Low order deflagration of unexploded ordnance reduces underwater noise impacts from offshore wind farm construction

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In collaboration with EODEX.

Summary

- Unexploded ordnance (UXO) poses a risk for marine infrastructure, often requiring UXO clearance that must be licenced and managed to minimise impacts of underwater noise on protected marine mammals.

- Controlled studies suggest that low-order deflagration techniques produce significantly less noise than the high-order detonations commonly used for UXO clearance. However, the efficacy of these techniques remained untested in the marine environment, constraining development of policy on best environmental practice.

- This paper describes how low-order deflagration techniques were used to clear 82 UXOs prior to construction of an offshore wind farm in the Moray Firth N.E. Scotland and presents results of underwater noise measurements made during disposal operations.

- Seven types of UXO, with net explosive quantities (NEQ) varying from 6 kg to 700 kg, were successfully neutralised using low-order deflagration, with none resulting in high-order detonation. The campaign used a total of 28 kg of explosive donor charges (a maximum of 250g per deflagration event). In comparison, traditional high-order clearance techniques would have required a total of donor charges between 830 kg and 2075 kg for the same number of UXO disposals.

- Calibrated noise measurements were made at 1 km, 5 km, and 10 km from a representative sample of 31 UXOs. The highest measured L0-pk sound level was 208.4 dB re 1 µPa, recorded at a range of 1 km. These data suggest that worst case impact ranges for marine mammals were for very high-frequency cetaceans (Harbour porpoises), but auditory injury impact ranges were all <1.5 km. This compared to the 2.55-14.25 km impact ranges predicted for equivalent high-order detonations of these UXOs.

- These data confirm that noise produced by low-order deflagration clearance is governed by the disposal tool charge size, as opposed to the UXO NEQ. This demonstrates that acoustic modelling, impact assessment, licencing and mitigation of UXO clearance by low-order deflagration can be based on known (and small) disposal tool charge sizes, rather than less certain (and often large) estimates of the NEQ of UXO.

- This paper provides accessible outputs that can be used to minimise precaution in future impact assessments and license applications for UXO clearance by low-order deflagration and facilitate the licensing decision-making process.

1. Introduction

UK waters contain unexploded ordnance (UXO) that potentially pose a risk for infrastructure, maritime users and marine wildlife (Long 2009; Cooper & Cooke 2017). Given that offshore wind farm sites often overlap with areas previously used in military conflicts or training, developers must ensure that they have reduced the risk from UXO as low as reasonably possible (ALARP). This requires surveys to detect any UXO that could pose a risk to construction vessels or new infrastructure. Although some of the UXOs detected may be avoided to reduce any risk, there is likely to be a requirement for UXO clearance prior to construction at most, if not all, future offshore wind developments around the UK.

Previously, clearance of marine UXO has generally been undertaken by high-order detonation of the main UXO explosive charge using an additional high explosive donor charge. However, this release of energy can potentially injure or disturb protected marine mammals and fish, damage marine habitats, and create seabed craters which negatively affect the installation of infrastructure.

In recent years, offshore wind developers and their stakeholders have recognised the need for alternative methods of UXO disposal to reduce environmental impacts. In particular, there has been interest in the use of low-order techniques such as deflagration, a method developed for military Explosive Ordnance Disposal (EOD) operations in the early 2000s (Merchant and Robinson, 2020). This technique results in the explosive material within UXO being rapidly burned away rather than detonating. Research conducted under controlled conditions has demonstrated that deflagration results in significantly less acoustic noise generation and no cratering of the seabed (Robinson et al. 2020). These results highlight likely benefits for protection of the marine environment, and the technique is now being considered in the development of UK policy and guidance (DEFRA et al. 2022). However, low-order deflagration disposal methodology has not previously been successfully deployed in a UXO clearance campaign at a commercial offshore wind farm development, and their efficacy in this context remained unproven.

Here, we describe the successful use of a low-order deflagration technique to clear 82 UXOs from a commercial offshore wind farm in the Moray Firth NE Scotland. This paper aims to provide evidence on the effectiveness of low-order deflagration to minimising risks from UXO clearance both to offshore wind farm developers and to marine wildlife. We present the results of underwater noise measurements made during the Moray West UXO disposal operations that provide evidence of reduced environmental impacts through use of low-order deflagration. Finally, we discuss the lessons learned during the licencing, mitigation and deployment of the low-order deflagration methodology, with the aim of informing the development of robust guidance to improve future assessment, licencing and mitigation of UXO clearance.

2. Moray West Offshore Wind Farm Case Study

Background & licencing requirements

Moray West offshore wind farm is located in the Outer Moray Firth, NE Scotland[1]. The development phase commenced in 2016, and the project was consented by Scottish Government in June 2019. The development site covers an area of 225 km^2 over water depths ranging from 35 m to 55 m, with an export cable corridor coming ashore 65 km south of the development site (Figure 1).

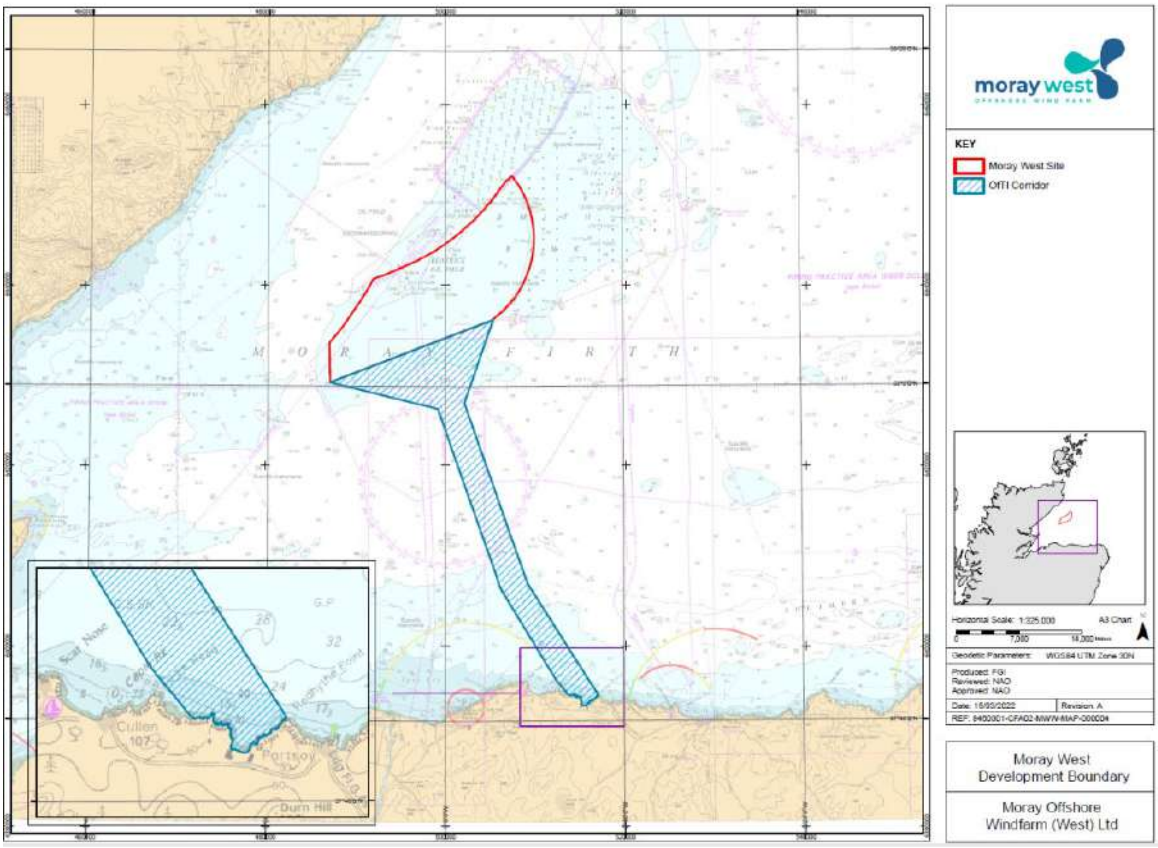

Figure 1 Map showing the geographical location of the Moray West offshore wind farm and the boundary of the Moray West site and OfTI corridor.

