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Article

Explosives use in Decommissioning – Guide for Assessment of Risk (EDGAR): II Determination of sound exposure levels for open water blasts and severance of conductors and piles from below the seabed

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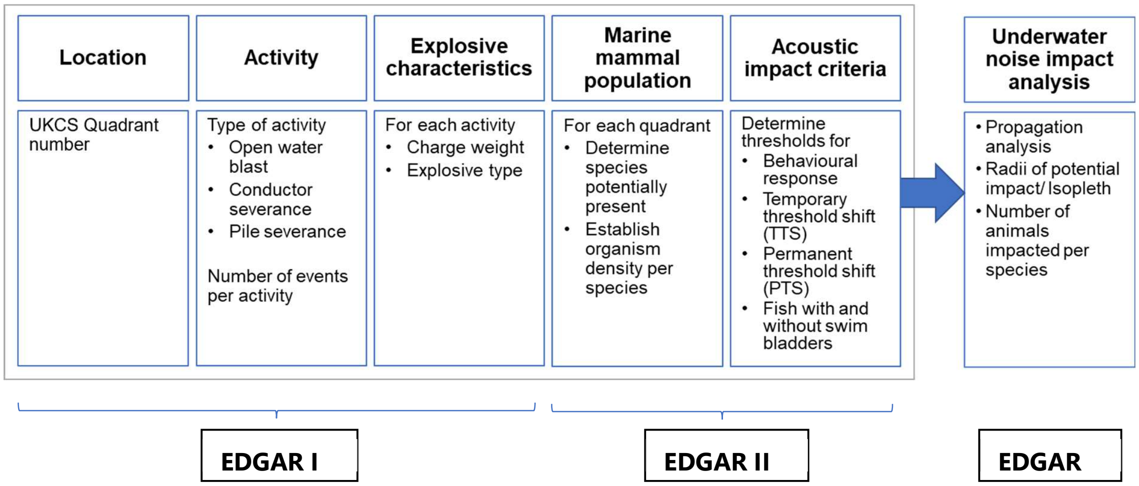
Abstract: A simple underwater noise model suitable for use with explosive severance of well conductors and piles during the decommissioning of oil and gas subsea structures is introduced and evaluated against data from five projects in the US. This study focuses on a novel model for the determination of sound exposure levels. The model has been developed to enable determination of impact areas for marine mammals and fish. Simulated received underwater sound exposure levels were significantly correlated with measurements for all scenarios. The maximum total error achieved between simulations and measurements was 2.6%, suggesting that predictions are accurate to within 3% of the average measurement. A low relative bias was observed in the simulations when compared to measured values, suggesting only a small systematic underestimate (≤ 0.5% of average measurement) for most severance operations and a small overestimate (0.14%) for open water blasts.

Keywords: Underwater noise modelling; decommissioning; explosives; sound exposure level; marine mammals; fish

Graphical Abstract:



EDGAR Model concept diagram illustrating inputs for EDGAR Part I (SPL) and EDGAR Part II (SEL) and EDGAR outputs for underwater noise impact analysis

1. Introduction

Oil and gas platforms in the Gulf of Mexico (GOM) are often decommissioned using predictability, and cost effectiveness of explosives to sever legs and piles. [1]. Using explosives during the cutting process minimises diver exposure, and reduces risk to humans, hence improving safety. Abrasive and mechanical cutters are less reliable than explosives for pile severance, and can lead to delays in vessel spreads, which are the primary reason for budgetary overspend. A comparative study of explosive and abrasive severing costs concluded that duration of the latter can be more than twice that of the former [2], resulting in increased costs of 15-18% for abrasive cutting over explosive cutting.

In the UK, the Department for Business, Energy and Industrial Strategy (BEIS) is responsible for licensing offshore operations after consideration of their effectiveness with respect to safety and environmental impact. Several of these activities require the underwater detonation of bespoke explosive charges designed to perform specific functions (e.g. conductor and pile severance) during the decommissioning of offshore structures and wells. However, the acoustic energy/shockwave released from the detonation of explosives has the potential to injure or kill marine protected species: marine mammals, fish and invertebrates. Consequently, the environmental impact of using explosives needs to be assessed.

1.1. Problem Definition

Underwater explosions are relatively brief, transitory events when compared to the existing ambient noise. Steep rapid rises, high peaks and swift falls in pressure caused by explosive cutting will generate impulsive underwater noise with near peak energy at frequencies of 10 Hz to 200 Hz before attenuation. The impact from this will likely dominate any continuous noise sources, such as from vessels.

As the material burns during a chemical explosion a bubble of expanding gases is created. Depending on charge-size and depth, the bubble can oscillate underwater with low-frequency energy or be vented to the surface. Close to the explosion, there is a very brief, high-pressure acoustic wavefront. The rapid onset time of the signal, and the high peak pressure, can result in auditory impacts in marine fauna. However, the brevity of the signal may not cause sufficient exposure to sound to be impactful. As the distance from the source increases, the transient signal gradually decays in magnitude and broadens in duration. The waveform transforms until it approximates a low-frequency, broadband signal with a continuous sound energy distribution across the spectrum.

Government regulators and their advisers often need to understand the effects of anthropogenic underwater noise on marine species, especially marine mammals. However, many underwater noise simulation models (e.g. ARA: [3]; REFM: Britt et al., 1991, as cited in [3]; CASS/GRAB: [4] are exceedingly complex, requiring too many parameters to be used by non-specialists.

Currently, many underwater noise models are propriety and/or black box. Indeed, the practice of underwater noise modelling is inconsistent amongst and between consultants, operators, and regulators. It is timely for an open-source model to be developed and evaluated. This model should be as simple and transparent as possible to enable easy use by stakeholders.

If a relatively simple, transparent, fit-for-purpose model can be realised, this could help industry access the science, reducing consultancy, regulator and operator decommissioning costs.

1.1.1. Regulatory context

In the UK, The Offshore Petroleum Activities (Conservation of Habitats) Regulations 2001 (as amended) set down the obligations for the assessment of the impact of offshore oil and gas activities on habitats and species protected under The Conservation of Offshore Marine Habitats and Species Regulations 2017. This aims to halt any decline, but

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also to ensure that the qualifying species and habitats recover sufficiently to enable them to flourish over the long-term. Part 5 provides powers to issue licences for specific activities that could result in the injury or disturbance of "European Protected Species (EPS)[1]" under Schedule 1. Under regulation 45 it is an offence *inter alia* "to deliberately capture, injure or kill any wild animal of such an EPS, or to deliberately disturb, or damage or destroy a breeding site or resting place of such an animal[2]".

In a marine setting, EPS include all species of cetaceans (whales, dolphins, and porpoises) [5]. As underwater noise has potential to cause injury and disturbance to cetaceans, an assessment of underwater noise generated by subsea decommissioning operations is required in line with guidance provided by the JNCC [6].

1.2. Receivers Potentially at Risk from Underwater Explosive Severance Noise

Underwater noise can affect the behaviour of, or may cause physical injury, or physiological change (e.g., increased stress), to several different marine taxa, e.g., to marine invertebrates, fish, and marine mammals such as pinnipeds and cetaceans.

The noise level experienced by an organism (the "received noise level") depends on the hearing sensitivity of the organism or receptor, and the level and frequency of the sound received at the organism's location. If a high source level sound is in the immediate vicinity of a receptor, a permanent threshold shift (PTS) in hearing can occur leading to hearing loss and with rising exposure, to potentially fatal physical injuries. However, the noise decreases with increasing distance from a source, reducing the risks, but still having the potential to cause the onset of a temporary shift in hearing thresholds (Temporary Threshold Shift (TTS)).

The rapid combustion reaction that is a chemical explosion results in increases in temperature, volume, and pressure. A high temperature/ high pressure gas sphere is formed, and a shock wave propagates out into the water [5]. As the distance from the source increases, so shock waves decay, gradually changing into ordinary sound waves. These acoustic waves may still have sufficient energy to harm animals submerged in the seawater. Blast trauma may occur as the rapid pressure oscillation following an explosion engages their soft tissues, membranes, and cavities filled with air [6].

Behavioural responses include any change in behaviour from small and short-duration movements to changes in migration routes and leaving a feeding or breeding site. Behavioural responses vary between species and can depend on factors such as an organism's age or level of motivation, or the time of day or season. Some changes in behaviour, such as startle reactions, may only be transient and have little consequence for the animal or population [7].

The ability of marine mammals and fish to detect and respond to biologically relevant sounds is critical and anthropogenic sound can hinder, or mask this [8]. Masking effectively raises the temporary or permanent hearing threshold of an organism, and the degree of masking is dependent on the received level and frequency content of the masking noise. Popper et al. [8] defined masking as impairment of hearing sensitivity by over 6 dB, and TTS as any persistent change in hearing of 6 dB or more.

Even if a sound is detected (e.g., a very low-frequency sound), an organism may show little or no behavioural response, possibly due to habituation. However, there is no guarantee that physical injury or physiological changes have not occurred [7].

1.2.1. Marine invertebrates

There have been few studies of the effects of underwater noise on marine invertebrates [9–12]. Impulsive noise, which involves sudden high pressure and particle motion changes, may cause behavioural disruption, physical injury, mortality, sensory damage and physiological changes in invertebrates [13,14].

[1] https://www.legislation.gov.uk/uksi/2017/1013/schedule/1/made
[2] https://www.legislation.gov.uk/uksi/2017/1013/regulation/45/made

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Invertebrate species that do not communicate acoustically may display altered behaviour in response to exposure to a sound source [15]. This can affect how invertebrate species mediate ecosystem processes known to be essential to their functioning [15]. Anthropogenic underwater noise was observed to: repress burying and bio-irrigation behaviour and considerably reduce locomotion activity in *Nephrops norvegicus*; and reduce surface relocation activity of the clam *Ruditapes philippinarum*, leading to a typical stress response where individuals moved to a position above the sediment-water interface, and closed their valves [15]. These responses restricted the mixing of the upper sediment layers by the organism and hampered suspension feeding.

