in Table 4-1.

Peak Pressure (psi)	Peak Pressure (kPa)	Effect
>2000	>13800	Death Certain
500 - 2000	3450 - 13800	Likely to cause death or severe injury
50 - 500	345 - 3450	Likely to cause injury
<50	<345	Unlikely to cause injury

Table 4-1: Injury potential of an underwater TNT blast based on Peak Pressure (US Navy, 1970)

The studies of Fletcher *et a*l. (1976) with submerged sheep indicate that incident peak sound pressures of over 100 psi (690 kPa or 237 dB re. 1µPa peak pressure) have a lethal effect causing pulmonary contusion, haemorrhage and arterial gas embolism. Arterial gas embolism has been demonstrated in a number of submerged animal models, including humans, and is usually accompanied by lung damage. Yelverton *et al*. (1976) found that arterial gas embolism in submerged terrestrial mammals usually results in immediate death.

O'Keefe and Young (1984), Young (1991), Goertner (1982), Richardson (1995) and Ketten (1995) present models to determine the "safe" stand-off range for marine mammals from underwater high explosive charges. The model of Young (1991) was based on preventing injury related to the response of gas cavities such as the lungs, or gas bubbles in the intestines. Examples are provided that are also reproduced in Richardson (1991 and 1995) whereby the 'slight' injury range from a 4540 kg (10,000 lb) TNT charge is estimated at 2300 m for a porpoise calf, 1700 m for an adult porpoise, 1600 m for a 6 m whale and 700 m for a 17 m whale. Using blast scaling laws these correspond to incident peak pressure and impulse levels of 77 kPa or

218 dB re. 1μPa and 1230 Pa.s for the porpoise calf, 116 kPa or 221 dB re. 1μPa and 1700 Pa.s for the 6 m whale and 296 kPa or 229 dB re. 1μPa and 3550 Pa.s for the 17m whale.

Yelverton *et al*. (1973, 1976) used terrestrial mammals immersed in shallow water to establish models for the potential lethal effects of underwater blast. The studies are referred to by Richardson (1995) in converting the expressions for fish mortality into those that are representative of larger sea mammals. The expressions relate the impulse I (Pa.s) of the underwater blast that would produce a mortality probability and "no-injury" exposure, for an animal weight W (kg), where for:

- 50 % mortality $\log_e(I_{50}) = 5.01 + 0.3857 \log_e W$ *eqn. 4.1*,
- 1% mortality $\log_e(I_1) = 4.55 + 0.3857 \log_e W$. *eqn. 4.2.*

For a small marine mammal of mass 80 kg these expressions indicate an incident impulse that will produce a 50% mortality I_{50} = 812 Pa.s and a 1% mortality I_1 = 516 Pa.s. For a larger mammal of mass 500 kg, mortality I_{50} = 1647 Pa.s and a 1% mortality I_1 = 1039 Pa.s.

4.2.3 Human exposures.

Hirsh and Ommaya (1972) report on the death of a 23 year old man accidentally exposed to the explosive shock from a firecracker whilst swimming underwater. The firecracker exploded underwater in contact with the skin and 6 inches (0.15 m) from the base of the skull causing severe head injury and death related to the underwater explosion. The reconstruction of the mechanics of the exposure indicated a peak pressure of 440 to 1800 psi (3034 to 12410 kPa or 250 – 262 dB re. 1μPa) with an impulse quoted as between 1.8 to 3.5 psi.sec (12500 to 24400 Pa.s).

Richmond (1977) describes tests with human volunteer subjects exposed to underwater blast waves both as 'head out' exposures and with subjects exposed at a depth of 1 ft (0.3 m). The peak pressures, impulses and cut-off times were measured adjacent to the swimmer. With subjects fully submerged, the underwater blast impacts were described as tolerable, and did not produce tinnitus at impulse levels of 0.25 to 1.31 psi.msec (1.7 to 9 Pa.s) with respective peak pressures of 12 to 52 psi (83 to 358 kPa or 218 to 231 dB re. 1μPa). This was also the case with 1.0 to 2.0 psi.msec (6.9 to 13.8 Pa.s) impulses with corresponding peak pressures of 48 to 71 psi (331 to 490 kPa or 230 to 234 dB re. 1μPa), using 0.5 lb (0.23 kg) charges at a depth of 10 ft.

Wright *et al* (1950) conducted a number of series of tests with fully submerged divers exposed to underwater explosive charges. In the first of these Wright subjected himself to the impact from small charges at short range. The impacts that Wright underwent concluded with some fairly pernicious effects and resulted in Wright having to spend several days in hospital. A summary of the impacts from a 5 lb (2.27 Kg) TNT charge at shallow depth (approx 5 m) in given in Table 4-2.

In the subsequent trial that occurred at Spithead, Portsmouth, divers were exposed to underwater blast at a considerably greater range than that which Wright underwent (see summary in Table 4-3). The results indicate that shallow water exposure to a 5 lb (2.27 kg) charge at a range of 411 m produced a "slight squeeze" and a sound like a "dull bang" or "rumble". There are no indications that any of the divers were unduly concerned by exposure to the charge at this range, or any signs of physical injury in the subsequent medical examination. However, the divers in this study underwent numerous exposures to underwater blast and so were somewhat accustomed to the effects. The divers involved in the Spithead study were eventually exposed to a 25 lb (11.3 kg) charge at a distance of 65.6 m. At this point the trial was terminated as a significant number of the divers were developing a “wheeziness” in the chest as a consequence of the repetitive transient underwater noise exposure.

Range		**Sensations**	**Estimated Shock Levels**			
feet	metres	Subjective comment	P psi	P MPa	I psi-msec	I Pa.s
110	33.5	Sound of intense bang.	160	1.1	75	516
100	30.5	Intense bang. Mild blow on chest.	175	1.2	85	585
90	27.4	Severe blow on chest.	195	1.3	95	654
80	24.4	Blow on head and torso. Body shaken. Brief paralysis of arms and legs.	220	1.5	105	720
75	22.9	Violent blow. Brief paralysis of limbs. Substernal pain for ½ to 1 hour.	240	1.65	110	760
70	21.3	Violent blow. Temporary paralysis of limbs. Substernal pain lasting several hours. Aural damage. Tongue lacerated. Mask blown off. Mild concussion.	260	1.8	115	790

Table 4-2: Subjective comment from a diver exposed to a 5 lb (2.27 kg) charge of TNT (Wright et al (1950))

Range (metres)	**Diver depth (metres)**	**Impulse (Pa.s)**	**Peak Pressure (kPa)**	**Subjective Comments** (Assessed from comments of up to six divers for each underwater blast)
411	3.05	50	83.6	Small impact, waist squeeze, push. Sound like bang, crack, rumble.
411	15.25	50	83.6	Jolt, vibrated through body, hardly felt a thing. Heard dull bang, like Chinese cracker.
183	3.05	103	209	Slight impact, slight vibration - lower half of body. Quite a loud bang, sharp and sudden bang.
183	15.25	103	209	Shudder all over, felt blast - shove from waist upwards. Louder than I expected, two pretty loud bangs.
122	3.05	134	311	Vibration of whole body, slight sharp squeeze all over, fairly powerful thump in belly. Sharp loud explosion, low rumble, fairly loud bang - two distinct echoes.
122	15.3	134	311	Shook whole body, squeeze all over, blow on front of chest and top of head, pressure in ears. Loud explosion, double very loud rumbling bang, loud muffled bang.

Table 4-3: Summary of results from exposure of divers to a 5 lb (2.27 kg) charge in shallow water (Wright et al (1950))..

Christan and Gaspin (1974) evaluated much of the submerged terrestrial animal data to develop guidance for exposure of human divers and swimmers to underwater transient noise. Tests with submerged animals, primarily sheep, indicated that there was no incidence of physical injury provided that the impulse did not exceed 5.5 psi-milliseconds (38 Pa.s) or a peak pressure of 125 psi (905 kPa or 239 dB re. 1µPa) (Yelverton *et al*, 1973 and 1976). A “safe” level for human swimmers of 2 psi-msec (14 Pa.s) was proposed by Christian and Gaspin together with a maximum peak overpressure of 50 psi (345 kPa or 231 dB re.1µPa). The figure of 50 psi for a non-injury peak pressure was quoted in the US Navy Diving Manual (1970). This level of peak pressure is comparable with the impulsive noise incident upon a diver operating some of the noisier underwater bolt guns (Parvin, 1994). It is an extremely loud noise even to a diver wearing a diving suit and head protection.

4.3 Levels of impulse that may cause lethal and physical injury.

As noted in section 3, the use of impulse is relevant where damage may be caused to air-containing structures. Yelverton *et al.* (1973 and 1976) conducted extensive studies using submerged terrestrial animals (sheep, dogs, monkeys) weighing between 5kg and 40kg. The conclusions of these studies are summarised in Table 4-4. These studies showed that for a given peak pressure the likelihood of fatality or injury is related to the incident impulse. Authors such as Richardson *et al* (1995) have extended these findings to applications involving the exposure of marine mammals to underwater impulsive sounds.

