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Criteria and Thresholds for U.S. Navy Acoustic and Explosive Effects Analysis

J. J. Finneran and A. K. Jenkins
SSC Pacific

SSC Pacific

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OPNAV Recommended Phase II Threshold Criteria, dated 20 January 2012.

Marine Mammal and Sea Turtle Criteria and Thresholds for Navy Effects Analyses, dated August 2010

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ACRONYMS AND ABBREVIATIONS

dB	decibel
dB re 1 μPa	decibels referenced to 1 microPascal
dB re 1 $\mu\text{Pa}^2\cdot\text{s}$	decibels referenced to 1 microPascal- squared – seconds
GI	gastrointestinal
HF	high-frequency
Hz	hertz
kHz	kilohertz
LF	low-frequency
MF	mid-frequency
psi	pounds per square inch
PTS	permanent threshold shift
SEL	sound exposure level
SPL	sound pressure level
TM	tympanic membrane
TTS	temporary threshold shift

1 INTRODUCTION

The U.S. Navy is required to assess the potential impacts to marine species from training and testing activities to remain in compliance with a suite of Federal environmental laws and regulations including, but not limited to, the Marine Mammal Protection Act, Endangered Species Act, and the National Environmental Policy Act. In cases where these activities introduce high-levels of sound or explosive energy into the marine environment, an effects analysis must be conducted. The acoustic effects analysis begins with mathematical modeling to predict the sound transmission patterns from Navy sources. These data are then coupled with marine species distribution and abundance data to determine the sound levels likely to be received by various marine species. Finally, criteria and thresholds are applied to estimate the specific effects that animals exposed to Navy-generated sound may experience.

Sounds produced from naval activities can be divided into seven categories: (1) Sonars and other active acoustic sources; (2) Explosive detonations; (3) Ship noise; (4) Aircraft noise; (5) Gunfire and other launch noise; (6) Pile driving; and (7) Airguns. This report summarizes the criteria and thresholds for marine mammals and sea turtles exposed to underwater explosive detonations and sonars and other acoustic sources. Pile driving and seismic airguns, although impulsive sources, lack the potential for shock wave generation and are therefore not treated as explosives, but rather rely on unique criteria and thresholds agreed upon by Navy and NMFS. The criteria and thresholds for pile driving and airguns are therefore not included in this document.

2 CRITERIA AND THRESHOLDS FOR MARINE MAMMALS

2.1 INTRODUCTION

The criteria and thresholds for marine mammals are similar to those proposed by Southall et al. (2007): Marine mammal species are divided into a number of functional hearing groups, with all species in the same group assumed to be equally susceptible to noise. Within each functional hearing group, auditory weighting functions are used to emphasize frequencies where sensitivity to noise is high and de-emphasize frequencies where sensitivity is low. Individual criteria and thresholds are defined for explosive and (non-explosive) acoustic sources. The criteria and thresholds presented here for explosive sources are similar to those proposed by Southall et al. (2007) for impulsive sources, and the criteria and thresholds presented here for acoustic sources are similar to the Southall et al. (2007) non-impulsive criteria.

2.2 FUNCTIONAL HEARING GROUPS

To facilitate the acoustic and explosive effects analyses, marine mammals are divided into eight functional hearing groups, and the same criteria and thresholds are used for all species within a group. Species were grouped by considering their known or suspected auditory sensitivity, ear anatomy, and acoustic ecology (i.e., how they use sounds), as has been done previously (e.g., Ketten, 2000; Southall *et al.*, 2007). Appendix A summarizes the specific families and subfamilies contained in each functional hearing group.

2.2.1 Low-frequency (LF) cetaceans

Low-frequency cetaceans include all of the mysticetes.

No direct measurements of hearing sensitivity in any LF cetacean are available. Sensitivity to LF sound by baleen whales has been inferred from observed vocalization frequencies, observed reactions to playback of sounds, and anatomical analyses of the auditory system (Houser et al., 2001; Parks et al., 2007). Baleen whales are estimated to hear from 15 Hz – 20 kHz, with good sensitivity from 20 Hz – 2 kHz (Ketten, 1998). Mathematical models of the humpback whale's ear developed from anatomical features and optimization techniques (Houser *et al.*, 2001) suggest that humpbacks are sensitive to frequencies between 40 Hz and 16 kHz, but best sensitivity is likely to occur between 100 Hz and 8 kHz. Based on these data, functional hearing limits for LF cetaceans are defined as 7 Hz – 22 kHz.

2.2.2 Mid-frequency (MF) cetaceans

Mid-frequency cetaceans include most delphinid species (e.g., bottlenose dolphin, common dolphin, killer whale, pilot whale; see high-frequency cetacean list for exceptions), beaked whales, bottlenose whales, and sperm whales (but not pygmy and dwarf sperm whales of the genus *Kogia*, which are treated as high-frequency species).

Hearing sensitivity has been directly measured for a number of species within this group, including Atlantic bottlenose dolphins (Johnson, 1967), belugas (Finneran et al., 2005; White, 1977), Indo-Pacific bottlenose dolphins (Houser et al., 2008), Black Sea bottlenose dolphins

(Popov et al., 2007), striped dolphins (Kastelein et al., 2003), white-beaked dolphins (Nachtigall et al., 2008), Risso's dolphins (Nachtigall et al., 2005), killer whales (Szymanski et al., 1999), false killer whales (Yuen et al., 2005), common dolphins (Touhey-Moore et al., unpublished), Atlantic white-sided dolphins (Touhey-Moore et al., unpublished), Gervais' beaked whales (Finneran et al., 2009), Blainville's beaked whale (Pacini et al., 2011), short-finned pilot whales (Schlundt et al., 2011), and long-finned pilot whales (Pacini et al., 2010). All audiograms exhibit the same general U-shape, with a nominal hearing range between approximately 150 Hz and up to 160 kHz; these two frequencies were used as the lower and upper cutoff frequencies for the functional hearing limits.

2.2.3 High-frequency (HF) cetaceans

High-frequency cetaceans include the porpoises (genus *Phocoena*, *Neophocaena*, *Phocoenoides*), river dolphins, *Kogia* species, and *Cephalorhynchus* species.

Hearing has been tested for harbor porpoises (Kastelein et al., 2002a), Yangtze finless porpoises (Popov et al., 2005), Amazon River dolphins (Popov and Supin, 1990b), and Tucuxi dolphins (Popov and Supin, 1990a). All audiograms exhibit the same general U-shape with nominal hearing range between 200 Hz and 180 kHz; these two frequencies were used as the lower and upper cutoff frequencies for the functional hearing limits.

2.2.4 Phocids

Phocids include all earless seals or "true seals," including the ice seals (harp, hooded, bearded, ringed, ribbon, spotted, Weddell, leopard, Ross, and crabeater seals); harbor or common seals; gray seals; inland seals (e.g., Caspian and Baikal seals); elephant seals (northern and southern); and monk seals (Hawaiian and Mediterranean). Since these animals are amphibious, separate criteria and thresholds are included for airborne and underwater exposure.

Phocid hearing limits are estimated to be 75 Hz – 30 kHz and 75 Hz – 75 kHz in air and water, respectively (Kastak and Schusterman, 1999; Kastelein et al., 2009; Møhl, 1968; Reichmuth, 2008; Terhune and Ronald, 1971; 1972).

2.2.5 Otariids and Odobenids

Otariids include all eared seals (fur seals and sea lions) and odobenids are walruses (the only extant species). Separate criteria/thresholds are included for airborne and underwater exposure. Since these animals are amphibious, separate criteria and thresholds are included for airborne and underwater exposure.

Otariid hearing limits are estimated to be 100 Hz – 35 kHz and 100 Hz – 50 kHz in air and water, respectively (Babushina et al., 1991; Kastak and Schusterman, 1998; Kastelein et al., 2005b; Moore and Schusterman, 1987; Mulsow and Reichmuth, 2007; Mulsow et al., 2011a; Mulsow et al., 2011b; Schusterman et al., 1972).

The ear morphology of the walrus is intermediate between the otariid and phocid ear; however, current data indicate that the hearing of the walrus is more similar to that of otariids (Kastelein et al., 2002c). Therefore, the hearing limits defined for otariids are also applied to walruses.

2.2.6 Mustelids

Mustelids include sea otters (in air and under water). Since these animals are amphibious, separate criteria and thresholds are included for airborne and underwater exposure.

Like the pinnipeds, sea otters are amphibious mammals in the order Carnivora. No published data are available for sea otter hearing, though it is reasonable to expect hearing ability similar to other mustelids (otters). Behavioral measures of hearing in air for two North American river otters indicate a functional hearing of approximately 450 Hz – 35 kHz (Gunn, 1988), which is similar to the in-air hearing range of otariids. Based on the limited available information and the fact that the otariid ear is very similar to the ear of other carnivores (Nummela, 2008), the functional hearing limits for otariid are used for sea otters.

2.2.7 Ursids

Ursids include polar bears (in air and under water). Since these animals are amphibious, separate criteria and thresholds are included for airborne and underwater exposure.

Like the pinnipeds and sea otters, polar bears are amphibious mammals in the order Carnivora. Hearing threshold measurements of polar bears (in air) have shown good sensitivity up to approximately 20 kHz, with a rapid decline in sensitivity above 20 kHz (Bowles et al., 2008; Nachtigall et al., 2007). Based on the limited available information and the fact that the otariid ear is very similar to the ear of other carnivores (Nummela, 2008), the functional hearing limits for otariid are used for polar bears.

2.2.8 Sirenians

Sirenians contain manatees and dugongs.

Gerstein et al. (1999) obtained behavioral audiograms for two West Indian manatees and found an underwater hearing range of approximately 400 Hz – 76 kHz, with best sensitivity around 16 – 18 kHz. Mann et al. (2009) obtained masked behavioral audiograms from two manatees; sensitivity was shown to range from 250 Hz – 90 kHz, although the detection level at 90 kHz was 80 dB above the manatee’s frequency of best sensitivity (16 kHz). This audible frequency range is similar to that of phocids (Gerstein *et al.*, 1999; Southall *et al.*, 2007), therefore the functional hearing range for phocids (75 Hz – 75 kHz) was applied to the Sirenians.

2.3 AUDITORY WEIGHTING FUNCTIONS

Human occupational noise exposure guidelines rely on numeric thresholds based on “weighted” noise levels. Weighted noise levels are calculated by applying frequency-dependent filters, or “weighting functions,” to the noise sound pressure measured in the workplace. The weighting functions are designed to emphasize frequencies (i.e., to add “weight”) where people are sensitive to noise and to de-emphasize frequencies (i.e., subtract weight) where people are not very sensitive. The weighted noise levels at each frequency are then combined to generate a single, weighted exposure value. This technique allows the use of a single, weighted threshold value, regardless of the noise frequency. The alternative would be to have a large number of individual threshold values, one for every frequency that might be encountered.

Weighting functions for humans were derived from equal loudness contours — graphs representing the sound pressure levels (SPLs) that give rise to a sensation of equal loudness magnitude in a human listener as a function of sound frequency (Suzuki and Takeshima, 2004). Equal loudness contours are in turn derived from subjective loudness experiments, where human listeners are asked to judge the relative loudness of two tones with different frequencies (e.g., Fletcher and Munson, 1933; Robinson and Dadson, 1956). For humans, the most commonly encountered weighting functions are the “A-weighting” and “C-weighting” functions. A-weighting resembles the human auditory sensitivity curve, and is the most common weighting function prescribed in noise regulations. The C-weighting curve is flatter, subtracts less energy at the extreme high and low frequencies, and better matches human sensitivity to louder sounds.

For marine mammals, several approaches have been used to define auditory weighting functions. See Appendix B for a summary of weighting functions and parameters specific for each functional hearing group.

2.3.1 Development of marine mammal auditory weighting functions

The first broadly applied marine mammal weighting functions were developed by Southall et al. (2007). Cetaceans and pinnipeds were divided into five functional hearing groups: LF cetaceans, MF cetaceans, HF cetaceans, pinnipeds in air, and pinnipeds in water. At the time, there were no equal loudness data for marine mammals. Although the use of species’ hearing sensitivities as weighting functions seems logical, existing audiograms for odontocetes typically possessed a much steeper reduction in sensitivity at low-frequencies compared to the dolphin and beluga temporary threshold shift (TTS) data, which showed little variation between 3 and 20 kHz. For these reasons, Southall et al. based their proposed weighting functions on the shape of the human “C-weighting” network, with the parameters adjusted so the weighting function shape better matched the known or suspected hearing range for each species group. The group of resulting weighting functions was referred to as the “M-weighting” functions (Southall *et al.*, 2007).

The “M-weighting” functions are described by the equation:

$$W(f) = K + 20\log_{10}\left[\frac{b^2 f^2}{(a^2 + f^2)(b^2 + f^2)}\right], \tag{1}$$

where f is the frequency (Hz), $W(f)$ is the weighting function amplitude (dB) at each frequency, a and b are constants related to the upper and lower hearing limits, respectively, and K is a constant used to normalize the equation at a particular frequency. Specific values for the constants a and b are given in Table 1 (Southall *et al.*, 2007). Figure 1 shows the resulting weighting functions. The M-weighting functions are nearly flat between the lower and upper cutoff frequencies (a and b, respectively) specified in Table 1. For this reason, they were believed to over-estimate the effects of noise at high and low frequencies and thus to be protective (Southall *et al.*, 2007).

Table 1. Parameters for the "M-weighting" functions defined by Southall et al. (2007).

