Department for
Energy Security
& Net Zero

The Use and Environmental Impact of Explosives in the Decommissioning of Offshore Wells and Facilities

December 2023

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Abbreviations

μPa	Micropascal
ADDs	Acoustic Deterrent Devices
AWJ	Abrasive Water Jet
BEIS	Department for Business, Energy and Industrial Strategy
c.	Circa
CFD	Computing Fluid Dynamics
CLER	Classification and Labelling of Explosives Regulations 1983
COER	Control of Explosives Regulations 1991
dB	Decibel
DESNZ	Department for Energy Security and Net Zero
EDGAR	Explosives use in Decommissioning - Guide for Assessment of Risk
EFD	Energy Flux Densities
EPS	European protected species
ESD	Energy Spectral Density
FEA	Finite Element Analysis
ft	Feet
g	gram
GoM	Gulf of Mexico
HF	High Frequency
HSE	Health and Safety Executive
Hz	Hertz
ITOER	Identification and Traceability of Explosives Regulations 2013
J/m2	Joules per Square Metre

JNCC	Joint Nature Conservation Committee
kg	Kilogramme
km/sec	Kilometres per second
lbs	Pounds
LF	Low Frequency
LSC	Linear Shaped Charge
m^3/hr	Metres cubed per hour
MF	Mid Frequency
mm	Millimetre
MMO	Marine Mammal Observers
MSER	Manufacture and Storage of Explosives Regulations 2005
NMFS	National Marine Fisheries Service
NnG	Neart na Gaoithe
NOAA	National Oceanic and Atmospheric Administration
OD	Outside diameter
OEUK	Offshore Energy UK
OPRED	Offshore Petroleum Regulator for Environment and Decommissioning
OWDM	Open Water Detonation Models
Pa	Pascal
Pa2s	Pascal square seconds
PAM	Passive Acoustic Monitoring
POMSTER	Placing on the Market and Supervision of Transfers of Explosives Regulations 1993
psi	Pounds per Square Inch
PTS	Permanent threshold shift

RDX	Research Department eXplosive
ROV	Remotely Operated Vehicle
SEL	Sound exposure level
SPL	Sound Pressure Level
TCP	Tubing Conveyed Perforating Charges
TNT	Trinitrotoluene
TTS	Temporary Threshold Shift
UKCS	United Kingdom Continental Shelf
UXO	Unexploded Ordnance
VHF	Very High Frequency
WFA	Weighting Factor Adjustments

Executive Summary

This report presents the results of a study into the use of explosives during the decommissioning of offshore wells and facilities (platforms and other subsea installations), and their potential impact on the marine environment.

Explosives may be used in decommissioning activities for:

- Plugging and abandonment operations using downhole explosives tools[1];
- Severance/cutting of piles, well conductors, caissons, risers and tubing; and
- Cutting of mooring cables, lines, and chains.

Explosives have been used successfully for a particular range of decommissioning applications in the United Kingdom Continental Shelf (UKCS). In contrast, explosive cutting for platform removal has been widely used in the Gulf of Mexico (GoM), with nearly 70 percent of the platforms removed using explosives (National Research Council, 1996).

Although the focus of the report is on explosive techniques, an overview of the use of non-explosive techniques in decommissioning activities is included in order to understand the advantages and disadvantages of each technology and what factors might dictate selection of explosive or non-explosive methods for decommissioning. Non-explosive methods generate less noise but can require a greater duration to cut selected targets and although Remotely Operated Vehicles (ROVs) are the preferred option it is recognised in some cases additional diver support may be required, resulting in greater safety concerns compared to explosive cutting methods.

Explosives can generate high levels of underwater noise. Available noise measurements made during the explosive severance of piles and well conductors in the GoM have been analysed and compared to impact thresholds for marine mammals and fish. The measurements show that noise levels generated during the explosive severance of piles and well conductors can be above the recommended thresholds developed by the National Marine Fisheries Service (NMFS , 2018) and Southall *et al.* (2019) for permanent threshold shift (PTS) and temporary threshold shift (TTS) to marine mammals and the Popper et al. (2014) threshold for injury to fish. However, the available noise measurements are limited to a maximum distance of 100 m from the explosives making it difficult to extrapolate the level of potential impacts at greater distances. Whilst there are noise measurements available for the use of explosives in the GoM, there have been few measurements made for the use of explosives in the UK or other sectors of the North Sea.

Noise modelling has been conducted to estimate noise levels from explosive severance of piles and well conductors at distances beyond 100 m to estimate potential impacts to marine

[1] Recent use of explosives to perforate wells during abandonment at relatively shallow depths below mud line are not included in this study.

mammals and fish. Distances to thresholds have been estimated using several models developed specifically for the prediction of noise from explosive severance of piles and well conductors. Models developed for open water detonations are also used to provide worst-case estimations of potential impacts. The worst-case modelling results suggest that PTS impacts to the most sensitive marine mammals may occur over several kilometres.

Measurements at large distances are required during explosive severance of piles and well conductors to better understand at what distance from the explosion potential PTS impacts to marine mammals may occur. This would allow a better evaluation of whether current guidance on mitigation (JNCC, 2010a) is sufficient for mitigating potential impacts to marine mammals. JNCC guidance focuses primarily on minimising impacts through visual and acoustic observation prior to the use of explosives, to detect any receptors present in the area and delay operations to avoid any potential impacts. Impacts can also be mitigated through detailed design resulting in noise reduction at source by minimising the quantity of explosive used for a specific application. In shallow water and for specific applications such as piling, bubble curtains have been successfully used to reduce noise propagation (Dahne *et al*., 2017; Lucke *et al*., 2011; Koschinski and Ludemann, 2013; Bellman, 2014).

1 Introduction

In recent years, the use of explosives in offshore decommissioning operations has received increased attention, generating discussion around safety and their potential impacts on the marine environment. The Offshore Petroleum Regulator for Environment and Decommissioning (OPRED), part of the Department for Energy Security and Net Zero (DESNZ) (formerly the Department for Business, Energy and Industrial Strategy (BEIS)), has commissioned Genesis to undertake a study to assess the use of explosives for the decommissioning of offshore wells and facilities (platforms and other subsea installations) and the potential impacts on the marine environment. Genesis sub-contracted SPEX to provide specialist inputs on the use of explosives. SPEX are a specialist provider of energetic products. They design, model and manufacture specialised shaped charges specifically for the decommissioning process.

The aim of the study is to improve the understanding of the use of explosives and the environmental impact of explosives used during decommissioning activities.

The remainder of this report is organised as follows:

- Section 2 provides an overview of the use of explosives in offshore oil and gas decommissioning activities;
- Sections 3 presents an overview of alternative (non-explosive) cutting technologies that are often used in place of explosives for offshore oil and gas decommissioning activities and compares the advantages and disadvantages of the two methods;
- Section 4 presents measurements of underwater noise made for explosive severance of piles and well conductors and presents noise modelling results used to predict potential impacts to marine mammals and fish. The monitoring and modelling results are also compared to recognised impact thresholds for marine mammals and fish;
- Section 5 discusses existing measures used for mitigating the impact of explosives use on marine fauna; and
- Section 6 presents the Conclusions and Recommendations of the study;
- Additional information on legislation, sound metrics and noise modelling is provided in the Appendices.

2 Explosives Use During Decommissioning

Explosives have been and continue to be used in the offshore oil and gas sector on a regular basis for a wide variety of applications. They are routinely used for perforating the wellbore to provide communication from the oil and gas reservoir into the wellbore to allow production of oil and gas to occur. They are also used for the severance of tubulars that are stuck in the wellbore to re-establish access to the wellbore.

Uses of explosives specific to decommissioning include:

- Severance of wellheads following plug and abandonment operations[2]. This includes breakup of the cemented annuli between casing strings.
- Cutting of piles and steel members on a variety of subsea structures. This can include platform removal as well as smaller structures such as caissons, pipework, ballast tanks, cables, chains, and mooring lines.
- The breakup of any concrete/cement accumulations to expose the piles and steel members ready for explosive cutting.

Further information on target structures is given in Section 2.1, types and sizes of explosive charges are discussed in Section 2.2, and examples of where explosives have been used during decommissioning in the UKCS are given in Section 2.4

Piles and conductors can also be cut by mechanical means (non-explosive). These methods are discussed in Section 3 to provide a comparison with explosive methods.

2.1 Target Structures

To aid the understanding of how and why explosives are used during decommissioning, a summary of the types of structures that can be removed using explosives is provided in this section.

2.1.1 Well Related Targets

A well is a series of interlocking casings set into the seafloor. The outer conductor casing can be up to 48 inches in diameter and is fixed to the surrounding formation with cement. Wellheads and conductors can either be accessible from the surface (if they were tied-in to a platform) or subsea (no connection to the surface) (US Dept of the Interior, 2005). Background information on well decommissioning can be found in OEUK (2022).

[2] Perforating of well bore during decommissioning of wells is not included in this report.

The well plugging and abandonment operations using downhole explosives tools are carried out whilst the well is fully sealed from the environment, including the sea. Typical downhole explosive tools include, but are not limited to:

- Long lengths of perforating guns using Tubing Conveyed Perforating charges (TCP); typically, a minimum of 100 ft;
- Cutting tools to cut tubing or casing;
- Perforating tools to punch tubing casing;
- Deep penetrating charges where two or more layers of tubing/casing are to be perforated;
- Expansion tools where the inner tubing/casing is expanded against the next tubing/casing to seal micro-annuli in the cement between tubing/casing or casing/casing; and
- Severing the subsea wellhead (only used after the well has been plugged and abandoned subsurface).

The wellhead conductor and all well-related equipment (e.g., Blow Out Preventer, Christmas Tree) need to be removed once the well has been plugged. In the UKCS, it is considered good practice to remove all casing strings to a depth of 10 ft (c. 3.3 m) below the seabed (OEUK Well Decommissioning Guidelines, 2022). The depth should be reviewed on a well-by-well basis to take account of local prevailing conditions with respect to sand and waves scouring. It should be noted that the minimum cut depth is to be agreed with the Regulators (OPRED and NSTA) prior to the commencement of any well decommissioning activities. In other parts of the world minimum depth guidelines differ, for example in the GoM, casings must be cut to a minimum of 4.6 m depth below the mudline. In some cases, the smaller internal casings also need to be removed and pulled out to allow access to the larger outer casing. If the inner casing is obstructed, jetting to remove mud from the exterior of the casing may be required prior to cutting.

Severance operations are similar for subsea wellheads and may require the use of divers to set explosive charges. However, ROV intervention and support of explosives operations is now commonplace. Explosive charges are often designed with ROV handling mechanisms such that they can be safely and effectively intercepted by ROVs and deployed around tubulars or into wellheads.

From a review of the UK subsea well decommissioning planned for the period 2014-2020 (Oil & Gas UK, 2014) and SPEX’s subsea well decommissioning case history, only 15 of a total of approximately 200 subsea wellheads were removed using explosives i.e. only 7.5% of subsea wellheads were removed using explosives. The number of subsea wellheads cut and removed using different techniques (hydro-abrasive, laser, explosive etc.) depends on the demand from the Operators to abandon their subsea wells. However, wellhead abandonment and subsea salvage activity continues to include the use of explosives as a viable means of structural cutting and removal.

As of 2023, multiple explosives circular cutter devices have been designed and supplied as part of the Oil Spill Response Ltd's global emergency initiative for severance of marine risers during Deepwater Horizon/Macondo type well-control disasters.

2.1.2 Platform-Related Targets

Jacketed platforms are secured to the seafloor by piles driven through the jacket legs. The number of legs can range from 3 to 12 or more (US Dept of the Interior, 2005) with diameters from 18 inches to 96 inches. Pile sizes up to 80 inches have been successfully severed using linear shaped explosive charges during the Maureen and Hutton abandonments, UKCS. Generally, the UK methodology focusses on using engineered solutions that minimise the quantity of explosives, whereas in the US there has been a higher reliance on bulk explosives deployment. The piles are driven tens to hundreds of feet into the seabed and are often grouted or cemented to the surrounding jacket leg. Additional stability may also be provided by skirt piling (i.e. external piles/pile clusters on jackets legs).

Prior to severing operations, pilings are jetted out to remove debris and embedded sediments. Conventional piles accessible through the jacket legs can be severed internally using either non-explosive or explosive cutters. In the case of explosive charges, these are lowered internally to the appropriate depth using wire ropes and suspension bridles. An armoured electric cable is typically connected from the explosive charge back to the firing panel location and is used to pass the firing signal to the charge when ready to initiate. Similar methods can be used to externally sever skirt piling.

Steel jacket members (bracings) may need to be cut to allow the jacket to be divided into smaller sections for removal. The bracings are most commonly located in open water but can be in air above the water level if the scope of work dictates. These structures are often very large and unique in geometry requiring detailed planning prior to cutting. To date jacket members are most commonly cut using non-explosive methods using an ROV, with potential assistance from divers. However small external shaped explosive charges can also be deployed, again using divers or ROV assistance when cutting subsea targets.

Caissons generally consist of a single diameter steel pipe driven either over a well or other subsea equipment to provide protection from the sea. Caissons are piled into the seabed and therefore also require cutting below the mudline. This can be done using either explosive or non-explosive cutting devices. Caisson sizes typically range from 24 inches to 48 inches.

Explosives are also effective at severing flexible risers, comprising a combination of steel and plastic (polymer) materials.

2.1.3 Mooring-Related Targets

In deeper water, beyond the range of bottom-founded structures, a range of mooring systems are used for mooring of semi submersibles, spars and mobile offshore production units. During decommissioning these require severing. Some mooring systems have quick-disconnect technology allowing release mechanisms to be activated from the vessel (e.g., exploding bolts, electromechanical couplings, hydraulic actuated connections) (US Dept of the Interior, 2005). Where these are not available, mechanical or explosive tools can be required to cut cables, lines and chains from their moorings, which are later recovered. Such mooring systems have been severed or recovered using explosives technology either by cutting suspension chains or simply penetrating the mooring tanks for surface recovery. Penetrations into the tanks are made to remove any seawater in the tanks during lifting operations through the splash zone to reduce the weight of the load lifted.

2.1.4 Other Obstructions

There are a range of other structures where explosives can be used during removal operations. These include cement and concrete piles and cement present around the base of jackets. Jetting is normally undertaken around the piles to allow access for external cutting which can be carried out either using wire cutters or explosive charges. Large concrete slabs may require explosives to break up the concrete prior to removal. Small bulk charges, no more than 2 kg in mass have been used to break up concrete and cement accumulations during Maureen and Hutton TLP decommissioning activity. Grout break-up charges are currently being supplied for a UK North Sea operator.

2.2 Size and Type of Explosive Charge

In the context of this report, ‘explosives’ are of the type that decompose by detonation at speeds in excess of 6,000 m/s, i.e., a supersonic shock wave is produced in the secondary high explosive material which will easily overcome the tensile strength of a steel target, causing it to fragment in the case of a bulk charge or be accurately displaced in the case of a Linear Shaped Charge (LSC). Detonation events are measured in terms of microseconds. Explosives work to sever their targets in three ways (US Dept of the Interior, 2005):

- Mechanical distortion (ripping);
- High-velocity jet cuttings; and
- Fracturing (also referred to as spalling).

Explosives work by a very rapid chemical reaction, where a solid transforms into heat and gas, which in the case of a LSC creates a high-pressure jet travelling at speeds of up to 5 km/sec.

For a specific application, the type of explosive, amount and size of charge can be determined exactly to minimise the impact on the environment. As an example, the most common of charge sizes for subsea wellhead severance can be from 40 kg to 50 kg which carries sufficient energy to sever four casing strings ranging from 9-5/8 out to 30 inches (information supplied by SPEX to Genesis, 2022). This depends on the well geometries, water depth and layers of casing and cement to be severed. In some cases, a smaller explosive charge (generally 50 g) may be used to initiate a larger explosive charge, for example a 1 kg explosive charge housed in a LSC.

The aim is to try to minimise the quantity of explosives required as far as possible. This is achieved through a combination of charge selection, computational analysis of the charge effectiveness and historical reference material. Computer software applying hydro-code and multi-physics techniques can be used to model specific applications to optimise the design and simulate the explosive event and the target material response.

Explosive charges used for offshore decommissioning applications fall into two categories:

- Bulk charges; and
- Cutting charges.

2.2.1 Bulk Charges

Bulk charges are the most commonly used technique for explosive cutting of piles and conductors (Continental Shelf Associates, 2004). Specific to the UKCS, bulk charges are often employed in the severance and recovery of subsea wellheads which often consist of four concentric casing strings. These charges are typically designed and manufactured to pass any restriction in the target tubular but when detonated, contains a sufficient energy output to sever the target(s). The most common bulk charge used in wellhead recovery is derived from a Class 3 flammable liquid, nitromethane, which when sensitised at point of use can be caused to detonate to good effect. Nitromethane is however very insensitive and can only be detonated using a combination of strong initiation products, for example Exploding Bridge Wire (EBW) Detonators and pressed Research Department eXplosive (RDX) pellets.

Plastic bonded explosives (PBXs) can also be used in bulk form but are much less commonplace in the UKCS. PBXs such as PE-4 and Composition B (both containing high amounts of RDX explosive) have a high velocity on detonation and therefore a high shattering power. They are relatively insensitive and can be moulded in the field to specific sizes and shapes. This flexibility is useful if charges need to be reshaped because of differences between “planned” and “as built” internal and external diameters of piles or well strings encountered in the field. Detailed physical characteristics of different types of explosives can be found in Continental Shelf Associates (2004).

In the case of the nitromethane-filled abandonment charge, the initiation products are positioned at either end of the charge column and detonated simultaneously. The resulting detonation fronts meet in the centre of the charge and the resultant shock wave is directed radially outwards, giving a greatly enhanced performance over single point-initiated charges. The shock wave generated creates tensile failure in the steel tubulars and helps break up any cement surrounding the outermost casing. Following this radial shock wave, a large pressure increase generated by the rapid evolution of gases expands and "bursts" the casings.

Bulk charges are lowered into prepared pilings or well conductors and detonated nearly simultaneously with a 0.9 second delay in groups of eight or less. There is normally a pause of a few minutes before the next detonation sequence is initiated. It typically takes one to two hours to sever all piles and wells on a platform including the time for loading the charges and undertaking required marine mammal surveys (Continental Shelf Associates, 2004). If a bulk charge does not completely sever the piles or conductor, a back-up charge can be deployed relatively quickly.

Configured bulk charges such as ring charges and focusing charges are designed to collide or “focus” the detonation front to concentrate more energy along the fracture line, and thus reduce the size of the charge needed to cut.

2.2.1.1 Ring Charges

These are made from the same explosive material as bulk charges (Nitromethane, Composition B or PE-4), and are formed into doughnut-shaped rings, which concentrates the explosive closer to the inside of the pile wall, thus making it more effective. Using this technique, the total weight of explosive charges can be reduced theoretically by approximately 10 to 15 % compared to unfocussed bulk charges (NRC, 1996 as quoted in Continental Shelf Associates, 2004).

2.2.1.2 Focusing Charges

These charges are configured with steel tamping plates above and below the explosive payload. The tamping plates have the effect of delivering more of the force horizontally, which allows reductions in explosive weight comparable to ring charges, with the added benefit of reducing or eliminating "belling” (bulging) of the pile. The concept is proprietary and patented.

The drawback of ring and focusing charges is that they must be prefabricated and sized to fit each application however, it is normal practice to supply contingency charge fabrications in the case that more than one run is required to achieve the objective. They cannot be set internally and used to sever wells as the diameter of the inner casing is too small to accommodate the charge size to cut multiple casing strings. They are typically used to sever larger piles and tubular targets from the inside. Focussing charges are not known to have been used in UK decommissioning operations but are more commonly used in the GoM.

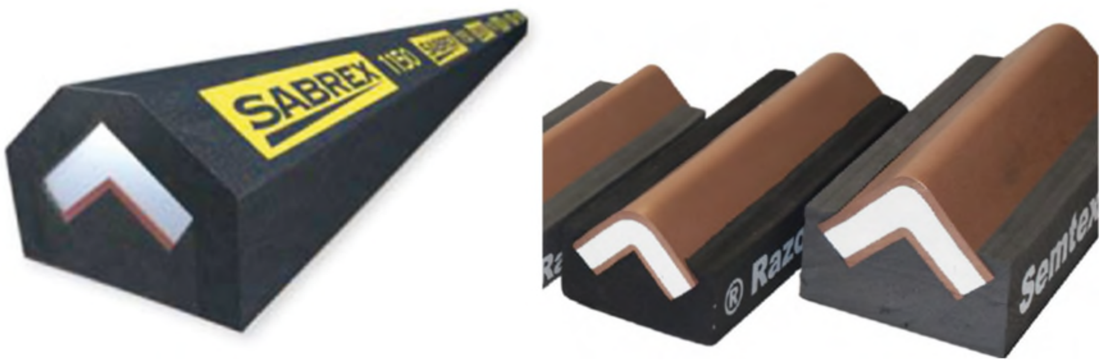
2.2.2 Cutting Charges

Cutting charges such as LSCs are those based upon the application and phenomena of the conical ’shaped charge’. The LSC uses similar principles in that the explosive material (RDX, PBX) is moulded in close contact with an extruded metal (usually copper) liner and upon detonation, a fast-moving longitudinal jet or blade is formed moving in excess of 3,000 m/s.

The combination of its velocity and density gives the blade sufficient energy to penetrate steel targets with the capability of severing up to 75 mm thickness in some instances. For concrete coated steel, the concrete is typically removed either mechanically or by using explosives and a second LSC would be used to complete the cut of the tubular.

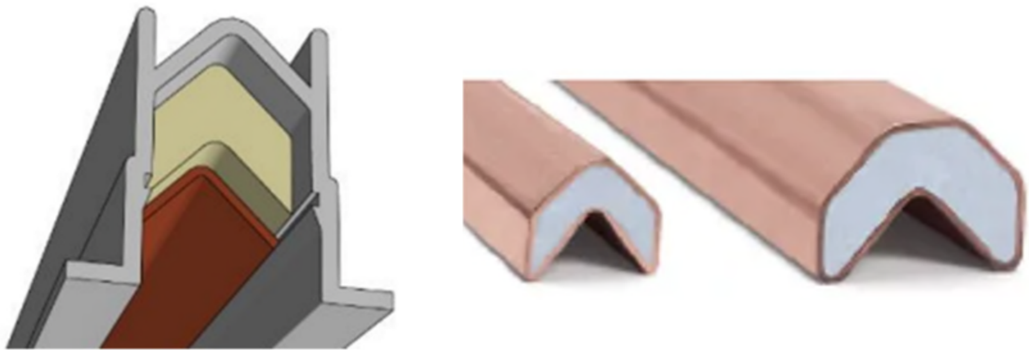
There are two main variants of LSC used in decommissioning, one being a flexible foam-clad breaching charge (sometimes referred to as ‘cutting tape’ in the US) that can be bent around and attached to the outside of a tubular such as those shown in Figure 2-1. These charges are produced using comparatively soft materials and as a result do not produce any fragmentation or shrapnel as a by-product of detonation and so lend themselves to exposed or ‘top-side’ decom rather than subsea. They can however be deployed to shallow depths up to 10 m and remain effective in cutting tubulars in submerged conditions.

Figure 2-1: Foam Clad LSC Cutting Charges



The other variant used is a rigid, often copper or aluminium clad charge such as those shown in Figure 2-2.

Figure 2-2: Rigid Clad LSC Cutting Charges



A LSC can be housed in a specially manufactured ring-shaped container made to fit around the outside of a pile, or it can be used with a running tool and an articulated device for making an internal cut. When accurately positioned to a precisely calculated stand-off distance between the charge and the target, smooth cuts can be obtained. The stand-off distance is a function of the charge size and thickness of the steel target.

LSCs can be manufactured in a range of sizes and use smaller quantities of explosive charge compared to bulk charges. For instance, during the Maureen and Hutton TLP drilling template removal activity in 2001 and 2002, the average charge size used for cutting a 30 inch tubular was in the region of 25 kg, whereas a comparative LSC charge may only be approximately 2 kg in explosive weight. The sound and overpressure imparted to the surrounding medium is therefore markedly reduced in this case.

An example of a steel tubular severance using a LSC is shown in Figure 2-3.

Figure 2-3: Steel tubular severance using an external LSC

There are several limitations to using LSCs (Continental Shelf Associates, 2004):

- If an external charge is used to cut a pile, there is limited attenuation of the explosive energy afforded by the mudline. However, in this instance, it would be advisable to cut below the mud line in line with country specific guidelines and as such, a degree of charge attenuation would indeed be seen;
- If the thickness of the pile section is unknown (possible in older structures), if the pile is out of round, if the charge is not placed directly against the target, or if a stabbing guide is at the proposed cut elevation, a successful cut may not be obtained. Larger, higher performing LSC could be used to overcome some of these detrimental aspects, depending on the overall thickness to be severed.
- Shaped charges require longer lead times to fabricate the atmospheric housings or containers and articulated devices and could cost more than bulk charges;
- Divers may be required to place the shaped charges resulting in additional safety and cost implications, albeit ROV supported activity has become more commonplace and the preferred option.
- Performance of a shaped charge depends on the presence of an air gap between the liner of the charge and the target (the stand-off). Water infiltration between the charge and the pile greatly diminishes performance. It is best practice for charge housings to be designed and tested in line with the expected hydrostatic conditions prior to live deployment.

2.3 Computational Analysis for Explosive Use

The simulation or computational analysis of the performance of various sizes and designs of charges is routinely used and can be performed multiple times with varying scenarios including attempting to identify the nominal charge size required to accomplish the objective. This then allows the final selection of the charge size to be adjusted to include enough charge to provide extra confidence in achieving the goal without disproportionately oversizing the charge to ensure success.

The computational analysis is carried out using specialist software that includes finite element analysis and Computational Fluid Dynamics (CFD). There are several software systems available for CFD analysis, with some capable of blast analysis, shock wave propagation and environmental impact assessments. The ability to perform such detailed analysis in relatively short timeframes is a very powerful tool in assisting in reducing the overall charge size requirement and explosives used in the operation whilst still giving the required confidence in achieving the required result. This type of modelling or simulation work is routinely carried out on various component systems that make up the overall system used, for example, in subsea wellhead severance and removal. These simulations include those performed to predict the performance of LSCs, shaped perforating charges, colliding shock wave severance tools and subsea wellhead severance modelling.

Additionally, computational analysis has been used to investigate and demonstrate the effectiveness of mitigation methods, such as the use of bubble curtains in dissipating the shock wave caused by the detonation of explosives.

2.4 Examples of Decommissioning using Explosives

Explosive cutting for platform removal has been widely used in the GoM, with nearly 70 percent of the platforms removed using explosives. Explosive severance of wells and piles reportedly began in the 1950s, not long after the installation of the first offshore platforms (c. 1947). Non-explosive methods used to remove the other 30 percent include mechanical cutting, diamond wire cutting, abrasive cutting, and thermal (torch) cutting by divers.

In the UKCS, explosives, including LSCs, bulk explosives and other perforating charges have been successfully used for decommissioning a range of structures spanning several decades from 1980s to the present day, including:

- Brae Bravo - All tubing in the wells were severed using shape charges, which can effectively detonate separately and in succession.
- Piper Alpha – Explosives were used to topple the jacket.
- Brent Spar – Explosives were used for anchor chain cutting and shaped charges designed and trialled for cutting holes in preparation for sinking of the structure.
- Emerald Field Tripod Mooring System – Eight mooring piles, six mooring chains, sixteen subsea wellheads, and four riser bases were cut using explosive charges.
- Maureen Platform – Cut a vast range of tubulars ranging from 10 inches OD to 80 inches OD, cut template into eight sections each weighing 65 tonnes, seventy-seven external circular shaped charges were used on the project (Figure 2-4). The operation also involved breaking up significant cement deposits that were occluding the steel targets.

- Murchison – Shaped charge cutting of Platform Water Caisson.
- Hutton TLP – Wellhead severance, pile severance and template recovery. 54 circular shaped charges ranging from 16 inches OD up to 72 inches OD and over 30 wellhead severance charges were used.
- Durward and Dauntless – Severance of multiple subsea wellheads; and
- Blenheim and Bladon – Severance of multiple subsea wellheads.

Figure 2-4: Use of cutting charges to cut 80-inch diameter composite piles on the Phillips Maureen Platform

3 Alternative (Non-Explosive) Cutting Technologies

Although the primary focus of this report is around the use of explosives for offshore decommissioning and their impact on the environment, it is useful to understand what non-explosive cutting technologies are available. This provides a useful context to understanding the advantages and disadvantages of each technology and what factors might dictate selection of explosive or non-explosive (also referred to as non-detonating) methods for decommissioning.

3.1 Currently Available Cutting Technologies

Several non-explosive cutting technologies are available, or are being further developed, for offshore applications. These include:

- Mechanical cutters, that use hydraulically actuated, carbide-tipped tungsten blades to mill through tubular structures;
- Hydraulic shears, which have jaws that close around a tubular element;
- Diamond wire cutters, which use a steel wire with small beads embedded with diamond particles mounted on the wire at regular intervals;
- Abrasive cutters, which inject cutting materials into a high-pressure water jet and abrasively wear away the steel material; and
- Thermal cutters, where divers use oxygen-fed hollow rods or exothermic rods connected to a direct current welding machine to burn through steel under water.

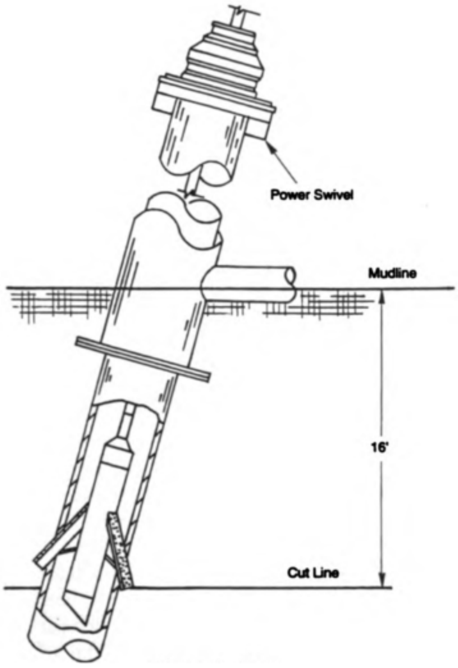
3.1.1 Internal Mechanical Cutters

Internal mechanical cutters have been used with increasing frequency since 1987. Figure 3-1 shows a sketch of a mechanical cutter in position on a battered pile.

The tool is lowered into an open pile (or well), and the power swivel is supported and connected to the top of the pile or well. The power swivel turns the drill string so that the milling blades are forced outward hydraulically to cut the pile or well. Centralizers on the tool keep it concentric inside of the pile or well. Mechanical cutters have been used most successfully for cutting shallow-water, small-diameter caissons with individual wells and shallow-water well-protector platforms with vertical piles. Note that, whilst there is not a depth which is considered to be most effective, in general, subsea internal mechanical cutters are limited by depth due to rotation of the drill string being delivered by the power swivel. With respect to the cutting of open-ended driven steel piles, the cutter requires pilings to be open at the surface to allow access through the top of the jacket leg above the waterline to accommodate the power swivel.

Subsequently, internal mechanical cutters are principally suited to the cutting of shallow water structures.

Figure 3-1: Sketch of an internal mechanical cutter on a pile



Internal Mechanical Cutter (Kaiser et. al., 2004)

On wells where the casing strings are not cemented, lateral movement after the inner string is cut causes uneven cutting of the next casing. Uncemented strings can be pulled after each successive cut, but this requires lifting equipment and time to remove and reinstall the tool each time. Concentric casing strings that are cemented together may also require trips in and out of the well to replace worn blades. Once all cemented strings are completely cut, larger lifting equipment is required for removal. Variations in casing strings may result in incomplete cuts at the outer string.

3.1.2 Hydraulic Shears

Hydraulic shears (Figure 3-2) have jaws that close around a tubular element, like scissors. It is a field proven decommissioning cutting technology with a severance range up to 62 inches OD for cutting jacket structural members, subsea structural members, rigid and flexible pipelines, umbilicals and cables. The upper jaw is driven by a hydraulic jack mounted on the lower jaw. Thus, the shears do not require a fixed position to operate but can be suspended from a crane with the proper rigging; the position is controlled by a counterweight. The position can be fixed with a hydraulic gripper. For subsea use, the hydraulic shears are deployed using a vessel crane and operated using a power pack or from surface power. Subsea operation is similar to that for above water cutting. Hydraulic shears do not produce a clean cut and consequently should not be used when precision cutting is required.