Impulse (bar.msec)	Impulse (Pa.s)	Effect
2.76	276	No mortality. High incidence of moderately severe blast injuries, including eardrum rupture. Animals should recover on their own.
1.38	138	High incidence of slight blast injury, including eardrum rupture. Animals should recover on their own.
0.69	69	Low incidence of trivial blast injuries. No eardrum rupture.
0.34	34	No injuries.

Table 4-4. Summary of effects of different impulses on mammals diving beneath the water surface (Yelverton et al, (1973), Richardson et al, 1995)).

4.4 Auditory injury.

Noise-induced hearing loss is well understood in man and other terrestrial mammals and may, by inference, occur in aquatic mammals. The terms Temporary Threshold Shift (TTS) and Permanent Threshold Shift (PTS) are used to describe the upward shift in hearing threshold that can occur after exposure to loud noise. TTS is believed to result from metabolic exhaustion of the sensory cells and reversible damage at the cellular level following over-stimulation. PTS is caused by more pronounced anatomical changes.

Finneran et *al.* (2005), found TTS in bottlenose dolphin (*Tursiops truncatus*) exposed to short duration (a few milliseconds) underwater noise from a seismic source at 224 dB re. 1µPa. TTS has been demonstrated in bottlenose dolphins exposed to single 1 second pulses of narrow band sound (Ridgway *et al,* 1997). TTS was found to occur at received levels of 194-201 dB re. 1µPa at 3 kHz, 193-196 dB at 20 kHz and 192-194 dB at 75 kHz. Schlundt *et al.* (2000) also reports on TTS in bottlenose dolphins and beluga whales (*Delphinapterus leucas*) exposed to simulated 1 second sonar signals at frequencies from 3 kHz to 75 kHz, at incident sound levels from 192 to 201 dB re. 1µPa. Nachtigall *et al.* (2004) report on inducing a small (< 10 dB) TTS in hearing level in the bottlenose dolphin and the monitoring of hearing recovery following continuous 30 minute duration exposures to incident underwater sound at a level of 160 dB re. 1µPa. The TTS occurred at test frequencies of 8, 11.2 and 16 kHz, but not at 22.5 or 32 kHz.

The data for marine mammals presented above, and that for terrestrial animals indicates that hearing damage is related both to the level and to the duration of the exposure. Data for submerged human subjects has indicated, for example, that a 15 minutes continuous exposure to underwater sound at levels of approximately 167 to 180 dB re. 1µPa causes a measurable TTS in hearing level (Smith *et al.*,1996. See Table 4-5). In comparison, however, with an exposure duration of 32 seconds, there was no significant difference in hearing level in a group of human divers exposed to underwater sound over the same frequency range when exposed at levels of up to 191 dB re. 1µPa (Parvin *et al.*, 2002).

	500 Hz (n=11)		1000 Hz (n=6)		2000 Hz (n=13)		4000 Hz (n=11)	
	Mean	SD	Mean	SD	Mean	SD	Mean	SD
SPL in water	174.5	16.6	167.1	8.9	176.2	15.8	179.0	17.4
SPL in air	132.7	12.1	119.9	4.1	123.2	5.1	123.1	8.2
SPL diff	41.8	17.6	47.2	7.3	53.0	15.5	55.9	14.2

Table 4-5. Summary of Sound Pressure Levels causing a 10 dB TTS in bareheaded divers after a 15 minute continuous noise exposure (SPL in dB re. 1µPa) (Smith et al,1996).

The underwater hearing threshold for typical fish and marine mammal species and for human divers and swimmers are compared in Figure 4-1. The different curves for each group represent different species or trials and give an indication of the variation in sensitivity for each group. From 500 Hz to 2000 Hz human underwater hearing threshold is at a level of approximately 70 dB re. 1µPa, and therefore appears to be more sensitive over this frequency range than most marine mammal species. Assuming a similar dynamic range, it is therefore unlikely that marine mammals would incur an auditory injury to components of anthropometric noise coinciding with the frequencies, exposure levels and durations for human divers set out in Table 4-5 above. At higher frequencies (above 10 kHz) marine mammals have very much more sensitive hearing, with a very wide hearing bandwidth, and are therefore more susceptible to the very high frequency components of underwater sound. Therefore, when assessing the potential for auditory injury in the form of a TTS, the frequency content of the sound as well as the level and duration is of critical importance. High frequency sonar and sound sources such as echosounders and fish finders may therefore be more likely to cause auditory injury in marine mammals than low frequency systems.

Whilst the capacity of underwater noise sources to cause auditory injury is clear, estimating the range from a given source of sound at which this will occur is not easy. In human noise exposure, a frequency weighted measure of sound, the dB(A), is used as a metric for evaluating the effects of noise, and in particular for evaluating its capacity for behavioural effects and its capacity for auditory injury. The frequency weighting approximates the threshold of human hearing, and thus it may be considered to be a measure of the “loudness” or “perception” of the sound. Nedwell *et al* (1998 and 2005) has proposed generalising this scale into a frequency weighted metric, the dB_{ht}, as a means of assessing the effects of underwater noise on fish and marine mammal species. This technique allows potential harmful noise sources to be identified, as well as eliminating those sources that are not hazardous. There is evidence that at levels of 90 dB_{ht} and above, auditory injury can occur.

The scale is in the final stages of validation on behalf of the DTI, the MoD and oil and gas industries. Whilst computationally onerous to implement, the scale is very easy to use and offers similar advantages to the use of the simple hand-held sound level meter for evaluating the effects of sound in air.

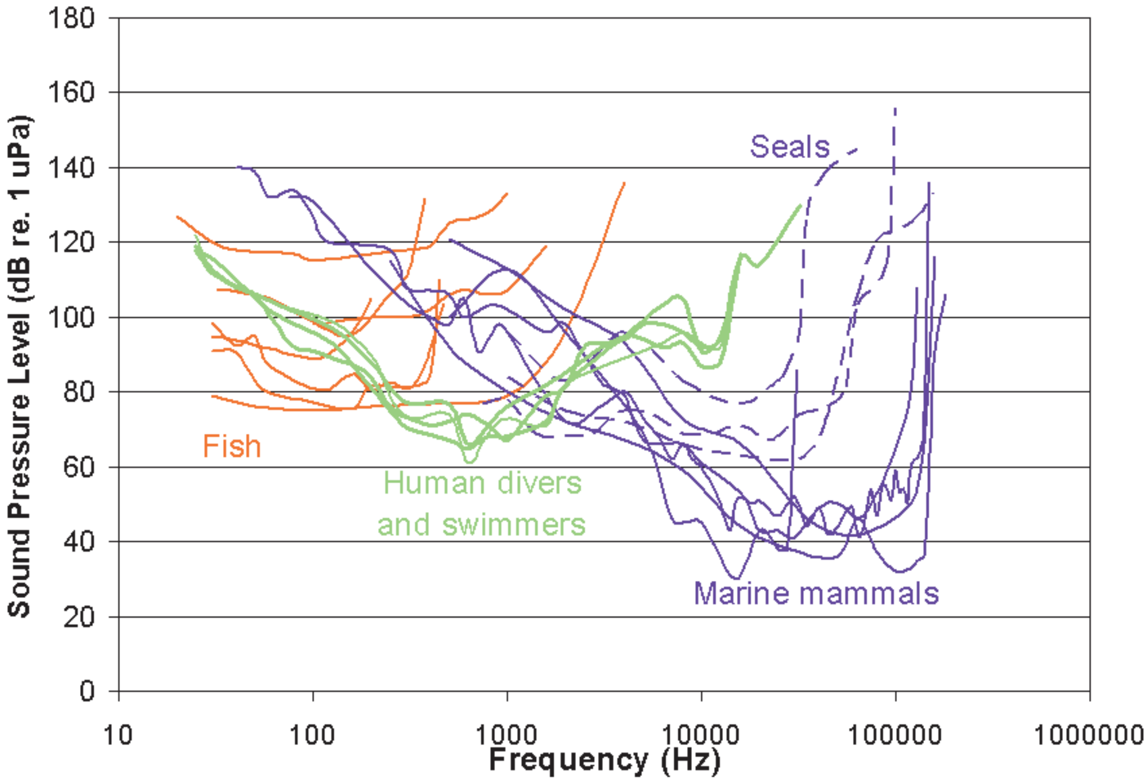

Figure 4-1. Comparison of underwater hearing threshold for species of fish, marine mammal and human divers and swimmers (Parvin et al, 1999).