Species Group	*K*	*a* (Hz)	*b* (Hz)
LF cetaceans	0	7	22,000
MF cetaceans	0	150	160,000
HF cetaceans	0	200	180,000
Pinnipeds in water	0	75	75,000
Pinnipeds in air	0	75	30,000

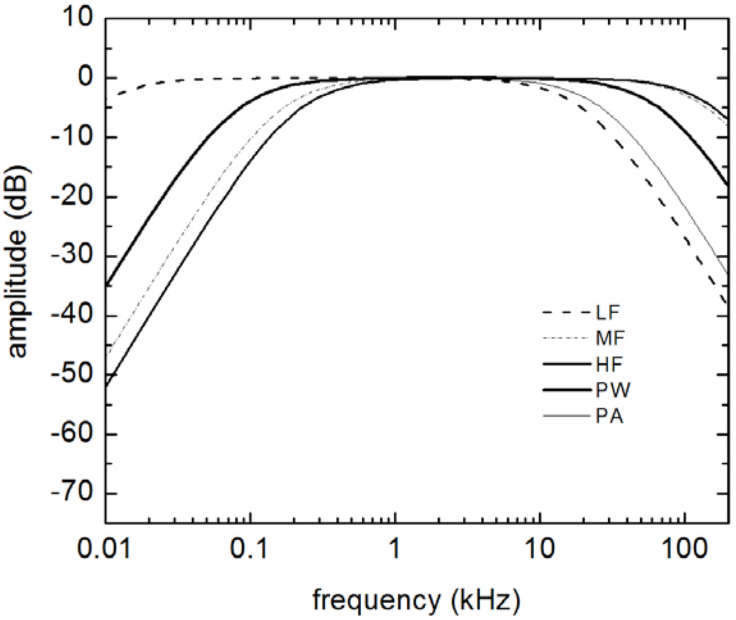

Figure 1. Marine mammal auditory weighting functions proposed by Southall et al. (2007). LF – low-frequency cetacean, MF – mid-frequency cetacean, HF – high-frequency cetacean, PW – pinnipeds in water, PA – pinnipeds in air.

The next advancement of marine mammal weighting functions occurred in 2011, when subjective loudness measurements were made with a bottlenose dolphin, the first time such an experiment has been conducted with a non-human animal (Finneran and Schlundt, 2011). From the subjective loudness data, equal loudness contours were derived, using the same procedures as those used to derive human equal loudness contours (e.g., Suzuki and Takeshima, 2004). Finally, Eq. (1) was fit to the equal loudness contour data, providing a set of auditory weighting functions. Three weighting functions based on equal loudness contours (the "EQL weighting functions") were presented by Finneran and Schlundt (2011); the functions were based on the equal loudness contours passing through 90, 105, and 115 dB re 1 μPa at 10 kHz.

Figure 2 compares the Finneran and Schlundt (2011) bottlenose dolphin EQL weighting functions with the Southall et al. (2007) M-weighting function for MF cetaceans. Also shown in Fig. 2 is the relative susceptibility to noise, based on the TTS onset data for dolphins (Finneran, 2010; Finneran and Schlundt, 2009). In contrast to the onset of TTS, which represents an exposure threshold, the hazardousness of a noise exposure can also be described by the *susceptibility* of the listener, which represents the listener's sensitivity to noise. The *relative susceptibility* is obtained by negating the onset TTS levels (in dB), then normalizing these data at some frequency. High values of susceptibility therefore indicate frequencies where noise is more hazardous. The susceptibility data can be directly compared to auditory weighting functions, which preferentially emphasize (apply larger weight to) frequencies where noise is more hazardous and de-emphasize those frequencies where noise is less hazardous. In Fig. 2, the EQL weighting functions, M-weighting function, and susceptibility data are all normalized at 3 kHz.

At frequencies above 3 kHz, the dolphin susceptibility to TTS increases (the TTS onset is lower); however, the MF cetacean weighting function proposed by Southall et al. (2007) is flat between 3 and 20 kHz and does not reflect the dependence of TTS on exposure frequency. In contrast, the EQL weighting functions predict larger effects from noise than the MF cetacean M-weighting function above 3 kHz, and better match the susceptibility data. The best fit to the susceptibility data is found with the EQL weighting function based on the 90-dB re 1 µPa equal loudness contour (adjusted $R^2 = 0.831$). Below 3 kHz, the EQL weighting functions are similar and predict increasingly lower effects compared to the MF cetacean M-weighting function. No MF cetacean TTS data exist for frequencies below 3 kHz and the equal loudness data only extend down to 2.5 kHz, therefore the accuracy of the EQL weighting functions at lower frequencies is unknown.

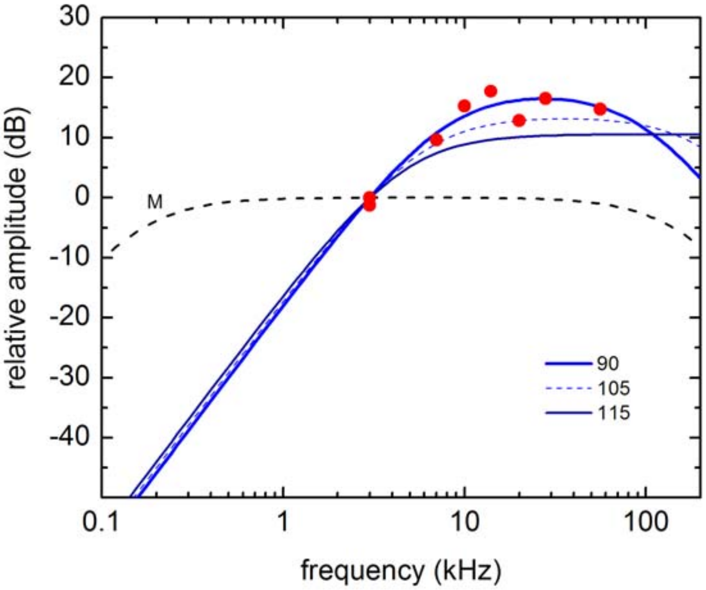

Figure 2. Comparison of dolphin auditory weighting function (solid lines), relative susceptibility to noise measured in a bottlenose dolphin (symbols), and Southall et al. mid-frequency cetacean “M-weighting” (dashed line).

2.3.1.1 Estimating EQL weighting functions for LF and HF cetaceans

Although equal loudness data only exist for bottlenose dolphins, EQL weighting functions can be estimated for other species by adjusting the parameters for Eq. (1), on a relative basis, to fit the known or suspected hearing range of each species group. This process can only be used for functional hearing groups that are closely related to the MF cetaceans (the group for whom the EQL functions exist) — the LF and HF cetaceans.

Because the frequency excitation pattern within the mammalian ear is organized logarithmically, not linearly (Ketten, 2000), the adjustment of the parameters *a* and *b* is done on a logarithmic basis. Specifically, the parameters *a* and *b* are adjusted so that the relationship, in terms of octaves, between *a* and *b* for the EQL weighting function and the functional hearing limits is preserved between the MF cetacean group and the other species groups. The extrapolation is performed using:

$$\frac{\log_2 a' - \log_2 f_L'}{\log_2 f_U' - \log_2 f_L'} = \frac{\log_2 a - \log_2 f_L}{\log_2 f_U - \log_2 f_L}, \tag{2}$$

and

$$\frac{\log_2 b' - \log_2 f_L'}{\log_2 f_U' - \log_2 f_L'} = \frac{\log_2 b - \log_2 f_L}{\log_2 f_U - \log_2 f_L}, \tag{3}$$

where *a* and *b* are the EQL weighting function parameters for MF cetaceans, *a′* and *b′* are the (extrapolated) parameters for the LF or HF species group, f_L and f_U are the lower and upper frequency limits for MF cetaceans (150 Hz and 160 kHz, respectively), and f_L' and f_U' are the lower and upper frequency limits for LF cetaceans or HF cetaceans. Taking the logarithm to the base 2 ($\log_2$) converts each frequency to octave spacing (re 1 Hz); this is done because the frequency organization of the inner ear is logarithmically spaced, not linearly (Ketten, 2000).

For low-frequency cetaceans, f_L' = 7 Hz and f_U' = 22 kHz, so application of Eqs. (2) and (3) yields a' = 674 Hz and b' = 12,130 Hz. A value of K = 0.94 is needed to normalize the peak of the curve to 0 dB.

For high-frequency cetaceans, f_L' = 200 Hz and f_U' = 180 kHz, so application of Eqs. (2) and (3) yields a' = 9,480 Hz and b' = 108,820 Hz. A value of K = 1.4 is needed to normalize the peak of the curve to 0 dB.

Parameters used to generate the LF, MF, and HF cetacean EQL weighting functions from Eq. (1) are given in Table 2. Graphs of the EQL weighting functions for the LF, MF, and HF cetaceans are shown in Fig. 3.

Table 2. Parameters for the EQL weighting functions for the LF, MF, and HF cetaceans. The MF cetacean function is based on the 90 dB re 1 μPa equal loudness contour for dolphins (Finneran and Schlundt, 2011). The LF and HF functions were extrapolated form the MF function based on the functional hearing limits for the LF and HF cetacean groups. The value of K was adjusted for each function to set the peak amplitude to 0 dB.

Functional Hearing Group	*K*	*a* (Hz)	*b* (Hz)
LF cetacean (extrapolated)	0.9	674	12,130
MF cetacean (based on dolphin 90-dB re 1 μPa equal loudness function)	1.4	7,829	95,520
HF cetacean (extrapolated)	1.4	9,480	108,820

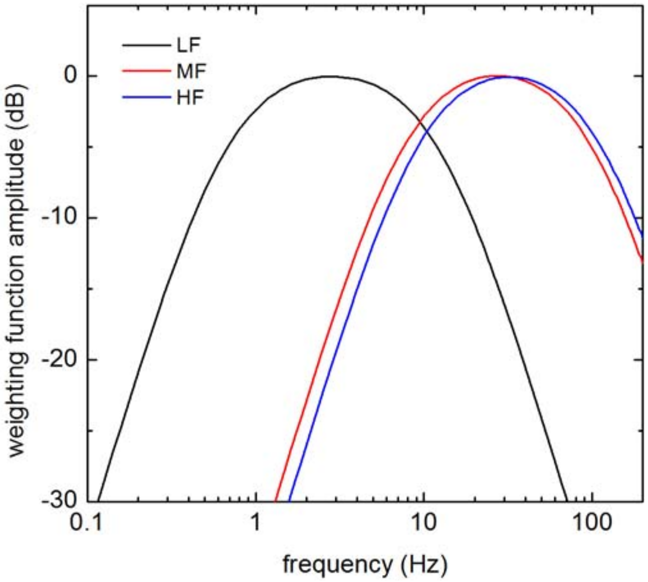

Figure 3. EQL weighting functions for the LF, MF, and HF cetaceans. The MF cetacean function is based on the 90 dB re 1 μPa equal loudness contour for dolphins (Finneran and Schlundt, 2011). The LF and HF functions were extrapolated form the MF function based on the functional hearing limits for the LF and HF cetacean groups.

2.3.2 Navy marine mammal weighting functions

Auditory weighting functions developed for Navy acoustics effects analyses utilize features of both the M-weighting functions and the EQL weighting functions. Two types of Navy weighting functions are defined: Type I weighting functions and Type II weighting functions.

Type I weighting functions are similar to the M-weighting functions and have two parameters (*a*, *b*) that define the lower and upper frequencies where the amplitude begins to decline (the "rolloff" or "cutoff" frequencies), and one parameter (*K*) that defines the amplitude of the flat portion of the curve. Type I functions are flat over a broad range of frequencies. As with the M-weighting functions, the cutoff frequencies are based on the known or estimated hearing range for each functional hearing group. The equation for the Type I weighting function is

$$W_I(f) = K + 20\log_{10}\left[\frac{b^2 f^2}{\left(a^2 + f^2\right)\left(b^2 + f^2\right)}\right], \qquad (4)$$

where $W_I(f)$ is the weighting function amplitude (in dB) at the frequency f (in Hz), and a, b, and K are constants defining the shape of the function for each functional hearing group.

Table 3 lists the parameters used to generate the Type I weighting functions from Eq. (4) for each functional hearing group defined in Section 2-2. The weighting functions are displayed in Fig. 4. The Navy Type I weighting functions for the cetaceans are identical to the Southall et al. (2007) M-weighting functions. The Type I weighting functions (in air and underwater) for the phocids are identical to the Southall et al. (2007) M-weighting functions for pinnipeds (the pinniped M-weighting functions were based on the hearing ranges for phocids seals). The Type I functions for otariids, odobenids, mustelids, ursids, and sirenians are based on the estimated functional hearing limits for these functional groups as defined in Section 2.2.

Table 3. Parameters for the Navy marine mammal Type I weighting functions.

Functional Hearing Group	*K*	*a* (Hz)	*b* (Hz)
LF cetaceans	0	7	22,000
MF cetaceans	0	150	160,000
HF cetaceans	0	200	180,000
Phocids (in water), Sirenians	0	75	75,000
Phocids (in air)	0	75	30,000
Otariids, Odobenids, Mustelids, Ursids (in water)	0	100	40,000
Otariids, Odobenids, Mustelids (in air)	0	100	30,000

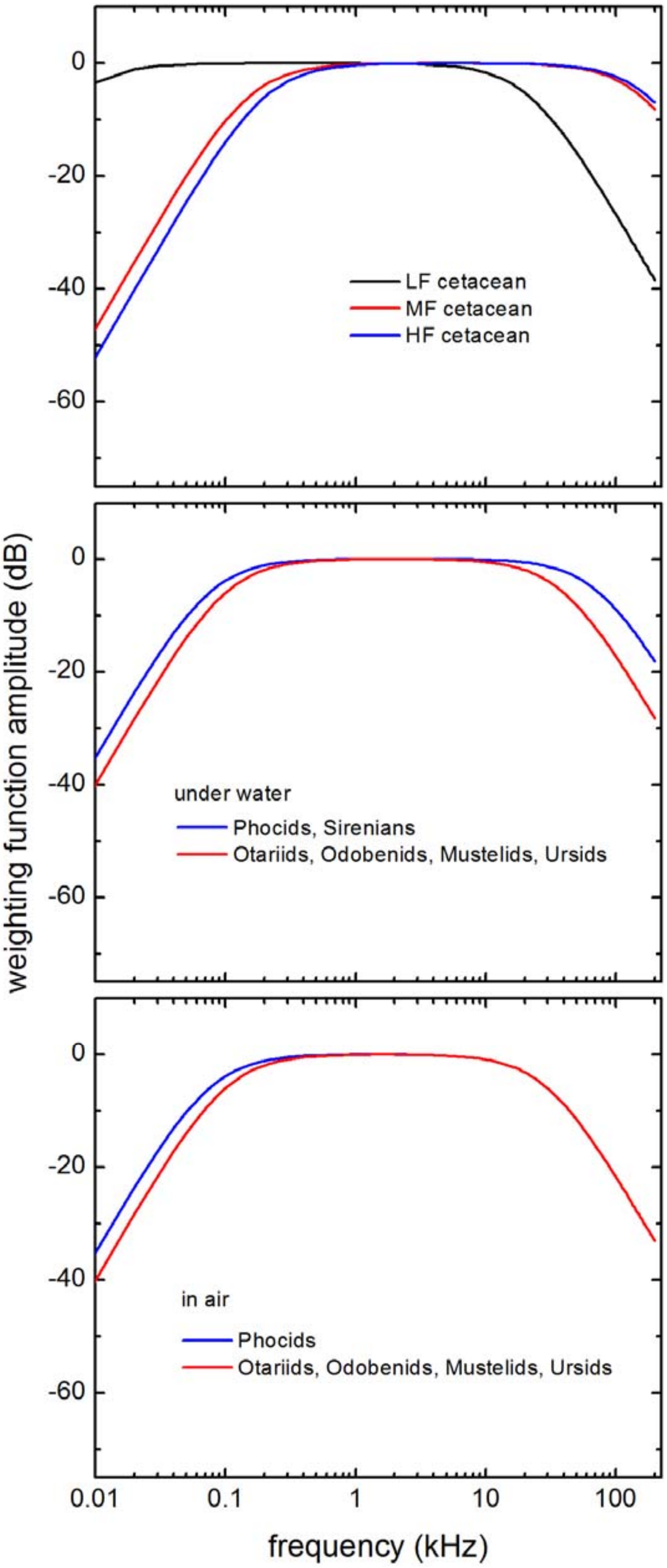

Figure 4. Navy Type I weighting functions.

