Underwater environmental impact assessments on marine mammals and fish by high power anthropogenic radiated sound

Antoine David
Technical Operations, Department of Environment and Resource Management, 400 George Street, Brisbane, Australia

ABSTRACT

A methodology to assess the environmental impacts from high power underwater sound sources on marine mammals and fish is presented. The methodology was first developed for low frequency navy sonar and was later extended to different types of high power underwater sound sources, including underwater blasting for demolition, shock testing and seismic surveys. The methodology assumes that any species of marine mammal or fish may be present and defines two impact zones corresponding to the limit of inner ear permanent injuries and the limit of temporary threshold shift in hearing. The size of the impact zones depends on several key factors: the level of the anthropogenic sound radiated underwater; its nature, such as the duration and frequency characteristics; and the sound propagation characteristics of the marine environment that are dependent on factors such as water depth and sea bed material. The methodology was first developed and tested by the UK Ministry of Defence to conduct underwater environmental impact assessments to protect underwater wildlife from low frequency sonar. It was later successfully applied to the demolition of the North Sea petrochemical Phillips 66 Maureen oil platform sub-structure. The methodology can be tailored to any specific marine species or generalised when any type of marine animal may be present. This means the methodology can be applied to a wide range of projects that need to use high-level underwater sound sources which may impact on marine fauna. The implementation of the methodology has ensured no incidents have occurred during the deployments of all low frequency sonar trials in the UK.

INTRODUCTION

Both the number and the radiated sound power of underwater anthropogenic sound sources are steadily increasing due to the rising number of sound sources such as shipping lanes or industrial activities on the continental shelves for construction or demolition. Furthermore, the machinery used is increasing in size and radiated sound power is therefore also increasing. The sound power level and frequency content of the anthropogenic source sources determine the volume of water which will impact the wildlife. The first and worst effect is permanent injury to the inner ear of marine mammals as it is these organs that are the most sensitive to sound. This may result in death for marine mammals as they lose the ability to communicate and orientate. Numerous reports have been made of marine mammals beaching and dying with inner ear injury. The onset of this effect is called a permanent threshold shift (PTS) and corresponds to a permanent loss in hearing sensitivity. The second effect, as a result of lower sound pressure levels is temporary injury to the inner ears. This second effect is referred to as a temporary threshold shift (TTS). This means a temporary loss in hearing sensitivity that will return to normal after some time.

Establishing the distance from a given sound source at which those effect occurs are dependent upon the characteristic of the sound source such as the frequency content, its duration for continuous and for intermittent or impulsive sounds, the duty cycle and number of total impulses. Further the sound propagation underwater is dependent upon the specific location given the sound speed profile, sea states, composition of the sea bed and water depth. An underwater propagation model is required to relate the sound source to the received sound pressure levels at a given location. This enables the identification of the correct distance at which each of the onset of effects are anticipated.

The availability of data on the effects of noise on marine mammals is variable in quantity and quality across species. A precautionary approach is therefore required given the data gaps and uncertainties. “normal” audiogram data for humans varies from 10dB to 25dB at any given frequency (This variability may be due to difference from one person hearing sensitivity to another) and therefore such an amount in variability would be expected across one marine mammal species. This variability is expected to increase when considering several species and difference in audiogram collection techniques. Whilst in humans it is relatively easy to establish minimum thresholds of hearing, the techniques for marine mammals cannot provide such an exact answer. Conditioning an animal requires a lot of time and the threshold of hearing may only be available for one animal per species, whilst for humans wide-range population data enables associated data tolerances and confidence limit.

An understanding of many different fields is necessary to assess the impact of sound underwater on wildlife and provide an adequate methodology.

