# Awel y Môr Offshore Wind Farm

## Category 6: Environmental Statement

## Volume 4, Annex 7.3: Marine Mammal Quantitative Assessment Assumptions

**Date: April 2022**

**Revision: B**

Application Reference: 6.4.7.3

Pursuant to: APFP Regulation 5(2)(a)

| REVISION | DATE | STATUS/ REASON FOR ISSUE | AUTHOR: | CHECKED BY: | APPROVED BY: |
|---|---|---|---|---|---|
| **A** | August 2021 | PEIR | SMRUC | RWE | RWE |
| **B** | March 2022 | ES | SMRUC | RWE | RWE |
| | | | | | |
| | | | | | |
| | | | | | |

www.awelymor.cymru

RWE Renewables UK
Swindon Limited

Windmill Hill Business Park
Whitehill Way
Swindon
Wiltshire SN5 6PB
T +44 (0)8456 720 090
www.rwe.com

Registered office:
RWE Renewables UK
Swindon Limited
Windmill Hill Business Park
Whitehill Way
Swindon

SMRU Consulting
understand ◆ assess ◆ mitigate

# Awel y Môr
# Marine Mammal Quantitative Noise Impact Assessment – Assumptions, Limitations and Uncertainties

| | |
|---|---|
| Authors: | Sinclair, RR & Verfuss, UK |
| Report Code: | SMRUC-GOB-2021-009 |
| Date: | Thursday, 10 March 2022 |

THIS REPORT IS TO BE CITED AS: SINCLAIR, RR & VERFUSS, UK. (2021). AWEL Y MÔR MARINE MAMMAL QUANTITATIVE NOISE IMPACT ASSESSMENT – ASSUMPTIONS, LIMITATIONS AND UNCERTAINTIES. SMRU CONSULTING REPORT NUMBER SMRUC-GOB-2022-003, SUBMITTED TO GOBE AND RWE, MARCH 2022.

Document Control

Please consider this document as uncontrolled copy when printed

| Rev. | Date. | Reason for Issue. | Prep. | Chk. | Apr. | Client |
|---|---|---|---|---|---|---|
| 1 | May 2021 | First draft | RRS | | | |
| 2 | Feb 2022 | Updates for DCO | RRS & UKV | UKV | | |
| | | | | | | |

# Contents

Contents ........ 2
1 Purpose ........ 4
2 PTS-onset assumptions ........ 4
  2.1 Assessment methodology summary ........ 4
  2.2 Proportion impacted ........ 5
  2.3 Exposure to noise ........ 5
  2.4 Cumulative PTS ........ 5
    2.4.1 Equal-energy hypothesis ........ 6
    2.4.2 Impulsive characteristics ........ 11
  2.5 Density ........ 14
  2.6 Predicting response ........ 15
  2.7 Duration of impact ........ 15
3 UXO assessment ........ 15
  3.1 UXO disturbance ........ 16
    3.1.1 Available thresholds ........ 17
    3.1.2 Underwater noise propagation ........ 21
    3.1.3 Modelled impact ranges ........ 23
    3.1.4 Summary ........ 24
4 TTS Assessment ........ 26
5 References ........ 28

## FIGURES

FIGURE 1 TEMPORARY THRESHOLD SHIFT (TTS) ELICITED IN A HARBOUR PORPOISE BY A SERIES OF 1-2 KHZ SONAR DOWN-SWEEPS OF 1 SECOND DURATION WITH VARYING DUTY CYCLE AND A CONSTANT SELCUM OF 198 AND 204 DB RE1 µPA²S, RESPECTIVELY. ALSO LABELLED IS THE CORRESPONDING 'SILENT PERIOD' IN-BETWEEN PULSES. DATA FROM KASTELEIN ET AL. (2014). ........ 7

FIGURE 2 RELATIONSHIP BETWEEN THE STARTING DISTANCE FROM THE PILE UPON PILING START AND THE RECEIVED CUMULATIVE SEL FROM THE PILING SEQUENCE FOR MINKE WHALE (LF-CETACEAN, BLUE LINE). INTERSECTS OF THE SELCUM WITH THE DIFFERENT THRESHOLD VALUES GIVE THE STARTING DISTANCE, AT WHICH THE ANIMAL WOULD AT MINIMUM BE TO MEET THE CRITERION FOR THE THRESHOLD (GREEN SOLID LINE: TTS-THRESHOLD, RED SOLID LINE: PTS-THRESHOLD, RED DASHED LINE: PTS-THRESHOLD + 2 DB, PURPLE DASHED LINE: PTS-THRESHOLD + 3 DB) . TOP = SINGLE MONOPILE, BOTTOM = CONCURRENT PIN PILES AT THE SAME LOCATION. ........ 9

FIGURE 3 RELATIONSHIP BETWEEN THE STARTING DISTANCE FROM THE PILE UPON PILING START AND THE RECEIVED CUMULATIVE SEL FROM THE PILING SEQUENCE FOR HARBOUR PORPOISE (VHF-CETACEAN, BLUE LINE). INTERSECTS OF THE SELCUM WITH THE DIFFERENT THRESHOLD VALUES GIVE THE STARTING DISTANCE, AT WHICH THE ANIMAL would at minimum be to meet the criterion for the threshold (green solid line: TTS-threshold, red solid line: PTS-threshold, red dashed line: PTS-threshold + 2 dB, purple dashed line: PTS-threshold + 3 dB) . Top = single monopile, bottom = concurrent pin piles at the same location.................... 10

Figure 4 Modelled functions describing the probability of a signal being defined as "impulsive" based on the rise time being less than 25 ms. ........................................................................................ 12

Figure 5 The range of kurtosis weighted by LF-C and VHF-C Southall et al. (2019) auditory frequency weighting functions for 30 min of impact pile driving data measured in 25 m of water at the Block Island Wind Farm. ........................................................................................................ 13

Figure 6 Behavioural response probability for deep-feeding blue whales exposed to MFAS and PRN as a function of received cSEL (dB re. 1 $\mu Pa^2 s$) for different source–receiver ranges and expert scored response severities. Response probability model predictions (black lines) with 95% confidence limits (shaded grey areas) are shown for 1, 2 and 5 km source–receiver ranges for moderate (scores 4–6) and high response severity (scores 7–9). Figure obtained from Southall et al. (2019b)................ 20

Figure 7 Sound exposure levels calculated with the Soloway and Dahl equation (S&D) for a TNT weight of 1 kg at distances of 1 to 100 km in comparison with sound of the same SEL at 1 km with a cylindrical (10logR, blue line) and spherical (20logR, red line) transmission loss, and a spherical transmission loss including absorption at a frequency of 1 kHz (dashed red line) and 10 kHz (dotted red line), respectively. ....................................................................................................... 22

## TABLES

Table 1 Difference in PTS impact ranges when using the current Southall et al. (2019a) thresholds, compared to increasing the threshold by 2 and 3 dB, respectively. ........................................... 11

Table 2 TTS-onset thresholds for impulsive noise as proposed by Southall et al. (2019), with relevance for species in UK waters. ............................................................................................... 19

Table 3 Impact ranges for harbour porpoise – calculated using the Soloway & Dahl (2014) equation with an attenuation correction. Data provided by Subacoustech. .................................................. 24

Table 4 Pros and Cons for the disturbance thresholds available .................................................... 24

Table 5 TTS-onset thresholds for impulsive noise (from Southall et al 2019).................................. 28

# 1 Purpose

The purpose of this document is to outline the key assumptions, limitations, and uncertainties in the quantitative noise impact assessment for marine mammals in relation to the Awel y Môr offshore wind farm (AyM). Broadly, these relate to predicting the exposure of animals to underwater noise, predicting the response of animals to underwater noise, and predicting potential population consequences of disturbance from underwater noise. The underwater noise modelling is presented in Volume 4, Annex 6.2: Subsea Noise Technical Report (application ref: 6.4.6.2) and the results of the quantitative noise impact assessment for marine mammals are presented in Volume 2, Chapter 7: Marine Mammals (application ref: 6.2.7).

# 2 PTS-onset assumptions

There are no empirical data on the threshold for auditory injury in the form of PTS-onset for marine mammals, as to test this would be inhumane. Therefore, PTS-onset thresholds are estimated based on extrapolating from TTS-onset thresholds. For pulsed noise, such as piling, NOAA have set the onset of TTS at the lowest level that exceeds natural recorded variation in hearing sensitivity (6 dB), and assumes that PTS occurs from exposures resulting in 40 dB or more of TTS measured approximately four minutes after exposure (NMFS 2018).

## 2.1 Assessment methodology summary

For marine mammals, the main impact from AyM will be as a result of underwater noise produced during construction. Therefore, a detailed assessment has been provided for this impact pathway. Exposure to loud sounds can lead to a reduction in hearing sensitivity (a shift in hearing threshold), which is generally restricted to particular frequencies. This threshold shift results from physical injury to the auditory system and may be temporary (TTS) or permanent (PTS). The PTS and TTS onset thresholds used in this assessment for both ‘instantaneous’ PTS ($SPL_{peak}$), and ‘cumulative’ PTS ($SEL_{cum}$, over 24 hours) are those presented in Southall et al. (2019). The noise levels likely to occur as a result of the construction of AyM were predicted by Subacoustech Environmental Ltd using their INSPIRE (Impulse Noise Sound Propagation and Impact Range Estimator) model. A detailed description of the modelling approach is presented in the Volume 4, Annex 6.2: Subsea Noise Technical Report (application ref: 6.4.6.2).

In calculating the received cumulated noise level that animals are likely to receive during the whole piling sequence, all animals were assumed to start moving away at a swim speed of 1.5 m/s once the piling has started (based on reported sustained swimming speeds for harbour porpoises) (Otani et al. 2000), except for minke whales which are assumed to swim at a speed of 3.25 m/s (Blix and Folkow 1995). The calculated PTS and TTS-onset impact ranges therefore represent the minimum starting distances from the piling location for animals to escape and prevent them from receiving a dose higher than the threshold.

The assessment of disturbance was based on the current best practice methodology, making use of the best available scientific evidence. This incorporated the application of a species-specific dose-response approach rather than a fixed behavioural threshold approach. Noise contours at 5 dB intervals were generated by noise modelling and were overlain on species density surfaces to predict the number of animals potentially disturbed. This allowed for the quantification of the number of animals that will potentially respond.

The following sections detail the key assumptions, limitations, and uncertainties associated with these quantitative impact assessment methods.

## 2.2 Proportion impacted

It is important to note that it is expected that only 18-19% of animals are predicted to actually experience PTS at the PTS-onset threshold level. This was the approach adopted by Donovan et al. (2017) to develop their dose response curve implemented into the SAFESIMM (Statistical Algorithms For Estimating the Sonar Influence on Marine Megafauna) model, based on the data presented in Finneran et al. (2005). Therefore, where PTS-onset ranges are provided, it is not expected that all individuals within that range will experience PTS. Therefore, the number of animals predicted to be within PTS-onset ranges presented in this assessment are precautionary, since they assume that all animals respond.

## 2.3 Exposure to noise

There are uncertainties relating to the ability to predict the exposure of animals to underwater noise, as well as in predicting the response to that exposure. These uncertainties relate to a number of factors: the ability to predict the level of noise that animals are exposed to, particularly over long periods of time; the ability to predict the numbers of animals affected, and the ability to predict the individual and ultimately population consequences of exposure to noise. These are explored in further detail in the paragraphs below.

The propagation of underwater noise is relatively well understood and modelled using standard methods. However, there are uncertainties regarding the amount of noise actually produced by each pulse at source and how the pulse characteristics change with range from the source. There are also uncertainties regarding the position of receptors in relation to received levels of noise, particularly over time, and understanding how position in the water column may affect received levels. Noise monitoring is not always carried out at distances relevant to the ranges predicted for effects on marine mammals, so effects at greater distances remain un-validated in terms of actual received levels. The extent to which ambient noise and other anthropogenic sources of noise may mask signals from the offshore wind farm construction are not specifically addressed. The dose-response curves for porpoise include behavioural responses at noise levels down to 120 dB $SEL_{ss}$ which may be indistinguishable from ambient noise at the ranges these levels are predicted.

## 2.4 Cumulative PTS

The cumulative sound exposure level ($SEL_{cum}$), is energy-based and is a measure of the accumulated sound energy an animal is exposed to over an exposure period. An animal is considered to be at risk of experiencing "cumulative PTS" if the $SEL_{cum}$ exceeds the energy-based threshold. The calculation of $SEL_{cum}$ is done with frequency-weighted sound levels, using species group-specific weighing functions to reflect the hearing sensitivity of each functional hearing group. To assess the risk of cumulative PTS, it is necessary to make assumptions on how animals may respond to noise exposure, since any displacement of the animal relative to the noise source will affect the sound levels received. For this assessment, it was assumed that animals would flee from the pile foundation at the onset of piling. A fleeing animal model was therefore used to determine the cumulative PTS impact ranges to determine the minimum distance to the pile site at which an animal can start to flee without the risk of experiencing cumulative PTS.

