BOEM Recommendations for Offshore Wind Project Pile Driving Sound Exposure Modeling and Sound Field Measurement

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Abbreviations, Acronyms, and Definitions

BOEM	Bureau of Ocean Energy Management
CMA	Center for Marine Acoustics
COP	Construction and Operations Plan
DP	dynamic positioning
ESA	Endangered Species Act
HFC	high-frequency cetaceans
IBM	individual-based-model
L_{cum}	cumulative sound exposure level
L_{E}	sound exposure level (same as SEL)
$L_{\mathrm{E,cum}}$	cumulative sound exposure level (same as SEL_{cum})
$L_{\mathrm{E,24}}$	24-hour cumulative sound exposure level (same as $SEL_{cum,24}$)
$L_{\mathrm{E,ss}}$	single strike sound exposure level
LFC	low-frequency cetaceans
$L_{\mathrm{p,pk}}$	peak sound pressure level (same as SPL_{pk})
$L_{\mathrm{p,rms}}$	root-mean-square sound pressure level (same as SPL_{rms})
MMPA	Marine Mammal Protection Act
MFC	mid-frequency cetaceans
NEPA	National Environmental Policy Act
NMFS	National Marine Fisheries Service
NOAA	National Oceanic and Atmospheric Administration
OW	other marine carnivores (including otariid pinnipeds, sea otter, and polar bear)
PDE	project design envelope
PTS	permanent threshold shift
PW	phocid pinniped
SEL	sound exposure level (same as L_{E})
SEL_{cum}	cumulative sound exposure level (same as $L_{\mathrm{E,cum}}$)
$SEL_{cum,24}$	24-hour sound exposure level (same as $L_{\mathrm{E,24}}$)
SI	Sirenians
SPL	sound pressure level
SPL_{pk}	peak sound pressure level (same as $L_{\mathrm{p,pk}}$)
SPL_{rms}	root-mean-square sound pressure level (same as $L_{\mathrm{p,rms}}$)
$R_{95\%}$	The range in which 95% of the modeled points exceeding a given sound level would be within a circle of radius R95% centered on the source. This metric should be computed for uniform range steps and for the maximum-over-depth levels.
R_{max}	maximum range from a source at which a sound level is predicted to occur
SNR	signal-to-noise ratio
TTS	temporary threshold shift
TU	sea turtles

1 Introduction

For offshore wind projects authorized by the Bureau of Ocean Energy Management (BOEM), developers are required to assess potential environmental impacts resulting from project construction. Because intense underwater sounds generated from impact pile driving for the construction of offshore energy projects can impact marine species near the project area, an important aspect of the environmental impact assessment is to estimate and validate the ensonified area. Specifically, two processes are required: (1) a noise impact assessment is conducted during the pre-construction phase, via modeling and analyses, and (2) ensonified areas are validated during the construction phase via sound field measurements.

The primary outputs from this modeling are the sound fields associated with the project design envelope (PDE) and an estimate of “exposures” for each species of interest in a development area. An “exposure” occurs when a particular individual of a particular species is exposed to sound level above a given threshold. It is important to note that a single “exposure” does not necessarily equate to a “take” under the Endangered Species Act (ESA) or the Marine Mammal Protection Act (MMPA); take estimates are determined through consultation between BOEM and National Marine Fisheries Service (NMFS) under the ESA and through the Lessees’ Incidental Take Authorization application process with NMFS and any resulting authorization(s) issued to the Lessee under the MMPA. Lessees should ensure the modeling methods also meet the needs of any authorizations that are applied for under the MMPA through consultation with NMFS. Nonetheless, the outputs of the sound modeling and exposure assessment are used by BOEM to inform preparation of the environmental impact assessment prepared under the National Environmental Policy Act (NEPA), biological assessments under the ESA, and Essential Fish Habitat assessments under the Magnuson-Stevens Fishery Conservation and Management Act.

Sound field measurements of pile-driving noise facilitate verification of the modeled distances to harassment thresholds and allow lessees, stakeholders, and regulators to determine the adequacy of the certain mitigation and monitoring procedures implemented under the authorizations issued by regulators. The marine acoustic environment, by its very nature, is complex and variable. Therefore, modeling should incorporate enough conservatism, and verification enough variance, to ensure that the acoustic environment surrounding construction is within the scope of a proposed activity.

Following the aforementioned two processes, this document is composed of two sections. The first section aims to provide general recommendations to operators as they develop the acoustic models. We recognize that models are continually being refined and improved. As such, these recommendations are not meant to be prescriptive nor restrain operators to using a specific type of model(s). Instead, the goal is to ensure that key physical and biological factors are incorporated into the modeling and outputs, and to ensure a uniform presentation of modeling results to aid BOEM with its assessment. The second section provides recommendations for sound field measurements. Because of the complexity of these calculations and the variability from location to location, it is nearly impossible to provide universal direction that would cover every possible scenario. This document provides a list of the minimum requirements to begin to fill the need. In addition to these BOEM recommendations, early coordination with both BOEM and NMFS is encouraged to ensure any additional information needs are satisfied.

This document is designed to provide guidance about several of the key concerns or issues that can typically arise during these analyses; however, it is not an exhaustive list and is only intended as basic directives for generic scenarios. Nothing written in this document is intended to override an author’s use of their technical or scientific expertise or experience. In fact, authors should be aware that guidance or references in this document may have been replaced by more current information and should always be confirmed.

2 Recommended Sound Exposure Assessment and Information Needs Concerning Pile-Driving Impacts on Biological Resources

To meet the broad information and regulatory requirements, BOEM developed these recommendations for a consistent approach to determine model inputs, assessment, and outputs to be included in a COP. It is important to provide a high-level overview of the modeling results in the main body of the assessment (in plain language and using standard terminology); include summary tables and figures. Provide the details of the modeling itself in an appendix for acoustician review. The physical and biological elements described below should be included in the acoustic modeling appendix.