4.5 Amalgamation and discussion of data.

Currently, the levels of underwater sound that have the potential to be harmful to marine life are not accurately defined. Unless a systematic study of physiological impact from underwater sound sources is conducted, across a wide range of marine species and sound source types (explosive shock, impulse, sonar, shipping, etc), then this position is unlikely to change.

Hill (1978) describes the mechanisms and sites of explosion damage in submerged land mammals and discusses the likely resilience of marine mammals to these affects due to strengthened lungs and air passages that are adapted for deep diving. However, it might equally be argued that less compliant (strengthened) gas cavities might be more susceptible to the forces of a transient pressure wave, and hence greater injury might occur.

The results of human diver and submerged animal exposures indicate agreement with the general philosophy stated by Rawlins (1987), that “the shallower the safer”. Theoretical calculations indicate that the inverted reflection from the water surface will tend to reduce underwater impulse and hence the risk of injury (Nedwell 1989). This might suggest that marine mammals at depth are at increased risk of physical injury. However, unlike human divers and submerged terrestrial animals, diving marine mammals are not provided with a gas supply at ambient pressure. Consequently, as the marine mammal dives, gas contained within the body compresses, and is reduced in volume, the volume varying in inverse proportion with absolute pressure. It is possible that at great enough depth, the gas containing structures may be sufficiently small and the gas contained within them at a density whereby the risk of direct physical injury is reduced from that near surface (i.e. there is less risk of injury from overexpansion when exposed to reduced external pressure). There is, however, no observational data to support this.

On a physical basis, there is unlikely to be much difference in the interaction of a blast wave with a marine mammal body compared with its interaction with a submerged terrestrial animal or human diver, the acoustic impedance of the tissues and anatomical structures being broadly similar. Any small variations in stiffness forces caused by differing stiffness of body structures will be greatly exceeded by the large forces experienced during exposure to the high pressures of a blast wave. The motion of body tissues is therefore unlikely to be significantly different between marine and terrestrial mammals.

At present, therefore, it must be assumed that the effects of blast on different species are likely to be similar at least to a first order. The large scale studies that have been undertaken on fish, terrestrial mammals and human divers offer the best information that is currently available, and can provide guidance as to safe levels of impulsive noise, although the guidance should be moderated with the limited available data for marine mammal exposure.

4.6 Criteria for the impact of transient waves.

In broad terms, the data on impact of underwater transient pressure waves can be summarised as follows:

- At incident peak underwater sound levels of ≥10 MPa (≥260 dB re. 1µPa), or at 700 Pa.s and above – always lethal.
- At incident peak underwater sound levels of ≥1 MPa (≥240 dB re. 1µPa) – increasing likelihood of death or severe injury leading to death in a short time.
- At incident peak underwater sound levels of ≥0.1 MPa (≥220 dB re. 1µPa) – Direct physical injury to gas-containing structures and auditory organs may occur, particularly from repeat exposures.

For a small marine mammal of mass 80 kg

- incident impulse 812 Pa.s - 50% mortality
- incident impulse = 516 Pa.s - 1% mortality.

And for levels unlikely to cause injury

- peak pressure below 220 dB re.1µPa and impulse below 100 Pa.s – unlikely to cause injury

For continuous sound, direct injury to gas-containing structures or auditory organs, or threshold shifts in hearing level can occur at lower incident sound levels depending upon the duration and frequency content of the sound.

5 Anthropometric noise sources.

5.1 Introduction.

This section of the report reviews typical source levels from various high level underwater sound sources; the use of explosives, seismic surveying using airguns, impact piling, and low frequency sonar systems have been chosen as being noise sources that are of high level and which have recently been the subject of environmental concern.

5.2 Underwater high explosives.

When an explosion is initiated in a mass of explosive material, a pressure wave propagates into the surrounding medium. In all explosives this pressure wave results from the conversion of the solid explosive material into gaseous reaction products. The way in which the conversion process occurs, and the form of the accompanying pressure wave, depend on the category of explosive.

5.2.1 Freely suspended high explosives.

High explosives like TNT and other nitro-glycerine based explosives have a rapid detonation process. A violent chemical reaction, following in the wake of the shock front propagating through the explosive, turns the solid of the explosive into incandescent gaseous reaction products at extremely high pressure. The velocity of detonation of high explosives is about 5,000 to 10,000 ms^{-1}, and a shock wave that propagates in all directions is produced in the medium.

When a freely suspended charge is exploded underwater, the initial mass of explosive rapidly expands to produce a large volume of superheated gas. The boundary of the gas bubble radiates out supersonically creating a wave disturbance that is transmitted to the surrounding water by the accelerating interface between the explosive gas bubble and the water. The wave in the vicinity of the explosive does not propagate in an identical manner to small amplitude acoustic waves. The leading edge of the blast front, generated by the accelerating boundary of the gas bubble, rises in a very short time and hence contains much of the high frequency energy. The region of the wave that is at high pressure travels through the water at a greater speed than the main body of the blast wave and consequently the wave propagates as a non-linear wave which changes its form during propagation. The leading edge of the wave steepens to form a shock, and the tail of the wave becomes extended. The rise time associated with the underwater blast wave is so short it occupies only a few millimetres of the waterspace as it propagates. The whole of the passage of the blast front may occupy less than a metre (assuming a 0.1 ms duration blast front propagating at 1500 ms^{-1}).

At large distances from the source the propagation of the pressure wave usually approximates to that of other sound waves. However, the high frequency energy is absorbed and scattered, and the waveform becomes extended in time. It is therefore common that the pressure wave from an explosive at a distant point is dominated by low frequency components, and is perceived as a “rumble”.

The rapid expansion of hot gases associated with an underwater explosion force back the surrounding mass of water. The momentum of the water immediately surrounding the bubble causes the gas bubble to expand beyond equalisation pressure (ambient hydrostatic pressure). Hence, at its maximum radius, the pressure within the gas bubble is lower than that of the surrounding water and the bubble starts to re-compress. The momentum of the water mass forces the gas bubble past equilibrium once again, this time into compression. Hence, the momentum imparted to the surrounding water in the very near field of the gas bubble produces a series of secondary pressure waves that gradually decay toward static ambient pressure.

Whereas the initial wavefront contains much of the high frequency energy of the blast wave, and consequently has a much higher acoustic pressure, the secondary pulses produce a longer duration waveform with significant low frequency energy components. This low frequency energy has the potential to cause injury at long range.

5.2.2 Blast waves at distance.

An underwater blast measured at short range is characterised by a very rapid rise in pressure to the peak pressure value, followed by an exponential decay. Due to the dominance of high frequency energy associated with the rapid rise in pressure, the limiting criteria in this case is likely to be related to the peak pressure.

The maximum peak pressure for a high explosive (TNT) charge freely suspended in water can be estimated from Arons (1954), as summarised later by Urick (1983). In the SI system of units the expression can be written in the form

$$P = 5 \times 10^{7} W^{0.37} R^{-1.13}, \qquad \textit{eqn. 5-1.}$$

where P is the peak pressure in Pascals (Pa), W is the weight of the explosive charge in kilogrammes (kg) and R is the range in metres. Therefore, for a charge of mass 4540 kg this gives a source peak pressure (by convention, at a range of 1 m) of approximately 1 GPa or 300 dB re. 1µPa @ 1 m. For operations such as well head severance typical charge weights of 40 kg might be used, giving a source peak pressure of 195 MPa or 285 dB re. 1µPa @ 1 m. Measurements at a nominal range of 600 m (Nedwell *et al.*, 2001), indicated levels form 37 kPa to 198 kPa (211 to 226 dB re. 1µPa), which are in reasonable agreement with the expression above, which would suggest 142 kPa.

For smaller charge weights typical of those used during human and animal exposure experiments, the source peak pressure P for a 5 lb (2.27 kg) charge, using the expression above is approximately 67 MPa or 276 dB re. 1µPa @ 1 m.

5.2.3 Underwater TNT explosions in rock.

For the case of explosives buried in a rock seabed the level of blast can be related to that for the equivalent unconfined charge. Nedwell (1989) showed that the peak pressure for an embedded charge is reduced substantially, to approximately 5 percent, and the impulse to approximately 30 percent of that for the equivalent unconfined charge. However, the duration of the blast wave is increased tenfold over that for an equivalent freely-suspended charge, typically to 1-2 ms. The rise time of the wave is also greatly extended to the order of a millisecond. The resulting blast wave is therefore likely to contain a high proportion of low frequency energy components. There is, however, no bubble pulse.

