# Appendix B: Supplemental Information

# Appendix B. Supplemental Information

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## B.1 Supplemental Information on Underwater Sound

### B.1.1 Background on Underwater Acoustics

### B.1.2 Sources of Underwater Sound

Ocean sounds originate from a variety of sources. Some come from non-biological sources such as wind and waves, while others come from the movements or vocalizations of marine life (Hildebrand 2009). In addition, humans introduce sound into the marine environment through activities like oil and gas exploration, construction, military sonars, and vessel traffic (Hildebrand 2009). The acoustic environment or "soundscape" of a given ecosystem comprises all such sounds—biological, non-biological, and anthropogenic (Pijanowski et al. 2011). Soundscapes are highly variable across space, time, and water depth, among other factors, due to the properties of sound transmission and the types of sound sources present in each area. A soundscape is sometimes called the "acoustic habitat," as it is a vital attribute of a given area where an animal may live (i.e., habitat) (Hatch et al. 2016).

### B.1.3 Physics of Underwater Sound

Sounds are created by the vibration of an object within its medium (Figure B-1). This movement generates kinetic energy (KE), which travels as a propagating wave away from the sound source. As this wave moves through the medium, the particles undergo tiny back-and-forth movements ("particle motion") along the axis of propagation, but the particles themselves do not travel with the wave. Instead, they oscillate in roughly the same location, transferring their energy to surrounding particles. Instead, the vibration is transferred to adjacent particles, which are pushed into areas of high pressure (compression) and low pressure (rarefaction). Acoustic pressure is a non-directional (scalar) quantity, whereas particle motion is an inherently directional quantity (a vector) taking place in the axis of sound transmission. The total energy of the sound wave includes the potential energy (PE) associated with the sound pressure as well as the KE from particle motion.

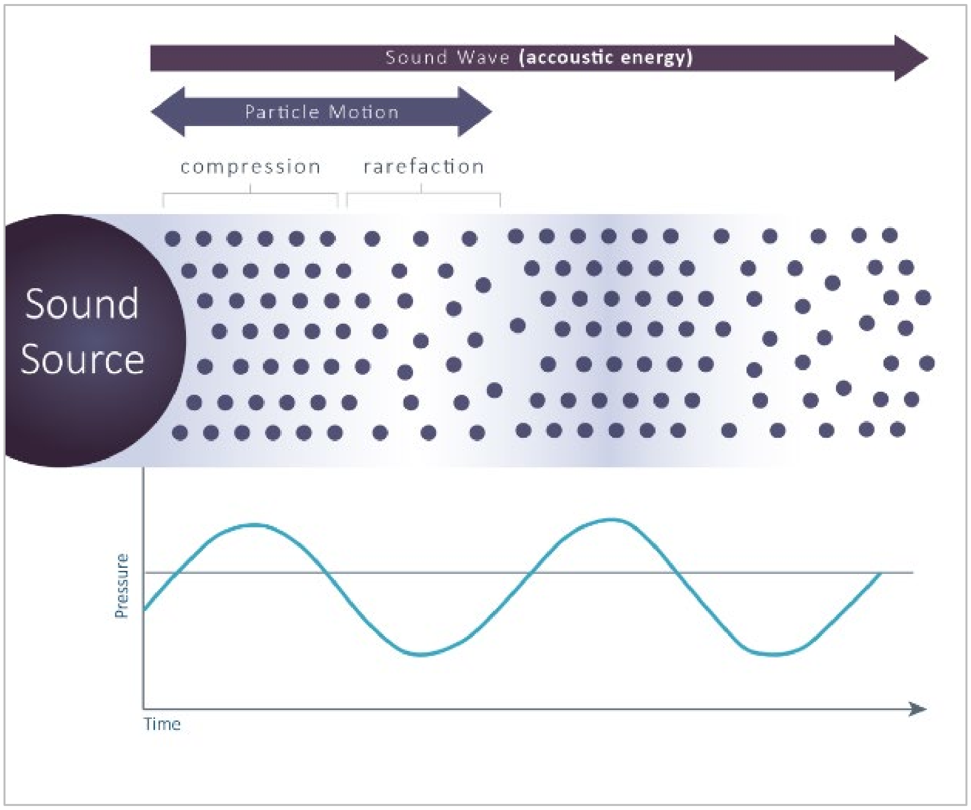

Figure B-1. Basic mechanics of a sound wave

### B.1.3.1 Units of Measurement

Sound can be quantified and characterized based on a number of physical parameters. A complete description of the units can be found in *ISO* 18405*:2017 Underwater acoustics-Terminology*: ISO (ISO/TC 43/SC 3 (2017). Some of the major parameters and their SI units (in parentheses) are:

***Acoustic pressure (pascal, Pa):*** The values used to describe the acoustic (or sound) pressure are peak pressure, peak-to-peak pressure and root-mean-square (rms) pressure deviation. The peak sound pressure is defined as the maximum absolute sound pressure deviation within a defined time period and is considered an instantaneous value. The peak-to-peak pressure, is the range of pressure change from the most negative to the most positive pressure amplitude of a signal (Figure B-2). Whereas the rms sound pressure represents a time-averaged pressure and is calculated as the square root of the mean (average) of the time-varying sound pressure over a given period (Figure B-2). The peak level ($L_{pk}$) peak-to-peak level ($L_{pk\text{-}pk}$), and sound pressure level ($L_{rms}$ or SPL) are computed by multiplying the logarithm of the ratio of the peak or rms pressures to a reference pressure (1 µPa in water) by a factor of 20 and are reported in decibels, see ***Sound Levels***.