2.1 General Approaches

Acoustic propagation modeling requires inputs related to the source generating the sound and the environment through which the sound will propagate. To ensure validity and ensure reproducibility of the model results, the acoustic modeling report must contain documentation of the model, as well as its inputs and assumptions. Description of the modeling should include the 1) numerical methods, 2) environment, 3) construction scenarios, and 4) species considered.

As long as the following scenarios have been modeled, use any identification system to clearly and consistently differentiate between the scenarios throughout the sound exposure guidance of this document.

2.2 Description of Numerical Methods

Various sound source and propagation models have been developed to approximate the solution to the linear wave equation. Not all models are appropriate for a given source and environment. Applicants should specify which model or models are used by the class of model (e.g., finite element model for source characteristics; ray trace, parabolic equation, or normal mode for sound propagation). Inclusion of any model classes in this guidance should not be considered endorsements of the applicability of a model. If a commonly known or documented version of a model is implemented, the applicant should provide the generic name. If multiple models are used, a description should be provided on how the different models (e.g., frequency bands, range limits) were used to derive the results in specific acoustic metrics (e.g., sound exposure level [SEL] or sound pressure level [SPL]). Refer to **Section 2.5** (Description of the Biological Element) and **Section 2.6** (Presentation of Results) for specific acoustic metrics required for different species under the COP.

If any of the values used in the modeling are based on prior empirical measurements, they should be derived from peer-reviewed publication(s) or technical reports that have been reviewed by BOEM subject matter experts.

The COP should detail the spatial dependence and resolution of the modeled results, such as plots showing modeled power spectral densities of the source at various modeled distances or a table of 1/3-octave band levels.

2.3 Description of the Environment

Acoustic propagation models may rely on parameterization of the environment. Bathymetry, sound velocity profile, and sediment properties and characteristics can influence the propagation of sounds and, thus, the modeling results. Some models incorporate range-dependent environments. Report the sources and methods of estimating the environmental parameters for the model, as well as the spatial and temporal extents over which the environmental parameters are derived. In the COP, provide justification for the seasonal representation of the environment. The COP also should include a map showing rastered bathymetry and a plot showing sound velocity profiles for different months or seasons (specify the timeframes used). In addition, the COP should consider temporal extent of the activities due to potential delays. The goal should be a balance between covering all likely scenarios and not over extending the period of actual construction to the detriment of producing a reasonable estimate of impact.

A summary of environmental parameters required for the modeling is provided below:

- Geotechnical information (use best scientific judgement to decide the number of appropriate/representative locations for modeling)
- Bathymetry data source, resolution, vertical datum
- Substrate layering and methods for approximating acoustic parameters from available data
    - Porosity, grain size, qualitative description, depth
    - Data source (e.g., geotechnical surveys, Navy Surficial Sediment model)
- Sound velocity profiles for relevant times of year
    - Temporal and spatial representation of sound velocity profiles
    - Range dependence
    - Data source (e.g., Global Digital Elevation Model, World Ocean Atlas)

2.4 Description of the Construction Scenario

Information on construction scenarios used for modeling should include the following:

- Sound sources (e.g., type of pile driving) that will be used; for an example of the most recent state-of-the-art information on approaches to predicting pile driving noise during the planning phase of projects; Lippert et al. (2016 and 2018) used a variety of finite element modeling methods
- For pile-driving propagation include
    - Water depths for each pile type selected at each location
    - Foundation type (monopole or jacket)
        - For jacket foundations – pre- or post-piled
        - Vertical or raked (at an angle)
    - Pile geometry, diameter, length, taper, and wall thickness (if available)
    - Pile penetration (given that different energy may be used throughout duration of the pile installation, this information may need to be presented incrementally)
        - Number of strikes per pile
        - Hammer energy
        - Penetration depth
        - Strike rate
        - Time and duration for each pile to be driven
    - Hammer type(s) and energy outputs in kilojoules
        - Hammer based noise mitigation included (e.g., Menck MNRU or IHC Pulse)

  - Expected number of piles driven over 24 hours or total number of piles driven over 24-hour periods for marine mammals and sea turtles, and the total duration of daily pile driving
    - Distance between foundations modeled within one 24-hr period
    - Total number of foundations and total number of days pile driving may occur
    - Description of any simultaneous pile driving that may occur

Modeling results that are used to derive impact assessment should include the following information:

- Modeling results should include plots showing power spectral density source levels (i.e., at 1 m from an imaginary point source) or at a certain reasonable distance where measurement can be made (e.g., 750 m; see **Section 2**) for each pile diameter under a range of potential power levels (not only the maximum).
  - Modeled source power spectral density should cover frequencies from 10 Hz to at least 20 kHz.
  - Horizontal distances at which the nominal sound levels are encountered is based on modeling the following:
    - The absolute maximum range at which a given sound level is encountered in the modeled sound field (R_{max})
    - The 95-percentile of the range at which a given sound level is encountered in the modeled sound field ($R_{95\%}$)
    - The predicted area that is computed using $R_{95\%}$ of the modeled range that would be exposed to sounds at a given level
  - Include a description of how R_{max} and $R_{95\%}$ values have been calculated through the modeling and transformed into ranges. The $R_{95\%}$ range for each threshold should be used to establish threshold distances.
- If known, describe any attenuation methods that are proposed and why particular attenuation levels (e.g., 6 dB, 10 dB, 12 dB) were incorporated into the modeling. If frequency-dependent attenuation is derived, describe in detail how this is modeled. If frequency-dependent attenuation is not included, describe assumptions made on how noise level reduction is considered for different hearing groups. Provide relevant citations explaining the probability that various attenuation levels can be achieved at the project site. If the attenuation method is not known, discuss with BOEM and include a summary of published field measurements, the rationale for sound reductions included, and proposed sound reduction targets that will be monitored during pile installation.