[1] Moray West Offshore Wind Farm Project - Renewable wind energy

Moray West offshore construction works commenced in Q1 2023 at the landfall with the horizontal directional drilling and cable duct installation immediately followed by UXO identification works. No UXOs were identified in the landfall area. Installation works commenced within the Moray West offshore export cable corridor and wind farm site from Q2 2023, following necessary pre-construction seabed preparations, including UXO identification and clearance operations.

The potential for UXO to exist within the Moray West development site was initially assessed through a site-specific desktop threat and risk assessment (TARA). The TARA informs the need for subsequent geophysical surveys, licencing and planning required to undertake UXO clearance (Figure 2). All confirmed UXO targets deemed to be hazardous that could not be avoided or otherwise removed, had to be safely disposed of using controlled clearance methodologies as a necessary measure to mitigate this potentially major risk to safety.

Critically, the deposit or use of explosives is a licensable marine activity under UK legislation, meaning that UXO clearance operations require a marine licence[2]. Where these marine activities could cause disturbance or injury to a European Protected Species (EPS), which includes all cetaceans, an EPS licence is also required from the relevant licensing authority[3] (Figure 2).

Current guidance in Scotland advises applicants to submit marine licence applications at least 14 weeks prior the works commencing[2]. However, detailed UXO surveys and clearance operations should be ideally undertaken immediately before major construction works to ensure that ALARP certification (Figure 2) is valid during critical construction periods. Consequently, details of the numbers and characteristics of UXO are not available in the initial licence application stage, potentially constraining environmental assessment and the design of mitigation measures, and risking delays to construction. This is particularly problematic if high-order clearance of UXOs is used, given that assessment and mitigation requirements are dependent upon both the exact number and size of the UXO and the high-order donor charge required for disposal operations (Robinson et al. 2022). This challenge, and the potential benefits of using low-order techniques to clear UXO, is illustrated below through the licencing required for the work described in this case study.

2 Marine environment: licensing and consenting requirements - gov.scot (www.gov.scot)

3 Marine European Protected Species and basking sharks: licensing - gov.scot (www.gov.scot)

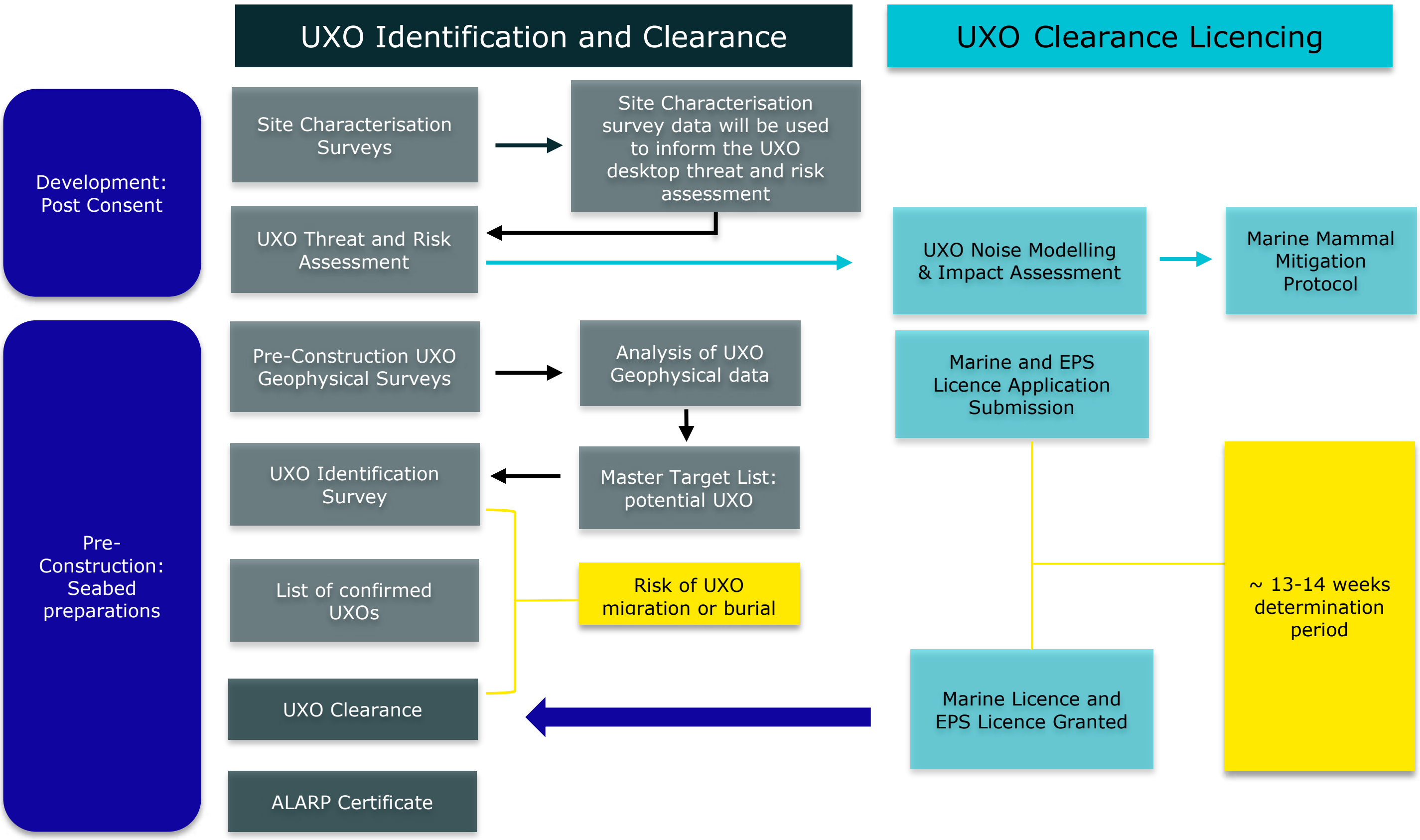

Figure 2 Schematic showing the UXO identification and clearance process from site characterisation surveys carried out at early stages of offshore wind farm development (post consent), until the EOD operations undertaken during seabed preparations prior offshore construction required to obtain the ALARP certificate. The schematic illustrates at what stages of the process the relevant information feeds into the licensing process for UXO clearance.

Moray West submitted marine and EPS Licence applications in Q3 2022 to Marine Directorate Licencing and Operations Team (MD-LOT)[4] in advance of the pre-construction UXO geophysical surveys (completed in February 2023) and the UXO identification surveys (completed between February and April 2023) to ensure the required licences were received in time for UXO clearance operations that were scheduled to occur before the commencement of main offshore construction works. Thus, detailed information on the number, type and location of UXOs that might be encountered was unknown at the time of the licence application. To reduce the impact of these uncertainties during determination of the EPS licence, the Moray West application for UXO clearance prioritised the use of low-order deflagration clearance methods as an alternative to high-order detonation. Nevertheless, due to a lack of evidence on the efficiency of low-order deflagration methods in a commercial context such as this, MD-LOT applied the precautionary principle through the licensing application and determination process.

[4] Moray West Offshore Windfarm | Marine Scotland Information

This meant that the licence application also had to include high-order clearance, even though the intention was to only deploy the low-order deflagration techniques.