Although many anthropogenic sound-producing activities are in direct contact with the seabed and many marine invertebrates are benthic dwellers, little is known about the potential effects of vibration within the seabed [16]. Substrate-borne vibrational waves may also propagate through the seabed, particularly when a source is in direct contact with the sediment [16].

Impact pile driving generates water-borne pressure and particle motion, which propagate through the water column and the seabed. Spiga et al. [17] observed that blue mussels (*Mytilus edulis*) compensated for the stress caused by pile driving by moving from a physiologically maintenance state to active metabolism. This led to increased clearance rates when feeding upon microalgae during piling than those observed under ambient conditions. Roberts et al. [18,19] found that anthropogenic substrate-borne vibrations resulting from noise pollution have a clear effect on the behaviour of the hermit crab (*Pagurus bernhardus)* and the blue mussel.

Many animals use chemical cues and signals to sense their surroundings over vast distances and locate key resources, such as food and shelter. However, the use of chemosensory information may be impaired in the marine environment by anthropogenic activities, which generate impulsive noise. Roberts and Laidre [20] reported that hermit crabs were less likely to be attracted to a chemical cue suggestive of a newly available shell home after noise exposure in field experiments.

Zooplankton underpin the health and productivity of global marine ecosystems. McCauley et al. [14] suggested that seismic surveys cause significant mortality to zooplankton populations.

Although marine invertebrates may be affected by decommissioning activities, there is insufficient knowledge currently available to be able to make an assessment.

1.2.2. Fish

Fish use a variety of sensory systems to learn about their environments and to communicate. Hearing is understood to be present among virtually all fish [21] and supplies information in 3-D, often from great distances. Fish use sound for communication, orientation and migration, to detect predators and prey to determine habitat suitability, and during mating behaviour. Thus, the survival and fitness of individuals and populations can be impacted if the ability of a fish to detect and respond to biologically relevant sounds is impaired [7].

Fish species vary in many ways, anatomically, physiologically, ecologically and behaviourally in their response to sound, such that a guideline for a behavioural response can never fit all fish [8]. An overpressure in excess of 100 kPa will cause many finfish species to display an alarm "startle" response of tightening schools, increased speed and moving towards the seabed [22,23,24]. Such responses last less than a second and do not necessarily result in significant changes in subsequent behaviour. Any resulting damage depends on: type of explosive, size and pattern of the charge(s), method of detonation, intensity of the shock wave, distance from the source of the explosion, water depth, and species, size, depth and life stage of fish [25].

There is also evidence [26–28] that fish without a swim bladder incur little or no damage from an underwater explosion unless they are in close proximity to it. The range over

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which injury may occur to a non-swim bladder fish is in the order of 100 times less than that for swim bladder fish [29].

Fish eggs and larvae also may be killed or damaged [24,30]. The effects may be intensified in the presence of ice and in areas of hard substrate [24,30].

Hearing loss

At high sound levels there may be temporary or partial loss of hearing, particularly in fish where the swim bladder is used in hearing, as it can detect sound pressure. The time interval between explosions may be important when considering effects upon hearing, as there may be sufficient time for hearing to recover. Rogers and Zeddies [31] speculated that the density of swim bladder gas will increase with increasing depth. This could lead to a decrease in pressure-aided hearing sensitivity, the swim bladder would stiffen.

Masking of any biologically relevant sounds during an explosion would be brief, occurring only during the short pulse of sound.

Injury

The water volume affected by the pressure wave generated by an explosion is a function of detonation depth, water depth, and substrate type. Fish are most at risk within two zones of the affected volume. The first is where the compressive forces of the shock wave predominate in the immediate vicinity of the explosion. In the second more distant zone, surface reflection and overshoot of the bubble pulse can cause cavitation, and negative pressures low enough to cause harmful expansion of swim bladders and other barotraumas, including mortality [32]. Swim bladder rupture, or damage, such as haemorrhage, inflicted on other body organs may result in immediate or delayed death [8].

Increased injury rates, primarily damage to the swim bladder and kidney, have been found in fish at some distance from the source of an explosion which led to the suggestion that bottom reflection and the associated negative pressure were connected with swim bladder expansion [33]. Injury in fish from blasting has been documented to distances of 100 m from the blast site with most fish being found within 50 m [34]. This is also in line with what was observed by Dos Santos et al. [35], where dead fish were collected from the sea surface near the blasting site, having been killed by injuries indicative of the shock trauma from the blasts.

Particle motion

Fish initially detect pressure signals via an air bubble in the body, for example by the gas-filled swim bladder. Vibration of the air bubble acts as a small sound source which reradiates the signal as a near-field particle motion directly to the inner ear. Acoustic particle motion induced tissue oscillation occurs in fish as their average density and elasticity is very similar to that of water [36].

Particle motion is an extremely important signal to fish as they use this component of a sound field to determine about where a source of sound originates from [32]. This is because particle motion is highly directional. Conversely, pressure does not appear to come from any particular direction [36].

Both particle motion and pressure are always present in the signal as it propagates from the source. As attenuation of the signal from particle motion is much greater over distance than that for pressure, a fish that is only able to detect particle motion will be most sensitive to sounds in the near-field [32]. Consequently, fish that detect both particle motion and pressure are more sensitive to sound.

Most fish respond to the particle motion component of sound waves whereas marine mammals do not. Animals near the seabed may not only detect water-borne sounds, but also sound that propagates through the substrate and re-enters the water column [8].

Sound exposure guidelines

Fish may be grouped into different functional categories, depending on their structure and degree of hearing specialisation [7,8,12,37,38].

Since air guns are an impulsive and low frequency source, they are fairly representative of an explosive sound at large distances in shallow water as very low frequencies propagate poorly in shallow waters [39]. As such, the more fully defined thresholds for fish for seismic airguns (**Table 1**) have been adopted by EDGAR, rather than the less conservative explosives guidelines [8].

Reviews on the effects of anthropogenic sound on fishes concluded that there are substantial gaps in the knowledge that need to be filled before meaningful noise exposure criteria can be developed, especially for explosives [8,37,38,40].

Table 1: Mortality and potential mortal injury, recoverable injury and Temporary Threshold Shift (TTS) onset dual metric threshold levels for impulsive sound. Peak sound pressure levels (SPL_{pk}) dB re 1 µPa; cumulative sound exposure levels (SEL_{cum}) dB re 1 $\mu Pa^2 \cdot s$. All criteria are presented as sound pressure even for fish without swim bladders since no data for particle motion exist. After [8] guidelines for seismic airguns.

Type of Animal	Mortality and potential mortal injury	Recoverable injury	TTS
Category 1 Fish: no swim bladder (particle motion detection)	> 219 dB SEL_{cum} or > 213 dB SPL_{pk}	> 216 dB SEL_{cum} or > 213 dB SPL_{pk}	>> 186 dB SEL_{cum}
Category 2 Fish: swim bladder is not involved in hearing (particle motion detection)	210 dB SEL_{cum} or > 207 dB SPL_{pk}	203 dB SEL_{cum} or > 207 dB SPL_{pk}	>> 186 dB SEL_{cum}
Category 3 Fish: swim bladder is involved in hearing (primarily pressure detection)	207 dB SEL_{cum} or > 207 dB SPL_{pk}	203 dB SEL_{cum} or > 207 dB SPL_{pk}	186 dB SEL_{cum}
Eggs and larvae	> 210 dB SEL_{cum} or > 207 dB SPL_{pk}		

1.2.3. Marine mammals

Among the anthropogenic sources of underwater noise and disturbance in marine environments, the rapidly generated, high energy shock waves from explosions can be considered especially dangerous to marine mammals [7,41]. However, exposure to sounds from underwater detonations in cutting operations on the behavioural or vital rates of marine mammals would be brief, as each event is spatiotemporally discrete.

Behavioural changes will vary from a minor change in direction to confusion and altered diving behaviours, which may have varied medium and long-term effects on the individual.

Marine mammals are at greatest risk of injury when they are at the same depth as, or slightly above, the explosion [6]. Risks drop off quite sharply above and below this depth; however, the pressure waves produced from an explosion may propagate very differently, depending on environmental factors. Additionally, smaller marine mammals are more susceptible to blast injury than larger animals at the same exposure levels. Frequently occurring or repeated detonations over a given time period may cause behavioural changes that disrupt biologically important behaviours or result in TTS. The extent of injury largely depends on the intensity of the shock wave and the size and depth of the animal [42].

Brain damage may occur in marine mammals, as a result of a sudden increase in cerebrospinal fluid pressure in the presence of a shock wave. They may also suffer middle and inner ear damage, or lung and intestinal haemorrhaging (see [43]). The effects of sound waves, especially if PTS is produced rather than TTS, may be less obvious than blast shock trauma but equally serious. Pinnipeds (seals, sea lions, and walruses) and

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Cetaceans (whales and dolphins) use sound for navigation, communication and prey detection. Their sounds are used primarily in critical social and reproductive interactions [45].

Marine mammal PTS/TTS distances resulting from a blast with a source level of SL_{rms} = 283 dB re 1 μPa m from 35 kg Gelamonite charge in a Portuguese harbour at a depth of 14 m were measured by Dos Santos et al. [35]. Sound pressure levels higher than Southall's behavioural response thresholds for bottlenose dolphin were recorded at distances of more than 2 km.

Whilst TTS itself is not evidence of injury [44], it may result from injury and increase the risk that an organism may not survive. Its ability to communicate, respond to predators and search for prey may be compromised.