2.5 Description of the Biological Elements

Biological modeling methods and information should include the following:

- A list of species that could potentially be present during the construction period
- Seasonality and changes in density and abundance of protected species over the construction period, including a description of any seasonal restrictions based on species' occurrences and an explanation why only certain months were modeled
- Acoustic criteria applied for species in the project area in a table format; recommended thresholds currently include:

- *Marine Mammal Auditory Injury* (**Table 1**): National Oceanic and Atmospheric Administration (NOAA) exposure guidance (NMFS 2018) for onset of permanent threshold shift (PTS) in marine mammal hearing groups reports both peak sound pressure level ($L_{p,pk}$) and 24-hour SEL ($L_{E,24}$) thresholds for impulsive sounds (impact pile driving) and $L_{E,24}$ for non-impulsive sound (vibratory pile driving)
- *Marine Mammal Behavioral Step Response* (**Table 2**): Gradual increase in the probability of a response with increasing weighted sound levels (Wood et al. 2012)
- *Marine Mammal Single Behavioral Threshold* (**Table 2**): NMFS interim criteria of 160 dB re 1 µPa $L_{p,rms}$ for behavioral response to impulsive/intermittent sounds and 120 dB re 1 µPa $L_{p,rms}$ for behavioral response to continuous sound (NMFS 2018)
- *Fish Injury* (**Table 3**): Threshold standards developed for injury to fish. The ANSI-accredited thresholds (Popper et al. 2014) should be the standard for reporting. NMFS lists separate "interim guidance" of peak onset of injury or mortality from impact pile driving regardless of fish size or hearing type, and an L_{cum} onset of injury or mortality for fish 2 g or larger (Fisheries Hydroacoustic Working Group 2008) and for fish smaller than 2 g. These criteria apply to impact pile driving only. Until these thresholds are updated for both impact and vibratory pile driving, BOEM requires COPs to include both the ANSI-accredited acoustic thresholds for fish, as well as the 2008 interim criteria.
- *Fish Behavioral Response* (**Table 4**): NMFS interim guidance for the onset of behavioral response: 150 dB re 1 µPa $L_{p,rms}$ (Fisheries Hydroacoustic Working Group 2008). There are no ANSI-accredited or other recommended behavioral threshold for fish available at this time.
- *Sea Turtle Injury and TTS* (**Table 3**): Onset of injury and temporary threshold shift (TTS) for impulsive and non-impulsive sound (Department of the Navy 2017)
- *Sea Turtle Behavioral Response* (**Table 4**): Behavioral avoidance responses at 175 dB re 1 µPa $L_{p,rms}$ (Department of the Navy 2017; McCauley et al. 2000a; McCauley et al. 2000b; O'Hara and Wilcox 1990)

Table 1. Acoustic injury criteria and metrics for marine mammals

Faunal Group	Impulsive Signals		Non-impulsive Signals
	$L_{E,24}$ dB re 1 µPa^2·s (weighted)	$L_{p,pk}$ dB re 1 µPa (unweighted)	$L_{E,24}$ dB re 1 µPa^2·s (weighted)
Low-frequency cetaceans (LFC)	183	219	199
Mid-frequency cetaceans (MFC)	185	230	198
High-frequency cetaceans (HFC)	155	202	173
Phocid pinnipeds in water (PW)	185	218	201
Other marine carnivores (OW)	203	232	219
Sirenians (SI)	190	226	206

$L_{E,24}$ = cumulative SEL over 24 hours; $L_{p,pk}$ = peak sound pressure level
Source: NMFS (2018)

Table 2. Acoustic thresholds to evaluate potential behavioral effects to marine mammals

Marine Mammal Group	Probabilistic Behavioral Thresholds[a] M-Weighted[b] dB re 1 µPa ($L_{p,rms}$)				NMFS Behavioral Threshold Unweighted dB re 1 µPa[c] 120 (non-impulsive) / 160 (impulsive)
	120	140	160	180	
Porpoises/beaked whales	50%	90%	--	--	100%
Migrating mysticete whales	10%	50%	90%	--	100%
All other species/behaviors	--	10%	50%	90%	100%

[a] Probabilistic thresholds by Wood et al. (2012) (required by BOEM for NEPA; note that Wood et al. [2012] was developed to assess noise impacts from seismic airguns)
[b] M-weighting metrics provided by Southall et al. (2007)
[c] NMFS interim recommended threshold for exposure to impulsive sounds (interim thresholds as of October 2020 [Scholik-Schlomer 2015])

Table 3. Acoustic thresholds for potential injury and TTS for fishes and sea turtles

Fish Group	Impulsive Signals			Non-impulsive Signals	
	Injury		TTS (temporary, recoverable hearing effects)	Injury	TTS (temporary, recoverable hearing effects)
	dB re 1 µPa^2·s	dB re 1 µPa	dB re 1 µPa^2·s	dB re 1 µPa	dB re 1 µPa
Fish without swim bladder[a]	> 216 SEL_{cum} (unweighted)	> 213 $L_{p,pk}$ (unweighted)	≫ 186 SEL (unweighted)	--	--
Fish with swim bladder not involved in hearing[a]	203 SEL_{cum} (unweighted)	> 207 $L_{p,pk}$ (unweighted)	>186 SEL (unweighted)	--	--
Fish with swim bladder involved in hearing[a]	203 SEL_{cum} (unweighted)	> 207 $L_{p,pk}$ (unweighted)	186 SEL (unweighted)	170 $L_{p,rms}$ (unweighted, for 48 h)	158 $L_{p,rms}$ (unweighted, for 12 h)
All Fish mass ≥ 2 g[b,c]	187 SEL_{cum} (unweighted)	206 $L_{p,pk}$ (unweighted)	--	--	--
All Fish mass < 2 g[b,c]	183 SEL_{cum} (unweighted)	206 $L_{p,pk}$ (unweighted)	--	--	--
Sea turtles[c]	204 SEL (weighted)	232 $L_{p,pk}$ (unweighted)	189 SEL (weighted) (or 226 $L_{p,pk}$ unweighted)	220 SEL (weighted)	200 SEL (weighted)

[a] Popper et al. (2014)
[b] NMFS recommended criteria adopted from the Fisheries Hydroacoustic Working Group (2008)
[c] Department of the Navy (2017)

Table 4. Acoustic thresholds to evaluate potential behavioral impacts to fishes and sea turtles