Type II weighting functions modify the Type I functions (or M-weighting functions) by including a region of increased amplitude (increased susceptibility) based on the EQL weighting functions. Type II functions are only derived for the cetaceans, because the underlying data necessary for the functions are only available for bottlenose dolphins (MF cetaceans). Although TTS data exist for three pinniped species (harbor seal, California sea lion, northern elephant seal), most exposures consisted of octave band noise centered at 2.5 kHz, thus data are insufficient to either derive weighting functions in a manner analogous to that used for MF cetaceans or to verify the effectiveness of extrapolations from the MF cetacean group.

Type II functions are defined using two component curves: one based on the Type I weighting function and the other based on the EQL weighting function. At each frequency, the amplitude of the weighting function is defined using the larger value from the two component curves, as illustrated in Fig. 5. In practice, the Type I component will dominate below some frequency, denoted as the “inflection point” frequency, and the EQL component will dominate above the inflection point. The idea behind the Type II function is to enhance the Type I weighting function by accounting for the increased susceptibility to noise seen in the bottlenose dolphin TTS data at frequencies above 3 kHz. The EQL weighting functions are not used by themselves because of the uncertainty regarding the weighting function amplitude at low frequencies, below the range of the TTS and equal loudness data. The Type I function is used at lower frequencies as a protective approach since there are no TTS or equal loudness data below 2.5 – 3 kHz. The Type II weighting function represents a way to incorporate new data showing increased susceptibility to noise at higher frequencies with the broad, protective weighting functions proposed by Southall et al. (2007).

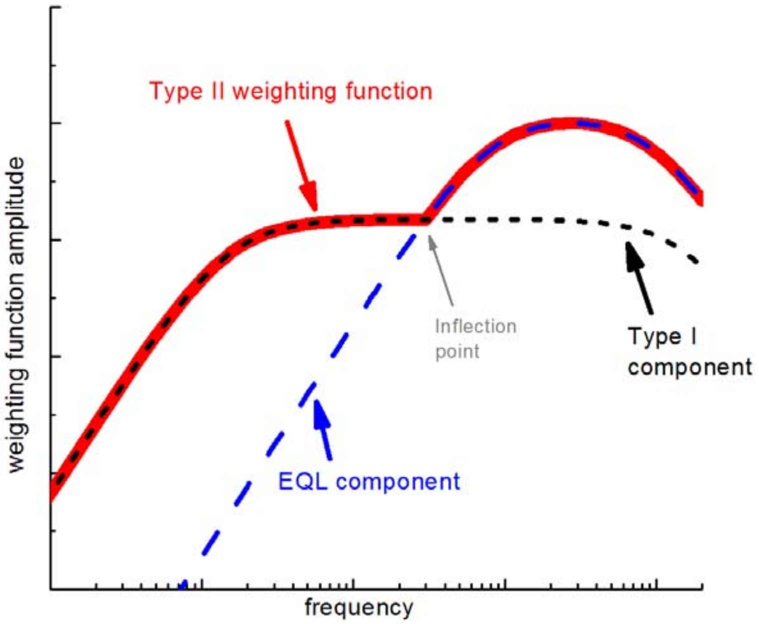

Figure 5. Illustration of the Type II weighting function concept. Below the inflection point frequency, the Type II weighting function matches the shape of the Type I function. Above the inflection point, the Type II function matches the EQL-based weighting function.

The Type II weighting functions are mathematically defined as:

$$W_{II}(f) = \text{maximum}\{G_1(f), G_2(f)\}, \tag{5}$$

where $W_{II}(f)$ is the weighting function amplitude (dB) at the frequency f (Hz),

$$G_1(f) = K_1 + 20\log_{10}\left[\frac{b_1^2 f^2}{\left(a_1^2 + f^2\right)\left(b_1^2 + f^2\right)}\right], \tag{6}$$

$$G_2(f) = K_2 + 20\log_{10}\left[\frac{b_2^2 f^2}{\left(a_2^2 + f^2\right)\left(b_2^2 + f^2\right)}\right], \tag{7}$$

the parameters a_1, b_1, and K_1 define the Type I component of the function and a_2, b_2, and K_2 define the EQL component of the function. The specific parameters for the LF, MF, and HF cetaceans are given in Table 4. Note that the values for a_1, b_1 match the parameters a and b for the Type I (and M-weighting) functions and a_2, b_2 match the parameters for the EQL weighting functions. The values for K_2 match the values for K for the EQL weighting function, so the Type II functions also have their peak amplitudes at 0 dB. The values for K_1 are adjusted from the Type I functions so that the MF and HF cetaceans have the inflection point at 3 kHz. For the LF cetaceans, K is adjusted so that the flat portion of the Type I component is 16.5 dB below the peak, identical to the value for the MF cetaceans. This places the inflection point for the LF cetacean function at 267 Hz. The Type II weighting functions are shown graphically in Fig. 6.

Table 4. Marine mammal Type II weighting function parameters for use in Eq. (5).

Functional Hearing Group	**K_1 (dB)**	**a_1 (Hz)**	**b_1 (Hz)**	**K_2 (dB)**	**a_2 (Hz)**	**b_2 (Hz)**	**Inflection point (Hz)**
LF cetaceans	-16.5	7	22,000	0.9	674	12,130	267
MF cetaceans	-16.5	150	160,000	1.4	7,829	95,520	3,000
HF cetaceans	-19.4	200	180,000	1.4	9,480	108,820	3,000

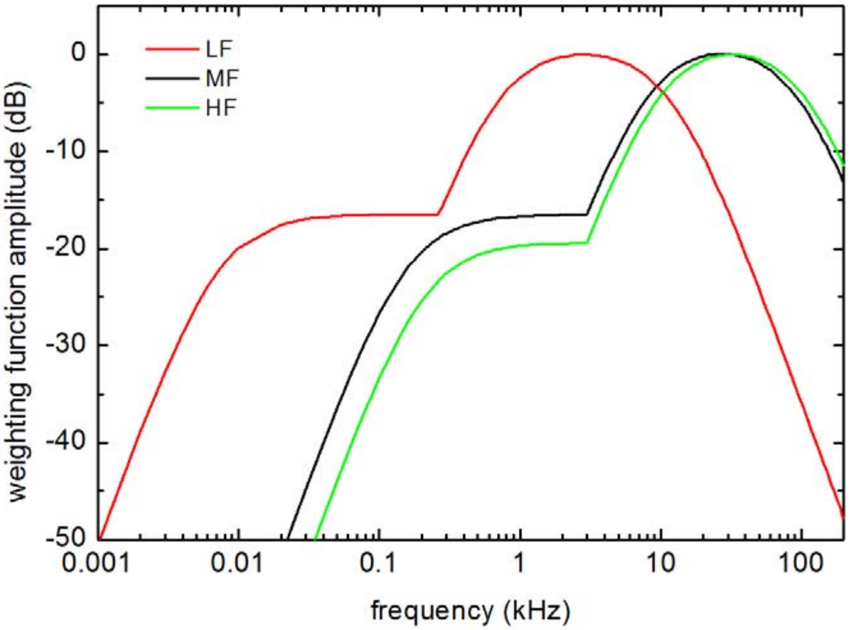

Figure 6. Navy Type II weighting functions for LF, MF, and HF cetaceans.

2.4 CRITERIA AND THRESHOLDS FOR SONARS AND OTHER ACTIVE ACOUSTIC SOURCES

2.4.1 Introduction

Criteria for marine mammals exposed to sonars and other active acoustic sources are divided into physiological effects and behavioral effects. Physiological effects criteria and thresholds are based on temporary and permanent threshold shift (TTS and PTS). Behavioral thresholds are based on observational data documenting the reactions of various marine mammal species to sound. For TTS, PTS, and behavioral responses, criteria and thresholds are provided for each functional hearing group. A summary of the various criteria and thresholds is provided in Appendix C.

2.4.2 Criteria and thresholds for TTS

TTS criteria and thresholds are based on TTS onset values obtained from representative species of MF and HF cetaceans and pinnipeds. The data obtained from MF and HF cetaceans and pinnipeds were then extrapolated to the other functional hearing groups.

Criteria for TTS are based on the sound exposure level (SEL) received by the animal. SEL is used, rather than sound pressure level (SPL), because SEL includes the effect of the exposure duration, which is a key factor is the likelihood that a noise exposure will produce TTS.

The threshold value for TTS for each functional hearing group is defined in terms of the *weighted* SEL. This means that the SEL corresponding to the onset of TTS is “weighted” by the appropriate weighting function. For cetaceans, Type II weighting functions are used for sonars and other active acoustic sources, since the EQL portion of the Type II functions are based on tonal noise exposures most closely related to sonars. For the other functional hearing groups, where Type II weighting functions do not exist, Type I functions are used instead.

For meaningful comparison to the weighted SEL threshold value, the SEL received by an animal must also be weighted by the same function. To determine if a TTS occurs, the frequency content of the SEL is first determined. The appropriate weighting function is then used to weight each frequency band. Then, the total, weighted SEL is calculated by integrating the weighted frequency content. Finally, the weighted exposure is compared to the weighted threshold value for TTS. If the weighted exposure SEL meets or exceeds the weighted SEL threshold value, then TTS is assumed to occur.

2.4.2.1 Low-Frequency Cetaceans

No direct measurements of TTS are available for any LF cetaceans. For this reason, the MF criteria and thresholds are also applied to LF cetaceans; however, exposures and threshold SEL values are weighted using the Type II LF cetacean weighting function rather than the MF cetacean function. This provides higher susceptibility to low frequency sound, consistent with the inferred frequencies of best hearing for LF cetaceans. The resulting (Type II) weighted exposure SEL for LF cetaceans is 178 dB re 1 $\mu Pa^2 \cdot s$.

2.4.2.2 Mid-Frequency Cetaceans

To date, TTS data has been collected for bottlenose dolphins and belugas, two diverse odontocetes. Both species had similar TTS thresholds (Schlundt et al., 2000). Due to the similarity in the known audiograms and TTS thresholds, the TTS thresholds for dolphins and belugas are applied to all MF cetaceans.

A number of studies have shown that an SEL of 195 dB re 1 $\mu Pa^2 \cdot s$ is a reasonable threshold for TTS in dolphins and belugas exposed to 3 kHz tones (Finneran, 2005; Finneran et al., 2010; Mooney et al., 2009; Nachtigall et al., 2004; Schlundt *et al.*, 2000). This threshold was also supported by Southall et al. (2007) as the best estimate of onset-TTS for non-impulsive noise exposure in cetaceans. For the MF cetacean Type II weighting function, the weighting function amplitude at 3 kHz is -16.5 dB. This means that the (Type II) weighted exposure SEL for MF cetaceans is 178 dB re 1 $\mu Pa^2 \cdot s$.

2.4.2.3 High-Frequency Cetaceans

At the time the Navy criteria were developed, no direct measurements of TTS were available for any HF cetacean exposed to non-impulsive sound (such as that produced by sonars). TTS thresholds for HF cetaceans were therefore based on data published by Lucke et al. (2009), who measured TTS in a harbor porpoise exposed to impulses produced by a small seismic air gun. The TTS threshold for impulsive noise obtained from the airgun TTS data was adjusted to estimate the TTS threshold for sonars and other active acoustic sources (which are non-impulsive sources) using the method outlined by Southall et al. (2007) (Type II weighted SEL = 146 dB re 1 $\mu Pa^2 \cdot s$). This method relies on the relationship between impulsive and non-impulsive TTS onset values for MF cetaceans, which means that the non-impulsive threshold is 6 dB higher than the impulsive threshold (Southall *et al.*, 2007). For the harbor porpoise, this results in a non-impulsive, (Type II) weighted TTS threshold of 152 dB re 1 $\mu Pa^2 \cdot s$.

Due to the similarities in the known audiograms, the TTS threshold derived for harbor porpoises is used for all HF cetaceans. Newly published TTS data for the Yangtze finless porpoise (Popov et al., 2011) were not directly used to derive threshold values, although this study supports the concept that the HF cetacean thresholds are significantly lower than those for the MF cetaceans. Kastelein et al. (2011) have also presented results of TTS experiments with harbor porpoise, though, at present, these data have not been published.

2.4.2.4 Phocids (in water)

TTS thresholds for phocids exposed to underwater sonars and other active acoustics are based on data reported by Kastak et al. (2005), who provided estimates of the average SEL for onset-TTS for a harbor seal, sea lion, and Northern elephant seal exposed to underwater, octave-band noise centered at 2.5 kHz. The most sensitive of the two phocids was the harbor seal, with a TTS onset threshold of 183 dB re 1 $\mu Pa^2 \cdot s$. For phocids, only a Type I weighting function is used; the weighting function amplitude at 2.5 kHz is 0 dB. This means the (Type I) weighted exposure SEL for harbor seals under water is 183 dB re 1 $\mu Pa^2 \cdot s$.

Due to the similarities in the known audiograms, and the fact that the only other phocid for whom TTS data are available had a higher TTS onset threshold (Northern elephant seal, with

TTS onset 204 dB SEL), the underwater TTS threshold for the harbor seal is used for all phocids seals. Recently, Kastelein et al. (2011) have presented results of TTS experiments with harbor seals exposed to underwater noise, though, at present, these data have not been published.