There is much more uncertainty associated with the prediction of the cumulative PTS impact ranges than with those for the instantaneous PTS. One reason is that the sound levels an animal receives, and which are cumulated over a whole piling sequence are difficult to predict over such long periods of time as a result of uncertainties about the animal's (responsive) movement in terms of its changing distance to the sound source and the related speed, and its position in the water column.

Another reason is that the prediction of the onset of PTS (which is assumed to be at the $SEL_{cum}$ threshold values provided by Southall et al. 2019) is determined with the assumptions that:

a) the amount of sound energy an animal is exposed to within 24 hours will have the same effect on its auditory system, regardless of whether it is received all at once (i.e. with a single bout of sound) or in several smaller doses spread over a longer period (called the equal-energy hypothesis); and,

b) the sound keeps its impulsive character, regardless of the distance to the sound source.

In practice:

a) there is a recovery of a threshold shift caused by the sound energy if the dose is applied in several smaller doses (e.g. between pulses during pile driving or in piling breaks) leading to an onset of PTS at a higher energy level than assumed with the given $SEL_{cum}$ threshold; and,

b) pulsed sound loses its impulsive characteristics while propagating away from the sound source, resulting in a slower shift of an animal's hearing threshold than would be predicted for an impulsive sound.

Both assumptions therefore lead to a conservative determination of the impact ranges and are discussed in further detail in the sections below.

Modelling the $SEL_{cum}$ impact ranges of PTS with a 'fleeing animal' model, as is typical in noise impact assessments, are subject to both above-mentioned uncertainties and the result is a highly precautionary prediction of impact ranges. As a result of these and the uncertainties on animal movement, model parameters, such as swim speed, are generally chosen conservative and, when considered across multiple parameters, this precaution is compounded therefore the resulting predictions are very precautionary and very unlikely to be realised.

### 2.4.1 Equal-energy hypothesis

The equal-energy hypothesis assumes that "exposures of equal energy are assumed to produce equal amounts of noise-induced threshold shift, regardless of how the energy is distributed over time". However, a continuous and an intermittent noise exposure of the same SEL will produce different levels of temporary threshold shift (TTS) (Ward 1997). Ward (1997) highlights that the same is true for impulsive noise, giving the example of simulated gunfires of the same $SEL_{cum}$ exposed to human, where 30 impulses with an $SPL_{peak}$ of 150 dB re 1 mPa result in a TTS of 20 dB, while 300 impulses of a respectively lower $SPL_{peak}$ did not result in any TTS.

Finneran (2015) showed that several marine mammal studies have demonstrated that the temporal pattern of the exposure does in fact affect the resulting threshold shift (e.g. Kastak et al. 2005, Mooney et al. 2009, Finneran et al. 2010a, Kastelein et al. 2013a). Intermittent noise allows for some recovery of the threshold shift in-between exposures, and therefore recovery can occur in the gaps between individual pile strikes and in the breaks in piling activity, resulting in a lower overall threshold shift compared to continuous exposure at the same SEL. Kastelein et al. (2013a) showed that, for seals, the threshold shifts observed did not follow the assumptions made in the guidance regarding the equal-energy hypothesis; instead, the threshold shifts observed were more similar to the hypothesis presented in Henderson et al. (1991) – that hearing loss induced due to noise does not solely depend upon the total amount of energy, but on the interaction of several factors such as the level and duration of the exposure, the rate of repetition, and the susceptibility of the animal. Therefore, the equal-energy hypothesis assumption behind the $SEL_{cum}$ threshold is not valid, and as such, models will overestimate the level of threshold shift experienced from intermittent noise exposures.

One more detailed example to give is the study of Kastelein et al. (2014), where a harbour porpoise was exposed to a series of 1-2 kHz sonar down-sweep pulses of 1 second duration of various combinations with regard to received sound pressure level, exposure duration and duty cycle (% of time with sound during a broadcast) to quantify the related threshold shift. The porpoise experienced a 6 to 8 dB lower TTS when exposed to sound with a duty cycle of 25% compared to a continuous sound (Figure 1). A 1-sec silent period in-between pulses resulted in a 3 to 5 dB lower TTS compared to a continuous sound (Figure 1).

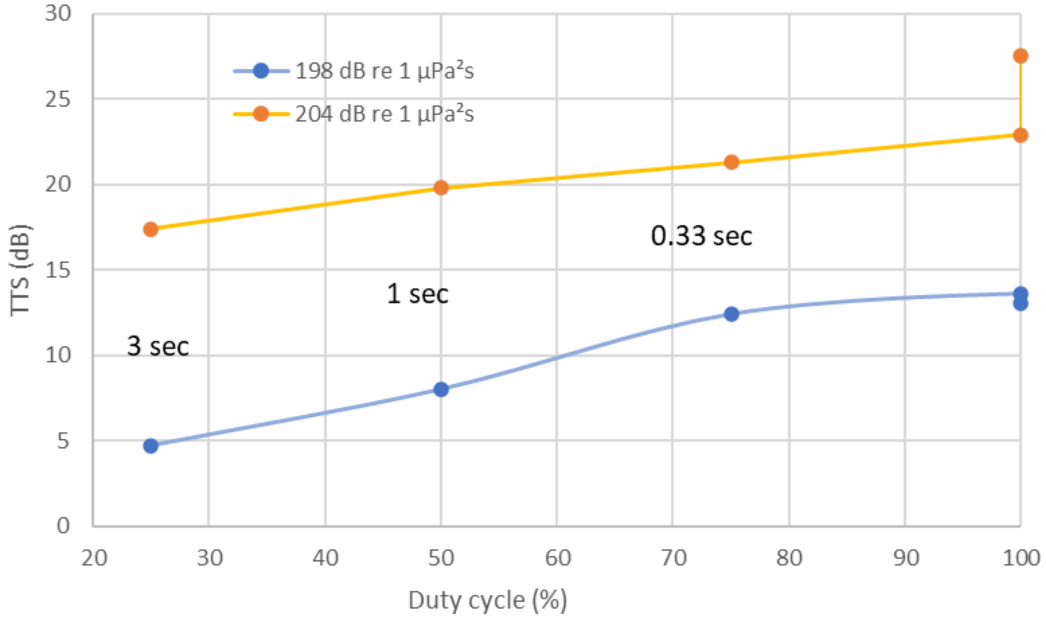


**Figure 1 Temporary threshold shift (TTS) elicited in a harbour porpoise by a series of 1-2 kHz sonar down-sweeps of 1 second duration with varying duty cycle and a constant SELcum of 198 and 204 dB re1 µPa²s, respectively. Also labelled is the corresponding 'silent period' in-between pulses. Data from Kastelein et al. (2014).**

Pile strikes are relatively short signals; the signal duration of monopile pile strikes may range between 0.1 sec (De Jong and Ainslie 2008) and appr. 0.3 sec (Dähne et al. 2017, Fig.4) measured at a distance of 3.3 to 3.6 km. Duration will however increase with increasing distance from the pile site. For the first 20 minute of pile driving at AyM, a strike rate of 10 strikes per minute is planned. Assuming a signal duration of around 0.5 sec for a pile strike, this relates to an 8% duty cycle (0.5 sec pulse followed by 5.5 sec silence). For the remaining part of the ramp-up and at full hammer energy, the duty cycle will be 28% (0.5 sec pulse followed by a 1.26 sec silent period) at a strike rate of 34 strikes per minute. In the study of Kastelein et al. (2014), a silent period of 1.5 seconds corresponds to a duty cycle of 40%. The reduction in TTS at a duty cycle of 40% is greater 6 dB, at a duty cycle of 25% more than 8 dB. Southall et al. (2019a) calculates the PTS-onset thresholds based on the assumption that a TTS of 40 dB will lead to PTS, and an animal's hearing threshold will shift by 2.3 dB per dB SEL received from an impulsive sound. This means, to elicit the same threshold shift with a 40% or 25% duty cycle as with a sound of 100% duty cycle, more than 2.6 dB (6 dB/2.3) will need to be added to the SEL of the 100% duty cycled sound. The threshold for PTS can therefore be raised by a minimum of 2.6 dB. Assuming similar effects to the hearing system of marine mammals in the Moray Firth, the PTS-onset threshold would expected to be at minimum 2.6 dB higher than that proposed by Southall et al. (2019) and used in the current assessment. While more research needs to be conducted to understand the exact magnitude of this effect in relation to pile driving sound, the study of Kastelein et al proves a significant reduction in the risk of PTS even through short silent periods for TTS recovery as found in pile driving.

Below is an illustration of how the predicted cumulative PTS impact ranges can change if the PTS-onset threshold is increased by 2 and 3 dB, respectively. Figure 2 illustrates the change in the impact range for cumulative PTS for minke whales for a single monopile (top) and concurrent pin-piles (bottom) using the current PTS-onset threshold compared to the threshold increased by 2 and 3 dB, respectively. Figure 3 illustrates the change in impact range for harbour porpoise for a single monopile (top) and concurrent pin-piles (bottom) using the current PTS-onset threshold compared to the threshold increased by 2 and 3 dB, respectively.

Table 1 summarises the difference in the predicted PTS impact ranges using the current and adjusted thresholds. In summary, if the threshold accounts for recovery in hearing between pulses, then PTS impact ranges for a single monopile decrease from 4.625 km to for harbour porpoise to 3.05 km or 2.375 km (assuming a 2 and 3 dB increase in the threshold, respectively).

Therefore, accounting for recovery in hearing between pulses by increasing the PTS-onset threshold by 2 or 3 dB significantly decreases the predicted PTS-onset impact ranges. This approach to modelling cumulative PTS is in development and has not yet been fully assessed or peer reviewed. Therefore, the AyM impact assessment will present the cumulative PTS impact ranges using the current Southall et al. (2019a) PTS-onset impact threshold, however the predicted ranges should be viewed with caution in light of the illustrated examples below.

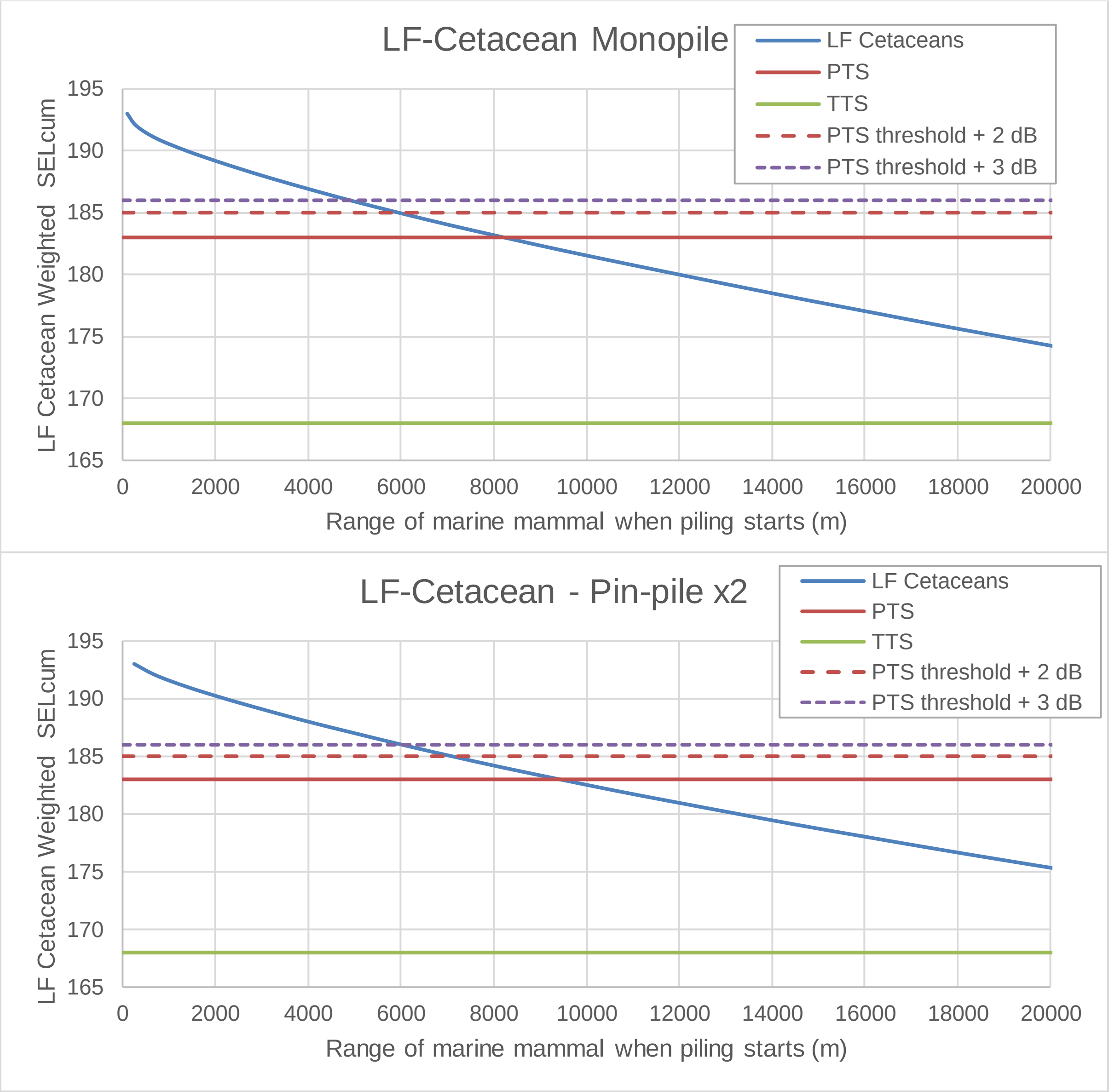


**Figure 2 Relationship between the starting distance from the pile upon piling start and the received cumulative SEL from the piling sequence for minke whale (LF-Cetacean, blue line). Intersects of the SELcum with the different threshold values give the starting distance, at which the animal would at minimum be to meet the criterion for the threshold (green solid line: TTS-threshold, red solid line: PTS-threshold, red dashed line: PTS-threshold + 2 dB, purple dashed line: PTS-threshold + 3 dB) . Top = single monopile, bottom = concurrent pin piles at the same location.**