Characterisation of hearing sensitivities

Criteria for predicting the onset of injury and behavioural response in marine mammals were defined by Southall et al. [45], after reviewing the impacts of underwater noise on marine mammals. These criteria are based on frequency-based hearing characteristics (Table 2), and pulse-based noise exposures (

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Table 3).

Table 2: Functional cetacean and pinniped hearing groups including examples of species found on the UK Continental Shelf.

Functional hearing group	Estimated auditory bandwidth	Species
Low-frequency cetaceans	7 Hz – 25 kHz	Minke whale (*Balaenoptera acutorostrata*) Long-finned pilot whale (*Globicephala melas*) Fin whale (*Balaenoptera physalus*) Sperm whale (*Physeter macrocephalus*) Cuvier's beaked whale (*Ziphius cavirostris*), Gervais' beaked whale (*Mesoplodon europaeus*), Sowerby's beaked whale (*Mesoplodon bidens*), Northern Bottlenose whale (*Hyperoodon ampullatus*)
Mid-frequency cetaceans	150 Hz – 160 kHz	White-beaked dolphin (*Lagenorhynchus albirostris*) Atlantic white-sided dolphin (*Lagenorhynchus acutus*) Bottlenose dolphin (*Tursiops truncates*) Common dolphin (*Delphinus delphis*) Risso's dolphin (*Grampus griseus*) Striped dolphin (*Stenella coeruleoalba*)
High-frequency cetaceans	200 Hz – 180 kHz	Harbour porpoise (*Phocoena phocoena*)
Pinnipeds in water	75 Hz – 100 kHz	Grey seal (*Halichoerus grypus*) Common seal (*Phoca vitulina*)

Sources: [45–48]
Note that Southall et al. [48] reclassified mid- and high- frequency cetaceans as high- and very high- frequency cetaceans, respectively.

Table 3: Noise types and use of explosives in decommissioning activities

Noise type	Acoustic characteristics	Decommissioning activities
Single-pulse	Brief, broadband, atonal, transient, single discrete noise event; characterised by rapid rise to peak pressure (> 3 dB difference between received level using impulsive vs equivalent continuous time constant)	Single explosion: explosive cutting, one charge per well with a > 24 h interval between explosions
Multiple-pulse	Multiple discrete acoustic events within 24 hours; (> 3 dB difference between received level using impulsive vs equivalent continuous time constant)	Serial explosions: explosive cutting, one charge per well with a < 24 h interval between explosions
Non-pulse	Intermittent or continuous, single or multiple discrete acoustic events within 24 hours; tonal or atonal and without rapid rise to peak pressure	Vessel activity, rock-placement, well Plug & Abandonment, underwater cutting by water jet, diamond wire or abrasive cutting

Source: [45].

The 2007 Southall study has been updated and revised noise exposure criteria to predict the onset of auditory effects in marine mammals have been published [48]. The study includes estimated audiograms and hearing-weighted functions which are in line with the details documented in the NOAA 2018 Guidelines [46] (**Error! Reference source not found.**). The only exception is the re-classification in Southall et al. [48] of the mid- and high-frequency hearing groups to high- and very-high- frequency groups, respectively. The current study uses the NOAA 2018 terminology [46].

Table 4. Behaviour, TTS and PTS onset dual metric threshold levels for explosives and other impulsive sound sources.

Group	Behaviour $SEL_{weighted}$ (dB re 1 µPa² s)	TTS-onset: $SEL_{weighted}$ (dB re 1 µPa² s)	TTS-onset: SPL_{pk} (dB re 1 µPa)	PTS-onset: $SEL_{weighted}$ (dB re 1 µPa² s)	PTS-onset: SPL_{pk} (dB re 1 µPa)
Low-Frequency Cetaceans	163	168	213	183	219
Mid-Frequency Cetaceans	165	170	224	185	230
High-Frequency Cetaceans	135	140	196	155	202
Phocid Pinnipeds	165	170	212	185	218

Source: [46]
Note that Southall et al. [48] reclassified mid- and high- frequency cetaceans as high- and very high- frequency cetaceans, respectively.

For impulsive sound, it is also important to consider the peak sound pressure levels **Error! Reference source not found.**. SPL_{pk} can induce TTS or PTS regardless of its energy and frequency content. Hence for impulsive noise, un-weighted SPL_{pk} thresholds also need to be considered in parallel with the frequency-weighted SEL thresholds [46]. Consequently, the threshold resulting in the largest impact radius/isopleth for the calculation of PTS onset should be adopted.

Generally, animals do not hear equally well at all frequencies within their hearing range. Even if an animal cannot hear a noise well, a noise with a high pressure level can still lead to disturbance or physical injury [49]. NOAA [46] developed frequency weighting criteria to make allowance for differential frequency response of sensory systems.

1.3. Innovation

Here, a simple underwater noise model," Explosives use in Decommissioning – Guide for Assessment of Risk (EDGAR)", is introduced, which can be implemented using only the limited information available for the modelling required by regulators. EDGAR

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has been written in Microsoft Excel so that it is transparent and easily accessible for different uses by regulators, industry, and other researchers. The model combines a new formulation of existing underwater noise models.

EDGAR Part I details the development of a simple transparent model for the determination of SPL by inputting the explosive charge weight. The SPL model is evaluated against data from several decommissioning projects using explosive severance in the GOM.

EDGAR Part II describes the application of EDGAR to investigate the impact risk of underwater noise to marine mammals and fish in terms of SEL. This requires the determination of isopleths for behavioural, TTS and PTS thresholds. EDGAR II introduces a novel model to determine the radius of impact from these thresholds from what is essentially a time dependent function.

1.4. Aims

The aims of this study are to (1) describe the structure of the underwater noise model for the determination of SEL and impact radii for marine mammals and fish, (2) explain the methodology developed to initialise and run the model, and (3) present an evaluation of the underwater noise model.

2. Materials and Methods

2.1. Sound Pressure

Derivation of shockwave pressure, source level (SL), and sound pressure level (SPL) are detailed in EDGAR Part I [50].

Exposure to brief, high pressure, transient sounds (impulsive sounds, such as explosions, airgun shots or pile strikes) can be more damaging than exposure to continuous sound at lower pressures. The hearing threshold rises faster when exposed to impulsive sound than to non-impulsive sound (such as from drilling and shipping). Consequently, the sound energy required to induce TTS or PTS is lower.

2.2 Sound Exposure Level

Sound Exposure Level (SEL) is sometimes taken as a proxy for the energy content, $E_f(t)$, of a sound wave and is useful as a measure of the exposure of a receptor to a sound field [51].

$$SEL = \rho_w c_w E_f(t) \tag{1}$$

and

$$E_f(t) = {\rho_w}^{-1} {c_w}^{-1} \int_0^T p^2(t)\, dt \tag{2}$$

where ρ_w is the density of seawater (1,027 kg m^{-3}), c_w is the speed of sound in seawater (1,500 m s^{-1}), T is the time window of integration which represents the exposure duration (s) and $p(t)$ is the sound pressure (Pa).

There is no standard for the definition of the integration time window, ($T = \tau\theta$ in s), although it is a critical entity in these calculations: different SPL (and SEL) results may be obtained from the same time domain pressure signal according to the size of the time window [52,53]. In order to ensure that all of the energy was accounted for Blackstock et al. (2018) used a time window of 50 ms. Integration techniques varied across all GOM projects. BOEM 2016-019 energy values were calculated by summing the area under the pressure-time curve for 5 time constants [55], whilst TAP-570 used an integration factor of 6.7 [56]. The window was extended to the time at which surface cut-off occurred for TAP-118 [57] and energy time integrals for TAP-025 were taken to 1 ms [58].

For other impulsive sound sources, the time window metric is often normalised to a single sound exposure of 1 s. However, the NOAA guidelines intend that the weighted

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SEL_{cum} metric should account for the accumulated exposure (i.e., weighted SEL_{cum} cumulative exposure over the duration of the activity within a 24 h period) [46].

The time constant, θ (s), is given by:

$$\theta = K_t W^{1/3} \left(\frac{W^{1/3}}{r}\right)^{\alpha_t} \tag{3}$$

where W is the charge weight (kg), r is the slant range (m), and K_t and α_t are empirical parameters that depend on the explosive type. In this study the parameter values used were $K_t = 8.4 \text{ x } 10^{-5}$ and $\alpha_p = -0.23$ [59].

The SEL for a single shot, SEL_{ss} (dB re 1 μPa²), indicative for the amount of sound (SPL_{pk}) received at one location, over a specific time duration, T (s), is defined as:

$$SEL_{ss} = SPL + 10log_{10}(T) = 10log_{10}\left(\frac{p_{max}}{p_{ref}}\right) + 10log_{10}\left(\frac{T}{t_{ref}}\right) \tag{4}$$

where p_{max} is the peak sound pressure (Pa), p_{ref} is the reference pressure in water of 1 μPa and t_{ref} is the reference time of 1 s.

The cumulative SEL, SEL_{cum} (dB re 1 μPa²), considers both the received level and the duration of exposure, as both factors contribute to noise induced hearing loss, and

$$SEL_{cum} = SPL + 10log_{10}(N\tau\theta)$$

or

$$SEL_{cum} = SEL_{ss} + 10log_{10}(N) \tag{5}$$

where N is the number of events in a 24 h period, τ is the time integration factor and θ is the decay constant (s) (see EDGAR Part I [50]: Sections 2.2.2 and 2.2.3).00

NOAA [46] recommend that the weighted SEL_{cum} metric should only be applied to predict impacts for a single source/activity in a discrete spatiotemporal scale [46].

2.2.1. Marine mammal auditory weighting functions

Auditory weighting functions best reflect an animal's ability to hear a sound (and do not necessarily reflect how an animal will perceive and behaviourally react to that sound). To reflect higher hearing sensitivity at particular frequencies, sounds are often weighted.

