Nationwide Recommendations for Impact Pile Driving Sound Exposure Modeling and Sound Field Measurement for Offshore Wind Construction and Operations Plans

August 2023

U.S. Department of the Interior
Bureau of Ocean Energy Management
Headquarters, Sterling, VA

Bureau of Ocean Energy Management

August 2, 2023

Guidance Disclaimer

This guidance document is not a rule, regulation, or other legally binding instrument, and the recommendations it contains may not apply to a particular situation, depending on case-specific facts and circumstances. Nothing in this document is intended to modify or amend any Federal statutes, regulations, permits, or leases, nor create any rights or cause of action or trust obligation that any person or party may enforce through litigation or otherwise against the United States Government or any of its employees or officers. This document is not legally enforceable. To the extent that there is any inconsistency between the provisions of this document and any Federal statutes, regulations, leases, or permits, the statutes, regulations, leases, or permits will control.

U.S. Department of the Interior

Bureau of Ocean Energy Management

Headquarters, Sterling, VA

BOEM
Bureau of Ocean Energy Management

August 2, 2023

Contents

List of Tables

Abbreviations, Acronyms, and Definitions

BOEM	Bureau of Ocean Energy Management
CMA	Center for Marine Acoustics
COP	Construction and Operations Plan
dB	decibel
DP	dynamic positioning
ESA	Endangered Species Act
GPS	Global Positioning System
HFC	high-frequency cetaceans
Hz	Hertz
IBM	individual-based-model
kHz	Kilohertz
L_{E}	sound exposure level (same as SEL)
$L_{\mathrm{E,cum}}$	cumulative sound exposure level (same as $\mathrm{SEL}_{\mathrm{cum}}$)
$L_{\mathrm{E,24}}$	24-hour cumulative sound exposure level (same as $\mathrm{SEL}_{\mathrm{cum,24}}$)
$L_{\mathrm{E,ss}}$	single strike sound exposure level
LFC	low-frequency cetaceans
$L_{\mathrm{p,pk}}$	peak sound pressure level (same as $\mathrm{SPL}_{\mathrm{pk}}$)
$L_{\mathrm{p,rms}}$	root-mean-square sound pressure level (same as $\mathrm{SPL}_{\mathrm{rms}}$)
MMPA	Marine Mammal Protection Act
MFC	mid-frequency cetaceans
MNRU	Menck Noise Reduction Unit
NEPA	National Environmental Policy Act
NMFS	National Marine Fisheries Service
NOAA	National Oceanic and Atmospheric Administration
OCS	Outer Continental Shelf
OW	other marine carnivores (including otariid pinnipeds, sea otter, and polar bear)

PDE	project design envelope
PTS	permanent threshold shift
PW	phocid pinniped
$R_{95\%}$	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
SEL	sound exposure level (same as L_E)
SEL_{ss}	single strike sound exposure level (same as $L_{E,ss}$)
SEL_{cum}	cumulative sound exposure level (same as $L_{E,cum}$)
$SEL_{cum,24}$	24-hour sound exposure level (same as $L_{E,24}$)
SFV	Sound field verification
SI	Sirenians
SPL	sound pressure level
SPL_{pk}	peak sound pressure level (same as $L_{p,pk}$)
SPL_{rms}	root-mean-square sound pressure level (same as $L_{p,rms}$)
SNR	signal-to-noise ratio
TTS	temporary threshold shift
TU	sea turtles

1 Introduction

All proposed offshore wind energy projects described in a Construction and Operations Plan (COP) that are submitted to the Bureau of Ocean Energy Management (BOEM) for review must include assessments of potential environmental impacts resulting from project construction. *See* 30 CFR 585.627. Because underwater sounds generated from impact pile driving during foundation installation as part of the construction of offshore energy projects can impact marine species near the project area, BOEM's environmental assessment is required to consider this impact producing factor. Specifically, two processes are typically performed: (1) noise impact and exposure assessments are conducted during the permitting 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 lessee's project design envelope (PDE) and an estimate of "exposures" for each species of interest in a project development area. An "exposure" occurs when a particular individual of a particular species is exposed to sound above a given threshold. It is important to note that there may not be a one-to-one relationship between modeled "exposure" and requested "take" under the Endangered Species Act (ESA) or the Marine Mammal Protection Act (MMPA). However, exposure modeling does provide an indication of the type and magnitude of impacts that may potentially occur for any given species. Allowable take is determined through consultation between BOEM and the National Marine Fisheries Service (NMFS) under the ESA and through the Incidental Take Authorization that may be issued by NMFS to the lessee under the MMPA. Lessees should consult with NMFS to ensure their modeling methods meet the needs of NMFS to assess take applications under the MMPA. The outputs of the sound modeling and exposure assessment are used by BOEM to inform the environmental impact assessment prepared under the National Environmental Policy Act (NEPA), biological assessments under ESA, and essential fish habitat assessments under the Magnuson-Stevens Fishery Conservation and Management Act.

These recommendations are specific to impact pile driving and are not comprehensive. Lessees should evaluate the effects of other noise generating activities associated with construction and operation of wind farms (e.g., vibratory pile driving, socket drilling, horizontal directional drilling, trenching, unexploded ordnance disposal, vessel noise, turbine operation, etc.) with the appropriate level of detail for the corresponding potential level of effect.

Sound field verification (SFV) 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 certain mitigation and monitoring procedures implemented under the authorizations issued by regulators. The marine acoustic environment is, by its very nature, complex and variable. Therefore, the modeling should incorporate enough conservatism, and the verification enough samples, to ensure that the acoustic environment surrounding construction is within the PDE for the entire spatial and temporal scope of the construction activity.

This document comprises two sections. The first section aims to provide general recommendations to lessees as they develop the acoustic and exposure models of impact pile driving to be included with their COP submittals prior to issuance of a Notice of Intent to prepare an Environmental Impact Statement. BOEM recognizes that models are continually being refined and improved. As such, these recommendations are not meant to be prescriptive, nor restrain lessees to using a specific type of model. Instead, the goals are to ensure that key physical and biological factors are incorporated into the modeling and reported in the outputs, and that a uniform presentation of the modeling results aids BOEM with its assessments. The second section provides recommendations for SFV measurements to verify anticipated sound fields after COP approval. Such SFV measurements are typically incorporated into the conditions of COP approval. Because these projects and environments are complex, universal direction for every scenario is impossible to provide. Instead, this document describes the information that BOEM would find helpful in its assessment of environmental impacts. 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 provides guidance on several key concerns or issues that can typically arise during underwater acoustic modeling and SFV measurements. However, it is not an exhaustive list. Nothing written in this document is intended to override an lessee'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 use the most current information and references.