2.4.2.5 Phocids (in air)

TTS thresholds for phocids exposed to acoustic sources in-air are based on data reported by Kastak et al. (2004), who provided estimates of the average SEL for onset-TTS for a harbor seal, sea lion, and Northern elephant seal exposed to in-air, octave-band noise centered at 2.5 kHz. The most sensitive of the two phocids was the harbor seal, with a TTS onset threshold of 131 dB re (20 μPa)^2·s. For phocids, only a Type I weighting function is used; the weighting function amplitude at 2.5 kHz is 0 dB. This means the (Type I) weighted exposure SEL for harbor seals in air is 131 dB re (20 μPa)^2·s.

Due to the similarities in the known audiograms, and the fact that the only other phocid for whom TTS data are available had a higher TTS onset threshold [northern elephant seal, with TTS onset 163 dB re (20 μPa)^2·s], the in-air TTS threshold for the harbor seal is used for all phocids seals.

2.4.2.6 Otariids and odobenids (in water)

TTS thresholds for otariids exposed to underwater sonars and other active acoustics are based on data reported by Kastak et al. (2005), who provided estimates of the average SEL for onset-TTS for a harbor seal, sea lion, and Northern elephant seal exposed to underwater, octave-band noise centered at 2.5 kHz. The California sea lion TTS onset threshold was 206 dB SEL. For otariids, only a Type I weighting function is used; the weighting function amplitude at 2.5 kHz is 0 dB. This means the (Type I) weighted exposure SEL for California sea lions exposed under water is 206 dB re 1 μPa^2·s.

As the only otariid species for whom TTS data are available, the California sea lion TTS threshold is used for all otariids. No TTS data exist for the walrus; however, underwater audiograms (Kastelein et al., 2002b) for the walrus show a strong similarity to those of other otariids, therefore, the otariid TTS threshold is also used for odobenids.

2.4.2.7 Otariids and odobenids (in air)

TTS thresholds for otariids exposed to acoustic sources in-air are based on data reported by Kastak et al. (2007; 2004), who provided estimates of the average SEL for onset-TTS for a California sea lion exposed to in-air, octave-band noise centered at 2.5 kHz. The California sea lion TTS onset threshold was 154 dB re (20 μPa)^2·s. For otariids, only a Type I weighting function is used; the weighting function amplitude at 2.5 kHz is 0 dB. This means the (Type I) weighted exposure SEL for California sea lions exposed in air is 154 dB re (20 μPa)^2·s.

As the only otariid species for whom TTS data are available, the California sea lion TTS threshold is used for all otariids. No TTS data exist for the walrus; however, underwater audiograms (Kastelein *et al.*, 2002b) for the walrus show a strong similarity to those of other otariids, therefore, the otariid TTS threshold is also used for odobenids.

2.4.2.8 Mustelids

Based on the limited data available for sea otters and the similarities between these species and pinnipeds, the otariid TTS criteria and thresholds are used for mustelids.

2.4.2.9 Ursids

Based on the limited data available for polar bears and the similarities between these species and pinnipeds, the otariid TTS criteria and thresholds are used for polar bears.

2.4.2.10 Sirenians

No TTS data for manatees and dugongs exist; however, because the hearing ranges of phocids and sirenians are roughly equivalent, the phocid TTS threshold (the lowest of any of the pinnipeds), is used for sirenians.

2.4.3 Criteria and thresholds for PTS

In contrast to TTS, which represents a temporary reduction of hearing sensitivity, PTS represents tissue damage that does not recover and leads to a permanent reduced sensitivity to sounds over specific frequency ranges. Since no studies have been designed to intentionally induce PTS in marine mammals, onset-PTS levels for marine mammals must be estimated using available information. TTS data are available for some marine mammal species, and a large amount of TTS and PTS data exist for terrestrial mammals. Differences in auditory structures and sound propagation and interaction with tissues prevent direct application of numerical thresholds for PTS in terrestrial mammals to marine mammals. However, the inner ears of marine and terrestrial mammals are analogous and certain relationships are expected to relate to both groups of mammals. Experiments with marine mammals have revealed similarities between marine and terrestrial mammals with respect to features such as TTS, age-related hearing loss, ototoxic drug-induced hearing loss, masking, and frequency selectivity (e.g., Finneran, 2012; Finneran *et al.*, 2005; Nachtigall et al., 2000). For this reason, relationships between TTS and PTS from human and terrestrial mammal data can be used, along with TTS onset values for marine mammals, to estimate exposures likely to produce PTS in marine mammals (Southall *et al.*, 2007).

A variety of terrestrial and marine mammal data sources indicate that threshold shifts up to 40 to 50 dB may be induced without PTS, and that 40 dB is a reasonable upper limit for threshold shift to prevent PTS (e.g., Kryter et al., 1966; Miller et al., 1963; Ward, 1960; Ward et al., 1958; Ward et al., 1959). A conservative assumption is that 40 dB of TTS is an upper limit for reversibility and that any additional exposure will result in some PTS. This means that 40 dB of TTS essentially defines the onset of PTS. To estimate the exposure necessary to induce 40 dB of TTS (and thus PTS), TTS growth rates from marine and terrestrial mammals are used to estimate the additional exposure required to “grow” TTS from the onset value (6 dB of TTS) to the point of the onset of PTS (40 dB of TTS) — a 34 dB difference.

Data from Ward et al. (1958) reveal a linear relationship between TTS and SEL with growth rates of 1.5 to 1.6 dB TTS per dB increase in SEL. This value for the TTS growth rate is larger than those experimentally measured in a dolphin exposed to 3 and 20 kHz tones (Finneran and Schlundt, 2010), and so appears to be a protective value to use for cetaceans. The additional exposure above onset-TTS that is required to reach PTS is therefore 34 dB divided by 1.6 dB, or approximately 20 dB. For cetaceans, exposure to sonars and other active acoustics sources with an SEL 20 dB above that producing TTS may be assumed to produce a PTS. For example, an onset-TTS threshold of 195 dB re 1 $\mu Pa^2 \cdot s$ would have a corresponding onset-PTS threshold of 215 dB re 1 $\mu Pa^2 \cdot s$. This extrapolation process is identical to that recently proposed by Southall et al. (2007).

Kastak et al. (2007) reported a TTS growth rate of 2.5 TTS per dB increase in SEL for a California sea lion. This growth rate results in a 14 dB difference between TTS onset and PTS onset. Since this results in a more protective approach, this value is used for all pinnipeds, not just the otariids. The same 14 dB difference is also used for the functional groups that utilize the same thresholds as the pinnipeds: the odobenids, mustelids, ursids, and sirenians..

2.4.3.1 LF Cetaceans

PTS onset for LF cetaceans is defined as the exposure 20 dB above TTS onset: a (Type II) weighted SEL of 198 dB re 1 $\mu Pa^2 \cdot s$.

2.4.3.2 MF Cetaceans

PTS onset for MF cetaceans is defined as the exposure 20 dB above TTS onset: a (Type II) weighted SEL of 198 dB re 1 $\mu Pa^2 \cdot s$.

2.4.3.3 HF Cetaceans

PTS onset for HF cetaceans is defined as the exposure 20 dB above TTS onset: a (Type II) weighted SEL of 172 dB re 1 $\mu Pa^2 \cdot s$.

2.4.3.4 Phocids (in water)

PTS onset for phocids seals is defined as the exposure 14 dB above TTS onset: a (Type I) weighted SEL of 197 dB re 1 $\mu Pa^2 \cdot s$.

2.4.3.5 Phocids (in air)

PTS onset for phocids seals is defined as the exposure 14 dB above TTS onset: a (Type I) weighted SEL of 145 dB re $(20\ \mu Pa)^2 \cdot s$.

2.4.3.6 Otariids and odobenids (in water)

PTS onset for otariids and odobenids is defined as the exposure 14 dB above TTS onset: a (Type I) weighted SEL of 220 dB re 1 $\mu Pa^2 \cdot s$.

2.4.3.7 Otariids and odobenids (in air)

PTS onset for otariids and odobenids is defined as the exposure 14 dB above TTS onset: a (Type I) weighted SEL of 168 dB re $(20\ \mu Pa)^2 \cdot s$.

2.4.3.8 Mustelids

Based on the limited data available for sea otters and the similarities between these species and pinnipeds, the otariid PTS criteria and thresholds are used for mustelids: a (Type I) weighted SEL of 220 dB re 1 $\mu Pa^2 \cdot s$ in water and 168 dB re $(20\ \mu Pa)^2 \cdot s$ in-air.

2.4.3.9 Ursids

Based on the limited data available for polar bears and the similarities between these species and pinnipeds, the otariid PTS criteria and thresholds are used for polar bears: a (Type I) weighted SEL of 220 dB re 1 $\mu Pa^2 \cdot s$ in water and 168 dB re $(20\ \mu Pa)^2 \cdot s$ in-air.

2.4.3.10 Sirenians

Because the hearing ranges of the phocids and sirenians are roughly equivalent, the phocid PTS threshold (the lowest of any of the pinnipeds), is used for sirenians: a (Type I) weighted SEL of 197 dB re 1 $\mu Pa^2 \cdot s$.

2.4.4 Criteria and thresholds for behavioral effects

Marine animals are likely to exhibit any of a suite of potential behavioral responses or combinations of behavioral responses upon exposure to sonars and other active acoustic sources. Potential behavioral responses include, but are not limited to, avoiding exposure or continued exposure, behavioral disturbance (including distress or disruption of social or foraging activity), habituation to the sound, becoming sensitized to the sound, or not responding to the sound.

In Navy acoustic impact analyses, two types of criteria/thresholds are utilized to estimate behavioral effects of noise:

(1) In cases where a specific taxonomic group's behavioral responses to sound have been well documented, a single sound pressure level (SPL) threshold has been provided to predict the number of behavioral disturbances. As an example, for harbor porpoises (but not other HF cetaceans), a behavioral response threshold of 120 dB SPL (no weighting function) is used for sonars and other active acoustic sources because of the demonstrated high behavioral sensitivity of harbor porpoises to these types of sounds.

(2) For all other taxa, the likelihood of behavioral effects is based on a probabilistic function (termed a behavioral response function – BRF), that relates the likelihood (i.e, probability) of a behavioral response to the received SPL. The BRF is used to estimate the percentage of an exposed population that is likely to exhibit altered behaviors or behavioral disturbance at a given exposure SPL. The BRF relies on the assumption that sound poses a negligible risk to marine mammals if they are exposed to SPL below a certain "basement" value. Above the basement exposure SPL, the probability of a response increases with increasing SPL.

Two BRFs are used in Navy acoustic impact analyses: BRF_1 for LF cetaceans and BRF_2 for all other functional hearing groups (i.e., MF and HF cetaceans, pinnipeds, mustelids, ursids, and sirenians). The BRF functions are based on three sources of data: behavioral observations during TTS experiments conducted at the US Navy Marine Mammal Program (Finneran and Schlundt, 2004); reconstruction of sound fields produced by the USS Shoup associated with the behavioral responses of killer whales observed in Haro Strait (Department of the Navy, 2003; Fromm, 2009); and observations of the behavioral response of North Atlantic right whales exposed to alert stimuli containing mid-frequency components (Nowacek et al., 2004). For a detailed discussion of the derivation of the BRFs, see Department of the Navy (2008a).

The BRFs are calculated using:

$$R(L)=\frac{1-\left(\dfrac{L-B}{K}\right)^{-A}}{1-\left(\dfrac{L-B}{K}\right)^{-2A}}, \tag{8}$$

where $R(L)$ is the probability of a response, L is the received SPL, and B and K are parameters that define the shape of the curve. For both BRFs, the "basement" parameter $B = 120$ dB re 1 µPa and the factor $K = 45$. For the BRF$_1$, $A = 8$; for BRF$_2$, $A = 10$. Both functions are illustrated in Fig. 7. Note that the received SPL is weighted using the Type I weighting functions when applying the BRFs.

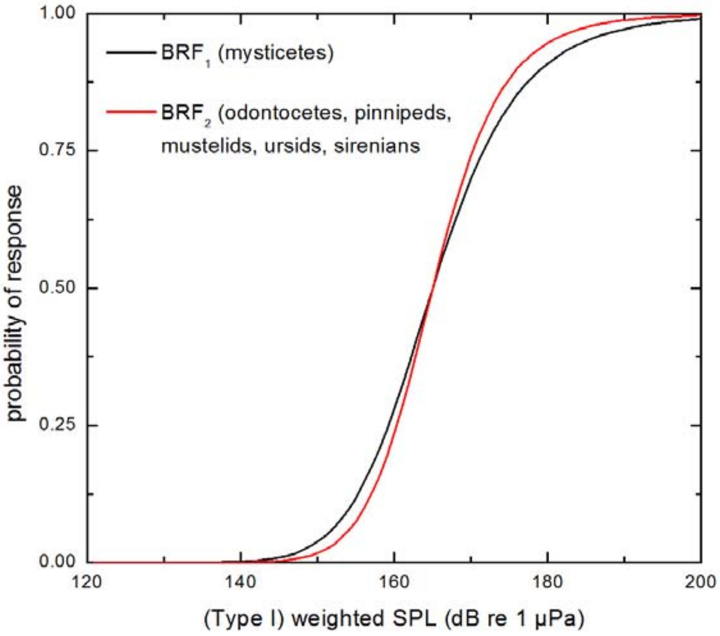

Figure 7. Navy Behavioral response functions (BRFs).

2.4.4.1 LF cetaceans

BRF_1 is used to assess behavioral effects from sonars and other active acoustic sources for all LF cetaceans. The LF cetacean Type I weighting function is used when determining the received SPL to use with the BRF.

2.4.4.2 MF cetaceans

To assess behavioral effects from sonars and other active acoustic sources to all MF cetaceans *except beaked whales*, BRF_2 is used, with the exposure weighted using the Type I weighting function for MF cetaceans.

Data obtained from *Mesoplodon densirostris* suggest greater responsiveness of beaked whales to a variety of sonars and active acoustic sources compared to other species exposed to the same or similar sounds (Tyack et al., 2011). For this reason, an (unweighted) SPL of 140 dB re 1μPa is used for beaked whales as a threshold to predict behavioral disturbance when exposed to sonars or other active acoustic sources.