Frequency-dependent auditory weighting functions have been proposed for marine mammals, specifically associated with PTS onset thresholds expressed in the weighted SEL_{cum} metric (**Error! Reference source not found.**), which take into account what is known about marine mammal hearing [45,60,61]. Separate functions were derived for each marine mammal hearing group.

The auditory weighting function amplitude, $W_{aud}(f)$ (dB) at a particular frequency, f (kHz) is given by:

$$W_{aud}(f) = C + 10log_{10}\left\{\frac{(f/f_1)^{2a}}{[1+(f/f_1)^2]^a[1+(f/f_2)^2]^b}\right\} \tag{6}$$

The function shape is determined by the following auditory weighting function parameters, where the low-frequency cutoff (f_1) is directly dependent on the value of the low-frequency exponent (a); the high-frequency cutoff (f_2) is directly dependent on the value of the high-frequency exponent (b); and C is the weighting function gain. The influence of each parameter value on the shape of the auditory weighting function is detailed in the NOAA guidelines [46].

The default weighting adjustment factor (WFA) for explosives is assumed to be similar to seismic sources at 1 kHz (after [46]). This is likely to be conservative.

Error! Reference source not found. gives the auditory weighting function parameters for marine mammal hearing groups for use with explosive sound sources.

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Table 5. Auditory weighting function parameters for cetacean and pinniped hearing groups for use in steady state exposures to explosives (* assumes a weighting factor adjustment frequency of 1 kHz as for seismic airguns).

Auditory Weighting Function Parameters	Low-Frequency Cetaceans	Mid-Frequency Cetaceans	High-Frequency Cetaceans	Phocid Pinnipeds
a	1	1.6	1.8	1
b	2	2	2	2
f_1 (kHz)	0.2	8.8	12	1.9
f_2 (kHz)	19	110	140	30
C (dB)	0.13	1.2	1.36	0.75
Adjustment (dB)*	**-0.06**	**-29.11**	**-37.55**	**-5.90**

Source: [46]
Note: Southall et al. [48] have since reclassified mid- and high- frequency cetaceans as high- and very high- frequency cetaceans, respectively.

2.2.2. Marine Mammal density estimates

The UK Continental Shelf (UKCS) is divided into numbered rectangular Quadrants, each one degree of latitude by one degree of longitude. Maps have been compiled to enable ease of marine mammal risk assessment in EDGAR. An Oil and Gas Authority (OGA) UKCS Quadrants [62] layer has been laid over each of the Small Cetaceans in the European Atlantic and North Sea (SCANS) III survey areas [63], the Harbour Seal Total Mean Usage Maps, and the Grey Seal Total Mean Usage Maps [47] (**Figure 1**).

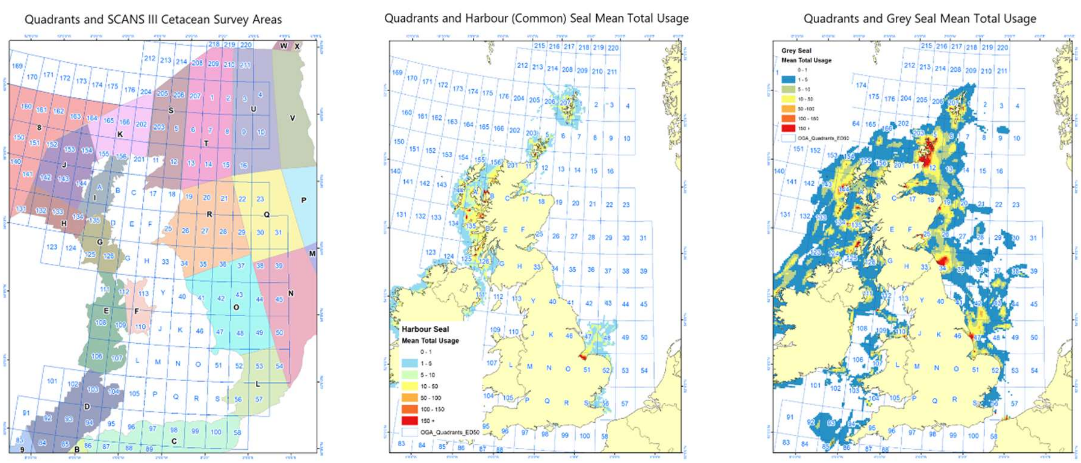

Figure 1: EDGAR Marine mammal risk assessment maps. Adapted from [47,62,63].

Approximate densities of marine mammals in the area, based on the SCANS III (July 2016) survey [64]; and the mean Grey and Harbour Seal Usage Maps [47] have been used to estimate the number of animals of each species present in a quadrant and potentially experiencing PTS, TTS or behavioural displacement from explosive cutting.

It should be noted that the predicted number of animals impacted is likely to be an overestimate. Further, individuals or pods of marine mammals are likely to be spread out and move over large areas. Maine mammals may not be present within the predicted impact zones during decommissioning activities.

2.3. EDGAR

The derivation of EDGAR for the determination of SPL is detailed in EDGAR Part I [50].
In its final form the EDGAR model for SPL_{pk} is given by:

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$$SPL_{pk} = \begin{cases} \left(\dfrac{SL_{pk} + A_{ED}W^{b_{ED}/3}}{r^{m_x/10^3}}\right) & m_x = 44, \text{ for open water} \\ \left(\dfrac{SL_{pk} + A_{ED}W^{b_{ED}}}{r^{m_x/10^3}}\right) & m_x = 64, \text{ for conductor or pile} \end{cases} \quad (7)$$

where SL_{pk} is the source level (zero-peak in dB re 1 µPa m), r is the impact radius (m) and m_x is a dimensionless gradient factor. Far-field adjustment is given by $A_{ED}W^{b_{ED}/3}$ for open water blasts and $A_{ED}W^{b_{ED}}$ for pile and conductor severance, where A_{ED} = 4.8256, b_{ED} = 0.1969 and W is the charge weight in kg.

2.3.1 Input requirements for EDGAR

In this study, the following essential user supplied data were input to run the underwater noise model:

- Explosive type and charge weight.
- Number of explosive events in a 24 h period.
- Location in terms of the UKCS Oil and gas quadrant number.

2.3.2 Using EDGAR to calculate SEL and determine impact radii

Combining **Error! Reference source not found.**, **Error! Reference source not found.** and the auditory weighting function amplitude $W_{aud}(f)$ from **Error! Reference source not found.** gives the cumulative weighted SEL, SEL_{cum}, as follows:

$$\begin{aligned} SEL_{cum} &= SPL_{pk} + 10log_{10}(N\tau\theta) \\ &= \frac{SL_{pk} + W_{aud}(f) + A_{ED}W^{b_{ED}}}{r^{m_x/10^3}} + 10log_{10}(N\tau\theta) \end{aligned} \quad (8)$$

where SPL_{pk} is the peak SPL as determined using EDGAR, N is the number of events in a 24 h period, τ is an integration factor, θ is the time constant (s), SL_{zp} is the source level (zero-peak in dB re 1 µPa m), r is the impact radius (m) and m_x is a dimensionless gradient factor. Far-field adjustment is given by $A_{ED}W^{b_{ED}/3}$ for open water blasts and $A_{ED}W^{b_{ED}}$ for pile and conductor severance, where A_{ED} = 4.8256, b_{ED} = 0.1969 and W is the charge weight in kg.

Alternatively, to determine impact radii using the NOAA thresholds [46], **Error! Reference source not found.** can be rearranged to give:

$$r = \begin{cases} \left(\dfrac{SL_{pk} + W_{aud}(f) + A_{ED}W^{b_{ED}/3}}{SEL - 10log_{10}(N\tau\theta)}\right)^{10^3/m_x} & m_x = 44, \text{ for open water} \\ \left(\dfrac{SL_{pk} + W_{aud}(f) + A_{ED}W^{b_{ED}}}{SEL - 10log_{10}(N\tau\theta)}\right)^{10^3/m_x} & m_x = 64, \text{ for conductor or pile} \end{cases} \quad (9)$$

2.3.3. Outputs from EDGAR

The model outputs include SL_{pk} and SPL_{pk} (Part I); and SEL_{ss}, SEL_{cum}, behavioural, TTS and PTS, SPL_{pk} and weighted SEL_{cum} thresholds [46], distance of impact radii for marine mammal species and fish (with and without swim bladders) and estimates of marine mammal abundance likely to be impacted.

2.4. Model Assumptions

2.4.1. Operational assumptions

Single detonations are treated as isolated events, such that exposures represent short-term and immediate impacts.

Multiple Successive Explosive events over a 24 h period are treated as events requiring the accumulation of received energy (SEL_{cum}).

2.4.2. Oceanographical and physical assumptions

The marine environment is complex, and sound propagation can be affected in many ways [51].

- Geometrical and cylindrical spreading of sound away from its source
- Sound absorption by seawater and seabed
- Interactions with the
  - sea surface (reflection and scattering)
  - seabed (and transmission through)
- Refraction of sound
- Water depth and bathymetry between source and receiver
- Depth of source and receiver.

The model assumes both a consistent uniform seabed geology and sea state; and in deeper water there is less sound and energy propagation interference associated with the seabed and water surface.

2.4.3. Biological assumptions

Potential impacts are determined by considering the sound received by an organism. Receivers are assumed to be stationary within the water column for the entire duration of the activity and not avoid the sound. Also, that animals on the edge of the isopleth (in order to exceed a threshold) will remain there. In reality, most receivers will minimise their time at close range to a sound source/activity [65].

The receiver is assumed to accumulate sound via exposure to a single pass of the source, which implies that this method is essentially independent of time [46]. Accumulation over a 24 h period, which is dependent on how many strikes or shots occur, could lead to unrealistically large isopleths associated with PTS onset.