First an understanding of human audiology is required so that the mechanism of hearing damage as well as vestibular (balance mechanism) damage is understood. The field of comparative audiology is necessary so that the mechanism of hearing in humans and the process of damage in the inner ears and vestibular system may be transferred to marine mammals and to all species that may be impacted by sound underwater. It is important to understand the factors that may be transferred and anticipated in relation to a marine mammal's potential hearing damage. Marine mammal autopsy is crucial for example to access the cause of death of a marine mammal. A brief review of past criteria and guidelines are presented, then a generic audiogram that aims to encompass the most sensitive species at all frequencies is presented. Finally the concept of equal energy for the time dependency of sound exposure limit derived for humans is combined to derive the onset of both the PTS and TTS.

REVIEW OF EXISTING CRITERIA AND GUIDELINES

A brief summary of the most important guidelines and criteria outlines the complexity of the issue.

USA Marine Mammal Protection Act 1972 (MMPA)

To the US Navy and related research (2003), harassment is an act which:

- Level A: Injures or has a significant potential to injure.
- Level B: Disturb or is likely to disturb (causes disruption to a point where behaviour patterns are abandoned or significantly altered).

All research may be conducted only under approved scientific permit.

Other activities that introduce sound need a Letter of Authorization or an Incidental Harassment Authorization.

USA Endangered Species Act (ESA)

In any instance in which the Marine-Mammal Protection Act is more restrictive than the Endangered Species Act, the Marine-Mammal Protection Act takes precedent.

Marine Mammal Protection Act Negligible Impact is more restrictive than Endangered Species Act Jeopardy

Incidental Take Authorization under Endangered Species Act requires a prior Incidental Take Authorization under Marine-Mammal Protection Act

Table 1. Summary of guidelines and criteria - Marine

Guideline – Criteria	
USA National Marine Fisheries Service (NMFS) 1995 Guidelines	
Underwater Sound Pressure Levels (RMS)	
> 180 dB re 1μ Pa leads to Temporary Threshold Shift in Cetaceans	
> 190 dB re 1μ Pa Temporary Threshold Shift in Pinnipeds	
> 160 dB re 1μ Pa Harassment Criteria	
USA National Oceanic and Atmospheric Administration (NOAA) 2006 Guidelines	
Sound Exposure Levels	
195 dB re 1μ Pa^2 S onset of Temporary Threshold Shift	
215 dB re 1μ Pa^2 S onset of Permanent Threshold Shift	
Southall et al 2007	
Onset of Permanent Threshold Shift	
Cetacean SPL	230 dB Peak re 1μ Pa
Pinnipeds SPL	218 dB Peak re 1μ Pa
Sound Exposure Levels	
M weighted on Cetaceans	198 dB re 1μ Pa^2 s
M weighted on Pinnipeds	186 dB re 1μ Pa^2 s
Onset of Temporary Threshold Shift	
Cetacean SPL	224 dB Peak re 1μ Pa
Pinnipeds SPL	212 dB Peak re 1μ Pa
Sound Exposure Levels	
M weighted on Cetaceans	183 dB re 1μ Pa^2 s
M weighted on Pinnipeds	171 dB re 1μ Pa^2 s
High Energy Seismic Survey (HESS) 1997	
Onset disturbance behavioural threshold	
140 dB re 1μ Pa (RMS)	
UK Ministry Of Defence 2000	
Onset of Permanent Threshold Shift	
95 dB above Threshold of Hearing for 8 hours exposure (time exposure correction)	
Onset Temporary Threshold Shift	
75 dB above Threshold of Hearing for 8 hours exposure (time exposure correction)	

The review of existing criteria shows that some criteria are species dependent, some are referring to absolute sound pressure level, others refer to a sound exposure level and some as a relative level from the threshold of hearing. Some criteria are dependent upon the duration of the sound exposure and some are also dependent upon the frequency of the sound source and give a correction depending upon the audiogram of that species in relation to the frequency of the received sound.