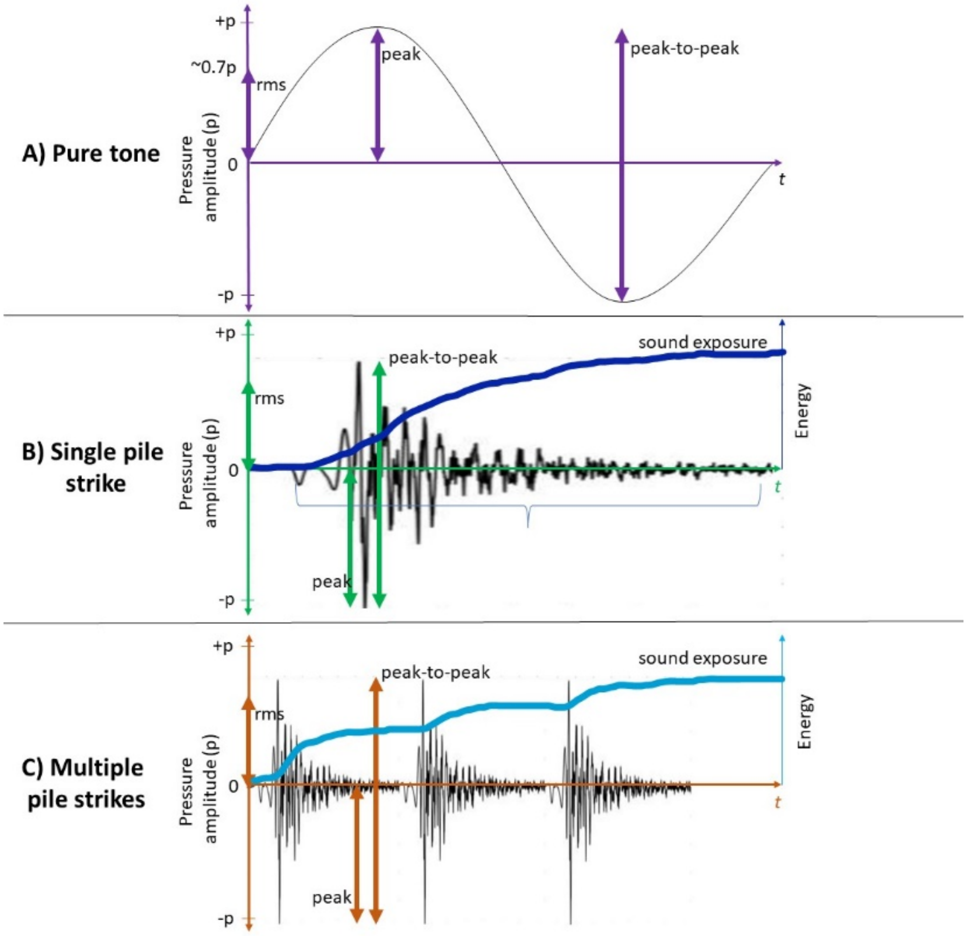

**Figure B-2. Sound pressure wave representations of four metrics**

Root-mean-square ($L_{rms}$), peak ($L_{pk}$), peak-to-peak ($L_{pk\text{-}pk}$), and sound exposure (SEL). A) A sine wave of a pure tonal signal with equal positive and negative peaks, so peak-to-peak is exactly twice the peak and rms is approximately 0.7 × peak. B) A single pile driving strike with one large positive pulse and a large negative pulse that isn't necessarily the same magnitude. In this example, the negative pulse is more extreme so is the reported peak value and peak-to-peak is less than double that. Sound exposure is shown as it accumulates across the time window. The final sound exposure would be considered the "single - shot" exposure and the rms value is the that divided by the duration of the pulse. C) Three consecutive pile driving strikes with peak and peak-to-peak assessed the same way as in B). Sound exposure is shown accumulating across all three strikes and rms is the total sound exposure divided by the entire time window shown. The cumulative sound exposure for this series of signals would be considered the total energy from all 3 pile-strikes.

***Particle velocity (meter per second, m/s):*** Particle velocity describes the change in position of the oscillating particles about its origin over a unit of time. Similar to sound pressure, particle velocity is dynamic and changes as the particles move back and forth. Therefore, peak particle velocity and root-mean-square particle velocity can be used to describe this physical quantity. One major difference between sound pressure and particle velocity is that the former is a scalar (i.e., without the directional component) and the latter is a vector (i.e., includes both magnitude and direction). Particle acceleration can also be used to describe particle motion, and is defined as the rate of change of velocity of a particle with respect to time. It is measured in units of meters per second squared, or $m/s^2$.

***Sound exposure (pascal-squared second, or $Pa^2$-s):*** Sound exposure is proportional to the acoustic energy of a sound. It is the time-integrated squared sound pressure over a stated period or acoustic event (see Figure B-2). Unlike sound pressure, which provides an instantaneous or time-averaged value of acoustic pressure, sound exposure is cumulative over a period of time.

***Acoustic intensity (watts per square meter, or W/m²):*** Acoustic or sound intensity is the amount of acoustic energy that passes through a unit area normal to the direction of propagation per second. It is the product of the sound pressure and the sound velocity. With an idealized constant source, the pressure and particle velocity will vary in proportion to each other at a given location, but the intensity will remain constant.

***Sound Levels:*** There is an extremely wide dynamic range of values when measuring acoustic pressure in pascals, so it is customary to use a logarithmic scale to compress the range of values. Aside from the ease it creates for comparing a wide range of values, animals (including humans) perceive sound on a logarithmic scale. These logarithmic acoustic quantities are known as sound levels and are expressed in decibels (dB), which is the logarithmic ratio of the measurement in question to a fixed reference value. Underwater acoustic sound pressure levels are referenced to a pressure of 1 micropascal (µPa) (equal to $10^{-6}$ pascals [Pa] or $10^{-11}$ bar). Note: airborne sound pressure levels have a different reference pressure: 20 µPa.

The metrics previously described (sound pressure, sound exposure, and intensity) can also be expressed as levels, and are commonly used in this way:

- root-mean-square sound pressure level ($L_{rms}$ or SPL, units of dB re 1 µPa)
- peak pressure level ($L_{pk}$, units of dB re 1 µPa)
- peak-to-peak pressure level ($L_{pk\text{-}pk}$, units of dB re 1 µPa)
- sound exposure level (SEL, units of dB re 1 $\mu Pa^2 s$)

**Note:** There are a few commonly-used time periods used for SEL, including a 24 hour period (used in the U.S. for the regulation of noise impacts to marine mammals ($SEL_{24}$)), or the duration of a single event, such as a single pile driving strike or an airgun pulse, called the single strike SEL ($SEL_{ss}$). A sound exposure for some other period of time, such as the entire installation of a pile, may be written without a subscript (SEL), but in order to be meaningful, should always denote the duration of the event.

***Source Level:*** Another commonly discussed concept is source level. Source level is a representation of the amount of acoustic power radiated from the sound source being described. It describes how loud a particular source is in a way that can inform expected received levels at various ranges. It can be conceptualized as the product of the pressure at a particular location and the range from that location to a spherical (omnidirectional) source in an idealized infinite lossless medium. The source level is the sum of the received level and the propagation loss to that receiver. It is often discussed as what the received level would be 1 m from the source, but this can lead to confusion as an actual measurement at 1 m is likely to be impossible for large and/or non-spherical sources. The most common type is an SPL source level in units of dB re 1 µPa-m, though in some circumstances a SEL source level (in dB re 1 $\mu Pa^2 s\text{-}m^2$) may be expressed; peak source level (in units of dB re 1 µPa-m) may also be appropriate for some sources.

### B.1.3.2 Propagation of Sound in the Ocean

Underwater sound can be described through a source-path-receiver model. An acoustic source emits sound energy that radiates outward and travels through the water and the seafloor. The sound level decreases with increasing distance from the acoustic source as the sound travels through the environment. The amount by which the sound levels decrease between the theoretical source level and a receiver is called propagation loss. Among other things, the amount of propagation loss that occurs depends on the source-receiver separation, the geometry of the environment the sound is propagating through, the frequency of the sound, the properties of the water column, and the properties of the seafloor and sea surface.

When sound waves travel through the ocean, they may encounter areas with different physical properties that will likely alter the propagation pathway of the sound, compared to a homogenous and boundaryless environment. For example, near the ocean's surface, water temperature is usually higher, resulting in relatively fast sound speeds. As temperature decreases with increasing depth, the sound speed decreases. Sounds bend toward areas with lower speeds (Urick 1983). Ocean sound speeds are often slowest at mid-latitude depths of about 1,000 m, and because of sound's preference for lower speeds, sound waves above and below this "deep sound channel" often bend towards it. Sounds originating in this layer can travel great distances. Sounds can also be trapped in the mixed layer near the ocean's surface (Urick 1983). Latitude, weather, and local circulation patterns influence the depth of the mixed layer, and the propagation of sounds near the surface is highly variable and difficult to predict.

At the boundaries near the sea surface and the sea floor, acoustic energy can be scattered, reflected, or attenuated depending on the properties at the surface (e.g., roughness, presence of wave activity, or bubbles) or seafloor (e.g., bathymetric features, substrate heterogeneity). For example, fine-grain sediments tend to absorb sounds well, while hard bottom substrates reflect much of the acoustic energy back into the water column. The presence of ice on the ocean's surface can also affect sound propagation. For example, the presence of solid ice may dampen sound levels by blocking surface winds. The presence of ice can also increase sound levels when pieces of ice break and/or scrape together (Urick 1983). The effect will also depend on the thickness and roughness of the ice, among many other factors related to the ambient conditions. As a sound wave moves from a source to a receiver (i.e., an animal), it may travel on multiple pathways that may be direct, reflected, refracted, or a combination of these mechanisms, creating a complex pattern of transmission across range and depth. The patterns may become even more complicated in shallow waters due to repeated interactions with the surface and the bottom, frequency-specific propagation, and more heterogenous seafloor properties. All of these variables contribute to the difficulty in reliably predicting the sound field in a given marine environment at any particular time.

### B.1.3.3 Sound Source Classification

In the current regulatory context, anthropogenic sound sources are divided into four types: impulsive, non-impulsive, continuous, and intermittent, based on their differing potential to affect marine species (NMFS 2018). Specifically, when it comes to potential damage to marine mammal hearing, sounds are classified as either impulsive or non-impulsive, and when considering the potential to affect behavior or acoustic masking, sounds are classified as either continuous or intermittent.