Species Group	Behavior (impulsive and non-impulsive)
	$L_{p,rms}$ dB re 1 µPa (unweighted)
Fishes (mass < 2 g)	150[a]
Fishes (mass ≥ 2 g)	150[a]
Sea turtles	175[b]

[a] NMFS Greater Atlantic Regional Fisheries Office (2018) recommended criteria, last updated July 9, 2018
[b] McCauley et al. (2000b), O'Hara and Wilcox (1990), Department of the Navy (2017)

2.5.1 Sound Exposure Modeling for Marine Species

An individual-based model (IBM; also called agent-based or animal movement models) is any animal sound exposure model that incorporates movements of animals. IBMs can simulate the actions of autonomous agents in a virtual environment. When it comes to predicting exposure of individual marine organisms to underwater sound, it is generally accepted that IBMs provide the most accurate assessment methods currently available (Stöber and Thomsen 2019). Results are most accurate when the individual elements (sometimes called "animats") are parameterized with reliable data (as measured from field observations). For example, it is essential to have realistic swimming speeds and reasonable estimates of species density for a given area. Therefore, it is recommended that only reliable behavioral data (need to provide citations and justification) for species or taxa be applied to individual-based modeling; when these data are not available, alternative methods for estimating exposures are required (e.g., using stochastic or random movement model and assuming uniform distribution).

The modeling assessment should describe the basic functionality of the IBM, how it integrates animal densities, and methods for calculating exposures using the following guidance:

- Provide a table with density estimates for each species with relevant citations and justifications for given density datasets (include breakdown by month or season if relevant).
- Describe the basic functionality of the IBM, how it integrates animal densities, and methods for calculating exposures by modeling without aversion. Describe the animal movement model that was used and how the animal exposures are calculated. Specific parameters (e.g., dive behavior, swimming speed) can be included in a separate appendix.
- Aversion modeling may be considered by BOEM as an addition to assess how species-specific behaviors may impact the exposure and behavioral response of individuals. Some IBMs may include biases or aversions (e.g., through a biased correlated random walk framework). It may be desirable to simulate aversion behavior in this way, e.g., a simulated animal can avoid a sound source rather than swimming entirely at random. This component of the model should be considered an extra add-on for discussion with BOEM, without compromising all the basic modeling information described above. If aversion is included, characterize the pertinent factors and thresholds used, including references for any sources that specify the probability of aversion at given SPLs, distance from the source, duration of exposure, behavioral context for the species, change in course, and duration of the aversion event. Aversion should only be modeled for species for which aversion is demonstrated to occur and for which data is available and applicable to the location and time of year of the project and the sound source. Aversion should be based upon project parameters (e.g., location, time of year of construction) and context of exposure (e.g., migratory, nursing, or feeding animals).

2.6 Presentation of Results

2.6.1 Presentation of Radial Distances

The ranges to the underwater exposure thresholds from the proposed PDE are essential for an analysis of impacts and for BOEM to communicate the impacts to stakeholders.

The raw modeling results can be presented in tables in the appendix, but the main text should include summary tables that show the radial thresholds for each faunal group for each sound source and/or foundation/hammer type and hammer energy in different seasons (if applicable), with the attenuation options (if applicable) that are important to the description of activities, analysis, or proposed mitigation. It is recommended the same lettering/numbering scheme be used throughout the report to keep track of the scenarios that were modeled. The numbers in the summary tables should depict the maximum values for the various sites and power settings/hammer energies that were modeled for the maximum impact scenario. However, for large PDEs, the range of impacts from both the lower and upper PDE should be represented when there are notable differences in the level of impacts or number of animals that may be impacted.

The results for ensonification thresholds for different species and different impact levels should include the following information:

- Provide distances of all modeled $L_{p,pk}$, $L_{E,24}$, and $L_{p,rms}$ from the pile for the respective thresholds for fish, sea turtles, and marine mammal hearing groups. For additional information on these sound metrics, see the NMFS sound exposure guidance (NMFS 2018).
- Include the following tables:
  - Raw data and summary tables for distances to the $L_{p,pk}$ and $L_{E,24}$ auditory injury threshold for each faunal group (**Tables 5a and 5b**)
  - Raw data table for distances to $L_{p,rms}$ unweighted levels of 120, 140, 150, 160, 175, and 180 dB re 1 μPa (**Table 6a**)
  - Summary table for distances to the behavioral $L_{p,rms}$ threshold for each faunal group and distances to the fixed, unweighted behavioral threshold of 160 dB re 1 μPa $L_{p,rms}$ (**Table 6b**)
- Report radial distances as $R_{95\%}$ levels to determine the threshold distances. The hammer type, foundation type, and season (if multiple seasons are included) should be reported as applicable. Within each raw data table, results from the two modeled sites and the various power settings or hammer energies could be included as distinct columns. Depict various levels of attenuation.

For the purposes of sound field verification, data are needed to represent the variability predicted. In the COP, provide plots of sound levels versus horizontal range for all data points for each scenario (foundation type, location, penetration, season, and mitigation). For each plot, include the 25-, 50- (median), 75-, 95-percentile, and minimum and maximum sound levels within the water column. Ensure that these data (sound levels vs. range) are available for comparison with the values measured through sound field verification.

Table 5a is an example table of raw data for inclusion in the appendix for a COP. Numbers represent the distance (R95% in meters) at which the threshold for auditory injury would be reached. For $L_{E,24}$ measurements, a single number is shown for all hammer energies because it considers the total acoustic energy over 24 hours—and the fact that different parts of each pile may require different hammer energies; the strike rate and energy required for different penetration depths should be considered in these calculations. Add rows for fish and sea turtles. The same table format could be repeated for each of the different scenarios (e.g., foundation type/size, hammer type, attenuation level).