Figure 3-2: Hydraulic shear (L) and deployment example (R)

3.1.3 Diamond Wire Cutters

Diamond wire cutters (Figure 3-3) use a steel wire with small beads embedded with diamond particles mounted on the wire at regular intervals. The cutting machine is hydraulically clamped or manually strapped to the structure to be cut. The diamond wire is driven at high speeds and depending on the material and thickness, wire speeds are maintained to produce the cut. Diamond wire cutting systems can be configured to cut virtually any structural component and are not limited by size, material, or water depth as long as the cutting tool can be fixed to the cut member (Kaiser *et al*., 2004). Diamond wire cutting is an established and field proven technology which has been used extensively in the UKCS to cut jacket members, caissons, conductors, risers, and pipelines up to 288 inches OD. Noise measurements made during diamond wire cutting for the severance of a conductor on an oil and gas platform in the North Sea suggests showed that the noise from the cutting operation was not easily discernible above background noise (Pangerc *et al*., 2016).

Figure 3-3: Diamond wire cutter (L) and deployment example (R)

Diamond wire cutters (Kaiser et. al., 2004)

3.1.4 Abrasive Cutters

Abrasive cutters (also called sand cutters, abrasive water jet cutters, or abrasive slurry cutters) inject cutting materials into a water jet and abrasively wear away steel. There are two types presently in use:

- cutters that use sand or slag mixed with water at relatively low pressure (275 to 690 bar, or 4,000 to 10,000 psi) and high volume (22 to 27 m^3/hour, or 80 to 100 gallons/minute); and
- those that use garnet or other abrasive materials injected at the nozzle at relatively high-water pressure (3,445 to 4,825 bar, or 50,000 to 70,000 psi) with smaller volume of water.

The first type (commonly called a sand cutter) uses a turning mechanism, or power swivel, similar to the mechanical cutter. The power swivel rests on and is connected to the top of an open pile or conductor. The entire drill string, or "work string" turns the cutting head at about one revolution per minute, and the centralizing ring centres the cutting head.

Sand cutters are mostly used for cutting open-pile, well-protector jackets; single-thickness, small vertical caissons; and wells with uncemented casing strings. Single strings of casing can be cut quickly (20 minutes cutting time each) and removed separately, but, like mechanical cutters, sand cutters require frequent trips in and out of the well. Cemented casing strings require longer cutting times, and reliability decreases with distance from the nozzle. Sand cutters have seldom been successful in cutting more than two cemented casing strings at a time. Sand cutters can be used on open piles after soil plugs or other obstructions have been removed. If a mechanical failure occurs, the tool must be removed, a new cut may be required because returning to the same partial cut cannot be assured.

The second type of abrasive cutter is commonly called an abrasive water jet (AWJ) cutter. The AWJ benefits from its extreme cutting power which provides it with the ability to cut 10 inch wall thickness and through several layers, including multiple strings of grouted casing, giving flexibility and a higher level of assurance that a verified cut has been made This cutter produces a cutting jet of water mixed with garnet under very high pressure directed through a diamond orifice (Figure 3-4). Jet cutters are an established cutting technology that are proven and have a track record in the UKCS. There are two versions of abrasive jet cutters, external and internal. External cutters must be deployed and retrieved by divers. Internal cutters do not rely on top-drive power swivels. Instead, a downhole motor turns the cutting head one revolution per cut at a speed dependent on the thickness of the cut. This allows the operator to monitor acoustically the sound level in the water outside the cut. Changes in the sound level indicate penetration of the cutting jet. Abrasive cutters are categorised as an unintentional anthropogenic source of noise which is subject to environmental consenting process and requires an environmental impact assessment to be undertaken before the activity can take place. To the authors knowledge, there have been no recorded measurements of the underwater noise generated during abrasive cutting operations in oil and gas activities.

Figure 3-4: Abrasive water jet cutting

3.1.5 Thermal Cutters

Thermal cutting is generally limited to caissons, pilings, bracing, or other structural components, but not wells.

For underwater burning a general rule of thumb is that a diver can burn 1 linear inch (25 mm) of steel per inch of thickness per minute. A piling 1.5 inch (38 mm) thick would be cut at the rate of two-thirds of an inch (17 mm) per minute. Current guidelines require piles to be severed to a minimum depth of 10 ft (3.3 m) below the mudline (OEUK, 2022), so cuts made from the outside of a pile require excavation (which also adds to cost).

Thermal cutting using divers can be costly, when costs associated with charter of a Dive Support Vessel (DSV) with cutting spread, and costs associated with excavation of soil around the piles, are accounted for. Also, costs can increase significantly at deeper water depths, as the bottom time per dive decreases and diver decompression time per dive increases.

Safety is a significant consideration when divers are required to be utilised either for external cutting in excavated areas or potentially for internal cutting.

3.2 Developing Technologies

Two key emerging cutting technologies may potentially be applied to offshore decommissioning; laser cutting and chemical cutting.

The laser cutting technique uses beams of coherent light focused onto the material to be cut, which creates high enough temperatures in a concentrated area to vaporize the material.

While some trials have been carried out successfully for the nuclear decommissioning industry, laser cutting requires considerable further development of both process and equipment to determine the feasibility and cost effectiveness of offshore use.

The chemical cutting technique uses highly corrosive liquids such as hydrofluoric compounds that are squirted from chemical flasks pressurized by a pyrotechnic mixture. Multiple jets are used to produce a series of closely packed perforations inside the casing. This technique is rarely used because of the hazardous nature of the compounds. New techniques have been developed using inert chemicals in separate containers, which are punctured in situ to allow the chemicals to combine. The reaction produces a corrosive liquid for perforating the structure.

Other projects are underway to adapt the electro-chemical machining process, which has been used successfully in the manufacturing industry, for subsea applications. This method requires an electrical current to be passed through the cutting jet to accelerate the erosion process.

3.3 Comparison of Explosives and Non-Explosive Cutting Techniques

A high-level comparison of the explosive and non-explosive techniques is provided in Table 3-1

Table 3-1 Comparison of explosive and non-explosive cutting techniques.

Aspect	Explosive cutting techniques	Non-explosive cutting techniques
Environment	• The adoption of LSC technology in cutting charges greatly reduces the net explosive weight of a given charge in comparison to the aforementioned plastic pressed charges used in the Maureen and Hutton TLP decom activity, by a factor of 10. • Advances in modelling and simulation techniques offer potential for reduced impact as allows better calibration of explosive requirements and therefore a reduction of the size of charges required for specific jobs. • Potential Permanent Threshold Shift (PTS) or Temporary Threshold Shift (TTS) to marine mammals could occur to marine mammals (see Section 4). Level of injury will depend on size of the charge, but worst-case indications are that impacts may occur to the most sensitive species beyond the 1 km radius mitigation zone currently recommended by JNCC (JNCC, 2010a). • Potential injury to fish the shockwave generated by the explosion. Level of	• Sound radiated from the diamond wire cutting of a conductor or abrasive water jets is not easily discernible above the background noise (increase of 4-15 dB) (Pangerc *et al*, 2016). Any impacts from cutting noise will be behavioural rather than physical, e.g., may cause marine mammals or fish to vacate the area. However, they would be expected to return once the decommissioning activities have been completed. This is supported by the fact that marine mammals displaced during seismic surveys and piling (which generate much higher noise levels) have been observed to return to the area of displacement within a few days after the cessation of noise (Thompson *et al*., 2013; Brandt *et al*., 2016, 2017, 2018; Carstensen *et al*., 2006). • Prolonged duration of work results in greater noise from supporting vessels. However, noise from supporting vessels is unlikely to have a significant impact on marine mammals as it is continuous and in a narrow band of tonal sounds and frequencies. JNCC considers the temporary exposure to sound from vessels unlikely to cause more than trivial

Aspect	Explosive cutting techniques	Non-explosive cutting techniques
	injury will depend on the size, shape and anatomy of the fish, orientation relative to explosion, as well as size of charge and location, (Continental Shelf Associates, 2004). Worst case modelling indicates that impacts are unlikely to occur beyond the 1 km radius mitigation zone: the EDGAR and Connor models predict that injury to fish will be limited to within 100 m and the Open Water Detonation Model (OWDM) predicts that injury to fish will occur between 230 – 460 m for explosive charges ranging from 11.3 kg to 90.7 kg (see Section 4.3.2) Uncertainty around how much protection/blast reduction is provided when explosives are set a greater depth • Manual excavation may be required to reach a predetermined target depth for a tubular situated in and around the seabed. Following charge detonation, further cratering would exist and may require backfill depending on the depth and radial extent.	disturbance to marine mammals (JNCC, 2010b) • Prolonged presence of supporting vessels may restrict access to other users during duration of work (shipping and fishing). However, much of this work is likely to be carried out within an existing exclusion zone. • Can result in limited additional seabed disturbance if excavation is required to allow access for cutting equipment. • Potential for accidental event of small discharge to sea due to leak of hydraulic fluid from cuttings equipment

Aspect	Explosive cutting techniques	Non-explosive cutting techniques
Safety	• To date no serious injuries to personnel recorded offshore. • Requires less personnel, lower risk of personal injury. • May require diver deployment (e.g., shape charges are placed by divers), but for shorter periods than during non-explosive cutting. ROV use has largely superseded the use of diver intervention when placing charges subsea. • May require surface vessels to stand back • Needs special storage, transportation, and handling of explosives.	• Risks to divers for external cutting piles below mudline • Risks to divers when cutting under mud mats. • Risks from material handling and prolonged marine operations • Risks to divers from poor visibility in shallow water or turbid conditions • Overall requires more personnel and increases risk of personal injury
Technical	• Established track record spanning over five decades • No moving parts once assembled, deployed, and positioned on the subsea target. • Predictable results based upon previous empirical data and FEA models. • Use of explosives for wellhead severance has potential to 'bell' out piles and conductors which may restrict recovery to the surface however will also rubblise (break up of	• Established track record • No 'belling' (bulging) of piles / conductors which can make recovery difficult. • Difficult to redeploy mechanical cutters to same cut. • Abrasive cutters require cleaner surface. • Complex machinery with many moving parts • Difficult to verify successful cut. • Explosives are used in case of failure

Aspect	Explosive cutting techniques	Non-explosive cutting techniques
	concrete into rubble) the immediate surroundings. • As experienced on some recent operations, the ability of the lift vessel to pull the wellhead after detonation can be insufficient. The crane and slinging capacity must be adequately specified to pull the severed wellhead from the mud line. Upwards of 80 Te is typically required. It is advantageous to not only pull vertically but also at an angle to help dislodge the wellhead due to effects of mud suction.	
Flexibility	• Can be used for all platform types and in hard-to-access locations. • Suitable for internal and external cuts • Explosive charges can be designed and manufactured to fit most subsea tubulars and associated targets. • Easily deployed with relatively small crew requirement, shaped and wellhead abandonment charges use routine procedures to prepare, deploy, and place	• Requires custom fit for each application. • Sensitive to water depth and weather conditions. In deeper water dive-time is very restricted. • Requires extensive planning and scheduling

Aspect	Explosive cutting techniques	Non-explosive cutting techniques
	whether using ROV or diver intervention. • Small storage footprint • Bulk charge does not give a clean, precise cut. • Performance depends on air gap, stand-off distance and target thickness, all of which are considered during the charge design and manufacture. • LSCs require long lead time for manufacture (several weeks)	

4 Underwater Noise from Explosives used in Decommissioning

The pressure wave of underwater explosive detonations is composed of a very high-pressure shock wave that that has an almost instantaneous rise time and exponential decay, followed by a series of bubble pulses (Cole, 1948). As the shock wave propagates away from the source it gradually decays to a regular acoustic wave. At distances close to the explosive event, the very high pressures can cause damage to organs and tissues and in extreme cases may result in mortality (Wright, 1971), although currently employed mitigation measures (see Section 5) are generally sufficient to avoid such extreme cases. However, underwater noise generated from the use of explosives has the potential to adversely impact marine mammals and fish (OSPAR, 2009; Richardson, et al., 1995; Southall et al., 2007, 2019; NMFS, 2018; Popper et al., 2014). The noise generated by underwater explosives used during decommissioning can be much higher than other sources of noise from oil and gas activities (e.g., airgun arrays, piling, sub-bottom profilers etc.).

This section considers the potential impacts that underwater noise generated by explosives used during decommissioning activities may have on marine mammals and fish, focussing specifically on the explosive severance of piles and well conductors. These activities will generate higher noise levels compared to other methods of severance (such as mechanical cutting, abrasive cutting and diamond wire cutting (Pangerc *et al*., 2016)).

This section describes:

- Noise thresholds above which impacts to marine mammals and fish could occur;
- Measurements of noise levels generated during the explosive severance of piles and well conductors (Connor, 1990; Barkaszi *et al*., 2016; Poe *et al*., 2009). These measurements are compared to the impact thresholds; and
- Noise modelling to predict noise levels and potential impacts to marine mammals and fish from the explosive severance of piles and well conductors. A comparison between measured and modelled results is also presented.

4.1 Noise Impact Thresholds

4.1.1 Marine Mammals

For marine mammals it is generally accepted that the auditory system is the most sensitive organ to acoustic injury, meaning that injury to the auditory system will occur at lower levels than injuries to other tissues (Tougaard, 2016; Southall *et al*., 2007, 2019; NMFS, 2018). High levels of underwater noise can cause a PTS or TTS to a marine mammals' hearing sensitivity. PTS is a permanent elevation of a marine mammals' hearing sensitivity (i.e., a permanent loss of hearing), whilst TTS is a temporary elevation in hearing sensitivity that will be recovered from over time. Numerous studies have been conducted to estimate the noise levels required to cause PTS and TTS to marine mammals (Finneran *et al*. 2010a, 2010b; Finneran and Schlundt, 2013, Finneran 2015; Kastelein *et al*., 2012, 2013, 2014a, 2014b, 2015; Lucke *et al*., 2009; Tougaard, 2016; Southall *et al*., 2007, 2019; NMFS, 2018). In the UKCS, the PTS and TTS thresholds proposed by NMFS (2018) and Southall *et al*. (2019) are commonly adopted for estimating impacts and these thresholds are used in this report for assessing potential impacts to marine mammals.

4.1.1.1 Marine Mammal Hearing Groups

NMFS (2018) and Southall *et al*. (2019) proposed grouping marine mammals into different hearing groups when assessing potential impacts of underwater noise. NMFS (2018) grouped marine mammals into low frequency (LF) cetaceans, mid frequency (MF) cetaceans, high frequency (HF) cetaceans, phocid pinnipeds, otariid pinnipeds and sirenians. Southall et al. (2019) proposed equivalent hearing groups but renamed the NMFS (2018) MF cetacean and HF cetacean groups as HF cetaceans and very high frequency (VHF) cetaceans, respectively. Although named slightly differently, the marine mammal hearing groups proposed by NMFS (2018) and Southall *et al*. (2019) are equivalent and contain the same marine mammal species. Table 4-1 shows marine mammal species commonly sighted in UK waters (Hammond *et al*., 2021; Waggitt *et al*., 2019; Reid *et al*., 2003; Carter *et al*., 2022 categorised according to these hearing groups. There are no marine mammals in UK waters that belong to the otariid pinnipeds (e.g., sea lions and walruses) and sirenians (e.g., dugongs) hearing groups and these groups are therefore not considered further in this report.

Table 4-1: Marine mammals commonly sighted in the North Sea categorised by hearing group

Hearing Group		Generalised Hearing Range	Species (*)
NOAA (NMFS, 2018)	Southall et al. (2019)		
LF cetaceans	LF cetaceans	7 Hz to 35 kHz	Minke whale
MF cetaceans	HF cetaceans	150 Hz to 160 kHz	White-beaked dolphin, white-sided dolphin, bottlenose dolphin, Risso’s dolphin, striped dolphin, pilot whale, beaked whale, common dolphin, killer whale

Hearing Group		**Generalised Hearing Range**	**Species (*)**
NOAA (NMFS, 2018)	Southall et al. (2019)		
Phocid pinnipeds	Phocid pinnipeds	50 Hz to 86 kHz	Grey seal, harbour seal
(*) Species listed are the most sighted marine mammal species in the North Sea (Hammond *et al*., 2021; Waggitt *et al*., 2019; Reid *et al*., 2003; Carter *et al*., 2022).			

4.1.1.2 PTS and TTS Thresholds

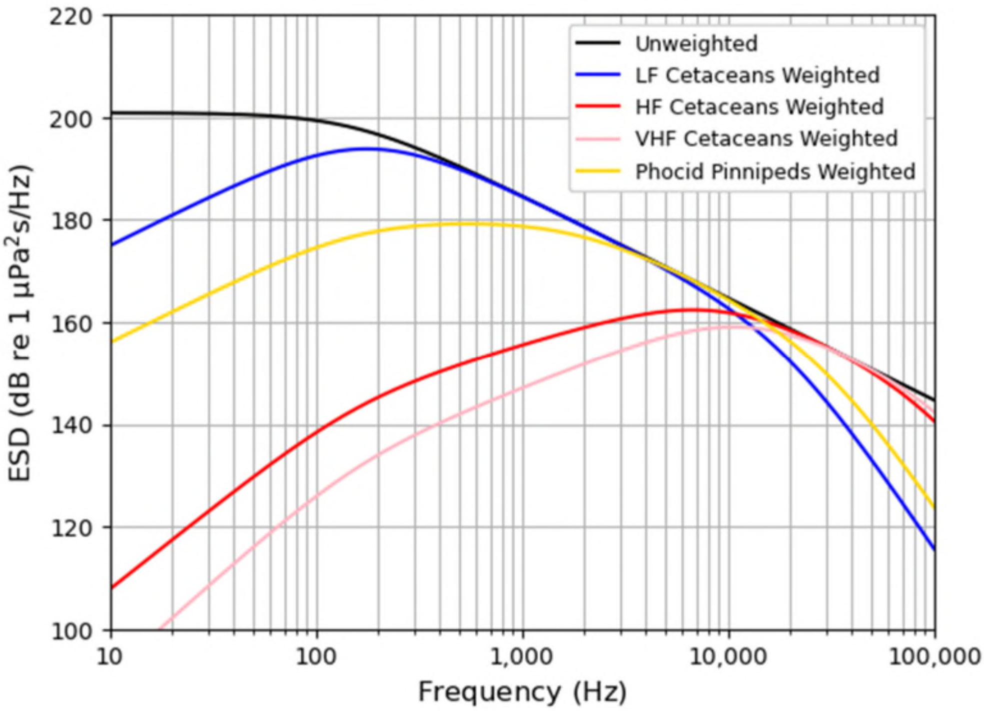
NMFS (2018) and Southall *et al*. (2019) proposed thresholds for impulsive and non-impulsive noise. Noise generated by explosives is highly impulsive near the source and likely remains impulsive over large distances. Therefore, only the impulsive thresholds proposed by NMFS (2018) and Southall *et al*. (2019) are considered in this report. The PTS and TTS thresholds proposed by NMFS (2018) and Southall *et al*. (2019) are in fact the same and are shown in Table 4-2.

Table 4-2: Thresholds for PTS and TTS to marine mammals.

Hearing Group		**Zero-to-peak SPL Threshold (dB re 1 µPa)**		**Weighted Cumulative SEL Threshold (dB re 1 µPa2s)**	
NMFS (2018)	Southall et al. (2019)	PTS	TTS	PTS	TTS
LF cetaceans	LF cetaceans	219	213	183	168
MF cetaceans	HF cetaceans	230	224	185	170
HF cetaceans	VHF cetaceans	202	196	155	140
Phocid pinnipeds	Phocid pinnipeds	218	212	185	170

The PTS and TTS thresholds in Table 4-2 are expressed using two different metrics: zero-to-peak sound pressure level (SPL) and weighted cumulative sound exposure level (SEL) (see Appendix B: Sound Metrics and Theory for a description of these and other metrics used throughout this report). The zero-to-peak SPL is a measure of the maximum absolute value of sound pressure and is an unweighted metric, meaning that it is calculated without adjusting the level of sound energy at specific frequencies. In contrast, the SEL thresholds for PTS and TTS in Table 4-2 are based on weighted sound levels. Received sound exposures should be frequency-weighted using generalised auditory weighting functions and the resulting weighted SELs integrated over the duration of exposure to calculate the weighted cumulative SEL. The generalised auditory weighting functions proposed by NMFS (2018) and Southall *et al*. (2019) for different marine mammal hearing groups are shown in Figure 4-1 (note that the NMFS (2018) and Southall *et al*. (2019) auditory weighting functions are the same for the equivalent marine mammal hearing groups). The effect of the auditory weighting functions is to reduce received sound exposures at frequencies for which a hearing group is less sensitive.

Figure 4-1: Auditory weighting functions for marine mammals hearing groups



In the remainder of this report, the Southall *et al*. (2019) nomenclature is used when referring to different marine mammal hearing groups. However, it is important to note that the PTS and TTS threshold values and the auditory weighting functions proposed by Southall *et al*. (2019) and NMFS (2018) are the same for the comparative marine mammal hearing groups and therefore result in the same levels of estimated impacts.

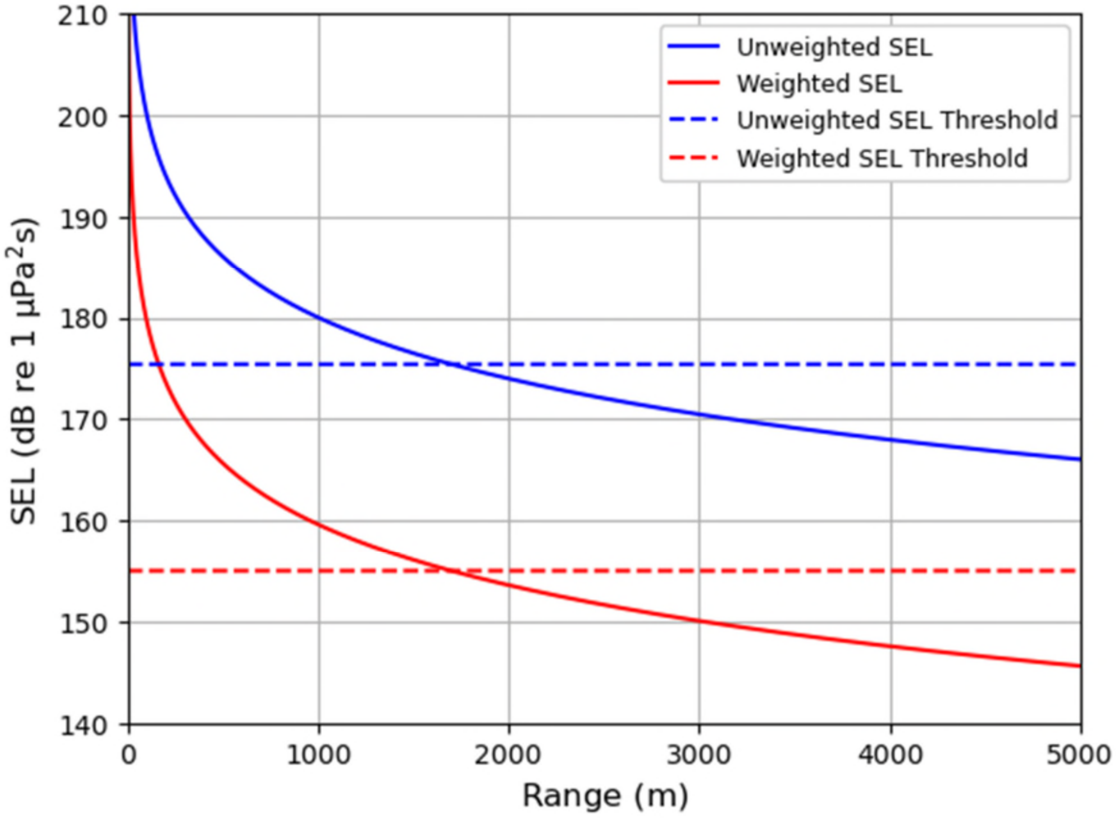
As discussed previously, the SEL thresholds proposed by NMFS (2018) and Southall et al. (2019) are based on weighted SEL incorporating the auditory weighting functions shown in Figure 4-1. To properly apply the auditory weighting functions, the SELs received by marine mammals (either measured or modelled) must be frequency resolved. The measurements analysed in this report are reported as broadband quantities (i.e., are not frequency resolved) and the models investigated estimate broadband noise levels. The direct application of the auditory weighting functions in Figure 4-1 to received SELs is therefore not possible. To circumvent this problem, weighting factor adjustments (WFAs) and equivalent unweighted SEL thresholds for assessing PTS and TTS from explosive severance of piles and well conductors have been calculated (see Appendix C: Weighting Factor Adjustments and Equivalent Unweighted SEL Thresholds for details). The use of WFAs is recommended by NMFS (2018) as an appropriate method to weight received SELs when they are not frequency resolved. The WFAs and equivalent unweighted SEL thresholds are summarised in Table 4-3.

Table 4-3: WFAs and equivalent unweighted SEL thresholds for PTS and TTS to marine mammals from explosive severance of pile and well conductors

Hearing Group	Weighted SEL Threshold (dB re 1 µPa2s)		WFA (dB)	Unweighted SEL Threshold (dB re 1 µPa2s)	
	PTS	TTS		PTS	TTS
LF cetaceans	183	168	3.1	186.1	171.1
HF cetaceans	185	170	18.6	203.6	188.6
VHF cetaceans	155	140	20.4	175.4	160.4
Phocid pinnipeds	185	170	10.1	195.1	180.1

The SEL thresholds shown in Table 4-3 can be applied in two equivalent ways. The WFA for a given hearing group can be subtracted from the received unweighted broadband SEL and the subsequent weighted SEL can be compared to the weighted SEL thresholds for that group. Alternatively, the received unweighted broadband SEL can be compared with the corresponding unweighted SEL thresholds. Both methods result in the same predicted PTS and TTS impacts. This equivalence is illustrated in Figure 4-2. Despite both methods being equivalent, it is advantageous to use the unweighted thresholds since these allow measurements and/or modelling results to be directly compared to all thresholds simultaneously. This is not true for the weighted thresholds because the received SELs must be weighted individually for the different hearing groups. Another advantage of the unweighted thresholds is that the thresholds for the different hearing groups are directly comparable. For example, from the unweighted thresholds shown in Table 4-3 it can be observed that the VHF cetaceans hearing group will be most susceptible to PTS and TTS from the explosive severance operations since their threshold values are lower than the other hearing groups. The weighted SEL thresholds in Table 4-3 cannot be directly compared to each other since the weighted SELs received by each hearing group will be different.

Figure 4-2: Illustration of the equivalence of comparing unweighted and weighted received SELs with corresponding unweighted SEL thresholds



4.1.2 Fish

Effects of underwater explosives on fish have been well documented (see reviews by Christian, 1973; Hill, 1978; Baxter *et al*. 1982; Lewis, 1996; and Keevin and Hempen, 1997; Popper *et al*., 2014). Empirical studies indicate that at very close range, underwater explosions are lethal to most fish species regardless of size, shape, or internal anatomy. At greater distances from the explosive source, fish species with gas-filled swim bladders (which act as a pressure receiver) suffer higher mortality rates than those without swim bladders.

Popper et al. (2014) defined criteria for potential injury to fish based on a review of publications related to impacts from various high-energy sources including underwater explosives. The thresholds for mortality and potential mortal injury to fish from underwater explosives proposed by Popper et al. (2014) are based on results presented by Hubbs and Rechnitzer (1952), who showed that zero-to-peak SPLs of 229 dB re 1 µPa to 234 dB re 1 µPa consistently resulted in mortality to fish. As a conservative measure, only the lower zero-to-peak SPL threshold value of 229 dB re 1 µPa is used in this report to assess the potential impact that explosive severance of piles and well conductors may have on fish. This threshold is applied for assessment of injury for all fish species regardless of their anatomy or size (Popper *et al*., 2014).

4.2 Noise Measurements

Whilst there have been some measurements made of noise levels generated during explosives used during decommissioning activities in the UK, the measurements are either limited or not easily accessible. Further studies are recommended to better understand both the near and far field impacts of noise generated from the use of explosives during decommissioning activities.

Numerous measurements have been made of the noise levels generated by explosives during pile severance and well conductor severance operations in the Gulf of Mexico (Connor, 1990; Barkaszi *et al*., 2016; Poe *et al*., 2009). Table 4-4 summarises projects where noise measurements have been made that have been used in this report. The severance activities were conducted with different explosive charges ranging from 11.3 kg to 90.7 kg of Composition B with the charges typically deployed 5 to 10 m below the seabed.

Table 4-4: Summary of projects in the Gulf of Mexico where noise measurements have been made during pile severance and well conductor severance.

Project	Severance Targets	Explosive Type (*)	Charge Weight		Charge Depth (**)	
			(lbs)	(kg)	(ft)	(m)
West Delta 30 (WD-30) Platform (Connor, 1990)	Piles	Composition B	38	17.2	16	4.9
	Well Conductors	Composition B	25	11.3	20	6.1
	Well Conductors	Composition B	50	22.7	20	6.1
West Delta 40A (WD-40A) Platform and West Delta 40B (WD-40B) Platform	Piles	Composition B	200	90.7	20	6.1
	Well Conductors	Composition B	75	34.0	15	4.6

Project	**Severance Targets**	**Explosive Type (*)**	**Charge Weight**		**Charge Depth (**)**	
			(lbs)	(kg)	(ft)	(m)
(Barkaszi *et al*., 2016)	Well Conductors	Composition B	75	34.0	25	7.6
	Well Conductors	Composition B	100	45.4	15	4.6
	Well Conductors	Composition B	100	45.4	25	7.6
Eugene Island Block 128 (EI-128) Platform F-4 and East Cameron Block 32 (EC-32) Platform A (Poe *et al*., 2009)	Piles	Composition B	50	22.7	15	4.6
	Piles	Composition B	50	22.7	20	6.1
	Piles	Composition B	50	22.7	25	7.6
	Piles	Composition B	50	22.7	30	9.1
	Piles	Composition B	80	36.3	15	4.6
	Piles	Composition B	80	36.3	20	6.1
	Well Conductors	Composition B	25	11.3	15	4.6
	Well Conductors	Composition B	50	22.7	30	9.1
	Well Conductors	Composition B	65	29.5	30	9.1
	Well Conductors	Composition B	75	34.0	20	6.1

Project	Severance Targets	Explosive Type (*)	Charge Weight		Charge Depth (**)	
			(lbs)	(kg)	(ft)	(m)
	Well Conductors	Composition B	145	65.8	30	9.1

(*) Explosive type are discussed in Section 2.2.

(**) Charge depth refers to the depth of the charge below the seabed.

4.2.1 Zero-to-Peak SPL

Figure 4-3 and Figure 4-4 show the zero-to-peak SPL measurements made during explosive severance of piles and well conductors, respectively, for the projects in Table 4-4. The adopted marine mammal PTS and TTS thresholds and the fish injury threshold are also highlighted on these figures. Most measurements are above the PTS and TTS thresholds for marine mammals and the injury threshold for fish (70% of the pile severance measurements and 64% of the well conductor measurements are above all impact thresholds). 98% of the pile severance measurements and over 99% of the well conductor severance measurements are above the PTS threshold for VHF cetaceans (which is the most sensitive marine mammal hearing group to zero-to-peak SPL). The measurement results clearly indicate that explosive severance of piles and well conductors have the potential to generate zero-to-peak SPLs that are above the PTS and TTS thresholds for marine mammals and injury thresholds for fish. These activities may therefore have an adverse impact on marine mammals and fish. However, it should be noted that the measurements are limited to distances less than 100 m and are not sufficient to estimate distances where PTS or TTS could occur to marine mammals or injury could occur to fish.

Figure 4-3: Zero-to-peak SPL measurements from explosive severance of piles.

