



Underwater acoustic characterisation of unexploded ordnance disposal using deflagration



Stephen P. Robinson^{a,*}, Lian Wang^a, Sei-Him Cheong^a, Paul A. Lepper^b, Francesca Marubini^c, John P. Hartley^c

^a National Physical Laboratory, Hampton Road, Teddington TW11 0LW, UK

^b Loughborough University, Loughborough LE11 3TU, UK

^c Hartley Anderson Ltd, Aberdeen AB11 5BE, UK

ARTICLE INFO

Keywords:
UXO
Acoustic
Noise
Pollution
Deflagration

ABSTRACT

The seabed off North West Europe contains much unexploded ordnance (UXO), posing a hazard to offshore developments such as windfarms. The typical removal method is through high-order detonation of a donor charge placed adjacent to the UXO. This method poses a risk of injury or death to marine mammals and other fauna from the high sound levels produced. This paper describes a controlled field experiment to compare the sound produced by high-order detonations with a low-order disposal method called deflagration, which uses a shaped charge of modest size, is less energetic, and offers reduced environmental impact from lower acoustic output. The results demonstrate a substantial reduction over high order detonation, with the peak sound pressure level and sound exposure level being more than 20 dB lower for the deflagration, and with the acoustic output depending only on the size of the shaped charge (rather than the size of the UXO).

1. Introduction

Unexploded ordnance (UXO) litters the seafloors of European seas such as the North Sea, the Irish Sea and the Baltic, mainly as the result of past military conflicts, but also from military firing ranges, shipwrecks, and offshore munition disposal (Davies, 1996; Eitner and Tröster, 2018; Albright, 2012; Beddington and Kinloch, 2005). In some cases, the UXO can be avoided or safely removed. However, for some offshore developments, these pose a hazard and must be made safe.

In particular, the location and spatial scale of many offshore wind farm developments and cable connector projects means there is a high potential to encounter UXO during construction. This is particularly so where there is overlap with World War I and World War II conflict areas, military training areas and munitions disposal sites (Davies, 1996; Eitner and Tröster, 2018; Detloff et al., 2012). As part of development planning, detailed surveys are undertaken to identify possible UXO and confirm what action is needed to reduce health and safety risks to a tolerable level. When UXO cannot be avoided or safely removed, explosive ordnance disposal (EOD) is necessary. This typically involves detonation on site, and the favoured disposal method is to use a high-order detonation conducted by exploding a donor charge placed adjacent to the UXO munition (Albright, 2012; Aker et al., 2012; Sayle

et al., 2009; Cooper and Cooke, 2018).

These disposals produce acoustic pulses, which can make significant contributions to the soundscape over a wide area (Sertlek et al., 2019; Merchant et al., 2020), and can have a number of adverse environmental consequences, one of which is the risk to marine fauna from exposure to the high amplitude sound levels produced (von Benda-Beckmann et al., 2015; Yelverton et al., 1973; Dahl et al., 2020; Todd et al., 1996; Finneran et al., 2000; Ketten et al., 1993; Lewis, 1996; Danil and St. Leger, 2011; Brownlow et al., 2015; Sundermeyer et al., 2012; Parsons et al., 2000).

Impulsive sounds of very high-amplitude also presents challenges for effective mitigation for compliance with regulations, with potentially large exceedance areas for commonly-used exposure thresholds (Southall et al., 2019; NMFS, 2018; Finneran and Jenkins, 2012; Popper et al., 2014). Common mitigation strategies involve the use of spatial and temporal restrictions on the activity, passive acoustic monitoring, and the introduction of additional noise of lower amplitude to create an aversive reaction by use of Acoustic Deterrent Devices, and occasionally by use of small “scare” charges (JNCC, 2010; Merchant and Robinson, 2020). Noise abatement technologies have also been employed including the use of bubble curtains to attenuate the radiated sound (Merchant and Robinson, 2020; Loya and Arndt, 1948; Domenico,

* Corresponding author.

E-mail address: stephen.robinson@npl.co.uk (S.P. Robinson).