Table 5a. Auditory injury radial distances for marine mammal exposure to impact pile-driving noise

Source	Faunal Group	Metric	Threshold*	$R_{95\%}$ at Site 1 (m)				$R_{95\%}$ at Site 2 (m)			
				Hammer Energy				Hammer Energy			
				500 J	1,000 J	1,500 J	2,000 J	500 J	1,000 J	1,500 J	2,000 J
NMFS (2018)	LFC	$L_{p,pk}$	219	20	25	30	35	21	26	31	36
NMFS (2018)	LFC	$L_{E,24}$	183	5,000	5,000	5,000	5,000	5,100	5,100	5,100	5,100
NMFS (2018)	MFC	$L_{p,pk}$	230	6	8	10	12	7	9	11	13
NMFS (2018)	MFC	$L_{E,24}$	185	55	55	55	55	65	65	65	65
NMFS (2018)	HFC	$L_{p,pk}$	202	120	180	190	220	130	190	200	210
NMFS (2018)	HFC	$L_{E,24}$	155	150	150	150	150	110	110	110	110
NMFS (2018)	PW	$L_{p,pk}$	218	25	35	45	55	30	40	50	60
NMFS (2018)	PW	$L_{E,24}$	185	400	400	400	400	500	500	500	500

*Threshold units: $L_{E,24}$ = dB re 1 µPa^2·s; $L_{p,pk}$ = dB re 1 µPa

Table 5b is an example summary table to be presented in the executive summary and/or main body of the document. Numbers represent the distance (R95% in meters) at which the various thresholds would be reached. To populate the cells, take the maximum (across two sites) of the two largest radial distances from the raw data table. The same table format could be repeated for the different scenarios (e.g., foundation type and number of piles/day).

Table 5b. Distances at which auditory injury (PTS) could potentially occur from impact pile-driving noise for all faunal groups

Source	Faunal Group	Metric	Threshold	0 dB	6 dB	12 dB	18 dB
NMFS (2018)	LFC	$L_{p,pk}$	219	36	n	n	n
NMFS (2018)	LFC	$L_{E,24}$	183	5,100	n	n	n
NMFS (2018)	MFC	$L_{p,pk}$	230	13	n	n	n
NMFS (2018)	MFC	$L_{E,24}$	185	65	n	n	n
NMFS (2018)	HFC	$L_{p,pk}$	202	220	n	n	n
NMFS (2018)	HFC	$L_{E,24}$	155	150	n	n	n
NMFS (2018)	PW	$L_{p,pk}$	218	60	n	n	n
NMFS (2018)	PW	$L_{E,24}$	185	500	n	n	n

Source	Faunal Group	Metric	Threshold	0 dB	6 dB	12 dB	18 dB
Department of the Navy (2017)	sea turtle	$L_{p,pk}$	232	n	n	n	n
Department of the Navy (2017)	sea turtle	L_E	204	n	n	n	n
Popper et al. (2014)	fish with swim bladder involved in hearing	$L_{p,pk}$	207	n	n	n	n
Popper et al. (2014)	fish with swim bladder involved in hearing	L_E	207	n	n	n	n
Popper et al. (2014)	fish without swim bladder	$L_{p,pk}$	213	n	n	n	n
Popper et al. (2014)	fish without swim bladder	L_E	219	n	n	n	n
Popper et al. (2014)	fish with swim bladder not involved in hearing	$L_{p,pk}$	207	n	n	n	n
Popper et al. (2014)	fish with swim bladder not involved in hearing	L_E	210	n	n	n	n
NMFS recommended criteria adopted from the Fisheries Hydroacoustic Working Group (2008)	large fish	$L_{p,pk}$	206	n	n	n	n

*Threshold units: $L_{E,24}$ and $L_{E,24}$ = dB re 1 µPa^2·s; $L_{p,pk}$ = dB re 1 µPa; L_E = xxx

Table 6a is an example table of raw data for the appendix. Numbers represent the distance ($R_{95\%}$ in meters) at which the various unweighted SPL thresholds would be reached. The same table format could be repeated for each of the different scenarios (e.g., foundation type/size, hammer type, attenuation level, etc.).

Table 6a. Unweighted SPL levels for use in calculating the distance at which certain behavioral thresholds would be reached

Source	Metric	Threshold	$R_{95\%}$ at Site 1 (m)				$R_{95\%}$ at Site 2 (m)			
			Hammer Energy (J)				Hammer Energy (J)			
			500	1,000	1,500	2,000	500	1,000	1,500	2,000
Unweighted	$L_{p,rms}$	120	34,000	36,000	40,000	45,000	34,100	36,100	40,100	45,100
Unweighted	$L_{p,rms}$	140	11,000	13,000	14,000	15,000	11,100	13,100	14,100	15,100
Unweighted	$L_{p,rms}$	150	6,500	8,000	9,000	1,000	6,600	8,100	9,100	1,100
Unweighted	$L_{p,rms}$	160	3,000	4,000	5,000	6,000	3,100	4,100	5,100	6,100
Unweighted	$L_{p,rms}$	166	2,600	3,600	4,600	5,600	2,700	3,700	4,700	5,700
Unweighted	$L_{p,rms}$	175	2,000	3,000	4,000	5,000	2,100	3,100	4,100	5,100
Unweighted	$L_{p,rms}$	180	400	8,00	1,200	1,300	410	810	1,210	1,310

Table 6b is an example summary table for the executive summary and/or the main body of the COP. Numbers represent the distance ($R_{95\%}$ in meters) at which the various thresholds would be reached. To populate the cells, take the maximum (across two sites) of the two largest radial distance from the raw data table on behavioral disturbance for the corresponding SPL level (from **Table 6a**). The same table format could be repeated for the different scenarios (e.g., foundation type and number of piles/day).