An "equal energy" approach is adopted where SEL_{cum} is used as a simplifying assumption to accommodate sounds of various SPLs, durations, and duty cycles. SEL is related to the energy of the sound and this approach assumes exposures with equal SEL result in equal effects, regardless of the duration or duty cycle of the sound. The equal energy rule overestimates the effects of intermittent noise, as the pauses between noise exposures will promote some hearing recovery. Exposure to continuous noise with the same total SEL [46], but different durations, will tend to produce more TTS with increased duration (i.e., if the weighted SEL_{cum} of two sources are similar, a short duration/high source level noise may have similar risks to long duration/low source level sound) [46].

The potential for recovery from hearing loss exists between successive sound exposures or after sound exposure ceases, with TTS resulting in complete recovery and PTS resulting in incomplete recovery. Predicting recovery from sound exposure is not straightforward.

Since air guns are an impulsive and low frequency source, they are fairly representative of an explosive sound at large distances in shallow water [39]. As such, the more fully defined thresholds for fish for seismic airguns have been adopted by EDGAR, rather than the less conservative explosives guidelines [8].

2.5. Model Evaluation

Environmental science models should be previously evaluated with techniques that allow for their performance assessment. This consists of an investigation of how well the model fits the data and whether outliers are present, the magnitude of any prediction errors and if the model is biased. The evaluation methodology is detailed in EDGAR Part I [50].

2.6. Underwater noise data for model evaluation

See EDGAR Part I [50] for detail relating to the data sources used for the evaluation of EDGAR.

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3. Results and Discussion

3.1. Underwater noise simulations with EDGAR

The simulated and measured values of SEL_{cum} for explosive conductor/pile severance and open water blasts were highly associated (**Table 4**) suggesting that the trends in measured values are well simulated. The correlation coefficient between the simulated and measured values for all of the scenarios is highly statistically significant ($p < 0.0001$), with r varying from 0.88 to 0.99 for all scenarios (**Table 4**).

The EDGAR simulations for the open water blasts indicated a consistent overestimate (bias) of 12.31 dB re 1 μPa² (**Table 4**) and hence a correction was made to the cumulative SEL, SEL_{cum}, open water model to account for this:

$$SEL_{cum} = SPL_{pk} + 10log_{10}(N\tau\theta) - 12.31 = \frac{SL_{pk} + W_{aud}(f) + A_{ED}W^{b_{ED}/3}}{r^{m_x/10^3}} + 10log_{10}(N\tau\theta) - 12.31 \quad (10)$$

where SL_{pk} is the source level (zero-peak in dB re 1 μPa m), N is the number of events in a 24 h period, τ is an integration factor, θ is the time constant (s), r is the impact radius (m) and m_x is a dimensionless gradient factor equal to 44 for open water blasts. The far-field adjustment factor is given by $A_{ED}W^{b_{ED}/3}$ for open water blasts, where A_{ED} = 4.8256, b_{ED} = 0.1969 and W is the charge weight in kg.

Table 4: Statistical evaluation of EDGAR simulated values and measured Gulf of Mexico project data for combined conductor, pile and conductor/pile severance BML and for open water blasts (before and after model adjustment applied). Adj R^2: adjusted coefficient of determination; MAE: mean absolute error; RMSE: root mean squared error; and NRMSE: normalised root mean squared error.

Severance type	r	Adj R²	Lower bound (=MAE) (dB re 1 μPa² s)	RMSE (dB re 1 μPa² s)	Upper bound ($=\sqrt{n}$ MAE) (dB re 1 μPa² s)	RMSE (%)	Nash-Sutcliffe Efficiency index, E_f	NRMSE	Bias (dB re 1 μPa² s)	Relative bias (%)	n
Conductor (BML)	0.88	0.76	3.14	3.94	42.92	1.91	0.68	0.56	0.64	0.31	187
Conductor & Pile	0.91	0.83	3.60	4.41	78.69	2.17	0.82	0.42	-0.15	-0.07	478
Pile	0.90	0.81	1.41	5.30	24.52	2.64	0.81	0.43	-0.11	-0.05	303
Open water	0.99	0.97	12.31	12.48	110.76	5.64	-0.10	1.05	12.31	5.56	81
Open Water (adj)	0.99	0.97	1.66	2.10	14.95	0.95	0.97	0.18	0.31	0.14	81

Note: Conductor (BML) refers only to conductors where the explosive charge was placed below the mudline. Sources: Conductors: TAP-025 [58] and BOEM 2016-019 [55]. Piles: TAP-570 [56] and BOEM 2016-019 [55]. Open water:TAP-025 [58] and TAP-570 [56].

All conductor and pile severance simulations showed acceptable relative biases of less than 0.4%, whilst the relative bias for open water blasts (adj) was 0.14% (**Table 4**). Relative biases were positive for conductor severance and open water blasts, suggesting only a small systematic overestimation, hence these models were slightly conservative (Table 4). Pile severance and combined pile and conductor severance had negligible negative relative biases of -0.05% and -0.07%, respectively.

All conductor/pile severance and open water (adj) scenarios displayed coincidence with total errors close to the lower RMSE bounds and acceptable RMSEs of less than 3%

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(**Table 4**). Overall, EDGAR performed well, and all these scenarios had efficiency indices of > 0.68 and NRMSEs of 0.56 or less (**Table 4**).

The integration factors, τ, used in this study were τ = 6.7 for TAP-570 [56] and τ = 5 for BOEM 2016-019 [55]. These were found to give overall time windows of 1 ms. For TAP-118, average direct shock cut-off times [57] were used as proxies for T, and τ values for each of the air-vented conductors (τ = 78), water-vented conductor stubs (τ = 81), air-vented main piles (τ = 37) and water-vented skirt piles (τ = 44) were chosen in order to achieve this. The same method was used to determine the value of τ required to realise a 1 ms time window for TAP-025 [58]. As a result, τ = 9 was chosen for the open water shots, however, EDGAR appeared to consistently over-predict SELs for the buried TAP-025 conductors. The TAP-025 project was based on experiments using ½ scale well heads with C-4, TNT and NM explosive charges of 7.0 lbs (3.175 kg) fired at 7½ feet (2.286 m) BML in the Potomac river using non-degraded pipework [58]. Consequently, an integration factor of one was chosen for TAP-025 conductors.

The slant range, r, from the centre of the explosive charge to a reference distance is normally defined as 1 m. This is the value that has been adopted in the calculation of time constants for the open water shots in this study. Most conductors and piles are part of a complex structure consisting of an outer drive pipe or caisson, a conductor pipe, and an inner casing pipe with cement grouting in the annuli between pipes. Consequently, it was decided that a shorter reference distance of 0.1 m should be utilised for the determination of time constants for conductor and pile severance.

The simulated SELs were plotted against measured values (**Error! Reference source not found.**). A 1:1 line which represents perfect agreement between the simulations and the measurements, is shown on all plots. The spread of points around the 1:1 line indicates the errors in the simulations of SELs compared to the measurements. **Error! Reference source not found.** shows that all simulations were within ± 10% of the measured values for all scenarios.

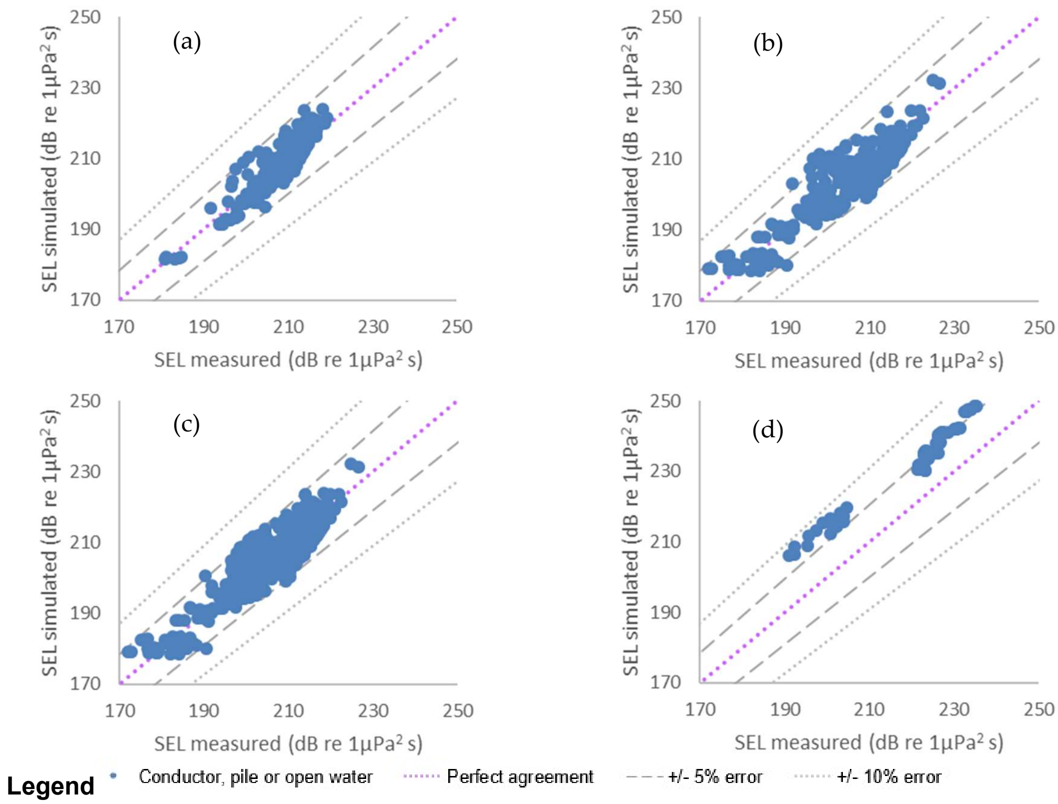

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Figure 2. Comparison of simulated against measured values of SEL for data from: TAP-025 [58], TAP-118 [57]; TAP-570 [56] and BOEM 2016-019 [55] (a) Conductors (BML) (not TAP-570); (b) Piles (not TAP-025); (c) Conductors and piles; and from TAP-025 and TAP-570 (d) Open water (before model adjustment).