Impulsive noises are characterized as having (ANSI S1.13-2005 , Measurement of Sound Pressure Levels In Air (Finneran 2016)):

- broadband frequency content
- fast rise-times and rapid decay times
- short durations (i.e., <1 s)
- high peak sound pressures.

Whereas the characteristics of non-impulsive sound sources are less clear but may be:

- variable in spectral composition, i.e., broadband, narrowband, or tonal
- longer rise-time/decay times, and total durations compared to an impulsive sound
- continuous (e.g., vessel engine radiated noise), or intermittent (e.g., echosounder pulses).

It is generally accepted that sources like explosions, airguns, sparkers, boomers, and impact pile-driving are impulsive and have a greater likelihood of causing hearing damage than non-impulsive sources (note: explosions are further considered for non-auditory injury, see *Thresholds for Explosives* section). At close distances to impulsive sounds, physiological effects to an animal are likely, including TTS and PTS. This binary, at-the-source classification of sound types, therefore, provides a conservative framework upon which to predict potential adverse hearing impacts to marine mammals.

For behavioral effects of anthropogenic sound on marine mammals, NMFS classifies sound sources as either intermittent or continuous (NMFS 2018). Continuous sounds, such as drilling or vibratory pile-driving, remain “on”, i.e., above ambient noise, for a given period of time, though this is not well-defined. An intermittent sound typically consists of bursts or pulses of sound on a regular on-off pattern, also called the duty-cycle. Examples of intermittent sounds are those from scientific echosounders, sub-bottom profilers, and even pile-driving. It is important to recognize that these delineations are not always practical in application, as a continuous yet moving sound source (such as a vessel passing over a fixed receiver) could be considered intermittent from the perspective of the receiver.

In reality, animals will encounter many signals in their environment which may contain many or all of these sound types, called complex sounds. And even for sounds that are impulsive at the source, as the signal propagates through the water, the degree of impulsiveness decreases (Martin et al. 2020). While there is evidence, at least in terrestrial mammals (Hamernik and Hsueh 1991), that complex sounds can be more damaging than continuous sounds, there is not currently a regulatory category for this type of sound. One current approach for assessing the impulsiveness of a sound that has gained attention is to compute the kurtosis of that signal. Kurtosis is a statistical measure that describes the prevalence of extreme values within a distribution of observations, in other words the “spikiness” of the data. Martin et al. (2020) showed that a sound with a kurtosis value of 3 or less has very few extreme values and is generally considered Gaussian (i.e., normally distributed) noise, whereas a kurtosis value greater than 40 represents a distribution of observations with many extreme values and is very spiky. This generally describes an impulsive noise. A distribution of sound level observations from a time series with a kurtosis value somewhere in between these two values would be considered a complex sound.

## B.2 Sound Sources Related to Offshore Wind Development

### B.2.1 Geophysical and Geotechnical Surveys

Geophysical and geotechnical surveys are conducted to characterize the bathymetry, sediment type, and benthic habitat characteristics of the marine environment. They may also be used to identify archaeological resources or obstacles on the seafloor. These types of surveys occur in the site assessment phase in order to inform the routing and placement of cables and foundations but may also occur intermittently during and after construction to identify, guide, and confirm the positions. The suite of high-resolution geophysical (HRG) sources that may be used in geophysical surveys includes side-scan sonars (SSS), multibeam echosounders (MBES), magnetometers and gradiometers, parametric sub-bottom profilers, compressed high-intensity radiated pulses (CHIRP) sub-bottom profilers, boomers, and/or sparkers. Seismic airguns are not expected to be used for offshore wind applications. These HRG sources may be towed behind a ship, mounted on a ship’s hull, or deployed from ROVs or AUVs.

All HRG sources are active acoustic sources, meaning they produce sound deliberately in order to obtain information about the environment. Except for some MBES and SSS, these HRG sources produce sounds below 180 kHz and thus may be audible to marine species. Source levels vary widely depending on source type and operational power level used, from ~145 dB re 1 µPa-m for towed sub-bottom profilers up to 245 dB re 1 µPa-m for some multibeam echosounders (Crocker and Fratantonio 2016). In other words, HRG sources that emit sound in narrow beams directed at the seafloor are less likely to affect marine species because they ensonify a small portion of the water column, thus reducing the likelihood that an animal encounters the sound. While sparkers are omnidirectional, most other HRG sources have narrow beamwidths (e.g., MBES: up to 6°, parametric SBPs: 30°, boomers: 30-90°), (Crocker and Fratantonio 2016). Most HRG sources emit short pulses of sound, with periods of silence in between. This means that only several “pings” emitted from a vessel towing an active acoustic source would reach an animal below, even if the animal was stationary (Ruppel et al. 2022). HRG surveys may occur throughout the construction area with the potential for greater effort in some areas.

Geotechnical surveys may use vibracores, jet probes, bottom-grab samplers, deep borings, or other methods to obtain samples of sediments at each potential turbine location and along the cable route. For most of these methods, source levels have not been measured, but it is generally assumed that low-frequency, low-level noise will be introduced as a byproduct of these actions. It is likely that the sound of the vessel will exceed that generated by the geotechnical method itself.

### B.2.2 Unexploded Ordnance (UXO) Detonations

Unexploded Ordnances (UXOs) may be discovered on the seabed in offshore wind lease areas or along export cable routes. While non-explosive methods may be employed to lift and move these objects, some may need to be detonated. Underwater explosions of this type create a shock wave with a nearly instantaneous rise in pressure, followed by a series of symmetrical bubble pulses. Shock waves are supersonic, so they travel faster than the speed of sound. The explosive sound field is extremely complex, especially in shallow waters. In 2015, (von Benda-Beckmann et al.) measured received levels of explosions in shallow waters at distances ranging from 100–2000 m from the source, in water depths ranging from 6-22 m. The measured SEL from the explosive removal of a 263 kg charge was 216 dB re 1 µPa$^2$s at a distance of 100 m and 196 dB re 1 µPa$^2$s at 2,000 m. They found that SELs were lower near the surface than near the seafloor or in the middle of the water column, suggesting that if an animal is near the surface, the effects may be less damaging. Most of the acoustic energy for underwater explosions is below 1,000 Hz.

As an alternative to traditional detonation, a newer method called deflagration allows for the controlled burning of underwater ammunition. Typically, an ROV uses a small, targeted charge to initiate rapid burning of the ordnance; once this process is complete, the remaining debris can be cleared away. Recent work has demonstrated that both peak sound pressure $L_{pk}$ and SEL measured from deflagration events may be as much as 20 dB lower than equivalently sized high-order detonations (Robinson et al. 2020).

## B.2.3 Construction and Installation

### B.2.3.1 Impact and Vibratory Pile-Driving

At present, the installation of turbine foundations is largely done using pile-driving. There are several techniques, including impact and vibratory driving, and many pile designs and sizes, including monopile and jacket foundations. Impact pile driving employs a hammer to strike the pile head and force the pile into the sediment with a typical hammer strike rate of approximately 30 to 50 strikes/minute. Typically, force is applied over a period of less than 20 ms, but the pile can generate sound for upwards of 0.5 s. Pile driving noise is characterized as impulsive because of its high peak pressure, short duration, and rapid onset time. Underwater sound levels generated during pile-driving depend on many factors including the pile material and size, characteristics of the substrate, penetration of the pile in the seabed, hammer energy and size, and water depth. Currently the design envelope for most offshore wind turbine installations anticipates hammer energy between 2,500 and 4,000 kJ, but generally speaking, with increasing pile diameter, greater hammer energy is used. The propagation of pile-driving sounds depends on factors such as the sound speed in the water column (influenced by temperature, salinity, and depth), the bathymetry, and the composition of sediments in the seabed and will therefore vary among sites. Due to variation in these features, sounds may not radiate symmetrically outward from a pile.