Table 6b. Behavioral disturbance thresholds

Source	Faunal Group	Metric	Threshold	0 dB	6 dB	12 dB	18 dB
NMFS (2018)	all species/behaviors	$L_{p,rms}$ unweighted 100% response	160	6,100	n	n	n
Wood et al. (2012)	beaked whales and other harbor porpoises	L_p unweighted 50% response	120	45,100	n	n	n
Wood et al. (2012)	migrating mysticete whales	L_p unweighted 50% response	140	15,100	n	n	n
Wood et al. (2012)	all other species/behaviors	L_p 50% response	160	6,100	n	n	n
McCauley et al. (2000b)	sea turtle	L_p unweighted	166	5,100	n	n	n
McCauley et al. (2000b)	sea turtle	L_p unweighted	175	6,600	n	n	n

2.6.2 Presentation of Exposure Estimates

Exposure modeling is important for evaluating the types of impacts (behavioral or auditory), number of animals exposed, and level of impacts that may result (e.g., duration or consequence of exposure). Exposure modeling is essential for BOEM to assess impacts under the NEPA. However, additional considerations may influence the amount of take requested in an incidental take permit application submitted to NMFS pursuant to MMPA. The Lessee should independently coordinate with NMFS on the information requirements under the MMPA.

Pile-driving activity is typically expressed as the number of piles driven per day. The output of the agent-based exposure modeling should produce the results of the daily exposure history for the relevant thresholds of interest, for each moving individual animal over a 24-hour period for marine mammals and sea turtles.

The density or number of individuals used in the model is usually not the same as real-world density, so after the model is run, the numbers need to be scaled appropriately to reflect the actual number of predicted exposures based on the best available density information for the project area.

Include the following exposure estimate information:

- Raw data tables from an agent-based exposure model may present the number of *agents* exposed to sound levels above threshold, but summary tables (in main text, see **Table 7**) should present number of animals (scaled to real-world densities).
- If aversion is included in the model, provide additional exposure tables in the appendix; summary table can include the lower numbers.
- Report the percent of population or stock exposed at the different levels of exposure, with the reference for the species abundance estimate.

Table 7 is an example summary table to be included in the executive summary and/or main text of the COP. The same table format could be repeated for the different scenarios (e.g., foundation type and number of piles/day).

Table 7. Number of individuals estimated to experience sound levels above thresholds during pile driving

Species	No Attenuation			6 dB Attenuation			12 dB Attenuation		
	Injury ($L_{p,pk}$)	Injury (L_E)	Behavior Max SPL ($L_{p,rms}$)	Injury ($L_{p,pk}$)	Injury (L_E)	Behavior Max SPL ($L_{p,rms}$)	Injury ($L_{p,pk}$)	Injury (L_E)	Behavior Max SPL ($L_{p,rms}$)
Fin whale	0.5	15	45	0.15	3.5	35	0.05	0.025	20
Humpback whale	0.1	15	30	0.05	5	20	0.01	0.5	12
Minke whale	0.1	2	15	0.05	0.1	10	0	0.03	5
Harbor porpoise	12	0.25	300	5	0.2	180	2	0	110

Graphical representation of the modeling results showing the various threshold distances for species groups are encouraged as an effective means to visually communicate the results to regulators and the public. Please ensure that axis labels are readable and color coding is clearly explained.

3 Offshore Wind Pile Driving Sound Field Measurement Recommendations

The purpose of this section is to provide recommendations to offshore wind developers and/or permit applicants for conducting sound field measurements of in-water impact pile driving during wind farm construction. Various regulatory stipulations may be required to meet environmental compliance for offshore wind farm construction activities, and one of them is to validate the predicted distances from underwater noise impact distances using empirical measurements. Noise levels measured at various distances from the pile-driving activities are used to understand the sound field characteristics (intensity, frequency, duty cycle, etc.) and propagation features of the noise, as well as to validate the modeled impact analysis for marine mammals, sea turtles, and fishes.

Many of the recommendations described in this document are based on the *International Standard on Underwater Acoustics - Measurement of Radiated Underwater Sound from Percussive Pile Driving* (ISO 2017) and NMFS's *Guidance Document: Data Collection Methods to Characterize Impact and Vibratory Pile Driving Source Levels Relevant to Marine Mammals* (NMFS 2012).

Activities approved in the COP process assume that, within reason, the acoustic and exposure modeling accurately describe the sound fields generated by in situ impact pile driving. To ensure that regulatory decisions and mitigation practices are reasonable, BOEM requires operators to submit sound field verification measurements to compare with model predictions.

To properly validate acoustic modeling results, multiple measurements must be collected. A precise number cannot be provided, as different situations may require different measurements. For a given pile-driving activity, employ stationary acoustic recording systems at multiple ranges along multiple azimuths extending from the activity. In addition, mobile recording systems (e.g., vessel or autonomous underwater vehicle) may be employed to inform the propagation effects with higher spatial resolution. However, as the sound generated from pile driving varies over the course of a single pile installation, collection of simultaneous data from multiple ranges is necessary.

3.1 Measurement Instrument

The measurement system includes one or more hydrophone(s), an amplifier and signal conditioning device, and a digital signal recorder. A variety of commercially available self-contained systems and individual components are available and sufficient to address these needs. These recommendations should not be construed as BOEM endorsing any specific equipment or manufacturer. To ensure that the data collected are sufficient to verify the sound fields, the instrument performance, calibration, and recording and data format must meet the requirements provided below.

Instrument Performance: The measurement systems should have a sensitivity appropriate for the expected sound levels from pile driving received at the nominal ranges throughout the installation of the pile. Pile-driving signals should be detectable and within the maximum limits of the system's dynamic range. The frequency range of the systems should cover the range of at least 20 Hz to 20 kHz, including any high pass and anti-aliasing filters. The system should be designed to have omnidirectional sensitivity, so that sounds arriving from any direction experience gain differences of no more than 2 dB, notwithstanding the hydrophone cable direction. The system should be designed so that the predicted broadband received level of all impact pile-driving strikes exceed the system noise floor by at least 10 dB. The amplitude resolution of the analog to digital converter should be at least 12 bits. The dynamic range of the system (hydrophone, amplifier, digitizer) should be sufficient such that at each location, pile-driving signals are not clipped and are not masked by noise floor, which may require multiple measurement channels per location with different hydrophones and/or gain settings.