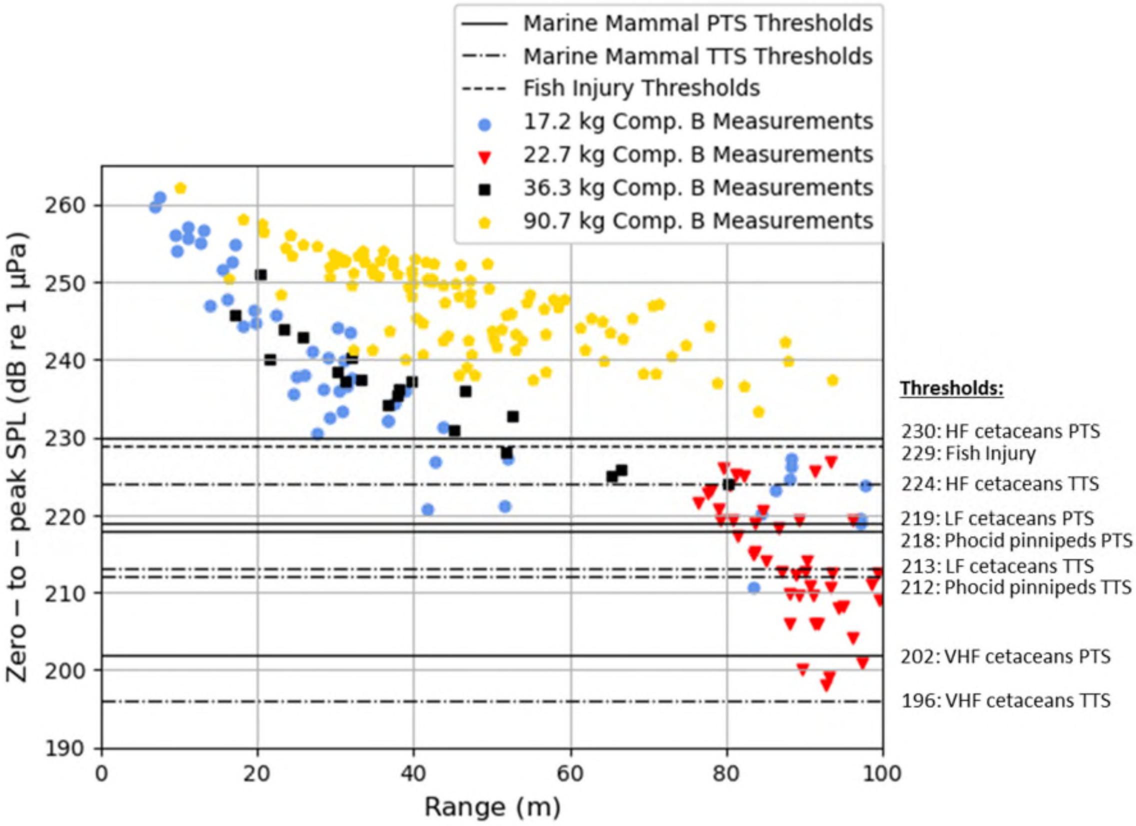
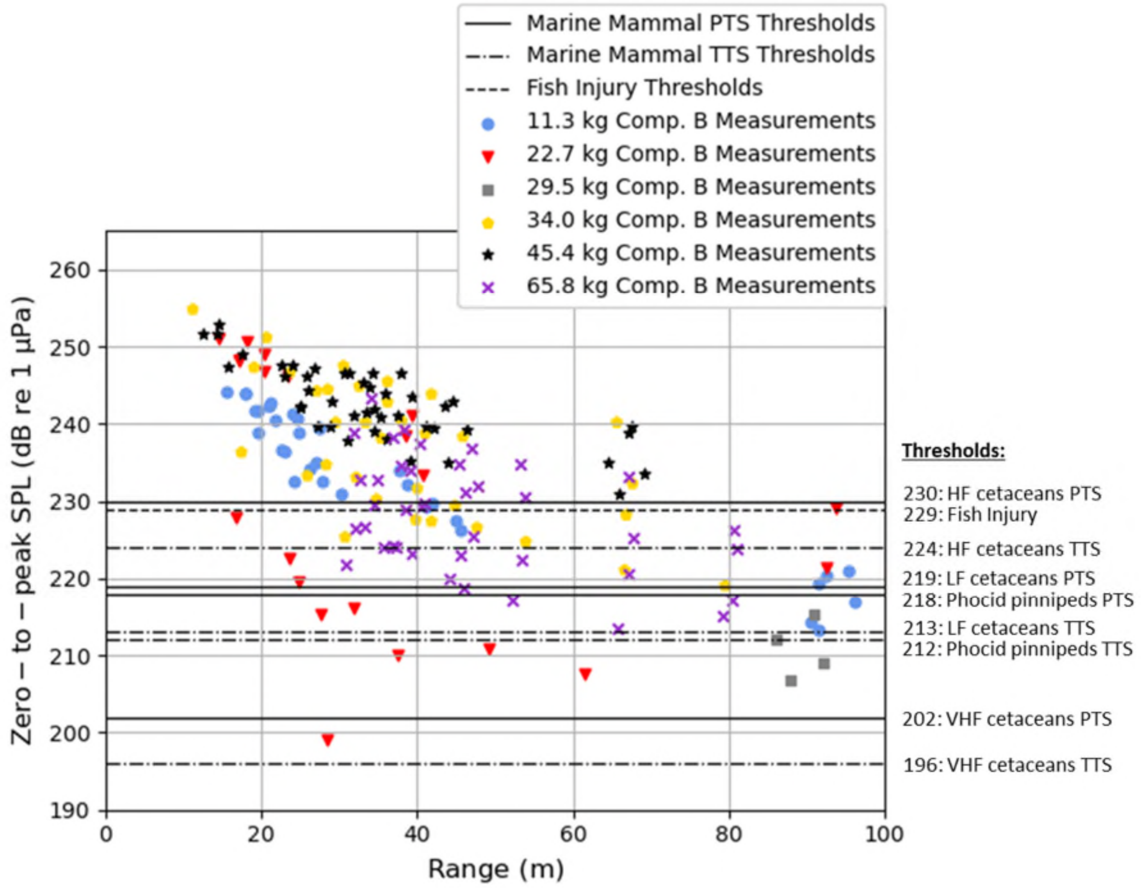


Figure 4-4: Zero-to-peak SPL measurements from explosive severance of well conductors.



4.2.2 SEL

The SEL was not directly measured during the measurement campaigns for the projects shown in Table 4-4. However, all projects measured energy flux densities (EFDs) or acoustic intensity. The EFD is closely related to sound exposure (see Sections 9.2 and 9.4 in Appendix B). The sound exposure can be obtained by multiplying the EFD with the characteristic acoustic impedance of the propagation medium, which is given by the product of the speed of sound in water and the density of water (Jensen *et al*., 2011; Lurton, 2010; Urick, 1983). Subsequently the sound exposure can be expressed as SEL. In the following analysis, all measured EFDs have been converted to sound exposures assuming nominal values of 1,500 m/s for the speed of sound in water and 1,000 kg/m3 for water density.

Figure 4-5 and Figure 4-6 show the SELs calculated from the measurements of EFD for explosive severance of piles and well conductors, respectively, for the projects in Table 4-4. In these figures the SELs calculated from the measure EFDs are compared to the unweighted SEL thresholds for PTS and TTS to marine mammals (see Table 4-3). Comparing the estimated unweighted SELs with these thresholds is equivalent to weighting the received SELs and comparing to the weighted SEL thresholds shown in Table 4-3 i.e., comparing to the NMFS (2018) and Southall *et al*. (2019) thresholds. It is observed that a significant proportion of the SELs calculated from the EFD measurements are above all thresholds for PTS and TTS to marine mammals (56% of the pile severance SELs and 48% of the well conductor severance SELs are above all impact thresholds). All SELs calculated from the measurements are above the PTS and TTS thresholds for VHF cetaceans.

Figure 4-5: SELs calculated from EFD measurements from explosive severance of piles

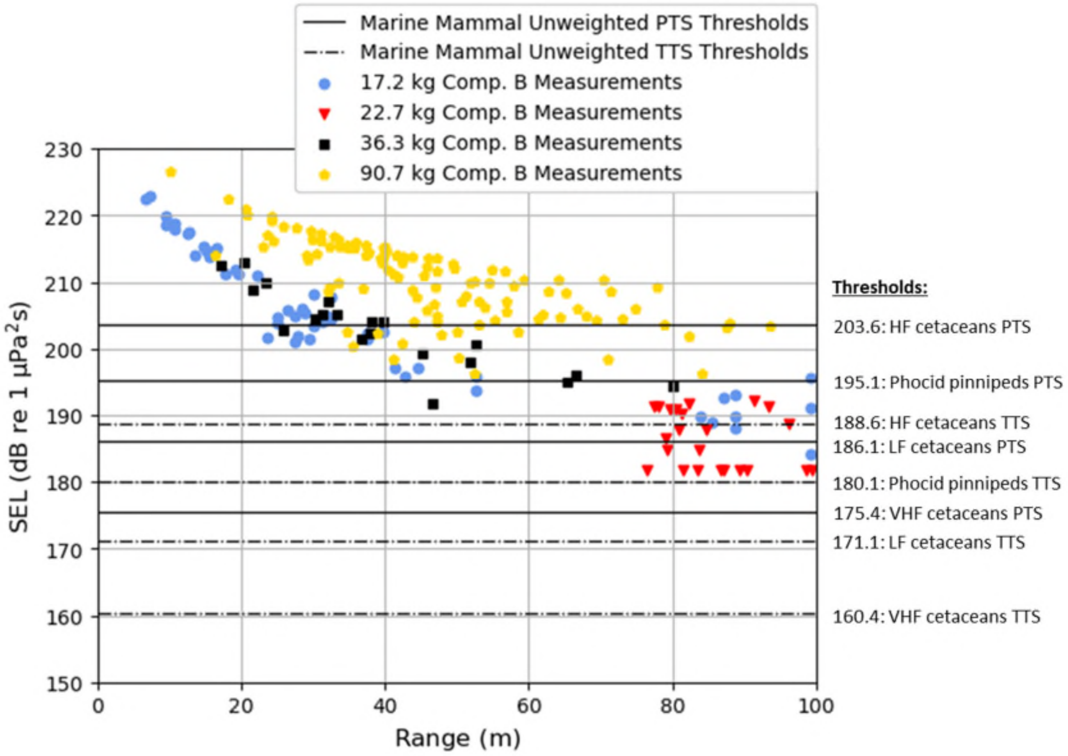
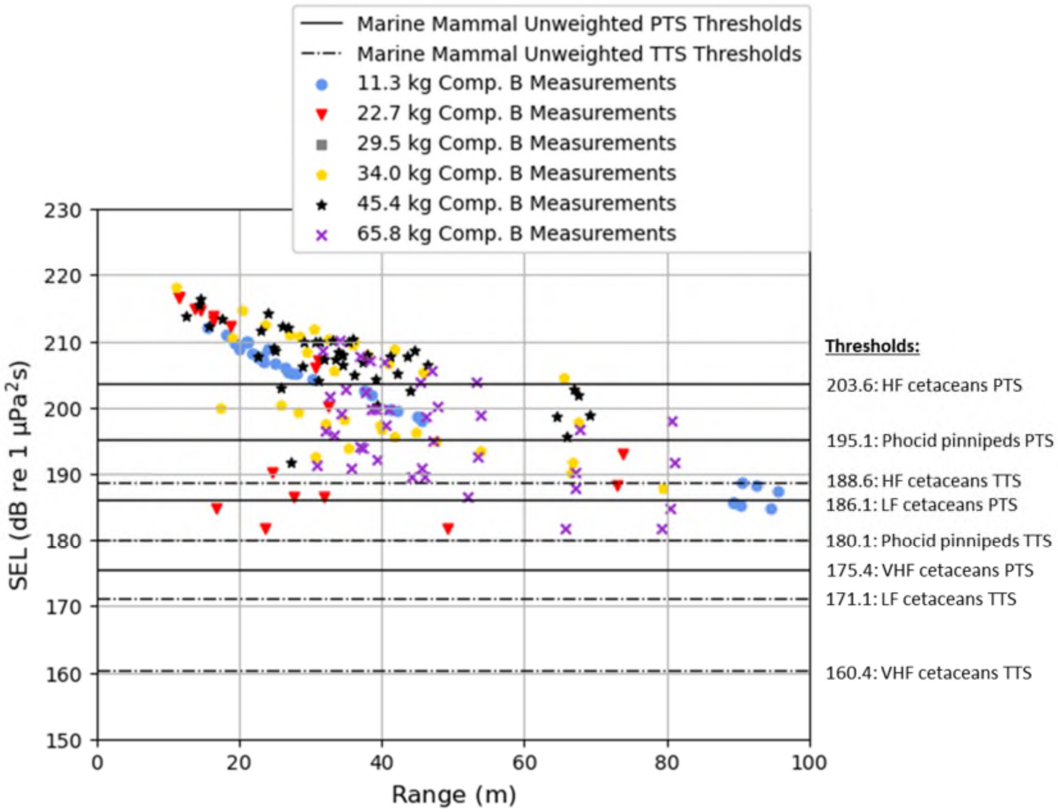


Figure 4-6: SELs calculated from EFD measurements from explosive severance of well conductors



4.3 Noise Modelling

The measurement results presented in the previous section clearly demonstrate that unmitigated explosive severance of piles and well conductors generate noise levels that are above the thresholds for PTS and TTS to marine mammals and the injury threshold for fish. However, all measurements were made over a limited range (with most measurements made at less than 100 m from the explosive charges).

To estimate noise levels at larger distances, several models have been investigated:

- The Connor (1990) models for estimating noise levels from explosive severance of piles and well conductors;
- The EDGAR (Explosives use in Decommissioning – Guide for Assessment of Risk) model for estimating noise levels from explosive severance of piles and well conductors (Brand 2021a, 2021b); and
- Open water detonation models (Cole, 1948; Swisdack, 1978; and Slifko, 1967; Soloway and Dahl, 2014).

These models are presented in more detail in Appendix D: Models for Estimating Noise Levels from Explosive Severance of Piles and Well Conductors of this report. The open water detonation models (OWDMs) refer to models that have been developed for explosives detonated in open water. Open water detonations do not typically occur during decommissioning activities (such as pile and well conductor severance), where the explosive charges are generally confined and deployed below the seabed. However, as will be seen in the following sections, the OWDMs can be useful for providing worst-case estimates of noise levels generated during explosive severance of piles and well conductors. In fact, in some cases the OWDMs may be the most appropriate models to use. For example, Nedwell and Edwards (2004) observed that the noise generated during a wellhead severance in the North Sea was like that expected from an open water detonation. It was conjectured that this behaviour occurred because the pipework and sediment surrounding the charge did not act as an effective confinement (Nedwell and Edwards 2004).

4.3.1 Comparison of Model Estimates with Measurements

In this section, estimates of noise obtained using the aforementioned models are compared to the noise measurements presented in Section 4.2. This comparison is important to understand the usefulness and/or limitations of using the models to predict noise levels for different charge sizes and at different ranges. Model based estimates of noise levels are used to predict distances where potential impacts to marine mammals and fish may occur in Section 4.3.2.

4.3.1.1 Zero-to-Peak SPL

The Connor and EDGAR models for explosive severance of piles and well conductors have been used to estimate zero-to-peak SPLs for all severance activities summarised in Table 4-4. For comparison, an OWDM has also been used to predict the zero-to-peak SPLs. For each individual charge weight, the model estimates have been compared to the measured data for that charge weight. The figures in Section 12.1.1 of Appendix E: Comparison of Model Estimates of Noise from Explosive Severance of Piles and Well Conductors with Measured Data show the modelled and measured zero-to-peak SPLs individually for each charge weight used for explosive severance of piles. The figures in Section 12.1.2 of Appendix E: Comparison of Model Estimates of Noise from Explosive Severance of Piles and Well Conductors with Measured Data show the analogous results for explosive severance of well conductors. For the purposes of verifying the performance of the OWDM, the estimates of zero-to-peak SPL from this model have been compared to estimates made from UXO detonations at the Neart na Gaoithe (NnG) wind farm in Appendix F: Comparison of Open Water Detonation Models with UXO Measurements.

To plot all measurements and model estimates of zero-to-peak SPL for all charge weights on a single figure, the zero-to-peak SPLs are plotted against reduced ranges. For a given charge weight, the reduced range (also commonly referred to as the scaled range) is given by the measurement/model range divided by the cubic root of the charge weight. The theory of similarity for explosives (Cole, 1948) shows that many properties of an explosive shock wave (including the zero-to-peak sound pressure) can be expressed as simple power functions of reduced range (see Section 9.7 in Appendix B: Sound Metrics and Theory). Plotting the zero-to-peak SPL against reduced range allows for the model estimates to be compared to the measurements for all charge weights and provides an overview of how well the model estimates match the measurements.

Figure 4-7 shows the zero-to-peak SPLs estimated by the various models and the zero-to-peak SPL measurements for explosive severance of piles for all charge weights plotted against reduced ranges. The analogous results for the explosive severance of well conductors are shown in Figure 4-8. It is noted that the Connor models and OWDM were developed according to the principle of similarity for explosives and the resulting equations for zero-to-peak sound pressure for these models are expressed as power functions of the reduced range (see Sections 11.1 and 11.3 in Appendix D: Models for Estimating Noise Levels from Explosive Severance of Piles and Well Conductors). Therefore, these models are represented by single lines in Figure 4-7 and Figure 4-8. In contrast, the EDGAR model is not naturally expressed as a function of reduced range and the model estimates cannot be plotted as single lines on Figure 4-7 and Figure 4-8. Therefore, the zero-to-peak SPLs for the EDGAR model have been plotted as a range of zero-to-peak SPLs obtained from the smallest and largest charge sizes used for explosive severance of piles (17.2 – 90.7 kg charges) and well conductors (11.3 – 65.8 kg charges). In Figure 4-7 and Figure 4-8, lines of best fit to the measurement points are also plotted for comparison. The lines of best fit have been obtained by minimising the sum of squared errors between the estimated and measured values (i.e., they are least squares fits).

From Figure 4-7 and the figures in Section 12.1.1 of Appendix E: Comparison of Model Estimates of Noise from Explosive Severance of Piles and Well Conductors with Measured Data, it is observed that the EDGAR model generally underestimates the zero-to-peak SPL measurements for the explosive severance of piles. The Connor model provides a better fit to the measurement data, which is illustrated by the fact that it more closely matches the line of best fit compared to the other models. However, the Connor model can also underestimate the zero-to-peak SPLs when compared to the measurements. Whilst the OWDM was not developed to estimate noise from the explosive severance of piles, Figure 4-7 and the figures in Section 12.1.1 of Appendix E: Comparison of Model Estimates of Noise from Explosive Severance of Piles and Well Conductors with Measured Data show that it appears to provide a useful upper bound to the measured data and may therefore be useful for providing worst-case estimates of potential impacts.

Similar observations are made for the well conductor results shown in figure 4.8 and the figures in Section 12.1.2 of Appendix E: Comparison of Model Estimates of Noise from Explosive Severance of Piles and Well Conductors with Measured Data. Whilst the EDGAR model provides a better fit to the well conductor measurement data than it did to the pile severance measurement data, it still underestimates the measured zero-to-peak SPLs for a large number of data points. The Connor model consistently estimates higher zero-to-peak SPLs than the EDGAR model, but it too often underestimates the measured zero-to-peak SPLs. The OWDM may again provide a useful upper bound since it consistently estimates higher zero-to-peak SPLs compared to the measured data.

It is important to note that the measurements made during the explosive severance of piles and well conductors were made over a very limited range with all measurements being made at less than 100 m. Therefore, the measurements can only be used to establish model performance over this range. The accuracy of the models at distances beyond 100 m cannot be verified since no measurements have been made at these distances. The OWDMs have been compared to measurements made of UXO detonations.

Figure 4-7: Comparison of model estimates with measurements of zero-to-peak SPL from explosive severance of piles for all charge weights.

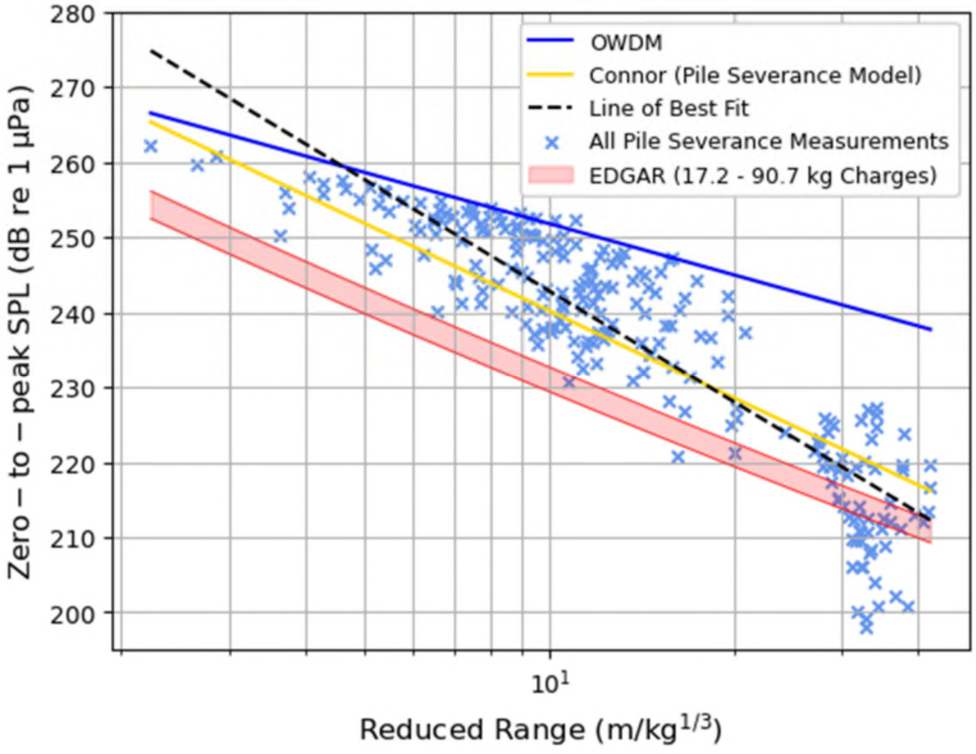
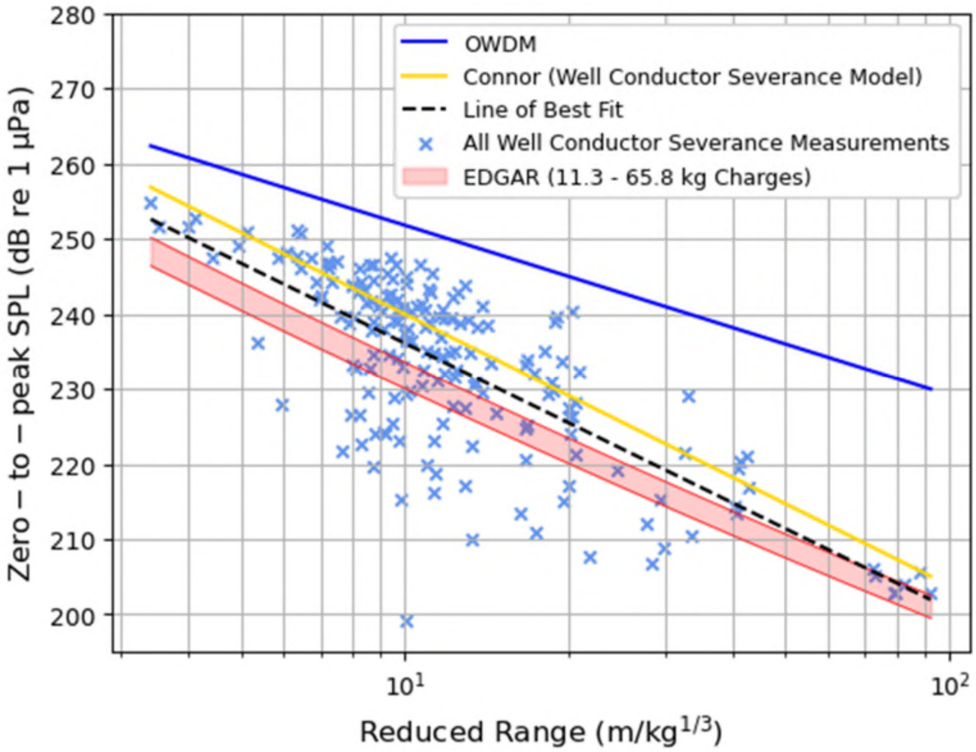


Figure 4-8: Comparison of model estimates with measurements of zero-to-peak SPL from explosive severance of well conductors for all charge weights.



4.3.1.2 SEL

The Connor models for explosive severance of piles and well conductors have also been used to estimate SELs for the severance activities summarised in Table 4-4. For comparison, two OWDMs developed by Soloway and Dahl (2014) and Swisdack (1978) have also been used to predict SELs. The Soloway and Dahl OWDM directly estimates SEL. However, the Swisdack OWDM estimates EFD. The EFDs estimated by the Swisdack model have been converted to sound exposures, which in turn can be expressed as SELs, assuming nominal values of 1,500 m/s for the speed of sound in water and 1,000 kg/m3 for water density (see Section 9.4 of Appendix B: Sound Metrics and Theory for the relationship between EFD and sound exposure).

For each individual charge weight considered, the model estimated SELs have been compared to the measured data. The figures in Sections 12.2.1 and 12.2.2 of Appendix E: Comparison of Model Estimates of Noise from Explosive Severance of Piles and Well Conductors with Measured Data show the modelled and measured SELs individually for each charge weight used for explosive severance of piles and well conductors. To plot all measurements and model estimates of SEL for all charge weights on a single figure, the reduced SELs are plotted against reduced ranges (see Section 9.7 in Appendix B: Sound Metrics and Theory for the definition of reduced SEL used here). Figures 4.9 and 4.10 show the SEL measurements and model estimates of reduced SEL plotted against reduced range. The Connor pile severance and well conductor models and the Swisdack OWDM were developed to follow the principle of similarity for explosives and the equations for reduced EFD (and therefore reduced SEL) for these models are expressed as functions of reduced range. As such, they are represented by single lines in Figure 4.9 and Figure 4.10. The Soloway and Dahl OWDM estimates of reduced SEL are plotted as a range obtained from the smallest and largest charge sizes used for explosive severance of piles (17.2 – 90.7 kg charges) and well conductors (11.3 – 65.8 kg charges). Linear least squares lines of best fit to the measurement points are also plotted in Figure 4-9 and Figure 4-10.

Figure 4-9 and the figures in Section 12.2.1 of Appendix E: Comparison of Model Estimates of Noise from Explosive Severance of Piles and Well Conductors with Measured Data show that the SEL predicted by the Connor model provides a very good fit to the measurements which is signified by the fact that it very closely matches the linear least squares solution. However, due to the scattering of the measurement data, the Connor model underestimates a lot of the SEL measurements. The Swisdack OWDM appears to provide useful conservative estimates of SEL over the ranges that the measurements were conducted. The gradients of the upper bound and lower bound curves for the Soloway and Dahl OWDM shown in Figure 4.9 are much lower than the other models. This signifies that at larger ranges this model will estimate much higher SELs than the other models. The figures in Section 12.2.1of Appendix E: Comparison of Model Estimates of Noise from Explosive Severance of Piles and Well Conductors with Measured Data show that even for relatively small distances (50 – 100 m) the Soloway and Dahl model estimates SEL's that are much higher than the measurements.

Figure 4-10 and the figures in Section 12.2.2 of Appendix E: Comparison of Model Estimates of Noise from Explosive Severance of Piles and Well Conductors with Measured Data show that the SEL predicted by the Connor model for explosive severance of well conductors generally estimates SEL's slightly higher than the measurements. However, this means that it could be a useful model for providing conservative estimates of potential impacts. The results also demonstrate that the Swisdack OWDM consistently overestimates SELs compared to the measured values.

Figure 4-9: Comparison of model estimates with SEL calculated from EFD measurements from explosive severance of piles for all charge weights.

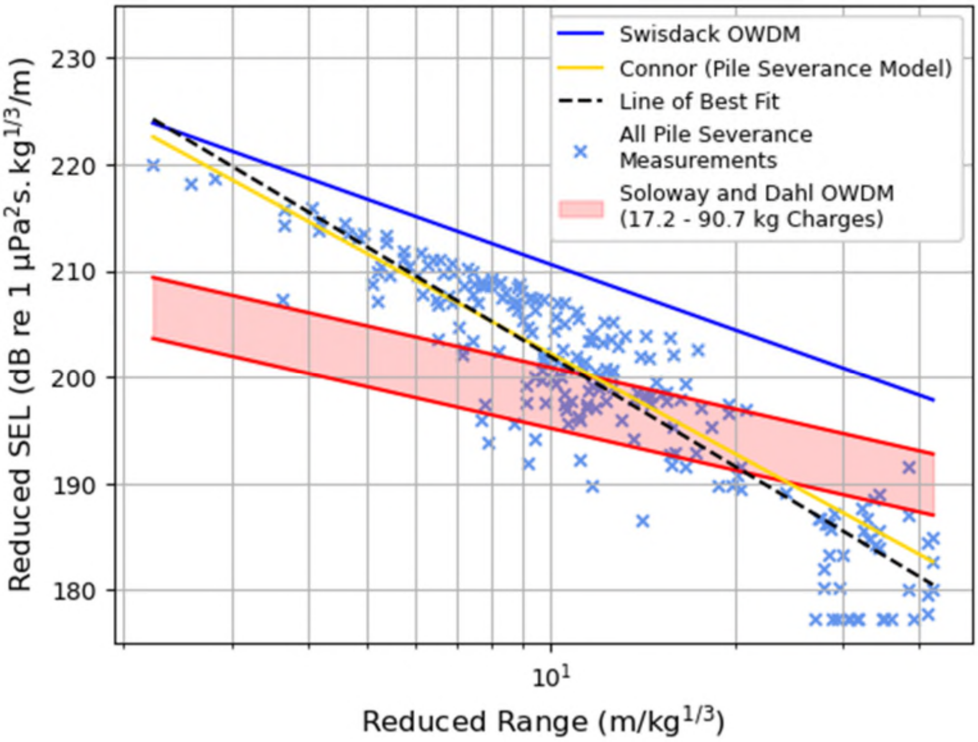
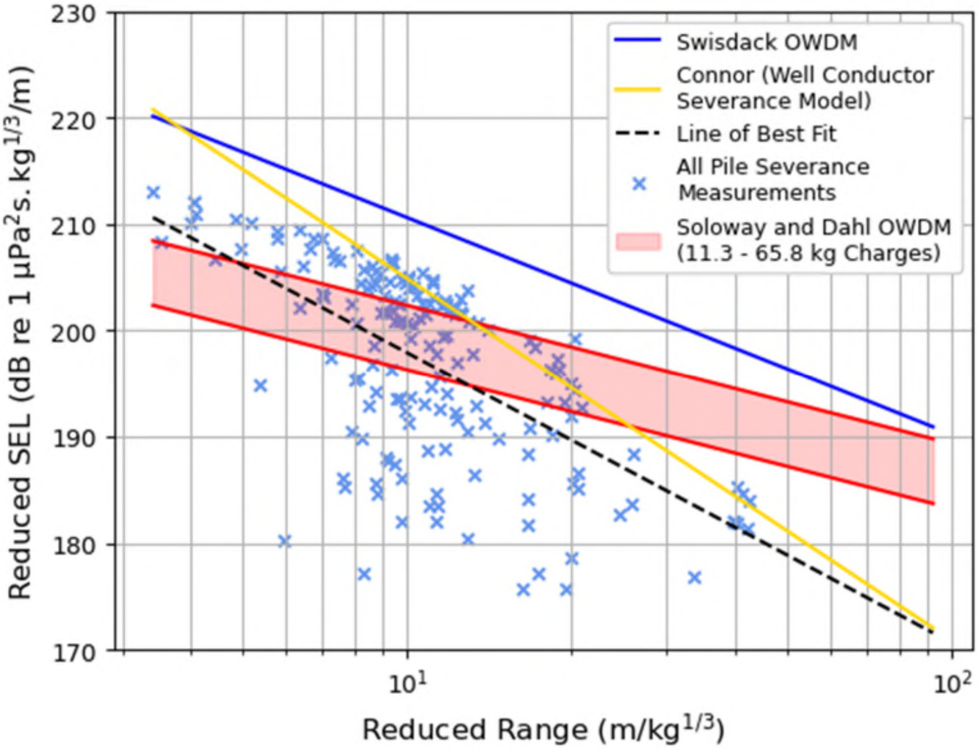


Figure 4-10: Comparison of model estimates with SEL calculated from EFD measurements from explosive severance of well conductors for all charge weights.