BOEM has invested in the Realtime Opportunity for Development of Environmental Observations (RODEO) efforts to measure sound installation and operation of Block Island Wind Farm (BIWF) and Coastal Virginia Offshore Wind (CVOW). Similar studies have been completed at multiple facilities in Europe. Measurements of sounds from impact pile driving at CVOW were conducted at ranges between 750 m and 30 km from the two 7.8-meter diameter monopiles. Results showed that without any noise abatement method in place, the maximum broadband peak sound pressure $L_{pk}$ at 750 m from the pile was 190 dB re 1 µPa, and the maximum single strike sound exposure level (SEL) at that range was 170 dB re 1 µPa$^2$s. Most of the acoustic energy occurred between 30 and 300 Hz (HDR 2020). At 7.5 km distance, the maximum measured $L_{pk}$ was 174 dB re 1 µPa, and at 25 km, it fell to 144 dB re 1 µPa. The peak particle velocity on the seabed, measured 500 m from the foundation, was 114 dB re 1 nm/s (Amaral et al. 2021).

Jacket foundations are also common, if not for the main turbine structures, for other structures associated with the wind farm such as the offshore substations (OSS). Jacket foundations are installed using pin piles which are generally significantly smaller than monopiles, on the order of 2-5 meters in diameter, but more pin piles are needed per foundation. The sound levels generated will vary depending on the pile material, size, substrate, hammer energy, and water depth. At BIWF, the 1.4 m pin piles were installed using <160 kJ of energy, compared to the 7.8-meter diameter monopiles installed at CVOW which required >320 kJ, sometimes as much as 700 kJ, to install. The maximum single strike sound exposure levels (SEL) measured at 750 m from the jacket foundations at BIWF ranged from 160 to 168 dB re 1 $\mu Pa^2 s$, nearly 10 dB lower than CVOW. Using measurements combined with acoustic modeling, the peak-peak source levels for pile driving at BIWF were estimated to be between 233 and 245 dB re 1 µPa-m (Amaral et al. 2018).

Vibratory hammers may be used as an alternative to impact pile driving. The vibratory hammer continuously exerts vertical vibrations into the pile, which causes the sediment surrounding the pile to liquefy, allowing the pile to penetrate the substrate. The vibratory hammer typically oscillates at a frequency of 20 to 40 Hz (Matuschek and Betke 2009) and produces most of its acoustic energy below 2 kHz. While measurements of vibratory pile driving of large monopiles have not been reported, Buehler et al. (2015) measured sound levels at 10 m distance from a 72” steel pile, and found them to be 185 dB re 1 µPa Vibratory pile-driving is a non-impulsive sound source, but because the hammer is on continuously, underwater sound introduced would be into the water column for a longer period of time than with impact pile-driving.

A technique that is quickly gaining use for installation in hard rock substrates is down-the-hole pile (DTH) driving, which uses a combination of percussive and drilling mechanisms, with a hammer acting directly on the rock to advance a hole into the rock, and also advance the pile into that hole (Guan et al. 2022). Noise characteristics for DTH pile driving include both impulsive and non-impulsive components. The impulsive component of the DTH pile driving is the result of a percussive hammer striking the bedrock, while the non-impulsive component is from drilling and air-lifting of cuttings and debris from the pile. While only limited studies have been conducted on DTH pile driving noise, its characteristics strongly resemble those of impact pile driving, but with a higher hammer striking rate (approximately 10 to 15 Hz). The dominant frequencies from DTH pile driving are below 2 kHz, similar to conventional impact pile driving. Due to the high rate of hammer striking, along with the sounds of drilling and debris clearing out, sound levels in between the pulses are much higher than conventional impact pile driving (Guan et al. 2022).

Various noise abatement technologies, such as bubble curtains, arrays of enclosed air resonators, or segmented nets of rubber or foam, may be employed to reduce noise from impact pile driving. Measurements from European wind farms have shown that a single noise abatement system can reduce broadband sound levels by 10 to 15 dB, while using two systems together can reduce sound levels as much as 20 dB (Bellmann et al. 2020). Based on RODEO measurements from CVOW, double Big Bubble

Curtains (dBBC) are shown to be most effective for frequencies above 200 Hz, and greater noise reduction was seen in measurements taken in the middle of the water column compared to those near the seabed. Approximate sound level reduction is 3 to 5 dB below 200 Hz, and 8 to 20 dB above 200 Hz, depending on the characteristics of the bubble curtain (Amaral et al. 2020).

#### B.2.3.2 Vessels

During construction, vessels and aircraft may be used to transport crew and equipment. See the **Operations and Maintenance** section for further detail about sounds related to those activities. Large vessels will also be used during the construction phase to conduct pile-driving, and may use Dynamic Positioning (DP) systems. DP is the process by which a vessel holds station over a specific seafloor location for some time period using input from gyrocompasses, motion sensors, GPS, active acoustic positioning systems, and wind sensors to determine relative movement and environmental forces at work. Generally speaking, most acoustic energy is <1,000 Hz, often below 50 Hz, with tones related to engine and propeller size and type. The sound can also vary directionally, and this directionality is much more pronounced at higher frequencies. Because this is a dynamic operation, the sound levels produced will vary based on the specific operation, DP system used (e.g., jet or propeller rotation, versus a rudder or steering mechanism), and factors such as the blade rate and cavitation, in some cases. Representative sound field measurements from the use of DP are difficult to obtain because the sound transmitted is often highly directional and context specific. The direction of sound propagation may change as different DP needs requiring different configurations are applied.

Many studies have found that the measured sound levels of DP alone are, counterintuitively, higher than those of DP combined with the intended activities such as drilling (Jiménez-Arranz et al. 2020; Kyhn et al. 2011; Nedwell and Edwards 2004) and coring (Warner and McCrodan 2011). Nedwell and Edwards (2004) reported that DP thrusters of the semi-submersible drill rig *Jack Bates* produced periodic noise (corresponding to the rate of the thruster blades) with most energy between 3 to 30 Hz. The received SPL measured at 100 m from the vessel was 188 dB re 1 µPa. Warner and McCrodan (2011) found that most DP related sounds from the self-propelled drill ship, R/V *Fugro Synergy* were in the 110 to 140 Hz range, with an estimated source level of 169 dB re 1 µPa-m. Sounds in this frequency range varied by 12 dB during DP, while the broadband levels, which also included diesel generators and other equipment sounds, varied by only 5 dB over the same time period. All of the above sources report high variability in levels with time. This is due in part to the intermittent usage and relatively slow rotation rates of thrusters used in DP. It is also difficult to provide a realistic range of source levels from the data thus far because most reports do not identify the direction from which sound was measured relative to the vessel, and DP thrusters are highly directional systems.

The active acoustic positioning systems used in DP can be additional sources of high frequency sound. These systems usually consist of a transducer mounted through the vessel's hull and one or more transponders affixed to the seabed. Kongsberg High Precision Acoustic Positioning (HiPAP) systems produces pings in the 10 to 32 kHz frequency range. The hull-mounted transducers have source levels of 188 to 206 dB re 1 µPa-m depending on adjustable power settings (Kongsberg Maritime AS 2013). The fixed transponders have maximum source levels of 186–206 dB re 1 µPa-m depending on model and beam width settings from 15 to 90° (Jiminez-Arranz et al. 2020). These systems have high source levels, but beyond 2 km, they are generally quieter than other components of the sound from DP vessels for various reasons including: their pulses are produced in narrowly directed beams, each individual pulse is very short and their high frequency content leads to faster attenuation.

#### B.2.3.3 Dredging, Trenching, and Cable-Laying

The installation of cables can be done by towing a tool (i.e. jet plow, mechanical cutting/trenching tool, conventional cable plow) behind the installation vessel to simultaneously open the seabed and lay the cable, or by laying the cable and following with a tool to embed the cable. Possible installation methods for these options include jetting, vertical injection, control flow excavation, trenching, and plowing. Burial depth of the cables is typically 1 to 2 m. Cable installation vessels may use utilize dynamic positioning to lay the cables.