For Further Information Contact

- BOEM Center for Marine Acoustics, boemacoustics@boem.gov.
- BOEM Office or Renewable Energy Programs, renewable_reporting@boem.gov.

Paperwork Reduction Act Statement

These guidelines provide clarification, description, or interpretation of requirements contained in 30 CFR part 585, subpart F. An agency may not conduct or sponsor a collection of information unless it displays a currently valid information collection control number issued by the Office of Management and Budget (OMB). OMB has approved the information collection requirements in the 30 CFR part 585, subpart F regulations under OMB Control Number 1010-0176. These guidelines do not impose additional information collection requirements subject to the Paperwork Reduction Act of 1995.

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

To meet the broad information and regulatory requirements associated with COP submittals (30 CFR 585.626 - 627), BOEM developed these recommendations for a consistent approach to determine model inputs, assessment, and outputs to be included in a COP submission.[1] Lessees should provide a high-level overview of the modeling results in the main body of the assessment (in plain language and using standard terminology) and include summary tables and figures. A qualitative analysis of the trends observed and any anomalous results should be included in a discussion of the results. Lessees should 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 uses inputs related to the source generating the sound and the environment through which the sound will propagate. To ensure validity and reproducibility of the model results, the acoustic modeling report should 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.

2.2 Description of Numerical Methods

Various sound source and propagation models have been developed to estimate underwater sound fields. Not all models are appropriate for a given source and environment. Lessees 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, semi-empirical). 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 lessee should provide the generic name in addition to a proprietary name (e.g., RAM (parabolic equation)). 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 that should be used for different species within the COP. For spatially dependent propagation models, a maximum of 20° azimuthal spacing between adjacent 2D models shall be used.

---

1 *See* BOEM's *Information Guidelines for a Renewable Energy Construction and Operations Plan (COP) available at* https://www.boem.gov/sites/default/files/documents/about-boem/COP%20Guidelines.pdf. Page 43 states the COP should provide information for Threatened and Endangered Species, in accordance with 30 CFR 585.627(a)(4) "In lieu of direct observations, modeling of impact-producing factors and their potential effects on threatened and endangered species may include, but are not limited to, the following: 1) Sound dispersion models."

If any of the values used in the modeling are based on prior empirical measurements, they should be derived from peer-reviewed publications or technical reports that are cited and can be 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 decidecade band levels.

2.3 Description of the Environment

Acoustic propagation models may rely on parameterization of the environment. Bathymetry, sound speed 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 speed profiles for different months or seasons (specify the time frames used). In addition, the COP should consider the temporal extent of the activities due to potential delays. The goal should be a balance between covering all likely scenarios and not overextending the period of actual construction to the detriment of producing a reasonable estimate of impact.

Lessees should summarize the environmental parameters used for the modeling, including:

- Geotechnical information (use best scientific judgement to decide the number of appropriate and representative locations for modeling and provide justification)
- 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 speed profiles for relevant times of year
  - Temporal and spatial representation of sound speed profiles
  - Range dependence
  - Data source (e.g., Global Digital Elevation Model, World Ocean Atlas)

2.4 Description of the Construction Scenario

The lessee's information on construction scenarios used for modeling should include the following:

- Sound sources that will be used. For an example of recent approaches to predicting pile driving noise during the planning phase of projects, see von Pein et al. (2021) and Lippert et al. (2016 and 2018) that used a variety of finite element modeling methods.
- For pile-driving source and scenario description, include:
  - Water depths for each pile type selected

- Water depth for each modeled location
  - Justification that the modeled sites are representative of the project area
- Foundation type (e.g., monopile 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 types and energy outputs in kilojoules
  - Hammer-based noise reduction included (e.g., Menck MNRU or IQIP Pulse)
- Expected number of piles driven over 24 hours or total number of piles driven over 24-hour periods, and the total daily duration of active pile driving
  - Distance between foundations modeled within one 24-hour period
  - Total number of foundations and total number of days pile driving may occur
  - Description of any simultaneous pile driving that may occur
  - Duration of pile driving for each pile driven

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

- Modeling results should include plots showing power spectral source levels (i.e., at 1 meter (m) from an imaginary point source) and power spectral received levels at a range of 750 m for each pile diameter and hammer energy level modeled (not only the maximum). If source levels are estimated as simple functions of relative hammer energy to the maximum, providing that spectrum and the scaling function is sufficient.
  - Modeled source power spectral density should cover frequencies from 10 hertz (Hz) to at least 20 kilohertz (kHz).
  - Maximum broadband source levels for SEL, SPL, and Lpk for each scenario
  - Horizontal distances at which the nominal sound levels are encountered may be 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.
- The ensonified area (km^2) in which the modeled noise exceeds criteria thresholds for fish. Include all impact pile driving within a 24-hour period and calculate based on 100% of the area exceeding threshold.

- If known, describe any attenuation methods that are proposed and why particular attenuation levels (e.g., 6 decibels (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 marine mammal hearing groups or taxa (i.e., sea turtle, fishes). 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.
- Propagation loss approximations derived from the modeled results. Approximations should be best fit estimates of the maximum over depth, broadband, single strike received SEL (weighted and unweighted) for the first 10 km along each modeled radial based on the transmission loss equation:

$$TL = F \cdot log_{10}(R) + \alpha \frac{R}{1000} \quad \text{dB} \qquad (1)$$

where TL is transmission loss in dB, *F* is the spreading loss coefficient in dB/decade of range, α is absorption coefficient in dB/km, and *R* is distance in m. The best fit parameters, along with the azimuthal direction from which it was calculated, should be reported for the directions with the greatest propagation (lowest *F* parameter) and least propagation (highest *F* parameter).

2.5 Description of the Biological Elements

Biological modeling methods and information should include the following:

- A list of species that, at minimum, includes those protected under either the MMPA or ESA 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 (e.g., lessee proposed mitigation).