The corresponding peak pressure for an underwater TNT explosion in rock, typical of that during borehole blasting, can be estimated from

$$P = 2.5 \times 10^{6} W^{0.37} R^{-1.13} \quad \text{Pa}, \qquad \textit{eqn. 5-2.}$$

with the impulse estimated from

$$I = 1.8 \times 10^{3} W^{0.63} R^{-0.89} \quad \text{Pa.s.} \qquad \textit{eqn 5-3.}$$

Borehole blasting operations typically use up to a tonne of explosive in a single blasting operation, but distributed on delay timers in individual charge weights or “delays” of approximately 20 kg, so that each explosion is a discrete event. The peak pressure from a typical

20 kg buried charge can therefore be estimated at 7.5 MPa or 257 dB re. 1µPa @ 1 m, with an associated source impulse of 11.9 kPa.s

5.2.4 Propellants.

With other explosives, such as black powder, the explosion process is one of deflagration, or burning, rather than detonation. Consequently the process occurs at a much lower velocity of approximately 5 ms^{-1} and gives rise to a relatively low, broad pressure peak. Although the pressure from propellants is comparatively low and they are usually thought of as being "safe", the pressure wave is of much greater duration than that for high explosives and hence the impulse may be high also.

5.3 Seismic sources.

Sources used in marine seismic exploration use a pressure chamber to rapidly vent high pressure air into the underwater environment. The gas bubble expands violently, before contracting and re-expanding. Underwater sound is generated by the initial gas bubble pulse and by the subsequent oscillations. Seismic surveys are conducted by towing an array of multiple airgun sources behind the survey vessel. The airgun array is typically fired once every few seconds, with individual airguns being triggered in a controlled, rapid sequence. Listening hydrophones towed behind the array receive the reflected signals from beneath the seabed, allowing the seabed substrate to be imaged. Typically it is the low frequency components of the airgun noise that penetrate effectively into the seabed strata and allow an acoustic image to be formed.

Source	Chamber pressure (MPa)	Total volume (Litres)	Depth (m)	Source Ac pressure (bar @ 1 m)	Source Ac pressure (MPa @ 1 m)	Source Ac pressure (dB re. 1 uPa @ 1 m)
Airgun arrays						
GSC 7900	-	129.5	-	174	17.4	265
ARCO 4000	12.9	65.6	10	110	11.0	261
GECO 3100 + 1640	13.8	77.7	7.6	82.4	8.24	258
GSI 4000 pnu-con	13.8	66.8	6.1	80.0	8.00	258
GECO 3100	13.8	50.8	7.6	76.3	7.63	258
SSL 4440	13.8	72.8	8.5	73.4	7.34	257
GSI Jonsson 2000	13.8	32.8	6.1	55.0	5.50	255
GECO 1985 + 1640	13.8	59.4	7.6	49.4	4.94	254
Western 1050	31.0	17.2	6.1	42.0	4.20	252
GECO 1985	13.8	32.5	7.6	41.9	4.19	252
SSL 1460	13.8	23.9	7.6	25.3	2.53	248
Western 555	31.0	9.1	6.1	25.2	2.52	248
GECO 594 subarray	13.8	9.7	8.2	11.9	1.19	241
Single airguns						
Small airgun	13.8	0.16	9.1	1.2	0.12	222
Mid sized airgun	13.8	4.92	9.1	3.4	0.34	231
Large airgun	13.8	32.8	9.1	8.0	0.80	238

Table 5-1. Characteristics of some seismic sound sources used for offshore exploration (from Richardson (1995), original data from Johnson and Cain (1981) except for the ARCO 4000 (Greene 1985), GSC 7900 (Parrott 1991) and single airguns (Lugg 1979).

Seismic noise is characterised by a transient event, rising to peak level in approximately 1 ms, and then decaying over several bubble pulses during a period of approximately 0.1 second. A typical noise time history from a seismic airgun is shown in Figure 5-1. Peak sound pressure levels vary depending upon the airgun array used. A summary of peak pressure level from typical single airguns and airgun arrays is provided in Table 5-1. Source acoustic (Ac) pressures are provided as peak to peak values at a reference distance of 1 m. The chamber pressure relates to the pressure within the guns prior to release and the total volume is the total volume of the airgun or airgun array respectively.

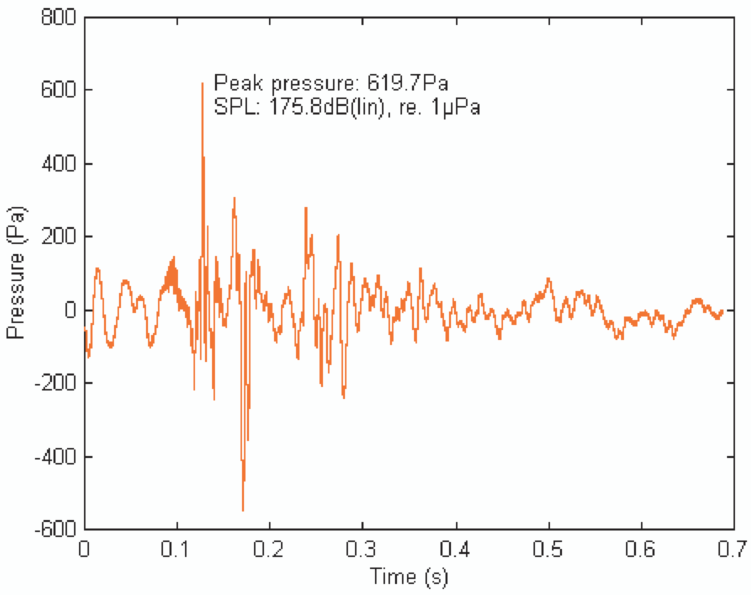

Figure 5-1. A typical unweighted pressure time history of underwater noise from a seismic airgun operation, measured at 10 metres depth and 3000 metres range

5.4 Impact piling.

In offshore impact pile driving, a pile is driven by the impact of a heavy weight or "ram" onto the head of the pile, driving it into the seabed. Typically several hundred strikes are required to fully drive the pile, and are delivered at a rate of 40-60 strikes per minute. In large offshore piling operations, piles of up to 6.5 m diameter and 50 m in length may be driven. Each blow of the pile driver may be of 500 kJ or more, hence having roughly the same energy as 8 kg of TNT. The noise radiated may hence be very significant.

Following each strike, waves travel down through the pile and radiate outwards through the water. The waves can travel outwards through the seabed, or by reflection from deeper sediments. As they propagate, sound will tend to "leak" upwards into the water, contributing to the waterborne wave. As the speed of sound is generally greater in consolidated sediments than in water, these waves usually arrive first as a precursor to the waterborne wave.

Source level noise from impact piling, and therefore the magnitude of the pressure wave propagated in the surrounding water medium, is related to the diameter of the pile being driven. Recent measurements of underwater noise in the Hamble River with 0.33 to 0.35 m cross-section diameter wooden piles indicated Source Level noise of approximately 216 dB re. 1µPa @ 1 m (Nedwell *et al.,* 20005b). In contrast the large diameter piles used in offshore construction produce source peak pressure levels similar to that during seismic and underwater blasting operations. A linear fit of measurements of piling noise for windfarm installation by Nedwell *et al* (2003) at North Hoyle off the North Wales coast of the UK indicated a Source Level of 260 dB re. 1µPa @ 1 m for 5 m depth, and 262 dB re. 1µPa @ 1 m at 10 m depth, associated with a Transmission Loss given by 22 log (R), where R is the range. The authors noted in the report that the levels of sound recorded during piling are such that within perhaps 100 m they could cause injury. Recent measurements during piling with 4.7 m diameter piles fitted to an improved combined geometrical and absorption model have indicated a Source Level of 252 dB re. 1µPa @ 1 m (Parvin *et al.,* 2006). Impact piling with larger 6.0 m diameter piles, proposed for some future offshore construction activities, may produce peak Source Levels of up to 260 dB re. 1µPa @ 1 m (Parvin *et al.,* 2006). Currently however, there are no documented measurements of underwater sound transmission during impact piling operations with pile diameters greater than 4.7 m.

At close range, impact piling noise is typically characterised by a transient peak pressure wave, reaching a peak pressure level in approximately 1 ms, with reflections, reverberation and ringing of the hollow pile extending the total time history for each impact event to a duration of several hundred milliseconds. At greater range the transient event is further spread and can last for up to a second. The pile is usually struck at a repetition rate of one strike every 1 to 2 seconds, for a period of several hours, depending upon the seabed and the pile penetration depth required.

Figure 5-2 presents an underwater noise time history recorded at a distance of 955 m from an impact piling operation with a 4.3 m diameter steel pile. The data in the figure show that at this range the peak to peak noise is at a level of 8000 Pa or 198 dB re. 1µPa @ 1 m. The initial peak pressure wavefront reaches a maximum in a few milliseconds, with a total duration of each transient event of approximately 200 ms.