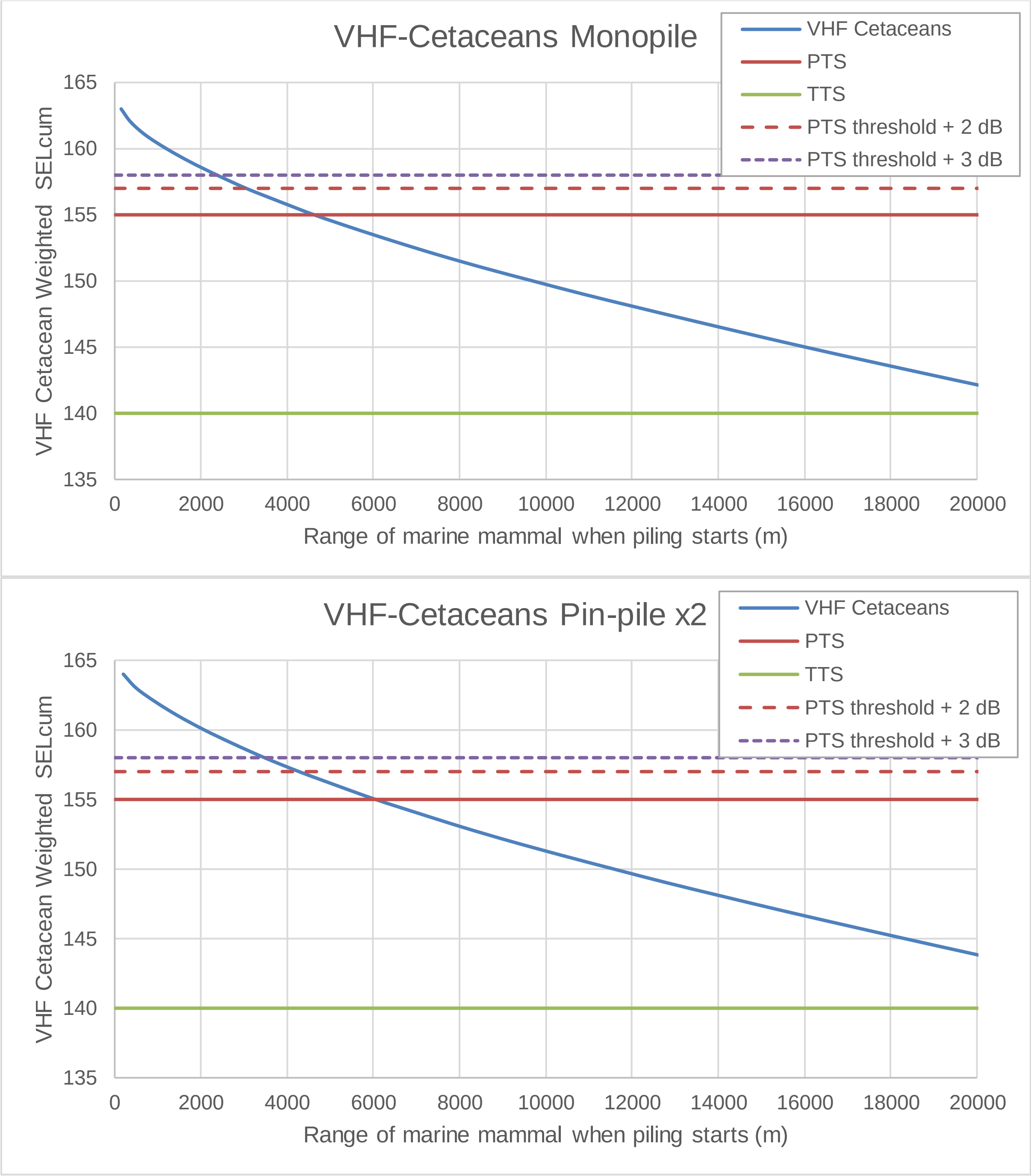


**Figure 3 Relationship between the starting distance from the pile upon piling start and the received cumulative SEL from the piling sequence for harbour porpoise (VHF-Cetacean, blue line). Intersects of the SELcum with the different threshold values give the starting distance, at which the animal would at minimum be to meet the criterion for the threshold (green solid line: TTS-threshold, red solid line: PTS-threshold, red dashed line: PTS-threshold + 2 dB, purple dashed line: PTS-threshold + 3 dB) . Top = single monopile, bottom = concurrent pin piles at the same location.**

**Table 1 Difference in PTS impact ranges when using the current Southall et al. (2019a) thresholds, compared to increasing the threshold by 2 and 3 dB, respectively.**

| | cumulative PTS safe distance (m) | | | |
|---|---|---|---|---|
| | Monopile | | Pinpile (x2) | |
| **Threshold** | **LF** | **VHF** | **LF** | **VHF** |
| Southall et al 2019 | 8,225 | 4,625 | 9,425 | 6,050 |
| +2 dB | 5,950 | 3,050 | 7,100 | 4,275 |
| *% of original* | *72%* | *66%* | *75%* | *71%* |
| +3 dB | 4,900 | 2,375 | 6,025 | 3,475 |
| *% of original* | *60%* | *51%* | *64%* | *57%* |

### 2.4.2 Impulsive characteristics

Southall et al. (2009) calculated the PTS-onset thresholds based on the assumption that an animal's hearing threshold will shift by 2.3 dB per dB SEL received from an impulsive sound, but only 1.6 dB per dB SEL when the sound received is non-impulsive. The PTS-onset threshold for non-impulsive sound is therefore higher than for impulsive sound, as more energy is needed to cause PTS with non-impulsive sound compared to impulsive sound. Consequently, an animal subject to both types of sound will be at risk of PTS at an $SEL_{cum}$ that lies somewhere between the PTS-onset thresholds of impulsive and non-impulsive sound.

Southall et al. (2019a) acknowledges that as a result of propagation effects, the sound signal of certain sound sources (e.g. pile driving) loses its impulsive characteristics and could potentially be characterised as non-impulsive beyond a certain distance. The changes in noise characteristics with distance generally result in exposures becoming less physiologically damaging with increasing distance as sharp transient peaks become less prominent (Southall et al. 2007). The Southall et al. (2019a) updated criteria proposed that, while keeping the same source categories, the exposure criteria for impulsive and non-impulsive sound should be applied based on the signal features likely to be perceived by the animal rather than those emitted by the source. Methods to estimate the distance at which the transition from impulsive to non-impulsive noise are currently being developed (Southall et al. 2019a).

Using the criteria of signal duration[1], rise time[2], crest factor[3] and peak pressure[4] divided by signal duration[5], Hastie et al. (2019) estimated the transition from impulsive to non-impulsive characteristics of pile driving noise during the installation of offshore wind turbine foundations at the Wash and in the Moray Firth. Hastie et al. (2019) showed that the noise signal experienced a high degree of change in its impulsive characteristics with increasing distance. Southall et al. (2019a) state that mammalian hearing is most readily damaged by transient sounds with rapid rise-time, high peak pressures, and sustained duration relative to rise-time. Therefore, of the four criteria used by Hastie et al. (2019), the

---

[1] Time interval between the arrival of 5% and 95% of total energy in the signal.

[2] Measured time between the onset (defined as the 5th percentile of the cumulative pulse energy) and the peak pressure in the signal.

[3] The decibel difference between the peak sound pressure level (i.e. the peak pressure expressed in units of dB re 1 µPa) of the pulse and the root-mean-square sound pressure level calculated over the signal duration.

[4] The greatest absolute instantaneous sound pressure within a specified time interval.

[5] Time interval between the arrival of 5% and 95% of total energy in the signal.

rise-time and peak pressure may be the most appropriate indicators to determine the impulsive/non-impulsive transition.

Based on the rise-time criterion (rise time <25 ms defines a signal as impulsive), Hastie et al. (2019) showed that the noise signal experienced a high degree of change in its impulsive characteristics within 3 - 9 km from the source (Figure 4). For pile driving at the Moray Firth (1.8 m diameter pin-piles in 42 m water depth), the probability of the piling noise being impulsive reduced from 70% at ~0.7 km down to 1% at ~3.1 km. For pile driving at The Wash (5.2 m diameter monopiles in water depths of 8-20 m), this probability reduced from 70% at ~1.4 km down to 1% at ~8.6 km. This study shows not only that impulsive sound becomes non-impulsive at greater distance to the sound source, but also that the portion of impulsive sound when exposed to a piling sequence, reduces with increasing distance to the pile site (as the probability of a piling noise to be impulsive reduces).

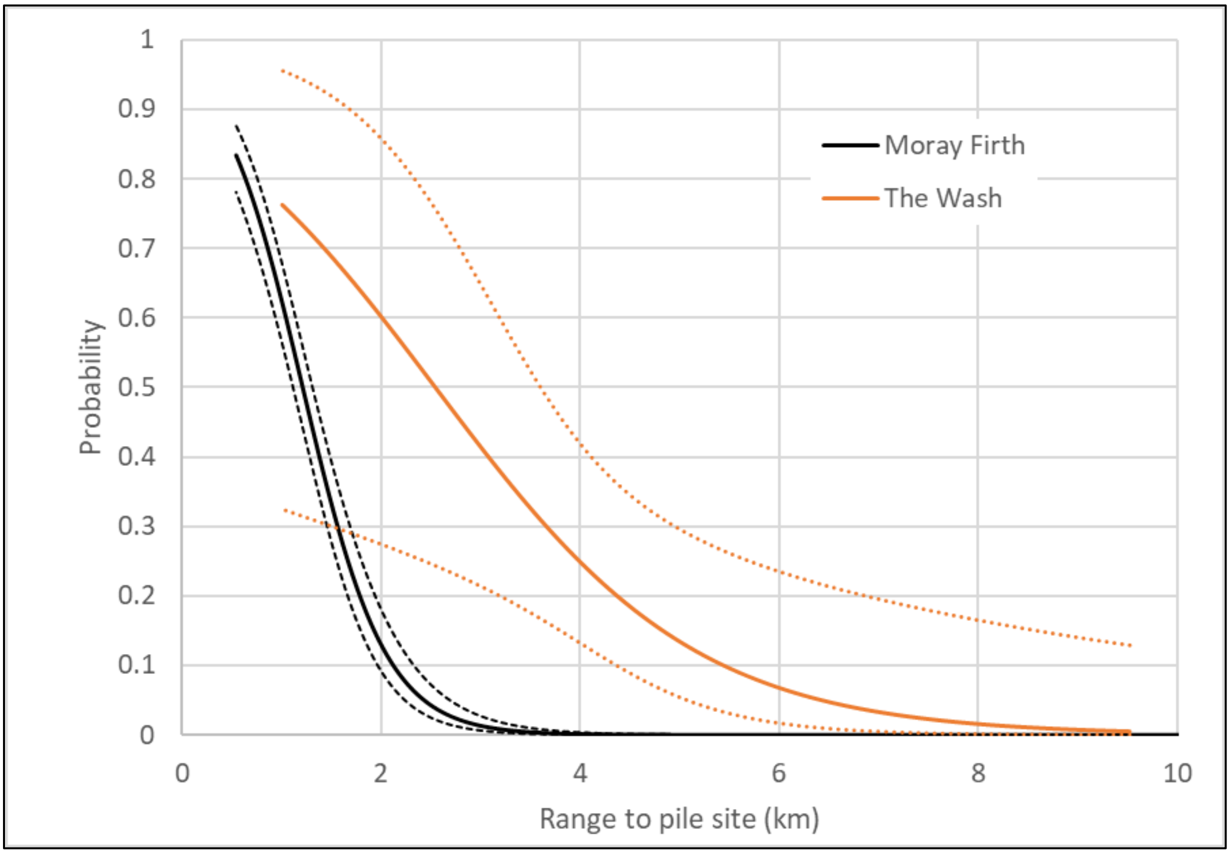


**Figure 4 Modelled functions describing the probability of a signal being defined as "impulsive" based on the rise time being less than 25 ms.**

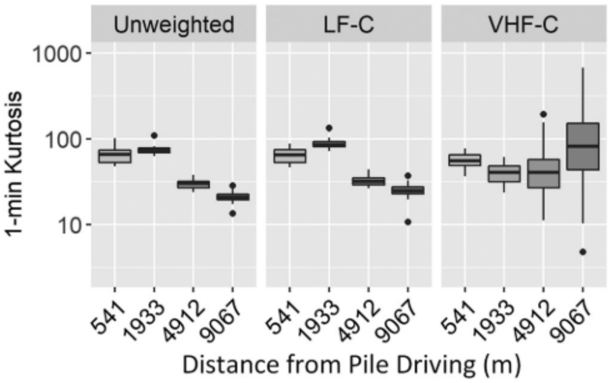
The lines represent the modelled fits (solid lines) and their 95% confidence intervals (dashed lines) for Moray Firth (black) and The Wash (orange). Figure adapted from Hastie et al. (2019).