- Acoustic criteria applied for species in the project area in a table format; recommended thresholds currently include (analysis will be expected for any revisions or updates to these criteria):
    - *Marine Mammal Auditory Injury* (**Table 1**): National Oceanic and Atmospheric Administration (NOAA) Technical Guidance for Assessing the Effects of Anthropogenic Sound on Marine Mammal Hearing (NMFS 2018) for onset of permanent threshold shift (PTS) and temporary threshold shift (TTS) for various marine mammal hearing groups. Criteria for species outside of NMFS' jurisdiction (e.g., manatees, sea otters) are provided in Southall et al. (2019). Criteria metrics include both peak sound pressure level (Lpk) and 24-hour SEL thresholds for impulsive sounds (impact 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 SPL for behavioral response to impulsive/intermittent sounds (NMFS 2023a)
    - *Fish Injury* (**Table 3**): Threshold standards developed for injury to fish. A Technical Report prepared by ANSI-Accredited Standards Committee (Popper et al. 2014) should be the basis 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 SEL 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 impact pile driving, BOEM has asked for COPs to include both the ANSI-accredited Technical Report on acoustic thresholds for fish, as well as the 2008 interim criteria.
    - *Fish Behavioral Response* (**Table 5**): NMFS interim guidance for the onset of behavioral response: 150 dB re 1 µPa SPL (Andersson et al. 2007; Mueller-Blenke et al. 2010; Purser and Radford 2011; Wysocki et al. 2007). Currently, there are no ANSI-accredited or other recommended behavioral threshold for fish available.
    - *Sea Turtle Injury and TTS* (**Table 4**): Onset of injury and temporary threshold shift (TTS) for impulsive (Department of the Navy 2017).
    - *Sea Turtle Behavioral Response* (**Table 5**): Behavioral responses at 175 dB re 1 µPa SPL (Department of the Navy 2017; McCauley et al. 2000a; McCauley et al. 2000b; O'Hara and Wilcox 1990).

Table 1. Permanent and temporary threshold shift onset criteria and metrics for marine mammals (NMFS 2018, Southall et al. 2019)

Faunal Group	PTS			
	SEL* (weighted)	**Lpk*** (unweighted)	**SEL*** (weighted)	**Lpk*** (unweighted)
Low-frequency cetaceans (LFC)	183	219	168	213
Mid-frequency cetaceans (MFC)	185	230	170	224
High-frequency cetaceans (HFC)	155	202	140	196
Phocid pinnipeds in water (PW)	185	218	170	212
Otariids/Other marine carnivores (OW)	203	232	188	226
Sirenians (SI)	190	226	175	220

*Threshold units: SEL in dB re 1 µPa^2·s over a period of 24 h; Lpk in dB re 1 µPa

Table 2. SPL thresholds to evaluate potential behavioral disturbance to marine mammals

Marine Mammal Group	Probabilistic Thresholds[a,b] (Weighted)[c]				Non-Probabilistic Thresholds[b,d] (Unweighted)
	120	**140**	**160**	**180**	**160 (intermittent)**
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] Threshold units: SPL in dB re 1 µPa
[c] M-weighting functions from Southall et al. (2007)
[d] NMFS recommended impulsive/intermittent threshold for Level B harassment, as defined under the MMPA (NMFS 2023a)

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

Fish Group	Impulsive Signals		
	Injury		**TTS (temporary, recoverable hearing effects)**
	SEL[a] (unweighted)	Lpk[a] (unweighted)	SEL[a] (unweighted)
Fish without swim bladder[b]	> 216	> 213	≫ 186
Fish with swim bladder not involved in hearing[b]	203	> 207	>186
Fish with swim bladder involved in hearing[b]	203	> 207	186
All Fish mass ≥ 2 g[c]	187	206	--
All Fish mass < 2 g[c]	183	206	--

[a] Threshold units: SEL in dB re 1 µPa^2·s over a period of 24 h; Lpk in dB re 1 µPa
[b] Popper et al. (2014)
[c] NMFS recommended criteria adopted from the Fisheries Hydroacoustic Working Group (2008)

Table 4. Acoustic thresholds for potential injury and TTS for sea turtles

	Impulsive Signals			
	Injury		TTS (temporary, recoverable hearing effects)	
	SEL[a] (weighted)	Lpk[a] (unweighted)	SEL[a] (weighted)	Lpk[a] (unweighted)
Sea turtles (TU)	204	232	189	226

[a] Threshold units: SEL in dB re 1 µPa^2·s over a period of 24 h; Lpk in dB re 1 µPa
[b] Department of the Navy 2017

Table 5. Acoustic thresholds to evaluate potential behavioral impacts to fishes and sea turtles

Species Group	Behavior (impulsive) SPL[a] (unweighted)
Fishes (mass < 2 g)	150[b]
Fishes (mass ≥ 2 g)	150[b]
Sea turtles	175[c]

[a] Threshold units: SPL in dB re 1 µPa
[b] NMFS recommended criteria adopted from Andersson et al. 2007; Mueller-Blenke et al. 2010; Purser and Radford 2011; Wysocki et al. 2007
[c] 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 can 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 (supported by citations and justification) for species or taxa be applied to individual-based modeling. When these data are not available, alternative methods for estimating exposures should be used (e.g., using a surrogate (or proxy) movement model or assuming no movement and assuming uniform distribution). Fleeing models are not appropriate for estimates of impact ranges or exposures.

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:

- Include 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 along with specific parameters (e.g., dive behavior, swimming speed), which can be included in a separate appendix.
- An explanation and justifiable methodology should be included for any exposure range estimates based on a combination of animal movement modeling with acoustic modeling.
- 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 aversions to certain stimuli. It may be desirable to simulate aversion behavior in this way, e.g., a simulated animal can avoid or flee a sound source rather than swimming without respect for the stimulus. This component of the model should be considered an extra add-on for discussion with BOEM, without compromising 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 received levels, 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 Acoustic Modeling 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, foundation type, hammer type, and hammer energy modeled in different seasons (if applicable), with the attenuation options (if applicable) that are important to the description of activities, analysis, or proposed mitigation. BOEM recommends the same lettering and numbering scheme be used throughout the report to keep track of the scenarios that were modeled. The results in the summary tables should depict the maximum values for the various sites and power settings and hammer energies that were modeled for the maximum impact scenario. However, BOEM understands that broad PDEs may need to be considered prior to issuance of the Notice of Intent to Prepare a Draft Environmental Impact Statement. Therefore, applicants should follow the guidance within BOEM's Notice of Intent Checklist ("NOI

Checklist") regarding refinement of the PDE.[2] Updates to the acoustic assessments should follow the timelines presented to minimize the risk of delays and facilitate clearer communication of project evolution to all stakeholders.