Using the desktop TARA, Moray West's initial impact assessment assumed that a maximum of 30 UXO would need clearing, with estimated a Net Explosive

Quantity (NEQ) ranging from 6 kg to 364 kg. However, UXO geophysical surveys subsequently identified 230 potential UXO targets, and during the UXO identification works an additional 51 potential UXOs were discovered and subsequently identified as confirmed UXO, increasing the overall number of UXO targets requiring disposal up to 81 (Figure 3), with a NEQ ranging from 6 kg (6-inch and 4.5-inch artillery projectiles) up to a 94 kg anti-submarine weapon (Table 1). Given these new findings, a new marine licence application had to be made to MD-LOT, for the same licenced activity, which was then subject to a new determination process including an additional consultation period.

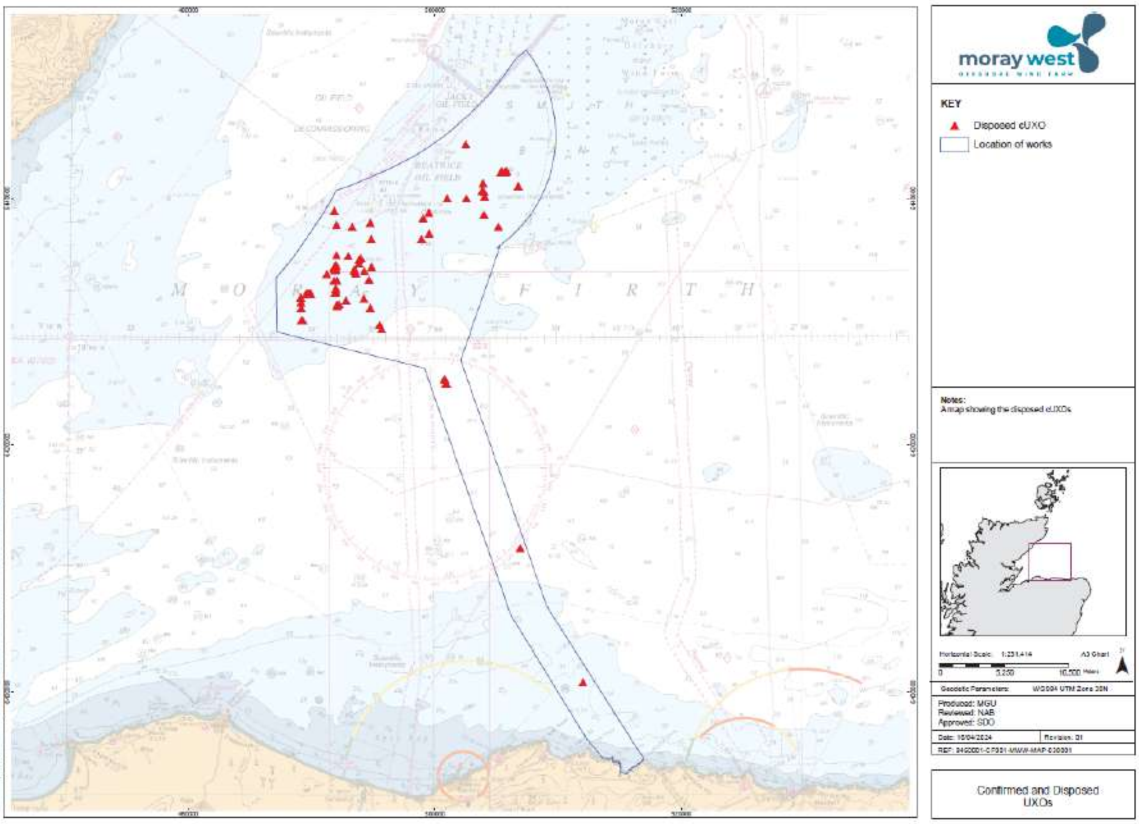

Figure 3 Map showing the locations of confirmed UXO encountered and cleared by low-order deflagration, which are shown as red triangles (see Table 1).

Table 1. UXO types encountered in the Moray West offshore wind farm and its export cable corridor.

UXO Type	Number of UXO targets	Ferrous Mass	Net Explosive Quantity (NEQ)	Dimensions
4.5-inch Projectile	1	25 kg	6 kg	800mm x 100mm
6-inch Projectile	3	39.4 kg	6 kg	582mm x 152mm
10-inch Projectile	2	126 kg	12 kg	1000mm x 254mm
15-inch Projectile	72	879 kg	20.7 kg	1,300mm x 381mm
Anti-Submarine Weapon	1	181 kg	94 kg	1,448mm x 305mm
500lb Air Dropped Weapon	2	226 kg	89 kg	900mm x 300mm
German Luftmine B Mine	1	14 kg	700 kg	2600mm x 660mm

As described in the sections below, these 81 UXOs were successfully cleared using low-order deflagration, without the need for high-order clearance techniques that had been licenced as a precautionary measure. However, illustrating the unpredictable nature of this issue, a 700kg (NEQ) German Luftmine B was subsequently identified from an ROV video while boulders were being relocated during seabed preparation within the export cable corridor. Moray West subsequently prepared and submitted a new marine licence application for the clearance of this single UXO using low-order deflagration. In this case, the clearance operations of the 81 UXOs and the acoustic monitoring of the 30 UXOs preceding this provided evidence on the efficacy of this method and its reduced impacts on the marine environment.

Low-order UXO disposal methodology

The UXO clearance method used during EOD operations at the Moray West offshore wind farm was low-order deflagration. Moray West is the first offshore wind project in the UK to successfully use low-order deflagration methods for UXO clearance for an entire UXO clearance campaign.

EODEX UK Subsea Limited (EODEX) were contracted by Moray West to undertake EOD of confirmed UXO targets by low-order deflagration. EOD operations were undertaken between 16th April - 2nd September 2023 using the Alford Technologies disposal tool previously used in controlled studies (Robinson et al. 2020). Seiche Limited (Seiche) were contracted through EODEX, first, to undertake marine mammal mitigation and, second, to conduct in-situ underwater sound measurements of the disposal operations.

In practice, UXO disposal operations required favourable weather conditions (wave height < 1m), as EOD operations were carried out from a small support vessel, usually a fast rescue craft (FRC) or a rigid inflatable boat (RIB), and so that the primary operations vessel remained at a safety distance from the UXO location once the firing mechanism was deployed adjacent to the UXO.

EODEX used the Alford Technologies disposal tool, which consists of a hand size plastic housing filled with plastic explosive, which is placed in an incendiary cone to create a shaped charge. Initially, a Remotely Operated Vehicle (ROV) operated from the operations vessel was used to remove sediment and expose the UXO target, to identify the generic and specific features of the UXO, including type, arming state and fusing (Figure 4).

The amount of plastic explosive and shape of the charge was then optimised for each UXO in order to achieve deflagration without detonation. For example, a sea-mine has a thinner casing than an airdropped bomb, requiring a smaller charge with a different shape. The NEQ of the explosive placed in the shaped charge used to dispose of the 81 UXOs and the LMB mine encountered at the Moray West site and offshore export cable corridor were between 100 g and 250 g. In comparison, traditional high-order clearance techniques would have required between 5 kg and 10 kg of high explosive per UXO.