Open water blast SELs simulated by EDGAR and the model proposed by Soloway and Dahl [66] were plotted against measured values (**Figure 2**). Simulations using both models were also plotted against each other for comparison. EDGAR (adjusted) simulated the measured SELs very well, whilst the trend of the Soloway and Dahl [66] model values was different to that of the measured values; TAP-570 values were overestimated and TAP-025 values underestimated.

The relationship between the models was exceptionally good ($R^2 = 0.98$) and is given by:

$$SEL_{ED} = 1.8475\ SEL_{S\&D} - 173.36 \tag{11}$$

where SEL_{ED} represent the EDGAR simulated values and $SEL_{S\&D}$ represent the Soloway and Dahl [66] modelled values, both are in dB re 1 μPa² s.

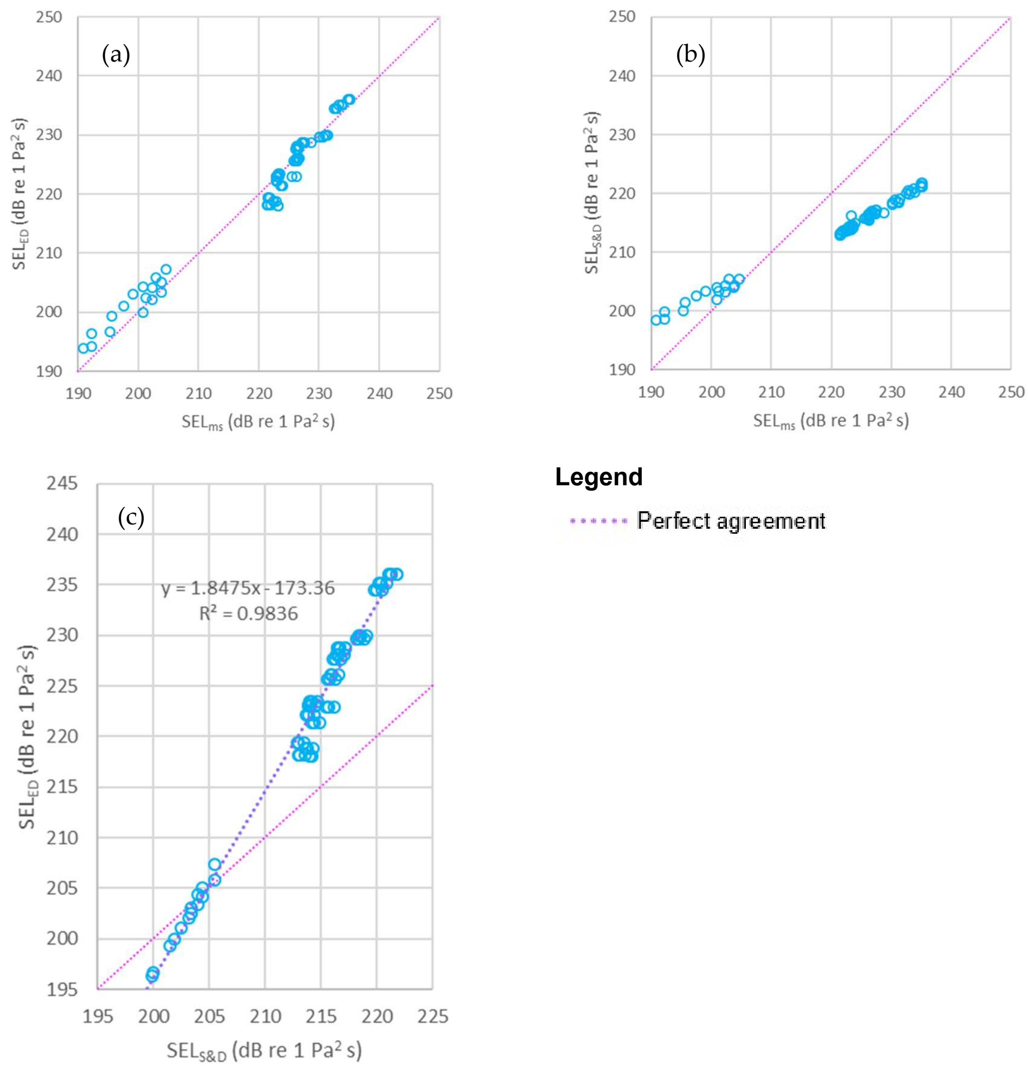

Figure 2: Comparison of simulated and measured values of SEL for open water blast data from: TAP-025 [58] and TAP-570 [56], using EDGAR and Soloway and Dahl [66] models (a) EDGAR simulated values against measured values of SEL; (b) Soloway and Dahl [66] simulated values against

measured values of SEL; (c) EDGAR simulated values against Soloway and Dahl [66] simulated values of SEL.

Overestimation by the (unadjusted) open water model may be caused by interaction with the sea floor, energy loss by cavitation close to the surface, or propagation losses due to reflection among multiple piles within a platform structure [56] or multiple interactions with wind-generated bubbles in the far-field [67]. The explosion source model assumed that there was no surface blow-out. Surface blow-out may lead to pressure release in the bubble, energy loss, and lowered (horizontal) radiation efficiency.

Porous materials are often used for shock isolation. Explosively produced shock waves move through some materials (e.g., steel or water) more readily than others (e.g., sediments). Boundaries between different materials and also the shock impedance of a material determine how an explosive shock wave attenuates [56]. Interstitial spaces between sediment particles can be occupied by a varying quantity of other materials (e.g., water, silt, air or gas). Close to the seabed, sediments tend to be waterlogged which suspends the sediment particles. The shock wave travels through this suspension in a similar way to how it would move through water rather than through sediment. At greater depths BML, there is less water within the interstitial spaces and there is particle to particle transmission of shock waves. Reflective and rarefaction waves are created by crossing boundaries between materials (water to steel to sediment, or between sediment particles through interstitial substances). These waves promote a faster decay of the shock front [56]. Specifically, softer sediments will attenuate acoustic and pressure waves more effectively than harder sediments. Medium sand will reflect sound more readily than clay or silt [68].

EDGAR overestimated SEL for TAP-570 conductors. The main assumption made by TAP-570 assumed that increasing the BML cut depth for an explosive-severance charge would increase attenuation from the pile/conductor surface and surrounding sediments [56]. In turn this would work to reduce the pressure wave and acoustic energy released during detonation [56]. Further, differences in conductor wall thicknesses as well as the condition and consistency of the grout between the walls also influenced the charge energy transmission loss (efficiency) [56]. It has also been assumed that the explosive cut location equates as an energy point source [56]. However, in addition to the BML cut location, acoustic energy also radiates from the length of the pile/conductor surface [56].

The water depths at the BOEM 2016-019 study sites were between 27 and 29 m [55], almost twice as deep as the data collection efforts at the 16 m TAP-118 [57] and 15 m TAP-570 [56] study sites. The difference in water depth may also be a factor.

A proper assessment of the environmental impact of seismic surveys, wind farm construction and explosions on aquatic life relies on having realistic estimates of SEL and SPL for short-pulse "transients" [53]. Sertlek et al. [53] suggested that in order to allow future comparisons among measurements made by different research groups or regulators it is highly desirable for the averaging time to be standardised, as SPL and SEL are sensitive to the temporal resolution determined by the choice of averaging time.

4. Conclusions

A simple, but dynamic, underwater noise model driven by only simple, minimal input data has been described and estimates of the underwater noise (SPL: EDGAR Part I [50] and SEL: EDGAR Part II) generated during explosive activities evaluated. This model will be easily adaptable for different uses by other researchers as it is highly transparent, on account of being written in Excel, and is documented in detail. Different modules could easily be incorporated, allowing the functionality of the rest the model to be used with any new additions.

EDGAR Part II performed well against several GOM project data sets in predicting SELs. The SEL estimates can be used to determine the impact radii/isopleths for behaviour, TTS and PTS thresholds for marine mammals and fish. Animal densities for the

UKCS can be predicted using the SMRU and Marine Scotland data sets [49,65] which are built into EDGAR.

A sound propagation model should be fit for purpose and suited to the task at hand. EDGAR has been benchmarked against historical GOM data and compared with other decommissioning underwater noise propagation models designed for use with explosives. EDGAR provides a good fit to the GOM measured data.

Many underwater noise models are complex multiparameter models, some of which may only be valid in limited environmental settings. EDGAR is an easy-to-use quick reference tool to aid industry and regulators alike to make decisions about environmental impacts of decommissioning.

Supplementary Materials: EDGAR the model is available from the author.

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Data Availability Statement: Data available in a publicly accessible repository that does not issue DOIs.