It is acknowledged that the Hastie et al. (2019) study is an initial investigation into this topic, and that further data are required in order to set limits to the range at which impulsive criteria for PTS are applied.

Since the Hastie et al. (2019) study, Martin et al. (2020) investigated the sound emission of different sound sources to test techniques for distinguishing between the sound being impulsive or non-impulsive. For impulsive sound sources, they included impact pile driving of four 4-legged jacket foundation installed at around 20 m water depth (at the Block Island Wind farm in the USA). For the pile driving sound they recorded sound at four distances between ~500 m and 9 km, recording the sound of 24 piling events. To investigate the impulsiveness of the sound, they used three different parameters: kurtosis[6], crest factor and Harris factor[7], which they computed over 1-minute time windows, i.e. integrated over multiple transients (please see Martin et al. (2020)for definitions). As their data showed a strong correlation between the three different factors, the authors argued for the use of kurtosis to further investigate the impulsiveness of sound. Hamernik et al. (2007) showed a positive correlation between the magnitude of PTS and the kurtosis value in chinchillas, with an increase in PTS for a kurtosis value from 3 up to 40 (which in reverse also means that PTS decreases for the same SEL with decreasing kurtosis below 40). Therefore, Martin et al. (2020) argued that:

- Kurtosis of 0-3 = continuous sinusoidal signal (non-impulsive)
- Kurtosis of 3-40 = transition from non-impulsive to impulsive sound
- Kurtosis of 40 = fully impulsive.

For the evaluation of their data, Martin et al. (2020) used unweighted as well as LF-Cetacean (C) and VHF-C weighted sound based on the species-specific weighting curves in Southall et al. (2019a) to investigate the impulsiveness of sound. Their results for pile driving are shown in Figure 5. For the unweighted and LF-C weighted sound, the kurtosis value was >40 within 2 km from the piling site. Beyond 2 km, the kurtosis value decreased with increasing distance. For the VHF-C weighted sound, kurtosis factor is more inconclusive with the median value >40 for the 500 m and 9 km measuring stations, and at 40 for the stations in-between. However, the variability of the kurtosis value for the VHF-C weighted sound increased with distance.



| | Median value (1-min kurtosis) | | |
|---|---|---|---|
| Distance (km) | Unweighted | LF-C | VHF-C |
| 0.541 | 65 | 65 | 60 |
| 1.933 | 70 | 85 | 40 |
| 4.912 | 30 | 30 | 40 |
| 9.067 | 20 | 25 | 80 |

**Figure 5 The range of kurtosis weighted by LF-C and VHF-C Southall et al. (2019) auditory frequency weighting functions for 30 min of impact pile driving data measured in 25 m of water at the Block Island Wind Farm.**

Unweighted data are 10 Hz and above high pass filtered. For each range and auditory frequency weighting function, the boxes show the interquartile range. The horizontal line in the box is the median value. The vertical lines show the range of values for the 25% of the data above or below the middle half. The dots above or below the line indicate outlier values (From: Martin et al. (2020): Figure 7). Table shows approximate median values extracted from the graph.

---

[6] Kurtosis is a measure of the asymmetry of a probability distribution of a real-valued variable.

[7] The Harris (1998) impulse factor is the maximum value for each minute of the impulse time-weighted SPL minus the slow time-weighted SPL.

Martin et al. (2020) used this data to conclude that the change to non-impulsiveness "*is not relevant for assessing hearing injury because sounds retain impulsive character when SPLs are above EQT*" (i.e. the sounds they recorded retain their impulsive character while being at sound levels that can contribute to auditory injury). We interpret their results differently. Figure 5 clearly shows (for unweighted and LF-C weighted sound) that piling sound loses its impulsiveness with increasing distance from the piling site - the kurtosis value decreases with increasing distance and therefore the sound loses its harmful impulsive characteristics. Based on this study and the study by Hastie et al we argue that the predicted PTS impact ranges based on the impulsive noise thresholds will over-estimate the risk of PTS-onset in cases and at ranges where the likelihood increases that an animal is exposed to sound with much reduced impulsive characteristics.

There are some points that need to be considered before adopting kurtosis as an impulsiveness measure, with the recommended threshold value of 40. Firstly, this value was experimentally obtained for chinchillas that were exposed to noise resembling a five-day working week. Caution may need to be taken to directly adopt this threshold-value (and the related dose-response of increasing PTS with increasing kurtosis between 3 and 40) to marine mammals, especially given that the PTS guidance considers time periods of up to 24 hours. Secondly, kurtosis is recommended to be computed over at least 30 seconds, which means that it is not a specific measure that can be used for single blows of a piling sequence. Instead, Kurtosis has been recommended to evaluate steady-state noise in order to include the risk from embedded impulsive noise (Goley et al. 2011). Metrics used by Hastie et al. (2019) computed for each pile strike (e.g., rise time) may be more suitable to evaluate single pile strikes. Which metric is the most useful and how they correlate with the magnitude of auditory injury in (marine) mammals is still to be investigated.

Southall (2021) point out that "*at present there are no properly designed, comparative studies evaluating TTS for any marine mammal species with various noise types, using a range of impulsive metrics to determine either the best metric or to define an explicit threshold with which to delineate impulsiveness*". He proposes that the presence of high-frequency noise energy could be used as a proxy for impulsiveness, as all currently used metrics have in common that a high frequency spectral content result in high values for those metrics. His suggestion is an interim approach: "*the range at which noise from an impulsive source lacks discernable energy (relative to ambient noise at the same location) at frequencies ≥ 10 kHz could be used to distinguish when the relevant hearing effect criteria transitions from impulsive to nonimpulsive*". Southall (2021), however, notes that "*it should be recognized that the use of impulsive exposure criteria for receivers at greater ranges (tens of kilometers) is almost certainly an overly precautionary interpretation of existing criteria*".

Considering that an increasing proportion of the sound emitted during a piling sequence will become less impulsive (and thereby less harmful) while propagating away from the sound source, and this effect starts at ranges below 5 km in all above mentioned examples, the cumulative PTS-onset threshold for animals starting to flee at 5 km should be higher than the Southall (2021) threshold adopted for this assessment (i.e. the risk of experiencing PTS becomes lower), and any impact range estimated beyond this distance should be considered as an unrealistic over-estimate, especially when they result in very large distances.

For the purpose of presenting a precautionary assessment, the quantitative impact assessment for AyM is based on fully impulsive thresholds, but the potential for overestimation should be noted.

## 2.5 Density

There are uncertainties relating to the ability to predict the responses of animals to underwater noise and the prediction of the numbers of animals potentially exposed to levels of noise that may cause an impact is uncertain. Given the high spatial and temporal variation in marine mammal abundance and distribution in any particular area of the sea, it is difficult to confidently predict how many animals may be present within the range of noise impacts. All methods for determining at sea abundance and distribution suffer from a range of biases and uncertainties and no single method or data source will provide a complete prediction of future conditions.

### 2.6 Predicting response

There is limited empirical data available to confidently predict the extent to which animals may experience auditory damage or display responses to noise. The current methods for prediction of behavioural responses are based on received sound levels, but it is likely that factors other than noise levels will influence the probability of response and the strength of response (e.g. previous experience, behavioural and physiological context, proximity to activities, characteristics of the sound other than level, such as duty cycle and pulse characteristics). However, at present, it is impossible to adequately take these factors into account in a predictive sense. This assessment makes use of the monitoring work that has been carried out during the construction of the Beatrice Offshore Wind Farm and therefore uses the most recent and site-specific information on disturbance to harbour porpoise as a result of pile driving noise.

There is also a lack of information on how observed effects (e.g. short-term displacement around pile-driving activities) manifest themselves in terms of effects on individual fitness, and ultimately population dynamics in attempting to quantify the amount of disturbance required before vital rates are impacted.

### 2.7 Duration of impact

The duration of disturbance is another uncertainty. Studies at Horns Rev 2 demonstrated that porpoises returned to the area one to three days after piling ceased (Brandt et al. 2011) and monitoring at the Dan Tysk Wind Farm as part of the Disturbance Effects on the Harbour Porpoise Population in the North Sea (DEPONS) project found return times of around 12 hours (van Beest et al. 2015). Two studies at Alpha Ventus demonstrated, using aerial surveys, that the return of porpoises was about 18 hours after piling (Dähne et al. 2013). A recent study of porpoise response at the Gemini wind farm in the Netherlands, also part of the DEPONS project, found that local population densities recovered between two and six hours after piling (Nabe-Nielsen et al. 2018). An analysis of data collected at the first seven offshore wind farms in Germany has shown that harbour porpoise detections were reduced between one and two days after piling (Brandt et al. 2018).

Analysis of data from monitoring of marine mammal activity during piling of jacket pile foundations at Beatrice Offshore Wind Farm (Graham et al. 2017, Graham et al. 2019) provides evidence that harbour porpoise were displaced during pile driving but return after cessation of piling, with a reduced extent of disturbance over the duration of the construction period. This suggests that the assumptions adopted in the current assessment are precautionary as animals are predicted to remain disturbed at the same level for the entire duration of the pile driving phase of construction.

## 3 UXO assessment

There is also a lack of data on the underwater noise produced by the clearance of various different types and sizes of Unexploded Ordnance (UXO). The current models to predict the noise propagation have not been validated at ranges relevant to the predictions and there is a possibility that models significantly overestimate ranges for large charge masses. Therefore, where there are empirical and modelled data available on impact ranges from UXO clearance, these have been presented to provide an estimate for the potential impacts at AyM.

There is a lack of information on the specifications of the UXOs expected (e.g. design, composition, age, position, orientation, whether it is covered by sediment) and how these factors will affect the sound produced by detonation are usually unknown and cannot be directly considered in this type of assessment. A worst-case estimation has therefore been used for calculations, assuming the UXO to be detonated is not buried, degraded or subject to any other significant attenuation from its "as new" condition.

Note: UXO clearance is not being licenced as part of this consent application, however a high-level assessment is provided on the basis of assumptions about the expected level of risk associated with any clearance activity on the assumption that it is "reasonably foreseeable". A detailed assessment of UXO clearance will be developed for a separate marine licence at a later stage.

### 3.1 UXO disturbance

There are currently no established regulatory guidance documents and few published scientific articles providing clear advice on how to approach the assessment of disturbance from underwater noise on marine mammal species. There are several different thresholds for disturbance that have been used for marine mammal EIAs, including:

1. effective deterrent ranges (EDRs),
2. fixed noise thresholds and
3. dose-response functions.

These methods are described in detail in Sinclair et al. (2021). In summary, an EDR assumes a fixed disturbance impact range from a noise source and assumes that all animals predicted to be present within the impact range are disturbed; fixed noise thresholds are sound level-based thresholds, where it is assumed that all animals that receive sound above a certain level are disturbed; and, dose-response functions assume that with an increasing level of noise ('dose') an increasing proportion of animals exposed to noise respond behaviourally.