Nedwell et al. (2003) recorded underwater sound at 160 m from trenching, in water depths of 7 to 11 m, and back-calculated the source level to be 178 dB re 1 µPa-m. They describe trenching sound as generally broadband in nature, but variable over time, with some tonal machinery noise and transients associated with rock breakage. McQueen et al. (2018) summarized results from several studies measuring the sounds of dredging operations. They report source levels from hydraulic and mechanical dredges typically used to excavate sand or rock. Source levels from cutterhead suction dredges range from 168 to 175 dB re 1 µPa-m, and trailing suction hopper dredges are typically 172 to 190 dB re 1 µPa-m. Most of the energy from dredging is below 1000 Hz (McQueen et al. 2018).

### B.2.4 Operations and Maintenance

#### B.2.4.1 Aircraft

Manned aircraft consist of propeller and jet engines, fixed-wing craft, as well as helicopters. Unmanned systems also exist. For jet engine aircraft, the engine is the primary source of sound. For propeller driven aircraft and helicopters, the propellors and rotors also produce noise. Aircraft generally produce low-frequency sound below 500 Hz (Richardson et al. 1995). While aircraft noise can be substantial in air, penetration of aircraft noise into the water is limited because much of the noise is reflected off the water's surface (Richardson et al. 1995). The noise that does penetrate into the water column does this via a critical incident angle or cone. With an idealized flat sea surface, the maximum critical incident angle is ~13 degrees (Urick 1983); beyond this, sound is reflected off the surface. When the sea surface is not flat, there may be some additional penetration into the water column in areas outside of this 13-degree cone. Nonetheless, the extent of noise from passing aircraft is more localized in water than it is in air.

Jiménez-Arranz et al. (2020) reviewed Richardson et al. (1995)'s sound measurements recorded below passing aircraft of various models. These SPL measurements included 124 dB re 1 µPa (dominant frequencies between 56-80 Hz) from a maritime patrol aircraft with an altitude of 76 m, 109 dB re 1 µPa (dominant frequency content below 22 Hz) from a utility helicopter with an altitude of 152 m, and 107 dB re 1 µPa (tonal, 82 Hz) from a turbo propeller with an altitude of 457 m. Recent published levels associated with unmanned aircraft (Christiansen et al. 2016; Erbe et al. 2017) indicate source levels around or below 100 dB re 1 µPa-m.

### B.2.4.2 Vessels in Transit

During operations, small vessels may be used to transport crew and supplies. Noise from vessel transit is considered to be continuous, with a combination of broadband and tonal sounds (Richardson et al. 1995; Ross 1976). Transiting vessels generate continuous sound from their engines, propeller cavitation, onboard machinery, and hydrodynamics of water flows (Ross 1976). The actual radiated sound depends on several factors, including the type of machinery on the ship, the material conditions of the hull, how recently the hull has been cleaned, interactions with the sea surface, and shielding from the hull, which reduces sound levels in front of the ship.

In general, vessel noise increases with ship size, power, speed, propeller blade size, number of blades, and rotations per minute. Source levels for large container ships can range from 177 to 188 dB re 1 µPa-m (McKenna et al. 2013) with most energy below 1 kHz. Smaller vessels typically produce higher-frequency sound concentrated in the 1-5 kHz range. Kipple and Gabriele (2003) measured underwater sound from vessels ranging from 14 to 65 ft long (25 to 420 horsepower) and back-calculated source levels to be 157 to 181 dB re 1 µPa-m. Similar levels are reported by Jiménez-Arranz et al. (2020), who provide a review of measurements for support and crew vessels, tugs, inflatable RIHBs, icebreakers, cargo ships, oil tankers, and more.

During transit to and from shore bases, survey vessels typically travel at speeds that optimize efficiency, except in areas where transit speed is restricted. The vessel strike speed restrictions that are in place along the Atlantic OCS are expected to offer a secondary benefit of underwater noise reduction. For example, recordings from a speed reduction program in the Port of Vancouver (210 to 250 m water depths) showed that reducing speeds to 11 knots reduced vessel source levels by 5.9 to 11.5 dB, depending on the vessel type (MacGillivray et al. 2019). Vessel noise is also expected to be lower during geological and geophysical surveys, as they typically travel around 5 knots when towing instruments.

### B.2.4.3 Turbine Operations

Once windfarms are operational, low-level sounds are generated by each wind turbine generator (WTG), but sound levels are much lower than during construction. This type of sound is considered to be continuous, omnidirectional radially from the pile, and non-impulsive. Most of the energy associated with operations is below 120 Hz. Sound levels from wind turbine operations are likely to increase somewhat with increasing generator size and power ratings, as well as with wind speeds. Recordings from Block Island Wind Farm indicated that there was a correlation between underwater sound levels and increasing wind speed, but this was not clearly influenced by turbine machinery; rather it may have been explained by the natural effects that wind and sea state have on underwater sound levels (Elliott et al. 2019; Urick 1983).

A recent compilation (Tougaard et al. 2020) of operational noise from several wind farms, with turbines up to 6.15 MW in size, showed that operational noise generally attenuates rapidly with distance from the turbines (falling to near ambient sound levels within ~1 km from the source), and the combined noise levels from multiple turbines is lower or comparable to that generated by a small cargo ship. Tougaard et al. (2020) developed a formula predicting a 13.6 dB increase for every 10-fold increase in WTG power rating. This means that operational noise could be expected to increase by 13.6 dB when increasing in size from a 0.5 MW turbine to a 5 MW one, or from 1 MW to 10 MW. The least squares fit of that dataset would predict that the SPL measured 100 m from a hypothetical 15 MW turbine in operation in 10 m/s (19 kt or 22 mph) wind would be 125 dB re 1 µPa. However, all of the 46 data points in that dataset -with the exception of the two from BIWF- were from WTGs operated with gear boxes of various designs rather than the newer use of direct drive technology, which is expected to lower underwater noise levels significantly. Stöber and Thomsen (2021) make predictions for source levels of 10 MW turbines based on a linear extrapolation of maximum received levels from WTGs with ratings up to 6.15 MW. The linear fit is likely inappropriate, and the resulting predictions may be exaggerated. Tougaard et al. (2020) point out that received level differences among different pile types could be confounded by differences in water depth and turbine size. In any case, additional data is needed to fully understand the effects of size, foundation type properties (e.g., structural rigidity and strength), and drive type on the amount of sound produced during turbine operation.

### B.2.5 Decommissioning

The methods that may be used for decommissioning are not well understood at this time. It is possible that explosives may be used (see **UXO section**). However, given the general trend of reducing the use of underwater explosives that has been observed in the oil and gas industry, it is likely that offshore wind structures will instead be removed by cutting. While it is difficult to extrapolate directly, we can glean some insights from a recent study which measured received sound levels during the mechanical cutting of well conductor casings on oil and gas platforms in California. The cutters operated at 60 to 72 RPM, and the cutting time varied widely between cuts (on the order of minutes to hours). At distances of 106 to 117 m from the cutting, received SPLs were 120 to 130 dB re 1 µPa, with most acoustic energy falling between 20 and 2,000 Hz (Fowler et al. 2022). This type of sound is considered to be non-impulsive and intermittent (i.e., continuous while cuts are actually being made, with quieter periods between cuts). Additional noise from vessels and other machinery may also be introduced throughout the decommissioning process.

## B.3 Regulation of Underwater Sound for Marine Mammals

The MMPA prohibits the “take” of marine mammals, defined as the harassment, hunting, capturing, killing, or an attempt of any of those actions on a marine mammal. This act requires that an incidental take authorization (ITA) be obtained for the incidental take of marine mammals as a result of anthropogenic activities. MMPA regulators divide the effects on marine mammals that could result in a take into Level A and Level B, defined as follows:

- Level A: Any act of pursuit, torment, or annoyance that has the potential to injure a marine mammal or marine mammal stock in the wild.