Table 2. Characteristic comparison of guidelines and criteria

Guideline – Criteria	Time dependence	Frequency dependence	Absolute or relative level	Species specific
USA National Marine Fisheries Service (NMFS) 1995 Guidelines	No	No	Absolute	Cetaceans and Pinnipeds
USA National Oceanic and Atmospheric Administration (NOAA) 2006 Guidelines	Yes	No	Absolute	No
Southall & al 2007	Yes	Yes	Absolute	Cetaceans and Pinnipeds
High Energy Seismic Survey (HESS) 1997	No	No	Absolute	Cetaceans and Pinnipeds
UK Ministry Of Defence 2000	Yes	Yes	Relative	No

TRANSFERRING THE UNDERSTANDING OF HUMAN AUDIOLOGY

The damage mechanism of the inner ear is clearly understood in humans starting with a Temporary Threshold Shift (TTS) which is a temporary loss in hearing sensitivity where the reduction of the hearing loss in dB and the duration of the hearing loss are proportional to the sound exposure both in level above the hearing threshold and the time of exposure. When both the parameters of the levels and corresponding time exceed a given threshold, then a permanent damage in the inner ears occurs. This is referred to as a Permanent Threshold Shift (PTS).

Legislation on continuous noise exposure limits for humans

Table 3 shows the legal maximum safe duration of noise exposure for a given sound pressure level. This table indicates that it is legal and safe to expose a human to 85 dBA above his hearing threshold for 8 hours and similarly 91dBA above threshold of hearing for 2 hours.

Table 3. Legal duration of noise exposure for human for given Sound Pressure Levels (KSC Hearing Loss Prevention Program)

DURATION[1]		EXPOSURE LEVEL2 (DBA RE20μPA)
(HOURS)	(MINUTES)	
16	960	82
8	480	85
4	240	88
2	120	91
1	60	94
0.5	30	97
0.25	15	100
0.125 OR LESS	7.5 OR LESS	103

[1] Using:

exchange rate = 3 dB
lower threshold = 82 dB,

$T=480/2^{(L-85)/3}$ where T=time in min. and L=exposure level

Meter set to slow response

[2] The exposure noted for each sound level for the duration noted is equivalent to 100% of the allowed noise dose. The Action Level is any exposure equivalent to 50% of the exposure duration in this Table.

Noise Exposure Limits for Impact or Impulsive Noise - Humans

Table 4. Permitted number of impulses per day as a function of their sound level pressure in dB Peak (KSC Hearing Loss Prevention Program)

Sound Level (dB re 20μPa)*	Permitted Number of Impulses or Impacts per day (imp/day)
>130	None
130	100
120	1,000
110	10,000
*Decibels peak sound pressure level measured with a Type I/II sound level meter with peak hold feature using C-weighting or linear scale at fast response.	

The following figure shows the equal loudness contour as a function of frequency from the threshold of audibility to the threshold of pain for humans in air. For continuous noise, an 8 hour noise exposure at level 85 dBA corresponds to the onset of TTS and 105 dB corresponds to the onset of PTS, as can be seen from the graph at 1kHz this correspond to 85 dB above the threshold of hearing (Johnson 1973).

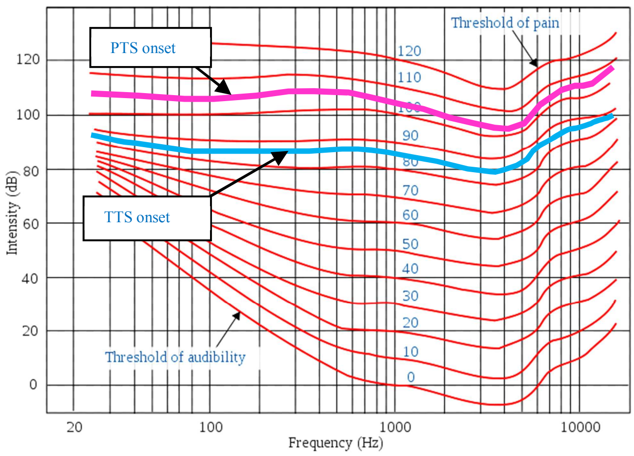

Figure 1. Threshold of audibility; free-field equal loudness contours; estimated threshold of pain and illustration of the onset of TTS and onset of PTS for 8 hours continuous noise exposure. (Robinson and Dadson 1956)

The time basis of Figure 1 is mixed. Pain relates to instantaneous pressure while TTS and PTS onset relates to equivalent 8 hour SEL.