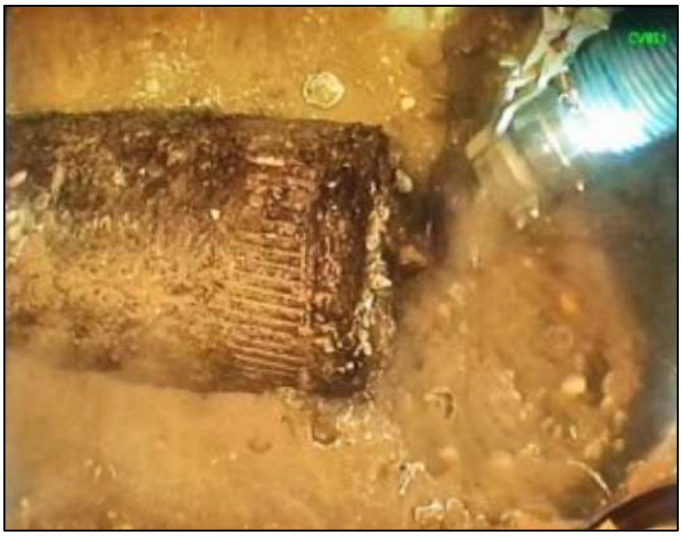

Figure 4 Localised sediment removal of 15-inch projectile for identification and subsequent low-order deflagration.

Following preparation of the explosive and a detonator, the shaped charge is placed on a metal frame, required to hold the tool in position on the seabed once laid. This is then positioned adjacent to the UXO using an ROV, with the stand-off distance, angle and target area on the UXO casing optimised to penetrate the casing and achieve a low-order deflagration effect without a detonation.

When the disposal tool is in place, the shaped charge is fired into the UXO, creating a plasma jet effect which penetrates the UXO casing at extreme temperatures (around 5,000° centigrade). This instantly ignites the explosive fill within the UXO in a self-sustaining thermal reaction (deflagration). This process results in the active components within the UXO being burned away and rendered safe and allow for all the remains of the UXO to be concentrated at its original location. This process occurs within a fraction of a second.

An initial deflagration attempt is used to assess the disposal tool penetration rate and the content of the UXO. In many cases, ROV inspection is able to confirm that the UXO explosive content is cleared following the first deflagration attempt. However, if the UXO remains partially intact, with explosive content, the deflagration process can be repeated to ensure all the UXO explosive content is neutralised, and the remaining components can be safely to recovered. During the Moray West UXO low-order deflagration clearance operations 53 of 82 UXOs (65%) were successfully neutralised following a single deflagration attempt, and a total of 28 kg of explosive used throughout disposal campaign (with a maximum of 250 g per deflagration). In comparison, traditional high-order clearance techniques would have used between 830 kg and 2075 kg for the same number of UXO disposals.

Following the completion of the low-order deflagration clearance events, a post-clearance visual inspection was conducted. For example, Figure 5 shows a comparison of the seabed before and after the clearance of an anti-submarine weapon (bottom images) and the LMB mine (top images), demonstrating the lack of any seabed crater. This observation was consistent for all clearance events.

The metal scrap of each neutralised UXO was then recovered with a grab (Figure 6) and inspected to ensure it was free from explosive content before being recycled.

Figure 5 Seabed comparison, before low-order deflagration (left) and after low-order deflagration (right) of the LMB mine (top images) and anti-submarine weapon (bottom images). No seabed disturbance is observed following on low-order deflagration disposal operations (note the complete lack of seabed crater).

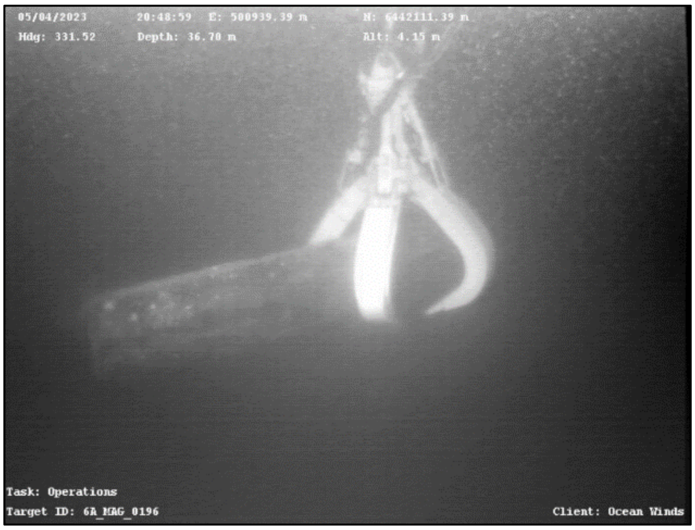

Figure 6 Recovery of scrap UXO after successful low-order deflagration for onward delivery to scrap recycling facility.

Acoustic modelling

Noise modelling for UXO clearance operations was conducted to support the assessments of potential impacts of UXO clearance on marine mammals that were required for licence applications to MD-LOT[5] (Figure 2). Assessments were based on Southall et al. (2019) impact criteria, which use weighted thresholds for groups of marine mammals with different hearing sensitivities (eg. Very High Frequency (VHF), High Frequency (HF) and Low Frequency (LF) cetaceans). These thresholds were used to indicate the risk of auditory injury (Permanent Threshold Shift (PTS)) at different distances from the UXO.

Unweighted Sound Exposure Levels (SEL) from underwater explosions (the source) were estimated using the below equation (equation 1) from Soloway and Dahl (2014) for a free-standing charge in mid water. Given that a UXO would be resting on the seabed and could potentially be buried, degraded or subject to other significant attenuation, this estimation of the source level is considered conservative.

Equation 1. $$SEL = 6.14 \times log_{10}\left(W^{1/3}\left(\frac{R}{W^{1/3}}\right)^{-2.12}\right) + 219$$

where "W" is equivalent to the weight of the charge (or equivalent trinitrotoluene (TNT) weight) and "R" is the distance from the noise source to receiver.

These SEL values were then related to marine mammal hearing thresholds by applying Southall et al. (2019) frequency dependent weighting functions to an assumed spectrum for unweighted sound at different distances from source. Southall et al. (2019) also includes criteria based on peak Sound Pressure Level (SPLpeak), which are unweighted and do not take species hearing sensitivity into account. SPLpeak values were similarly estimated using the following equation (equation 2) based on that used in Soloway and Dahl (2014) and Weston (1960).

Equation 2. $$SPL_{peak} = 52.4 \times 10^{6}\left(\frac{R}{W^{1/3}}\right)^{-1.13}$$

where "W" is equivalent to the weight of the charge (or equivalent trinitrotoluene (TNT) weight) *and "R" is the distance from the noise source to receiver.*

Robinson et al. (2020) conclude that that peak sound pressure during low-order deflagration is due only to the NEQ of the shaped disposal tool charge used to initiate deflagration. This results in much lower noise exposure than larger charges used in high-order detonations, where there is also considerable uncertainty over the size of the charge remaining within the UXO. Consequently, the acoustic output can be predicted for low-order deflagration as long as the

[5] Moray West Offshore Windfarm | Marine Scotland Information

size of the explosive contained within the shaped disposal tool charge is known.

Acoustic modelling for low-order deflagration used for the UXO clearance operations at Moray West was therefore based on the methodologies used previously for high-order detonations, but using a smaller disposal tool charge size (up to 250 g).

The maximum predicted impact ranges for PTS in harbour porpoise (VHF), dolphin species (HF) and minke whale (LW) from unmitigated 150 g and 250 g donor charges for low-order deflagration clearance are presented in Table 2. These were based on underwater noise modelling for a single deflagration attempt in a 24-hour period.

Table 2 The maximum predicted impact ranges (m) for PTS in marine mammals, based on the underwater noise modelling for a single low-order deflagration event using a 250 g and 150 g donor charge.