Compared with the EDR and fixed noise threshold approaches, the application of a dose-response function allows for more realistic assumptions about the likelihood of an animal's response varying with dose, which is supported by a growing number of studies. A dose-response function is used to quantify the probability of a response from an animal to a dose of a certain stimulus or stressor (Dunlop et al. 2017) and is based on the assumption that not all animals in an impact zone will respond. Dose-response functions have been determined using the distance from the sound source (which correlates with the received level) or the received weighted or unweighted sound level at the receiver (Sinclair et al. 2021).

Using a species-specific dose-response function rather than a fixed noise threshold to assess disturbance is currently considered to be the best practice methodology and the latest guidance provided in Southall *et al.* (2021) is that:

> "Apparent patterns in response as a function of received noise level (sound pressure level) highlighted a number of potential errors in using all-or-nothing "thresholds" to predict whether animals will respond. Tyack & Thomas (2019) subsequently and substantially expanded upon these observations. The clearly evident variability in response is likely attributable to a host of contextual factors, which emphasizes the importance of estimating not only a dose-response function but also characterizing response variability at any dosage." *(Southall et al. 2021)*

In their s42 comments on the AyM PEIR, NRW stated that:

> *"Given that a dose response approach has been used to assess impacts from other impulsive noise, NRW suggest it would be appropriate for a similar approach to be considered for disturbance from UXO as well."*

SMRU Consulting acknowledges that there are empirically-derived dose-response relationships for harbour porpoise for impulsive noise from pile driving. These are, however, **not directly applicable** to the assessment of UXO detonation due to the very different nature of the sound emission. While both sound sources (piling and explosives) are categorised as "impulsive" sound sources, they differ drastically in the number of pulses and the overall duration of the noise emission, both of which will ultimately drive the behavioural response. While one UXO-detonation is anticipated to result in a one-off startle-response or aversive behaviour, the series of pulses emitted during pile driving will more or less continuously drive animals out of the impacted area, giving rise to a measurable and quantifiable dose-response relationship. For UXO clearance, there are no dose-response functions available that describe the magnitude and transient nature of the behavioural impact of UXO detonation on marine mammals.

### 3.1.1 Available thresholds

Since there is no dose-response function available that appropriately reflects the behavioural disturbance from UXO detonation, other behavioural disturbance thresholds need to be considered instead. These alternatives are summarised in the sections below.

#### 3.1.1.1 EDR - 26 km (JNCC et al. 2020)

There is guidance available on the EDR that should be applied to assess the significance of noise disturbance against Conservation Objectives of harbour porpoise SACs in England, Wales & Northern Ireland (JNCC et al. 2020). This guidance advises that an effective deterrence range of 26 km around the source location is used to determine the impact area from UXO detonation with respect to disturbance of harbour porpoise in SACs.

However, the guidance itself acknowledges that this EDR is based on the EDR recommended for pile driving of monopiles (without noise abatement measures), since there is no equivalent data for explosives.

> *"The 26 km EDR is also to be used for the high order detonation of unexploded ordnance (UXOs) despite there being no empirical evidence of harbour porpoise avoidance." (JNCC et al. 2020)*

The guidance also acknowledges that the disturbance resulting from a single explosive detonation would likely not cause the more wide-spread prolonged displacement that has been observed in response to pile driving activities:

> *"… a one-off explosion would probably only elicit a startle response and would not cause widespread and prolonged displacement…" (JNCC et al. 2020)*

While NRW have expressed concerns regarding the use of the EDR approach to assess disturbance, they do remain the only published threshold currently advised by a regulator in UK waters to assess behavioral disturbance from high-order UXO detonations.

> *"NRW considers that there is still considerable uncertainty in the evidence underpinning the calculation of Effective Deterrent Range (EDR), especially in Welsh waters, and as such not a signatory to the cited JNCC guidance for assessing the significance of noise disturbance against Conservation Objectives of harbour porpoise SACs (England & Northern Ireland)." (NRW s42 comments)*

While SMRU Consulting acknowledges that NRW do not agree with the 26 km EDR for UXO detonation, SMRU Consulting intends to present the 26 km EDR in the AyM EIA for context and for comparison to the alternative fixed noise threshold described below.

#### 3.1.1.2 Fixed noise threshold – TTS-onset (Southall et al. 2007, 2019)

Some recent assessments of UXO clearance activities have used TTS-onset thresholds to indicate the level at which a 'fleeing' response may be expected to occur in marine mammals (e.g. Seagreen and Neart na Goithe). This is a result of discussion in Southall et al. (2007) which states that in the absence of empirical data on responses, the use of the TTS-onset threshold may be appropriate for single pulses (like UXO detonation):

> *"Even strong behavioral responses to single pulses, other than those that may secondarily result in injury or death (e.g., stampeding), are expected to dissipate rapidly enough as to have limited long-term consequence. Consequently, upon exposure to a single pulse, the onset of significant behavioral disturbance is proposed to occur at the lowest level of noise exposure that has a measurable transient effect on hearing (i.e., TTS-onset). We recognize that this is not a behavioral effect per se, but we use this auditory effect as a de facto behavioral threshold until better measures are identified. Lesser exposures to a single pulse are not expected to cause significant disturbance, whereas any compromise, even temporarily, to hearing functions has the potential to affect vital rates through altered behavior." (Southall et al., 2007)."*

> *"Due to the transient nature of a single pulse, the most severe behavioral reactions will usually be temporary responses, such as startle, rather than prolonged effects, such as modified habitat utilization. A transient behavioral response to a single pulse is unlikely to result in demonstrable effects on individual growth, survival, or reproduction. Consequently, for the unique condition of a single pulse, an auditory effect is used as a de facto disturbance criterion. It is assumed that significant behavioral disturbance might occur if noise exposure is sufficient to have a measurable transient effect on hearing (i.e., TTS-onset). Although TTS is not a behavioral effect per se, this approach is used because any compromise, even temporarily, to hearing functions has the potential to affect vital rates by interfering with essential communication and/or detection capabilities. This approach is expected to be precautionary because TTS at onset levels is unlikely to last a full diel cycle or to have serious biological consequences during the time TTS persists." (Southall et al., 2007).*

Therefore, an estimation of the extent of behavioural disturbance can be based on the sound levels at which the onset of TTS is predicted to occur from impulsive sounds. Marine Scotland and NatureScot currently accept that TTS-onset as a proxy for disturbance from UXO detonation is the most appropriate threshold to use given the lack of empirical data. TTS-onset thresholds are taken as those proposed for different functional hearing groups by Southall et al. (2019a) (Table 2).

While the TTS-onset thresholds can be used as a proxy for disturbance, the resulting impact assessment should detail the limitations to this approach, including the fact that it may over-estimate the potential for an ecologically significant effect, as acknowledged by Southall et al. (2007), and that impulsive noise becomes non-impulsive at large distances from the sound source due to propagation effects (Southall et al. 2007, Hastie et al. 2019, Martin et al. 2020) (see also section 4). The sound level at which an animal is at risk of TTS from less impulsive or non-impulsive sound will be above those indicated by the TTS-onset thresholds for impulsive sound.

Table 2 TTS-onset thresholds for impulsive noise as proposed by Southall et al. (2019), with relevance for species in UK waters.

| Hearing group | TTS-onset: weighted SEL (dB re 1 µPa$^2$s) | TTS-onset: unweighted $SPL_{0-p}$ (dB re 1 µPa) |
|---|---|---|
| Low frequency (minke whale) | 168 | 213 |
| High frequency (dolphin species) | 170 | 224 |
| Very high frequency (harbour porpoise) | 140 | 196 |
| Phocids in water (seals) | 170 | 212 |

#### 3.1.1.3 Fixed noise threshold – Lucke et al. (2009)

A study conducted by Lucke et al. (2009) on harbour porpoise detailed behavioural responses to an airgun source (note: a pulse of this noise source is considered to be similar in nature to an explosion, and used in the Lucke et al. study as a single pulse source). The porpoise involved in the study showed an aversive behavioural reaction to the stimuli at received $SPL_{pp}$ >174 dB re 1 µPa (equivalent to $SPL_{0-p}$ of 168 dB re 1 µPa) or an SEL of 145 dB re 1 µPa$^2$s, with the SEL being cumulated over one airgun impulse (a.k.a. the single strike SEL). It is important to note that in the experimental set up, the seismic airgun sound source was located between 14 and 150 m to the animal, i.e. at close range from the porpoise. The behavioural response shown by the porpoise was very likely influenced by the impulsive shape of the sound: a sudden onset caused by the rapid rise in sound pressure followed by a fast decay.

However, the characteristics of a sound pulse changes over distance as the sound propagates, from a short sharp broadband impulse at close range, to a longer more tonal pulse at long distances. The distance to the sound source and the associated change in sound shape has an influence on the behavioural response an animal displays to sound of a certain sound level. For example, Southall et al. (2019b) investigated the probability of a behavioural response from blue whales to military sonar with increasing distance from the source. They showed that, for a cumulative SEL of 145 dB re 1 µPa$^2$s, the probability of blue whales showing a moderate response to the sonar was reduced from 0.45 at 1 km from the sound source to 0.05 at 5 km distance (this equates to an 89% reduction in the probability of response) (Figure 6). The probability of response to an explosion of an SEL of 145 dB re 1 µPa$^2$s also likely decreases with increasing distance from the animal to the sound source, as the sound shape becomes “smoother” by losing its impulsive characteristics. Higher sound levels are expected to be needed at longer ranges (kms away from the sound source) to elicit the same response of a porpoise as an impulsive sound at close ranges. Therefore, the use of the Lucke et al. (2009) behavioural response threshold is considered as highly over-precautionary when resulting in long impact ranges within the km range.

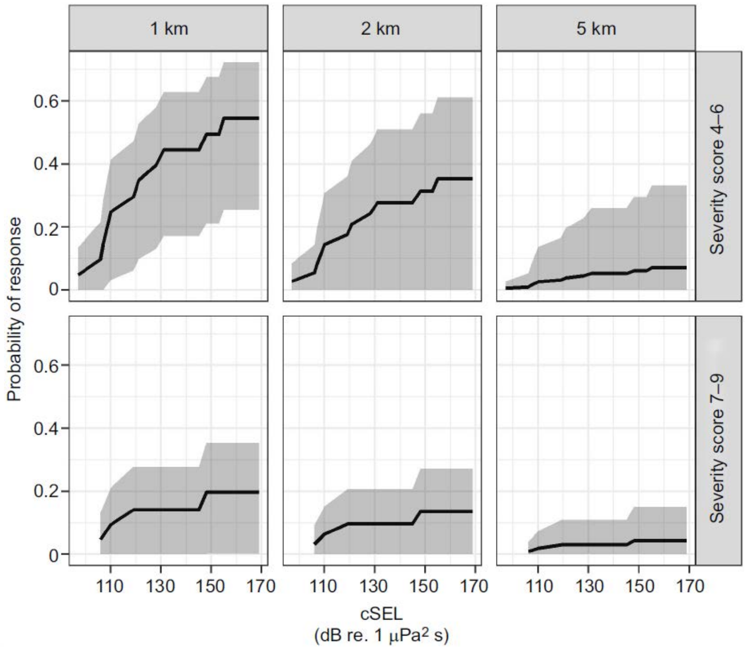


Figure 6 Behavioural response probability for deep-feeding blue whales exposed to MFAS and PRN as a function of received cSEL (dB re. 1 μPa$^2$s) for different source–receiver ranges and expert scored response severities. Response probability model predictions (black lines) with 95% confidence limits (shaded grey areas) are shown for 1, 2 and 5 km source–receiver ranges for moderate (scores 4–6) and high response severity (scores 7–9). Figure obtained from Southall et al. (2019b)[8]

### 3.1.1.4 Fixed noise threshold – Level B harassment

In the US, under the 1994 Amendments to the Marine Mammal Protection Act, Level B harassment is defined as any act of pursuit, torment or annoyance which has the potential to disturb a marine mammal or marine mammal stock in the wild by causing disruption of behavioural patterns (including, but not limited to, migration, breathing, nursing, breeding, feeding, or sheltering). The threshold for Level B harassment is 160 dB re 1µPa SPL$_{rms}$ from an impulsive sound source (NMFS 1995, 2005), based on studies of whale responses to seismic surveys, with added conservatism (as discussed in Tyack and Thomas 2019).

There are two key issues with the use of this threshold. Firstly, it is based on studies of multiple pulsed sounds (seismic surveys), not single pulses (like a UXO detonation). As outlined above, while one UXO-detonation is anticipated to result in a one-off startle-response or aversive behaviour, animals will be exposed to a series of pulses emitted during seismic surveys and for a longer time period, which is not considered to be comparable. However, unlike in a (stationary) pile driving scenario, the sound source "seismic survey vessel" is moving and therefore exposes animals for a shorter period to a series of pulses than piling would do. Secondly, the 160 dB re 1µPa SPL$_{rms}$ threshold is considered to be highly conservative, as studies have shown that at this threshold, there is a <10% probability of avoidance (for grey whales) (Tyack and Thomas 2019).