4.3.2 Estimation of Potential Impacts

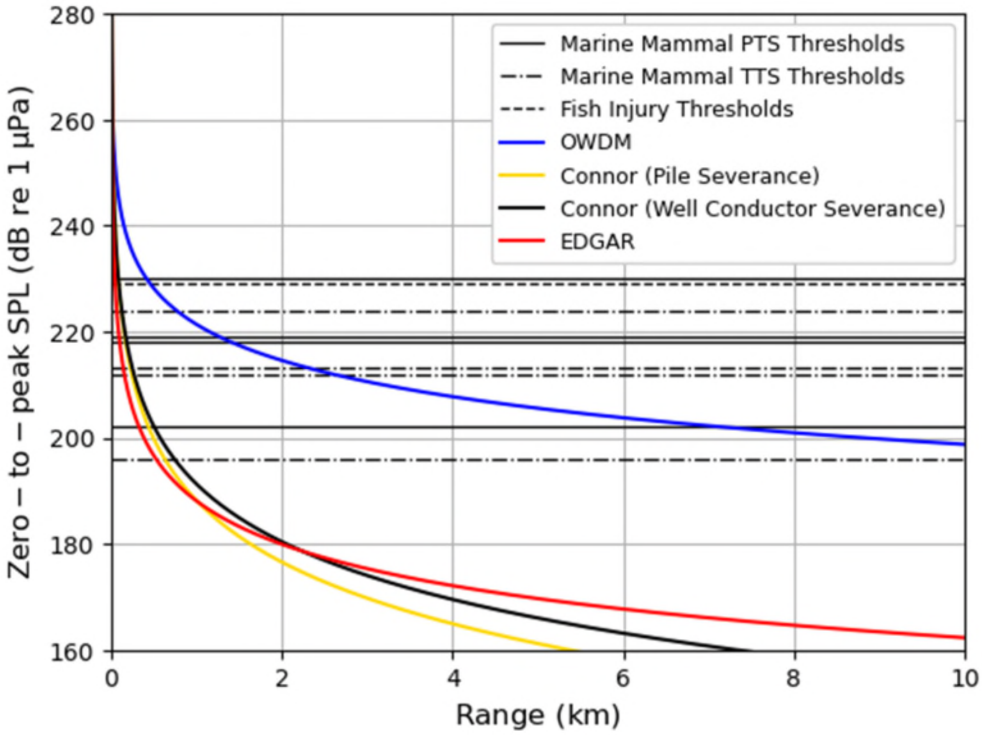
The measurements of noise from the explosive severance of piles and well conductors presented in previous sections can only be used to predict impacts over the limited ranges that the measurements were conducted. The measurements were limited to distances less than 100 m from the charges. It is evident from the measurements that many of the PTS and TTS thresholds for marine mammals and the injury threshold for fish could be exceeded at distances well beyond 100 m. In this section, the models have been used to predict distances where the zero-to-peak SPL and SEL impact thresholds may be exceeded.

4.3.2.1 Zero-to-Peak SPL

The models have been used to predict zero-to-peak SPLs from explosive severance of piles and well conductors over a much larger range than the measurements were made. The zero-to-peak SPL has been estimated for a select range of charge sizes that were used for the projects summarised in Table 4-4.

Figure 4.8 shows the estimated zero-to-peak SPLs over a range of 10 km for explosive severance of piles and well conductors with 90.7 kg Composition B charges. The estimation of zero-to-peak SPLs for other considered charge sizes are provided in Section 14.1 of Appendix G: Model Estimates of Noise for Explosive Severance of Piles and Well Conductors. It can be observed that over shorter distances (below 1 km) the EDGAR model predicts lower zero-to-peak SPLs compared to the Connor pile severance and well conductor severance models. However, beyond 1km the EDGAR model predicts higher zero-to-peak SPLs compared to the Connor models. As expected, the OWDM predicts significantly higher zero-to-peak SPLs compared to all other models. At 1 km the estimated zero-to-peak SPL from the OWDM can be over 30 dB higher than the other models (signifying zero-to-peak sound pressures more than 30 times higher).

Figure 4-11: Estimated zero-to-peak SPL from explosive severance of piles and well conductors with 90.7 kg Composition B charges.



The predicted distances to the marine mammal PTS and TTS thresholds are summarised in Table 4.5 and Table 4.6, respectively.

The models developed specifically for pile severance and well conductor severance (i.e., the EDGAR and Connor models) predict that the PTS threshold for PTS to LF cetaceans will be exceeded at distances of 70 – 90 m for the 11.3 kg charge weight (the smallest charge size modelled). Some of the measurements of zero-to-peak SPL for well conductor severance with an 11.3 kg charge (see Figure 4.4) were above the LF cetaceans PTS beyond 90 m. Therefore, the EDGAR and Connor models do not provide conservative estimations of PTS impacts to LF cetaceans. The EDGAR and Connor models predict that the LF cetaceans PTS threshold will be exceeded at 100 – 180 m when the charge size is increased to 90.7 kg (the largest charge size modelled). The noise measurements for pile and well conductor severances with 90.7 kg charges were limited to less than 100 m and it is therefore uncertain whether the models provide reasonable conservative estimations of impacts or not. The OWDM predicts that the LF cetaceans PTS threshold will be exceeded at 640 m for the 11.3 kg charge weight and.at 1,300 m for the 90.7 kg charge. These distances cannot be validated with the measurements available for explosive severance of piles and well conductors. However, for the purposes of mitigation, it is thought that the OWDM provides reasonable conservative estimates of distances where PTS could potentially occur to LF cetaceans.

The EDGAR and Connor models predict that the PTS thresholds for HF cetaceans (the least sensitive marine mammal group) will be exceeded at distances of 30 – 50 m for the 11.3 kg charge and at 50 – 90 m for the 90.7 kg charge. The measurement results for explosive severance of piles with 90.7 kg charges show zero-to-peak SPLs well above the HF cetaceans

PTS threshold at distance around 90 m. Therefore, the EDGAR and Connor models are not conservative when estimating PTS impacts to HF cetaceans. The OWDM estimates that the PTS threshold for HF cetaceans will be exceeded at 210 m and 420 m for the 11.3 kg and 90.7 kg charges, respectively. The OWDM provides a reasonable conservative estimate of PTS to HF cetaceans and therefore mitigation measures should be based on these impacts.

For VHF cetaceans, the predicted distances to PTS from the EDGAR and Connor models range from 220 – 260 m for the 11.3 kg charge and 330 – 510 m for the 90.7 kg charge. The performance of these models cannot be validated by the available noise measurements since the measurements were limited to ranges of less than 100 m. The OWDM predicts significantly larger distances to the PTS threshold for VHF cetaceans. It predicts that the PTS threshold will be exceeded at 3,600 m for the 11.3 kg charge and at 7,200 m for the 90.7 kg charge. The performance of the OWDM has been validated over large ranges for prediction of zero-to-peak SPLs from UXO detonations (see Appendix F: Comparison of Open Water Detonation Models with UXO Measurements) where it was shown to match well with measurements made at distance up to approximately 30 km. However, the model is likely to provide overly conservative estimates of impacts from pile severance and well conductor removal operations. Further measurements of the noise from the explosive severance of piles and well conductors are needed to verify the performance of any of the models over long distances and to gain a better understanding of potential impacts.

The predicted distances to where fish injury may occur are summarised in Table 4-7. The EDGAR and Connor models predict that injury to fish will be limited to within 100 m. The OWDM predicts that injury to fish will occur between 230 – 460 m for explosive charges ranging from 11.3 kg to 90.7 kg.

Table 4-5: Predicted distances to zero-to-peak SPL thresholds for PTS to marine mammals from explosive severance of piles and well conductors

Hearing Group	Predicted Distance to PTS Threshold (m) (*)			
	EDGAR (**)	Connor Pile Severance Model	Connor Well Conductor Severance Model	OWDM (***)
11.3 kg Composition B charge				
LF cetaceans	70	80	90	640
HF cetaceans	30	50	50	210
VHF cetaceans	220	220	260	3,600

Hearing Group	Predicted Distance to PTS Threshold (m) (*)			
	EDGAR (**)	Connor Pile Severance Model	Connor Well Conductor Severance Model	OWDM (***)
Phocid pinnipeds	70	90	100	710
22.7 kg Composition B charge				
LF cetaceans	70	100	110	800
HF cetaceans	40	60	60	270
VHF cetaceans	250	280	320	4,600
Phocid pinnipeds	80	110	120	890
36.3 kg Composition B charge				
LF cetaceans	80	120	130	940
HF cetaceans	40	70	70	310
VHF cetaceans	280	330	380	5,300
Phocid pinnipeds	90	130	140	1,100
65.8 kg Composition B charge				
LF cetaceans	90	150	160	1,200
HF cetaceans	40	80	80	380
VHF cetaceans	310	400	460	6,500
Phocid pinnipeds	100	160	170	1,300

Hearing Group	**Predicted Distance to PTS Threshold (m) (*)**			
	EDGAR (**)	**Connor Pile Severance Model**	**Connor Well Conductor Severance Model**	**OWDM (***)**
90.7 kg Composition B charge				
LF cetaceans	100	160	180	1,300
HF cetaceans	50	90	90	420
VHF cetaceans	330	440	510	7,200
Phocid pinnipeds	100	170	190	1,500
(*) Predicted distances less than 1,000 m have been rounded up to the nearest 10m and predicted distances above 1,000 m have been rounded up to the nearest 10 m. (**) The EDGAR model predicts the same impacts for both pile and well conductor severances. (***) The OWDM results are provided as a worst-case estimate of impacts from explosive severance of piles and well conductors.				

Table 4-6 Predicted distances to zero-to-peak SPL thresholds for TTS to marine mammals from explosive severance of piles and well conductors.

Hearing Group	Predicted Distance to TTS Threshold (m) (*)			
	EDGAR (**)	Connor Pile Severance Model	Connor Well Conductor Severance Model	OWDM (***)
11.3 kg Composition B charge				
LF cetaceans	100	120	130	1,200
HF cetaceans	50	60	70	390
VHF cetaceans	350	320	370	6,600
Phocid pinnipeds	110	130	140	1,300
22.7 kg Composition B charge				
LF cetaceans	110	150	160	1,500
HF cetaceans	50	80	80	480
VHF cetaceans	400	400	470	8,400
Phocid pinnipeds	120	160	170	1,700
36.3 kg Composition B charge				
LF cetaceans	120	170	190	1,800
HF cetaceans	60	90	100	570
VHF cetaceans	440	470	550	9,800
Phocid pinnipeds	130	180	200	2,000

Hearing Group	Predicted Distance to TTS Threshold (m) (*)			
	EDGAR (**)	Connor Pile Severance Model	Connor Well Conductor Severance Model	OWDM (***)
65.8 kg Composition B charge				
LF cetaceans	140	210	230	2,100
HF cetaceans	70	110	120	690
VHF cetaceans	500	570	670	11,900
Phocid pinnipeds	150	220	240	2,400
90.7 kg Composition B charge				
LF cetaceans	150	230	250	2,400
HF cetaceans	70	120	130	770
VHF cetaceans	530	630	740	13,300
Phocid pinnipeds	160	250	270	2,600

(*) Predicted distances less than 1,000 m have been rounded up to the nearest 10m and predicted distances above 1,000 m have been rounded up to the nearest 10 m.

(**) The EDGAR model predicts the same impacts for both pile and well conductor severances.

(***) The OWDM results are provided as a worst-case estimate of impacts from explosive severance of piles and well conductors.

Table 4-7 Predicted distances to zero-to-peak SPL thresholds for potential mortality to fish from explosive severance of piles.

Charge Weight	Predicted Distance Threshold for Potential Mortality to Fish (m) (*)			
	EDGAR (**)	Connor Pile Severance Model	Connor Well Conductor Severance Model	OWDM (***)
11.3 kg Composition B charge	40	50	50	230
22.7 kg Composition B charge	40	60	60	290
36.3 kg Composition B charge	40	70	70	340
65.8 kg Composition B charge	50	80	90	420
90.7 kg Composition B charge	50	90	90	460

(*) Predicted distances less than 1,000 m have been rounded up to the nearest 10m and predicted distances above 1,000 m have been rounded up to the nearest 10 m.

(**) The EDGAR model predicts the same impacts for both pile and well conductor severances.

(***) The OWDM results are provided as a worst-case estimate of impacts from explosive severance of piles and well conductors.

4.3.2.2 SEL

The models have been used to predict SELs from explosive severance of piles and well conductors. Figure 4-12 shows the estimated SELs over a range of 10 km for explosive severance of piles and well conductors with 90.7 kg Composition B charges. The estimation of SELs for other considered charge sizes are provided in Section 14.2 of Appendix G: Model Estimates of Noise for Explosive Severance of Piles and Well Conductors. In these figures

the unweighted SEL thresholds from Table 4-3 are shown. Comparing the estimated unweighted SELs with these thresholds is equivalent to weighting the received SELs and comparing to the weighted SEL thresholds shown in Table 4-3 i.e., comparing to the NMFS (2018) and Southall *et al*. (2019) thresholds. It can be observed from Figure 4-12 and the figures in Section 14.2 of Appendix G that the Connor pile severance and well conductor severance models predict much lower SELs compared to the Soloway and Dahl OWDM and Swisdack OWDM. The distances to the SEL thresholds for PTS and TTS to marine mammals predicted by the different models are summarised in Table 4-8 and

Table 4-9.

The Connor pile and well conductor severance models predict that PTS to LF cetaceans will be limited to below 110 m. Some of the measurements for pile severance were above the LF cetaceans PTS threshold at around 100 m (see Figure 4-5). However, the estimated distance for PTS to LF cetaceans from these models seems to be reasonable based on the measurements. The estimated distances for PTS to LF cetaceans from the Swisdack OWDM (530 m) and the Soloway and Dahl OWDM (1,200 m) appear to be overly conservative.

All models predict that the PTS threshold for HF cetaceans will not be exceeded beyond a maximum distance of 80 m for the 11.3 kg charge. The measurements in Figure 4.6 show that the 11.3 kg charges resulted in SELSs that were either slightly below or slightly above the PTS threshold for HF cetaceans at around 90 m. The Connor pile severance and well conductor severance models predict that the PTS threshold for HF cetaceans will not be exceeded beyond 80 m for the 90.7 kg charge. The measurements in Figure 4-5 show SELs above the PTS threshold at distances between 80 – 100 m.

The Connor pile severance and well conductor models predict that the PTS threshold for VHF cetaceans will be exceeded at distances of 210 m and 530 m for the 11.3 kg and 90.7 kg charges, respectively. The Swisdack OWDM predicts the VHF cetaceans PTS threshold will be exceeded at distances of 1,800 m for the 11.3 kg charge and 5,00m for the 90.7 kg charge. The Soloway and Dahl OWDM predicts much larger distances of 7,400 m and 25,000 m to the VHF cetaceans PTS threshold for 11.3 kg and 90.7 kg charges, respectively. Comparison of the Soloway and Dahl OWDM with measurements of UXO detonations showed that it significantly overestimated the SEL at large distances (see Appendix F: Comparison of Open Water Detonation Models with UXO Measurements). It is therefore likely that it significantly overestimates the distances to PTS for VHF cetaceans from explosive severance of piles and well conductors. It is likely that the Swisdack, Soloway and Dahl OWDMs overestimate the SEL from pile severance and well conductor explosive severance operations since these models are based on measurements from open water detonations and it is expected that there will be attenuation of the noise levels due to the charge confinement. Further measurements of the noise from the explosive severance of piles and well conductors are needed to verify the performance of any of the models over long distances and to gain a better understanding of potential impacts.

Figure 4-12: Estimated SEL from explosive severance of piles and well conductors with 90.7 kg Composition B charges.

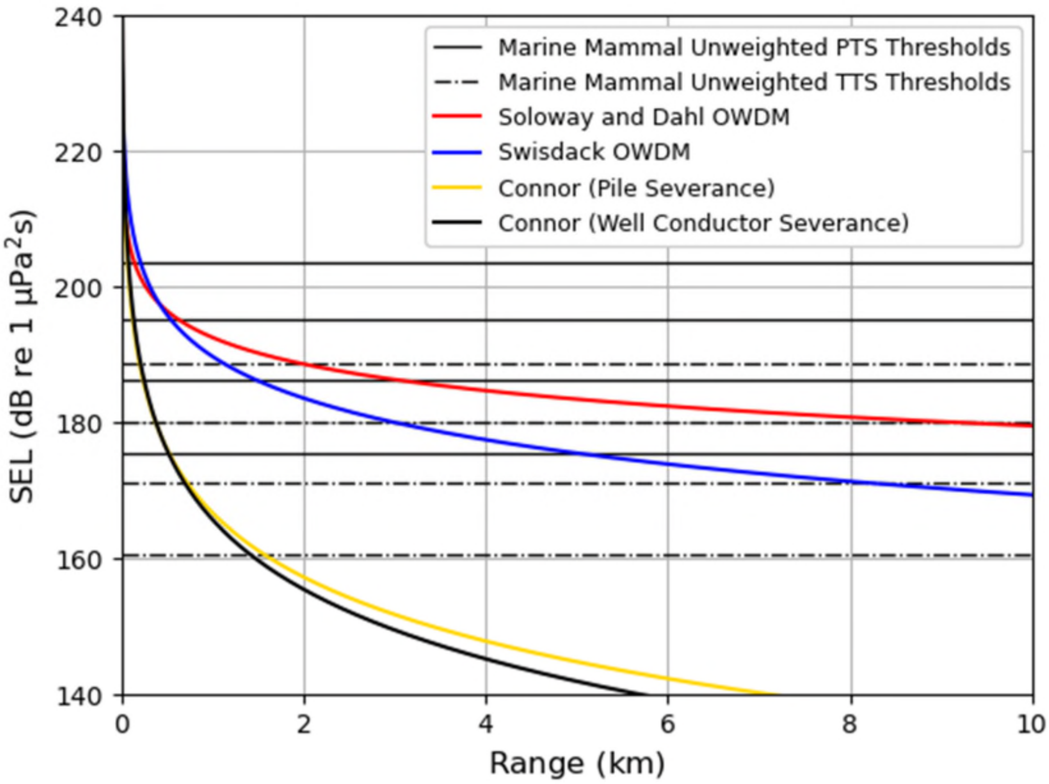


Table 4-8: Predicted distances to SEL thresholds for PTS to marine mammals from explosive severance of piles and well conductors

Hearing Group	Predicted Distance to PTS Threshold (m) (*)			
	Connor Pile Severance Model	Connor Well Conductor Severance Model (**)	Swisdack OWDM	Soloway and Dahl OWDM (**)
11.3 kg Composition B charge				
LF cetaceans	100	110	530	1,200
HF cetaceans	30	40	80	50
VHF cetaceans	210	210	1,800	7,400

Hearing Group	Predicted Distance to PTS Threshold (m) (*)			
	Connor Pile Severance Model	Connor Well Conductor Severance Model (**)	Swisdack OWDM	Soloway and Dahl OWDM (**)
Phocid pinnipeds	50	60	200	230
22.7 kg Composition B charge				
LF cetaceans	130	140	750	1,600
HF cetaceans	40	50	110	70
VHF cetaceans	290	290	2,600	10,400
Phocid pinnipeds	70	80	280	320
36.3 kg Composition B charge				
LF cetaceans	160	170	950	2,000
HF cetaceans	50	60	140	90
VHF cetaceans	350	350	3,200	13,100
Phocid pinnipeds	90	100	350	400
65.8 kg Composition B charge				
LF cetaceans	210	220	1,300	2,700
HF cetaceans	60	70	180	120

Hearing Group	Predicted Distance to PTS Threshold (m) (*)			
	Connor Pile Severance Model	Connor Well Conductor Severance Model (**)	Swisdack OWDM	Soloway and Dahl OWDM (**)
VHF cetaceans	460	450	4,300	17,500
Phocid pinnipeds	110	120	460	540
90.7 kg Composition B charge				
LF cetaceans	240	250	1,500	3,100
HF cetaceans	70	80	210	140
VHF cetaceans	530	520	5,000	20,500
Phocid pinnipeds	130	140	540	630

(*) Predicted distances less than 1,000 m have been rounded up to the nearest 10m and predicted distances above 1,000 m have been rounded up to the nearest 10 m.

(**) The Swisdack and Soloway and Dahl OWDM results are provided as worst-case estimates of impacts from explosive severance of piles and well conductors.

Table 4-9: Predicted distances to SEL thresholds for TTS to marine mammals from explosive severance of piles and well conductors

Hearing Group	Predicted Distance to TTS Threshold (m) (*)			
	Connor Pile Severance Model	Connor Well Conductor Severance Model (**)	Swisdack OWDM	Soloway and Dahl OWDM (**)
11.3 kg Composition B charge				
LF cetaceans	290	280	2,900	15,800
HF cetaceans	80	90	400	720
VHF cetaceans	630	580	9,700	100,000 (***)
Phocid pinnipeds	150	160	1,100	3,200
22.7 kg Composition B charge				
LF cetaceans	390	380	4,100	22,200
HF cetaceans	110	120	570	1,100
VHF cetaceans	860	790	13,700	100,000 (***)
Phocid pinnipeds	210	210	1,500	4,600
36.3 kg Composition B charge				
LF cetaceans	480	470	5,200	27,900
HF cetaceans	140	150	720	1,300

Hearing Group	Predicted Distance to TTS Threshold (m) (*)			
	Connor Pile Severance Model	Connor Well Conductor Severance Model (**)	Swisdack OWDM	Soloway and Dahl OWDM (**)
VHF cetaceans	1,100	960	17,300	100,000 (***)
Phocid pinnipeds	250	260	1,900	5,700
65.8 kg Composition B charge				
LF cetaceans	630	600	7,000	37,400
HF cetaceans	180	190	960	1,700
VHF cetaceans	1,400	1,300	23,200	100,000 (***)
Phocid pinnipeds	330	330	2,600	7,600
90.7 kg Composition B charge				
LF cetaceans	720	690	8,200	43,700
HF cetaceans	200	210	1,200	2,000
VHF cetaceans	1,600	1,500	27,200	100,000 (***)
Phocid pinnipeds	370	380	3,000	8,900
(*) Predicted distances less than 1,000 m have been rounded up to the nearest 10m and predicted distances above 1,000 m have been rounded up to the nearest 10 m. (**)The Swisdack and Soloway and Dahl OWDM results are provided as worst-case estimates of impacts from explosive severance of piles and well conductors.				

Hearing Group	Predicted Distance to TTS Threshold (m) (*)			
	Connor Pile Severance Model	Connor Well Conductor Severance Model (**)	Swisdack OWDM	Soloway and Dahl OWDM (**)
(***)The Swisdack and Soloway and Dahl OWDM predicted the VHF cetaceans TTS threshold would be exceeded at distances beyond the maximum distance of 100 km for which the model was run.				

5 Mitigation Measures

This section discusses some of the potential measures that might be applied to mitigate the potential environmental effects of explosions underwater on the marine environment.

5.1 Noise Reduction

5.1.1 Minimise Explosive Quantity Required

Recent advances in computer software and hardware technologies have increased accessibility to advanced numerical modelling capabilities. Modelling software includes finite element analysis (FEA), computational fluid dynamics (CFD), and Hydro-code (a hybrid of FEA and CFD) for modelling the explosive event and material response. Modelling allows the type of explosive, amount and size of charge required for each application to be calculated exactly, to minimise the quantity of explosive use. This minimises the noise generated during the potential impact that the explosive may have on the environment.

5.1.2 Bubble curtains

Bubble curtains work by pumping compressed air through a pipe that is deployed on the seabed around the noise source (e.g., pile or explosive). The pipe has nozzles out of which the air is pumped creating bubbles that rise to the water surface creating a "curtain" around the noise source. Due to the change in impedance between water and air, the bubbles reflect and absorb noise thus reducing overall noise levels.

Bubble curtains have been successfully used to reduce underwater noise levels from offshore piling (Bellman, 2014; Dahne *et al*., 2017; Koschinski and Ludemann, 2013) and have been shown to be effective at reducing piling noise in water depths up to about 40 m (Bellman, 2014). The effectiveness of bubble curtains in deeper waters is unknown, but it is thought that they will be less effective. Bubble curtains may also not be an effective form of mitigation in areas where currents speeds are high. A review of noise abatement systems (including bubble curtains) and their applicability in Scottish waters is provided in Verfuss *et al*. (2019), which highlighted that bubble curtains have been successfully used for mitigation in water depths up to 40 m but that their usefulness in deeper waters is unknown.

5.2 JNCC Guidance on Minimising Potential Impacts to Marine Mammals

JNCC have published guidelines for minimising the risk of injury to marine mammals from using explosives (JNCC, 2010a), which suggest mitigation measures including visual and acoustic observation and the use of Acoustic Deterrent Devices (ADDs). The current guidance (JNCC, 2010a) is in the process of being updated to consider both open water explosive detonations (such as UXO clearance) and explosives used below the mudline (such as in many decommissioning applications). The revised guidance is expected to be published soon.

5.2.1 Visual and Acoustic Observation

The JNCC (2010a) guidelines recommends that a 1 km radius mitigation zone should be employed around any explosive detonation location. Marine mammal observers (MMOs) should visually observe the mitigation zone prior to any detonation occurring to detect marine mammal presence in the mitigation zone. Passive acoustic monitoring (PAM) may also be used to aid visual observations by MMOs. The guidelines suggest that visual monitoring of the mitigation zone and supplementary acoustic monitoring (if required) should begin at least one hour before any detonation takes place (referred to as the pre-detonation search). The pre-detonation search should continue until the MMO advises that the mitigation zone is clear of marine mammals, and the detonation can start. The guidance also recommends that:

- Explosive detonations should not be undertaken within 20 minutes of a marine mammal being detected within the mitigation zone.
- If a marine mammal is observed, or acoustically detected, within the mitigation zone, it should be monitored and tracked until it moves out of range. The MMO should notify the relevant chain of command of the detection and advise that the operation should be delayed. If the marine mammal is not detected again within 20 minutes, it can be assumed that it has left the area and the detonation may commence.
- If an animal has been detected acoustically, the PAM operative should use a range indication and their judgement to determine whether the marine mammal is within the mitigation zone.
- If an MMO or PAM operative is uncertain whether marine mammals are present within the mitigation zone, they should advise that the activity should be delayed as a precaution until they are certain that no animals are present.

5.2.2 Acoustic Deterrent Devices

ADDs may be used to deter marine mammals from entering an area where explosives are going to be used. The JNCC (2010a) guidance for minimising the risk of injury to marine mammals from using explosives recommends the use of ADDs to deter marine mammals to distances where they are less likely to suffer injury. It is suggested that ADDs should be used in conjunction with visual and acoustic monitoring (and not as a replacement for monitoring) and for as short period as necessary to minimise the introduction of additional noise.

ADDs have been successfully deployed to deter harbour porpoise (Thompson *et al*., 2020) and minke whales (McGarry *et al*., 2017) from wind farm development areas prior to piling. Thompson et al. (2020) observed that acoustic detections of porpoises decreased following 15-min ADD playback, with a 50% probability of response within 21.7 km. McGarry *et al*. (2017) observed that minke whales increased their swim speed and swam away when exposed to ADD sound. A review of the effectiveness of different ADDs in mitigating potential injury to marine mammals from explosives use is provided by McGarry *et al*. (2022).

6 Conclusions and Recommendations

Explosives are regarded as one of a number of viable options available for the decommissioning of offshore installations and wells. They are potentially well-suited to many tasks where they may offer advantages over non-explosive cutting or severance techniques, for example reduced duration of operations and reduced reliance on divers.

State-of-the art computer-based modelling techniques are available to model explosive cutting and severance, thereby allowing optimisation of the design and minimising the quantities of explosive materials deployed. This can be used to minimise the impact of the explosive charge on the marine environment, whilst still maintaining a successful cut.

The use of explosives in the UKCS is well regulated and monitored and there is established guidance available to assess and mitigate the potential impact of their use on the marine environment.

Reported noise measurements during explosive severance of piles and well conductors (Connor, 1990; Barkaszi *et al*., 2016; Poe *et al*., 2009) show that these activities can generate noise levels that are above the NMFS (2018) and Southall et al. (2019) thresholds for PTS and TTS to marine mammals and the Popper et al. (2014) threshold for injury to fish species. However, measurements are typically limited to distances of less than 100 m and cannot be used to determine distances where PTS and TTS may occur to marine mammals and injury to fish beyond 100 m. Noise modelling was therefore conducted as part of the current study to estimate the distances where potential impacts may occur. The modelling was conducted using several models specifically developed for the estimation of noise from explosive severance of piles and well conductors (Connor, 1990; Brand, 2021a, 2021b). Worst-case estimates were obtained using models developed for open water detonations (Swisdack, 1978; Soloway and Dahl, 2014).

The models developed specifically for estimation of noise from explosive severance of piles and well conductors (i.e. the EDGAR and Connor models) suggest that PTS to VHF cetaceans (e.g. harbour porpoise), which are the most sensitive marine mammal hearing group, could occur up to 260 m for the smallest charge modelled (11.3 kg) and up to 530 m for the largest charge size modelled (90.7 kg). However, worst-case estimates calculated by open water detonation models predict that the PTS thresholds for VHF cetaceans could be exceeded at distances of over several kilometres to tens of kilometres. However, the open water detonation models are thought to provide overly conservative estimates of potential impacts from decommissioning activities such as pile and well conductor severance.

Further field measurements are required during explosive severance of piles and well conductors to better understand at what distance from the explosion potential PTS impacts to marine mammals may occur. It is also important to get noise measurements at large distances during these activities to understand if current guidance on mitigation (JNCC, 2010a) is sufficient for mitigating potential impacts to marine mammals. The JNCC (2010a) guidelines recommend that a 1 km radius mitigation zone should be employed around any explosive detonation location as this can be monitored using MMOs and PAM. The use of ADDs can be used to deter animals beyond this zone.

The EDGAR and Connor models predict that injury to fish will be limited to within 100 m whereas the open water model predicts that injury to fish will occur between 230 – 460 m for explosive charges ranging from 11.3 kg to 90.7 kg. All these distances are well within the existing mitigation zone defined by JNCC (JNCC, 2010a); therefore, existing mitigation measures are likely to be sufficient for mitigating potential impacts to fish.

JNCC guidance focuses primarily on minimising impacts through visual and acoustic observation to detect any receptors present in the area and the delay of operations to avoid any potential impacts. Impacts can also be mitigated through detailed design resulting in noise reduction at source by minimising the quantity of explosive used for a specific application. In shallow water and for specific applications such as piling, bubble curtains have been successfully used to reduce noise propagation.

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8 Appendix A: Regulations and Guidance

8.1 Regulations

8.1.1 Health and Safety

The UK Health and Safety Executive (HSE) has worked with other regulators in the UK and the explosives sector to review all health and safety explosives legislation, with the aim of reducing the regulatory burden on business through clarification and simplification.

The principal regulations currently governing the use of explosives are the Explosives Regulations 2014, and the Statutory Instrument 2016 No 315, owned and enforced by the HSE. These regulations are titled: "The Explosives Regulations 2014 (Amendment) Regulations 2016 (ERAR2016)" (https://www.legislation.gov.uk/uksi/2016/315/made).

ERAR2016 amended and updated the requirements for making civil use explosives available on the market and must be read alongside the Explosives Regulations 2014 (ER2014).

The HSE has produced two Legal Regulations documents:

- L150 The Explosives Regulations 2014 – Focuses on safety provisions; and
- L151 The Explosives Regulations 2014 – Covers security provisions.

A report commissioned by the HSE concluded that thorough research and legislation exists on the use of explosives underwater, suggesting that most related health and safety issues had been addressed (HSE Report OTR 2001/032, 2001).

8.1.2 Environment

Use of explosives during decommissioning comes under the following key regulations:

If explosives are going to be used within the UK marine licensing area either in the sea or on or under the seabed; there is a requirement for a Marine Licence under the Marine and Coastal Access Act 2009 or Marine (Scotland) Act 2010 for deposits in Scottish Internal or Controlled waters;

- If explosives will be used in abandonment operations discussions must be held with DESNZ and JNCC to ensure that consideration has been given to any habitats or species protected under the Offshore Petroleum Activities (Conservation of Habitats) Regulations 2001;
- Consideration needs to be given as to whether a Habitats Regulations Appraisal (HRA) and European Protected Species (EPS) licence is required. The Offshore Petroleum Activities (Conservation of Habitats) Regulations 2001 (as amended), requires that, before the grant of any licence, consent, authorisation or approval involving a proposed activity that is likely to have a significant effect on a relevant protected site, the

Secretary of State must make an appropriate assessment (an HRA) of the implications for the site in view of the site's conservation objectives.

- Use of explosives will need to be covered in the Environmental Impact Assessment that supports the decommissioning plan. The use of explosives can be permitted where it is shown to be the best practicable environmental option and it has been demonstrated that there is unlikely to be a significant impact. The impact assessment should include a description to justify the necessity to use explosives including the alternatives that have been considered and the proposed mitigation measures.

8.2 Guidelines and Guidance

Additional guidelines on the safe use of explosives, includes:

- American Petroleum Institute, "Recommended Practice for Oilfield Explosives Safety", API RP 67, Oct 1, 2019;
- British Standards, "Code of Practice for the Safe use of Explosives in the Construction industry", BS 5607:2017;
- Institute of Explosives Engineers, "Safety Training Standards for Explosives Supervisors in the Oil and Gas Industry", 2015; and
- Maritime Technology Directorate, "Guidelines for the Safe Use of Explosives Underwater".