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

- Distances of all modeled Lpk, SEL, and SPL from the pile for the respective thresholds for fish, sea turtles, and marine mammal hearing groups derived from acoustic propagation models. For additional information on these sound metrics, see the NMFS sound exposure guidance (NMFS 2018, 2023a&b).
- Tables including the following information:
    - Nominal isopleths for thresholds associated with Lpk and SEL (**Table 6a**)
    - Summary tables for distances to the Lpk and SEL auditory injury threshold for each faunal group (**Table 6b**)
    - Table for distances to SPL unweighted levels of 120, 140, 150, 160, 175, and 180 dB re 1 µPa (**Table 7a**)
    - Summary table for distances to the behavioral SPL threshold for each faunal group and distances to the fixed, unweighted behavioral threshold of 160 dB re 1 µPa SPL (**Table 7b**)
- At a minimum, report acoustic ranges as $R_{95\%}$ isopleths to thresholds using peak and SPL metrics (e.g., PTS peak, behavioral harassment). The hammer type, foundation type, and season (if multiple seasons are included) should be reported as applicable. Within each table, results from the modeled sites and the various power settings or hammer energies could be included as distinct columns. Depict various levels of attenuation.
- If multiple foundation installations per 24 h are being proposed, and ranges to SEL thresholds are based solely on acoustic modeling (e.g., $R_{95\%}$), these ranges should be calculated and presented with the installation of all foundations within the 24 h period occurring at a single location. Acoustic range calculations from multiple installation locations depend on too many factors to be reasonably informative. Assuming a single installation location is appropriately conservative. The range for the installation of a single foundation should be provided as well.
    - However, if ranges derived from animal movement modeling (exposure ranges) for multiple foundations in a 24 h period are presented, a thorough explanation of the methodology (e.g., timing and spacing of installations) is necessary. In such a scenario, the acoustic modeling derived ranges (e.g., $R_{95\%}$) only need to be provided for a single foundation per 24 h for each faunal group included in the movement modeling.

---

[2] See FINAL Information Needed for Issuance of a Notice of Intent (NOI) Under the National Environmental Policy Act (NEPA) for a Construction and Operations Plan (COP*) available* on the BOEM Guidance Portal under the Renewable Energy Tab at https://www.boem.gov/about-boem/regulations-guidance/guidance-portal

- Lessees should include broadband SPL, SEL (weighted and unweighted where appropriate), and Lpk (unweighted) received levels (95th percentile) estimated at 750 m from the source for each scenario modeled.

For the purposes of sound field verification, data are needed to represent the variability predicted. In the COP, lessees should provide plots of sound levels versus horizontal range (e.g., **Figure 1**) for all data points for the maximum source condition for each scenario (foundation type, location, and season). For each plot, lessees should include the 25-, 50- (median), 75-, and 95-percentiles, and minimum and maximum sound levels within the water column. While percentile data are often associated with measurements of multiple occurrences of repetitive events, similar statistical distributions can be obtained by aggregating modeling results over the spatial domain (range, depth, and azimuth). These data (sound levels vs. range) should be available for comparison with the values measured through sound field verification.

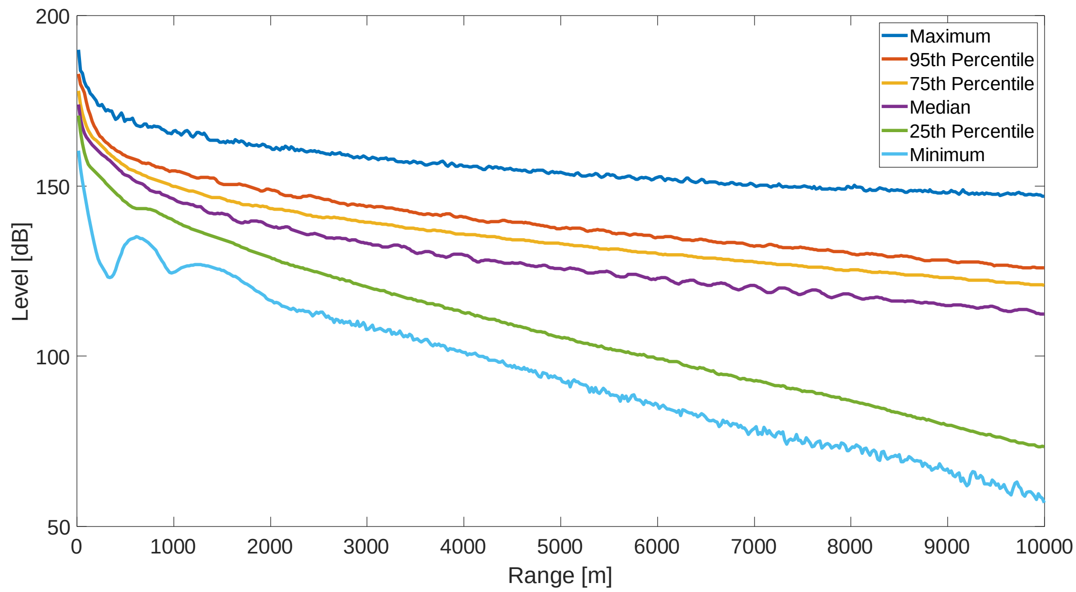

Figure 1. Example plot of percentiles of modeled received level vs range aggregated over the spatial variables.

Table 6a 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 h 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, pile size, hammer type, attenuation level).