Therefore, SMRU Consulting recommend that the Level B harassment threshold (160 dB re 1µPa SPL$_{rms}$) is overly precautionary in the context of UXO and therefore **less appropriate** to use to assess disturbance from UXO detonations.

---

[8] Date downloaded: 2/2/2022, Copyright 2022 The Company of Biologists

### 3.1.2 Underwater noise propagation

Once a threshold has been selected, it needs to be input into an underwater noise propagation model to estimate the range at which the selected threshold is met.

There are only few empirical noise measurements from UXOs at varying distances, and thus we lack a specific understanding of how the UXO detonation sound propagates through the water and what noise levels are reached at larger distances. There are a couple of simple underwater noise models that have been developed for explosives. These are presented in Soloway and Dahl (2014) and Brand (2021) and are described below.

#### 3.1.2.1 Soloway & Dahl (2014)

Soloway and Dahl (2014) conducted measurements of peak sound pressure and SEL from underwater explosions in shallow water (~15 m deep) and at short range (< 1 km), and used the data to provide equations that can be used to estimate the peak pressure in the initial positive-going shock wave and the SEL. Five explosives were deployed, with a TNT-equivalence of 0.1 to 6.1 kg, in water depths between 14.7 m to 15.0 m deep, with detonations occurring either 0.5 m from the seafloor or at 9 m depth and measurements recorded at 165 to 950 m from the source.

The peak pressure in the initial positive-going shock wave is calculated as:

$$P_{0-p} = 52.4 * \ 10^6 \ (\frac{R}{W^{1/3}})^{-1.13}$$

where $P_{0-p}$ is the peak pressure in Pa, R is the measurement range in meters, and W is the charge weight in kg TNT. This equation can be re-arranged to obtain the range (R) that a selected peak pressure threshold ($P_{0-p}$) is reached, given a certain explosive charge size (W).

$$R = \sqrt[1.13]{\frac{52.4 * \ 10^6 \ (\sqrt[3]{W})^{1.13}}{P_{0-p}}}$$

The SEL (dB re 1 µPa$^2$s) is calculated as:

$$SEL = 6.14 \, x \, log_{10} \left( W^{\frac{1}{3}} \, (\frac{R}{W^{1/3}})^{-2.12} \right) + 219$$

This equation can be re-arranged to obtain the range (R) that a certain SEL threshold is reached, given a certain explosive charge size (W).

$$R = \sqrt[2.12]{\frac{W^{1.04}}{10 \ \frac{SEL - 219}{6.14}}}$$

The key issue with the use of this model to assess disturbance from UXO detonations is that the equations are simplistic and do not account for environmental variables, such as water depth and transmission loss at larger ranges.

As water propagates through the water column, it loses acoustic energy due to geometrical spreading loss and absorption. In shallow water, the geometrical spreading loss is rather cylindrical, as the sound is trapped by the seafloor and water surface. The transmission loss follows a 10log(R) relationship. In deep water with no boundaries, the geometrical spreading loss is spherical and follows a 20log(R) relationship. In reality, the geometrical spreading loss is more complex, and the truth is likely in-between cylindrical and spherical spreading loss, such as the predictions by the Soloway & Dahl equations (Figure 7). However, with increasing water depth, the spreading loss increases with increasing distance between the boundaries, leading to an overestimate of sound levels by the Soloway & Dahl equation waters deeper than 15 m.

Absorption is the second parameter that adds to the transmission loss of acoustic energy. The absorption loss increases linearly with distance, with an absorption coefficient (in dB per km) that is frequency dependent. The absorption coefficient increases with increasing frequency. While low frequency sound is hardly absorbed by seawater over long ranges, the effect becomes noticeable at frequencies at and above 1 kHz (Figure 7). von Benda-Beckmann et al. (2015) present a frequency spectrum of a UXO measured at 2 km distance, and while the frequency spectrum has its main energy below 1 kHz, the acoustic energy is spread well over a frequency range up to 10 kHz. As the weighting function of Southall et al. (2019) for the VHF-species group filters out low frequencies and thereby emphasises higher frequencies for the calculation of impact ranges, the absorption loss is an important factor to consider at longer distances. As the Soloway & Dahl equation is based on measurements up to 1 km and does not factor in absorption loss, this adds to further overestimations of impact ranges based on weighted SEL, especially for harbour porpoise.

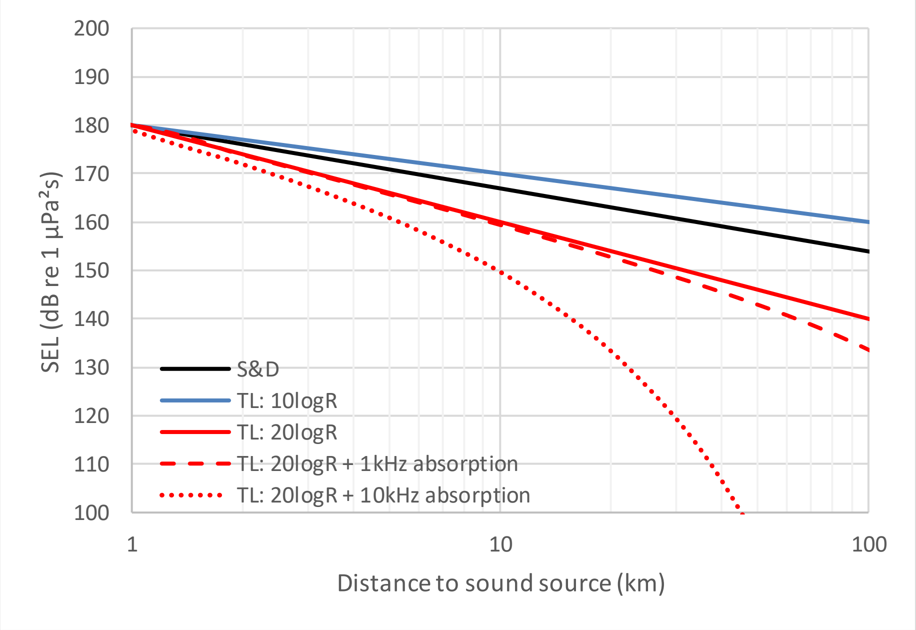


**Figure 7 Sound exposure levels calculated with the Soloway and Dahl equation (S&D) for a TNT weight of 1 kg at distances of 1 to 100 km in comparison with sound of the same SEL at 1 km with a cylindrical (10logR, blue line) and spherical (20logR, red line) transmission loss, and a spherical transmission loss including absorption[9] at a frequency of 1 kHz (dashed red line) and 10 kHz (dotted red line), respectively.**

### 3.1.2.2 Brand (2021)

Brand (2021) presents the EDGAR model (Explosives use in Decommissioning - Guide for Assessment of Risk), which is a simple underwater noise model that can be used to model sound levels from explosives used to cut well conductors and piles during decommissioning of offshore oil and gas structures. The model has only been developed and used for small, shaped charges associated with

---

[9] Calculated with [redacted] and standard settings for sea water, using the absorption coefficient from Ainslie and McColm (1998).

O&G decommissioning work, and is currently not suitable for large charge sizes and UXOs, nor has it been validated at large ranges, though this may be developed in a future iteration of the model.

#### 3.1.2.3 Impulsiveness of sound

Exposure to loud, brief, transient sounds (impulsive sounds, such as explosions, airgun shots or pile strikes) is more damaging to the mammalian ear as it increases the hearing threshold faster than exposure to non-impulsive sound (such as from drilling and shipping), i.e. less sound energy is needed to induce TTS or PTS. Southall et al. (2019a) acknowledges that, as a result of propagation effects, the signal of certain sound sources loses its impulsive characteristics and could potentially be characterised as a non-impulsive beyond a certain distance. The changes in noise characteristics with distance generally result in exposures becoming less physiologically damaging with increasing distance as sharp transient peaks become less prominent (Southall et al. 2019a). Methods to estimate the distance at which the transition from impulsive to non-impulsive noise are currently being developed (Southall et al. 2019a). Initial work on this has investigated sound from piling and seismic surveys and estimated the probability of the signal being defined as impulsive for varying ranges from the source (Hastie et al. 2019). Hastie et al. (2019) showed that a pile driving signal experienced a high degree of change in its impulsive characteristics within three to nine km from the source. However, at the current time, there has been no investigation into the change in impulsive characteristics for UXO sound. As such, it is not currently possible to take this into consideration in any modelling.

#### 3.1.2.4 Conclusion

In conclusion, there are issues with the current Soloway and Dahl (2014) equations as they have not been validated for large UXO charge sizes nor have they been validated at larger ranges from the source. However, this is the only option currently available.

There is a modification to the Soloway and Dahl (2014) equations that Subacoustech use in their assessments. They modify the Soloway and Dahl (2014) equations by adding an attenuation correction, which goes some way towards accounting for the absorption of sound over long ranges (i.e., of the order of thousands of metres). Their attenuation correction is based on measurements of high intensity noise propagation taken in the North and Irish Seas in similar depths to those present at AyM and includes a frequency dependent sound absorption term dependent on the range, temperature, depth, and other typical environmental parameters of the water in this area. It is recommended that this attenuated version of the Soloway and Dahl (2014) equations is used in assessments rather than the original equations. While it doesn't account for all the issues with the equations, it does provide at least some correction for absorption of sound over long ranges.

### 3.1.3 Modelled impact ranges

Subacoustech kindly provided estimated disturbance impact ranges using their attenuated version of the Soloway and Dahl (2014) equation for all disturbance thresholds outlined in section 3. This shows that the disturbance impact ranges for harbour porpoise from a 525 kg UXO can vary between 4 km (TTS-onset) to >1,000 km (Lucke aversive response) depending on the disturbance threshold used (Table 3).

This clearly highlights the issue with the use of the Lucke et al. (2009) 145 dB re 1 µPa$^2$s SEL threshold. This threshold is not met until >1,000 km from the source, and given what is known about sound propagation, there is simply no way that the received sound at that distance would be anything like the original short and sharp broad-band impulse that resulted in the behavioural reaction. Furthermore, it has to be taken into account, that the Lucke et al. (2009) threshold is based on an unweighted SEL. Any high frequency components of the UXO sound will be absorbed at these large distances and therefore it is unlikely that a harbour porpoise can hear the sound it is exposed to.

**Table 3 Impact ranges for harbour porpoise – calculated using the Soloway & Dahl (2014) equation with an attenuation correction. Data provided by Subacoustech.**

| UXO charge | Threshold | | Impact range |
|---|---|---|---|
| 525 kg | EDR | 26 km | 26 km |
| | Southall et al. (2019a) – TTS-onset | SEL 140 dB re 1 µPa$^2$s | 4 km |
| | Southall et al. (2019a) – TTS-onset | $SPL_{0-p}$ 196 dB re 1 µPa | 23.3 km |
| | Lucke et al. (2009) – aversive response | SEL 145 dB re 1 µPa$^2$s | >1,000 km |
| | Lucke et al. (2009) – aversive response | $SPL_{pp}$ 174 dB re 1 µPa | 365 km |
| | Level B harassment | 160 $SPL_{rms}$ | 437 km |
| 164 kg | EDR | 26 km | 26 km |
| | Southall et al. (2019a) – TTS-onset | SEL 140 dB re 1 µPa$^2$s | 3.3 km |
| | Southall et al. (2019a) – TTS-onset | $SPL_{0-p}$ 196 dB re 1 µPa | 15.9 km |
| | Lucke et al. (2009) – aversive response | SEL 145 dB re 1 µPa$^2$s | >1,000 km |
| | Lucke et al. (2009) – aversive response | $SPL_{pp}$ 174 dB re 1 µPa | 256 km |
| | Level B harassment | 160 $SPL_{rms}$ | 309 km |

## 3.1.4 Summary

### 3.1.4.1 Disturbance threshold

There is no disturbance threshold available that has been validated for UXOs of large charge size and measured at large ranges. Therefore, none of the disturbance thresholds presented here are ideal. Table 4 summarises the pros and cons of each disturbance threshold, and highlights that neither the Lucke et al. (2009) threshold nor the Level B harassment threshold are considered suitable for the purpose of predicting disturbance from large UXO charge sizes. There are issues with the EDR approach, such that the 26 km EDR should be used with caution and is currently only advised for harbour porpoise. Therefore, the TTS-onset threshold is considered the most suitable for all marine mammal species, though it is acknowledged that it is an indirect measure of disturbance. It is recommended that as we continue to understand more about how sound loses its impulsive characteristics with distance, that this is incorporated into the threshold as and when the required data are available.