Evidence of TTS in humans, and translated to marine mammals may be superimposed on their audiograms in dB above threshold of hearing. It is accepted that when at the maximum sensitivity in the frequency domain, the dynamic range of hearing is maximum. However while in the lower frequencies of the hearing range, the dynamic range of hearing is significantly reduced. This means that the TTS will occur at lower values above threshold of hearing when close to the lower frequencies.

TTS experiments have been conducted in three species of odontocetes and three species of pinnipeds, (Finneran et al. 2000, 2002, 2003; Nachtingall et al. 2003, 2004; Kastak et al. 1996, 1999; Schlundt et al. 2000). The three species of odontocetes are (bottlenose dolphin, false killer whale and beluga whale) using both behavioural and electrophysio-logical techniques. The three species of pinnipeds (harbour seals, California sea lion and elephant seal were assessed using behavioural techniques.

GENERATION OF A GENERIC AUDIOGRAM

Although it is possible to assess the necessary distance between species and the sound source it is difficult to have certainty of which species are present within the area where the underwater sound source is being deployed. Listening to a hydrophone and, visual checking on the surface are insufficient to be certain of the non-presence of marine mammals. The generic approach proposed is based on the precautionary principle in the sense many species may be present at that location in time. Yet more importantly, the lack of present knowledge on hearing in fish and marine mammals do not guarantee that the known species are in fact the most sensitive. Further, the few published audiograms in the literature are relying on one specimen as opposed to large average such as human audiograms. Published audiograms are gathered and presented by groups before being collated together.

Fish Audiograms

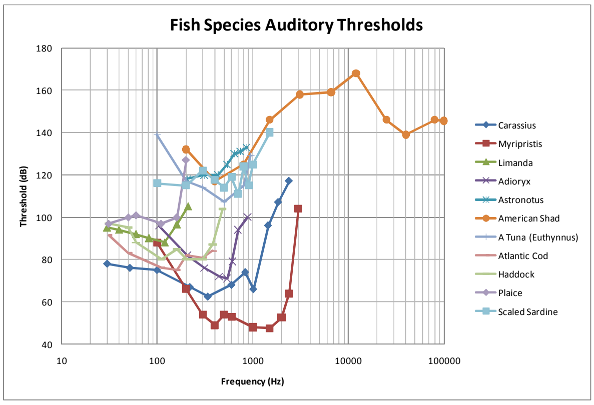

Figure 2. Fish audiograms (Hastings and Popper 2005, Nedwell et al. 2004)

Marine Mammals audiograms

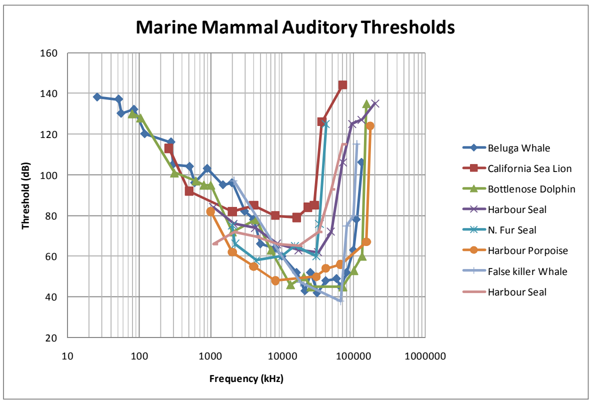

Figure 3. Marine mammal audiograms (Nedwell et al. 2004)

It is interesting to observe from the next figure that when collecting human underwater audiograms the variability is over 30dB for some frequencies.