Table 6a. 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	Lpk	219	20	25	30	35	21	26	31	36
NMFS (2018)	LFC	SEL	183	5000	5000	5000	5000	5100	5100	5100	5100
NMFS (2018)	LFC	Lpk	213	40	50	60	70	42	52	62	72
NMFS (2018)	LFC	SEL	168	10000	10000	10000	10000	10200	10200	10200	10200
NMFS (2018)	MFC	Lpk	230	6	8	10	12	7	9	11	13
NMFS (2018)	MFC	SEL	185	55	55	55	55	65	65	65	65
NMFS (2018)	MFC	Lpk	224	12	16	20	24	14	18	22	26
NMFS (2018)	MFC	SEL	170	110	110	110	110	130	130	130	130
NMFS (2018)	HFC	Lpk	202	120	180	190	220	130	190	200	210
NMFS (2018)	HFC	SEL	155	150	150	150	150	110	110	110	110
NMFS (2018)	HFC	Lpk	196	240	360	380	440	260	380	400	420
NMFS (2018)	HFC	SEL	140	300	300	300	300	220	220	220	220
NMFS (2018)	PW	Lpk	218	25	35	45	55	30	40	50	60
NMFS (2018)	PW	SEL	185	400	400	400	400	500	500	500	500
NMFS (2018)	PW	Lpk	212	50	70	90	110	60	80	100	120
NMFS (2018)	PW	SEL	170	800	800	800	800	1000	1000	1000	1000

*Threshold units: SEL in dB re 1 µPa^2·s (weighted); Lpk in dB re 1 µPa (unweighted)

Table 6b is an example summary table to be presented in the executive summary 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 all modeled sites) of the largest radial distances from the raw data table. For fish criteria, estimates of effects should be provided in units or area (e.g., km^2). *The same table format may be repeated for the different scenarios (e.g., foundation type and number of piles/day).*

Table 6b. Distances (and areas) at which injury could potentially occur from impact pile-driving

Source	Faunal Group	Metric	Threshold*	$R_{95\%}$ (m)|Area (km^2)†			
				0 dB	6 dB	12 dB	18 dB
NMFS (2018)	LFC	Lpk	219	36	n	n	n
NMFS (2018)	LFC	SEL	183	5,100	n	n	n
NMFS (2018)	MFC	Lpk	230	13	n	n	n
NMFS (2018)	MFC	SEL	185	65	n	n	n
NMFS (2018)	HFC	Lpk	202	220	n	n	n
NMFS (2018)	HFC	SEL	155	150	n	n	n
NMFS (2018)	PW	Lpk	218	60	n	n	n
NMFS (2018)	PW	SEL	185	500	n	n	n
Department of the Navy (2017)	sea turtle	Lpk	232	N	n	n	n
Department of the Navy (2017)	sea turtle	SEL	204	N	n	n	n
Popper et al. (2014)	fish with swim bladder involved in hearing	Lpk	207	N	n	n	n
Popper et al. (2014)	fish with swim bladder involved in hearing	SEL	207	N	n	n	n
Popper et al. (2014)	fish without swim bladder	Lpk	213	N	n	n	n
Popper et al. (2014)	fish without swim bladder	SEL	219	N	n	n	n
Popper et al. (2014)	fish with swim bladder not involved in hearing	Lpk	207	N	n	n	n
Popper et al. (2014)	fish with swim bladder not involved in hearing	SEL	210	N	n	n	n
NMFS recommended criteria adopted from the Fisheries Hydroacoustic Working Group (2008)	large fish	Lpk	206	N	n	n	n

*Threshold units: SEL in dB re 1 µPa²·s; Lpk in dB re 1 µPa
†Ranges provided for marine mammals and turtles; areas provided for fish

Table 7a 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 7a. Unweighted SPL levels for use in calculating the distance at which certain behavioral thresholds would be reached.

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
120	34,000	36,000	40,000	45,000	34,100	36,100	40,100	45,100
140	11,000	13,000	14,000	15,000	11,100	13,100	14,100	15,100
150	6,500	8,000	9,000	1,000	6,600	8,100	9,100	1,100
160	3,000	4,000	5,000	6,000	3,100	4,100	5,100	6,100
175	2,000	3,000	4,000	5,000	2,100	3,100	4,100	5,100
180	400	8,00	1,200	1,300	410	810	1,210	1,310

* Threshold units: SPL in dB re 1 µPa

Table 7b is an example summary table for the executive summary 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 all modeled sites) of the 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 per day).

Table 7b. Behavioral disturbance thresholds

Source	Faunal Group	Weighting	Response Level	SPL Threshold*	0 dB	6 dB	12 dB	18 dB
NMFS (2018)	all species/behaviors	Unweighted	100%	160	6,100	n	n	n
Wood et al. (2012)	beaked whales and other harbor porpoises	Weighted	50%	120	38,000	n	n	n
Wood et al. (2012)	migrating mysticete whales	Weighted	50%	140	14,900	n	n	n
Wood et al. (2012)	all other species/behaviors	Weighted	50%	160	6,000	n	n	n
McCauley et al. (2000b)	sea turtle	Unweighted	100%	175	5,100	n	n	n

*Threshold units: SPL in dB re 1 µPa

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 NEPA. However, additional considerations may influence the amount of take requested in an incidental take permit application submitted to NMFS pursuant to MMPA. Lessees 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. Artificially large numbers of individuals are often modeled to achieve a statistically robust result predicting rare events of exposure above threshold. Therefore, 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. Exposure estimates should be presented based on the density models. When density values are provided for a guild, specific exposure estimates for each species should not be calculated by further scaling by abundance (e.g., from stock assessment reports). Lessees are encouraged to qualitatively describe estimates for individual species included in a guild based on local observations.

Lessees should include the following exposure estimate information:

- Raw data tables from an agent-based exposure model may present the average number of *agents* exposed to sound levels above threshold for each scenario (pile type, hammer, season, foundations per day), but summary tables (see **Table 8**) should present number of animals (scaled to real-world densities) above threshold for the project.
- Exposure estimates without aversion must be presented. If aversion is also included in the model, the results with aversion may be provided in additional exposure tables in the appendix. Summary table may include the lower numbers in addition to results without aversion if clearly labeled.
- Report the percent of population or stock exposed at the different levels of exposure, with the reference to the species abundance estimate.

Table 8 is an example summary table to be included in the executive summary 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 per day).

Table 8. Number of individuals estimated to be exposed above thresholds during pile driving [insert scale (e.g., per pile, per day, annually, all years, etc.)

Species	No Attenuation			6 dB Attenuation			12 dB Attenuation		
	Injury (Lpk)	Injury (SEL)	Behavior Max SPL	Injury (Lpk)	Injury (SEL)	Behavior Max SPL	Injury (Lpk)	Injury (SEL)	Behavior Max SPL
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

3 Offshore Wind Pile Driving Sound Field Measurement Recommendations

The purpose of this section is to provide recommendations to lessees for conducting sound field measurements of in-water impact pile driving during the installation of OCS facilities. Various stipulations may be required to meet environmental compliance for offshore wind farm construction activities. One stipulation may require the lessee to validate the predicted impact distances from underwater noise levels 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. A draft, high-level sound field measurement plan should be included in the COP submission prior to the issuance of the Notice of Intent to Prepare an Environmental Impact Statement. BOEM understands that the details will change throughout the NEPA process with the final verification plan review detailed in the Record of Decision. Requirements in the Record of Decision will include details of plan and measurement report review by BOEM and cooperating agencies.