2.4.4.3 HF cetaceans

To assess behavioral effects from sonars and other active acoustic sources to all HF cetaceans *except harbor porpoises*, BRF_2 is used, with the exposure weighted using the Type I weighting function for HF cetaceans.

For harbor porpoises, the information currently available suggests a very low threshold level of response for both captive and wild animals. Threshold levels at which both captive (Kastelein et al., 2005a; Kastelein et al., 2000) and wild harbor porpoises (Johnston, 2002) responded to sound (e.g. acoustic harassment devices, acoustic deterrent devices, or other non-impulsive sound sources) is very low (e.g. an SPL of approximately 120 dB re 1 μPa), although the biological significance of the disturbance is uncertain. Therefore, an (unweighted) SPL of 120 dB re 1μPa is used for harbor porpoises as a threshold to predict behavioral disturbance.

2.4.4.4 Phocids (in water)

To assess behavioral effects from sonars and other active acoustic sources to all phocids in water, BRF_2 is used, with the exposure weighted using the Type I weighting function for phocids.

2.4.4.5 Phocids (in air)

A number of investigators have studied pinniped reactions to rocket launches (Berg et al., 2004; Berg et al., 2002; Berg et al., 2001; Holst et al., 2005; Thorson et al., 2000a; b; Thorson et al., 1999; Thorson et al., 1998). In some cases severe reactions such as stampeding were recorded by pinnipeds exposed to rocket launch noise with SPLs of approximately 110–120 dB re 20 μPa. Distant rocket launches with received SPLs of approximately 60-70 dB re 20 μPa tended to be ignored by hauled-out pinnipeds. Southall et al. (2007) reviewed these studies and recommended an (unweighted) SEL of 100 dB re $(20\ \mu Pa)^2 \cdot s$ as the threshold to predict effects to pinnipeds in air. Despite this threshold being based on reactions to launch noise, not sonars or other active acoustics, Navy uses this threshold as a protective measure for pinnipeds exposed to in-air acoustic sources. Therefore, the behavioral response threshold for phocids exposed to acoustic sources in-air is an (unweighted) SEL of 100 dB re $(20\ \mu\text{Pa})^2 \cdot \text{s}$.

2.4.4.6 Otariids and odobenids (in water)

To assess behavioral effects from sonars and other active acoustic sources to all otariids and odobenids in water, BRF_2 is used, with the exposure weighted using the Type I weighting function for otariids.

2.4.4.7 Otariids and odobenids (in air)

Similar to phocids seals, the behavioral response threshold for otariids and odobenids exposed to acoustic sources in-air is an (unweighted) SEL of 100 dB re $(20\ \mu\text{Pa})^2 \cdot \text{s}$.

2.4.4.8 Mustelids

Due to a lack of specific data regarding sea otter reactions to sound, and the phylogenetic and audiometric similarities between these amphibious carnivores and pinnipeds, the pinniped behavioral thresholds are also used to assess the potential behavioral effects to mustelids.

Therefore, to assess behavioral effects from in-water sonars and other active acoustic sources on sea otters, BRF_2 is used, with the exposure weighted using the Type I weighting function for mustelids. For in-air sounds, an (unweighted) SEL of 100 dB re $(20\ \mu\text{Pa})^2 \cdot \text{s}$ is used as a threshold for behavioral reactions in sea otters.

2.4.4.9 Ursids

Due to a lack of specific data regarding polar bear reactions to sound, and the phylogenetic and audiometric similarities between these amphibious carnivores and pinnipeds, the pinniped behavioral thresholds are also used to assess the potential behavioral effects to ursids.

Therefore, to assess behavioral effects from in-water sonars and other active acoustic sources on polar bears, BRF_2 is used, with the exposure weighted using the Type I weighting function for ursids. For in-air sounds, an (unweighted) SEL of 100 dB re $(20\ \mu\text{Pa})^2 \cdot \text{s}$ is used as a threshold for behavioral reactions in polar bears.

2.4.4.10 Sirenians

Due to a lack of specific data regarding sirenian reactions to sound, and the audiometric similarities between these animals and phocid pinnipeds, the phocid behavioral thresholds are also used to assess the potential behavioral effects to sirenians.

Therefore, to assess behavioral effects from in-water sonars and other active acoustic sources on sirenians (manatees and dugongs), BRF_2 is used, with the exposure weighted using the Type I weighting function for sirenians.

2.5 CRITERIA AND THRESHOLDS FOR EXPLOSIVE SOURCES

2.5.1 Introduction

Criteria and thresholds for predicting physical and behavioral effects to marine mammals exposed to underwater explosive detonations were initially developed for the U.S. Navy shock trials of the SEAWOLF submarine (Department of the Navy, 1998) and WINSTON S. CHURCHILL guided missile destroyer (Department of the Navy, 2001). After the SEAWOLF and CHURCHILL shock trials, additional data became available regarding the auditory effects of impulsive sounds, similar to underwater detonations, on marine mammals (e.g., Finneran, 2002). These data were incorporated into the analysis for the shock trial of the MESA VERDE amphibious transport dock ship (Department of the Navy, 2008b). The present US Navy criteria and thresholds for explosive sources follow the a similar approach to that used for the MESA VERDE acoustic impact analysis (Department of the Navy, 2008b).

Similarly to the criteria and thresholds for marine mammals exposed to sonars and other active acoustic sources, criteria and thresholds for explosive sources are divided into physiological effects and behavioral effects. Because of the increased hazardousness of the shock wave associated with underwater detonations, physiological effects not only include auditory effects (PTS and TTS), but also mortality and direct (i.e., non-auditory) tissue damage known as primary blast injury. Criteria and thresholds for physiological effects are presented in order of decreasing severity (i.e., mortality and most serious injuries first). These are followed by criteria and thresholds for PTS, TTS, and behavioral reactions for each functional hearing group. A summary of the various criteria and thresholds is provided in Appendix D.

2.5.2 Mortality and primary (non-auditory) blast injury

A considerable body of laboratory data exist on injuries from impulsive sound exposure, usually from explosive pulses, obtained from tests with a variety of lab animals (mice, rats, dogs, pigs, sheep and other species). Primary blast injuries from explosive detonations are the result of differential compression and rapid re-expansion of adjacent tissues of different acoustic properties (e.g., between gas-filled and fluid-filled tissues or between bone and soft tissues). These injuries usually manifest themselves in the gas-containing organs (lung and gut) and auditory structures (e.g., rupture of the eardrum across the gas-filled spaces of the outer and inner ear). This section describes criteria and thresholds for primary blast injury to non-auditory tissues such as the lungs and gastrointestinal (GI) tract.

2.5.2.1 Mortality

An analysis of potential mortality of submerged terrestrial mammals exposed to small explosive charges has been conducted and used to define Navy thresholds for mortality for marine mammals exposed to underwater detonations (U.S. Navy, 2001; Yelverton, 1981). These analyses found the most common injuries to submerged mammals exposed to underwater detonations to be hemorrhaging in the fine structure of the lungs, and that lung damage is governed by the magnitude of the acoustic impulse (the time integral of the instantaneous sound pressure) of the underwater blast, not the peak pressure or sound exposure level (Richmond et al., 1973; Yelverton, 1981; Yelverton et al., 1973; Yelverton et al., 1975). Therefore, Navy analyses use the value of the acoustic impulse to determine if mortality or slight lung injury occurs. This approach is consistent with other efforts to predict the effects of underwater detonations (Department of the Navy, 1998; 2001; 2008b).

Mortality thresholds resulting from studies of injuries to submerged terrestrial mammals exposed to underwater blasts were based on the occurrence of "extensive lung injury" resulting in "1% Mortality," defined as an exposure where most animals may have moderate blast injuries to the lungs but 99% would survive. The minimum acoustic impulse for predicting the onset of mortality (I_M) is defined as:

$$I_M(M,D) = 91.4 M^{1/3} \left(1 + \frac{D}{10.1}\right)^{1/2}, \qquad (9)$$

where M is the animal mass (kg), D is the animal depth (m), and the units of I_M are Pa·s. This equation is based on the Goertner injury model (Goertner, 1982), corrected for atmospheric and hydrostatic pressures and based on the cube root scaling of body mass (Richmond *et al.*, 1973; U.S. Navy, 2001). The impulse required for mortality is assumed to increase proportionally to the square root of the ratio of the combined atmospheric and hydrostatic pressures at a specific depth to the atmospheric pressure at the surface. The critical value is assumed to be delivered during a time period that is the lesser of the positive pressure duration, or 20% of the natural period of the assumed-spherical lung adjusted for the size and depth of the animal. As depth increases, the impulse delivery time decreases (Goertner, 1982).

The impact analyses completed for the SEAWOLF and CHURCHILL shock trials (Department of the Navy, 1998; 2001) and other Navy compliance documents used a single body mass, that of a dolphin calf (12.2 kg), to represent all marine mammals for the derivation of the mortality threshold; however, thresholds based on the mass of a dolphin calf may underestimate mortality in smaller marine mammals and may overestimate mortality in larger marine mammals. Species-specific masses are therefore used for determining mortality thresholds because they most closely represent effects to individual species. Table D-2, in Appendix D, provides a nominal body mass for each species based on newborn individuals, a protective approach since the impulse threshold is lower for smaller masses and only a small percentage of a marine mammal population would consist of newborns (i.e., most would be larger and therefore have a higher threshold for mortality). In some cases, body masses were not available for the listed species and were therefore extrapolated from similar species.

2.5.2.2 Slight lung injury

Thresholds for slight lung injury to marine mammals exposed to underwater blasts were based on the occurrence of "slight lung injury" resulting in "0% Mortality," defined as an exposure where most animals may have slight blast injuries to the lungs but all would survive. The minimum acoustic impulse for predicting the onset of slight lung injury (I_S) is defined as:

$$I_S(M,D) = 39.1M^{1/3}\left(1+\frac{D}{10.1}\right)^{1/2}, \tag{10}$$

where M is the animal mass (kg), D is the animal depth (m), and the units of I_S are Pa·s. This equation is based on the Goertner injury model (Goertner, 1982), corrected for atmospheric and hydrostatic pressures and based on the cube root scaling of body mass (Richmond *et al.*, 1973; U.S. Navy, 2001). The impulse required for a slight lung injury is assumed to increase proportionally to the square root of the ratio of the combined atmospheric and hydrostatic pressures at a specific depth to the atmospheric pressure at the surface. As with the mortality thresholds, species-specific masses (see Table D-2, in Appendix D) are used for determining thresholds for slight lung injury.

In-air mortality and slight lung injury criteria and thresholds for pinnipeds (i.e., otariids, phocids, and odobenids) were not developed. Navy explosive training and testing activities do not normally coincide with pinniped, polar bear, or sea otter terrestrial habitat and therefore exposure to explosive energy on land that could cause mortality and slight lung injury is unlikely.

2.5.2.3 GI tract injury

Slight injury to the GI tract appears to be better correlated with the peak sound pressure of the shock wave rather than the acoustic impulse and is independent of the animal's size and mass (Goertner, 1982). Slight contusions to the GI tract were reported during small charge tests (Richmond *et al.*, 1973), when the (unweighted) peak SPL was 237 dB re 1µPa, therefore an unweighted peak SPL of 237 dB re 1 µPa is used as a threshold for slight injury to the GI tract for all marine mammals exposed to underwater explosions.

In-air GI tract injury criteria and thresholds for pinnipeds (i.e., otariids, phocids, and odobenids) were not developed. Navy explosive training and testing activities do not normally coincide with pinniped, polar bear, or sea otter terrestrial habitat and therefore exposure to explosive energy on land that could cause GI tract injury is unlikely.

2.5.3 Auditory Effects (TTS and PTS)

Navy environmental analyses for auditory effects (TTS and PTS) from underwater detonations follow the approach proposed by Southall et al. (2007) and used in the MESA VERDE acoustic impact analysis (Department of the Navy, 2008b), where a weighted SEL threshold is used in conjunction with an unweighted peak SPL threshold. The threshold producing the greater range for effect is then used because it is the more protective of the dual thresholds. In most cases, a total weighted SEL is more conservative than the largest SEL in any single 1/3-octave band, which was used for some earlier ship shock trials (e.g., Department of the Navy, 2001). Type II weighting functions for each functional hearing group are used, when available, to determine the auditory effects of explosions. If a Type II weighting function is not available for a functional hearing group, the Type I function for the group is used.

SEL and peak SPL thresholds for TTS are based on TTS data from impulsive sound exposures when available. If impulsive TTS data are not available, but TTS data from non-impulsive exposures are available, the onset of TTS is estimated from the TTS onset for non-impulsive sound and the relationship between impulse and non-impulse TTS observed in dolphins and belugas. For those species for whom no TTS data exist, TTS onset thresholds are based on the most closely related species for whom TTS data exist.

Since marine mammal PTS data from impulsive noise exposures do not exist, onset-PTS levels for these animals are estimated by adding 15 dB to the SEL-based TTS threshold and adding 6 dB to the peak pressure based thresholds. These relationships were derived by Southall et al. (2007) from impulse noise TTS growth rates in chinchillas. The appropriate frequency weighting function (i.e., Type II when available, otherwise Type I) for each functional hearing group is applied when using the SEL-based thresholds to predict PTS. The peak SPL thresholds are not weighted.

The specific thresholds for TTS and PTS for each marine mammal functional hearing group are detailed below and summarized in Appendix D.

2.5.3.1 LF Cetaceans

No TTS data are available for LF cetaceans, so the MF cetacean TTS onset values are used for LF cetaceans as well. The dual TTS thresholds for LF cetaceans therefore consist of a (Type II) weighted SEL of 172 dB re 1 $\mu Pa^2 \cdot s$ and a peak SPL of 224 dB re 1 μPa.

The PTS thresholds for LF cetaceans consist of a total (Type II) weighted SEL of 187 dB re 1 $\mu Pa^2 \cdot s$ and a peak SPL of 230 dB re 1 μPa.

2.5.3.2 MF Cetaceans

The TTS onset thresholds for MF cetaceans are based on TTS data from a beluga exposed to an underwater impulse produced from a seismic watergun (Finneran et al., 2002). These thresholds were also recommended by Southall et al. (2007). The numeric thresholds for MF cetaceans consist of a (Type II) weighted SEL of 172 dB re 1 $\mu Pa^2 \cdot s$ and a peak SPL of 224 dB re 1 μPa.