Marine mammal hearing group	Auditory weighting function	PTS Criteria	Threshold	Impact Ranges (m)	
				250 g donor charge	150 g donor charge
Low-Frequency cetaceans	LF	Unweighted Peak SPL (SPL_{peak})	219 dB re 1 μPa	186	157
		Weighted SEL	183 dB re 1 μPa^2s	88	69
High-Frequency	HF	Unweighted Peak SPL (SPL_{peak})	230 dB re 1 μPa	61	51
		Weighted SEL	185 dB re 1 μPa^2s	3	2
Very High-Frequency	VHF	Unweighted Peak SPL (SPL_{peak})	202 dB re 1 μPa	1050	885
		Weighted SEL	155 dB re 1 μPa^2s	337	267
Phocids Carnivores in Water	PCW	Unweighted Peak SPL (SPL_{peak})	218 dB re 1 μPa	206	173
		Weighted SEL	185 dB re 1 μPa^2s	17	13

Noise monitoring

Underwater sound measurements were undertaken during EOD operations within the Moray West wind farm site and offshore export corridor. This is the first field-collected data set on noise monitoring undertaken during EOD operations using low-order deflagration of UXOs encountered at sea.

The primary objective of noise monitoring was to provide empirical data on noise levels resulting from low-order deflagration to compare with existing data on high-order detonations, and to objectively demonstrate and substantiate the predicted reduction in acoustic impact of the use of low-order deflagration over high-order detonation on the marine environment.

In discussion with MD-LOT and NatureScot, 30 confirmed UXOs were selected for acoustic monitoring, with the aim of collecting comparative data on noise levels from clearance of different types of UXO (Table 3). In addition, noise measurements were made during the disposal operations of the 700 kg LMB mine discovered after the main clearance campaign.

Table 3 UXOs acoustically monitored during low-order deflagration operations at Moray West.

UXO Description	UXO NEQ (kg)	Disposal Tool Charge NEQ (g)	Number of targets
6-inch Projectile	6	200	2
15-inch Naval Projectile	20.7	250	23
10-inch Projectile	12	200	2
Anti-submarine weapon	94	100	1
500lb Air dropped bomb	89	250	2
German Luftmine B (LMB) mine	700	125	1

Underwater sound measurements were made by deploying a series of Autonomous Recording Units (ARUs) on seabed moorings at approximately 1 km, 5 km and 10 km from selected individual UXO targets and clusters of UXOs. Recordings at 1 km and 5 km from the UXOs were made using Wildlife Acoustics SM4M recorders, and those at 10 km used an RTSys Sylence-LP. Details of these devices and their sampling rates are provided in Table 4. All hydrophones were calibrated in accordance with IEC 60565-1:2020, with a further pistonphone calibration check on the vessel prior to each deployment. All measurements were made in accordance with the Protocol for In-Situ Underwater Measurement of Explosive Ordnance Disposal for UXO Version 2 (Wang et al. 2020).

Table 4 ARU and hydrophone specifications

	Wildlife Acoustics – SM4M	RTSys – Sylence-LP
Sampling rate	96 kHz	128 kHz
Bit rate	16-Bit	24-Bit
Hydrophone make and model	HTI HiSPL	GeoSpectrum M36-900
Hydrophone sensitivity (dB re 1 µV/Pa)	-240	-220

At each ARU location, mooring equipment was enclosed within a case that was lowered to the seabed and placed at the required location using an ROV. Once in position, the case was opened by the ROV, releasing the mooring line, recording equipment and sub-surface float within the water column (Figure 7). Following the UXO clearance, ARUs were recovered using the ROV.

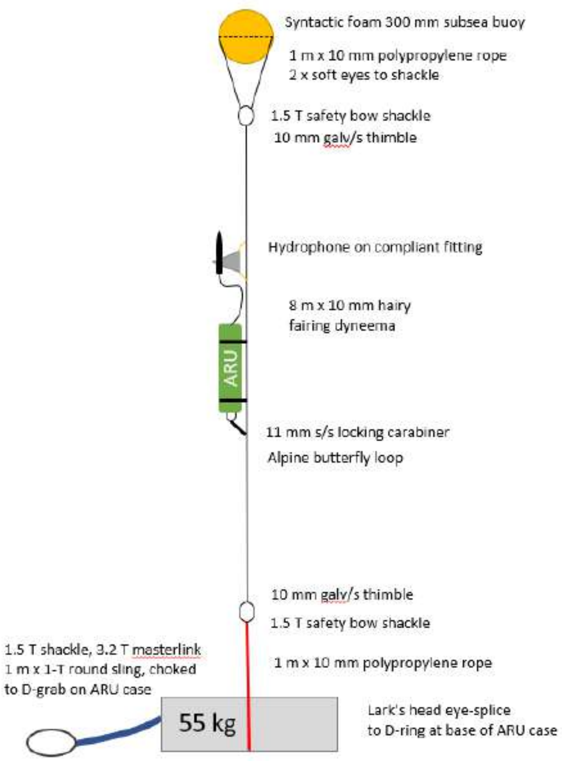

Figure 7 Schematic ROV released mooring.

Noise Monitoring Results

Sound recordings from each ARU were subsequently analysed to measure received unweighted $SPL_{0\text{-}pk}$ and frequency weighted SEL for each of the 31 UXO clearance monitored.

Maximum recorded levels during clearance of different UXO at each of the recording distances are presented in Table 6. The highest measured $L_{0\text{-}pk}$ sound level during the campaign was 208.4 dB re 1 μPa, recorded during clearance operations of a 15-inch naval projectile at a range of 1 km from the UXO. During the clearance operations of the largest UXO, the LMB mine, the maximum $L_{0\text{-}pk}$ was 206 dB re 1 μPa, recorded at 1 km during the fourth and final deflagration attempt. This is 22 dB lower than the predicted sound level for a high-order detonation of this UXO ($L_{0\text{-}pk}$ = 228 dB re 1 μPa at 1km).

Received sound levels can be compared to those predicted from acoustic modelling of a) the quantity of explosive of disposal tool charge and b) estimated quantity of explosive material within the UXO (see Table 3).

A comparison between the measured $SPL_{0\text{-}pk}$ and frequency weighted SEL for all clearances of UXOs with an NEQ of 20.7 kg (15-inch naval projectile) against the predicted levels using Soloway and Dahl (2014), Arons (1954) and Weston (1960) is shown in Table 5.

Table 5 Modelled received levels compared to mean measured received levels at ranges of 1km, 5km and 10 km from the UXO low-order deflagration for a UXO of 20.7 kg.

Range (m)	$SPL_{(0\text{-}pk)}$ (dB re 1μPa)				$SEL_{(t90)}$ (dB re 1μPa²s)			
	Modelled	**Measured**			**Modelled**	**Measured**		
1000	216.5	200.1	±	1.57	200.1	173.45	±	1.57
5000	200.7	181.1	±	2.4	181.1	162.4	±	2.4
10000	193.9	171.5	±	1.62	171.5	155.2	±	1.62

This comparison is also shown for $SPL_{0\text{-}pk}$ (Figure 8) and unweighted SEL (Figure 9). The dotted and dashed lines represent the modelled received level along a transect from the source of a 15-inch naval projectile with a NEQ of 20.7kg and disposal tool charge of 250g, respectively, and the crosses (*x*) show the measured sound levels for each UXO clearance at the respective ranges from the UXO (1 km, 5 km and 10 km). The 15-inch naval projectile accounted for 74.2% of all the confirmed UXO targets encountered and the same disposal tool size (250 g) was used and therefore offered some degree of reproducibility.