- Level B: Any act of pursuit, torment, or annoyance that has the potential to disturb a marine mammal or marine mammal stock in the wild by causing a disruption of behavioral patterns including, but not limited to, migration, breathing, nursing, breeding, feeding, or sheltering but that does not have the potential to injure a marine mammal or marine mammal stock in the wild (16 USC 1362).

With respect to anthropogenic sounds, Level A takes generally include injury impacts like PTS, whereas Level B takes include behavioral effects as well as TTS. The current regulatory framework used by NMFS for evaluating an acoustic take of a marine mammal involves assessing whether the animal's received sound level exceeds a given threshold. For Level A, this threshold differs by functional hearing group, but for Level B, the same threshold is used across all marine mammals.

### B.3.1 Thresholds for Injury

The current NMFS (2018) injury (Level A) thresholds consist of dual criteria of $L_{pk}$ and 24 hour-cumulative SEL thresholds (Table B-1). These criteria are used to predict the potential range from the source within which injury may occur. The criterion that results in the larger physical impact range is generally used to be most conservative. The SEL thresholds are frequency-weighted, which means that the sound is essentially filtered based on the animal's frequency-specific hearing sensitivity, de-emphasizing the frequencies at which the animal is less sensitive (see Chapter 3 the Affected Environment and Environmental Consequences section for the frequency range of hearing for each group). The frequency weighting functions are described in detail in Finneran (2016).

**Table B-1. The acoustic thresholds for onset of permanent threshold shift (PTS) and temporary threshold shift (TTS) for marine mammals for both impulsive and non-impulsive sound sources NMFS (2018)**

| Marine Mammal Functional Hearing Group | Effect | Impulsive Sources<br>$L_{pk}$ (dB re 1 µPa) | Impulsive Sources<br>Weighted $SEL_{24h}$ (dB re 1 µPa²s) | Non Impulsive Source<br>Weighted $SEL_{24h}$ (dB re 1 µPa²s) |
|---|---|---|---|---|
| Low-frequency cetaceans | PTS | 219 | 183 | 199 |
| Low-frequency cetaceans | TTS | 213 | 168 | 179 |
| Mid-frequency cetaceans | PTS | 230 | 185 | 198 |
| Mid-frequency cetaceans | TTS | 224 | 170 | 178 |
| High-frequency cetaceans | PTS | 202 | 155 | 173 |

| Marine Mammal Functional Hearing Group | Effect | Impulsive Sources<br>$L_{pk}$ (dB re 1 µPa) | Impulsive Sources<br>Weighted $SEL_{24h}$ (dB re 1 µPa$^2$s) | Non Impulsive Source<br>Weighted $SEL_{24h}$ (dB re 1 µPa$^2$s) |
|---|---|---|---|---|
| High-frequency cetaceans | TTS | 196 | 140 | 153 |
| Phocid pinnipeds underwater | PTS | 218 | 185 | 201 |
| Phocid pinnipeds underwater | TTS | 212 | 170 | 181 |
| Otariid pinnipeds underwater | PTS | 232 | 203 | 199 |
| Otariid pinnipeds underwater | TTS | 226 | 188 | 199 |

Note: $L_{pk}$ values are unweighted within the generalized hearing range of marine mammals (i.e., 7 Hz to 160 kHz): Values presented for SEL use a 24-hour accumulation period unless stated otherwise, and are weighted based on the relevant marine mammal functional hearing group (Finneran 2016). dB re 1 µPa = decibels relative to 1 micropascal; dB re 1 µPa2s = decibels relative to 1 micropascal squared second.

### B.3.2 Thresholds for Behavioral Disturbance

NMFS currently uses a threshold for behavioral disturbance (Level B) of 160 dB re 1 µPa SPL for non-explosive impulsive sounds (e.g., airguns and impact pile-driving) and intermittent sound sources (e.g., scientific and non-tactical sonar), and 120 dB re 1 µPa SPL for continuous sounds (e.g., vibratory pile-driving, drilling, etc.) (NMFS 2023a). This is an “unweighted” criterion that is applicable for all marine mammal species. In-air behavioral thresholds exist for harbor seals and non-harbor seal pinnipeds at 90 dB re 20 µPa SPL and 100 dB re 20 µPa SPL, respectively (NMFS 2023a). Unlike with sound exposure level-based thresholds, the accumulation of acoustic energy over time is not relevant for this criterion – meaning that a Level B take can occur even if an animal experiences a received SPL of 160 dB re 1 µPa very briefly just once.

While the Level B criterion is generally applied in a binary fashion, as alluded to previously, there are numerous factors that determine whether an individual will be affected by a sound, resulting in substantial variability even in similar exposure scenarios. In particular, it is recognized that the context in which a sound is received affects the nature and extent of responses to a stimulus (Ellison et al. 2012; Southall et al. 2007). Therefore, a “step function” concept for Level B harassment was introduced by Wood et al. (2012) whereby proportions of exposed individuals experience behavioral disturbance at different received levels, centered at an SPL of 160 dB re 1 µPa. These probabilistic thresholds reflect the higher sensitivity that has been observed in beaked whales and migrating mysticete whales (Table B-2). At the moment, this step function provides additional insight to calculating level B takes for certain species groups. The M-weighting functions, described by Southall et al. (2007) and used for the

Wood et al. (2012) probabilistic disturbance step thresholds are different from the weighting functions by Finneran (2016), previously mentioned. The M-weighting was specifically developed for interpreting the likelihood of audibility, whereas the Finneran weighting functions were developed to predict the likelihood of auditory injury.

**Table B-2. Probabilistic disturbance $\text{SPL}_{\text{rms}}$ thresholds (M-weighted) used to predict a behavioral response**

| Marine Mammals | Probabilistic disturbance $\text{SPL}_{\text{rms}}$ thresholds* M-weighted dB re: 1 µPa (rms) | | | |
|---|---|---|---|---|
| Marine mammal group | 120 | 140 | 160 | 180 |
| Porpoises/beaked whales | 50% | 90% | - | - |
| Migrating mysticete whales | 10% | 50% | 90% | - |
| All other Species/behaviors | - | 10% | 50% | 90% |

*Probabilities are not additive and reflect single points on a theoretical response curve.
From Wood et al. (2012)

### B.3.3 Thresholds for Explosives

Shock waves associated with underwater detonations can induce both auditory effects (PTS and TTS) and non-auditory physiological effects, including mortality and direct tissue damage, such as injury to the lungs and gastrointestinal (G.I.) tract. The auditory effects from explosions are treated similarly to impulsive sounds and the criteria in Table B-2 for PTS and TTS apply (NMFS 2018). Due to the ephemeral nature of an explosion, only short-term startle responses are expected as far as behavioral responses. Therefore, no unique threshold is used for behavioral responses to a single detonation, rather the threshold used is the SEL-based acoustic threshold for TTS from an impulsive sound. For multiple detonations, the threshold applied for behavioral effects is that same TTS threshold minus 5 dB. The acoustic impulse, measured in Pascal-seconds is the integral of the pressure shock pulse over time and serves as the threshold to predict non-auditory lung injury and mortality. Because lung capacity or size is generally directly related to the size of an animal, body mass is one parameter used to predict the likelihood of lung injury. In addition, the depth of the animal is used, as this represents the ambient pressure conditions of the animal and its vulnerability to a rapid change in pressure. The threshold upon which each effect may occur is based on a modified Goertner Equation (Department of Navy 2017), dependent on the animal’s mass and depth at exposure (Table B-3). Impulse thresholds for mortality and slight lung injury are calculated using the modified Goertner Equation presented in Department of Navy (2017), Equations 11 (slight lung injury) and 12 (mortality), where M is the animal’s mass in kilograms and D is the depth of the animal at exposure in meters. G.I. tract injury is also possible and is considered to occur at a peak sound pressure level of 237 dB re 1 µPa.