Underwater Human audiograms

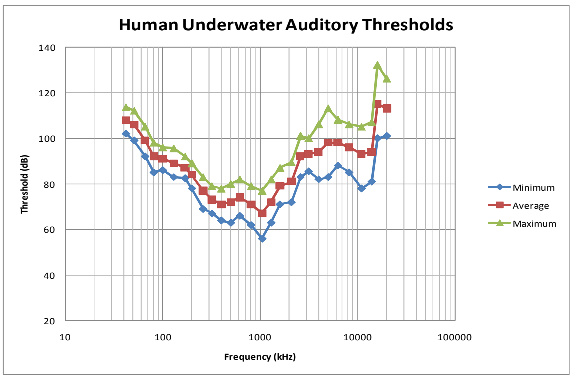

Figure 4. Human underwater auditory thresholds of hearing (Parvin et al. 1995, 1998, 1999)

Given the human audiograms measured underwater, the extent of variability when performing such measures can be appreciated. Since audiograms in fish and marine mammals mostly consist of one measurement, precautionary principles should be applied by taking the most sensitive audiograms when several audiograms are available.

Proposed Generic Audiogram

Combining the audiograms collected from fish with those collected from marine mammals (pinnipedes and odontocetes) and adding the human underwater audiograms, we can extract the minimum of those audiograms and propose this minimum curve as the generic audiogram. Since species hearing will evolve according to the ambient noise of the ocean, sea ambient noise levels for glassy state is also a guide to determine the shape of the generic audiogram. For this reason the ambient noise is added for several sea states, and is used to determine the generic audiogram in the frequency band from 400Hz to 1 KHz. The curve of the generic audiogram must be reviewed as new audiograms are discovered and published.

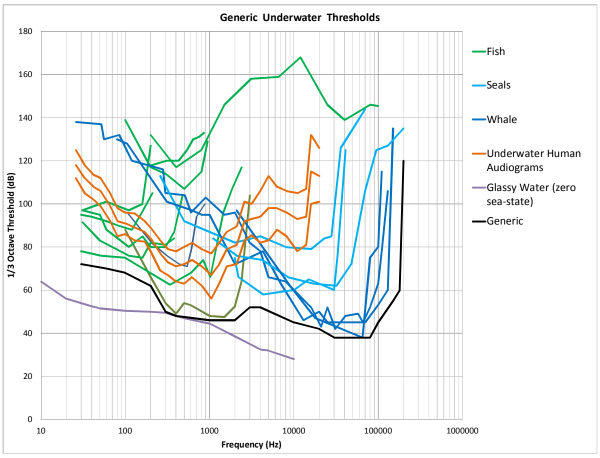

Figure 5. Generic Audiogram (black) with audiogram and sea-states

ESTABLISHING THE GENERIC ONSET OF TTS

Now that the generic audiogram is established, we can propose a generic onset of TTS curve. The onset of TTS is dependent upon the time of exposure so we need to know the cumulative exposure from the sound source. Having this data will determine how many dB above threshold of hearing we need to shift the generic threshold and this will become the generic onset of TTS for a given sound exposure duration.

Answering the question of how many dB above the threshold of hearing corresponds to the onset of TTS is achieved by collating the guidelines established for humans. Several guidelines exist that determine safe exposure to sound from short duration to permanent exposure. For short duration, the 1968 proposed criterion is established for impulse noise based on a Temporary Threshold shift of 10dB at 1 kHz 2 minutes after termination of noise exposure. This work led to the Damage Risk Criteria for intermittent to continuous sound exposure. For impulsive noise exposure, a correction factor of 10dB for the number of impulses being multiplied by 100 was agreed.

Figures 6 shows the values for which the onset of TTS takes place in dB above threshold of hearing as a function of the cumulative noise exposure duration in seconds. There are three distinct zones in the graph. The first zone is for impulse noise exposure. In this region the CHABA Damage Risk Criteria (DRC) are represented for 100 impulses.

The second region of the graph is for intermittent noise exposure. This region is governed by the Damage Risk Criteria curve for noise exposure which may be brief, transient and intermittent. The cumulative noise exposure per 24 hours may be added and the level of dB above threshold of hearing leading to TTS may be extracted from this curve. The third region is considered as permanent sound exposure where the mechanism of recovery from the inner ear has reached a steady state from the sound exposure and no longer varies with time.