The PTS thresholds for MF cetaceans consist of a total (Type II) weighted SEL of 187 dB re 1 $\mu Pa^2 \cdot s$ and a peak SPL of 230 dB re 1 μPa.

2.5.3.3 HF Cetaceans

The TTS onset thresholds for HF cetaceans are based on TTS data from a harbor porpoise exposed to an underwater impulse produced from a seismic airgun (Lucke *et al.*, 2009). The numeric thresholds for HF cetaceans consist of a (Type II) weighted SEL of 146 dB re 1 $\mu Pa^2 \cdot s$ and a peak SPL of 195 dB re 1 μPa are used for HF cetaceans.

The PTS thresholds for HF cetaceans consist of a (Type II) weighted SEL of 161 dB re 1 $\mu Pa^2 \cdot s$ and a peak SPL of 201 dB re 1 μPa.

2.5.3.4 Phocids (in water)

Criteria for predicting TTS in phocid seals exposed to underwater pulses were based on underwater TTS data from a harbor seal exposed to octave band noise (Kastak *et al.*, 2005) and the extrapolation procedures described by Southall et al. (2007). The resulting TTS threshold values are: a (Type I) weighted SEL of 177 dB re 1 $\mu Pa^2 \cdot s$ and a peak SPL of 212 dB re 1 µPa.

The PTS thresholds for phocid seals exposed to underwater explosives consist of a total (Type I) weighted SEL of 192 dB re 1 $\mu Pa^2 \cdot s$ and a peak SPL of 218 dB re 1 µPa.

2.5.3.5 Phocids (in air)

The only known data regarding TTS in pinnipeds exposed to in-air impulse noise are from an unpublished report [Bowles et al. (unpublished data), as cited by Southall et al. (2007)] of TTS in harbor seals exposed to simulated sonic booms. The report cites onset-TTS at a peak SPL of 143 dB re 20 µPa or 129 dB re $(20\ \mu Pa)^2 \cdot s$. Southall et al. 2007 also reported that Bowles tested other pinnipeds whose TTS thresholds were higher, but actual numeric thresholds were not reported. Based on the only available TTS data for pinnipeds exposed to in-air impulsive noise, TTS thresholds for phocid seals exposed to in-air blasts consist of a (Type I) weighted SEL of 129 dB re $(20\ \mu Pa)^2 \cdot s$ and a peak SPL of 143 dB re 20 µPa.

The PTS thresholds for phocid seals exposed to in-air explosives consist of a (Type I) weighted SEL of 144 dB re $(20\ \mu Pa)^2 \cdot s$ and a peak SPL of 149 dB re 20 µPa.

2.5.3.6 Otariids and odobenids (in water)

Criteria for predicting TTS in otariids and odobenids exposed to underwater pulses were based on underwater TTS data from a California sea lion exposed to octave band noise (Kastak *et al.*, 2005) and the extrapolation procedures described by Southall et al. (2007). The resulting threshold values are: a (Type I) weighted SEL of 200 dB re 1 $\mu Pa^2 \cdot s$ and a peak SPL of 212 dB re 1 µPa.

The PTS thresholds for otariids and odobenids exposed to underwater explosives consist of a (Type I) weighted SEL of 215 dB re 1 $\mu Pa^2 \cdot s$ and a peak SPL of 218 dB re 1 µPa.

2.5.3.7 Otariids and odobenids (in air)

Based on the only available TTS data for pinnipeds exposed to in-air impulsive noise [Bowles et al., as cited by Southall et al. (2007)], TTS thresholds for otariids and odobenids exposed to in-air blasts consist of a (Type I) weighted SEL of 129 dB re $(20\ \mu Pa)^2 \cdot s$ and a peak SPL of 143 dB re 20 µPa.

The PTS thresholds for otariids and odobenids exposed to in-air explosives consist of a (Type I) weighted SEL of 144 dB re $(20\ \mu Pa)^2 \cdot s$ and a peak SPL of 149 dB re 20 µPa.

2.5.3.8 Mustelids

The explosive TTS and PTS thresholds for otariids are also used for sea otters because of the close taxonomic relationships and the similarities between audiograms. Therefore, for underwater exposures, the TTS threshold values for explosives consist of a (Type I) weighted

SEL of 200 dB re 1 μPa^2·s and a peak SPL of 212 dB re 1 μPa. For in-air exposures, a (Type I) weighted SEL of 129 dB re (20 μPa)^2·s and a peak SPL of 143 dB re 20 μPa are used.

The PTS threshold values for mustelids exposed to underwater explosives consist of a (Type I) weighted SEL of 215 dB re 1 μPa^2·s and a peak SPL of 218 dB re 1 μPa. For in-air exposures, mustelid PTS thresholds consist of a (Type I) weighted SEL of 144 dB re (20 μPa)^2·s and a peak SPL of 149 dB re 20 μPa.

2.5.3.9 Ursids

The explosive TTS and PTS thresholds for otariids are also used for polar bears because of the close taxonomic relationships and the similarities between audiograms. Therefore, for underwater exposures, the TTS threshold values for explosives consist of a (Type I) weighted SEL of 200 dB re 1 μPa^2·s and a peak SPL of 212 dB re 1 μPa. For in-air exposures, a (Type I) weighted SEL of 129 dB re (20 μPa)^2·s and a peak SPL of 143 dB re 20 μPa are used.

Similarly, the PTS threshold values for ursids exposed to underwater explosives consist of a (Type I) weighted SEL of 215 dB re 1 μPa^2·s and a peak SPL of 218 dB re 1 μPa. For in-air exposures, ursid PTS thresholds consist of a (Type I) weighted SEL of 144 dB re (20 μPa)^2·s and a peak SPL of 149 dB re 20 μPa.

2.5.3.10 Sirenians

The explosive TTS and PTS thresholds for phocid seals are also used for sirenians because of the similarities between the hearing ranges of phocids and manatees/dugongs. Therefore, for underwater exposures, the TTS threshold values for explosives consist of a (Type I) weighted SEL of 177 dB re 1 μPa^2·s and a peak SPL of 212 dB re 1 μPa.

The PTS thresholds for sirenians exposed to underwater explosives consist of a total (Type I) weighted SEL of 192 dB re 1 μPa^2·s and a peak SPL of 218 dB re 1 μPa.

2.5.4 Behavioral Effects

For single detonations, behavioral disturbance is likely to be limited to a short-lived startle reaction; therefore, Navy does not use any unique behavioral disturbance thresholds for marine mammals exposed to single explosive events.

For multiple, successive detonations (i.e., detonations happening at the same location within a 24-hour period), the threshold for behavioral disturbance is set 5 dB below the SEL-based TTS threshold, unless there are species or group specific data indicating that a lower threshold should be used. This is based on observations of behavioral reactions in captive dolphins and belugas occurring at exposure levels ~ 5 dB below those causing TTS after exposure to pure tones (Finneran and Schlundt, 2004; Schlundt *et al.*, 2000). The appropriate frequency weighting function (i.e., Type II when available, otherwise Type I) for each functional hearing group is applied when using the SEL-based disturbance thresholds.

The specific behavioral disturbance thresholds for the marine mammal functional hearing groups are detailed below and summarized in Appendix D.

2.5.4.1 LF Cetaceans

Specific data are lacking on the levels of sound that may illicit a behavioral reaction in LF cetaceans. Therefore, the disturbance threshold for LF cetaceans exposed to multiple, successive detonations is the TTS SEL-based threshold minus 5 dB: a (Type II) weighted SEL of 167 dB re 1 $\mu Pa^2 \cdot s$.

2.5.4.2 MF Cetaceans

The disturbance threshold for MF cetaceans exposed to multiple, successive detonations is a (Type II) weighted SEL of 167 dB re 1 $\mu Pa^2 \cdot s$, based on observations of behavioral reactions in captive dolphins and belugas occurring at exposure levels ~ 5 dB below those causing TTS after exposure to pure tones (Finneran and Schlundt, 2004; Schlundt *et al.*, 2000).

2.5.4.3 HF Cetaceans

Specific data are lacking on the levels of sound that may illicit a behavioral reaction in HF cetaceans. Therefore, the disturbance threshold for HF cetaceans exposed to multiple, successive detonations is the TTS SEL-based threshold minus 5 dB: a (Type II) weighted SEL of 141 dB re 1 $\mu Pa^2 \cdot s$.

2.5.4.4 Phocids (in water)

Specific data are lacking on the levels of sound that may illicit a behavioral reaction in phocid seals. Therefore, the disturbance threshold for phocids exposed to multiple, successive detonations is the TTS SEL-based threshold minus 5 dB: a (Type I) weighted SEL of 172 dB re 1 $\mu Pa^2 \cdot s$.

2.5.4.5 Phocids (in air)

As described in Section 2.4.4.5, a (Type I) weighted SEL of 100 dB re $(20\ \mu Pa)^2 \cdot s$ as the behavioral disturbance threshold for phocids exposed to multiple, successive, in-air blasts.

2.5.4.6 Otariids/odobenids (in water)

As with the phocids, the Navy the disturbance threshold for otariids and odobenids exposed to multiple, successive underwater detonations is the TTS SEL-based threshold minus 5 dB: a (Type I) weighted SEL of 195 dB re 1 $\mu Pa^2 \cdot s$.

2.5.4.7 Otariids/odobenids (in air)

As with the phocids, the Navy thresholds for otariids/odobenids exposed to multiple, successive explosive detonations in-air follows the Southall et al. (2007) recommendations: a (Type I) weighted SEL of 100 dB re $(20\ \mu Pa)^2 \cdot s$.

2.5.4.8 Mustelids

Specific data are lacking on the levels of sound that may illicit a behavioral reaction in sea otters. In light of the close taxonomic relationships and the similarities between the audiograms of otariids and mustelids, the behavioral disturbance thresholds for otariids exposed to multiple detonations are also used for sea otters. Therefore, the Navy the disturbance threshold for mustelids exposed to multiple, successive underwater detonations is a (Type I) weighted SEL of 195 dB re 1 $\mu Pa^2 \cdot s$.

For in-air exposures, the disturbance thresholds for mustelids exposed to multiple, successive explosive detonations consists of a (Type I) weighted SEL of 100 dB re (20 μPa)^2·s.

2.5.4.9 Ursids

Specific data are lacking on the levels of sound that may illicit a behavioral reaction in polar bears. In light of the close taxonomic relationships and the similarities between the audiograms of otariids and ursids, the behavioral disturbance thresholds for otariids are also used for polar bears. Therefore, the Navy the disturbance threshold for ursids exposed to multiple, successive underwater detonations is a (Type I) weighted SEL of 195 dB re 1 μPa^2·s.

For in-air exposures, the disturbance thresholds for ursids exposed to multiple, successive explosive detonations consists of a (Type I) weighted SEL of 100 dB re (20 μPa)^2·s.

2.5.4.10 Sirenians

The behavioral disturbance thresholds for phocid seals exposed to multiple, successive detonations are also used for sirenians because of the similarities between the hearing ranges of phocids and manatees/dugongs. Therefore, the disturbance threshold for sirenians exposed to multiple, successive detonations consists of a (Type I) weighted SEL of 172 dB re 1 μPa^2·s.

3 CRITERIA AND THRESHOLDS FOR SEA TURTLES

3.1 INTRODUCTION

The criteria and thresholds for sea turtles are similar to those proposed by Southall et al. (2007) for marine mammals: All sea turtles are placed into a single functional hearing group, and an auditory weighting function is used to emphasize frequencies where sensitivity to noise is high and de-emphasize frequencies where sensitivity is low. Individual criteria and thresholds are defined for sonars and other active acoustic sources and explosives.

3.2 FUNCTIONAL HEARING GROUP

To facilitate the acoustic and explosive effects analyses, animals are divided into functional hearing groups, and the same criteria and thresholds used for all species within a group. Several studies using green, loggerhead, and Kemp's ridley turtles suggest sea turtles are most sensitive to low-frequency sounds (Bartol and Ketten, 2006; Bartol et al., 1999; Lenhardt, 1994; Ridgway et al., 1969). Although hearing sensitivity varies slightly by species and age class, because of the similarities across the available data, all sea turtles are placed into a single functional hearing group.

3.3 AUDITORY WEIGHTING FUNCTION

Auditory weighting functions are used to emphasize frequencies where sensitivity to noise is high and to de-emphasize frequencies where sensitivity is low. The weighted noise levels at each frequency are then combined to generate a single, weighted exposure value. This technique allows the use of a single, weighted threshold value, regardless of the noise frequency.

For humans, weighting functions are based on subjective loudness data. Analogous data for dolphins was used to derive the Type II weighting functions for MF cetaceans, and by extrapolation, for the other cetaceans. For the other marine mammal functional groups, only Type I weighting functions, based on functional hearing limits, are used. Since there are no equal loudness data for sea turtles and the differences between turtles and cetaceans preclude extrapolation to derive a Type II function for turtles, only a Type I weighting function is used for sea turtles.

The sea turtle weighting function amplitude is calculated using Eq. (4). The parameters for the weighting function are provided in Table 5; these are based on the functional hearing range for sea turtles of approximately 100 Hz to 1 kHz, with an upper frequency limit of 2 kHz (Bartol and Ketten, 2006; Bartol *et al.*, 1999; Lenhardt, 1994; Ridgway *et al.*, 1969). Figure 8 shows the sea turtle weighting function. The sea turtle (Type I) weighting function is used with all sea turtle SEL-based thresholds.

Table 5. Parameters for the Navy sea turtle (Type I) weighting function.

Functional Hearing Group	*K*	*a* (Hz)	*b* (Hz)
Sea turtles	0	10	2,000

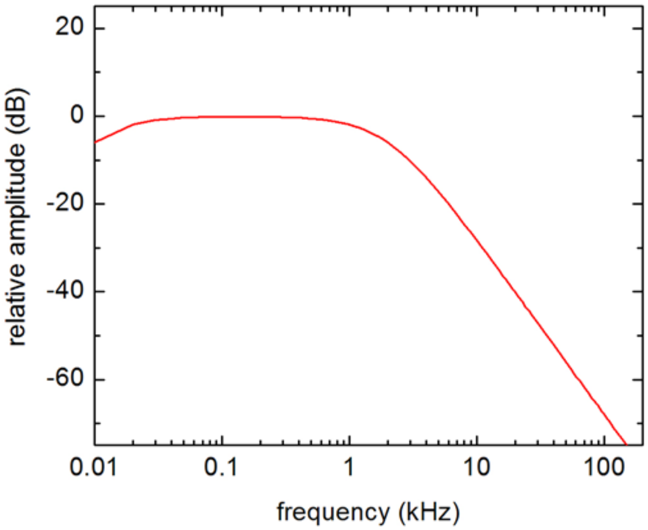

Figure 8. Auditory weighting function for sea turtles.