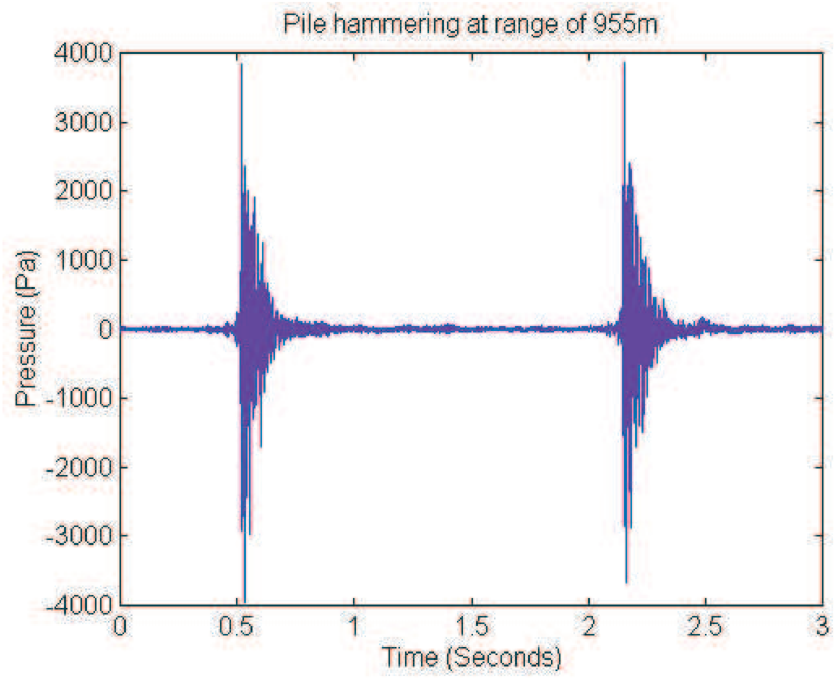

Figure 5-2. A typical noise time history of subsea noise, measured at a range of 955 m from an impact piling operation with a 4.3 m diameter pile (Nedwell et al., 2003).

5.5 Low Frequency Active Sonar.

Both the UK and US navies have developed Low Frequency Active Sonar systems to provide long range detection capability against current and future generations of quiet submarine. The underwater sound is generated by an array of underwater transducers each with a source level of approximately 215 dB re. 1µPa @ 1 m (US Navy, 2001). When measured at range in the interference field, the coherent low frequency sound source has an apparent (effective) source level of up to 240 dB re. 1 uPa @ 1 m (US Navy, 2001), although there is no point in the water-space where the sound level exceeds the 215 dB re. 1µPa @ 1 m., from a single transducer. Systems of this type transmit continuous wave sound in short duration pulses at frequencies from 100 Hz to 500 Hz, that may last of the order of 1 to 10 seconds, repeated at up to a few times per minute. Impact assessments for similar UK systems have been undertaken by QinetiQ for the MOD (Heathershaw *et al,* 2002a and 2002b).

The type of sound signal employed by sonar systems is very different from the transient signals from explosives, seismic operations or impact piling described earlier in this section. The data are included to provide a comparison with typical source levels from other anthropometric noise sources in the sea. The duration of the pressure wave for a sonar is very much greater than for a transient. As the exposure duration is much greater, the impact levels used to determine injury for a sonar are considerably lower than those used for transients. Based on the risk of soft tissue damage and the potential for hearing impairment, continuous wave sonar exposure is normally limited to 180 dB re. 1µPa, although a marine animal would have to remain within a sound field at this level for a considerable period before direct physical injury was likely to occur.

5.6 Summary of estimated impact range for typical sound sources.

Based on the potential onset of lethal injury at a Peak Pressure level of 240 dB re. 1µPa, and for injury from a transient event at incident levels above 220 re. 1µPa @ 1 m, Table 5-2 estimates the impact range for some typical anthropometric noise sources.

Source	**Source Level** (dB re. 1 µPa @ 1 m)	**Lethal range** (metres)	**Injury range** (metres)
Underwater blast 4540 kg freely suspended	300	520	4000
Wellhead severance. Underwater blast 40 kg freely suspended	285	110	900
Underwater blast 2.27 kg freely suspended	276	43	350
Borehole blasting. Underwater blast 20 kg confined in rock	257	6	48
Seismic survey Large airgun array	258	7	53
Impact piling 4.7 m diameter pile (measured)	252	4	81
Impact piling 6.0 m diameter pile (estimated)	260	65	530
Low frequency Active sonar*	230	-	250

*Based on a single transmission audiological injury (Heathershaw *et al,* 2002a and 2002b).

Table 5-2. Summary of estimated impact range for high level underwater sound sources.

6 Passive Acoustic Monitoring.

6.1 Introduction.

The range of detection of PAM systems depends on the level of the vocalisation by the animal, the decay in the sound level as it propagates, the level of background noise in the environment and the level at which the vocalisation has to be above the noise to be detected.

6.2 The Source Level of vocalisations.

The Source Level (SL) is defined as the Sound Pressure Level at a reference distance, usually 1 metre, from a sound source. In many cases it may not be physically possible to measure this because of the large size of the source, but a suitable measurement is made at distance and extrapolated back as if it were a point source.

In the sonar field, Source Level is usually quoted as the root-mean-square (RMS) level of a continuous sound. However, in other fields it is more normal to quote the peak or peak-to-peak (p-p) value. Peak-to-peak values are usually used to define very short pulses where an RMS measurement is virtually meaningless. Unfortunately, many source level measurements for marine mammals are made by marine biologists who are unaware of these differences and omit to define which method they have used.

Marine mammals make three classes of calls: echolocation clicks with very high instantaneous bandwidths, whistles with very low instantaneous bandwidths, and various signals such as roars with medium instantaneous bandwidths. Generally echolocation clicks are characterised using peak-to-peak source levels while other calls are characterised using RMS source levels. Echolocation calls for all but the sperm whale (*Physeter macrocephalus*) are centred in the band 30-140 kHz and with pulse lengths of less than 200 µs. The sperm whale has a pulse 1 ms long and with energy in the band 0.5-40 kHz. Odontocete whistles occur in the band 2-25 kHz, and may last for several seconds. Mysticete whistles can occur from 15 Hz (blue whale, *Balaenoptera musculus*) to 1.5 kHz (humpback whale, *Megaptera novaeangliae*). The medium bandwidth signals are used by the mysticetes and can occur from 20 Hz (fin whale) up to 1.5 kHz (humpback whale), but generally occur in the 50-500 Hz region.

Source levels are measured either with captive animals or wild animals. In both cases a received signal is measured and then corrected for range to the animal. Neither method is ideal. In the case of wild animals it is never possible to be absolutely certain that the animal vocalising is the animal seen at the surface so there is always some doubt over the range, and possibly the species. In the case of directional sounds, the angle of the animal relative to the receiver is also unknown. For captive animals there is some uncertainty as to whether they reduce source level or vary their waveforms because of the acoustic environment of captivity. A number of researchers have devised techniques to improve the accuracy of source level measurements in the wild, usually by using extended receive arrays so that range measurement is inherent in the source level estimate.

A problem that some groups have encountered is the dynamic range of their equipment. Most hydrophone systems are optimised for high performance at low signal levels. The signal from a nearby animal may be 120 dB above ambient noise and will clip many listening systems. If this is not recognised then an incorrect, low source level will be reported. Another strong signal effect that has received even less recognition is slew-rate limiting. This is only likely to be a problem at echolocation click frequencies. Many preamplifiers perform well at low signal levels, but with high amplitude signals the active devices are unable to supply enough current to drive capacitive loads, such as long cables, and change from being voltage drivers to constant-current drivers, resulting in reduced gain and high harmonic content. This effect has been observed in a number of commercial hydrophone/preamp combinations which are in use by cetacean researchers.

From the above it can be seen that attempting to measure source levels of marine mammals is no easy task and as a result the measurements made are of limited number; many are also of unreliable quality.

6.3 Vocalisation levels.

The following tables set out measurements that have been identified from the scientific press. Where a species has been measured numerous times e.g. bottlenose dolphin, harbour porpoise, only the most robust estimates have been included. Not all these species are UK species, but have been included to show the full range of measured vocalisations. All source levels are in dB re. 1µPa @ 1m. A dash means no data is available.