8.2.1 Department for Energy Security and Net Zero (DESNZ)

The Department provides guidance on the regulatory requirements for decommissioning in the "Offshore Oil and Gas Decommissioning Guidance Notes", November 2018 and the "Updates to Offshore Oil and Gas Decommissioning Guidance".

8.2.2 Joint Nature Conservations Committee (JNCC)

The JNCC "Guidelines for minimising the risk of injury to marine mammals from using explosives" (2010) have been written for activities on the UKCS and are aimed at reducing the risk of injury to negligible levels, and potentially reduce the risk of disturbance from explosive activities to marine mammals including seals, whales, dolphins and porpoises.

The guidelines represent current best practice and include a range of mitigation measures to be included both at the planning stage and at the time of operation.

8.2.3 Offshore Energy UK (OEUK)

The OEUK Well decommissioning Guidelines. Issue 7 (November 2022) provide industry recommendations and good practice for well decommissioning based on recent North Sea experience and notes the requirement for a Marine Licence for the use of explosives during decommissioning.

9 Appendix B: Sound Metrics and Theory

This appendix introduces some metrics, terminology and theoretical concepts that are used throughout this report.

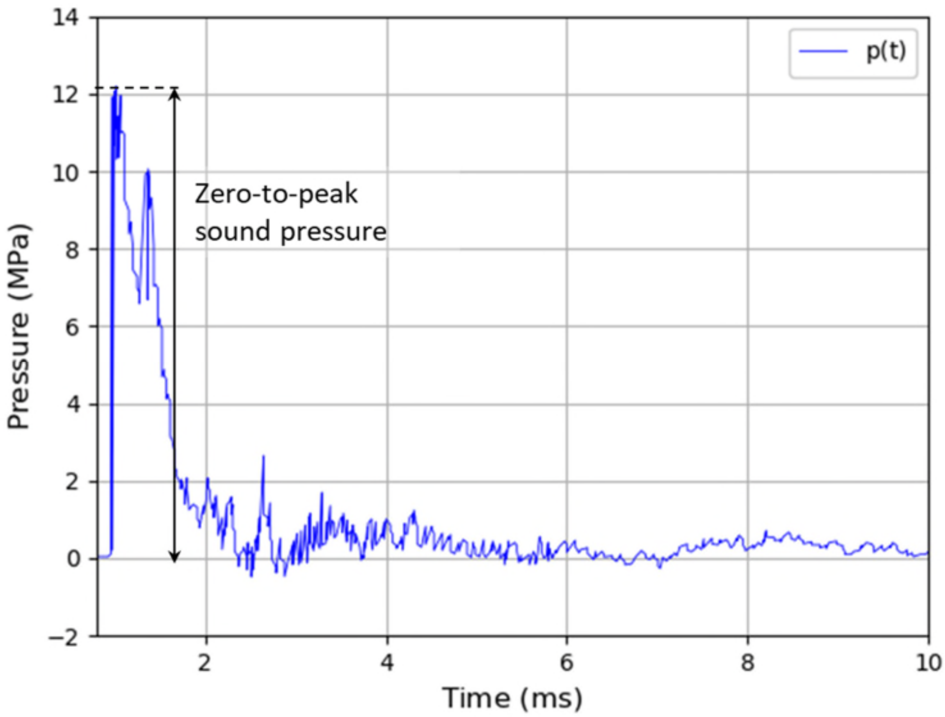
9.1 Zero-to-Peak Sound Pressure and Zero-to-Peak SPL

The zero-to-peak sound pressure, which is also often referred to as the peak pressure (Southall *et al*., 2007, 2019; NMFS, 2018), is the maximum absolute value of sound pressure during a stated time interval (Robinson *et. al.*, 2014). The zero-to-peak sound pressure, p_{pk}, has SI units of Pascals (Pa) (BIPM, 2006), and is mathematically given by:

$$p_{pk} = \max\{|p(t)|\}, \qquad (1)$$

where $p(t)$ is the sound pressure signal in units of Pascals (Pa), $\max\{.\}$ denotes the maximum of a series of values, and $|.|$ signifies the magnitude/absolute value. The zero-to-peak sound pressure of a pressure waveform is depicted graphically in Figure 9-1. The zero-to-peak sound pressure is always stated as a positive value, but it is important to note that it can result from either a positive pressure or a negative pressure (Robinson *et. al*., 2014).

Figure 9-1: Zero-to-peak sound pressure of a pressure waveform.



The zero-to-peak sound pressure is often expressed on a decibel scale relative to a reference pressure of one micropascal (µPa) in which case it is referred to as the zero-to-peak sound pressure level (SPL). The zero-to-peak SPL is given by

$$L_{pk} = 20\log_{10}\left[\frac{p_{pk}}{p_0}\right] \;, \quad (2)$$

where p_0 is the reference sound pressure of 1 μPa. The zero-to-peak SPL has units of decibels relative to one micropascal (dB re 1 μPa).

Zero-to-peak sound pressures and zero-to-peak SPLs are typically unweighted i.e., the sound pressure signal is not frequency weighted before the zero-to-peak sound pressures and zero-to-peak SPLs are calculated (NMFS, 2018; Southall *et al*., 2019). All zero-to-peak sound pressures and zero-to-peak SPLs presented in this report are unweighted.

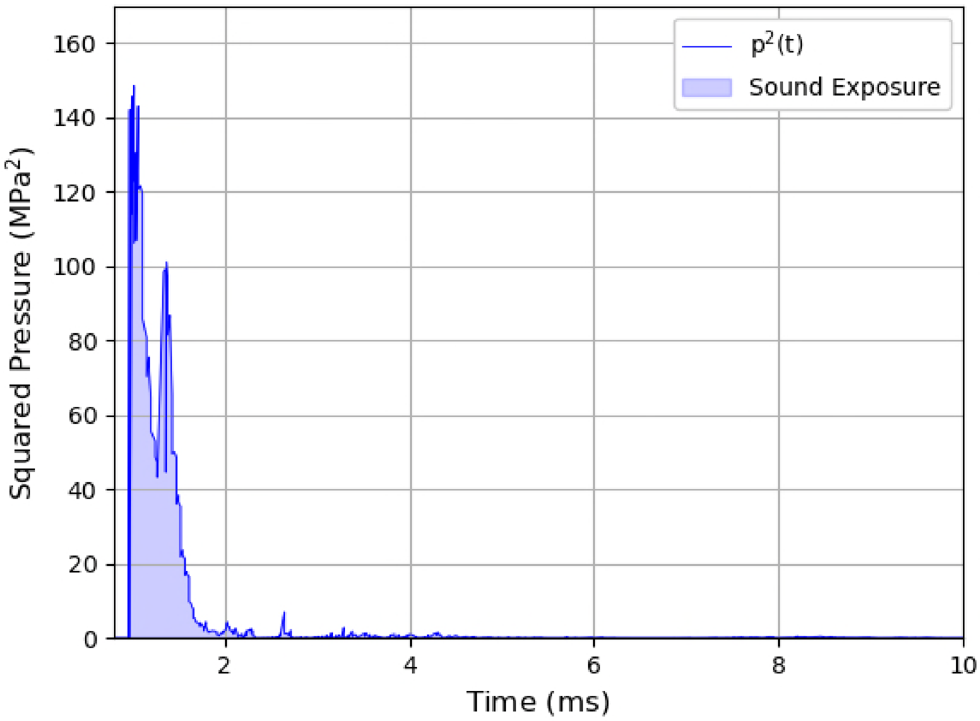
9.2 Sound Exposure and SEL

The sound exposure is defined as the squared pressure integrated over a stated time interval (Robinson *et. al.*, 2014). The sound exposure, e, has SI units of Pascal square seconds (Pa2s) (BIPM, 2006), and can be expressed mathematically as

$$e = \int_{t_1}^{t_2} p^2(t)\, dt \quad , \qquad (1)$$

where t_1 and t_2 signify the time interval that the sound exposure is calculated over. The sound exposure is useful as a measure of the exposure of a marine receptor to sound and is often used as a proxy for the sound energy (Robinson *et. al*., 2014). The sound exposure can be visualised graphically as the area under a squared pressure curve (Figure 9-2).

Figure 9-2: Sound exposure of a pressure waveform.



The sound exposure is often expressed on a decibel scale relative to a reference sound exposure of one micropascal square second (µPa2s) in which case it is referred to as the sound exposure level (SEL). The SEL is given by

$$SEL = 10\log_{10}\left[\frac{e}{e_0}\right] \ , \qquad (2)$$

where e_0 is the reference sound exposure of 1 µPa2s. The SEL has units of decibels relative to one micropascal square second (dB re 1 µPa2s).

Sound exposures and SELs are often frequency weighted to lower sound energies at frequencies that a receptor is less sensitive to. When sound exposures and SELs are weighted, they should be referred to as weighted sound exposures and weighted SELs to avoid ambiguity. If not explicitly stated, it should be obvious from context whether sound exposures and/or SELs are weighted or not. In this report, the terms sound exposure and SEL generally refer to unweighted quantities.

9.3 Cumulative Sound Exposure and Cumulative SEL

Sound exposures (either weighted or unweighted) can be aggregated by summation over multiple acoustic events (e.g., over multiple pulses). In this case, it is referred to as the cumulative sound exposure (also known as the total sound exposure or sound exposure dose). The cumulative sound exposure, $e_{cum.}$, has units of Pa2s and is given by

$$e_{cum.} = \sum_{i=1}^{N} e_i \ , \qquad (3)$$

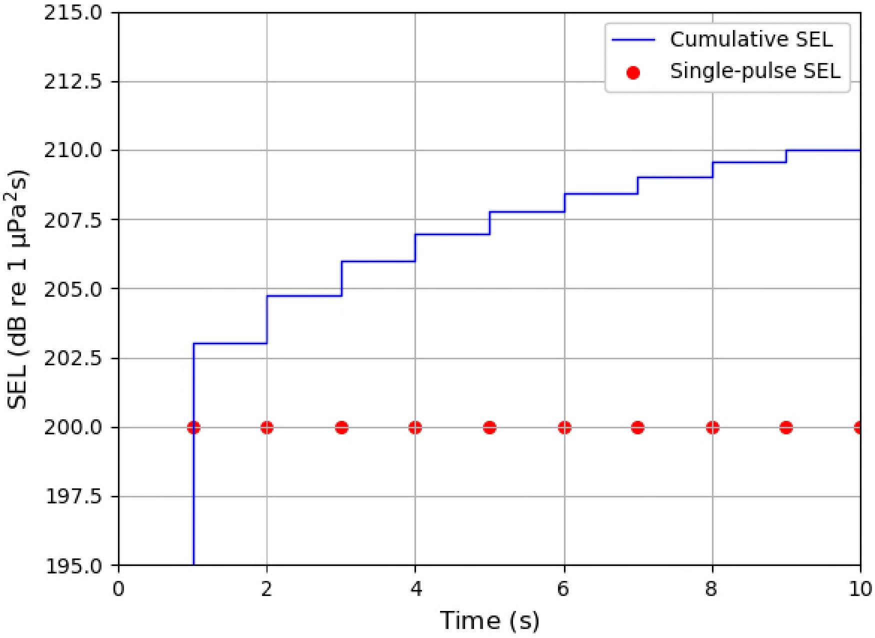
where e_i is the sound exposure of the i^{th} acoustic event (e.g., the i^{th} pulse) and N is the total number of acoustic events that the cumulative sound exposure is calculated over.

The cumulative sound exposure can be expressed as a cumulative SEL by dividing the cumulative sound exposure by the reference sound exposure of 1 µPa2s and expressing in decibels. The cumulative SEL is thus given by

$$SEL_{cum.} = 10\log_{10}\left[\frac{e_{cum.}}{e_0}\right] \ . \qquad (4)$$

The cumulative SEL calculated over multiple acoustic events is depicted graphically in Figure 9-3. The cumulative SEL is commonly used to assess potential impacts to marine mammals (Southall *et al*., 2007, 2019; NMFS, 2018) and fish (Popper *et al*., 2014) and is typically computed over the entire duration of the activity or over a maximum period of 24-hour period.

Figure 9-3: Cumulative SEL calculated over multiple acoustic events



9.4 Energy Flux Density

Energy flux density (EFD) is defined as the time integral of the pressure squared over a given time interval, divided by the characteristic impedance of the medium (which is given by the product of the medium density and the speed of sound in the medium). The EFD is given by

$$\varepsilon = \frac{1}{\rho c}\int_{t_1}^{t_2} p^2(t)\,dt \quad , \tag{5}$$

where ρ is the density of the medium and c is the speed of sound in the medium. The units of energy flux density are Joules per square metre (J/m2). The EFD is equal to the sound exposure (given by equation (1)) divided by the characteristic impedance of the medium (which is given by the product of the medium density and speed of sound in the medium).

9.5 Energy Spectral Density

The energy spectral density (ESD) of a sound pressure signal describes how the sound exposure is distributed with frequency. Given a pressure signal, $p(t)$, the ESD can be calculated as

$$E(f) = X(f)X^*(f) \quad , \tag{6}$$

where f is frequency in Hertz (Hz), $(.)^*$ denotes complex conjugation, and $X(f)$ is the Fourier transform of the pressure signal under consideration given by

$$X(f) = \int_{-\infty}^{\infty} p(t)\exp\{-j2\pi f t\}dt \quad . \tag{7}$$

In equation (7), $\exp\{.\}$ denotes the natural exponential function and j signifies the imaginary part of a complex number. The ESD defined by equation (6) has units of Pascal square seconds per Hertz (Pa2s/Hz). It is often convenient in underwater acoustics to express the ESD on a decibel scale as

$$SEL(f) = 10\log\left\{\frac{E(f)}{e_0}\right\} \, . \tag{8}$$

Here, $SEL(f)$ has units of decibels relative to one micro-pascal square second per Hertz (dB re 1 μPa2s/Hz) and describes how the SEL is distributed with frequency. The ESD of an example pressure waveform (Figure 9-4) is shown in Figure 9-5.

Figure 9-4: Example pressure waveform

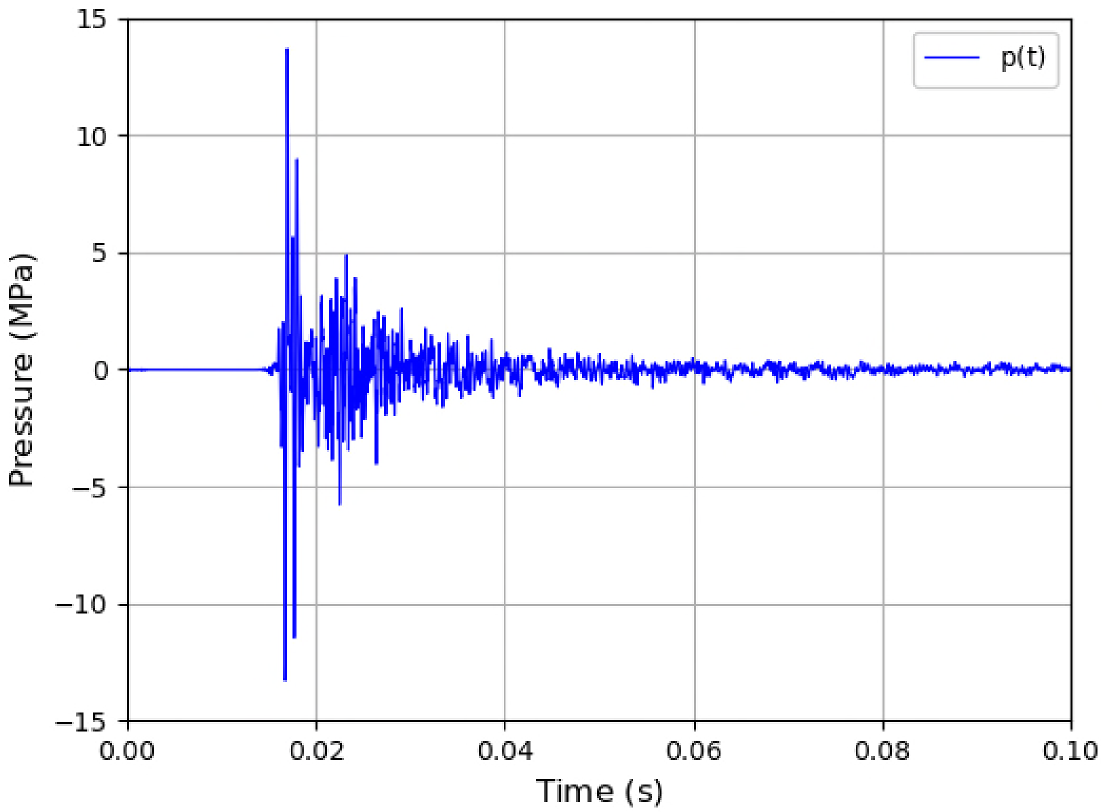
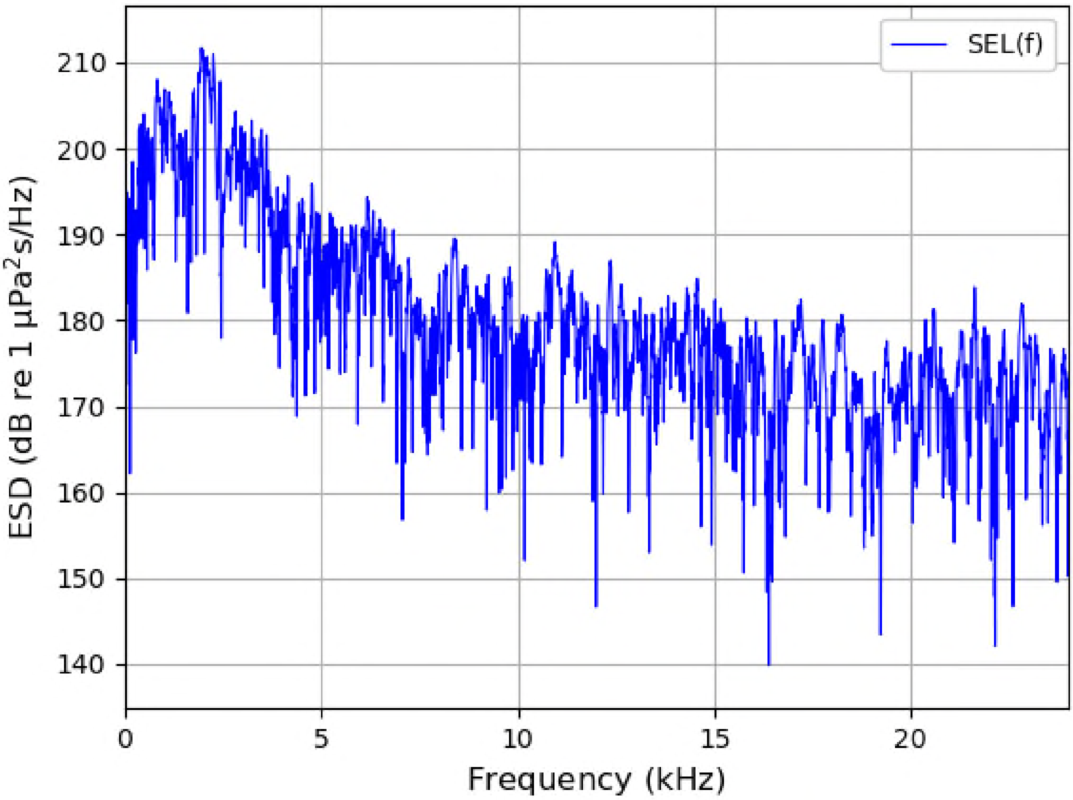


Figure 9-5: Example pressure waveform ESD



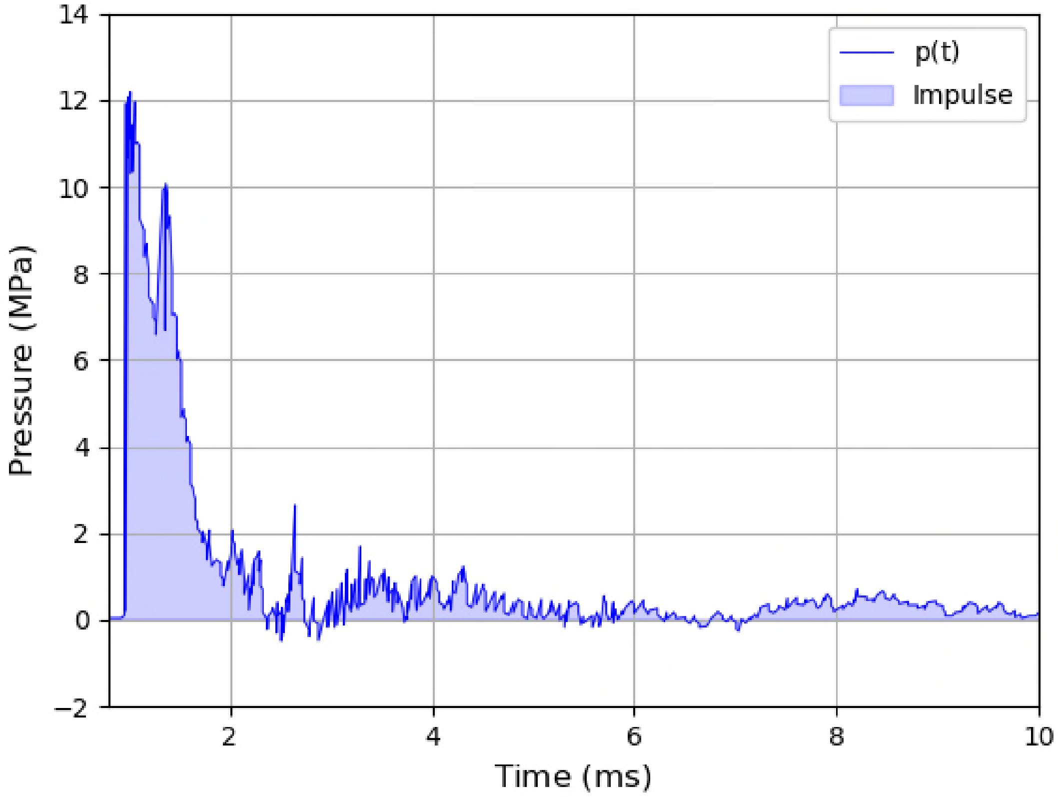
9.6 Impulse

The impulse is a metric commonly used to describe impulsive signals and is defined as the integral of the pressure over a stated duration. Mathematically, the impulse is given by

$$I = \int_{t_1}^{t_2} p(t)\, dt \quad , \tag{9}$$

where I is the impulse measured in Pascal seconds (Pa.s). The impulse is the area under the pressure curve and may be thought of as the average pressure of the wave multiplied by its duration. The impulse of a pressure waveform is depicted graphically in Figure 9-6.

Figure 9-6: Impulse of a pressure waveform.



9.7 Principle of Similarity for Explosives

A useful theory in the study of underwater explosives is the principle of similarity (Cole, 1948; Swisdack, 1978), which states that if the linear dimensions of a charge and all other lengths are altered in the same ratio for two explosions, the shock waves formed will have the same pressures at corresponding distances scaled by this ratio, if the times at which pressure is measured are also scaled by the same ratio (Swisdack, 1978). The principle of similarity has led to so called similitude equations that can estimate shock wave parameters based solely on the charge weight and distance from the measurement location to charge. The validity of these similitude equations has been verified through extensive measurements (Cole, 1948; Slifko, 1967; Swisdack, 1978; Chapman, 1985, 1988; Gaspin *et al*., 1979).

The similitude equation for zero-to-peak sound pressure is given by (Cole, 1948; Swisdack, 1978)

$$p_{pk} = K_p \left(\frac{r}{w^{1/3}}\right)^{\alpha_p} , \qquad (10)$$

where p_{pk} is the zero-to-peak sound pressure, w is the explosive charge weight and r is the measurement distance from the explosive charge. The parameters K_p and α_p are constants that are determined experimentally for different types of explosives. The quantity $r/w^{1/3}$ is referred to as the reduced range (often called the scaled range).

The similitude equation for EFD is given by (Cole, 1948; Swisdack, 1978)

$$\frac{\epsilon}{w^{1/3}} = K_{\epsilon}\left(\frac{r}{w^{1/3}}\right)^{\alpha_{\epsilon}} , \qquad (11)$$

where ϵ is EFD and K_{ϵ} and α_{ϵ} are constants that are determined experimentally for different types of explosives. The quantity $\epsilon/w^{1/3}$ is referred to as the reduced EFD since it is scaled by the cubic root of the charge weight. Given the similitude equation for reduced EFD, and the relationship between EFD and sound pressure (see Sections 9.2 and 9.4), the following similitude equation for reduced sound exposure can be defined

$$\frac{e}{w^{1/3}} = \rho c K_{\epsilon}\left(\frac{r}{w^{1/3}}\right)^{\alpha_{\epsilon}} , \qquad (12)$$

where ρ is the density of the medium and c is the speed of sound in the medium. From the reduced sound exposure in equation (12) and the definition of SEL (see Section 9.2) a reduced SEL quantity can be defined as

$$SEL_{red.} = 10\log_{10}\left[\frac{\rho c K_{\epsilon}}{e_0}\left(\frac{r}{w^{1/3}}\right)^{\alpha_{\epsilon}}\right] , \qquad (13)$$

where e_0 is the reference sound exposure of 1 μPa2s. The defined reduced SEL quantity has units of dB re 1 μPa2s.kg1/3/m.

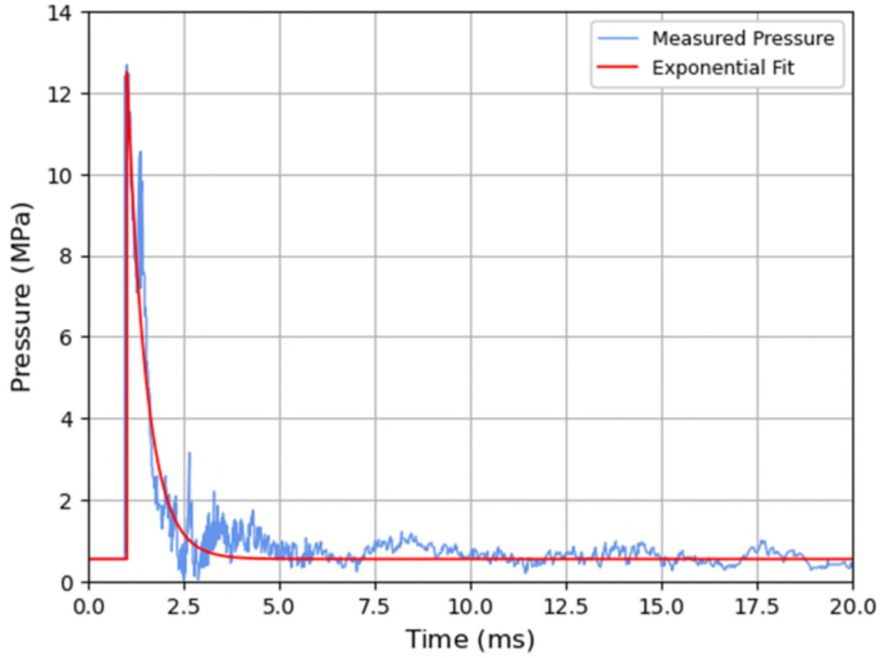
10 Appendix C: Weighting Factor Adjustments and Equivalent Unweighted SEL Thresholds

In this appendix, weighting factor adjustments (WFAs) and equivalent unweighted SEL thresholds for PTS and TTS to marine mammals from the noise generated during explosive severance of piles and well conductors are derived. Calculation of the WFAs and equivalent unweighted SEL thresholds is dependent on knowledge of the energy spectral density (ESD) of noise from the explosive severance of piles and well conductors, which describes how the signal energy is distributed with frequency (Ambardar, 1999). Ideally a measured ESD would be used. However, no useful measurements of the ESD of noise from the explosive severance of piles and well conductors could be obtained. Therefore, a theoretical ESD for underwater explosive signals has been used. The theoretical ESD is firstly derived in this appendix before the WFAs and equivalent unweighted SEL thresholds are calculated.

10.1 Theoretical ESD

The primary shock wave from an explosive detonated in open water can be well approximated by a decaying exponential function (see e.g., Richardson *et al*., 1995; Barrett, 1996; Urick, 1983; Nedwell and Edwards, 2004; Chapman, 1985, 1988; Gaspin *et al*., 1979; Cole, 1948; Slifko, 1967; Swisdack, 1978). The noise generated from explosive severance of piles and well conductors is not the same as that from open water detonations due to the explosives typically being confined in the structure to be severed and deployed below the seabed. Nevertheless, some measurements have shown that the noise from explosive severance of piles and well conductors also result in pulses that can be well approximated by decaying exponential functions. Figure 10-1 shows the sound pressure measured during the explosive severance of a pile (Barkaszi *et al*., 2016). It is evident that the measured sound pressure is well approximated by the fitted decaying exponential function. Pressure waveforms recorded during explosive severance of piles and well conductors are also presented in Connor (1990) where the primary pulses follow a decaying exponential profile.

Figure 10-1: Pressure pulse measured during pile severance and fitted exponential function



In the derivation of the ESD it is therefore assumed that the noise generated during explosive severance of piles and well conductors can be approximated by the right-sided decaying exponential function,

$$p(t) = \; p_{max}\exp\left(\frac{-t}{\tau}\right)\mathrm{u(t)} \;, \tag{14}$$

where p_{max} is the maximum pressure of the shock wave in Pascals (Pa), t denotes time in seconds (s), τ is the exponential decay constant in seconds, $\exp(.)$ Denotes the natural exponential function, and $u(t)$ denotes the unit step function (Ambardar, 1999).

The Fourier transform of (14) is given by

$$P(f) = \; \frac{p_{max}\tau}{1 + j2\pi f\tau}, \tag{15}$$

where $j = \sqrt{-1}$ signifies an imaginary number and f denotes frequency in Hertz (Hz). Multiplying (15) by its complex conjugate (Ambardar, 1999) yields the ESD which is given by

$$E(f) = \; \frac{p_{max}^2\tau^2}{1 + 4\pi^2 f^2\tau^2}. \tag{16}$$

The ESD, $E(f)$, is given in units of Pascal square seconds per Hertz (Pa2s/Hz) and describes how the sound exposure is distributed with frequency. To calculate the ESD in (16) for a given explosive charge, it is required that the maximum pressure p_{max} and the decay constant τ are known. These parameters have been empirically derived by Connor (1990) based on measurements of noise from explosive severance of piles and well conductors. For pile severance, the maximum pressure (which in this case corresponds to the zero-to-peak pressure) was derived in Connor (1990) as (converted here to SI units)

$$p_{max} = 87.0 \times 10^6 \left(\frac{w^{1/3}}{r}\right)^{1.93} , \tag{17}$$

where w is the weight of the explosive charge in kilograms (kg) and r is the distance from the explosive in meters (m). The decay constant is given by

$$\tau = \frac{I}{p_{max}} , \tag{18}$$

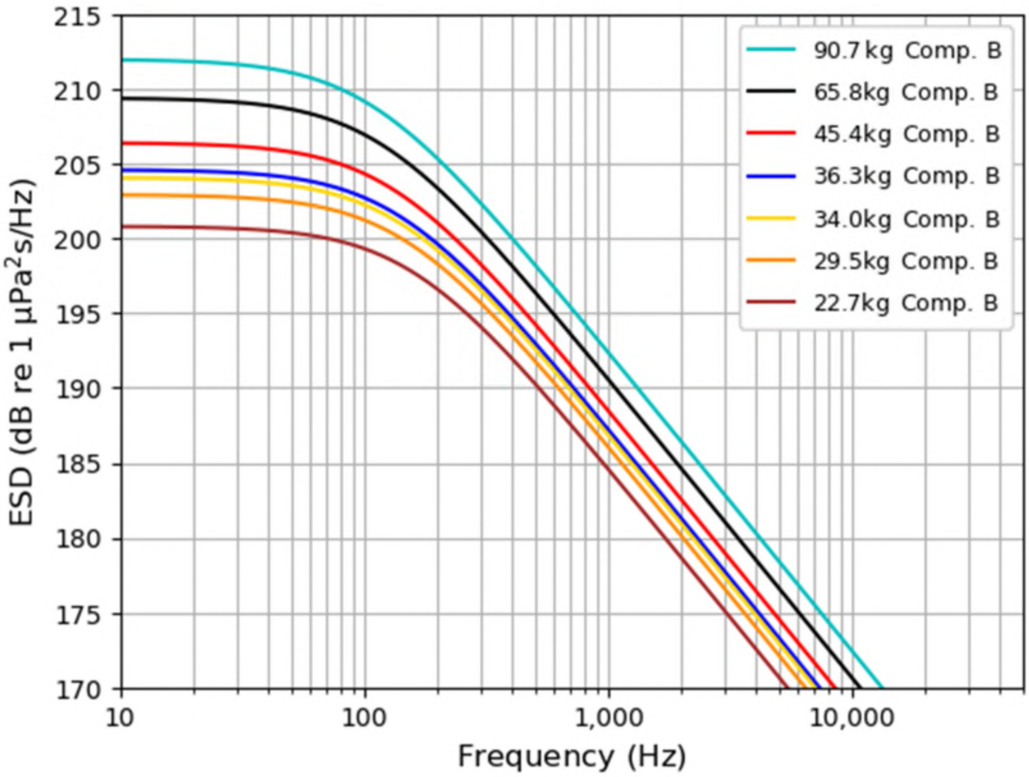
where I is the explosive impulse in Pascal seconds (Pa.s), which was derived by Connor (1990) for explosives used during pile severance to be (converted here to SI units)

$$I = 26.3 \times 10^3 \, w^{1/3} \left(\frac{w^{1/3}}{r}\right)^{1.79} . \tag{19}$$

Figure 10-2 shows the ESDs for various explosive charges used during the severance of piles and well conductors for the projects studied in this assessment (see **Error! Reference source not found.**). The ESD's shown in Figure 10-2 were calculated for an example distance of 10 m from the explosive charge.