Calibration: For the collected data to be useful, the system needs to be calibrated. Conduct end-to-end calibration with a pistonphone immediately prior to deployment and following retrieval of the system. Conduct broadband system calibration at least every 5 years and before the field measurements to ensure that, within the frequency range (minimum 20 Hz–20 kHz), the sensitivity is "flat" to less than ±3 dB.

3.2 Field Measurement Methods

To ensure adequate collection of acoustic data, deploy recording systems with the following considerations: platform (e.g., bottom mounted, buoy attached, vessel deployed, free drifting), hydrophone depth, distance from pile, measurement duration, and other environmental conditions. Field measurement methodology should be appropriate for sufficient data collection and in accordance with safety and environmental requirements of the specific situation. The recommendations provided below should not override health, safety, and environmental controls.

Measurement Platform: For sound field verification, stationary platforms—either bottom mounted or buoy moored systems—can be employed. Mobile platforms, either vessel, autonomous vehicle, or drifting, may be used to supplement the fixed recorders. Regardless of platform, the location of the system should be determined using GPS. For mobile systems, GPS coordinates should be recorded at least once per second, or once every 5 m, whichever provides greater resolution.

Hydrophone Depth: At any location, received levels may vary throughout the depth of the water. Therefore, it is recommended that hydrophones are deployed at a depth that will most likely produce the greatest received levels. Position hydrophones in the lower half of the water column between a height 2 m above the sea floor and one half the full depth of the water.

Hydrophone Distance to Pile: To adequately quantify the propagation loss in a given direction, the received level must be obtained at multiple ranges from the source. Furthermore, although impact pile driving (of vertical piles) is effectively an omnidirectional source, propagation in different directions may be disparately affected by the bathymetry, sediment, current, and other environmental characteristics. Deploy acoustic recorders along in multiple directions representing different propagation conditions (if such conditions exist). For vertical piles, select the directions based on the bathymetry of the region. If multiple radials are sampled, one radial should extend away from the pile towards deeper water, and another radial should be in a relatively constant depth direction. For raked piles, the measurement directions should include the direction the pile is angled from, and at least one direction orthogonal to that. It is understood that the environment may not have consistent or orthogonal gradients; determine deployment locations based on applicable experience and knowledge. At minimum, collect two recorder locations in each direction for each pile. Place recorders at approximately 750 m (close range) and 5 km (far range) from the pile along each radial sampled. The location of the close-range hydrophone should be no more than 1 km. If a third hydrophone per radial is available, it is recommended that it be placed mid-range, between the close- and far-range hydrophones.

Measurement Duration: The recordings should be continuous throughout the duration of all impact hammering of each pile monitored. The number of piles to be monitored should be determined by regulators during the permitting process.

Area with High Current: When deployed in high current, care should be taken to reduce flow noise. Consider including measurements during slack currents and/or limiting exposed cabling, and using acoustically transparent, gas permeable flow shields.

Areas with Other Significant Sources: If the location of the recording has additional sources (e.g., when pile driving is performed on a barge that is operating dynamic positioning [DP] systems), recording the sound from these significant sources without piling noise is encouraged.

Recording and Data Format: Record data in a lossless digital format with a sampling rate of a minimum of 48 kHz and amplitude resolution of at least 12 bits. Any metadata that is used for interpreting the measurements should be recorded along with the measurement data.

3.3 Signal Processing and Data Analysis

For validating model results used in regulatory applications, the entire duration of recording for driving of a given pile should be analyzed. Quality control should include aural review of portions of the recording as well as visual inspection of temporal and spectral representations. Perform comparison of calibration signals from pre- and post-deployment activity performed to ensure that the equipment sensitivity did not change over the course of the deployment. Visual and algorithmic checking of the signal should determine whether the system was saturated and the resulting data are clipped.

Acoustic Metrics: Establish a manual or automatic protocol to identify all pulses in the collected pile-driving data sets (e.g., SNR).

Appropriate acoustic metrics used in this document are defined in the **Abbreviations, Acronyms and Definitions** section above. The following provides an instruction of how these metrics should be computed.

$L_{\mathrm{p,pk}}$ is calculated for each acoustic pulse from the time domain (time series) waveform. $L_{\mathrm{p,pk}}$ is given by the equation below:

$$L_{p,pk} = 10\left(\frac{p_{pk}}{p_0}\right)^2 \text{ (dB re 1 μPa)} \quad (1)$$

where p_{pk} is the peak sound pressure and is defined as the maximum absolute sound pressure of a single pulse waveform (time domain), i.e.,

$$p_{pk} = max|p(t_i)| \quad (2)$$

and p_0 is the referenced sound pressure that is equal to 1 μPa.

$L_{p,\mathrm{rms}}$ using 90% of the acoustic energy is calculated for each acoustic pulse, based on Madsen (2005). $L_{\mathrm{p,rms}}$ is given by the equation below:

$$L_{p,rms} = 10\left[\frac{1}{T_{90}}\int_{T_{90}}\left(\frac{p(t_i)}{p_0}\right)^2 \mathrm{d}t\right] \text{ (dB re 1 μPa)} \quad (3)$$

where T_{90} is the time window that comprises 90% of acoustic energy of the pulse in seconds.

$L_{\mathrm{E,ss}}$ is calculated for each acoustic pulse for the entire pulse duration (i.e., the duration from the beginning of the strike to just before the beginning of the next strike). $L_{\mathrm{E,ss}}$ is given by the equation below:

$$L_{E,ss} = 10\left[\int_T \left(\frac{p(t_i)}{p_0}\right)^2 \mathrm{d}t\right] \text{ (dB re 1 μPa}^2\text{ s)} \quad (4)$$

where T denotes the pulse duration in seconds.

$L_{\mathrm{E,cum}}$ is the SEL accumulated for the entire duration of the installation of one pile (i.e., beginning of first strike to end of last strike, but not including the time period in which equipment is being placed in position). $L_{\mathrm{E,cum}}$ is given by the equation below:

$$L_{E,cum} = 10\left[\sum_{n=1}^{N}\int_T \left(\frac{p(t_i)}{p_0}\right)^2 \mathrm{d}t\right] \text{ (dB re 1 μPa}^2\text{ s)} \quad (5)$$

where *n* is the *n*th strike during the installation. We recommend that measurements be recorded during the entire duration of the installation of a pile to obtain the cumulative SEL from direct measurements.