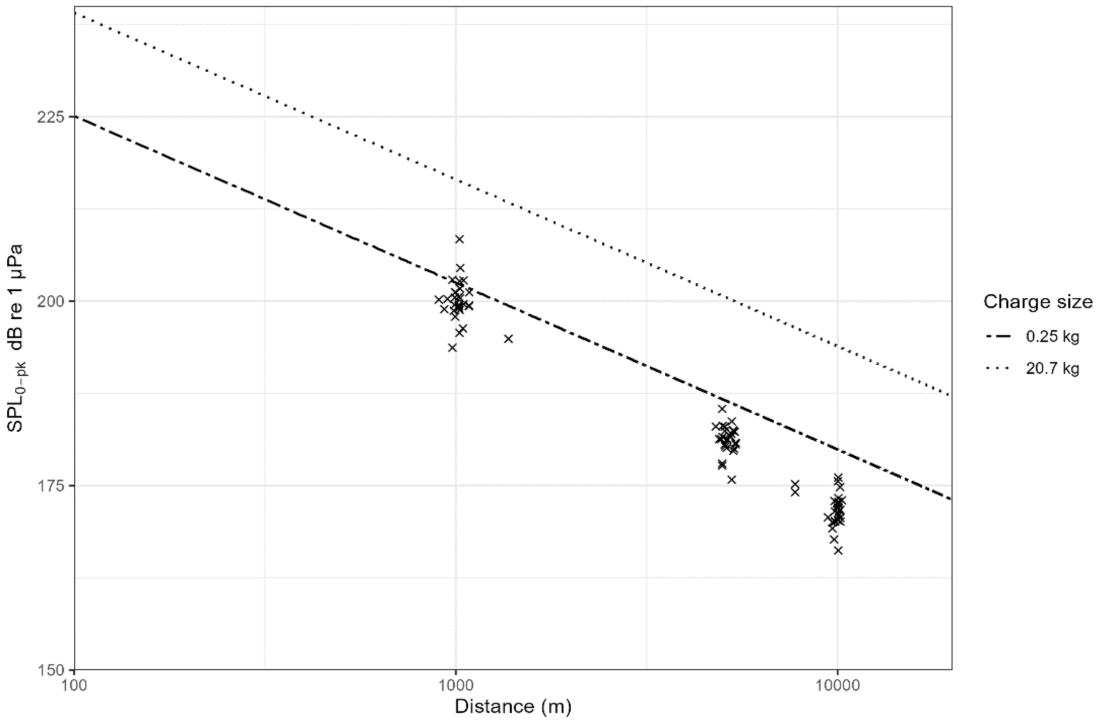

Figure 8 Comparison *of modelled received levels for 250 g disposal tool (—·—·—) and 20.7 kg (········) charges against measured received levels (SPL_{0-pk}) at 1 km, 5 km and 10 km for all UXO clearances in the campaign (x) which involved the low-order deflagration of a 15-inch naval projectile with a NEQ of 20.7 kg using a disposal tool charge of 250 g.*

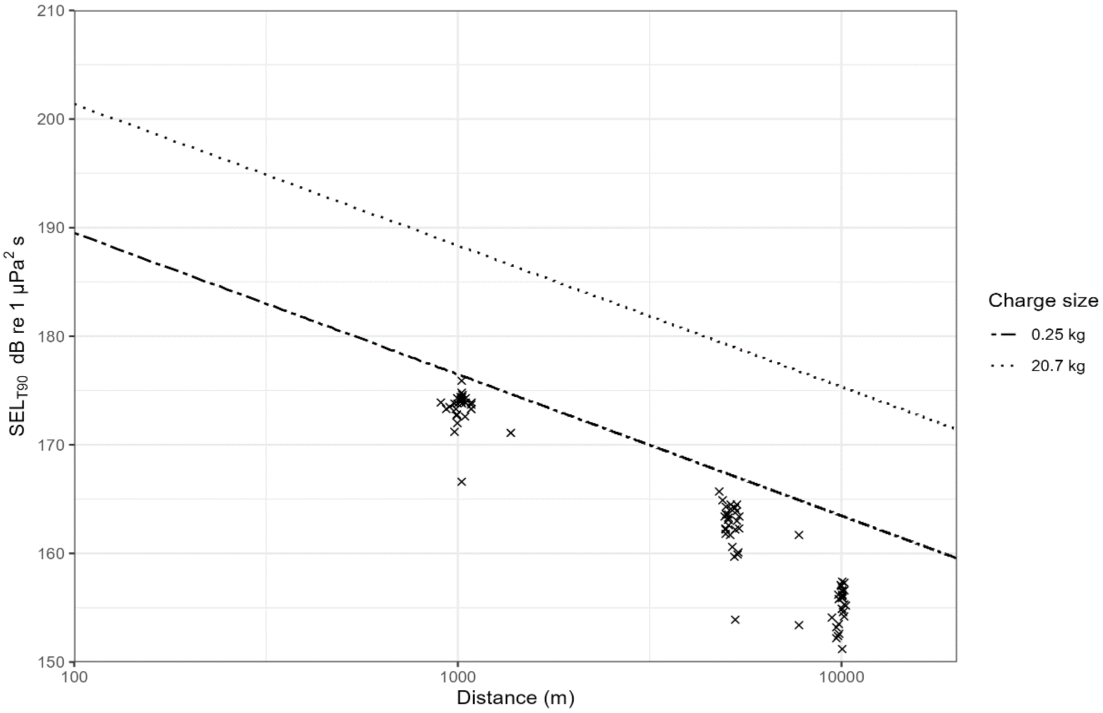

Figure 9 Comparison of modelled received levels for 250 g disposal tool (—·—·—) and 20.7 kg (········) charge against measured receive levels (unweighted SEL) at 1 km, 5 km and 10 km for all UXO clearances in the campaign (x) which involved the low-order deflagration of a 15-inch naval projectile with a NEQ of 20.7 kg using a disposal tool charge of 250 g.

These data show that measured $SPL_{0\text{-}pk}$ for each of the UXO clearance events were consistently below the expected received sound levels for the disposal tool charge of 250 g (Figure 8). This is likely to be partly because the acoustic model assumes the charge is in mid-water rather than at the seabed. Furthermore, this model does not consider the directionality of the shaped charge and the possibility that some energy may be dissipated or absorbed through interactions with the UXO and the seabed. Critically, Figures 8 and 9 also demonstrates that received sound levels were far below those expected for a high-order detonation of UXOs with a NEQ of 20.7 kg.

The largest UXO target, the 700 kg LMB mine, was successfully neutralised after four deflagration attempts using a 125 g disposal tool. Similarly to the 20.7 kg UXO targets, the measured levels (represented as "*x*") fell significantly below the modelled received levels (shown as dotted and dashed lines) for the clearance of a UXO target of this NEQ (Figure 10).