3.4 CRITERIA AND THRESHOLDS FOR SONARS AND OTHER ACTIVE ACOUSTIC SOURCES

3.4.1 Introduction

Criteria for sea turtles exposed to sonars and other active acoustic sources are divided into physiological effects and behavioral effects. Physiological effects criteria and thresholds are based on temporary and permanent threshold shift (TTS and PTS). Behavioral thresholds are based on experimental and observational data documenting the reactions of sea turtles to sound. A summary of the various criteria/thresholds and the sea turtle weighting function is provided in Appendix C.

3.4.2 Criteria and thresholds for TTS

To date, no known data are available on potential hearing impairments (i.e., TTS and PTS) in aquatic turtles. Sea turtles, based on their auditory anatomy (Bartol and Musick, 2003; Lenhardt et al., 1985; Wartzok and Ketten, 1999; Wever, 1978; Wyneken, 2001), are believed to have lower absolute sensitivity (i.e., higher thresholds) compared to cetaceans. Because of this, and the lack of data specific to sea turtles, previous Navy environmental analyses (e.g., Department of the Navy, 1998; 2001; 2008b), used the cetacean TTS threshold to define the sea turtle threshold. Since sea turtles have best sensitivity at low frequencies, similar to the LF cetaceans, the LF cetacean TTS threshold is applied to sea turtles. Therefore, the TTS threshold for sea turtles exposed to sonars and other active acoustic sources is a (Type I) weighted SEL of 178 dB re 1 $\mu Pa^2 \cdot s$.

3.4.3 Criteria and thresholds for PTS

As with the marine mammals, the PTS threshold for sea turtles exposed to sonars and other active acoustic sources is estimated as being 20 dB above the TTS threshold. This results in a PTS threshold consisting of a (Type I) weighted SEL of 198 dB re 1 $\mu Pa^2 \cdot s$.

3.4.4 Criteria and thresholds for behavioral effects

Potential behavioral changes could include a startle reaction, avoiding the sound source, increased swimming speed, increased surfacing time, and decreased foraging. No known studies have examined the reactions of sea turtles to sonars or other active acoustic sources. However, several studies have investigated the behavioral responses of sea turtles to impulsive sounds produced by seismic airguns. O’Hara and Wilcox (1990) reported that loggerhead turtles kept in a 300 × 45 m enclosure in a 10 m deep canal maintained a standoff range of 30 m from three small airguns fired simultaneously at 15-s internals (O'Hara and Wilcox, 1990). Although O’Hara and Wilcox did not report the actual received sound levels, McCauley et al. (2000) have estimated the received SPL for avoidance to be 175–176 dB re 1 μPa.

Moein et al. (1994) investigated the use of airguns to repel juvenile loggerhead sea turtles from hopper dredges. The results from all turtles tested (11 individuals, six trials each) indicated avoidance was seen during the first presentation of the air gun exposure at a mean range of 24 m; however, details of the airgun, its operational pressure, deployment depth, and the sound levels received by the turtles throughout the cage were not provided.

McCauley et al. (2000) measured behavioral responses in captive green and loggerhead turtles exposed to airgun impulses. The results showed that above a received SPL of 166 dB re 1 μPa the turtles noticeably increased their swimming activity compared to non airgun operation periods. Above 175 dB re 1 μPa, behavior became more erratic possibly indicating the turtles were in an agitated state (McCauley *et al.*, 2000). The authors noted that the point at which the turtles showed the more erratic behavior would be expected to approximately equal the point at which avoidance would occur for unrestrained turtles (McCauley *et al.*, 2000).

Cumulatively, these studies indicate that behavioral disturbance may occur in sea turtles exposed to impulsive noise with SPLs greater than 166 dB re 1 μPa and that more erratic behavior and avoidance may begin at SPLs of 175–179 dB re 1 μPa, with 175 dB re 1 μPa more likely to be the point at which avoidance may occur in unrestrained turtles (McCauley *et al.*, 2000). Navy effects analyses use the lower range of SPLs that caused avoidance as the behavioral disturbance threshold for sea turtles: a (Type I) weighted SPL of 175 dB re 1 μPa.

3.5 CRITERIA AND THRESHOLDS FOR EXPLOSIVE SOURCES

3.5.1 Introduction

Similarly to the marine mammal criteria and thresholds for sonars and other active acoustic exposures, criteria and thresholds for explosive sources are divided into physiological effects and behavioral effects. Because of the increased hazardousness of the shock wave associated with underwater detonations, physiological effects not only include auditory effects (PTS and TTS), but also mortality and direct (i.e., non-auditory) tissue damage known as primary blast injury. Criteria and thresholds for physiological effects are presented in order of decreasing severity (i.e., mortality and most serious injuries first). These are followed by criteria and thresholds for PTS, TTS, and behavioral reactions. A summary of the various criteria and thresholds is provided in Appendix D.

3.5.2 Mortality and primary (non-auditory) blast injury

Very little information exists regarding the impacts of underwater detonations on sea turtles. Impacts to sea turtles from explosive removal operations have ranged from non-injurious effects (e.g., acoustic annoyance, mild tactile detection or physical discomfort) to varying levels of injury (i.e., non-lethal and lethal injuries). Often, effects of explosive events on turtles must be inferred from documented effects to other vertebrates with lungs or other-gas containing organs, such as mammals and fish (Viada et al., 2008). As with marine mammals, primary blast injury almost exclusively affects the gas-containing organs: the lung and the ear. For this reason, the general principles of the Goertner injury model are applicable; however, since it is not known what degree of protection from a shock wave is provided by a turtle's shell, application of the Goertner injury model is believed to be protective (Viada *et al.*, 2008). Therefore, Eqs. (9) and (10) are used to calculate the mortality and slight lung injury thresholds, respectively, for sea turtles exposed to underwater detonations. Sea turtle body masses for use in Eqs. (9) and (10) are provided in Table D-2, in Appendix D. Since sea turtle hatchlings can weigh less than 0.5% of their adult mass, juvenile masses are used to avoid greatly over-estimating the potential effects of detonations.

Although the lungs and auditory system are considered to be the most likely site of injury to sea turtles exposed to underwater detonations, as a protective measure, the GI tract injury threshold used for marine mammals is also applied to sea turtles: an (unweighted) SPL of 237 dB re 1 μPa.

3.5.3 Auditory Effects (TTS and PTS)

No data exist to correlate the sensitivity of the sea turtle tympanum and middle and inner ear to trauma associated with the shock waves associated with underwater explosions (Viada *et al.*, 2008). Thus, similar to the turtle sonar and other active acoustic thresholds, sea turtle thresholds for TTS and PTS after exposure to underwater detonations are identical to the values for LF cetaceans.

Therefore, the dual TTS thresholds for sea turtles consist of a (Type I) weighted SEL of 172 dB re 1 μPa^2·s and a peak SPL of 224 dB re 1 μPa.

The PTS thresholds for sea turtles consist of a (Type I) weighted SEL of 187 dB re 1 μPa^2·s and a peak SPL of 230 dB re 1 μPa.

3.5.4 Behavioral Effects

As discussed in Section 3.4.4, several authors have investigated the behavioral responses of sea turtles to impulsive sounds produced by airguns (McCauley et al., 2000; Moein et al., 1994; O'Hara and Wilcox, 1990). Cumulatively, these studies indicate that a behavioral reaction to a sound may occur with SPLs greater than 166 dB re 1 μPa, and that more erratic behavior and avoidance, which may be indicative of a behavioral disturbance in wild animals, may occur at SPLs of 175–179 dB re 1 μPa. McCauley et al. determined that these SPLs would result in an SEL 11.4–14.6 dB lower than the SPL. For an SPL of 175 dB re 1 μPa, the comparable SEL would therefore be 163.6–160.4 dB re 1 μPa^2·s.

For Navy environmental documents, the sea turtle behavioral disturbance threshold after exposure to multiple, successive underwater impulses therefore consists of a (Type I) weighted SEL of 160 dB re 1 μPa^2·s.

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APPENDIX A. FUNCTIONAL HEARING GROUPS

Table A-1. Functional hearing groups used in Navy acoustic impact analyses.

Functional Hearing Group	Description
LF cetaceans	Suborder Mysticeti (baleen whales)
MF cetaceans	Family Ziphiidae (beaked whales) Family Physeteridae (Sperm whale) Family Monodontidae (Irrawaddy dolphin, beluga, narwhal) Subfamily Delphininae (white-beaked/white-sided/ Risso's/bottlenose/spotted/spinner/striped/common dolphins) Subfamily Steninae (rough-toothed/humpback dolphins) Subfamily Globicephalinae (melon-headed whales, false/pygmy killer whale, killer whale, pilot whales) Subfamily Lissodelphinae (right whale dolphins)
HF cetaceans	Family Phocoenidae (porpoises) Family Platanistidae (Indus/Ganges river dolphins) Family Iniidae (Amazon river dolphins) Family Pontoporiidae (Baiji/ La Plata river dolphins) Family Kogiidae (Pygmy/dwarf sperm whales) Subfamily Cephalorhynchinae (Commersen's, Black, Heaviside's, Hector's dolphins)
Phocids	Family Phocidae (earless seals)
Otariids and Odobenids	Family Otaridae (fur seals/sea lions) Family Odobenidae (walrus)
Mustelids	Family Mustelidae (sea otters)
Ursids	Family Ursidae (polar bears)
Sirenians	Order Sirenia (mantees/dugongs)
Sea turtles	Family Cheloniidae (loggerhead, green, hawksbill, Kemp's ridley, olive ridley, flatback sea turtle) Family Dermochelyidae (leatherback sea turtle)

APPENDIX B. AUDITORY WEIGHTING FUNCTIONS

B.1 TYPE I WEIGHTING FUNCTIONS

$$W_I(f) = K + 20\log_{10}\left[\frac{b^2 f^2}{\left(a^2 + f^2\right)\left(b^2 + f^2\right)}\right] \tag{B-1}$$

$W_I(f)$	weighting function amplitude (dB)
f	sound frequency (Hz)
a	lower cutoff frequency (Table B-1)
b	upper cutoff frequency (Table B-1)
K	gain (Table B-1)

Table B-1. Parameters for the Navy Type I weighting functions.

Functional Hearing Group	*K* (dB)	*a* (Hz)	*b* (Hz)
LF cetaceans	0	7	22,000
MF cetaceans	0	150	160,000
HF cetaceans	0	200	180,000
Phocids (in water), Sirenians	0	75	75,000
Phocids (in air)	0	75	30,000
Otariids, Odobenids, Mustelids, Ursids (in water)	0	100	40,000
Otariids, Odobenids, Mustelids, Ursids (in air)	0	100	30,000
Sea turtles	0	10	2,000

B.2 TYPE II WEIGHTING FUNCTIONS

$$W_{II}(f) = \text{maximum}\{G_1(f), G_2(f)\}, \tag{B-2}$$

$W_{\mathrm{II}}(f)$	weighting function amplitude (dB)
f	sound frequency (Hz)

$$G_1(f) = K_1 + 20\log_{10}\left[\frac{b_1^2 f^2}{\left(a_1^2 + f^2\right)\left(b_1^2 + f^2\right)}\right] \tag{B-3}$$

$G_1(f)$	amplitude of Type I function component (dB)
a_1	Type I component lower cutoff frequency (Table B-2)
b_1	Type I component upper cutoff frequency (Table B-2)
K_1	Type I component gain (Table B-2)

$$G_2(f) = K_2 + 20\log_{10}\left[\frac{b_2^2 f^2}{\left(a_2^2 + f^2\right)\left(b_2^2 + f^2\right)}\right] \tag{B-4}$$

$G_2(f)$	amplitude of EQL function component (dB)
a_2	EQL component lower cutoff frequency (Table B-2)
b_2	EQL component upper cutoff frequency (Table B-2)
K_2	EQL component gain (Table B-2)

Table B-2. Parameters for the Navy (cetacean) Type II weighting functions.

Functional Hearing Group	K_1 (dB)	a_1 (Hz)	b_1 (Hz)	K_2 (dB)	a_2 (Hz)	b_2 (Hz)	Inflection point (Hz)
LF cetaceans	-16.5	7	22,000	0.9	674	12,130	267
MF cetaceans	-16.5	150	160,000	1.4	7,829	95,520	3,000
HF cetaceans	-19.4	200	180,000	1.4	9,480	108,820	3,000

APPENDIX C. CRITERIA AND THRESHOLDS FOR SONARS AND OTHER ACTIVE ACOUSTIC SOURCES

Table C-1. Navy criteria and thresholds for marine mammals and sea turtles exposed to sonars and other active acoustic sources

Functional Hearing Group or Species	PTS Threshold (all weighted SEL)	TTS Threshold (all weighted SEL)	Behavioral Threshold
LF Cetaceans	(Type II) SEL: 198 dB re 1 μPa^2·s	(Type II) SEL: 178 dB re 1 μPa^2·s	(Type I) SPL: BRF_1
MF Cetaceans (*except beaked whales*)	(Type II) SEL: 198 dB re 1 μPa^2·s	(Type II) SEL: 178 dB re 1 μPa^2·s	(Type I) SPL: BRF_2
Beaked whales	(Type II) SEL: 198 dB re 1 μPa^2·s	(Type II) SEL: 178 dB re 1 μPa^2·s	(unweighted) SPL: 140 dB re 1 μPa
HF Cetaceans (*except harbor porpoises*)	(Type II) SEL: 172 dB re 1 μPa^2·s	(Type II) SEL: 152 dB re 1 μPa^2·s	(Type I) SPL: BRF_2
Harbor porpoises	(Type II) SEL: 172 dB re 1 μPa^2·s	(Type II) SEL: 152 dB re 1 μPa^2·s	(unweighted) SPL: 120 dB re 1 μPa
Phocids Sirenians (in water)	(Type I) SEL: 197 dB re 1 μPa^2·s	(Type I) SEL: 183 dB re 1 μPa^2·s	(Type I) SPL: BRF_2
Phocids (in air)	(Type I) SEL: 145 dB re (20 μPa)^2·s	(Type I) SEL: 131 dB re (20 μPa)^2·s	(unweighted) SEL: 100 dB re (20 μPa)^2·s
Otariids Odobenids Mustelids Ursids (in water)	(Type I) SEL: 220 dB re 1 μPa^2·s	(Type I) SEL: 206 dB re 1 μPa^2·s	(Type I) SPL: BRF_2
Otariids Odobenids Mustelids Ursids (in air)	(Type I) SEL: 168 dB re (20 μPa)^2·s	(Type I) SEL: 154 dB re (20 μPa)^2·s	(unweighted) SEL: 100 dB re (20 μPa)^2·s
Sea Turtles	(Type I) SEL: 198 dB re 1 μPa^2·s	(Type I) SEL: 178 dB re 1 μPa^2·s	(Type I) SPL: 175 dB re 1 μPa

APPENDIX D. CRITERIA AND THRESHOLDS FOR EXPLOSIVES

Table D-1. Navy criteria and thresholds for marine mammals and sea turtles exposed to explosive detonations.