A similar approach to that adopted was used in Robinson *et al*. (2022) for estimating the ESD for UXO detonations.

Figure 10-2: ESDs for different explosive charge weights.



10.2 WFAs and Equivalent Unweighted SEL Thresholds

To derive WFAs for different marine mammal hearing groups, the ESDs for the different explosive charge weights shown in Figure 10-2 were weighted by the marine mammal auditory weighting functions (see Figure 4-1). Figure 10-2 shows the weighted ESDs for an example explosive charge weight of 22.7 kg.

Integration of the ESD over all frequencies yields the SEL. Therefore, integration of the unweighted ESD over all frequencies yields the unweighted SEL, whilst integration of the weighted ESDs over all frequencies yield the weighted SEL for each marine mammal hearing group. The WFA for each marine mammal hearing group is then calculated by subtracting the weighted SEL from the unweighted SEL. The WFAs are therefore a measure of how much the auditory weighting functions reduce the SEL for each marine mammal hearing group. The calculated WFAs are dependent in the specific ESD under consideration and the calculated WFAs were slightly different for different charge sizes. Rather than utilising different WFAs for each explosive charge size, the minimum WFAs for each hearing group over all charge sizes shown in Figure 10-2 are adopted in this assessment. The adopted WFAs are shown in Table 10-1. It can be observed that the smallest WFA is applied for the LF cetaceans hearing group and the largest WFA for the VHF cetaceans hearing group. This is to be expected since the noise from underwater explosives is predominantly at lower frequencies. However, it is interesting to note that the VHF cetaceans’ hearing group have the lowest unweighted SEL threshold values, and this implies that they are more susceptible to PTS and TTS than the other hearing groups. This highlights an advantage of expressing the weighted thresholds as equivalent unweighted thresholds: the unweighted thresholds for each hearing group can be directly compared to predict what hearing group(s) may be most impacted.

Figure 10-3: Theoretical ESD weighted using the marine mammal auditory weighting functions

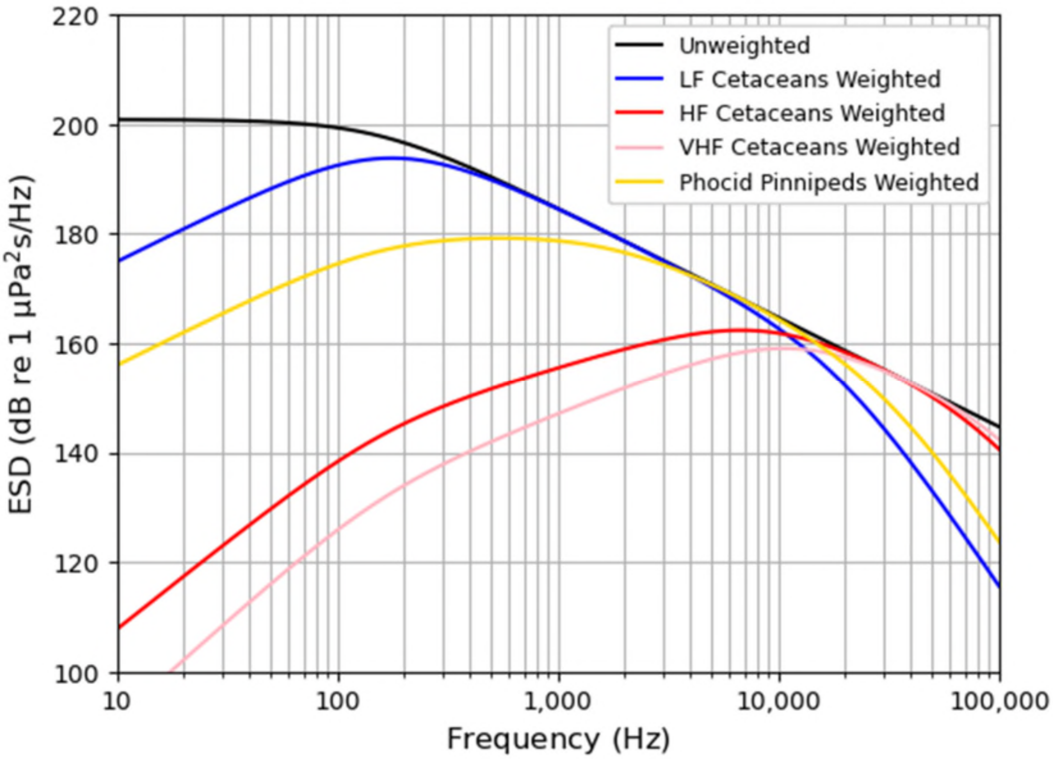


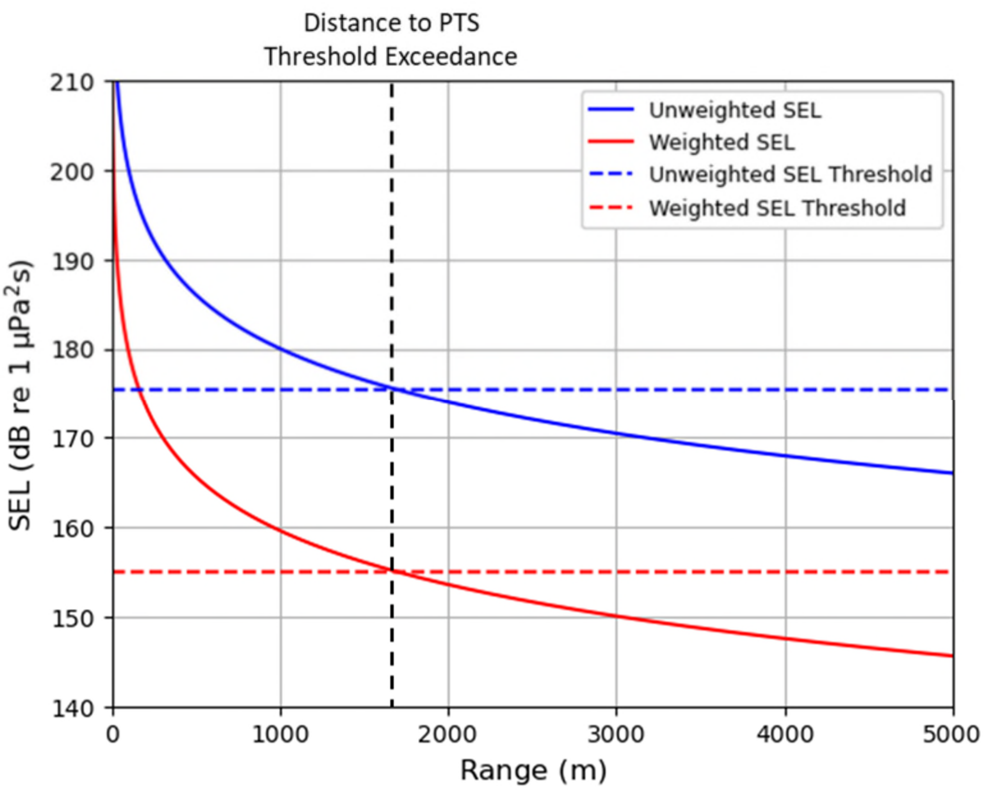
Table 10-1: WFAs and equivalent unweighted SEL thresholds for PTS and TTS to marine mammals from explosive severance of pile and well conductors

Hearing Group	Weighted SEL Threshold (dB re 1 µPa2s)		WFA (dB)	Unweighted SEL Threshold (dB re 1 µPa2s)	
	PTS	TTS		PTS	TTS
LF cetaceans	183	168	3.1	186.1	171.1
HF cetaceans	185	170	18.6	203.6	188.6
VHF cetaceans	155	140	20.4	175.4	160.4
Phocid pinnipeds	185	170	10.1	195.1	180.1

To summarise, the weighted SEL for a given marine mammal hearing group can be calculated by subtracting the WFA for that hearing group from the received broadband unweighted SEL.

The received weighted SEL can then be compared to the weighted SEL thresholds shown in Table 10-1. Alternatively, the WFAs can be used to calculated equivalent unweighted SEL thresholds. The unweighted SEL thresholds are obtained by adding the WFAs for each hearing group to the corresponding weighted SEL thresholds. These equivalent unweighted SEL thresholds are also shown in Table 10-1. Comparison of the weighted SEL with the corresponding weighted SEL thresholds and comparison of the unweighted SEL with the corresponding unweighted SEL thresholds result in the same estimated impact distances. This equivalence is illustrated in Figure 10-4.

Figure 10-4: Illustration of the equivalence of comparing unweighted and weighted received SELs with corresponding unweighted and weighted SEL thresholds



11 Appendix D: Models for Estimating Noise Levels from Explosive Severance of Piles and Well Conductors

This appendix presents several underwater noise models for estimating the noise levels generated during the explosive severance of piles and well conductors.

11.1 Connor Models

Connor (1990) derived expressions for the zero-to-peak sound pressure and EFD (which can be converted to sound exposure) from measurements made during explosive severance of piles and well conductors. The equations derived in Connor (1990) for the zero-to-peak sound pressure and EFD for explosive severance of piles and well conductors are presented in the following sections. It is noted that the original equations derived in Connor (1990) were expressed in imperial units. The equations have been modified here such that all quantities are expressed in SI units.

11.2 Pile Severance

Based on the measurements made during explosive severance of piles, the following equations were derived in Connor (1990) for the zero-to-peak sound pressure and EFD

$$p_{pk} = 87.0 \times 10^6 \left(\frac{w^{1/3}}{r}\right)^{1.93} \quad (20)$$

$$\varepsilon = 150.9 \times 10^3 \, w^{1/3} \left(\frac{w^{1/3}}{r}\right)^{3.13} \quad (21)$$

where p_{pk} is the zero-to-peak sound pressure in Pascals (Pa), ε is the EFD in units of Joules per square metre (J/m2), w is the weight of the explosive charge in kilograms (kg) and r is the measurement distance from the explosive charge in meters (m).

11.3 Well Conductor Severance

From the measurements made during explosive severance of well conductors, the following equations were derived in Connor (1990) for the zero-to-peak sound pressure and EFD

$$p_{pk} = 63.9 \times 10^6 \left(\frac{w^{1/3}}{r}\right)^{1.807} \quad (22)$$

$$\varepsilon = 517.0 \times 10^3 \, w^{1/3} \left(\frac{w^{1/3}}{r}\right)^{3.4} \tag{23}$$

where again p_{pk} is the zero-to-peak sound pressure in Pascals (Pa), ε is the EFD in units of Joules per square metre (J/m2), w is the weight of the explosive charge in kilograms (kg) and r is the measurement distance from the explosive charge in meters (m).

11.4 EDGAR Model

The EDGAR model has been developed for estimating noise levels generated during explosive severance of piles and well conductors (Brand, 2021a; Brand, 2021b). The model has been derived by fitting power curves to estimates of the zero-to-peak SPL obtained from other models (Connor, 1990; Dzwilewski and Fenton, 2003; Nedwell and Edwards, 2004; Marsh and Schulkin, 1962) for a notional charge weight of 1 kg. EDGAR estimates the zero-to-peak SPL from explosive severance of piles and well conductors from

$$L_{pk} = \frac{SL_{pk} + 4.8256 \, w^{1/3}}{r^{64/1000}} \, , \tag{24}$$

where L_{pk} is the zero-to-peak SPL in dB re 1 μPa, w is the explosive charge weight in kilograms (kg) and r is the measurement distance from the explosive charge in meters (m). In equation (24) the variable SL_{pk} is the zero-to-peak SPL source level of the explosive charge, which is given by

$$SL_{pk} = 274 + 7.533 \log_{10}[0.4536 \, w] \; . \tag{25}$$

The source level in equation (25) has units of decibels relative to one micropascal referred to one metre (dB re 1 μPa-m).

11.5 Open Water Models

The detonation of explosives in open water have been well studied (see e.g., Cole, 1948; Slifko, 1967; Swisdack, 1978; Chapman, 1985, 1988; Gaspin *et al*., 1979; Soloway and Dahl, 2014). Numerous measurements have shown that the zero-to-peak sound pressure from open water detonations can be well approximated by

$$p_{pk} = 52.4 \times 10^6 \left(\frac{w^{1/3}}{r}\right)^{1.13} \, , \tag{26}$$

where p_{pk} is the zero-to-peak sound pressure in Pascals (Pa), w is the explosive charge weight in kilograms (kg) and r is the measurement distance from the explosive charge in meters (m). This relationship has been shown to hold for various explosive charge sizes (Cole, 1948; Slifko, 1967; Swisdack, 1978).

The sound exposure from open water detonations has not been as well studied as the zero-to-peak sound pressure, though some expressions have been derived that can be used to estimate sound exposure and SEL. Swisdack (1978) reported that the EFD for trinitrotoluene (TNT) can be estimated from

$$\varepsilon = 84.4 \times 10^3\, w^{1/3} \left(\frac{w^{1/3}}{r}\right)^{2.04}, \qquad (27)$$

where ε is the EFD in units of J/m2, w is the weight of the explosive charge in kilograms (kg) and r is the measurement distance from the explosive charge in meters (m).

Soloway and Dahl (2014) derived an empirical equation for SEL based on measurements from the detonations of explosives in shallow water (the explosives were detonated in water depths of less than 15 m). Measurements were made of detonations of C-4 and CH-6 explosives at measurement ranges of 165 m, 430 m and 950 m. The charge sizes ranged from 0.07 kg to 4.5 kg. The empirical equation of SEL derived in Soloway and Dahl (2014) is given by

$$SEL = 219 + 6.14\log\left[w^{1/3}\left(\frac{w^{1/3}}{r}\right)^{2.12}\right], \qquad (28)$$

where SEL is expressed in units of dB re 1µPa2s, w is the explosive weight in kilograms (kg), and r is the measurement distance in metres (m).

12 Appendix E: Comparison of Model Estimates of Noise from Explosive Severance of Piles and Well Conductors with Measured Data

This appendix presents the comparisons of model estimated noise levels with measurements of zero-to-peak SPL and SEL during explosive severance of piles and well conductors.

12.1 Zero-to-Peak SPL

12.1.1 Pile Severance

Figure 12-1: Comparison of model estimated zero-to-peak SPL with measured data for explosive severance of piles with 17.2 kg of Composition B

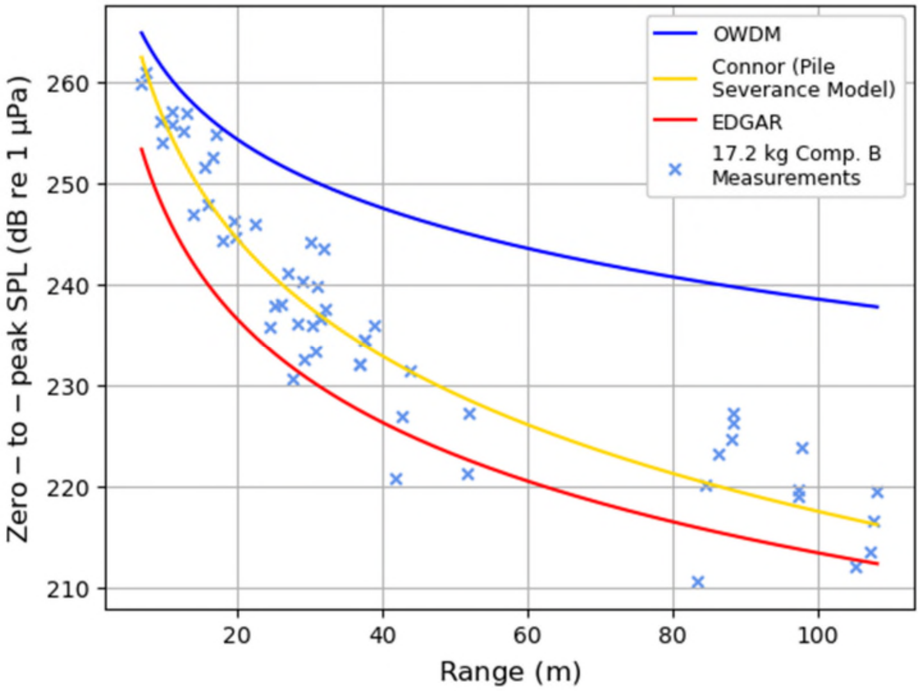


Figure 12-2: Comparison of model estimated zero-to-peak SPL with measured data for explosive severance of piles with 22.7 kg of Composition B

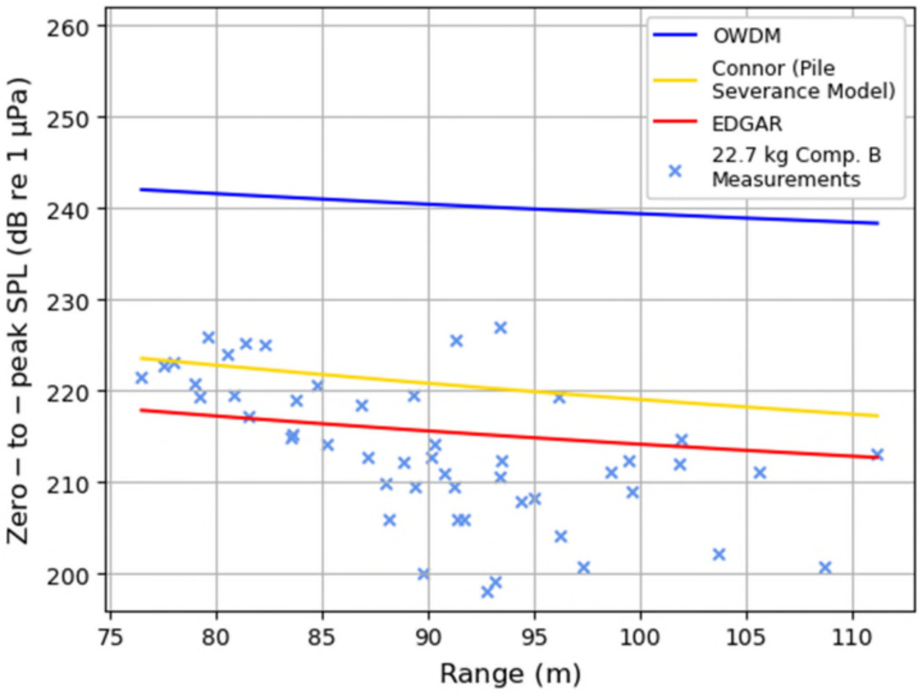


Figure 12-3: Comparison of model estimated zero-to-peak SPL with measured data for explosive severance of piles with 36.3 kg of Composition B

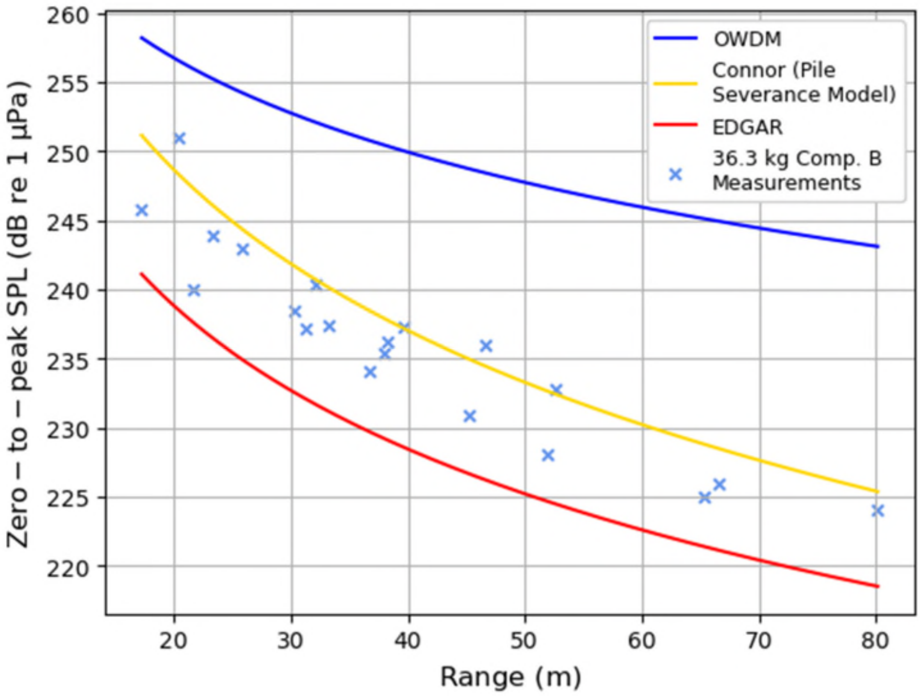
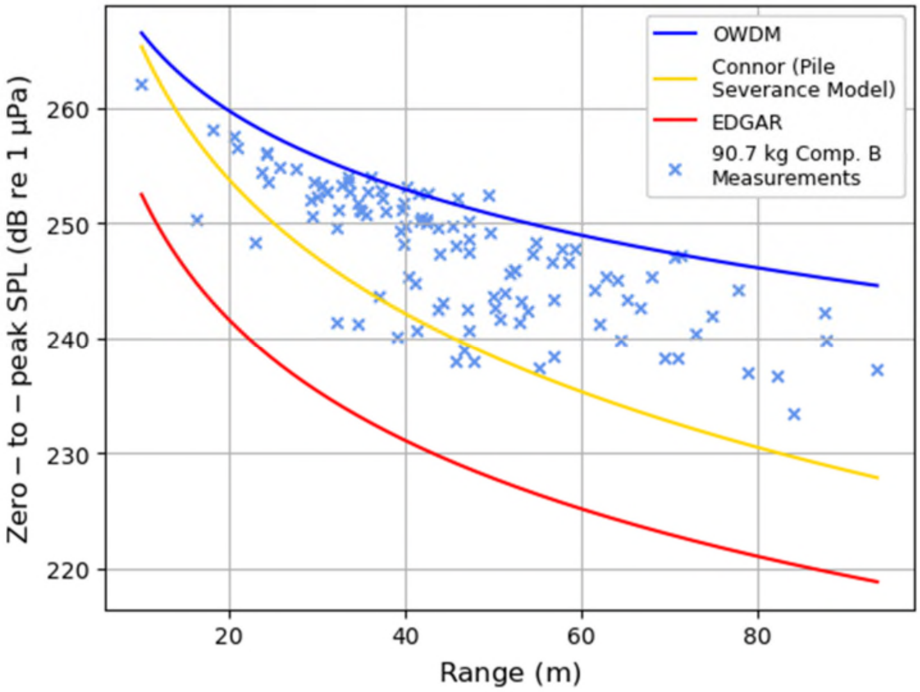


Figure 12-4: Comparison of model estimated zero-to-peak SPL with measured data for explosive severance of piles with 90.7 kg of Composition B



12.1.2 Well Conductor Severance

Figure 12-5: Comparison of model estimated zero-to-peak SPL with measured data for explosive severance of well conductors with 11.3 kg of Composition B

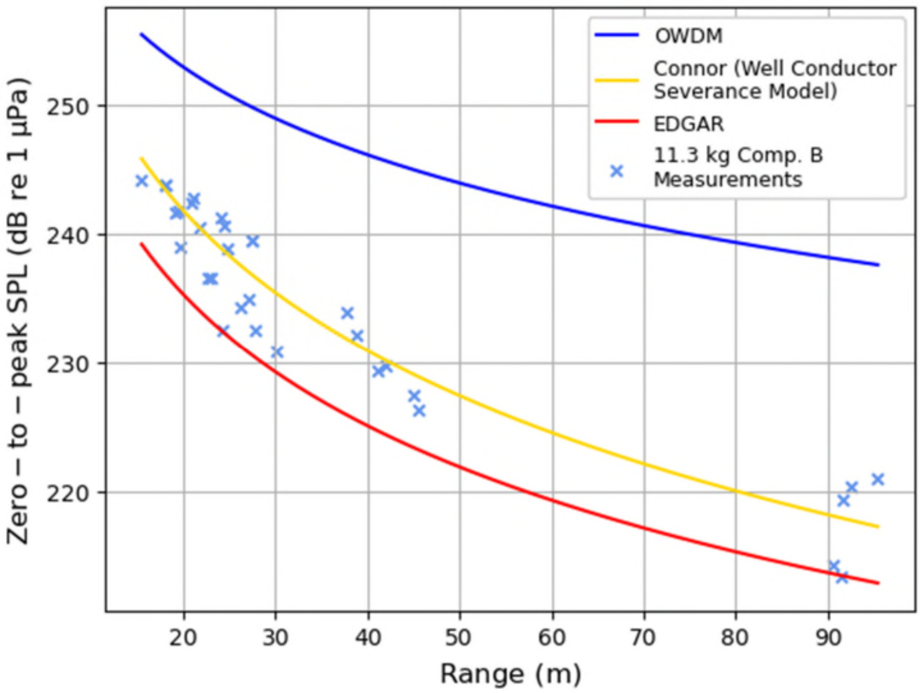


Figure 12-6: Comparison of model estimated zero-to-peak SPL with measured data for explosive severance of well conductors with 22.7 kg of Composition B

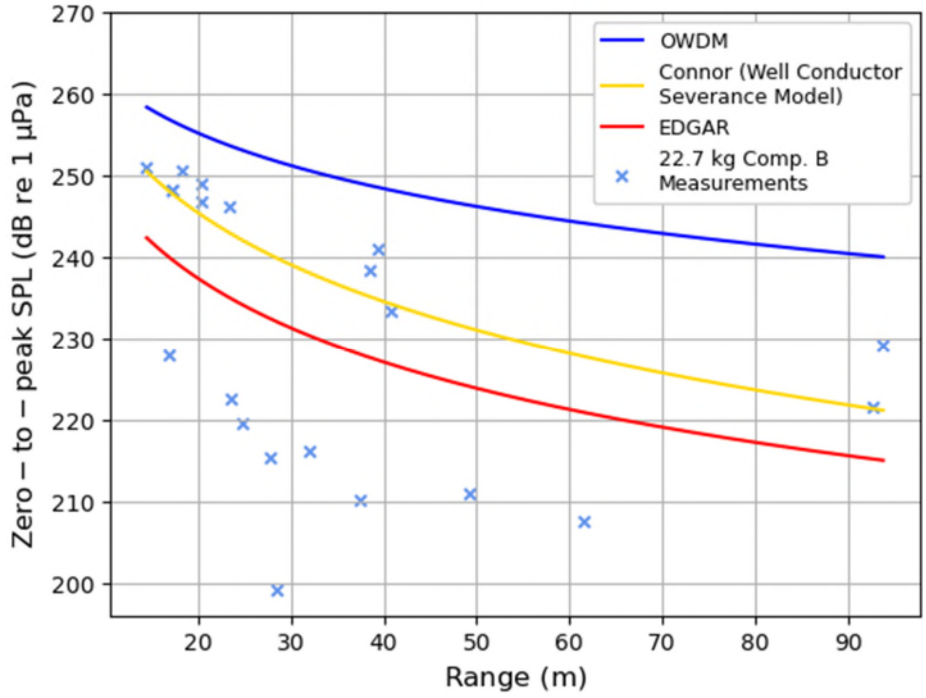


Figure 12-7: Comparison of model estimated zero-to-peak SPL with measured data for explosive severance of well conductors with 29.5 kg of Composition B

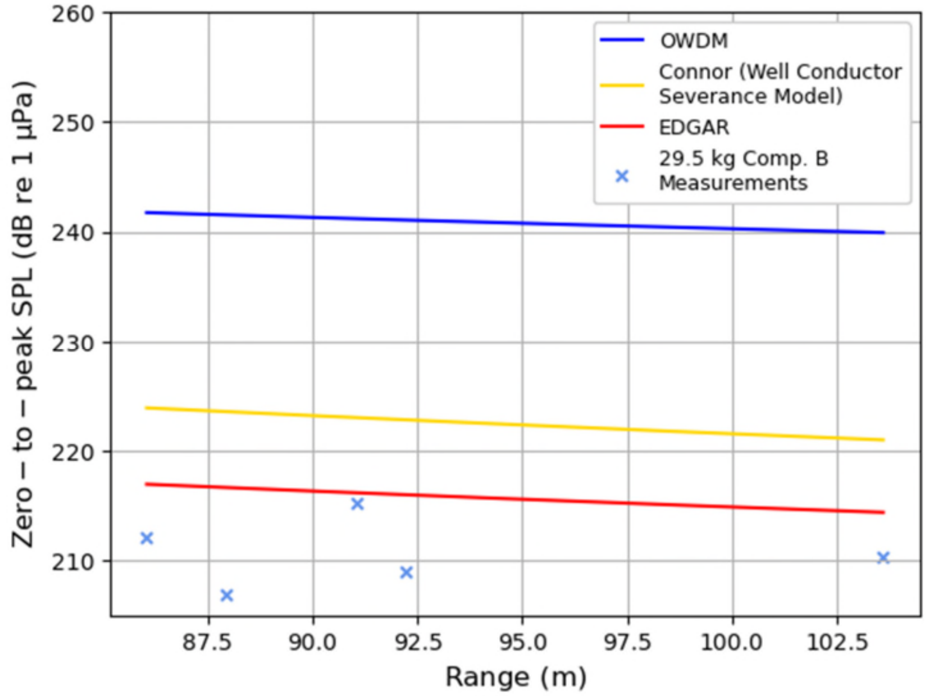


Figure 12-8: Comparison of model estimated zero-to-peak SPL with measured data for explosive severance of well conductors with 34.0 kg of Composition B

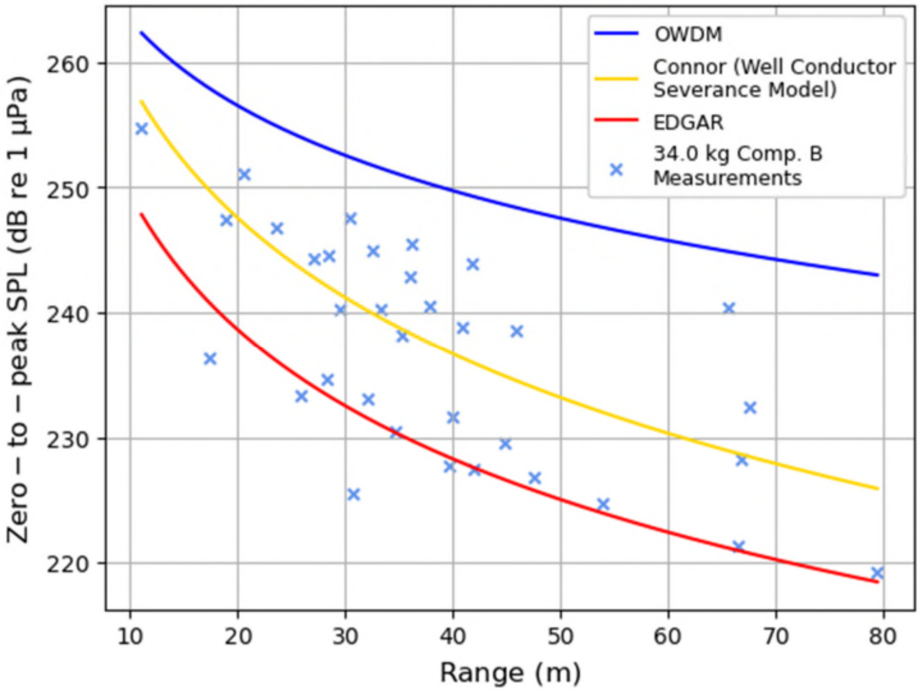


Figure 12-9: Comparison of model estimated zero-to-peak SPL with measured data for explosive severance of well conductors with 45.4 kg of Composition B