Many of the recommendations described in this document are based on the International Organization for Standardization's *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 through conditions of approved COPs that lessees submit SFV measurements to compare with model predictions.

To properly validate acoustic modeling results, measurements should be collected from each foundation installed. There is inherent variability in the sound levels produced during foundation installation in a complex environment. Some variation can be predicted based on foundation, construction, and environmental parameters. Lessees will conduct *Thorough SFV Monitoring* for the first three foundations of a project, and when a foundation is to be installed with a substantially different set of values for these parameters. There is other variation, however, that is more difficult to predict. An *Abbreviated SFV Check* (consisting of a single acoustic recorder) should be performed on any foundation installations for which a *Thorough SFV Monitoring* is not planned, to assess whether the cumulative variability led to received levels above what was modeled and considered in the authorizations. The exact number of *Thorough SFV Monitoring* measurements per project cannot be provided *a priori*, as different situations may require different measurements.

For *Thorough SFV Monitoring*, lessees should employ at least 4 stationary acoustic recording systems at multiple ranges along an azimuth extending from the activity in the direction of deeper water. 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 for validation. As part of the submissions detailing the sound field verification plans, lessees should provide justification (e.g., regulatory, or statistical) for choosing the number of foundations for which *Thorough SFV Monitoring* will be conducted and the ranges from the foundations at which measurements are collected. This justification may be used to demonstrate that the measurements will be sufficient to adequately capture the variability of the sound fields that will be produced over the course of project construction.

Special consideration should be given to concurrent pile driving operations, if proposed. Verification design characteristics should be specified to address contributions from multiple sources (pile installations).

3.1 Measurement System

The measurement system should include one or more hydrophones, 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. To ensure that the data collected are sufficient to verify the sound fields, the instrument performance, calibration, and recording and data format should meet the criteria 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. 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, gain settings, or both.

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.

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.

3.2 Field Measurement Methods Recommendations

To ensure adequate collection of acoustic data, lessees should 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.

Hydrophone Depth: At any location, received levels may vary throughout the depth of the water. Therefore, BOEM recommends 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 should be obtained at multiple ranges from each pile requiring *Thorough SFV Monitoring*. 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. The lessee should deploy acoustic recorders along multiple directions representing different propagation conditions (if such conditions exist). For vertical piles, select the directions based on the bathymetry of the region and the modeling results. Receivers at multiple distances should extend away from the pile towards deeper water or in the direction of greatest propagation as determined by the modeling. For raked piles, the measurement directions should include the direction the pile is angled from, and at least one direction orthogonal to that. BOEM understands that the environment may not have consistent or orthogonal gradients; determine deployment locations based on applicable experience and knowledge. At minimum, lessees should collect four recorder locations in the direction of greatest propagation for each pile for which *Thorough SFV Monitoring* is conducted along with at least one more recorders in an orthogonal direction. The first recorder in each direction monitored should be placed at approximately 750 m (close range) and for *Thorough SFV Monitoring* at increasing distances relevant to modeled harassment zones.

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 and included in the conditions of COP approval.

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

Areas with Other Significant Sources: If the location of the recording has additional noise 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.

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. Lessees should 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 clipped. Clipped signals must be excluded from further analyses and the total number of excluded pulses for each sensor reported.

Acoustic Metrics: Lessees should 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 on page ii. 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:

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

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.,

$$p_{pk} = max|p(t_i)| \qquad (3)$$

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:

$$L_{p,rms} = 10\log_{10}\left[\frac{1}{T_{90}}\int_{T_{90}}\left(\frac{p(t)}{p_0}\right)^2 \mathrm{d}t\right] \text{ (dB re 1 μPa)} \qquad (4)$$

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:

$$L_{E,ss} = 10\log_{10}\left[\int_T \left(\frac{p(t)}{p_0}\right)^2 \mathrm{d}t\right] \text{ (dB re 1 μPa}^2\text{ s)} \qquad (5)$$

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:

$$L_{E,cum} = 10\log_{10}\left[\sum_{n=1}^{N}\int_{T}\left(\frac{p(t)}{p_0}\right)^2 \mathrm{d}t\right] \text{ (dB re 1 μPa}^2\text{ s)} \tag{6}$$

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

$$L_{E,cum} = L_{E,ss} + 10\log_{10} N \tag{7}$$

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. If this is necessary, the $L_{E,ss}$ for a given hammer energy can be calculated from recorded strikes as

$$L_{E,e} = L_{E,e_0} + 8.3\log_{10}\frac{e}{e_0} \tag{8}$$

where *e* is the energy of the hammer for an unrecorded strike and e_0 is the energy for a strike for which the system was functioning. The factor of 8.8 is obtained from Bellmann et al. (2020).

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

The sound pressure kurtosis (β) is calculated over a specified time interval, t_0 to t_1, as $\beta = \frac{\mu_4}{\mu_2^2}$, where $\mu_4 = \frac{1}{t_1-t_0}\int_{t_0}^{t_1}[p(t)-\bar{p}]^4 dt$ and $\mu_2 = \frac{1}{t_1-t_0}\int_{t_0}^{t_1}[p(t)-\bar{p}]^2 dt$ is the variance of the pressure. $\bar{p}$ is the mean sound pressure in the time interval.

The rise time is the time between the occurrence of the peak pressure and the immediately preceding zero-crossing of the pressure signature.

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:

$$TL = F \cdot log_{10}(R) + \alpha\frac{R}{1000} \quad \text{dB} \tag{9}$$

where TL is propagation loss in dB, *F* is the transmission loss coefficient, 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 provide examples of the data for each of these categories. The report should also note any deviations of the above parameters from the approved COP.