Publicly available datasets were analyzed in this study. This data can be found here: TAP-025, TAP-118, TAP-429, TAP-570, OCS Study MMS 2003-059, OCS Study MMS 2005-013, OCS Study BOEM 2016-019

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References

1. Proserv Offshore Gulf of Mexico Deep Water Decommissioning Study. Review of the State of the Art for Removal of GOM US OCS Oil & Gas Facilities in Greater than 400′ Water Depth; U.S. Department of the Interior, Minerals Management Service: Houston, TX, 2009; p. 350;.
2. ICF Incorporated Decommissioning Methodology and Cost Evaluation | Bureau of Safety and Environmental Enforcement; U.S. Department of the Interior Bureau of Safety and Environmental Enforcement: 45600 Woodland Road Sterling, Virginia 20166, 2015; p. 241;.
3. Dzwilewski, P.T.; Fenton, G. Shock Wave/Sound Propagation Modeling Results for Calculating Marine Protected Species Impact Zones During Explosive Removal of Offshore Structures; U.S. Dept. of the Interior, Minerals Management Service, Gulf of Mexico OCS Region: New Orleans, LA, 2003; p. 39;.
4. Goddard, R.P. The Sonar Simulation Toolset, Release 4.6: Science, Mathematics, and Algorithms:; Defense Technical Information Center: Fort Belvoir, VA, 2008;
5. Chapman, N.R. Measurement of the Waveform Parameters of Shallow Explosive Charges. J. Acoust. Soc. Am. **1985**, 78, 672–681, doi:10.1121/1.392436.
6. Keevin, T.M.; Hempen, G.L. The Environmental Effects of Underwater Explosions with Methods to Mitigate Impacts; DTIC Document, 1997;
7. Popper, A.N.; Hawkins, A.D. An Overview of Fish Bioacoustics and the Impacts of Anthropogenic Sounds on Fishes. J. Fish Biol. **2019**, 2019, doi:10.1111/jfb.13948.
8. Popper, A.N.; Hawkins, A.D.; Fay, R.R.; Mann, D.A.; Bartol, S.; Carlson, T.J.; Coombs, S.; Ellison, W.T.; Gentry, R.L.; Halvorsen, M.B.; et al. ASA S3/SC1.4 TR-2014 Sound Exposure Guidelines for Fishes and Sea Turtles: A Technical Report Prepared by ANSI-Accredited Standards Committee S3/SC1 and Registered with ANSI; SpringerBriefs in Oceanography; Springer International Publishing: Cham, 2014; ISBN 978-3-319-06658-5.
9. Edmonds, N.J.; Firmin, C.J.; Goldsmith, D.; Faulkner, R.C.; Wood, D.T. A Review of Crustacean Sensitivity to High Amplitude Underwater Noise: Data Needs for Effective Risk Assessment in Relation to UK Commercial Species. Mar. Pollut. Bull. **2016**, 108, 5–11, doi:10.1016/j.marpolbul.2016.05.006.
10. Hawkins, A.D.; Popper, A.N. A Sound Approach to Assessing the Impact of Underwater Noise on Marine Fishes and Invertebrates. ICES J. Mar. Sci. **2017**, 74, 635–651, doi:10.1093/icesjms/fsw205.
11. Morley, E.L.; Jones, G.; Radford, A.N. The Importance of Invertebrates When Considering the Impacts of Anthropogenic Noise. Proc. R. Soc. B Biol. Sci. **2014**, 281, 20132683, doi:10.1098/rspb.2013.2683.

12. Spiga, I.; Cheesman, S.; Hawkins, A.; Perez-Dominguez, R.; Roberts, L.; Hughes, D.; Elliott, M.; Nedwell, J.; Bentley, M. Understanding the Scale and Impacts of Anthropogenic Noise upon Fish and Invertebrates in the Marine Environment. SoundWaves Consort. Tech. Rev. **2012**, 5205.
13. Fitzgibbon, Q.P.; Day, R.D.; McCauley, R.D.; Simon, C.J.; Semmens, J.M. The Impact of Seismic Air Gun Exposure on the Haemolymph Physiology and Nutritional Condition of Spiny Lobster, Jasus Edwardsii. Mar. Pollut. Bull. **2017**, 125, 146–156, doi:10.1016/j.marpolbul.2017.08.004.
14. McCauley, R.D.; Day, R.D.; Swadling, K.M.; Fitzgibbon, Q.P.; Watson, R.A.; Semmens, J.M. Widely Used Marine Seismic Survey Air Gun Operations Negatively Impact Zooplankton. Nat. Ecol. Evol. **2017**, 1, 0195, doi:10.1038/s41559-017-0195.
15. Solan, M.; Hauton, C.; Godbold, J.A.; Wood, C.L.; Leighton, T.G.; White, P. Anthropogenic Sources of Underwater Sound Can Modify How Sediment-Dwelling Invertebrates Mediate Ecosystem Properties. Sci. Rep. **2016**, 6, 20540, doi:10.1038/srep20540.
16. Roberts, L.; Elliott, M. Good or Bad Vibrations? Impacts of Anthropogenic Vibration on the Marine Epibenthos. Sci. Total Environ. **2017**, 595, 255–268, doi:10.1016/j.scitotenv.2017.03.117.
17. Spiga, I.; Caldwell, G.S.; Bruintjes, R. Influence of Pile Driving on the Clearance Rate of the Blue Mussel, Mytilus Edulis (L.). Proc. Meet. Acoust. **2016**, 27, 040005, doi:10.1121/2.0000277.
18. Roberts, L.; Cheesman, S.; Elliott, M.; Breithaupt, T. Sensitivity of Pagurus Bernhardus (L.) to Substrate-Borne Vibration and Anthropogenic Noise. J. Exp. Mar. Biol. Ecol. **2016**, 474, 185–194, doi:10.1016/j.jembe.2015.09.014.
19. Roberts, L.; Cheesman, S.; Hawkins, A.D. Effects of Sound on the Behavior of Wild, Unrestrained Fish Schools. In Proceedings of the The Effects of Noise on Aquatic Life II; Popper, A.N., Hawkins, A., Eds.; Springer: New York, NY, 2016; pp. 917–924.
20. Roberts, L.; Laidre, M.E. Finding a Home in the Noise: Cross-Modal Impact of Anthropogenic Vibration on Animal Search Behaviour. Biol. Open **2019**, 8, bio041988, doi:10.1242/bio.041988.
21. Ocean Noise and Marine Mammals; National Research Council, Ed.; National Academies Press: Washington, DC, 2003; ISBN 978-0-309-50694-6.
22. Fewtrell, J.L.; McCauley, R.D. Impact of Air Gun Noise on the Behaviour of Marine Fish and Squid. Mar. Pollut. Bull. **2012**, 64, 984–993, doi:10.1016/j.marpolbul.2012.02.009.
23. McCauley, R.D.; Fewtrell, J.; Popper, A.N. High Intensity Anthropogenic Sound Damages Fish Ears. J. Acoust. Soc. Am. **2003**, 113, 638–642, doi:10.1121/1.1527962.
24. Wright, D.G. A Discussion Paper on the Effects of Explosives on Fish and Marine Mammals in the Waters of the Northwest Territories. Can Tech Rep Fish Aquat Sci **1982**, 1052, v + 16.
25. Yelverton, J.T. The Relationship between Fish Size and Their Response to Underwater Blast; Lovelace Foundation for Medical Education and Research: Albuquerque, New Mexico 87115, 1975; p. 42;.
26. Goertner, J.F.; Wiley, M.L.; Young, G.A.; McDonald, W.W. Effects of Underwater Explosions on Fish without Swimbladders; DTIC Document, 1994;
27. Halvorsen, M.B.; Casper, B.M.; Matthews, F.; Carlson, T.J.; Popper, A.N. Effects of Exposure to Pile-Driving Sounds on the Lake Sturgeon, Nile Tilapia and Hogchoker. Proc. R. Soc. B Biol. Sci. **2012**, 279, 4705–4714, doi:10.1098/rspb.2012.1544.
28. Stephenson, J.R.; Gingerich, A.J.; Brown, R.S.; Pflugrath, B.D.; Deng, Z.; Carlson, T.J.; Langeslay, M.J.; Ahmann, M.L.; Johnson, R.L.; Seaburg, A.G. Assessing Barotrauma in Neutrally and Negatively Buoyant Juvenile Salmonids Exposed to Simulated Hydro-Turbine Passage Using a Mobile Aquatic Barotrauma Laboratory. Fish. Res. **2010**, 106, 271–278, doi:10.1016/j.fishres.2010.08.006.
29. Goertner, J.F. Dynamical Model for Explosion Injury to Fish; 1978;
30. Wright, D.G.; Hopky, G.E. Guidelines for the Use of Explosives in or near Canadian Fisheries Waters; Fisheries and Oceans Canada, 1998;
31. Rogers, P.H.; Zeddies, D.G. Multipole Mechanisms for Directional Hearing in Fish. In Fish Bioacoustics: With 81 Illustrations; Webb, J.F., Fay, R.R., Popper, A.N., Eds.; Springer Handbook of Auditory Research; Springer: New York, NY, 2008; pp. 233–252 ISBN 978-0-387-73029-5.
32. US Department of the Navy Silver Strand Training Complex. Environmental Impact Statement; 2011; p. 879;.
33. Dahl, P.H.; Keith Jenkins, A.; Casper, B.; Kotecki, S.E.; Bowman, V.; Boerger, C.; Dall'Osto, D.R.; Babina, M.A.; Popper, A.N. Physical Effects of Sound Exposure from Underwater Explosions on Pacific Sardines (Sardinops Sagax). J. Acoust. Soc. Am. **2020**, 147, 2383–2395, doi:10.1121/10.0001064.
34. Continental Shelf Associates, Inc. Explosive Removal of Offshore Structures Information Synthesis Report; MMS 2003-070; U.S. Department of the Interior, Minerals Management Service, Gulf of Mexico OCS Region: New Orleans, LA, 2004; p. 181;.
35. Dos Santos, M.E.; Couchinho, M.N.; Rita Luís, A.; Gonçalves, E.J. Monitoring Underwater Explosions in the Habitat of Resident Bottlenose Dolphins. J. Acoust. Soc. Am. **2010**, 128, 3805–3808.
36. Popper, A.N.; Hawkins, A.D. The Importance of Particle Motion to Fishes and Invertebrates. J. Acoust. Soc. Am. **2018**, 143, 470–488, doi:10.1121/1.5021594.
37. Hawkins, A.D.; Johnson, C.; Popper, A.N. How to Set Sound Exposure Criteria for Fishes. J. Acoust. Soc. Am. **2020**, 147, 1762–1777, doi:10.1121/10.0000907.
38. Popper, A.N.; Hawkins, A.D.; Thomsen, F. Taking the Animals' Perspective Regarding Anthropogenic Underwater Sound. Trends Ecol. Evol. **2020**, doi:10.1016/j.tree.2020.05.002.