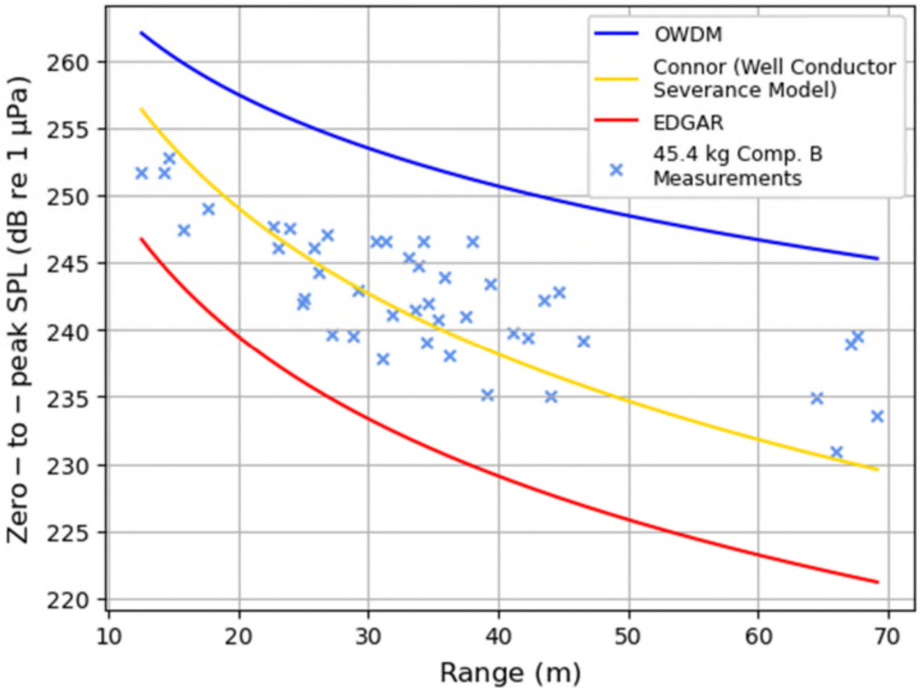
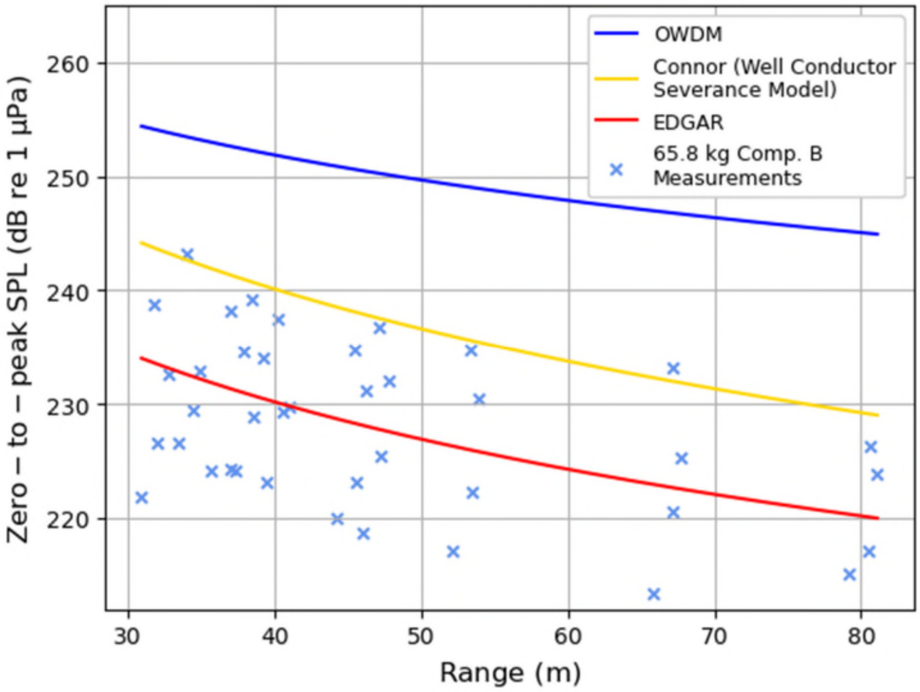


Figure 12-10: Comparison of model estimated zero-to-peak SPL with measured data for explosive severance of well conductors with 65.8 kg of Composition B



12.2 SEL

12.2.1 Pile Severance

Figure 12-11: Comparison of model estimated SEL with measured data for explosive severance of piles with 17.2 kg of Composition B

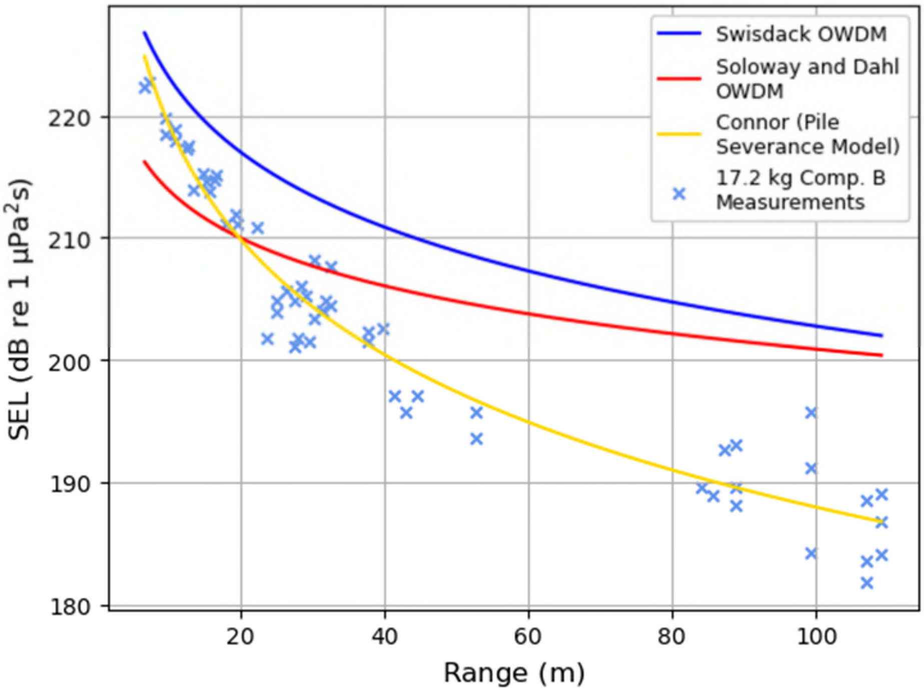


Figure 12-12: Comparison of model estimated SEL with measured data for explosive severance of piles with 22.7 kg of Composition B

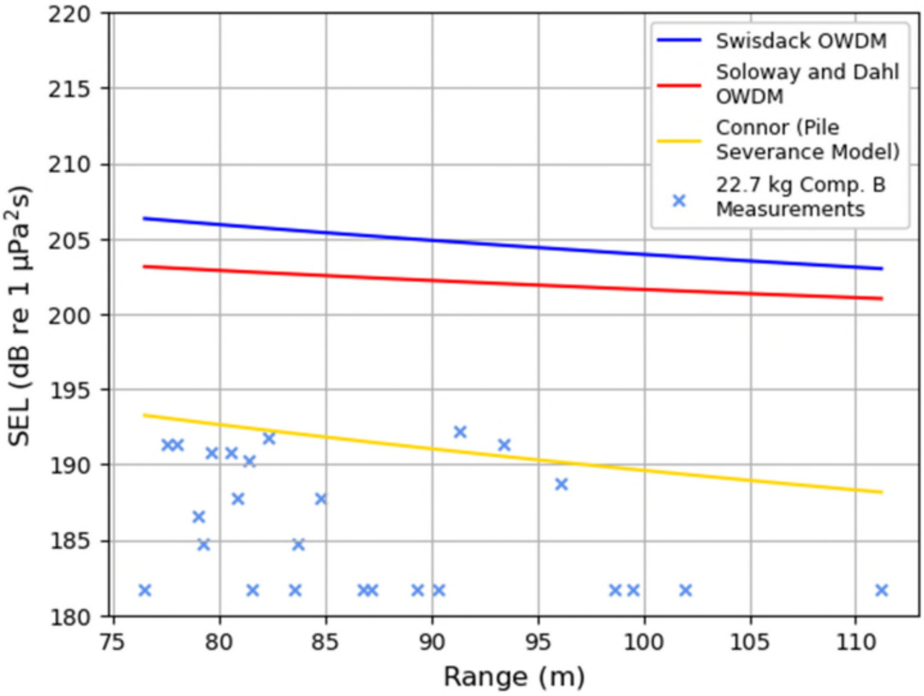


Figure 12-13: Comparison of model estimated SEL with measured data for explosive severance of piles with 36.3 kg of Composition B

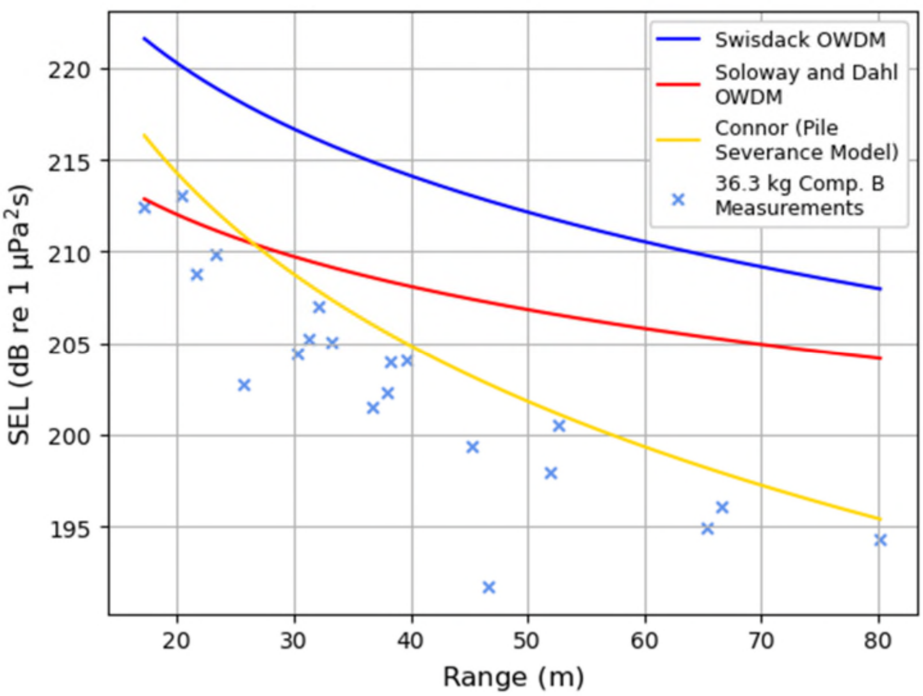
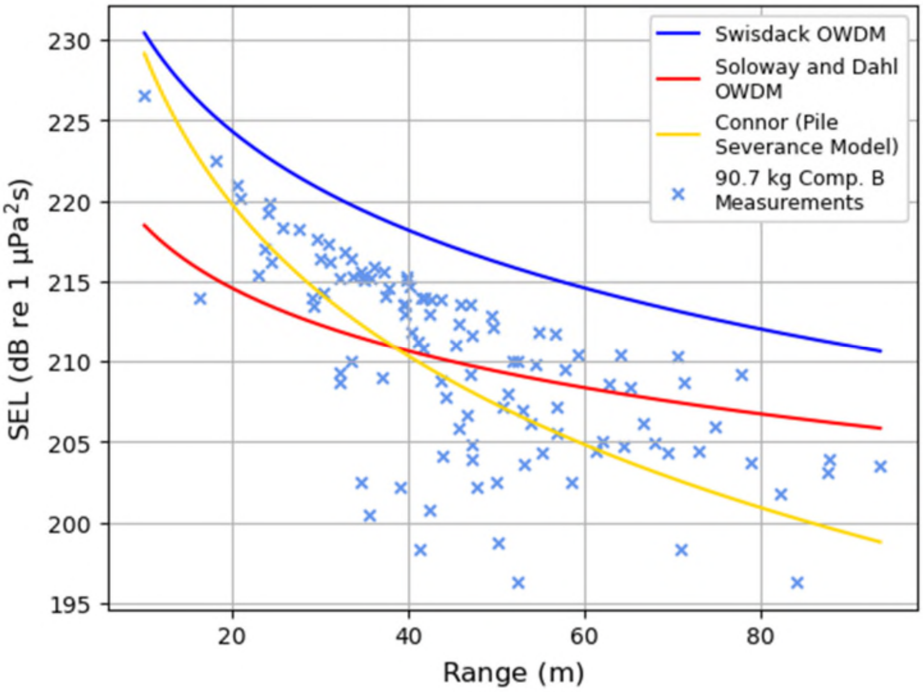


Figure 12-14: Comparison of model estimated SEL with measured data for explosive severance of piles with 90.7 kg of Composition B



12.2.2 Well Conductor Severance

Figure 12-15: Comparison of model estimated SEL with measured data for explosive severance of well conductors with 11.3 kg of Composition B

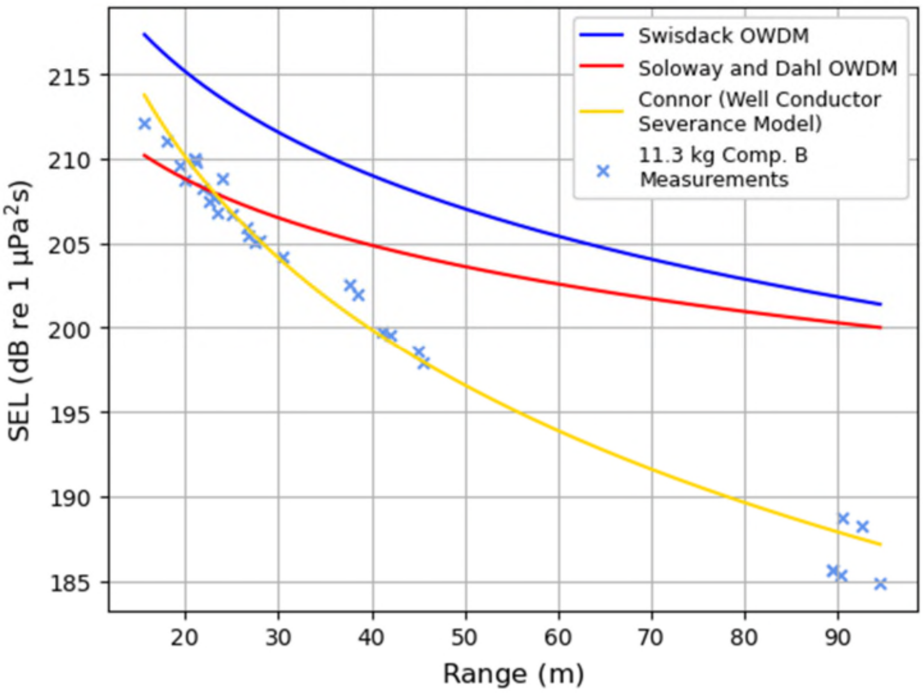


Figure 12-16: Comparison of model estimated SEL with measured data for explosive severance of well conductors with 22.7 kg of Composition B

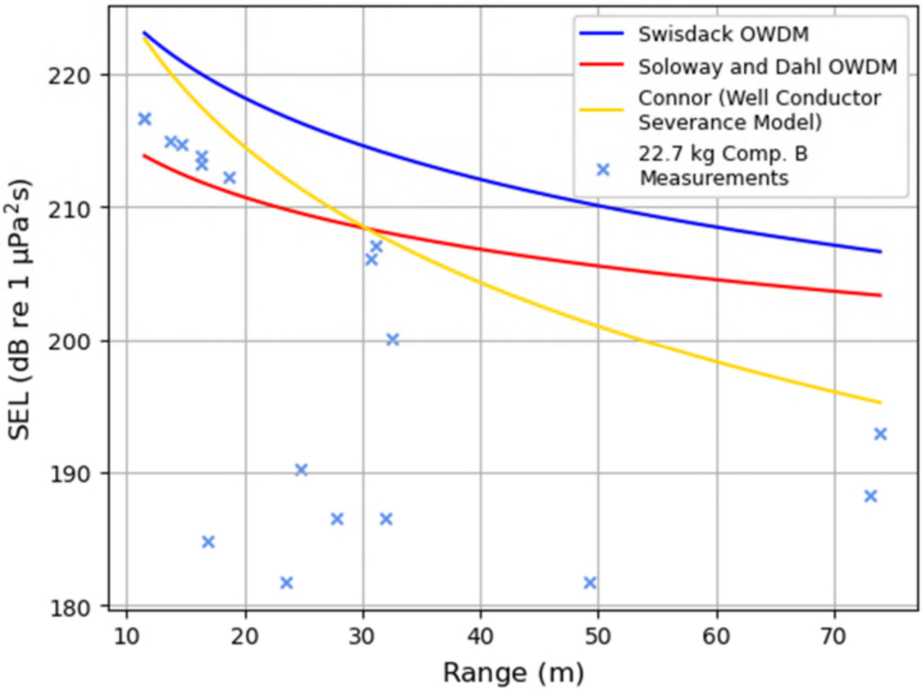


Figure 12-17: Comparison of model estimated SEL with measured data for explosive severance of well conductors with 29.5 kg of Composition B

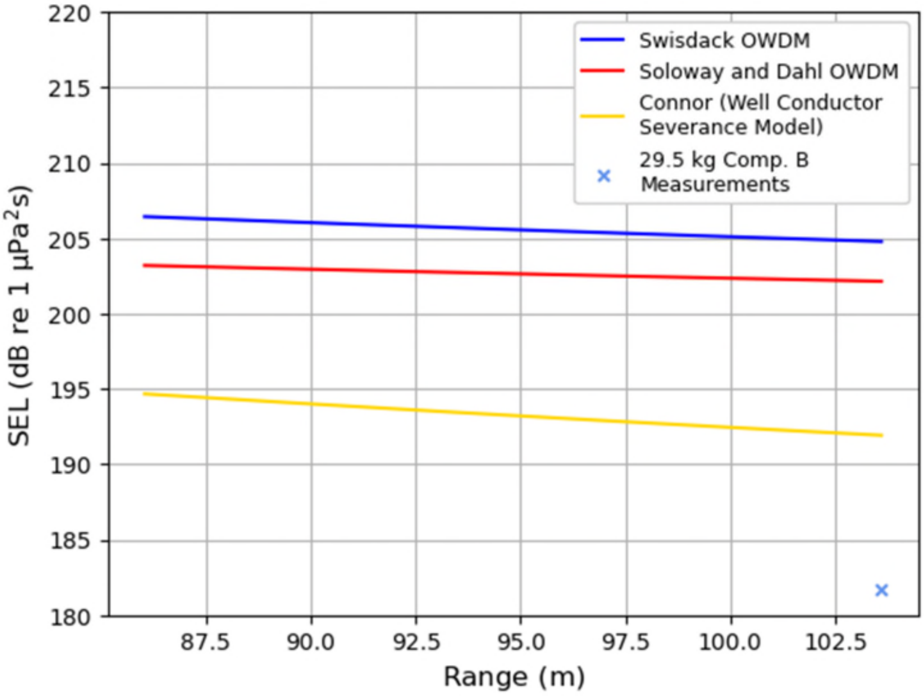


Figure 12-18: Comparison of model estimated SEL with measured data for explosive severance of well conductors with 34.0 kg of Composition B

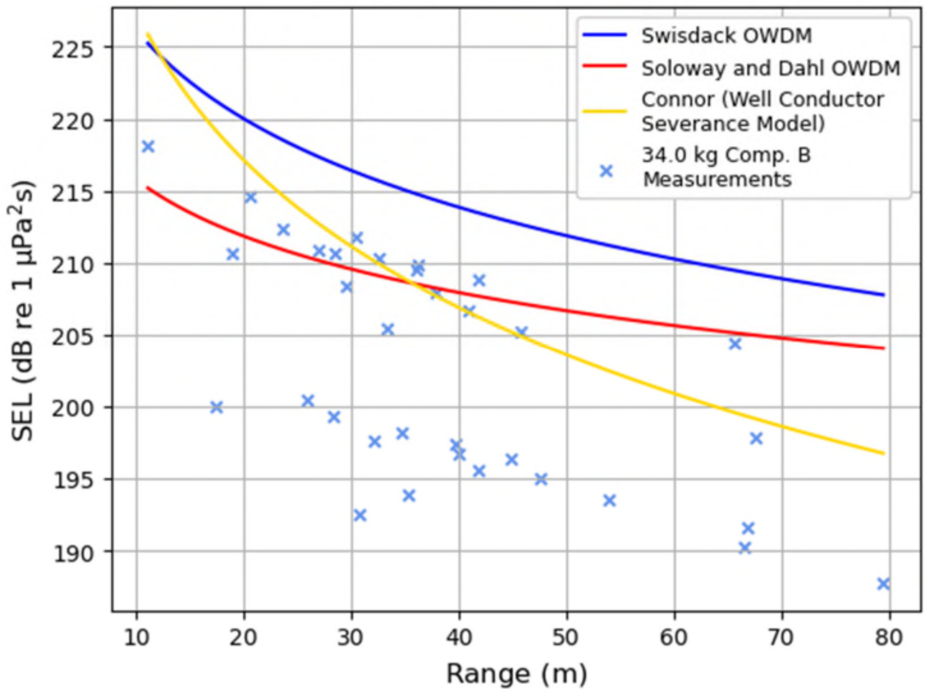


Figure 12-19: Comparison of model estimated SEL with measured data for explosive severance of well conductors with 45.4 kg of Composition B

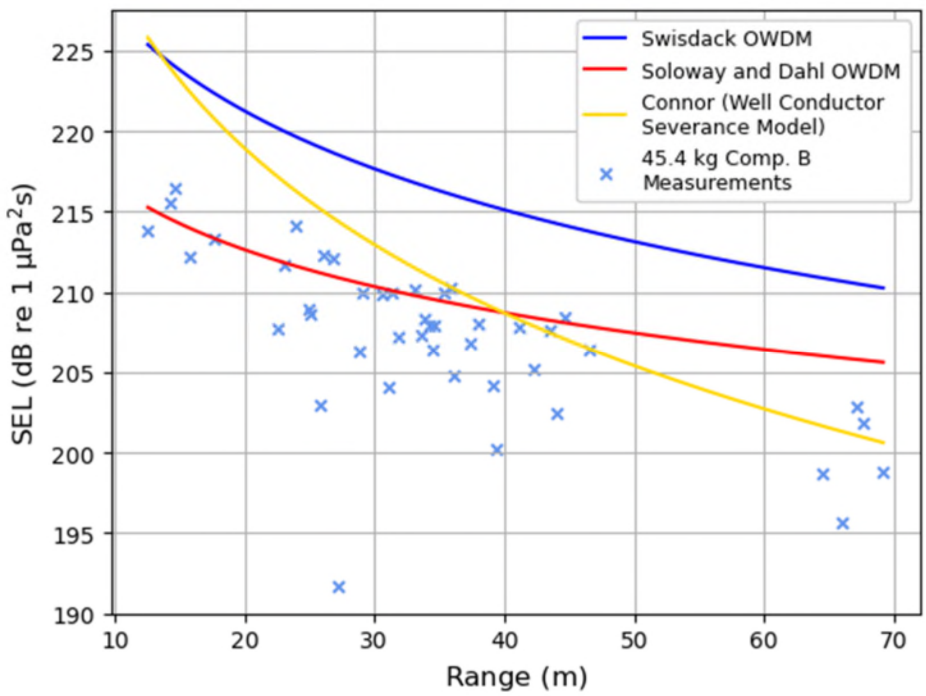
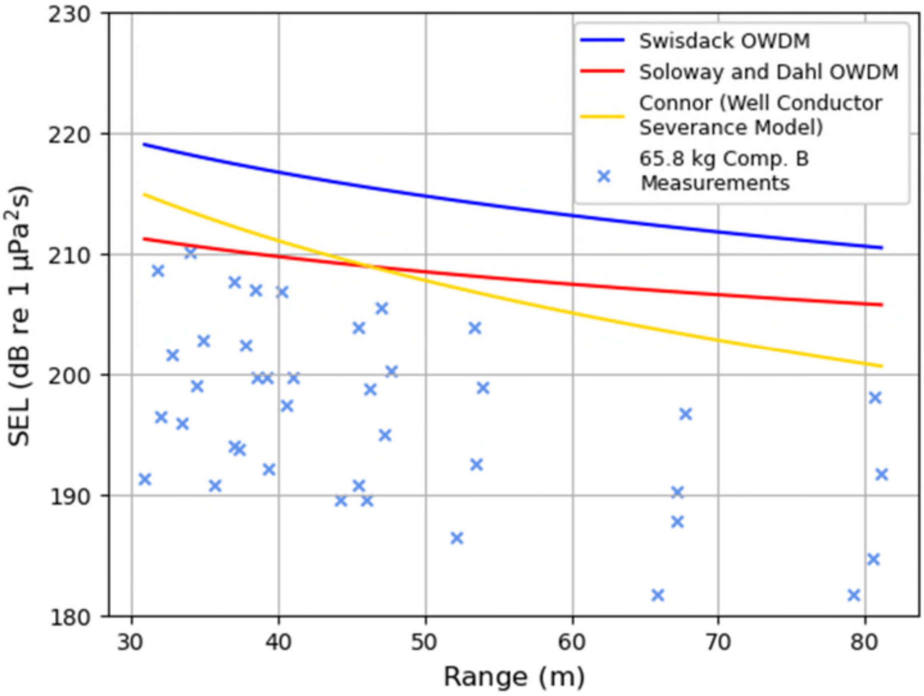


Figure 12-20: Comparison of model estimated SEL with measured data for explosive severance of well conductors with 65.8 kg of Composition B



13 Appendix F: Comparison of Open Water Detonation Models with UXO Measurements

In this appendix the OWDMs used in this report are compared to measurements made during UXO detonations at the Neart na Gaoithe (NnG) wind farm development (NnGOWL, 2021). Noise monitoring at the NnG wind farm was undertaken for 37 detonations of UXOs ranging 5 kg to 102 kg in weight. The measurements were made at various measurement locations with the distances from the UXO detonations and the measurement locations ranging from approximately 1.4 km to 33 km.

It was observed from the measurements that the UXO weight was not the main contributing factor to the zero-to-peak SPLs generated. The measured zero-to-peak SPLs better matched with estimated levels using the donor charge weight rather than the UXO weight (NnGOWL, 2021). A similar observation was made in Robinson *et al*., (2022) where measurements from UXO detonations at the NnG and Moray East wind farms were analysed for a range of UXO sizes. It was conjectured in NnGOWL (2021) and Robinson *et al*. (2022) that this phenomenon occurred because the UXO explosive material was highly degraded. Thus, it is thought the UXO explosive material did not fully detonate, which manifested as lower zero-to-peak SPL.

Figure 13-1 shows the measured zero-to-peak SPL for the detonation of a 102 kg UXO at NnG. The UXO was detonated using a donor charge size of 5 kg. It is observed that the OWDM (see Section 11.3 of Appendix D: Models for Estimating Noise Levels from Explosive Severance of Piles and Well Conductors) estimated zero-to-peak SPL for a 5 kg charge (the same as the UXO donor charge) matches very well with the measured data, whilst the OWDM estimated zero-to-peak SPL for a 102 kg charge (the same as the UXO explosive weight) estimates zero-to-peak SPLs much higher than the measured data. A similar observation was made in Robinson *et al*. (2022) where better predictions of zero-to-peak SPL were made when the adopted acoustic model was run using the donor charge size compared to the predictions from the acoustic model using the UXO weight.

Figure 13-1: Comparison of OWDM estimated zero-to-peak SPL with measured data for the detonation of a 102 kg UXO at the NnG wind farm

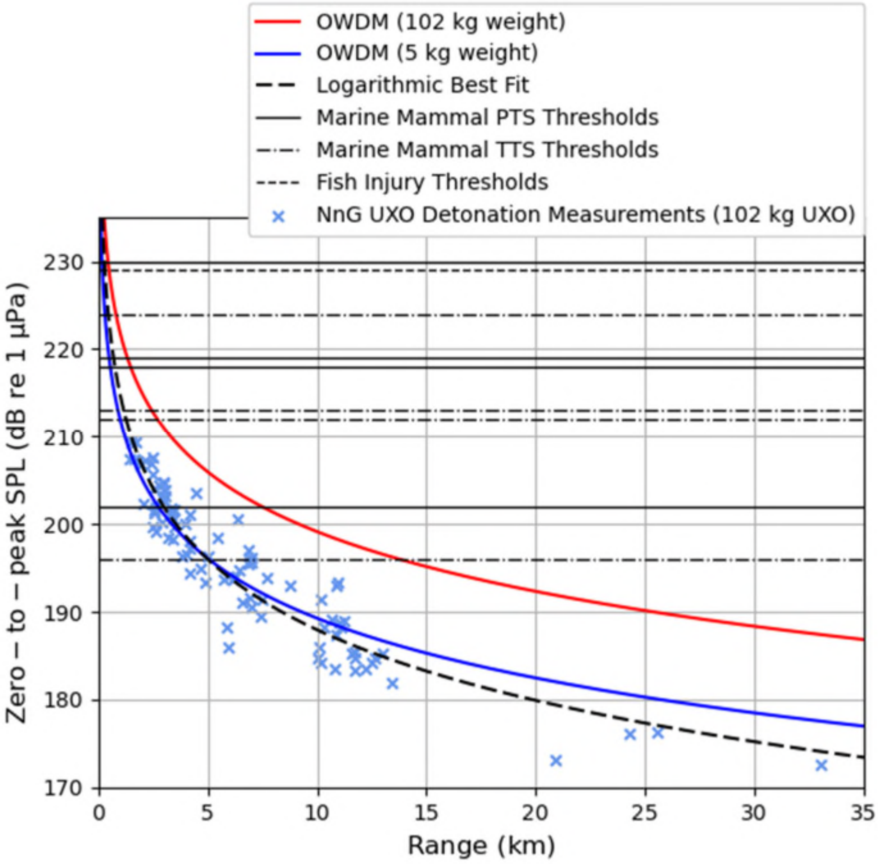


Figure 13-2 shows the measured SEL for the detonation of a 102 kg UXO at NnG. This figure also shows the SELs estimated by the Soloway and Dahl (2014) OWDM for charge sizes of 102 kg (the UXO weight) and 5 kg (the donor charge weight). The Swisdack OWDM (see Section 11.3of Appendix D: Models for Estimating Noise Levels from Explosive Severance of Piles and Well Conductors) has also been used to estimate the SELs for these two charge weights. The Swisdack model estimates of EFD have been converted to SELs assuming a value of 1,480 m/s for the speed of sound in water (which was the measured sound speed reported in NnGOWL (2021)) and a nominal value of 1,000 kg/m3 for water density.

It can be observed from Figure 13-2 that the Soloway and Dahl models do not provide good estimates of the measured SELs. At larger distances both models overestimate the SEL compared to the measurements. This may be explained by the fact that the Soloway and Dahl model was derived from measurements made in very shallow water (less than 15 m), whilst the UXO detonations at NnG were made in deeper waters (45 – 55 m). The shallower water depths for the Soloway and Dahl (2014) study resulted in a waveguide effect where spreading loss is decreased (Jensen, 2011).

The Swisdack model for the 102 kg UXO charge weight provides a very good fit to the measured SEL, whilst the Swisdack model for the 5 kg donor charge weight significantly underestimates the SEL. The opposite was true for the zero-to-peak SPL i.e., the zero-to-peak SPL model estimates for the 5 kg donor charge weight provided a better fit to the measurements than the estimate for the 102 kg UXO weight. This observation for the zero-to-peak SPL led to the conclusion that the UXO explosive weight was not being detonated and only the donor charge weight contributed to the noise (NnGOWL, 2021). The fact that the Swisdack model for the 102 kg UXO weight fits very well with the SEL measurements seems to contradict this conclusion. One possible explanation is that the UXO explosive weight is detonated, but the explosive detonation behaves differently to a 'normal' open water detonation of the same size (by 'normal' we mean that the explosive is in good condition as opposed to a UXO that has remained on the seabed for at least 77 years and whose explosive properties may have changed).