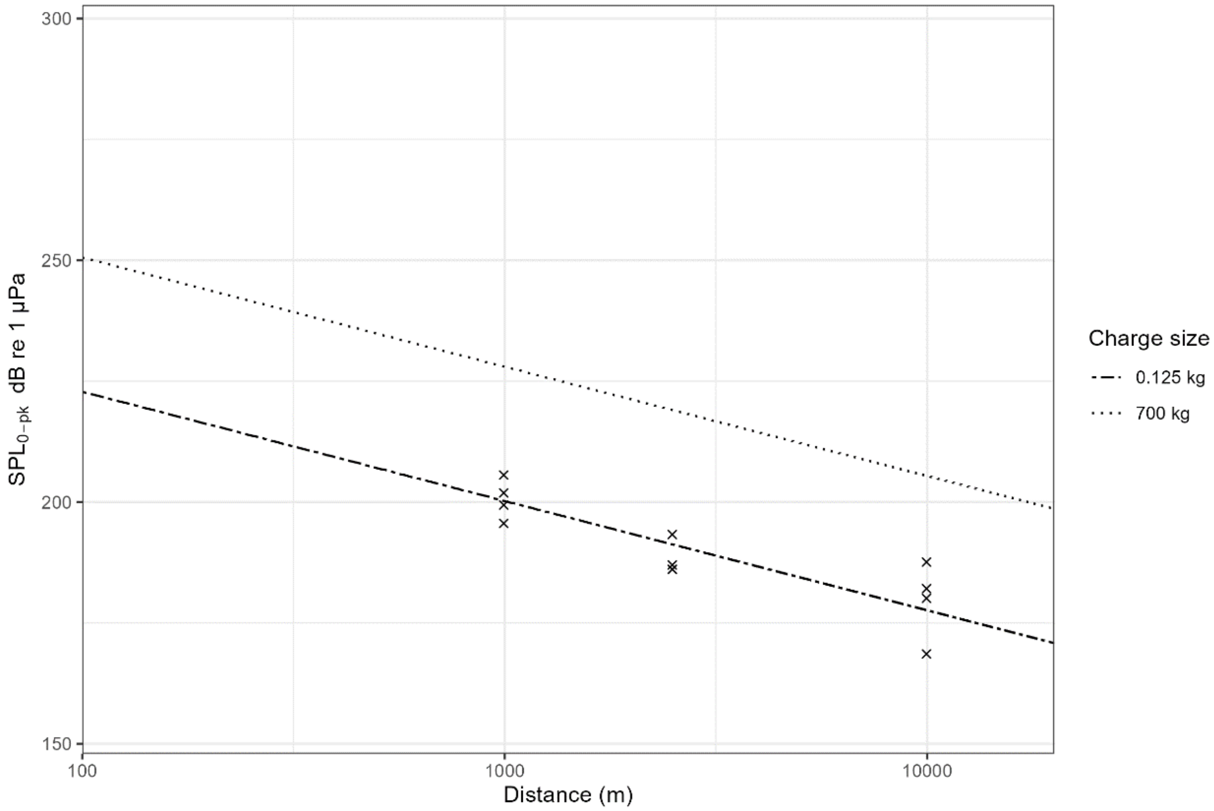

Figure 10 Comparison of modelled received levels for the disposal tool charge size of 125 g (–·–·–·) and 700 kg (·········) against measured received levels ($L_{0\text{-}pk}$) for all UXO clearance attempts for LMB mine (x), at 1 km, 5 km and 10 km.

It can therefore be concluded that none of these UXO targets underwent a high-order detonation during clearance events.

These sound measurements of $SPL_{0\text{-}pk}$ and marine mammal hearing weighted SEL can be compared with the Southall et al. (2019) PTS thresholds. The only PTS threshold exceeded was the unweighted peak sound pressure ($SPL_{0\text{-}pk}$) for very high frequency cetaceans (VHF), and this was only on seven occasions in recordings at 1 km from source. Although only approximate, sound measurements recorded along the transect (1 km, 5 km and 10 km) during the clearance of a 15-inch naval projectile where the highest sound level was measured ($L_{0\text{-}pk}$ of 208.4 dB re 1 µPa at 1 km) were used in a logarithmic regression to predict a maximum PTS impact range for VHF cetaceans, which was estimated to be 1.5 km. This is approximately 1 km lower than the modelled impact range for the smallest UXO with an NEQ of 6 kg. None of the Southall et al. (2019) marine mammal weighted SEL thresholds were exceeded at any measurement location, as predicted from acoustic modelling (Table 2). By way of comparison, acoustic modelling predicted PTS ranges of between 2.55 km and 14.25 km had the 6 kg and 700 kg UXO targets been cleared using high-order detonation.

The mitigation strategy for the UXO clearance campaign involved deploying an acoustic deterrent device (ADD) for 60 minutes prior to the low-order deflagration in order to displace marine mammals from the area around each of the 81 UXOs. Based on previous demonstrations of directional movements away from ADD (Graham et al. 2023), and an assumed swimming speed of 1.5 m/s (Otani et al, 2000), harbour porpoises in the area would be expected to reach a distance of at least 5.4 km from the source before deflagration. This is well beyond the distance at which measurements of received sound levels indicate a risk of PTS (Table 5), indicating that the mitigation measures agreed for this novel use of deflagration were conservative.

To reduce broader scale disturbance (eg. Thompson et al. 2020) or auditory damage (Findlay et al. 2021) that could result from excessive ADD use, the ADD deployment period was subsequently reduced from 60 to 23 minutes for the LMB mine clearance operations. Based on precautionary swimming speeds, a 23 minute ADD activation, harbour porpoises could move > 2.07 km away at 1.5m/s (Otani et al., 2000), dolphin species could move > 2.10 km away at 1.52m/s (Bailey and Thompson, 2006) and minke whale could move 3.17 km at 2.3m/s (Boisseau et al., 2021).

Table 6 Summary of measured received levels during low-order deflagration clearance of 30 UXO at each of the recording distances (1 km, 5 km and 10km). The table presents the maximum, minimum and mean SPL and frequency weighted SEL values from the deflagration attempts for each type of UXO acoustically monitored. The number of deflagration attempts presented in the table is higher than the number of UXO monitored as some UXO required more than a single deflagration attempt.

UXO type		15-inch Projectile			6-inch Projectile			10-inch Projectile			500lb Air dropped bomb			German Luftmine B (LMB) mine		
Number of UXO		23			2			2			2			1		
Number of deflagration attempts		31			3			3			3			4		
UXO NEQ (kg)		20.7			6			12			89			700		
Donnor charge size (kg)		0.25			0.2			0.2			0.25			0.15		
Measured Range (m)		1000	5000	10000	1000	5000	10000	1000	5000	10000	1000	5000	10000	1000	2500	10000
$L_{p,0-pk}$ (dB re 1 μPa)	Mean	198.1	183.5	171.6	200.9	180.8	170.5	201.4	183.9	174.6	201.0	180.4	173.7	200.6	188.1	179.6
	Min	172.0	175.8	166.2	198.9	180.6	168.8	199.6	180.3	172.7	200.2	176.7	166.5	195.6	186.1	168.6
	Max	208.4	201.7	176.1	203.3	181.1	171.8	203.5	189.1	176.7	201.8	183.1	178.5	205.6	193.3	187.6
SEL_{lf} (dB re 1 $\mu Pa^2 s$)	Mean	176.6	164.0	151.7	179.4	161.5	151.3	178.8	161.8	153.9	178.1	159.3	153.1	176.0	168.9	154.9
	Min	151.7	153.3	147.2	178.3	160.7	150.4	178.0	160.8	153.6	177.4	152.8	145.7	173.5	167.3	151.0
	Max	182.4	182.0	158.7	180.6	162.7	152.4	180.2	162.9	154.2	178.8	163.1	157.8	179.1	173.3	158.2
SEL_{hf} (dB re 1 $\mu Pa^2 s$)	Mean	160.8	144.5	137.4	163.3	140.7	139.5	162.5	140.8	142.6	161.2	143.4	146.3	158.6	150.3	131.9
	Min	139.5	139.8	126.0	160.8	139.8	139.5	162.2	140.4	142.4	159.5	140.4	142.6	154.1	148.3	119.7
	Max	167.7	161.4	139.8	165.6	142.2	139.6	162.9	141.5	142.8	162.8	148.8	150.9	162.7	156.2	139.4
SEL_{vhf} (dB re 1 $\mu Pa^2 s$)	Mean	158.2	142.5	137.4	160.6	139.0	140.0	159.8	139.1	140.7	158.4	141.9	145.0	155.5	146.7	127.7
	Min	139.9	138.4	125.5	158.2	138.4	140.0	159.4	138.7	140.5	157.1	138.6	140.7	151.6	144.8	114.4
	Max	164.2	158.8	140.1	162.8	140.2	140.0	160.2	139.6	140.9	159.7	148.0	150.3	159.2	151.9	136.3
SEL_{pcw} (dB re 1 $\mu Pa^2 s$)	Mean	170.7	155.1		173.8	151.8		173.1	152.2		172.0	151.5		163.7	156.1	138.3
	Min	140.3	148.2		171.8	150.5		172.4	151.3		170.5	148.6		158.4	153.5	127.0
	Max	178.1	172.8		176.1	153.9		174.0	153.4		173.4	153.1		168.4	162.6	145.0

3. Discussion

The Moray West case study demonstrates the successful use of low-order deflagration methodology to clear all types of UXO from the Moray West offshore wind farm development site whilst simultaneously reducing environmental impacts, including underwater noise and seabed disturbance. Seven types of UXO, with a wide range of NEQs from 6 kg to 700 kg (Table 1), were successfully cleared using low-order deflagration, including the complete removal of metal scrap from the marine environment. Although some UXOs required more than one deflagration attempt, none underwent high-order detonation during the EOD operations.