6.3.1 <u>Mysticetes</u>

Species	Source Level (dB re. 1µPa @ 1m)	Waveform	Source
Blue whale (*Balaenoptera musculus)*	186 180-190	Moan Moan	McDonald, 2001 Aroyan, 2000
Bowhead whale (*Balaena mysticetus)*	152-189	Complex moan	Cummings,1987
Bryde's whale (*Balaenoptera borealis*)	152-174 -	Moan Moan	Frankel, 2002 Oleson, 2003
Fin whale (*Balaenoptera physalus*)	159-184 -	Downsweep Downsweep	Charif, 2002 McDonald 1995
Grey whale (*Eschrichtius robustus*)	167-188	Tones and clicks	Frankel, 2002
Humpback whale (*Megaptera novaeangliae)*	171-189 162-192	Tones and pulses Tones	Au, 2001 Thompson, 1986
Minke whale (*Balaenoptera acutorostrata)*	>155 150-165 -	Pulses and tones Pulsive Pulsive	Gedamke, 1997 Gedamke, 2001 Rankin, 2005
Right whale (*Eubalaena* spp.)	- 174-192 137-162	Moan Gunshot Moan	Vaanderlaan, 2003 Parks, 2005 Parks, 2005
Sei whale (*Balaenoptera borealis)*	-	HF sweeps	Knowlton,1991

Table 6-1Vocalisation Source Levels for species of Mysticete.

Considering the difficulties, a surprising number of mysticete species have had their source level estimated. Because the ranges involved are usually high, it means the range of possible error is also high. Despite this, the reliability of these measurements is reasonably good. Most recent measurements have been made with some care and although there must be significant error associated with the result, the pattern across a number of measurements is reasonably consistent. The data indicates that the larger mysticetes achieve around 190 dB re. 1µPa @1m while the smaller mysticetes achieve only around 170 dB re. 1µPa @1m.

The species regularly found in UK waters are the blue, fin, humpback and minke whales. The Sei whale is less common.

6.3.2 Odontocetes.

Most of the early echolocation click source level measurements of the larger odontocetes were made with captive animals and some very suspect acoustic techniques. However, more recent measurements have used much improved methodology and have generally been made on wild animals. The recent work by Au and by Madsen is particularly good and appears to provide consistent data. There is very little information on the source level of whistles from these animals. The only measurement is of the bottlenose dolphin, and this measurement appears to be low when compared to the experience of listening to these animals.

All of the large odontocete species use high source level, high bandwidth pulses with source levels up to 225 dB re. 1µPa @ 1m., apart from the sperm whale, which uses a higher source level (236 dB dB re. 1µPa @ 1m.) into a very narrow beam (<5 degrees)

Species	**Source Level (dB re. 1µPa @ 1m)**	**Waveform**	**Source**
Beluga (*Delphinapterus leucas)*	206-225 -	Click Whistle	Au, 1985, 1993 -
Bottlenose dolphin (*Tursiops truncates)*	218 (p-p) 223 (p-p) 125-140 168 (p-p) 201 (p-p) 153	Click Click Whistle Tail slap Jaw pop Breach	Au, 1978 Au, 1974 Croll, 1999 Finneran, 2000 Finneran, 2000 Finneran, 2000
False killer whale (*Pseudorca crassidens)*	- 201-225	Click Click	Au, 1995 Madsen, 2004a
Killer whale (*Orcinus orca)*	- - 145-164 193	Whistle Click Pulsed call Tail slap	- - Erbe, 2002 Simon, 2005
Pilot whale (*Globicephala* sp.)	>180 -	Click Whistle	Fish, 1976 -
Pygmy Killer whale (*Feresa attenuate)*	197-223 228 -	Click Click Whistle	Madsen, 2004b Thomas, 1990 -
Risso's dolphin (*Grampus griseus)*	202-222 216 -	Click Click Whistle	Madsen, 2004a Philips, 2003 -
Sperm whale (*Physeter macrocephalus)*	226-236 220-236	Click Click	Mohl, 2003 Madsen, 2002
White-beaked dolphin (*Lagenorhynchus albirostris)*	219 -	Click Whistle	Rasmussen, 1999 -
White-sided dolphin (*Lagenorhynchus obliquidens)*	164 -	Click Whistle	Croll, 1999 -

Table 6-2. Vocalisation Source Levels for species of Large Odontocetes.

Species	Source Level (dB re. 1µPa @ 1m)	Waveform	Source
Common dolphin (*Delphinus delphis*)	180 (p-p) -	Click Whistle	Croll, 1999 -
Dall's porpoise (*Phocoenoides dalli*)	120-148 165-170	Click Click	Evans, 1984 Hatakeyama, 1990
Dusky dolphin (*Lagenorhynchus obscurus*)	210	Click	Au, 2004
Finless porpoise (*Neophocaena phocaenoides*)	167	Click	Akamatsu, 2000
Harbour porpoise (*Phocoena phocoena*)	157-169 (p-p) 133-166	Click Click	Teilmann, 2002 Goodson, 1996
Spotted dolphin (*Stenella attenuate*)	210	Click	Au, 2003
Striped dolphin (*Stenella coeruleoalba*)	-	-	-

Table 6-3. Vocalisation source levels for small odontocetes

The small odontocetes are small enough to keep in captivity while still having adequate space to move round freely. Virtually all measurements have been made with captive animals, although the trend to measure wild rather than captive animals is also evident here. No source level estimates have been identified for any of the whistle calls from the smaller animals, although it should be noted that none of the porpoises produce whistle calls. In general there are two echolocation strategies. The porpoises use very low power (~170dB dB re. 1µPa @1m.) and generally feed on or near the seabed, while the delphinid species use higher power (>200 dB re. 1µPa @ 1m.). Both groups use narrow beamwidths (<15 degrees). The pulses used by the porpoises are generally longer (> 150 µS), narrower in bandwidth, and higher in centre frequency (>110 kHz) than delphinids. The two species most often found in UK waters are the common dolphin and the harbour porpoise. The striped dolphin is on the northern end of its range. The others do not occur in UK waters but are included for completeness.

6.3.3 Beaked whales.

The beaked whales are poorly known in all aspects of their behaviour. The only acoustic data have been obtained from two species of animals that have been tagged. Note that Blainville's and Cuvier's beaked whales only vocalise below 200 metres depth. The two species most likely to be encountered in UK waters are Sowerby's beaked whale and the northern bottlenose whale.

Species	Source Level (dB re. 1µPa @ 1m)	Waveform	Source
Blainville's beaked whale *(Mesoplodon densirostris)*	200-220 (p-p)	Clicks	Johnson, 2004
Cuvier's beaked whale (*Ziphius cavirostris)*	214 (p-p)	Clicks	Zimmer, 2005
Northern bottlenose whale (*Hyperoodon ampullatus)*	- -	Click Whistle	Hooker, 1998
Sowerby's beaked whale *(Mesoplodon bidens)*	-	-	-

Table 6-4. Vocalisation source levels for species of beaked whale.

6.3.4 Pinnipeds.

For the pinnipeds species there is very little underwater source level information. There have been a few measurements of the aerial calls, and one measurement of a flipper slap. For the grey seal there appears to be a complete lack of information on any underwater sounds they may produce. The ribbon seal does not occur in UK waters but is included as it is one of the few species to have a source level estimated.

Species	**Source Level (dB re. 1µPa @ 1m)**	**Waveform**	**Source**
Bearded seal (*Erignathus barbatus*)	178	Song	Richardson, 1995
Grey seal (*Halichoerus grypus*)	-	Roar	-
Harbour seal (*Phoca vitulina*)	186-199 -	Flipper slap Roar	Wahlberg, 2002 -
Harp seal *(Phoca groenlandica)*	130-140 131-164	Song Clicks	Richardson, 1995
Hooded seal (*Cystophora cristata*)	-	-	-
Ribbon seal (*Phoca fasciata*)	160	Warble	Watkins, 1977
Ringed seal (*Phoca hispida*)	-	Trill	-

Table 6-5. Vocalisation source levels for species of pinniped.

6.4 Marine mammal vocalisation patterns.

There is little information published on vocalisation patterns of odontocetes. As a general guide, animals only vocalise if they have a need to. This may be for social, navigation, or hunting functions. From observation, odontocetes in transit in clear waters do not normally vocalise, particularly when alone. In all other circumstances they vocalise to a greater or lesser extent, and depending on species. In turbid coastal waters animals vocalise continuously.

Mysticetes do not use sound for hunting, so only vocalise for social purposes. Males are generally very vocal in the mating season, but otherwise all species make only the minimum necessary sounds for group cohesion and social interactions. There has been conjecture that some species make sound for navigational reasons. This is unproven, but it is possible that animals such as the fin whale can use sound for whole ocean basin navigation. The calling patterns have been studied using sea bed sensors. These have mostly been for the Pacific or Antarctic Oceans. The only UK studies are by Cornell University, funded by JNCC, and Aberdeen University (Clark and Charif 1998; Swift *et al*., 2002). Clark *et al* showed that there was a seasonal cycle of activity with a peak through the autumn months, with the fin whale continuing to call well into the winter.

Pinniped males are usually very vocal during the mating season, but otherwise the animals rarely vocalise underwater. The sole function of underwater sound is for social purposes.