**Table 4 Pros and Cons for the disturbance thresholds available**

| Threshold | Pros | Cons | Recommendation |
|---|---|---|---|
| 26 km EDR | Easy to implement | Derived from monopile data (1,000s pulses over hours) which is not a comparable sound type to a one-off explosive<br>Does not consider UXO charge size/ source level/ propagation conditions | To be used with caution, considering the cons. |

| | | | |
|---|---|---|---|
| | | Currently only advised for porpoise | |
| TTS-onset Southall et al. (2019a) | Thresholds available for all species<br>Thresholds available for impulsive as well as non-impulsive noise | Not a behavioural response per se | Suitable as an indirect measure to assess disturbance from UXO clearance for all species, consider the use of non-impulsive noise threshold at longer ranges once evidence available |
| Lucke et al. (2009) | Derived from single pulse exposure to explosions emitted by an airgun | Response measured at short distances – sound characteristics will change with propagation and response will decrease | Not suitable when obtaining longer distance impact ranges |
| Level B | Threshold available for all species | Derived from seismic survey data (multiple pulses over minutes) which is not a comparable sound type to a one-off explosive | Not suitable, or to be used with caution, considering the cons |

#### 3.1.4.2 Noise propagation

Currently there is a lack of underwater noise propagation models that are suitable for large UXO charge sizes, measured at large distances and in deeper waters. The only viable option available at this time is to use the Soloway and Dahl (2014) equations with the additional attenuation correction, as used by Subacoustech. Going forward, there is a pressing need to collate empirically measured data on sound levels from a range of UXO charge sizes, at a range of distances and in a range of water depths in order to improve models for future use.

#### 3.1.4.3 AyM UXO assessment

In the absence of agreed thresholds to assess the potential for behaviour disturbance in marine mammals from UXO detonations, the AyM impact assessment will present results for each of the following behavioural disturbance thresholds:

1. 26 km EDR
2. TTS-onset thresholds

While SMRU Consulting acknowledges that there is no empirical data to validate these thresholds as appropriate for behavioural disturbance from UXO detonations, these thresholds do cover our understanding of the range of potential behavioural responses from impulsive sound sources, and as such, provide the best indication as to the potential level of impact.

It is important for the impact assessment to acknowledge that our understanding of the effect of disturbance from UXO detonation is very limited, and as such the assessment can only provide an indication of the number of animals potentially at risk of disturbance given the limited evidence available.

In the estimation of noise impact ranges for high-order disposal of UXOs, it is not possible to take into account a range of variables such as UXO design, composition, age, condition, orientation, or whether the UXO is covered by sediment. Therefore, any assessment of potential impact provide only an indication of the noise output from each detonation, but are subject to uncertainty. Estimates are precautionary, as they assume the worst-case scenario: that the UXO is not buried, degraded or subject to any other significant departure from its original condition. The estimates also assume a worst-case freely suspended charge, and that the blast from the main and donor charges are combined.

# 4 TTS Assessment

It is recognised that TTS is a temporary impairment of an animal's hearing ability with potential consequences for the animal's ability to escape predation, forage and/or communicate, supporting the statement of Kastelein et al. (2012c) that "*the magnitude of the consequence is likely to be related to the duration and magnitude of the TTS*". An assessment of the impact based on the TTS thresholds as currently given in Southall et al. (2019a) (or the former NMFS (2016) guidelines and Southall et al. (2007) guidance) would lead to a substantial overestimate of the potential impact of TTS. Furthermore, the prediction of TTS impact ranges, based on the sound exposure level (SEL) thresholds, are subject to the same inherent uncertainties as those for PTS, and in fact the uncertainties may be considered to have a proportionately larger effect on the prediction of TTS. These concepts are explained in detail below based on the thresholds detailed by Southall et al. (2019a), as these are based upon the most up-to-date scientific knowledge.

It is SMRU Consulting's expert opinion that basing any impact assessment on the impact ranges for TTS using current TTS thresholds would overestimate the potential for an ecologically significant effect. This is because the species-specific TTS-thresholds in Southall et al. (2019a) describe those thresholds at which the onset of TTS is observed, which is, per their definition, a 6 dB shift in the hearing threshold, usually measured four minutes after sound exposure, which is considered as "*the minimum threshold shift clearly larger than any day-to-day or session-to-session variation in a subject's normal hearing ability*", and which "*is typically the minimum amount of threshold shift that can be differentiated in most experimental conditions*". The time hearing recovers back to normal (the recovery time) for such small threshold shifts is expected to be less than an hour, and therefore unlikely to cause any major consequences for an animal.

A large shift in the hearing threshold near to values that may cause PTS may however require multiple days to recover (Finneran 2015). For TTS induced by steady-state tones or narrowband noise, Finneran (2015) describes a logarithmic relationship between recovery rate and recovery time, expressed in dB/decade (with a decade corresponding to a ratio of 10 between two time intervals, resulting in steps of 10, 100, 1000 minutes and so forth): For an initial shift of 5 to 15 dB above hearing threshold, TTS reduced by 4 to 6 dB per decade for dolphins, and 4 to 13 dB per decade for harbour porpoise and harbour seals. Larger initial TTS tend to result in faster recovery rates, although the total time it takes to recover is usually longer for larger initial shifts (summarised in Finneran 2015). While the rather simple logarithmic function fits well for exposure to steady-state tones, the relationship between recovery rate and recovery time might be more complex for more complex broadband sound, such as that produced by pile driving noise.

For small threshold shifts of 4 to 5 dB caused by pulsed noise, Kastelein et al. (2016) demonstrated that porpoises recovered within one hour from TTS. While the onset of TTS has been experimentally validated, the determination of a threshold shift that would cause a longer term recovery time and is therefore potentially ecologically significant, is complex and associated with much uncertainty.

The degree of TTS and the duration of recovery time that may be considered severe enough to lead to any kind of energetic or fitness consequences for an individual, is currently undetermined, as is how many individuals of a population can suffer this level of TTS before it may lead to population consequences. There is currently no set threshold for the onset of a biologically meaningful TTS, and this threshold is likely to be well above the TTS-onset threshold, leading to smaller impact ranges (and consequently much smaller impact areas, considering a squared relationship between area and range) than those obtained for the TTS-onset threshold. One has to bear in mind that the TTS-onset thresholds as recommended first by Southall et al. (2007) and further revised by Southall et al. (2019a) were determined as a means to be able to determine the PTS-onset thresholds and represents the smallest measurable degree of TTS above normal day to day variation. A direct determination of PTS-onset thresholds would lead to an injury of the experimental animal and is therefore considered as unethical. Guidelines such as National Academies of Sciences Engineering and Medicine (2016) and Southall et al. (2007) therefore rely on available data from humans and other terrestrial mammals that indicate that a shift in the hearing threshold of 40 dB may lead to the onset of PTS.

For pile driving for offshore wind farm foundations, the TTS and PTS-onset thresholds for impulsive sound are the appropriate thresholds to consider. These consist of a dual metric, a threshold for the peak sound pressure associated with each individual hammer strike, and one for the cumulative sound exposure level ($SEL_{cum}$), for which the sound energy over successive strokes is summated. The $SEL_{cum}$ is based on the assumption that each unit of sound energy an animal is exposed to leads to a certain amount of threshold shift once the cumulated energy raises above the TTS-onset threshold. For impulsive sound, the threshold shift that is predicted to occur is 2.3 dB per dB noise received; for non-impulsive sound this rate is smaller (1.6 dB per dB noise) (Southall et al. 2007).

The $SEL_{cum}$ thresholds were determined with the assumption that:

a) the amount of sound energy an animal is exposed to within 24 hours will have the same effect on its auditory system, regardless of whether it is received all at once or in several smaller units spread over a longer period (called the equal-energy hypothesis), and

b) the sound keeps its impulsive character regardless of the distance to the sound source.

Both assumptions lead to a conservative determination of the impact ranges, as the magnitude of TTS induced might be influenced by the time interval in-between successive pulses, with some time for TTS recovery in-between pulses (e.g., Finneran et al. 2010b, Kastelein et al. 2014), therefore recovery may be possible in the gaps between individual pile strikes and in any short breaks in piling activity. Additionally, an impulsive sound will eventually lose its impulsive character while propagating through the water column, therefore becoming non-impulsive (as described in NMFS 2016, Hastie et al. 2019, Southall et al. 2019a), and then causing a smaller rate of threshold shift (see above). Modelling the $SEL_{cum}$ impact ranges of PTS with a 'fleeing animal' model (as is typical during in noise impact assessments) are subject to both of these precautions. Modelling the $SEL_{cum}$ TTS impact ranges will inherit the same uncertainties, however, over a longer period of time, and over greater ranges as the TTS impact ranges are expected to be larger than those of PTS. Therefore, these uncertainties and conservativisms will have a relatively larger effect on predictions of TTS ranges.

It is also important to bear in mind that the quantification of any impact ranges in the environmental assessment process, is done so as to inform an assessment of the potential magnitude and significance of an impact. Because the TTS thresholds are not universally used to indicate a level of biologically meaningful impact of concern per se but are used to enable the prediction of where PTS might occur, it would be very challenging to use them as the basis of any assessment of impact significance.

All the data that exists on auditory injury in marine mammals is from studies of TTS and not PTS. SMRU Consulting agrees with the studies' conclusion that we may be more confident in our prediction of the range at which any TTS may occur. However, this is not necessarily very useful for the impact assessment process. We accept that scientific understanding of the degree of exposure required to elicit TTS may be more empirically based than our ability to predict the degree of sound required to elicit PTS, it does not automatically follow that our ability to determine the consequences of a stated level of TTS for individuals is any more certain than our ability to determine the consequences of a stated level of PTS for individuals. It could even be argued that we are more confident in our ability to predict the consequences of a permanent effect than we are to predict the consequences of a temporary effect of variable severity and uncertain duration.

It is important to consider that predictions of PTS and TTS are linked to potential changes in hearing sensitivity at particular hearing frequencies, which for piling noise are generally thought to occur in the 2-10 kHz range and are not considered to occur across the whole frequency spectrum. Studies have shown that exposure to impulsive pile driving noise induces TTS in a relatively narrow frequency band in harbour porpoise and harbour seals (reviewed in Finneran 2015), with statistically significant TTS occurring at 4 and 8 kHz (Kastelein et al. 2016) and centred at 4 kHz (Kastelein et al. 2012a, Kastelein et al. 2012b, Kastelein et al. 2013b, Kastelein et al. 2017). Our understanding of the consequences of PTS within this frequency range to an individual's survival and fecundity is limited, and therefore our ability to predict and assess the consequences of TTS of variable severity and duration is even more difficult to do.

The ranges that indicate TTS-onset were modelled and are presented in this impact assessment (Table 5). However, as TTS-onset is defined primarily as a means of predicting PTS-onset, there is currently no threshold for TTS-onset that would indicate a biologically significant amount of TTS; therefore it was not possible to carry out a quantitative assessment of the magnitude or significance of the impact of TTS on marine mammals. This approach has been agreed with Natural England, the MMO and CEFAS and, as such, recent projects have not presented an assessment of magnitude, sensitivity or resulting significance for TTS-onset (for example, Hornsea Three EIA, Hornsea Four PEIR, Rampion 2 PEIR). In addition to this, the Scottish SNCBs do not require the assessment of TTS-onset in marine mammal EIAs.

Table 5 TTS-onset thresholds for impulsive noise (from Southall et al 2019).

| HEARING GROUP | SPECIES | CUMULATIVE TTS ($SEL_{CUM}$ dB re 1 $\mu Pa^2s$ weighted) | INSTANTANEOUS TTS ($SPL_{PEAK}$ dB re 1 µPa unweighted) |
|---|---|---|---|
| VHF Cetacean | Harbour porpoise | 140 | 196 |
| HF Cetacean | Bottlenose & Risso's dolphin | 170 | 224 |
| LF Cetacean | Minke whale | 168 | 213 |
| Phocid | Grey seal | 170 | 212 |

# 5 References

Ainslie, M. A., and J. G. McColm. 1998. A simplified formula for viscous and chemical absorption in sea water. The Journal of the Acoustical Society of America **103**:1671-1672.

Blix, A., and L. Folkow. 1995. Daily energy expenditure in free living minke whales. Acta Physiologica Scandinavica **153**:61-66.

Brand, A. M. 2021. Explosives Use in Decommissioning—Guide for Assessment of Risk (EDGAR): II Determination of Sound Exposure Levels for Open Water Blasts and Severance of Conductors and Piles from below the Seabed. Modelling **2**:534-554.

Brandt, M. J., A. Diederichs, K. Betke, and G. Nehls. 2011. Responses of harbour porpoises to pile driving at the Horns Rev II offshore wind farm in the Danish North Sea. Marine Ecology Progress Series **421**:205-216.