The 1997 NIOSH reversed from a 5dB exchange rate to a 3dB exchange rate based on results of research made in 1992. The 3dB exchange rate is known also as the equal-energy rule hypothesis because a 3dB increase or decrease represents a doubling or halving of the sound energy. The value of the exchange rate has been a long debate. It seems that the 3dB exchange rate best protects human hearing in the 4 kHz frequency range and the 5dB exchange rate would protect only the frequencies from 500Hz up to 2 kHz according to Johnson (1973).

The curves presented in Figure 6 are a summary of the cumulative sound exposure for a 24 hour period and the corresponding sound exposure level in dB above threshold of hearing. The lower the corresponding point (of both the sound exposure level in dB above threshold and the associated cumulative exposure in the 24 hours period) is below the CHABA or the NIOSH 1997 curve, the lower the risk of TTS. Conversely the higher above the curve, the stronger the TTS will be and the stronger the risk of PTS. When above the curve the value of the TTS will increase with more sound exposure and eventually will lead to PTS.

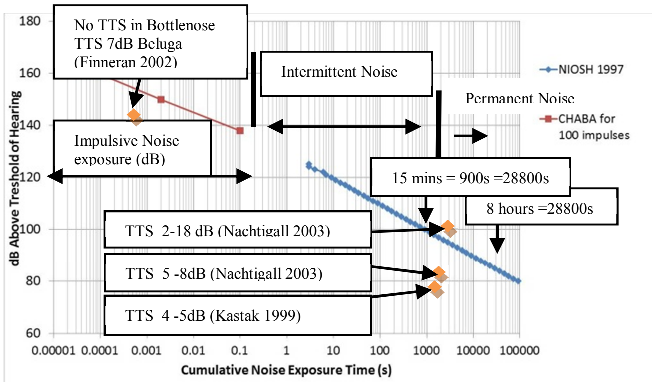

Figure 6. Onset of TTS in dB above threshold of hearing as a function of sound exposure duration. In yellow, some evidence of TTS.

While this mechanism of the onset of TTS in dB above threshold as a function of the cumulative noise exposure is derived and valid for humans in air, it is difficult to accept that such mechanism may apply for marine animals underwater. The field of comparative audiology provides crucial answers and the first important element is that the middle ear provides a mechanical impedance mechanism for sound transmitted from air or water to the fluid of the inner ear. The inner ear sustains similar damage despite the outer ear medium (air or water) as the middle ear provides the impedance match. Further, the few evidences for marine mammals (Figure 6) of TTS combined with the onset of TTS given by NIOSH 1997 and CHABA graph in dB above threshold provides a match. New evidences of onset of TTS in marine mammals are needed to gain confidence in this match. Figure 7 presents the proposed onset of TTS which is below the CHABA and NIOSH curves by approximately 10dB, and 15dB above this curve is the proposed onset of PTS.

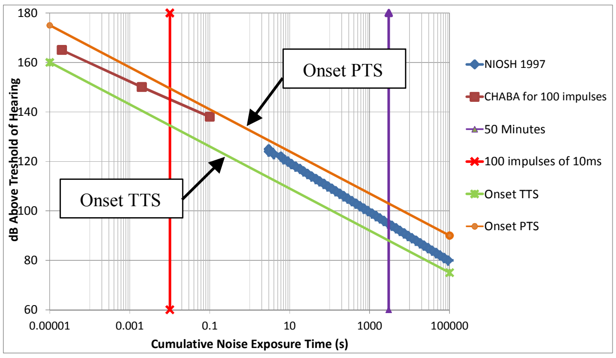

Figure 7. Proposed onset of TTS and PTS as function of the cumulative sound exposure

For example, for 100 airgun explosions with a pulse of 10ms each, due to the reverberation in shallow water, the curve indicates that the onset of TTS would be anticipated at 135 dB above threshold of hearing.