**Table B-3. Marine mammal acoustic thresholds used by NMFS for non-auditory injury and mortality from explosives**

| | Mortality (Pa·s) | Slight Lung Injury (Pa·s) | G.I. Tract Injury (Lpk, dB re 1μPa) |
|---|---|---|---|
| All marine mammals | $I=103M^{1/3}\left(1+\frac{D}{10.1}\right)^{1/6}$ | $I=47.5M^{1/3}\left(1+\frac{D}{10.1}\right)^{1/6}$ | 237 |

### B.3.4 Approach to Acoustic Exposure Modeling

In order to predict the number of individuals of a given species that may be exposed to harmful levels of sound from a specific activity, a series of modeling exercises are conducted. First, the sound field of a sound-generating activity is modeled based on characteristics of the source and the physical environment. From the sound field, the range to the U.S. regulatory acoustic threshold isopleths can be predicted. This approach is referred to as acoustic modeling. By overlaying the marine mammal density information for a certain species or population in the geographical area of the activity, the number of animals exposed within the acoustic threshold isopleths is then predicted. This is called exposure modeling. Some models further incorporate animal movement to make more realistic predictions of exposure numbers. Animal movement models may incorporate behavioral parameters including swim speeds, dive depths, course changes, or reactions to certain sound types, among other factors. Exposure modeling may be conducted for a range of scenarios including different seasons, energy (e.g., pile-driving hammers), mitigation strategies (e.g., 6 dB versus 10 dB of attenuation), and levels of effort (e.g., number of piles per day).

## B.4 Regulation of Underwater Sound for Fishes and Invertebrates

### B.4.1 Thresholds for Injury

During construction of the Bay Bridge in California, researchers observed dead fish near pile-driving operations, suggesting that fish could be killed when in very close proximity (<10 m) to the pile (Caltrans 2004). Further work around this construction project led to the formation of dual interim criteria by the Fisheries Hydroacoustic Working Group (2008), which were later adopted by the National Marine Fisheries Service (NMFS). With these interim criteria, the maximum permitted peak SPL for a single pile driving strike is 206 dB re 1 µPa, and the maximum accumulated SEL is 187 dB re 1µPa$^2$s for fishes greater than 2 grams, and 183 dB re 1µPa$^2$s for fishes below 2 grams (Table B-4). These criteria are still being used by NMFS, but given the new information obtained since 2008, the appropriateness of these thresholds is being reconsidered (Popper et al. 2019).

**Table B-4. Acoustic thresholds for exposure to pile-driving sound**

| | Mortality and Non-Recoverable injury | | Recoverable Injury | | TTS |
|---|---|---|---|---|---|
| Fish Hearing Group | $L_{pk}$ | SEL | $L_{pk}$ | SEL | SEL |
| [a]Fish without swim bladder (Group 1) | >213 | >219 | >213 | >216 | >>186 |
| [a]Fish with swim bladder not involved in hearing (Group 2) | >207 | 210 | >207 | 203 | >186 |
| [a]Fish with swim bladder involved in hearing (Group 3) | >207 | 207 | >207 | 203 | 186 |
| [a]Eggs and Larvae | >207 | >210 | -- | -- | -- |
| [b]Fish ≥2 g | | | 206 | 187 | |
| [b]Fish <2 g | | | 206 | 183 | |

[a] Popper et al. (2014) Sound Exposure Guidelines. Note that Popper et al. (2014) use the notation "$SEL_{cum}$," but SEL without a subscript is the preferred nomenclature, used here to describe the energy that would be accumulated over an entire pile-driving event (i.e., installation of a pile).

[b] Fisheries Hydroacoustic Working Group (2008).

These early findings prompted a suite of laboratory experiments in which a special testing apparatus was used to simulate signals from pile-driving that a fish would encounter around 10 m from a pile (Casper et al. 2013a; Casper et al. 2012; Casper et al. 2013b; Halvorsen et al. 2012a; Halvorsen et al. 2011; Halvorsen et al. 2012b). An important component of this work was the ability to simulate both the pressure and particle motion components of the sound field, which is rarely done in laboratory experiments. These studies showed that effects are greater in fishes with swim bladders than those without, and that species with closed swim bladders experienced greater damage than those with open swim bladders. Evidence of barotrauma was observed starting at peak pressures of 207 dB re 1 µPa (Halvorsen et al. 2012a). Larger animals seem to have a higher susceptibility to injury than smaller animals (Casper et al. 2013a). The researchers found that most of the species tested showed recovery from injury within 10 days of exposure, but they note that injured animals may be more vulnerable to predation while they are recovering, and these secondary effects have not been studied. The authors also conclude that SEL alone is not enough to predict potential impacts on fishes; the energy in a given strike and the total number of strikes are also important factors. These studies formed the foundation of the Guidelines for Fish and Sea Turtles by Popper et al. (2014), which became ANSI standard (#ASA S3/SC1.4 TR-2014) and have become widely accepted hearing thresholds for fishes and turtles.

No studies have directly measured TTS in fishes as a result of exposure to pile-driving noise. Popper et al. (2005) exposed caged fish to sounds of seismic airguns (an impulsive signal which can serve as a proxy) and tested their hearing sensitivity afterwards. Three species with differing hearing capabilities were exposed to 5 pulses at a mean received $L_{pk}$ of 207 dB re 1 µPa (186 dB re 1 $\mu Pa^2 s$ SEL). None of the fish showed evidence of barotrauma or tissue damage, nor was there damage to the hearing structures

(Song et al. 2008). The species with the least-sensitive hearing - the broad whitefish - showed no evidence of TTS. The northern pike and lake chub, species with more sensitive hearing, did exhibit TTS after exposure to seismic pulses, but showed recovery after 18 hours. The findings suggest that there is a relationship between hearing sensitivity and level of impact, and that species without a connection between the swim bladder and ear are unlikely to experience TTS. Nonetheless, Popper et al. (2014) propose 186 dB re 1 µPa$^2$s SEL as a conservative TTS threshold for all fishes exposed to either seismic airguns or pile-driving, regardless of hearing anatomy. They acknowledge that research is needed on potential TTS due to exposure to pile-driving noise, and that future work should measure particle motion as the relevant cue.

A handful of studies have directly investigated the effects of impulsive sounds on eggs and larvae of marine fishes and invertebrates, and most have taken place in the laboratory. Bolle et al. (2012) used a device similar to Halvorsen et al. (2012a) to simulate pile-driving sounds, and found no damage to larvae of common sole (which has a swim bladder at certain larval stages) from an SEL of 206 dB re 1 uPa$^2$s, which the authors surmise is equivalent to the received level at approximately 100 m from a 4 m diameter pile. Further work by Bolle et al. (2014) tested larvae of seabass and herring (both species have swim bladders). Several different life stages were tested, but none of the species showed a difference in mortality between control and exposed animals. The seabass were exposed to SELs up to 216 dB re 1 µPa$^2$s and maximum $L_{pk}$ of 217 dB re 1 µPa, while herring were exposed to SELs up to 212 dB re 1 µPa$^2$s and maximum $L_{pk}$ of 207 dB re 1 µPa. Together, the tested larvae represent the entire range of swim bladder shape types described by Popper et al. (2014). There was no difference in impacts experienced by species with and without a swim bladder, or between those with open or closed swim bladders. Based on this work, Popper et al. (2014) use 210 dB re 1 uPa$^2$s SEL as a threshold for mortality after exposure to both pile-driving and seismic airguns.

Popper et al. (2014) provide thresholds for non-recoverable injury, recoverable injury (i.e., mild forms of barotrauma), and TTS for the three hearing groups described in the Chapter 3 the Affected Environment and Environmental Consequences section, plus an additional category for eggs and larvae (Table B-4). Unlike with marine mammals, Popper et al. (2014) do not distinguish between impulsive and non-impulsive sounds; instead they provide thresholds for each sound type (explosions, pile-driving, seismic airguns, sonars, and continuous sounds). That said, studies focused on pile-driving are sometimes used to draw conclusions about impacts from seismic airguns, and vice versa. This is simply due to a lack of comprehensive data for each source type. The thresholds are all given in terms sound pressure, not particle motion, though many have acknowledged that these would be more appropriate (Popper and Hawkins 2018). Currently, there are no underwater noise thresholds for invertebrates, but the effect ranges are expected to be similar to those predicted for fishes in Group 1.