6.5 Ambient noise levels around the UK coast.

The requirement is to provide typical ambient noise levels in UK waters in order to assist estimation of range over which PAM will work. This is not an easy question to answer. For a more detailed description of ambient noise sources in UK waters see Harland (2005). Ambient noise will vary in a cyclic manner as a result of tidal, diurnal, weekly, lunar, monthly and annual cycles.

As a general rule, in deeper water the ambient noise levels will follow Wenz's curves (Wenz 1962)

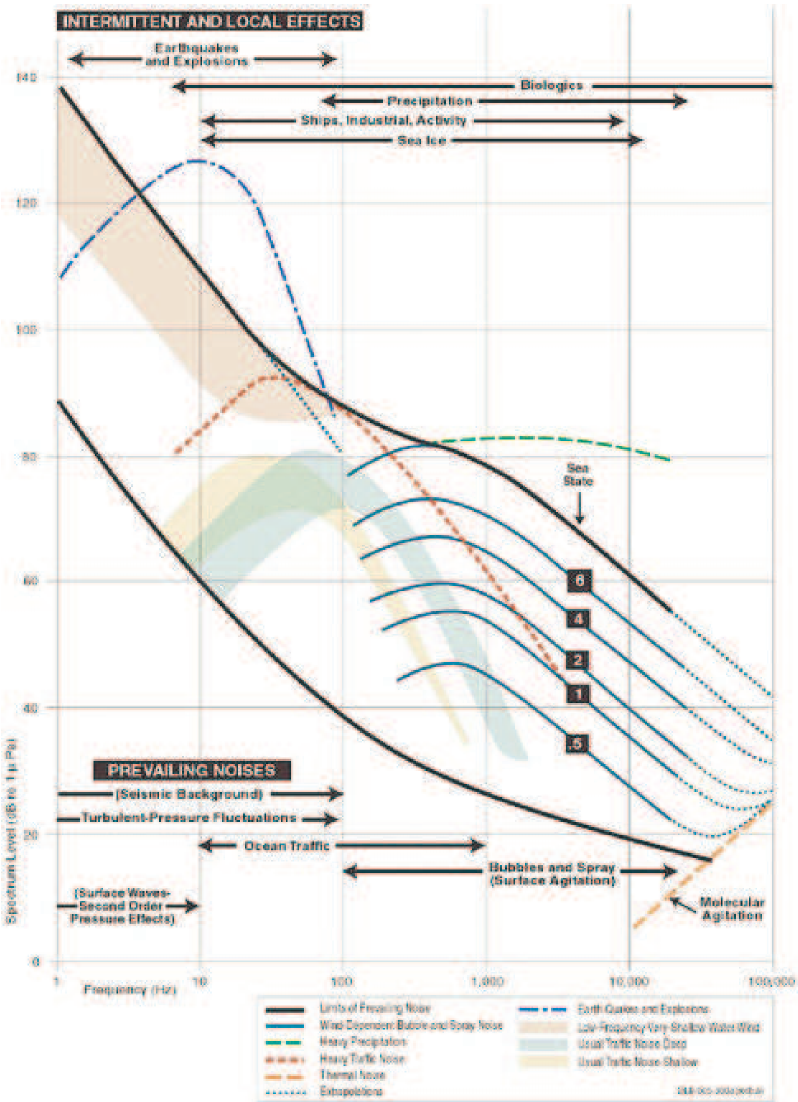

Figure 6-1. Estimated ambient sea noise spectrum levels (Wenz, 1962).

In and around the shipping lanes in the English Channel, Irish Sea and North Sea shipping noise will dominate up to around 10 kHz. Above 10 kHz it is likely that wind and rain noise will predominate for a high percentage of the time.

In very shallow waters close inshore, surf noise and other shoreline interaction noise will make a significant contribution to ambient noise. There is also a source of biological clicking noise which is widespread along the southern and western coasts of the UK and of uncertain origin, but may be generated by various types of snapping shrimp. Peak energy is around 7 kHz, but with significant energy over the range 1-100 kHz. On occasions, this can raise ambient noise levels by 20-30 dB. In some areas sediment transport noise can be considerable above 5 kHz, depending on the state of the tide. Areas where the water is less than 10 metres deep and which have highly mobile seabed material such as sand or shingle are particularly prone. When it happens, the wideband noise levels can increase by up to 40 dB and peak energy is in the 5-20 kHz region, depending on particle size.

6.6 Estimated detection range using PAM.

6.6.1 Introduction.

The sonar equation may be used to estimate the detection range of a PAM system (Urick, 1983), and may be written as

$$SE = SL - TL + DI - DT, \qquad \textit{eqn. 6-1.}$$

where:

SE is the received signal level excess,
SL is the source level of the animal's call,
TL is the transmission loss,
DI is the receiver directivity index and
DT is the receiver detection threshold.

For different species in different locations and at different times of the year, the parameters can vary significantly. It is therefore not possible to predict precise detection ranges for animal calls that will apply in all circumstances.

The propagation loss is a complex sum of spreading loss, attenuation, and boundary scattering loss. The spreading loss will be highly dependant on the velocity structuring of the water column and this will vary on a diurnal, lunar and annual basis. The attenuation is dependant on the frequency components of the call and the boundary loss will be dependant on the seabed characteristics and the surface wave spectrum. The formation of surface "ducts" (acoustic channels) can considerably enhance propagation if both the source and receiver are within the duct, but may also considerably increase propagation loss if the source is within the duct and the receiver is below it in the shadow zone.

A further confounding factor is that the calls may be projected into beams as narrow as four degrees so the received level may vary by up to 40 dB, depending on which way the animal is heading relative to the receiver. However, animals are mobile creatures and although there will be times when the animal is looking away from the receiver, there will also be times when the animal is looking at the receiver, so for the calculations that follow it is assumed in all cases that the receiver is at the peak of the projected beam.

The directivity index (DI) is dependant on the receiver beamwidth. The use of a single hydrophone gives a DI of 0 dB, while a military towed array will have a DI in excess of 20 dB. Use of a directional receiver can increase detection ranges by up to a factor of ten under the right conditions. The detection threshold (DT) will be dependant on the bandwidth of the receiver processing and the statistics of the ambient noise. A high-resolution receiver working with slowly changing tones will perform up to 30 dB better than a low resolution receiver working with echolocation pulses.

Note that there are two dependencies on the weather. The wind will agitate the sea surface and increase surface scattering loss and the combined effects of wind and rain will raise ambient noise levels. It is therefore inevitable that as the weather worsens the achieved detection ranges will drop. This can have a very significant effect with detection ranges dropping considerably during storms.

6.6.2 Mysticetes.

The mysticetes are mostly open ocean animals which vocalise over a range of depths. Some, such as the male humpback whales, sing close to the surface so it is likely that sound will be trapped in any surface duct present, while others sing at deeper depths, and/or at frequencies below that which are supported by duct propagation. A good approximation for these animals is to assume free-space propagation, with no enhancement due to ducting. An omni-directional receiver with DI of 0dB is assumed.

For the low frequency animals, such as fin or blue whales, calling around 20 Hz and generating a source level of 170 dB re. 1µPa @ 1 m, with ambient noise levels around 80 dB re 1µPa/√Hz, and with a receiver bandwidth of 0.5 Hz, will give a detection range around 10 km.

For the higher frequency mysticetes, calling around 200 Hz, generating a source level of 180 dB re. 1µPa @ 1m and ambient noise levels around 75dB re. 1µPa√Hz the detection range will be around 30 km.

Finally, the minke whale uses a lower source level of around 160 dB re. 1µPa @ 1 m, so assuming noise levels around 70 dB re. 1µPa/√Hz and a receive bandwidth of 10 Hz gives detection ranges around 3 km.

6.6.3 Large odontocetes.

The large odontocetes can produce two types of calls: echolocation pulses and tonal calls. The echolocation calls can also be run together at reduced power to produce a squawk-like sound. Although free-space propagation is assumed, in reality most of these animals are shallow water animals so the sound will interact strongly with the seabed and surface resulting in increased propagation loss that will reduce detection ranges. Ambient noise levels can also be higher in shallow water.

For an animal producing a whistle at a source level of 150 dB re. 1µPa @ 1m, an ambient noise level of 60 dB re. 1µPa√Hz and a receiver bandwidth of 20 Hz gives a detection range of around 2 km.

For an echolocating dolphin using a 100 kHz pulse with a source level of 220 dB re. 1µPa @ 1 m peak to peak, an omni-directional receiver, and with a bandwidth of 2kHz and ambient noise levels around 35 dB re. 1µPa/√Hz, a detection range of around 1.5 km is achieved when the animal is pointing at the receiver, but reducing to below 500 metres when it is out of the main beam. This assumes an attenuation of 20 dB/km.