Functional Hearing Group or Species	Mortality	Slight Lung Injury	GI tract injury	PTS Threshold	TTS Threshold	Behavioral Threshold
LF Cetaceans	Modified Goertner model, Eq. (D-1) Mass from Table D-2	Modified Goertner model, Eq. (D-2) Mass from Table D-2	(unweighted) SPL: 237 dB re 1 μPa	(Type II) SEL: 187 dB re 1 $\mu Pa^2 \cdot s$ (unweighted) peak SPL: 230 dB re 1 μPa	(Type II) SEL: 172 dB re 1 $\mu Pa^2 \cdot s$ (unweighted) peak SPL: 224 dB re 1 μPa	(Type II) SEL: 167 dB re 1 $\mu Pa^2 \cdot s$
MF Cetaceans	Modified Goertner model, Eq. (D-1) Mass from Table D-2	Modified Goertner model, Eq. (D-2) Mass from Table D-2	(unweighted) SPL: 237 dB re 1 μPa	(Type II) SEL: 187 dB re 1 $\mu Pa^2 \cdot s$ (unweighted) peak SPL: 230 dB re 1 μPa	(Type II) SEL: 172 dB re 1 $\mu Pa^2 \cdot s$ (unweighted) peak SPL: 224 dB re 1 μPa	(Type II) SEL: 167 dB re 1 $\mu Pa^2 \cdot s$
HF Cetaceans	Modified Goertner model, Eq. (D-1) Mass from Table D-2	Modified Goertner model, Eq. (D-2) Mass from Table D-2	(unweighted) SPL: 237 dB re 1 μPa	(Type II) SEL: 161 dB re 1 $\mu Pa^2 \cdot s$ (unweighted) peak SPL: 201 dB re 1 μPa	(Type II) SEL: 146 dB re 1 $\mu Pa^2 \cdot s$ (unweighted) peak SPL: 195 dB re 1 μPa	(Type II) SEL: 141 dB re 1 $\mu Pa^2 \cdot s$
Phocids Sirenians (in water)	Modified Goertner model, Eq. (D-1) Mass from Table D-2	Modified Goertner model, Eq. (D-2) Mass from Table D-2	(unweighted) SPL: 237 dB re 1 μPa	(Type I) SEL: 192 dB re 1 $\mu Pa^2 \cdot s$ (unweighted) peak SPL: 218 dB re 1 μPa	(Type I) SEL: 177 dB re 1 $\mu Pa^2 \cdot s$ (unweighted) peak SPL: 212 dB re 1 μPa	(Type I) SEL: 172 dB re 1 $\mu Pa^2 \cdot s$

Functional Hearing Group or Species	Mortality	Slight Lung Injury	GI tract injury	PTS Threshold	TTS Threshold	Behavioral Threshold
Phocids (in air)	See Note 1	See Note 1	See Note 1	(Type I) SEL: 144 dB re (20 μPa)^2·s (unweighted) peak SPL: 149 dB re 20 μPa	(Type I) SEL: 129 dB re (20 μPa)^2·s (unweighted) peak SPL: 143 dB re 20 μPa	(Type I) SEL: 100 dB re (20 μPa)^2·s
Otariids Odobenids Mustelids Ursids (in water)	Modified Goertner model, Eq. (D-1) Mass from Table D-2	Modified Goertner model, Eq. (D-2) Mass from Table D-2	(unweighted) SPL: 237 dB re 1 μPa	(Type I) SEL: 215 dB re 1 μPa^2·s (unweighted) peak SPL: 218 dB re 1 μPa	(Type I) SEL: 200 dB re 1 μPa^2·s (unweighted) peak SPL: 212 dB re 1 μPa	(Type I) SEL: 195 dB re 1 μPa^2·s
Otariids Odobenids Mustelids Ursids (in air)	See Note 1	See Note 1	See Note 1	(Type I) SEL: 144 dB re (20 μPa)^2·s (unweighted) peak SPL: 149 dB re 20 μPa	(Type I) SEL: 129 dB re (20 μPa)^2·s (unweighted) peak SPL: 143 dB re 20 μPa	(Type I) SEL: 100 dB re (20 μPa)^2·s
Sea Turtles	Modified Goertner model, Eq. (D-1) Mass from Table D-2	Modified Goertner model, Eq. (D-2) Mass from Table D-2	(unweighted) SPL: 237 dB re 1 μPa	(Type I) SEL: 187 dB re 1 μPa^2·s (unweighted) peak SPL: 230 dB re 1 μPa	(Type I) SEL: 172 dB re 1 μPa^2·s (unweighted) peak SPL: 224 dB re 1 μPa	(Type I) SEL: 160 dB re 1 μPa^2·s

1 - In-air GI tract injury, slight lung injury, and mortality criteria and thresholds for pinnipeds (i.e., otariids, phocids, and odobenids) were not developed. Navy explosive training and testing activities do not normally coincide with pinniped, polar bear, or sea otter terrestrial habitat and therefore exposure to explosive energy on land that could cause these injuries is unlikely.

$$I_M(M,D) = 91.4M^{1/3}\left(1+\frac{D}{10.1}\right)^{1/2} \tag{D-1}$$

$I_M(M,D)$	mortality threshold, expressed in terms of acoustic impulse (Pa·s)
M	Animal mass (Table D-1)
D	Water depth (m)

$$I_S(M,D) = 39.1M^{1/3}\left(1+\frac{D}{10.1}\right)^{1/2} \tag{D-2}$$

$I_S(M,D)$	slight lung injury threshold, expressed in terms of acoustic impulse (Pa·s)
M	Animal mass (Table D-1)
D	Water depth (m)

Table D-2. Representative animal masses for use in Eqs. (D-1) and (D-2).

Species Name	Common Name	Newborn Calf / Pup Mass (kg)	Reference
Cetaceans			
Family Balaenidae			
Eubalaena glacialis	North Atlantic right whale	910	Reeves et al. (2002)
Eubalaena japonica	North Pacific right whale	910	Reeves et al. (2002)
Family Balaenopteridae			
Balaenoptera acutorostrata	Minke whale	200	Mann et al. (2000)
Balaenoptera borealis	Sei whale	650	Gambell (1985)
Balaenoptera edeni	Bryde's whale	680	Reeves et al. (2002)
Balaenoptera musculus	Blue whale	2,000	Reidenberg and Laitman (2002)
Balaenoptera physalus	Fin whale	1,750	Reidenberg and Laitman (2002)
Megaptera novaeangliae	Humpback whale	680	Reeves et al. (2002)
Family Delphinidae			
Delphinus capensis	Long-beaked common dolphin	7	Surrogate: striped dolphin
Delphinus delphis	Short-beaked common dolphin	7	Surrogate: striped dolphin
Feresa attenuata	Pygmy killer whale	7	Surrogate: striped dolphin
Globicephala macrorhynchus	Short-finned pilot whale	37	Reeves et al. (2002)
Globicephala melas	Long-finned pilot whale	70	Reidenberg and Laitman (2002)
Grampus griseus	Risso's dolphin	47	Nachtigall et al. (2005)
Lagenodelphis hosei	Fraser's dolphin	19	Reeves et al. (2002)
Lagenorhynchus acutus	Atlantic white-sided dolphin	20	Reeves et al. (2002)
Lagenorhynchus albirostris	White-beaked dolphin	40	Reidenberg and Laitman (2002)
Lagenorhynchus obliquidens	Pacific white-sided dolphin	12	Heise (1997)
Lissodelphis borealis	Northern right whale dolphin	15	Surrogate: bottlenose dolphin/melon-headed whale
Orcinus orca	Killer whale	160	Reeves et al. (2002)
Peponocephala electra	Melon-headed whale	15	Reeves et al. (2002)
Pseudorca crassidens	False killer whale	80	Mann et al. (2000)
Stenella attenuata	Pantropical spotted dolphin	7	Surrogate: striped dolphin
Stenella clymene	Clymene dolphin	7	Surrogate: striped dolphin
Stenella coeruleoalba	Striped dolphin	7	Reeves et al. (2002)
Stenella frontalis	Atlantic spotted dolphin	7	Surrogate: striped dolphin
Stenella longirostris	Spinner dolphin	7	Surrogate: striped dolphin
Steno bredanensis	Rough-toothed dolphin	14	Surrogate: humpbacked dolphin
Tursiops aduncus	Indo-Pacific bottlenose dolphin	9	Reeves et al. (2002)
Tursiops truncatus	Common bottlenose dolphin	14	Reeves et al. (2002)
Family Eschrisctiidae			

Species Name	Common Name	Newborn Calf / Pup Mass (kg)	Reference
Eschrichtius robustus	Gray whale	500	Reidenberg and Laitman (2002)
Family Kogiidae			
Kogia breviceps	Pygmy sperm whale	23	Reeves et al. (2002)
Kogia sima	Dwarf sperm whale	14	Plön (2004)
Family Monodontidae			
Delphinapterus leucas	Beluga whale	80	Reeves et al. (2002) and Reidenberg and Laitman (2002)
Monodon monoceros	Narwhal	80	Reeves et al. (2002)
Family Phocoenidae			
Phocoenoides dalli	Dall's Porpoise	6	Ferrero and Walker (1999)
Phocoena phocoena	Harbor porpoise	5	Reeves et al. (2002) and Reidenberg and Laitman (2002)
Family Physeteridae			
Physeter macrocephalus	Sperm whale	1000	Reeves et al. (2002) and Reidenberg and Laitman (2002)
Family Ziphiidae			
Berardius arnouxii	Arnoux's beaked whale	250	Surrogate: Cuvier's beaked whale
Berardius berardii	Baird's beaked whale	250	Surrogate: Cuvier's beaked whale
Hyperoodon ampullatus	Northern bottlenose whale	250	Surrogate: Cuvier's beaked whale
Indopacetus pacificus	Longman's beaked whale	228	Dalebout et al (2003)
Mesoplodon bidens	Sowerby's beaked whale	170	Reeves et al. (2002)
Mesoplodon carlhubbsi	Hubb's beaked whale	170	Surrogate: Sowerby's beaked whale
Mesoplodon densirostris	Blainville's beaked whale	60	Reeves et al. (2002) and Reidenberg and Laitman (2002)
Mesoplodon europaeus	Gervais' beaked whale	49	Reidenberg and Laitman (2002)
Mesoplodon ginkgodens	Ginkgo-toothed beaked whale	170	Surrogate: Sowerby's beaked whale
Meosplodon hectori	Hector's beaked whale	60	Surrogate: Blainville's beaked whale
Mesoplodon layardii	Strap-toothed whale	136	Surrogate: True's beaked whale
Mesoplodon mirus	True's beaked whale	136	Reidenberg and Laitman (2002)
Mesoplodon perrini	Perrin's beaked whale	60	Surrogate: Blainville's beaked whale
Mesoplodon peruvianus	Pygmy beaked whale	49	Surrogate: Gervais' beaked whale
Mesoplodon stejnegeri	Stejneger's beaked whale	60	Surrogate: Blainville's beaked whale

Species Name	Common Name	Newborn Calf / Pup Mass (kg)	Reference
Tasmacetus shepherdi	Shepherd's beaked whale	250	Surrogate: Cuvier's beaked whale
Ziphius cavirostris	Cuvier's beaked whale	250	Reeves et al. (2002)
Carnivores			
Family Mustelidae			
Enhydra lutris	Sea otter	2	Reeves et al. (2002)
Family Phocidae			
Cystophora cristata	Hooded seal	11	Reeves et al. (2002)
Erignathus barbatus	Bearded seal	29	Lydersen et al. (2002)
Halichoerus grypus	Gray seal	13	Iverson et al. (1993)
Histriophoca fasciata	Ribbon seal	9	Reeves et al. (2002)
Mirounga angustirostris	Northern elephant seal	22	Le Boeuf et al. (1972)
Monachus schauinslandi	Hawaiian monk seal	10	Wirtz (1968)
Pagophilus groenlandicus	Harp seal	7	Reeves et al. (2002)
Phoca vitulina	Harbor seal	7	Ellis et al. (2000)
Pusa hispida	Ringed seal	4	Reeves et al. (2002)
Family Otariidae			
Arctocephalus townsendi	Guadalupe fur seal	2	Reeves et al. (2002)
Callorhinus ursinus	Northern fur seal	4	Reeves et al. (2002)
Eumetopias jubatus	Steller sea lion	16	Reeves et al. (2002)
Zalophus californianus	California sea lion	6	Reeves et al. (2002)
Family Ursidae			
*Ursinus maritimus**	Polar bear	10	DeMaster and Stirling (1981)
Sirenians			
Family Dugonginae			
Dugong dugong	Dugong	25	Reeves et al. (2002)
Family Trichechidae			
Trichechus manatus	West Indian manatee	27	Caldwell and Caldwell (1985)
Sea Turtles			
Family Cheloniidae			
Caretta caretta	Loggerhead turtle	8.7	Southwood, Higgins et al. (2007)
Chelonia mydas	Green turtle	8.7	Wood and Wood (1993)
Eretmochelys imbricata	Hawksbill turtle	7.4	Okuyama, Shimizu et al. (2010)
Lepidochelys kempii	Kemp's ridley turtle	6.25	McVey and Wibbels (1984) and Caillouet, Koi et al. (1986)
Lepidochelys olivacea	Olive ridley turtle	7.15	Rajagopalan (1984)
Family Dermochelyidae			
Dermochelys coriacea	Leatherback turtle	35.18	Jones (2009)

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