### B.4.2 Thresholds for Behavioral Disturbance

NOAA Fisheries currently uses an SPL criterion of 150 dB re 1 µPa for the onset of behavioral effects in fishes ((GARFO) 2020). The scientific rationale for this criterion is not well supported by the data (Hastings 2008), and there has been criticism about its use (Popper et al. 2019). Most notably, the differences in hearing anatomy among fishes suggest the use of a single criterion may be too simplistic.

Furthermore, a wide range of behavioral responses have been observed in the empirical studies thus far (ranging from startle responses to changes in schooling behavior), and it is difficult to ascertain which, if any, of those responses may lead to significant biological consequences. Interestingly, several recent studies on free-ranging fishes (e.g., [Hawkins et al. 2014; Roberts et al. 2016]), have observed the onset of different behavioral responses at similar received levels ($L_{pk\text{-}pk}$ of 152 to 167 dB re 1 µPa), and Popper et al. (2019) suggest that a received level of 163 dB re 1 µPa $L_{pk\text{-}pk}$ might be more appropriate than the current criterion of 150 re 1 µPa $L_{rms}$. Finally, given that most species are more sensitive to particle motion and not acoustic pressure, the criteria should, at least in part, be expressed in terms of particle motion. However, until there is further empirical evidence to support a different criterion, the 150 dB re 1 µPa $L_{rms}$ threshold remains in place as the interim metric that regulatory agencies have agreed upon.

### B.4.3 Thresholds for Explosives

Popper et al. (2014) present criteria for mortality and non-recoverable injury as a result of exposure to detonations. They note that it is difficult to disentangle the effects of the compressive forces of the shock wave (very close to the explosion) versus the decompressive effect (area of negative pressure, further from the explosion), but either can lead to barotrauma or mortality in fishes. Several studies (e.g., Goertner (1978); Yelverton (1975)) have worked with different species, with different charge sizes and water depths – all of which are important factors in predicting the effects of explosives. Yet Popper et al. (2014) derive their thresholds using data from an older study which represents the lowest amplitude that caused consistent mortality across species (Hubbs and Rechnitzer 1952). Therefore, for all fishes, regardless of hearing anatomy, the threshold for mortality and non-recoverable injury is given as a range: 229 to 234 dB re 1 µPa $L_{pk}$ by Popper et al. (2014), but in practice, 229 dB is likely used.

## B.5 Regulation of Underwater Sound for Sea Turtles

There are few empirical data available to form regulatory thresholds for sea turtle exposure to underwater sound. For several years, the regulatory community accepted the recommendations of Popper et al. (2014) and used their thresholds for fishes without swim bladders as a proxy for sea turtles. Work by the US Navy (Finneran et al. 2017) which was based on exposure studies (e.g., McCauley et al. 2000) now serve as the foundation of present-day thresholds for PTS, TTS, and behavioral responses and are recommended by NMFS (2023b). Dual criteria (Lpk and $SEL_{24h}$) have been suggested for PTS and TTS, along with auditory weighting functions published by Finneran et al. (2017) used in conjunction with SEL thresholds for PTS and TTS. The behavioral threshold recommended NMFS (2023b) is an SPL of 175 dB re 1 µPa (Finneran et al. 2017; McCauley et al. 2000) (Table B-5). These thresholds apply to all life stages.

**Table B-5. Acoustic thresholds for sea turtles currently used by National Marine Fisheries Service (NMFS) Greater Atlantic Regional Fisheries Office (GARFO) and Bureau of Ocean Energy Management (BOEM) for auditory effects from impulsive and non-impulsive signals, as well as thresholds for behavioral disturbance**

| Impulsive Signals | | | | Non-impulsive Signals | | All |
|---|---|---|---|---|---|---|
| PTS | | TTS | | PTS | TTS | Behavior |
| Lpk | SEL24hr | Lpk | SEL24hr | SEL24hr | | SPL |
| 232 | 204 | 226 | 189 | 220 | 200 | 175 |

Source: Finneran et al. (2017), McCauley et al. (2000)

Lpk = peak sound pressure level in units of dB re 1 µPa; PTS = permanent threshold shift; $SEL_{24h}$ = sound exposure level over 24 hours in units of dB re 1 µPa$^2$ s; SPL = root-mean-square sound pressure level in units of dB re 1 µPa; TTS = temporary threshold shift.

### B.5.1 Thresholds for Auditory Injury

As a conservative approach, Popper et al. (2014) recommended using thresholds developed for fishes without swim bladders for sea turtles in response to impulsive sounds. Finneran et al. (2017) agree, that while still unsatisfactory, data from fish provide a better analogy currently due to similar hearing range and that the functioning basilar papilla in the turtle ear is dissimilar to the functioning cochlea in mammals. When exposed to acoustic signals representative of low- and mid-frequency active sonar, Halvorsen et al. (2013) and Halvorsen et al. (2012c) reported TTS in some species of fish exposed to $SEL_{24h}$ of approximately 220 dB re 1 µPa$^2$ s between 2 and 3 kHz, and 210 to 215 dB re 1 µPa$^2$ s between 170 and 320 Hz, respectively (Finneran et al. 2017). Based on these data the US Navy uses an estimated $SEL_{24h}$ of 200 dB re 1 µPa2s for TTS onset in sea turtles. An 11 dB difference, on average, was found between SEL-based impulsive and non-impulsive TTS thresholds for marine mammals. By applying the same rule to turtles, Finneran et al. (2017) derived a weighted SEL-based impulsive TTS threshold of 189 dB re 1 µPa$^2$ s which is 3 dB higher than the previously recommended unweighted threshold by Popper et al. (2014) of 186 dB re 1 µPa$^2$ s (Finneran et al. 2017). Based on the relatively high SEL-based TTS threshold derived for sea turtles, Finneran et al. (2017) hypothesized that the Lpk based threshold for sea turtles would be higher than that for marine mammals. Consequently, the sea turtle Lpk based TTS threshold for impulsive noise is set to 226 dB re 1 µPa, to match the highest marine mammal value. Sea turtle PTS data from impulsive noise exposures do not exist, therefore PTS onset was estimated by adding 15 dB to the derived SEL-based TTS thresholds and adding 6 dB to the Lpk thresholds (Finneran et al. 2017)

### B.5.2 Thresholds for Behavioral Disturbance

There are limited data pertaining to behavioral responses of sea turtles to anthropogenic noise, and none specifically to sounds generated by offshore wind activities. Several publications have attempted to examine sea turtles' immediate behavioral responses mostly focusing on seismic airgun noise. McCauley et al. (2000) observed that one green turtle and one loggerhead sea turtle in an open water pen increased swimming behaviors in response to a single seismic airgun at received levels of 166 dB re 1 µPa and exhibited erratic behavior at received levels greater than 175 dB re 1 µPa. Other empirical work has shown a range of responses, but NMFS (2023b) recommends sea turtle behavioral criteria based on these studies by McCauley et al. (2000). The sound level at which sea turtles are expected to exhibit a behavioral response to both impulsive and non-impulsive sound is a received SPL of 175 dB re 1 µPa.

### B.5.3 Thresholds for Non-Auditory Injury

For both turtles and mammals, NMFS has adopted criteria used by the U.S. Navy to assess the potential for non-auditory injury from underwater explosive sources as presented in Finneran et al. (2017). The criteria include thresholds for the following non-auditory effects: mortality, lung injury, and gastrointestinal injury. Unlike auditory thresholds, these depend upon an animal's mass and depth (Table B-3 in Section B.3.3). The approach requires choosing a set of representative animal masses to assess.

## B.6 References

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