Brandt, M. J., A.-C. Dragon, A. Diederichs, M. A. Bellmann, V. Wahl, W. Piper, J. Nabe-Nielsen, and G. Nehls. 2018. Disturbance of harbour porpoises during construction of the first seven offshore wind farms in Germany. Marine Ecology Progress Series **596**:213-232.

Dähne, M., A. Gilles, K. Lucke, V. Peschko, S. Adler, K. Krugel, J. Sundermeyer, and U. Siebert. 2013. Effects of pile-driving on harbour porpoises (*Phocoena phocoena*) at the first offshore wind farm in Germany. Environmental Research Letters **8**.

Dähne, M., J. Tougaard, J. Carstensen, A. Rose, and J. Nabe-Nielsen. 2017. Bubble curtains attenuate noise from offshore wind farm construction and reduce temporary habitat loss for harbour porpoises. Marine Ecology Progress Series **580**:221-237.

De Jong, C. A. f., and M. A. Ainslie. 2008. Underwater radiated noise due to the piling for the Q7 Offshore Wind Park. Journal of the Acoustical Society of America **123**:2987.

Donovan, C. R., C. M. Harris, L. Milazzo, J. Harwood, L. Marshall, and R. Williams. 2017. A simulation approach to assessing environmental risk of sound exposure to marine mammals. Ecology and Evolution.

Dunlop, R. A., M. J. Noad, R. D. McCauley, L. Scott-Hayward, E. Kniest, R. Slade, D. Paton, and D. H. Cato. 2017. Determining the behavioural dose–response relationship of marine mammals to air gun noise and source proximity. Journal of Experimental Biology **220**:2878-2886.

Finneran, J. J. 2015. Noise-induced hearing loss in marine mammals: A review of temporary threshold shift studies from 1996 to 2015. The Journal of the Acoustical Society of America **138**:1702-1726.

Finneran, J. J., D. A. Carder, C. E. Schlundt, and R. L. Dear. 2010a. Growth and recovery of temporary threshold shift at 3 kHz in bottlenose dolphins: Experimental data and mathematical models. The Journal of the Acoustical Society of America **127**:3256-3266.

Finneran, J. J., D. A. Carder, C. E. Schlundt, and R. L. Dear. 2010b. Temporary threshold shift in a bottlenose dolphin (*Tursiops truncatus*) exposed to intermittent tones. Journal of the Acoustical Society of America **127**:3267-3272.

Finneran, J. J., D. A. Carder, C. E. Schlundt, and S. H. Ridgway. 2005. Temporary threshold shift in bottlenose dolphins (Tursiops truncatus) exposed to mid-frequency tones. The Journal of the Acoustical Society of America **118**:2696-2705.

Goley, G. S., W. J. Song, and J. H. Kim. 2011. Kurtosis corrected sound pressure level as a noise metric for risk assessment of occupational noises. The Journal of the Acoustical Society of America **129**:1475-1481.

Graham, I. M., A. Farcas, N. D. Merchant, and P. Thompson. 2017. Beatrice Offshore Wind Farm: An interim estimate of the probability of porpoise displacement at different unweighted single-pulse sound exposure levels. Prepared by the University of Aberdeen for Beatrice Offshore Windfarm Ltd.

Graham, I. M., N. D. Merchant, A. Farcas, T. R. C. Barton, B. Cheney, S. Bono, and P. M. Thompson. 2019. Harbour porpoise responses to pile-driving diminish over time. Royal Society Open Science **6**:190335.

Hamernik, R. P., W. Qiu, and B. Davis. 2007. Hearing loss from interrupted, intermittent, and time varying non-Gaussian noise exposure: The applicability of the equal energy hypothesis. The Journal of the Acoustical Society of America **122**:2245-2254.

Hastie, G., N. D. Merchant, T. Götz, D. J. Russell, P. Thompson, and V. M. Janik. 2019. Effects of impulsive noise on marine mammals: investigating range-dependent risk. Ecological Applications **29**:e01906.

Henderson, D., M. Subramaniam, M. A. Gratton, and S. S. Saunders. 1991. Impact noise: the importance of level, duration, and repetition rate. The Journal of the Acoustical Society of America **89**:1350-1357.

JNCC, Natural England, and DAERA. 2020. Guidance for assessing the significance of noise disturbance against Conservation Objectives of harbour porpoise SACs (England, Wales & Northern Ireland). Report No. 654, JNCC, Peterborough.

Kastak, D., M. Holt, C. Kastak, B. Southall, J. Mulsow, and R. Schusterman. 2005. A voluntary mechanism of protection from airborne noise in a harbor seal. Page 148 *in* 16th Biennial Conference on the Biology of Marine Mammals. San Diego CA.

Kastelein, R. A., R. Gransier, and L. Hoek. 2013a. Comparative temporary threshold shifts in a harbor porpoise and harbor seal, and severe shift in a seal (L). Journal of the Acoustical Society of America **134**:13-16.

Kastelein, R. A., R. Gransier, L. Hoek, and C. A. de Jong. 2012a. The hearing threshold of a harbor porpoise (Phocoena phocoena) for impulsive sounds (L). Journal of the Acoustical Society of America **132**:607-610.

Kastelein, R. A., R. Gransier, L. Hoek, A. Macleod, and J. M. Terhune. 2012b. Hearing threshold shifts and recovery in harbor seals (*Phoca vitulina*) after octave-band noise exposure at 4 kHz. Journal of the Acoustical Society of America **132**:2745-2761.

Kastelein, R. A., R. Gransier, L. Hoek, and J. Olthuis. 2012c. Temporary threshold shifts and recovery in a harbor porpoise (*Phocoena phocoena*) after octave-band noise at 4kHz. Journal of the Acoustical Society of America **132**:3525-3537.

Kastelein, R. A., R. Gransier, L. Hoek, and M. Rambags. 2013b. Hearing frequency thresholds of a harbor porpoise (*Phocoena phocoena*) temporarily affected by a continuous 1.5 kHz tone. Journal of the Acoustical Society of America **134**:2286-2292.

Kastelein, R. A., L. Helder-Hoek, J. Covi, and R. Gransier. 2016. Pile driving playback sounds and temporary threshold shift in harbor porpoises (Phocoena phocoena): Effect of exposure duration. The Journal of the Acoustical Society of America **139**:2842-2851.

Kastelein, R. A., L. Helder-Hoek, S. Van de Voorde, A. M. von Benda-Beckmann, F.-P. A. Lam, E. Jansen, C. A. de Jong, and M. A. Ainslie. 2017. Temporary hearing threshold shift in a harbor porpoise (Phocoena phocoena) after exposure to multiple airgun sounds. The Journal of the Acoustical Society of America **142**:2430-2442.

Kastelein, R. A., L. Hoek, R. Gransier, M. Rambags, and N. Claeys. 2014. Effect of level, duration, and inter-pulse interval of 1-2 kHz sonar signal exposures on harbor porpoise hearing. The Journal of the Acoustical Society of America **136**:412-422.

Lucke, K., U. Siebert, P. A. Lepper, and M. Blanchet. 2009. Temporary shift in masked hearing thresholds in a harbor porpoise (*Phocoena phocoena*) after exposure to siesmic airgun stimuli. Journal of the Acoustical Society of America **125**:4060-4070.

Martin, B., K. Lucke, and D. Barclay. 2020. Techniques for distinguishing between impulsive and non-impulsive sound in the context of regulating sound exposure for marine mammals. The Journal of the Acoustical Society of America **147**:2159-2176.

Mooney, T. A., P. E. Nachtigall, M. Breese, S. Vlachos, and W. W. Au. 2009. Predicting temporary threshold shifts in a bottlenose dolphin (Tursiops truncatus): The effects of noise level and duration. The Journal of the Acoustical Society of America **125**:1816-1826.

Nabe-Nielsen, J., F. van Beest, V. Grimm, R. Sibly, J. Teilmann, and P. M. Thompson. 2018. Predicting the impacts of anthropogenic disturbances on marine populations. Conservation Letters **e12563**.

National Academies of Sciences Engineering and Medicine. 2016. Approaches to Understanding the Cumulative Effects of Stressors on Marine Mammals. Washington, DC: The National Academies Press.

NMFS. 1995. Small takes of marine mammals incidental to specified activities; offshore seismic activities in southern California. Federal Register. 60(200), 53753-53760.

NMFS. 2005. Scoping Report for NMFS EIS for the National Acoustic Guidelines on Marine Mammals. National Marine Fisheries Service.

NMFS. 2016. Technical Guidance for Assessing the Effects of Anthropogenic Sound on Marine Mammal Hearing: Underwater Acoustic Thresholds for Onset of Permanent and Temporary Threshold Shifts. Page 189. U.S. Department of Commerce, Silver Spring.

NMFS. 2018. Revisions to: Technical Guidance for Assessing the Effects of Anthropogenic Sound on Marine Mammal Hearing (Version 2.0): Underwater Thresholds for Onset of Permanent and Temporary Threshold Shifts. Page 167. U.S. Department of Commerce, NOAA, Silver Spring.

Otani, S., Y. Naito, A. Kato, and A. Kawamura. 2000. Diving behavior and swimming speed of a free-ranging harbor porpoise, *Phocoena phocoena*. Marine Mammal Science **16**:811-814.

Sinclair, R., S. Kazer, M. Ryder, P. New, and U. Verfuss. 2021. Review and recommendations on assessment of noise disturbance for marine mammals. NRW Evidence Report No. 529.

Soloway, A. G., and P. H. Dahl. 2014. Peak sound pressure and sound exposure level from underwater explosions in shallow water. The Journal of the Acoustical Society of America **136**:EL218-EL223.

Southall, B. 2021. Evolutions in Marine Mammal Noise Exposure Criteria. Acoustics Today **17**.

Southall, B., J. J. Finneran, C. Reichmuth, P. E. Nachtigall, D. R. Ketten, A. E. Bowles, W. T. Ellison, D. Nowacek, and P. Tyack. 2019a. Marine Mammal Noise Exposure Criteria: Updated Scientific Recommendations for Residual Hearing Effects. Aquatic Mammals **45**:125-232.

Southall, B. L., A. E. Bowles, W. T. Ellison, J. J. Finneran, R. L. Gentry, C. R. J. Greene, D. Kastak, D. R. Ketten, J. H. Miller, P. E. Nachtigall, W. J. Richardson, J. A. Thomas, and P. L. Tyack. 2007. Marine mammal noise exposure criteria: initial scientific recommendations. Aquatic Mammals **33**:411-414.

Southall, B. L., S. L. Deruiter, A. Friedlaender, A. K. Stimpert, J. A. Goldbogen, E. Hazen, C. Casey, S. Fregosi, D. E. Cade, A. N. Allen, C. M. Harris, G. Schorr, D. Moretti, S. Guan, and J. Calambokidis. 2019b. Behavioral responses of individual blue whales (Balaenoptera musculus) to mid-frequency military sonar. The Journal of Experimental Biology **222**:jeb190637.

Southall, B. L., D. P. Nowacek, A. E. Bowles, V. Senigaglia, L. Bejder, and P. L. Tyack. 2021. Marine Mammal Noise Exposure Criteria: Assessing the severity of marine mammal behavioral responses to human noise. Aquatic Mammals **47**:421-464.

Tyack, P., and L. Thomas. 2019. Using dose–response functions to improve calculations of the impact of anthropogenic noise. Aquatic Conservation Marine and Freshwater Ecosystems. **29(S1)**:242-253.

van Beest, F. M., J. Nabe-Nielsen, J. Carstensen, J. Teilmann, and J. Tougaard. 2015. Disturbance Effects on the Harbour Porpoise Population in the North Sea (DEPONS): Status report on model development.

von Benda-Beckmann, A. M., G. Aarts, H. Ö. Sertlek, K. Lucke, W. C. Verboom, R. A. Kastelein, D. R. Ketten, R. van Bemmelen, F.-P. A. Lam, and R. J. Kirkwood. 2015. Assessing the impact of underwater clearance of unexploded ordnance on harbour porpoises (*Phocoena phocoena*) in the southern North Sea. Aquatic Mammals **41**:503.

Ward, W. D. 1997. Effects of high-intensity sound. Pages 1497-1507 *in* M. J. Crocker, editor. Encyclopedia of acoustics. John Wiley & Sons, New York.

Fferm Wynt Alltraeth
AWEL Y MÔR
Offshore Wind Farm

RWE Renewables UK
Swindon Limited

Windmill Hill Business Park
Whitehill Way
Swindon
Wiltshire SN5 6PB
T +44 (0)8456 720 090
**www.rwe.com**

Registered office:
RWE Renewables UK
Swindon Limited
Windmill Hill Business Park
Whitehill Way
Swindon