The sperm whale is somewhat different to all the other large odontocetes because of the much lower frequency of the echolocation pulse, and the much higher source level. For this animal, echolocating at 10 kHz and a source level of 236 dB re. 1µPa @ 1 m peak-peak, ambient noise levels around 50 dB re. 1µPa√Hz and a receiver bandwidth of 1 kHz, a detection range of around 40 km is achievable. However, the transmit beamwidth of the animals is only 4 degrees and the transmissions made when the animal is diving, or level at depths in excess of 600 metres. In reality the main beam signal is rarely heard and detection is made from either reflected signals or signals out of the main beam. Under these circumstances, ranges of the order of 8 km are more realistic.

6.6.4 Small odontocetes.

The small odontocetes generally produce weaker signals than the larger odontocetes. Assuming all conditions as for the large odontocetes, but source levels reduced by 10 dB, give detection ranges for the clicks of around 1 km at best, but more like 300 metres out of the main beam, and around 500 metres for whistles.

However, note that the phocoenids, the porpoises, use very low source level echolocation pulses and do not whistle, so for this group the detection range reduces to around 250 metres

6.6.5 Beaked whales.

The beaked whales are deep divers that do not echolocate near the surface. They also use a comparatively low source level. Evidence from the two species characterised so far suggests that they only produce echolocation pulses. So, for an animal using 40 kHz pulses at a source level of 215 dB re. 1µPa @ 1 m peak-peak, and an ambient noise level of 40dB re 1µPa√Hz a detection range of around 5 km is possible. However, because these animals transmit either while diving or foraging at depths over 600 metres it is very rare that a receiver near the surface will detect a signal from the main beam. It will be more usual to find a signal from the sidelobes at 30 dB down on the main beam and this will give a detection range around 2 km.

6.6.6 Pinnipeds.

There is very little information on the underwater source levels produced by the pinnipeds, so estimation of detection ranges for most of the species is not possible. Assuming a source level of 160 dB re. 1µPa @ 1 m for sounds around 4 kHz and ambient noise around 55 dB re 1µPa/√Hz gives a detection range of around 3 km. However, most pinnipeds are found in very shallow water where the propagation loss may be higher. The error associated with this detection range is high, and the combined effect of variations in propagation loss and the possible range of source levels gives detection ranges that vary from around 100 metres to a theoretical maximum of over 10 km.

6.6.7 Summary of predicted PAM detection range.

Based on the theoretical calculations undertaken in this report, Table 6-6 summarises the likely maximum detection range for Passive Acoustic Monitoring systems.

Species	Typical example	Theoretical maximum detection range
Mysticete	Blue whale (Balaenoptera musculus) Minke whale (Balaenoptera acutorostrata)	10 km 3 km
Large Odontocete	Bottlenose dolphin (*Tursiops truncates)*.	500 m to 1500 m (Directional source)
Small Odontocete	Harbour porpoise (*Phocoena phocoena*)	250 m
Beaked whale	Sowerby's beaked whale (*Mesoplodon bidens*)	2 km (Only whilst diving)
Pinniped	Common or harbour seal (*Phoca vitulina*)	> 100 m (Shallow water)

Table 6-6. Calculated marine mammal detection range by Passive Acoustic Monitoring technology.

7 Discussion.

7.1 Applicability of PAM systems.

By considering the typical lethal and physical injury range for offshore anthropometric noise sources (See Table 5-2), and comparing these with the theoretical detection range capability for vocalising marine mammals, the effectiveness of Passive Acoustic Monitoring as a mitigation measure for protecting marine mammals from direct physical injury from underwater noise can be assessed.

Table 7-1 indicates that for most operations, the theoretical detection range of a well designed PAM system should be suitable for detecting large whale (mysticete) and large odontocetes (such as delphinid species) at sufficient range that an activity can be suspended until the animal has moved away, in accordance with current JNCC guidelines. This of course is provided that the animals are vocalising, and applies to all but the largest operations involving tonnage-quantities of freely suspended explosives. The vocalisations of smaller animals such as seals and porpoises are less powerful however, and detection ranges are consequently much smaller. While this makes PAM detection potentially less suitable for larger marine operations involving freely suspended charges, they appear nonetheless to be of value for common operations with lower acoustic emissions, including borehole blasting, seismic surveying using airgun arrays, and various forms of pile-driving, including impact driving of large monopiles. For all these applications, Passive Acoustic Monitoring generally offers a potentially more reliable and versatile monitoring approach than might be expected using visual detection by Marine Mammal Observers alone.

Source	Baleen whales	Bottlenose dolphin	Harbour porpoise	Seal
Underwater blast 4540 kg freely suspended	X	X	X	X
Wellhead severance. Underwater blast 40 kg freely suspended	√	?	X	X
Underwater blast 2.27 kg freely suspended	√	√	X	X
Borehole blasting. Underwater blast 20 kg confined in rock	√	√	√	√
Seismic survey Large airgun array	√	√	√	√
Impact piling 4.3 m diameter pile	√	√	√	√
Impact piling 6.0 m diameter pile	√	√	X	?
Low frequency Active sonar	√	√	√	X

Table 7-1. Summary of the effectiveness of Passive Acoustic Monitoring at protecting marine mammals from direct physical injury from typical anthropometric noise.

7.2 Uncertainties of detection with PAM Systems.

The ranges quoted in this report may be regarded as physical limits of performance, and in many cases actual performance of PAM systems may fall below this theoretical limit. A number of factors may affect the detection range, which include

- quality of monitoring equipment (e.g. due to signal clipping, inadequate frequency response, electronic noise), or equipment not performing to specification,
- variations in the strength of vocalizations from time to time and from different animals, or variations in orientation of the animal relative to the monitoring point,
- Inadequate training of operators, leading to an increase in the required detection threshold,
- temporary or local increases in noise, for instance by wave slap against the observation vessel, clanking anchor chains, or underwater rigging squeaks.

For a given source level, detection ranges will also vary according to transmission losses between the source and PAM receiver, which will in turn depend upon water depth, stratification and other factors. In particular, in shallow water, say of a few tens of metres, the losses may be much higher than is the case in deeper coastal water. Finally, variations in background noise levels will cause the detection thresholds to vary, whether these be due to ambient sea conditions, vessels operating in the area or local engineering activities. Consequently, the detection ranges shown in Table 6-6 should be regarded as provisional until further data are gathered.

These ranges are the fundamental limits of performance and apply equally to the single hydrophone detection systems that are in general use at the moment, and to more complex array based systems that are required to both detect and localise marine mammals.

7.3 Perimeter protection for high level noise.

The present report has concentrated solely on PAM systems rather than the Active Acoustic Monitoring (AAM) or Acoustic Daylight Monitoring (ADM) systems mentioned in the introduction. Both of these other technologies are problematical, for reasons outlined: AAM in itself introduces another element of anthropogenic sound into the environment, while ADM is at present insufficiently developed and may well not be capable of increasing detection ranges beyond those for PAM systems. ADM, however, offers a passive means of detecting non-vocalising species. These techniques are discussed in two further reports.

PAM systems operated close to the source of the operational activity appear to be suitable for most applications other than where freely suspended charges are being used. It is of course possible to increase the effective range of a system by deploying more than one system around the perimeter of an underwater activity. When such high-level underwater noises are being emitted in areas where marine mammals may be at risk, the only possible approach may be to deploy a ring of PAM receivers to provide the necessary range of coverage. Such a network would however have the benefit that the time-of-travel data from multiple hydrophones would allow precise positioning of the vocalising mammal. This in turn would allow the provision of accurate data on vocalisation source levels.

It should be noted, however, that the simultaneous collection of broadband sound from a distributed set of hydrophones may prove an onerous task. The bandwidth required is well above that achievable from commercially available digital networks, and might be difficult to achieve even with lower quality analogue transmission.

8 Summary.

In summary:

1. Passive acoustic monitoring offers a means of detecting marine mammals by listening for their vocalisations or echolocation signals. Unlike the use of Marine Mammal Observers, it offers an approach which may be used in poor weather conditions and darkness, provided that the animals are vocalising.

2. A review has been conducted which has identified the documented Source Level of such vocalisations by various marine mammals. By combining this data with the expected levels of background noise, the maximum range at which the mammals may be detected has been calculated.

3. The calculations indicate that for most offshore activities other than very large blasting operations, a well designed PAM system should be suitable for detecting large whale (mysticete) and large odontocetes (such as delphinid species) at sufficient range that an activity can be suspended until the animal has moved away, in accordance with current JNCC guidelines.

4. The detection ranges for smaller animals such as seals and porpoises are much smaller,, such that a simple PAM system is unsuitable for detecting these animals during some blasting operations using unconfined charges. They are suitable, however, for use during borehole blasting, seismic surveying using airgun arrays, and various forms of pile-driving, including impact driving of large monopiles.

For vocalising marine mammals, Passive Acoustic Monitoring therefore generally offers a potentially more reliable approach than might be expected using visual detection by Marine Mammal Observers alone.

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