However, in the event that recording equipment fails or other unforeseen circumstances arise, it is possible to *approximate* $L_{E,cum}$ using the following equation:

$$L_{E,cum} = L_{E,ss} + 10N \qquad (6)$$

where N is the number of strikes to install a single pile. This approach is not encouraged because $L_{E,ss}$ from each strike is often different, so results will not be as accurate. It may only be used as a backup if all else fails.

Temporal Metrics: The pulse duration (T_{90}) is calculated as the time window comprising 90% of the pulse energy. The pulse repetition rate, which is the number of hammer strikes per second, should also be noted.

Impact Distance Delineation: Various acoustic impacts zones should be derived based on measurements collected at different distances using curve fitting. An example of the function is the following:

$$TL = F(R) - \alpha \frac{R}{1000} \quad \text{dB} \qquad (7)$$

where TL is propagation loss in dB, α is absorption coefficient in dB/km, and R is distance in m.

3.4 Reporting Recommendations

Sound field measurement reports should include (1) environmental and metadata for the measurement, (2) actual pile and hammer characteristics, (3) sensor deployment configuration, and (4) measurement results. The lists below specify the data for each of these categories. The report should also note any deviations of the above parameters from the initial COP report.

Environmental and Metadata Measurements

- Date and times of recordings
- Water temperature and salinity at measurement positions
- GPS locations of sources, hydrophones, and recording systems, with a diagram or map showing relative locations of piles (and other sources if applicable), noise abatement system, and sensors
- Substrate type at the pile and measurement locations
- Water depth at the pile and measurement locations
- Tidal variations during pile driving
- Operating conditions of vessels onsite

Pile and Hammer Characteristics

- Pile types and material (steel, concrete, compost, etc.)
- Pile dimensions: Pile diameter, length, and wall thickness (for hollow pipe piles)
- Hammer model and system
- Hammer energy output per blow, including soft ramp-up period
- Description of any noise attenuation system used, including any additional information which might have an influence on noise reduction (e.g., air flow in the case of a bubble curtain, direction of prevailing current, location of the noise abatement system relative to the pile and hydrophones)

- Foundation type (e.g., monopile or jacket)
- Substrate penetration depth (either as a depth history per blow or as a final depth)

Sensor Deployment Configuration

- Measurement system description (including acquisition system type, bandwidth, dynamic range, sampling rate, filtering used, etc.)
- Suspension system description/diagram and platform description (vessel, surface buoy, bottom mounting, etc.)
- Hydrophone type/model/directionality/nominal sensitivity
- Hydrophone depths
- Calibration details (including field calibration methods and results if available)

Measurement Results (include both close and far distances)

- Median, mean, maximum, and minimum of $L_{\mathrm{E,ss}}$ as broadband values (20–20,000 Hz)
- Median, mean, maximum, and minimum of $L_{\mathrm{E,ss}}$ in each frequency band of relevant marine organisms, if applicable
- Median, mean, maximum, and minimum of $L_{\mathrm{p,pk}}$ as broadband values (20–20,000 Hz)
- Median, mean, maximum, and minimum of $L_{\mathrm{p,rms}}$ that comprises 90% of pulse energy as broadband values (20–20,000 Hz)
- Median, mean, maximum, and minimum values of pulse duration (T_{90}, the time window comprising 90% acoustic energy)
- $L_{\mathrm{E,cum}}$ from the installation of a single pile
- Decidecade levels of the median and mean values for sound pressure peak levels, root-mean-square sound pressure levels, single strike sound exposure levels, and cumulative sound exposure levels
- Power spectrum density plots of the median values for sound pressure peak levels, root-mean-square sound pressure levels, single strike sound exposure levels, and cumulative sound exposure levels
- $L_{\mathrm{E,ss}}$ versus time at each recorder with different auditory weightings
- Weighted $L_{\mathrm{E,cum}}$ versus range, with curve fitting in the forms of $F(R)$ or $F(R) + \alpha\frac{R}{1000}$, where F is the transmission loss coefficient, R is the range in m, and α is the absorption in dB/km

Although raw acoustic recording data are not specifically required to be attached to the report, they should be made available upon request by BOEM or NMFS.

Sound level measurements at each direction and range from each pile can be reported using the following table template (**Table 8**). When using this table, also complete the highlighted areas in the notes below the table to provide the data about the recording.

Table 8. Measured sound levels

Metric*	Median	Mean	Maximum	Minimum
$L_{E,ss}$ (dB re 1 µPa^2 s)				
$L_{E,ss,LFC}$ (dB re 1 µPa^2 s)				
$L_{E,ss,MFC}$ (dB re 1 µPa^2 s)				
$L_{E,ss,HFC}$ (dB re 1 µPa^2 s)				
$L_{E,ss,SI}$ (dB re 1 µPa^2 s)				
$L_{E,ss,OW}$ (dB re 1 µPa^2 s)				
$L_{E,ss,PW}$ (dB re 1 µPa^2 s)				
$L_{E,ss,TU}$ (dB re 1 µPa^2 s)				
$L_{p,rms}$ (dB re 1 µPa)				
$L_{p,pk}$ (dB re 1 µPa)				
T_{90} (ms)				

Notes: LFC = low-frequency cetacean, MFC = mid-frequency cetacean, HFC = high-frequency cetacean, SI = sirenian, OW = other marine carnivores, PW = phocid pinniped, TU = sea turtle.
Information about the recording: Date/time of recording = xxx; pile ID = xxx; distance from pile where recording was made = xxx; water depth = xxx; and wydrophone depth = xxx.

4 For More Information

For COP-related questions, please contact Environmental Branch for Renewable Energy NEPA Coordinator. For underwater acoustics and acoustic modeling related questions, please contact BOEM Center for Marine Acoustics (CMA) at boemacoustics@boem.gov.

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