Now in Figure 8, using the generic audiogram, this means that the onset of Temporary Threshold Shift is 135dB above the generic Threshold of hearing. Using a second example with 50 minutes sound exposure leads to an onset of TTS with 87 dB above threshold of hearing. Both examples are represented in Figure 8.

Having the sound power spectra, using sound propagation modelling, the distance from the sound source can now be established at which the onset of TTS will occur.

This distance will correspond to the monitoring and mitigation distance from the sound source. Southall et al (2007) estimated that received levels would need to exceed the TTS threshold by at least 15dB for there to be risk of PTS.

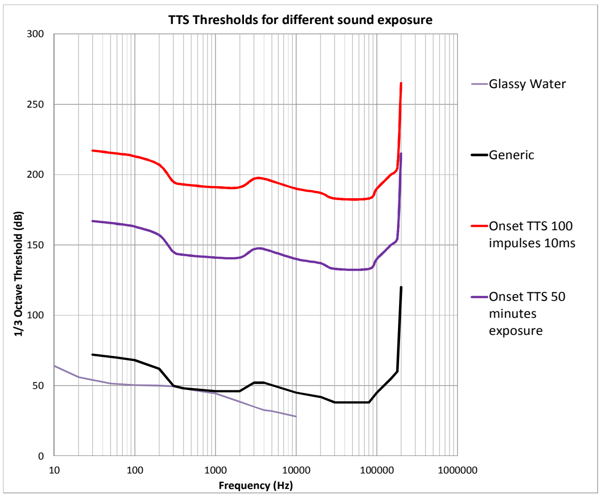

Figure 8. TTS threshold for 100 impulses of 10ms and 3000 seconds (50 minutes) of sound exposure

A difficulty with assessing the distance depending of impulsive sound is that the length of the pulse is changing with the distance and recursive modelling needs to be applied. While given an estimated pulse duration and number of impulses, the distance of the onset of TTS and therefore PTS can be established. This distance in turn can be used to model the new pulse duration. A pulse length from an airgun can be several hundreds of milliseconds at a distance. Once the pulse length is established, a new onset of TTS and respectively PTS distances may be derived. A result of such an analysis may be summarised as illustrated in Figure 9.

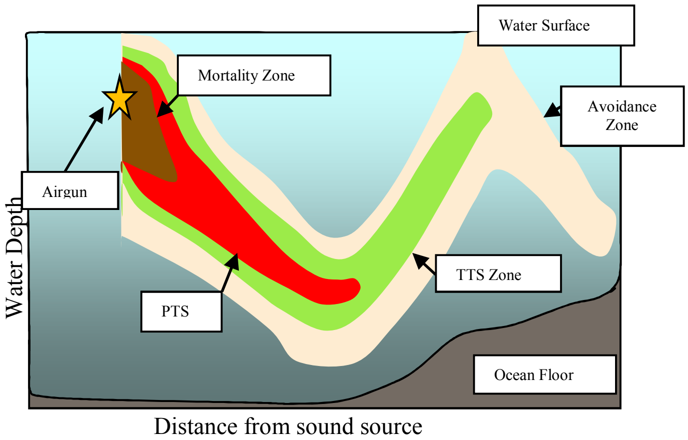

Figure 9. An example of PTS and TTS zone for a given sound source and sound propagation conditions (illustration)

CONCLUSION

A methodology is presented to predict the distance from the underwater sound source for which Temporary Threshold Shift of hearing occurs for the most sensitive species of marine animals. This methodology is based on the precautionary principle which encompasses the combination of all known species audiograms and uses the most sensitive audiogram at all frequencies. Further, the duration of the time exposure per 24 hour period is taken into consideration enabling the derivation of the correct level for which the TTS and respectively PTS is expected to occur.

This method enables the accurate establishment of the TTS level which using underwater sound propagation modelling may be converted to a distance. This distance is particularly important as the PTS level is the level correlated with the onset of permanent injury.

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