Low-order deflagration has previously been shown to produce lower levels of radiated sound in controlled experiments compared to high-order detonations (Robinson et al., 2020). This paper provides results from the first field-collected data set on noise monitoring undertaken during EOD operations of 31 of the 82 UXOs encountered at sea, demonstrating that low-order deflagration techniques reduced underwater noise, disturbance and the risk of injury to marine mammals during the clearance campaign at Moray West offshore wind farm.

Critically, these measurements highlight that noise produced by low-order deflagration clearance is governed by the disposal tool charge size, as opposed to the UXO explosive content (Figures 8, 9 and 10). This demonstrates that acoustic modelling, impact assessment, licencing and mitigation of future UXO clearance by low-order deflagration can be based on known (and small) disposal tool charge sizes, rather than less certain (and often large) estimates of the NEQ of UXO. This could have important implications, which we discuss below, for reducing the lead times required to manage the safe clearance of UXO prior to offshore wind farm construction. Furthermore, the disposal tool charges used during Moray West low-order deflagration clearance operations were significantly smaller than those used for high-order detonations. In turn, this reduces the level of additional noise (from ADD) that need to be introduced into the marine environment to displace protected species to mitigate the risk of injury.

More generally, the findings presented in this paper highlight how detailed and systematic noise monitoring when deploying novel techniques can support policy development. In future, it would be particularly valuable to identify opportunities where this understanding could be built upon by making measurements of alternative low-order disposal methodologies and tools, clearance of other sizes and types of UXO, and disposal operations in contrasting bathymetric conditions.

Implications for licencing & mitigation

Uncertainties over the required scale and timing of UXO clearance can be a significant risk to offshore wind farm project delivery, particularly where these activities must be tightly aligned to availability and procurement of specialised construction vessels. Although site-specific desk-based studies and geophysical surveys can reduce the risk from UXO to ALARP, a residual risk remains given unexpected UXOs may be encountered and identified during intrusive seabed activities, such as offshore wind farm construction, and operation and maintenance works. Where these UXOs cannot be avoided or safely recovered, they must be disposed of as rapidly as possible to ensure the safety of maritime personnel and offshore assets. However, developers are currently required to prepare new marine and EPS licence applications to dispose of any unexpectedly discovered UXO. As illustrated following discovery of the LMB mine in Moray West, the potential for UXOs to be encountered during construction activities following completion of a UXO clearance campaign can lead to significant delays in construction works and additional and complex marine licencing.

Concerns and uncertainties over the potential impacts of underwater noise on protected wildlife remain one of the key factors driving the time and resources required to licence UXO clearance operations. This case study provides data and understanding to reduce these uncertainties, creating opportunities to streamline assessments and licencing to improve environmental protection and reduce risks to delivery of renewables projects. For example, there has previously been a lack of evidence on the efficacy of low-order alternatives to high-order detonation of UXOs. Marine and EPS licence applications for UXO clearance have therefore had to consider precautionary worst-case scenarios (high-order detonation and largest UXO NEQs). This leads to conservative assumptions being built into impact assessments, resulting in highly precautionary impacts. In some cases, consent can depend upon mitigation measures that could themselves result in unintended environmental impacts, for example by using unnecessarily long deployments of ADD. As with management of other impulsive noise sources such as pile driving, this requires a careful balancing of risks from noise with the likely costs and benefits of different mitigation measures (see Thompson et al. 2020). These new data significantly reduce the conservatism required in future assessments of UXO disposal and should support the use of more proportionate mitigation. This is perhaps most clearly illustrated using the example of the 700 kg LMB mine, where current marine and EPS licencing would need to have considered potential auditory damage to marine mammals at distances up to 14.25 km (modelling predicted PTS ranges for the high-order detonation of 700 kg UXO target). Previously, mitigation for high-order clearance of a 295 kg UXO at Moray East Offshore Wind Farm had required a series of 50 g to 250 g scare charges to be deployed for 20-minutes prior to detonation of a 25 kg donor charge (Robinson et al. 2022). By contrast, we demonstrated that a 700 kg UXO could be neutralised using low-order techniques that required a disposal tool charge of 150 g; representing only one-third the cumulative size of scare charges previously used for mitigation. Measurements of this low-order disposal confirmed that the potential PTS impact range was reduced from 14.25 km to 1.5 km, resulting in an impact area that was around 1% of the original.

4. Recommendations

Building on this demonstration of the efficacy of the low-order deflagration and the evidence of significant reductions in environmental risks (such as underwater noise and seabed disturbance), we offer two recommendations that would streamline the licencing process for future UXO clearance through low-order deflagration and support the delivery of offshore renewables targets.

First, we propose that a faster-track licensing process be considered by regulators, where offshore developers commit to using only low-order deflagration methodologies to safely dispose of confirmed UXOs. To support this process, noise data collected in this study could be used to develop appropriate and proportionate mitigation measures, which meet pre-agreed criteria and embedded mitigation prior to and during low-order deflagration UXO clearance. Pre-agreed mitigation criteria when using low-order deflagration could also avoid the requirement for multiple licence applications, or variations for the same licensable activity.

Second, rather than specifying the maximum number and size of UXO on a licence, we suggest that regulators consider specifying the maximum number of low-order deflagration attempts that can be made using a specified disposal tool and size of donor charge, regardless of the number of UXOs and the UXOs NEQ.

In combination, these changes in the approach to licencing and clearance of UXO could reduce uncertainties in project timescales and prevent delays in consenting and delivery of renewables targets.

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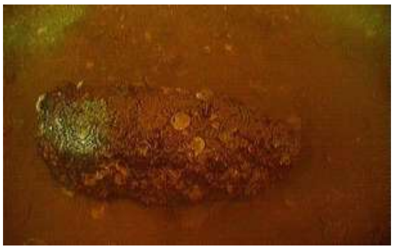
Appendix 1 UXOs encountered at Moray West Offshore Wind Farm Site

UXO Type	Ferrous mass	Net Explosive Quantity	Item/Example Before Deflagration	Post-Deflagration (Free of Explosives)
4.5" Projectile	25 kg	6 kg		
6" Artillery Projectile	39.4 kg	6 kg		
10" Projectile	126 kg	12 kg		
15" Projectile	879 kg	20.7 kg		

UXO Type	Ferrous mass	Net Explosive Quantity	Item/Example Before Deflagration	Post-Deflagration (Free of Explosives)
60" Anti Subma-rine Projectile	181 kg	94 kg		
Air dropped 500lb bomb	226 kg	89 kg		
Luftmine B (LMB)	14 kg	700 kg