Environmental and Metadata Measurements

- Date and times of recordings
- Water temperature and salinity
- 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
- Water depth at the pile and measurement locations
- Tidal variations during pile driving
- Operating status of vessels onsite (e.g., anchored, dynamically positioned, under way)

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 and diagram, and platform description (vessel, surface buoy, bottom mounting, etc.)
- Hydrophone type, model, directionality, and nominal sensitivity
- Hydrophone depths
- Calibration details (including field calibration methods and results if available)

Measurement Results (include both close and far distances calculated for each pile monitored)

- Maximum, 95th percentile, median, 5th percentile, and minimum of SEL_{ss} as broadband values (20–20,000 Hz)
- Maximum, 95th percentile, median, 5th percentile, and minimum of SEL_{ss} for each frequency weighting of relevant marine organisms, if applicable

- Maximum, 95^{th} percentile, median, 5^{th} percentile, and minimum of Lpk as broadband values (20–20,000 Hz)
- Maximum, 95^{th} percentile, median, 5^{th} percentile, and minimum SPL that comprises 90 percent of pulse energy as broadband values (20–20,000 Hz)
- Maximum, 95^{th} percentile, median, 5^{th} percentile, and minimum values of pulse duration (T_{90}, the time window comprising 90 percent acoustic energy)
- SEL from the installation of a single pile
- Decidecade levels 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
- 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
- $SEL_{,ss}$ versus time at each recorder with different auditory weightings
- Weighted SEL versus range, with curve fitting in the forms of $F \cdot log_{10}(R)$ or $F \cdot log_{10}(R) + \alpha \frac{R}{1000}$, where F is the transmission loss coefficient, R is the range in m, and α is the absorption in dB/km
- Maximum, 95^{th} percentile, median, 5^{th} percentile, and minimum of signal kurtosis.
- Maximum, 95^{th} percentile, median, 5^{th} percentile, and minimum of the rise time.

Although raw acoustic recording data are not typically 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 a table template similar to the following (**Table 9**). When using this table, also complete the highlighted areas in the notes below the table to provide the data about the recording. This list is not exhaustive; lessees should report all metrics and variations used in the underwater acoustic modeling submitted with the COP.

Table 9. Measured sound metrics

Metric*	Maximum	95th percentile	Median	5th percentile	Minimum
$SEL_{,ss}$					
$SEL_{,ss,LFC}$					
$SEL_{,ss,MFC}$					
$SEL_{,ss,HFC}$					
$SEL_{,ss,SI}$					
$SEL_{,ss,OW}$					
$SEL_{,ss,PW}$					
$SEL_{,ss,TU}$					
SPL					
Lpk					
T_{90} (ms)					
Kurtosis (β)					
Rise time (ms)					

*Measured units: SEL in dB re 1 µPa^2·s; SPL in dB re 1 µPa; Lpk in dB re 1 µPa

Information about the recording: Date/time of recording = xxx; pile ID = xxx; distance from pile where recording was made = xxx; water depth = xxx; and hydrophone depth = xxx.

4 For More Information

For COP-related questions, please contact the BOEM project coordinator. For underwater acoustics and acoustic modeling related questions, please contact BOEM Center for Marine Acoustics at boemacoustics@boem.gov.

5 References

Andersson, M.H., M. Gullstrom, M.E. Asplund, and M.C. Ohman. 2007. Swimming Behavior of Roach (Rutilus rutilus) and Three-spined Stickleback (Gasterosteus aculeatus) in Response to Wind Power Noise and Single-tone Frequencies. AMBIO: A Journal of the Human Environment 36: 636-638.

Bellmann M. A., Brinkmann J., May A., Wendt T., Gerlach S. & Remmers P. 2020. Underwater noise during the impulse pile-driving procedure: Influencing factors on pile-driving noise and technical possibilities to comply with noise mitigation values. Supported by the Federal Ministry for the Environment, Nature Conservation and Nuclear Safety (Bundesministerium für Umwelt, Naturschutz und nukleare Sicherheit (BMU)), FKZ UM16 881500. Commissioned and managed by the Federal Maritime and Hydrographic Agency (Bundesamt für Seeschifffahrt und Hydrographie (BSH)), Order No. 10036866. Edited by the itap GmbH.

Department of the Navy. 2017. Criteria and thresholds for U.S. Navy acoustic and explosive effects analysis (phase III). U.S. Navy SSC Pacific. [accessed 2021 Sep 24]. https://www.goaeis.com/portals/goaeis/files/eis/draft_seis_2020/supporting_technical/Criteria_and_Thresholds_for_U.S._Navy_Acoustic_and_Explosive_Effects_Analysis_June2017.pdf. 194 p.

Fisheries Hydroacoustic Working Group. 2008. Agreement in principle for interim criteria for injury to fish from pile driving activities (memorandum of agreement). Vancouver (WA): Fisheries Hydroacoustic Working Group. [accessed 2021 Sep 24]. https://dot.ca.gov/-/media/dot-media/programs/environmental-analysis/documents/ser/bio-fhwg-criteria-agree-a11y.pdf. 4 p.

ISO. 2017. ISO 18406-2017: Underwater acoustics – measurement of radiated underwater sound from percussive pile driving. Geneva (Switzerland): International Organization for Standardization.

Lippert S, Nijhof M, Lippert T, von Estorff O. 2018. COMPILE II – A benchmark of pile driving noise models against offshore measurements. In: INTER-NOISE and NOISE-CON Congress and Conference Proceedings. InterNoise 18; Chicago, IL. Institute of Noise Control Engineering. pp. 3082-3091(10).

Lippert S, Nijhof M, Lippert T, Wilkes D, Gavrilov A, Heitmann K, Ruhnau M, von Estorff O, Schäfke A, Schäfer I. 2016. COMPILE—a generic benchmark case for predictions of marine pile-driving noise. IEEE Journal of Oceanic Engineering. 41(4):1061–1071.

Madsen PT. 2005. Marine mammals and noise: problems with root mean square sound pressure levels for transients. The Journal of the Acoustical Society of America. 117(6):3952–3957.

McCauley RD, Fewtrell J, Duncan AJ, Jenner C, Jenner M-N, Penrose JD, Prince RIT, Adhitya A, Murdoch J, McCabe K. 2000a. Marine seismic surveys – a study of environmental implications. The Appea Journal. 40:692–708.