It is conjectured here that UXO detonations may result in shock waves where the zero-to-peak sound pressure is reduced compared to normal open water explosions of the same weight, but the decay constant is increased such that sound exposure (and energy) remains the same. This idea is illustrated in Figure 13-3, which shows theoretical shock waves for a normal open water detonation and UXO detonation both with 102 kg explosive weights. Both shock waves have been calculated assuming that they can be approximated by decaying exponential functions, which is a well-known result (Cole, 1948; Swisdack, 1978). The zero-to-peak pressure and decay constant for the normal open water detonation have been calculated from the equations presented in Swisdack (1978). The peak pressure of the UXO detonation has been calculated as that which would result from a 5 kg normal open water detonation (in keeping with the results of NnGOWL (2021)). The decay constant for the UXO detonation has been calculated such that the sound exposure of the UXO detonation matches that of the normal open water detonation. It should be noted that the idea that a UXO detonation results in the same sound exposure as a normal open water detonation (but with a reduced zero-to-peak sound pressure) is purely a conjecture based on the observation that the Swisdack OWDM estimates of SEL fit well with the measured SELs from UXO detonations at NnG. Further measurements would be required to confirm or disprove this conjecture.

Figure 13-2: Comparison of OWDM estimated SEL with measured data for the detonation of a 102 kg UXO at the NnG wind farm

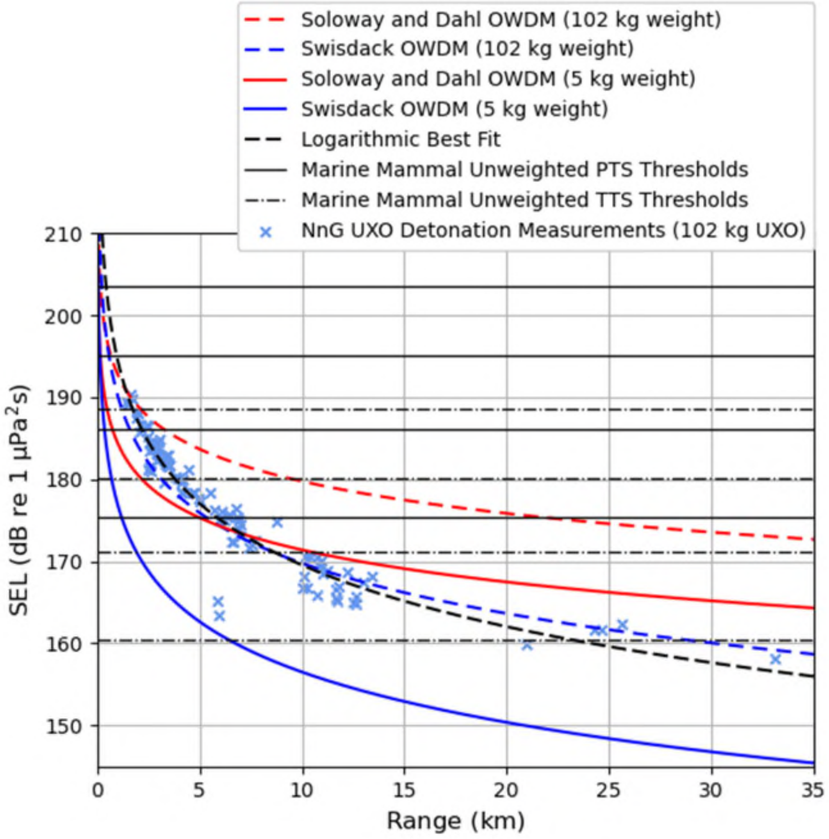
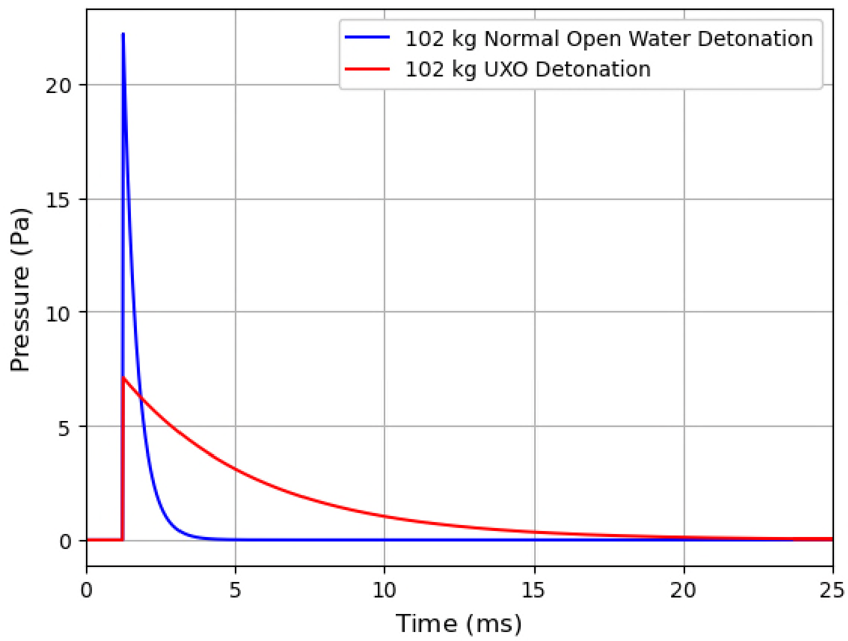


Figure 13-3: Illustration of different shock waves for normal open water and UXO detonations of 102 kg explosives



14 Appendix G: Model Estimates of Noise for Explosive Severance of Piles and Well Conductors

This appendix presents the model-based estimates of zero-to-peak SPL and SEL for explosive severance of piles and well conductors for different charge weights.

14.1 Zero-to-Peak SPL

Figure 14-1: Estimated zero-to-peak SPL from explosive severance of piles and well conductors with 11.3 kg Composition B charges

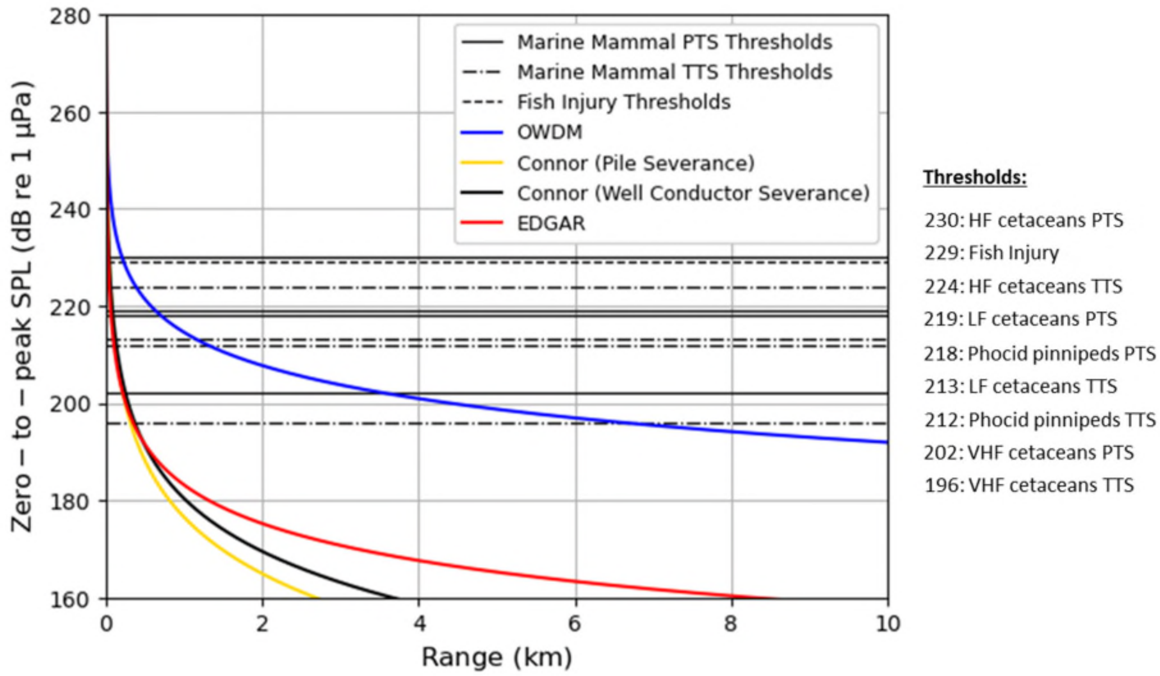


Figure 14-2: Estimated zero-to-peak SPL from explosive severance of piles and well conductors with 22.7 kg Composition B charges

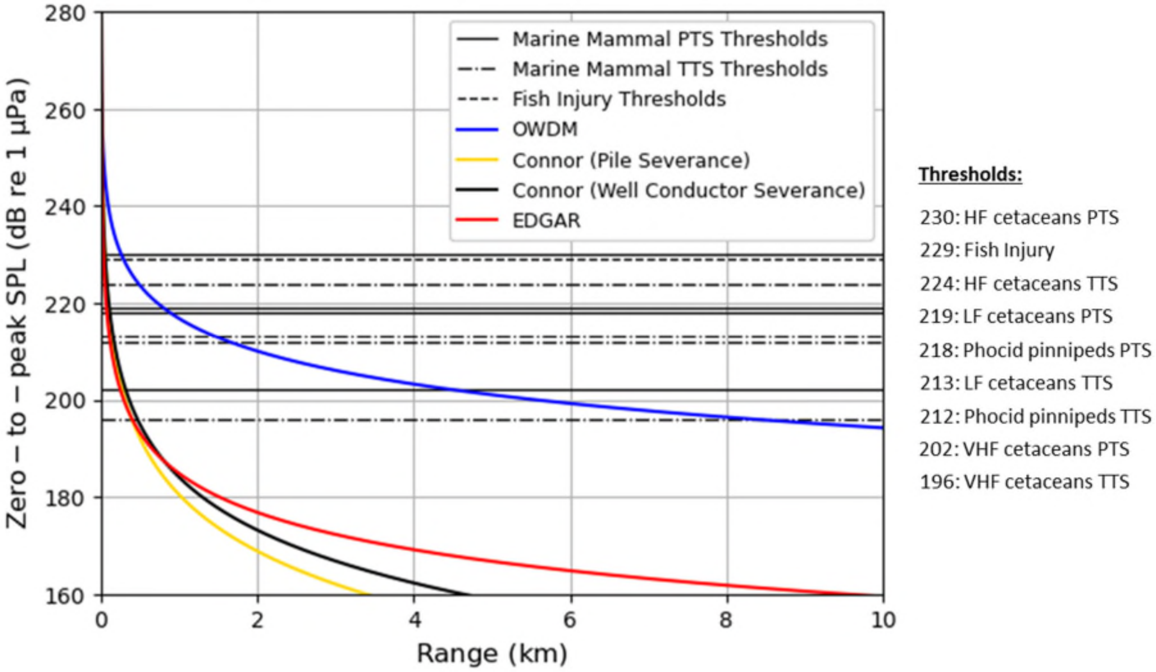


Figure 14-3: Estimated zero-to-peak SPL from explosive severance of piles and well conductors with 36.3 kg Composition B charges

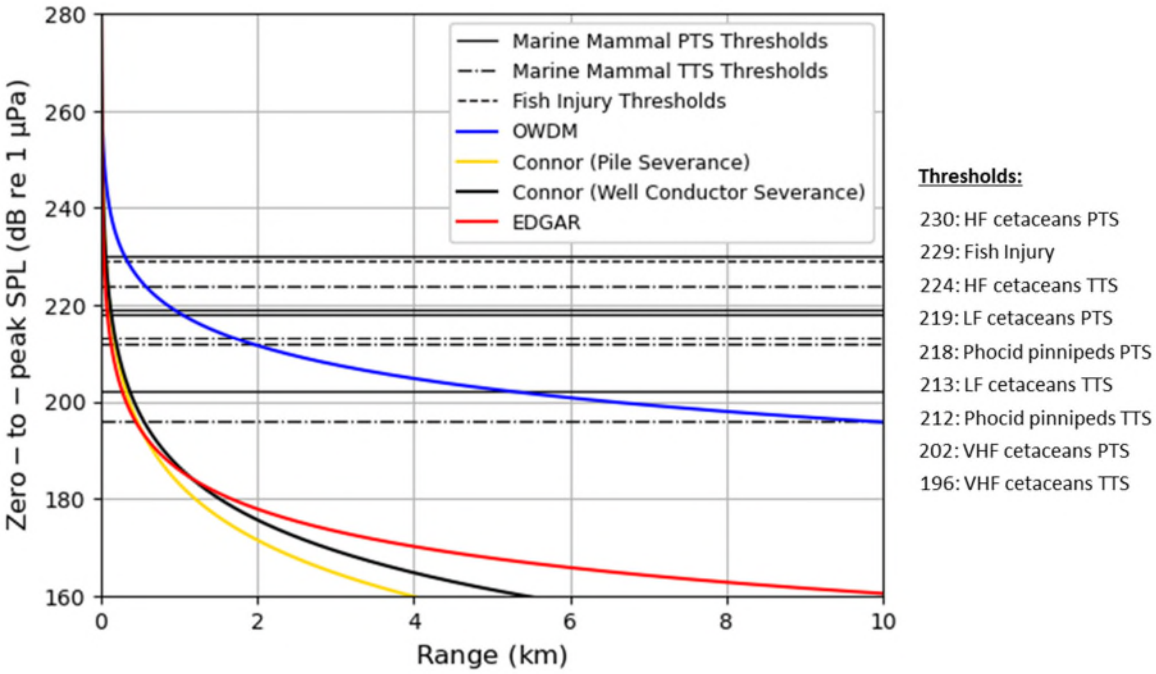


Figure 14-4: Estimated zero-to-peak SPL from explosive severance of piles and well conductors with 65.8 kg Composition B charges

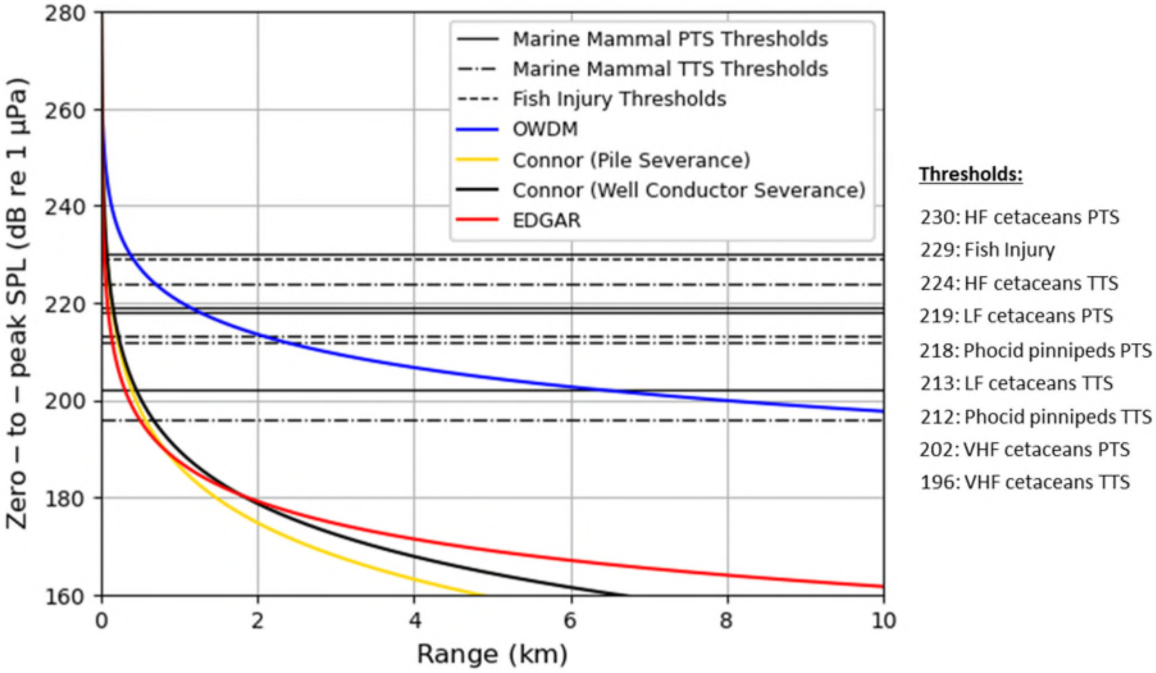
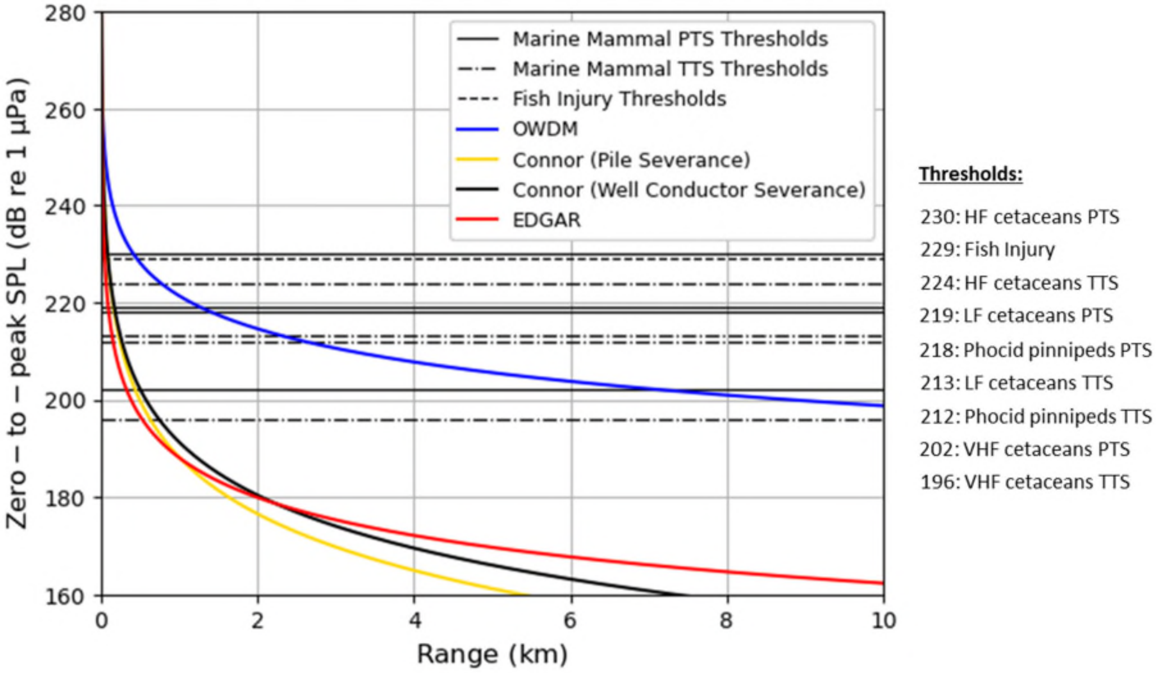


Figure 14-5: Estimated zero-to-peak SPL from explosive severance of piles and well conductors with 90.7 kg Composition B charges



14.2 SEL

Figure 14-6: Estimated SEL from explosive severance of piles and well conductors with 11.3 kg Composition B charges

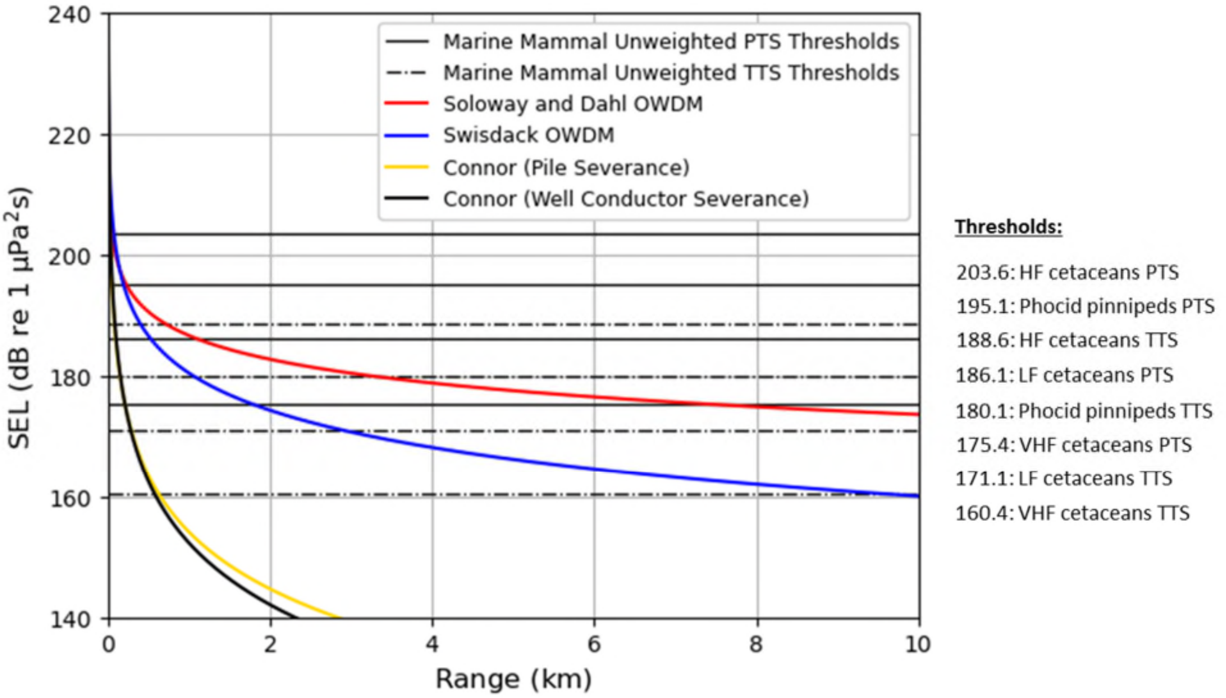


Figure 14-7: Estimated SEL from explosive severance of piles and well conductors with 22.7 kg Composition B charges

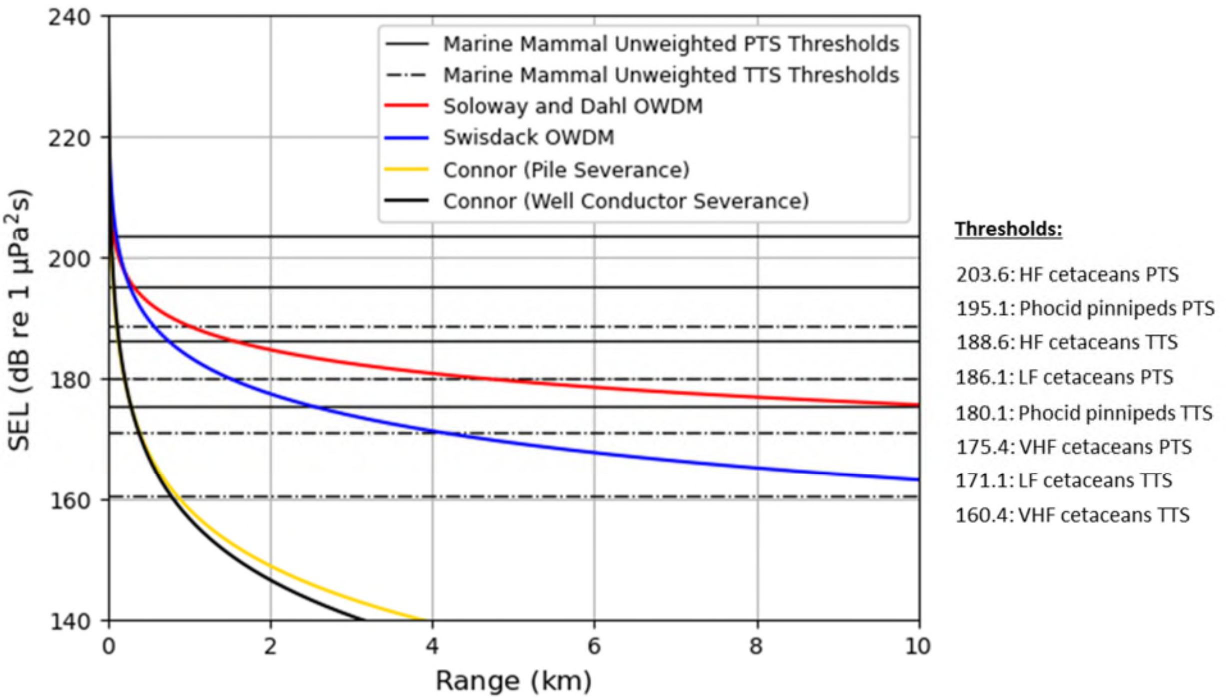


Figure 14-8: Estimated SEL from explosive severance of piles and well conductors with 36.3 kg Composition B charges

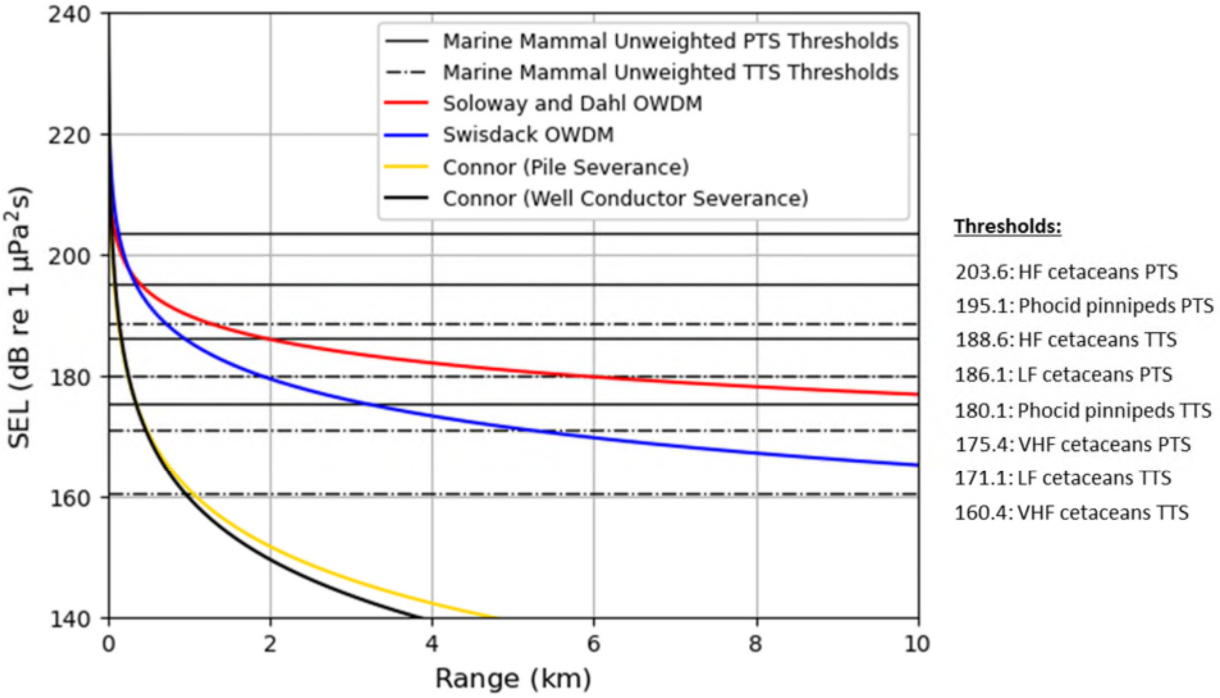


Figure 14-9: Estimated SEL from explosive severance of piles and well conductors with 65.8 kg Composition B charges

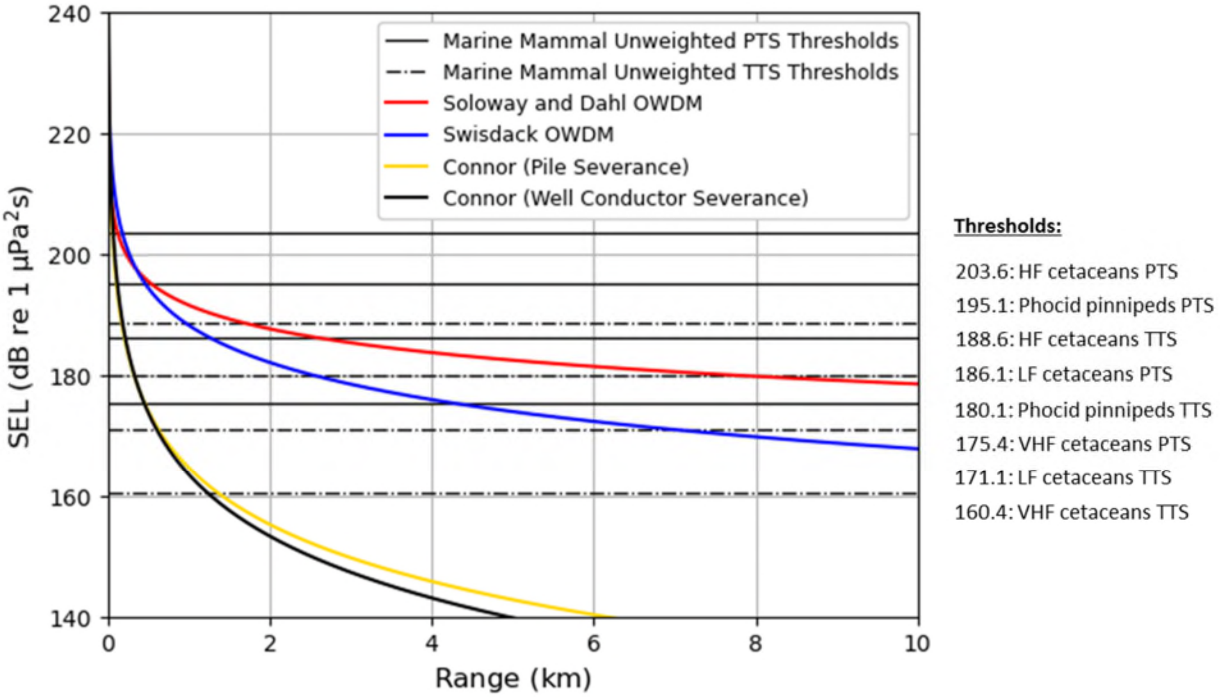
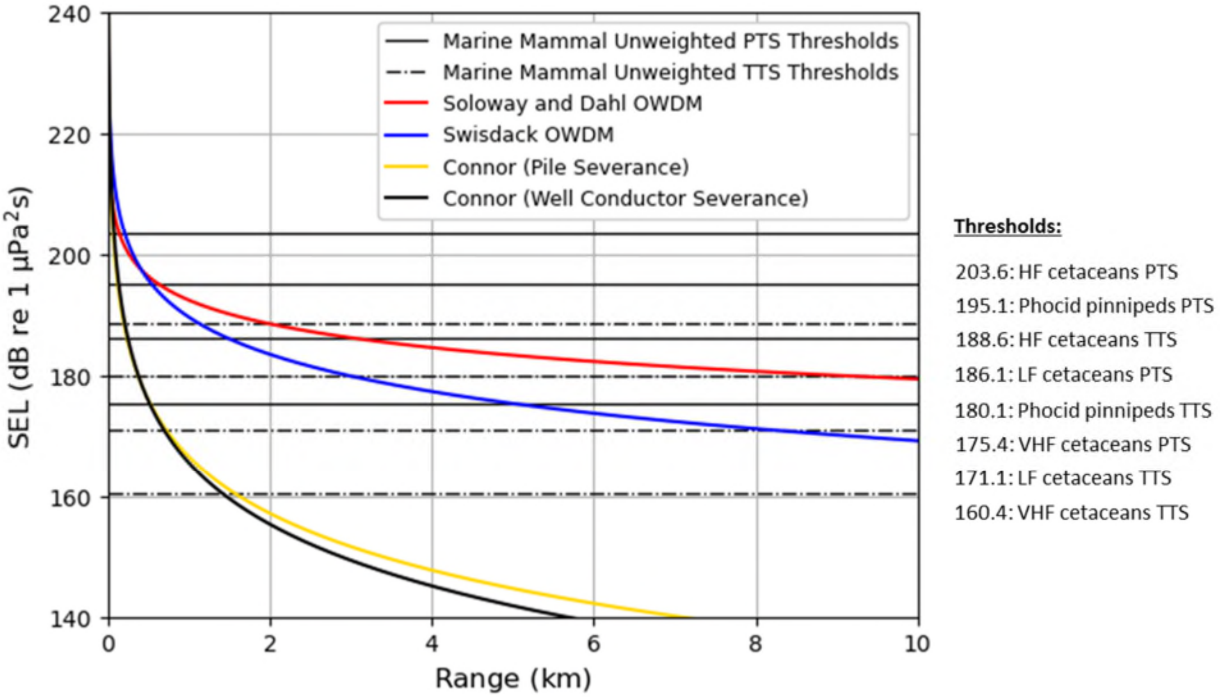


Figure 14-10: Estimated SEL from explosive severance of piles and well conductors with 90.7 kg Composition B charges



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