39. von Benda-Beckmann, A.M.; Aarts, G.; Sertlek, H.Ö.; Lucke, K.; Verboom, W.C.; Kastelein, R.A.; Ketten, D.R.; van Bemmelen, R.; Lam, F.-P.A.; Kirkwood, R.J.; et al. Assessing the Impact of Underwater Clearance of Unexploded Ordnance on Harbour Porpoises (Phocoena Phocoena) in the Southern North Sea. Aquat. Mamm. **2015**, 41, 503–523, doi:10.1578/AM.41.4.2015.503.
40. Popper, A.N.; Hastings, M.C. The Effects of Anthropogenic Sources of Sound on Fishes. J. Fish Biol. **2009**, 75, 455–489, doi:10.1111/j.1095-8649.2009.02319.x.
41. Finneran, J.J.; Schlundt, C.E.; Carder, D.A.; Clark, J.A.; Young, J.A.; Gaspin, J.B.; Ridgway, S.H. Auditory and Behavioral Responses of Bottlenose Dolphins (Tursiops Truncatus) and a Beluga Whale (Delphinapterus Leucas) to Impulsive Sounds Resembling Distant Signatures of Underwater Explosions. J. Acoust. Soc. Am. **2000**, 108, 417–431, doi:10.1121/1.429475.
42. Yelverton, J.T.; Richmond, D.R.; Fletcher, E.R.; Jones, R.K. Safe Distances from Underwater Explosions for Mammals and Birds:; Defense Technical Information Center: Fort Belvoir, VA, 1973;
43. Ketten, D. Sensory Systems of Aquatic Mammals; De Spil Publishers: Woerden, The Netherlands, 1995; pp. 391–408; ISBN 978-90-72743-05-3.
44. Richardson, W.J.; Jr, C.R.G.; Malme, C.I.; Thomson, D.H. Marine Mammals and Noise: A Sound Approach to Research and Management; Gulf Professional Publishing, 1995; ISBN 978-0-12-588441-9.
45. Southall, B.L.; Bowles, A.E.; Ellison, W.T.; Finneran, J.J.; Gentry, R.L.; Greene, C.R.; Kastak, D.; Ketten, D.R.; Miller, J.H.; Nachtigall, P.E.; et al. Marine Mammal Noise Exposure Criteria: Initial Scientific Recommendations. Aquat. Mamm. **2007**, 33, 411–414, doi:10.1578/AM.33.4.2007.411.
46. National Marine Fisheries Service 2018 Revisions to: Technical Guidance for Assessing the Effects of Anthropogenic Sound on Marine Mammal Hearing (Version 2.0): Underwater Thresholds for Onset of Permanent and Temporary Threshold Shifts.; U.S. Dept. of Commer., NOAA, 2018; p. 167;.
47. Sea Mammal Research Unit (SMRU) and Marine Scotland, R. Estimated At-Sea Distribution of Grey and Harbour Seals - Updated Maps 2017. **2017**, doi:10.7489/2029-1.
48. Southall, B.L.; Finneran, J.J.; Reichmuth, C.; Nachtigall, P.E.; Ketten, D.R.; Bowles, A.E.; Ellison, W.T.; Nowacek, D.P.; Tyack, P.L. Marine Mammal Noise Exposure Criteria: Updated Scientific Recommendations for Residual Hearing Effects. Aquat. Mamm. **2019**, 45, 125–232, doi:10.1578/AM.45.2.2019.125.
49. Matthews, M.N.R.; Zykov, M.; Deveau, T. Assessment of Underwater Noise for the Mary River Iron Mine: Construction and Operation of the Steensby Inlet Port Facility; LGL Ltd: King City, 2010;
50. Brand, A.M. Explosives Use in Decommissioning – Guide for Assessment of Risk (EDGAR): I Determination of Sound Pressure Levels for Open Water Blasts and Severance of Conductors and Piles from below the Seabed. Modelling **2021**, (submitted).
51. Robinson, S.P.; Lepper, P.A.; Hazlewood, R.A. Good Practice Guide for Underwater Noise Measurement; National Measurement Office, Marine Scotland, The Crown Estate, 2014; p. 97;.
52. Madsen, P.T. Marine Mammals and Noise: Problems with Root Mean Square Sound Pressure Levels for Transients. J. Acoust. Soc. Am. **2005**, 117, 3952–3957, doi:10.1121/1.1921508.
53. Sertlek, H.O.; Slabbekoorn, H.; Ten Cate, C.J.; Ainslie, M.A. Insights into the Calculation of Metrics for Transient Sounds in Shallow Water. Proc. Meet. Acoust. **2012**, 17, 070076, doi:10.1121/1.4789476.
54. Blackstock, S.A.; Fayton, J.O.; Hulton, P.H.; Moll, T.E.; Jenkins, K.; Kotecki, S.; Henderson, E.; Bowman, V.; Rider, S.; Martin, C. Quantifying Acoustic Impacts on Marine Mammals and Sea Turtles: Methods and Analytical Approach for Phase III Training and Testing; Naval Undersea Warfare Center Division: Newport, Rhode Island, 2018;
55. Barkaszi, M.J.; Frankel, A.; Martin, J.S.; Poe, W. Pressure Wave and Acoustic Properties Generated by the Explosive Removal of Offshore Structures in the Gulf of Mexico; U.S. Dept. of the Interior, Bureau of Ocean Energy Management, Gulf of Mexico OCS Region: New Orleans, LA, 2016; p. 69;.
56. Poe, W.T.; Adams, C.F.; Janda, R.; Kirklewski, D. Effect of Depth Below Mudline of Charge Placement During Explosive Removal of Offshore Structures (EROS); U.S. Department of the Interior, Minerals Management Service, 2009; p. 71;.
57. Connor, J.G. Underwater Blast Effects from Explosive Severance of Offshore Platform Legs and Well Conductors; Naval Surface Warfare Center, USA, 1990; p. 135;.
58. Heathcote, T.B. An Experimental Program to Determine the Environmental Impact of Explosive Removal of Oil Wellheads; Naval Surface Weapons Center: White Oak, Silver Spring, Maryland 20910, n.d.; p. 27;.
59. Swisdak, M.M. Explosion Effects and Properties. Part II. Explosion Effects in Water:; Defense Technical Information Center: Fort Belvoir, VA, 1978;
60. Erbe, C.; Ainslie, M.A.; de Jong, C.A.F.; Racca, R.; Stocker, M. Summary Report Panel 1: The Need for Protocols and Standards in Research on Underwater Noise Impacts on Marine Life. In The Effects of Noise on Aquatic Life II; Popper, A.N., Hawkins, A., Eds.; Springer New York: New York, NY, 2016; Vol. 875, pp. 1265–1271 ISBN 978-1-4939-2980-1.
61. Finneran, J.J.; Mulsow, J.; Schlundt, C.E. Using Reaction Time and Equal Latency Contours to Derive Auditory Weighting Functions in Sea Lions and Dolphins. In The Effects of Noise on Aquatic Life II; Popper, A.N., Hawkins, A., Eds.; Springer New York: New York, NY, 2016; Vol. 875, pp. 281–287 ISBN 978-1-4939-2980-1.
62. OGA OGA Quadrants. Oil and Gas Authority Open Data. Available at: https://data-ogauthority.opendata.arcgis.com/datasets/oga-quadrants-ed50. 2020.
63. Thomas, L.; Buckland, S.T.; Rexstad, E.A.; Laake, J.L.; Strindberg, S.; Hedley, S.L.; Bishop, J.R.B.; Marques, T.A.; Burnham, K.P. Distance Software: Design and Analysis of Distance Sampling Surveys for Estimating Population Size. J. Appl. Ecol. **2010**, 47, 5–14, doi:10.1111/j.1365-2664.2009.01737.x.

 doi:10.20944/preprints202107.0535.v1

64. Hammond, P.; Lacey, C.; Gilles, A.; Viquerat, S.; Börjesson, P.; Herr, H.; Macleod, K.; Ridoux, V.; Santos, M.; Teilmann, J.; et al. Estimates of Cetacean Abundance in European Atlantic Waters in Summer 2016 from the SCANS-III Aerial and Shipboard Surveys. **2017**, 40.
65. Gedamke, J.; Gales, N.; Frydman, S. Assessing Risk of Baleen Whale Hearing Loss from Seismic Surveys: The Effect of Uncertainty and Individual Variation. J. Acoust. Soc. Am. **2011**, 129, 496–506, doi:10.1121/1.3493445.
66. Soloway, A.G.; Dahl, P.H. Peak Sound Pressure and Sound Exposure Level from Underwater Explosions in Shallow Water. J. Acoust. Soc. Am. **2014**, 136, EL218–EL223, doi:10.1121/1.4892668.
67. Cole, R.H. (Robert H. Underwater Explosions; Princeton, Princeton Univ. Press, 1948;
68. Dekeling, R.P.A.; Tasker, M.L.; Van Der Graaf, A.J.; Ainslie, M.A.; Andersson, M.H.; André, M.; Borsani, J.F.; Brensing, K.; Castellote, M.; Cronin, D.; et al. Monitoring Guidance for Underwater Noise in European Seas - Part I: Executive Summary; EN, Publications Office of the European Union: Luxembourg, 2014;