McCauley RD, Fewtrell J, Duncan AJ, Jenner C, Jenner M-N, Penrose JD, Prince RIT, Adhitya A, Murdoch J, McCabe K. 2000b. Marine seismic surveys: analysis and propagation of air-gun signals; and effects of air-gun exposure on humpback whales, sea turtles, fishes and squid. Western Australia: Curtin University of Technology, Centre for Marine Science and Technology. [accessed 2021 Sep 24]. https://cmst.curtin.edu.au/wp-content/uploads/sites/4/2016/05/McCauley-et-al-Seismic-effects-2000.pdf. Report No.: R99-15. 203 p.

Mueller-Blenkle, C., P.K. McGregor, A.B. Gill, M.H. Andersson, J. Metcalfe, V. Bendall, P. Sigray, D.T. Wood, and F. Thomsen. 2010. Effects of Pile-driving Noise on the Behaviour of Marine Fish. COWRIE Ref: Fish 06-08, Technical Report. March 31, 2010.

NMFS. 2018. 2018 revision to: technical guidance for assessing the effects of anthropogenic sound on marine mammal hearing (version 2.0): underwater thresholds for onset of permanent and temporary threshold shifts. Silver Spring (MD): U.S. Department of Commerce, National Oceanic and Atmospheric Administration, National Marine Fisheries Service. [accessed 2021 Sep 42]. https://media.fisheries.noaa.gov/dam-migration/tech_memo_acoustic_guidance_%2820%29_%28pdf%29_508.pdf. 178 p.

NMFS. 2023a. Summary of Marine Mammal Protection Act Acoustic Thresholds. 7 pp. https://www.fisheries.noaa.gov/s3/2023-02/MMAcousticThresholds_secureFEB2023_OPR1.pdf

NMFS. 2023b. Summary of Endangered Species Act Acoustic Thresholds. 10 pp. https://www.fisheries.noaa.gov/s3/2023-02/ESA%20all%20species%20threshold%20summary_508_OPR1.pdf

NMFS. 2012. Guidance document: data collection methods to characterize impact and vibratory pile driving source levels relevant to marine mammals. Seattle (WA): U.S. Department of Commerce, National Oceanic and Atmospheric Administration, National Marine Fisheries Service. [accessed 2021 Sep 24]. https://media.fisheries.noaa.gov/dam-migration/characterize_pile_driving_source_levels_guidance_memo.pdf. 7 p.

NMFS Greater Atlantic Regional Fisheries Office. 2018. Section 7: consultation technical guidance in the Greater Atlantic Region. Washington (DC): National Oceanic and Atmospheric Administration, NOAA Fisheries. [updated 2018 Jul 9; accessed 2021 Sep 29]. www.fisheries.noaa.gov/new-england-mid-atlantic/consultations/section-7-consultation-technical-guidance-greater-atlantic.

O'Hara J, Wilcox JR. 1990. Avoidance responses of loggerhead turtles, *Caretta*, to low frequency sound. Copeia. 1990(2):564–567.

Popper AN, Hawkins AD, Fay RR, Mann DA, Bartol S, Carlson TJ, Coombs S, Ellison WT, Gentry RL, Halvorsen MB, Løkkeborg S, Rogers PH, Southall BL, Zeddies DG, Tavolga WN. 2014. Sound exposure guidelines. In: ASA S3/SC1.4 TR-2014 sound exposure guidelines for fishes and sea turtles: a technical report prepared by ANSI-accredited standards committee S3/SC1 and registered with ANSI. Switzerland: Springer Nature. p. 33–51.

Purser J, Radford AN. 2011. Acoustic Noise Induces Attention Shifts and Reduces Foraging Performance in Three-Spined Sticklebacks (Gasterosteus aculeatus). PLoS ONE 6(2): e17478. https://doi.org/10.1371/journal.pone.0017478

Scholik-Schlomer AR. 2015. Where the decibels hit the water: perspectives on the application of science to real-world underwater noise and marine protected species issues. Acoustics Today. 11:36–44.

Southall BL, Bowles AE, Ellison WT, Finneran JJ, Gentry RL, Greene Jr CR, Kastak D, Ketten DR, Miller JH, Nachtigall PE, Richardson WJ, Thomas JA, Tyack PL. 2007. Marine mammal noise exposure criteria: initial scientific recommendations. Aquatic Mammals. 33:411–521.

Southall, BL, Finneran, JJ, Reichmuth, C, Nachtigall, PE, Ketten, DR, Bowles, AE, Ellison WT, Nowacek DP, Tyack, PL. 2019. Marine mammal noise exposure criteria: Updated scientific recommendations for residual hearing effects. Aquatic Mammals, 45(2), 125-232.

Stöber U, Thomsen F. 2019. Effect of impact pile driving noise on marine mammals: a comparison of different noise exposure criteria. Journal of the Acoustical Society of America. 145:3252–3259.

von Pein J, Lippert S, von Estorff O. 2021. Validation of a finite element modelling approach for mitigated and unmitigated pile driving noise prognosis, Journal of the Acoustical Society of America 149:1737-1748.

Wood J, Southall BL, Tollit D J. 2012. PG&E offshore 3-D seismic survey project EIR – marine mammal technical draft report. SMRU Ltd. [accessed 2021 Sep 24]. https://www.coastal.ca.gov/energy/seismic/mm-technical-report-EIR.pdf. Report No.: SMRUL-NA0611ERM. 121 p.

Wysocki, L.E., J.W. Davidson, III, M.E. Smith, A.S. Frankel, W.T. Ellison, P.M. Mazik, A.N. Popper, and J. Bebak. 2007. Effects of aquaculture production noise on hearing, growth, and disease resistance of rainbow trout Oncorhynchus mykiss. Aquaculture 272: 687-697.

U.S. Department of the Interior (DOI)
The DOI protects and manages the Nation's natural resources and cultural heritage; provides scientific and other information about those resources; and honors the Nation’s trust responsibilities or special commitments to American Indians, Alaska Natives, and affiliated island communities.

Bureau of Ocean Energy Management (BOEM)
BOEM’s mission is to manage development of U.S. Outer Continental Shelf energy and mineral resources in an environmentally and economically responsible way.

BOEM Environmental Studies Program
The mission of the Environmental Studies Program is to provide the information needed to predict, assess, and manage impacts from offshore energy and marine mineral exploration, development, and production activities on human, marine, and coastal environments. The proposal, selection, research, review, collaboration, production, and dissemination of each of BOEM’s Environmental Studies follows the DOI Code of Scientific and Scholarly Conduct, in support of a culture of scientific and professional integrity, as set out in the DOI Departmental Manual (305 DM 3).