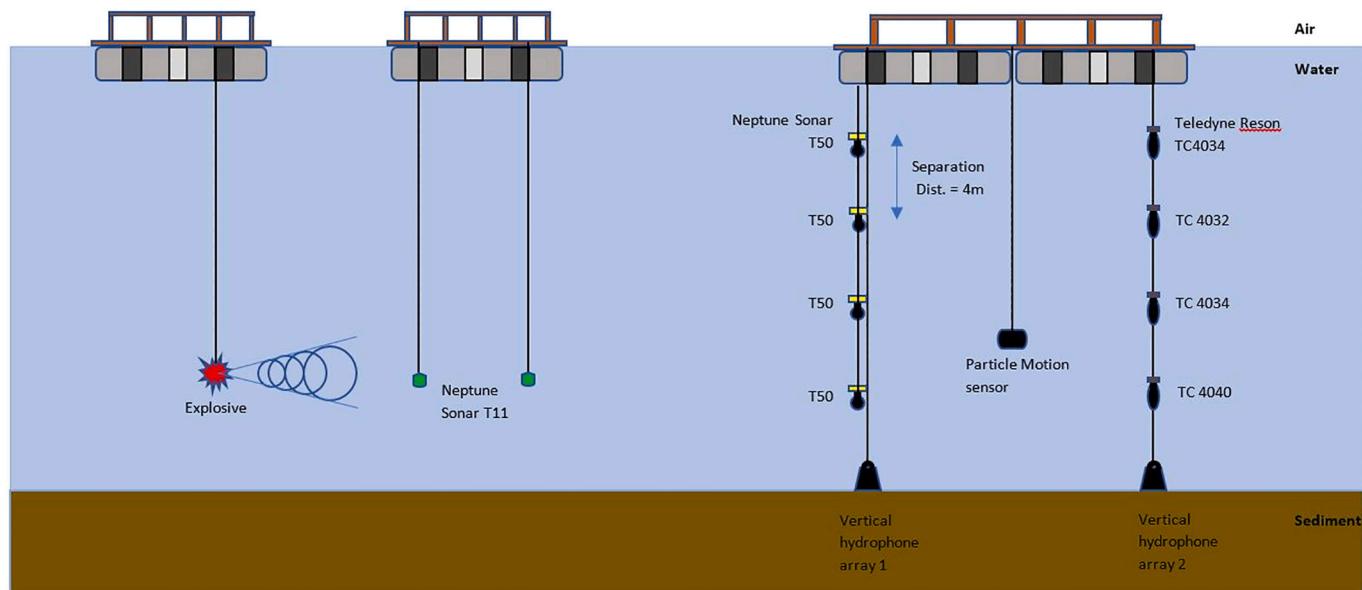


Fig. 1. Schematic diagram of the measurement configuration in the trial (distances shown are not to scale).

1982; Croci et al., 2014; Schmidtke, 2010; Schmidtke, 2012). In recent years, there has been a focus on alternative methods of disposing of UXO (Koschinski, 2011; Koschinski and Kock, 2009; Koschinski and Kock, 2015) including the use of low-order techniques such as deflagration, a method that until recently has been more commonly used for military EOD operations (Merchant and Robinson, 2020; ESTCP, 2002). Deflagration consists of a process where the UXO shell is penetrated by a shaped charge with insufficient shock to detonate, and with the explosive material inside the UXO reacting with a rapid burning rather than a chain reaction that would lead to a full explosion (ESTCP, 2002). Deflagration is a much less energetic process and anecdotal evidence has suggested that it is “quieter” than traditional high-order detonation, but until now no acoustic measurements have been reported to support this conclusion.

This paper describes experimental work to compare the characteristics of the sound produced by deflagration with that of a traditional high-order detonation method (Cheong et al., 2020). Underwater explosions as sources of sound have been the subject of considerable scientific study since the 1940s, both theoretically and experimentally (Cole, 1948; Arons, 1954, 1970; Weston, 1960), including characterisation of explosive sources in shallow water environments (Gaspin and Shuler, 1972; Gaspin et al., 1979; Chapman, 1985, 1988; Hannay and Chapman, 1999; Soloway and Dahl, 2014). In an explosion, the chemical chain-reaction occurs at supersonic speed producing a high-amplitude pressure pulse which propagates nonlinearily in the form of a shock-wave which reaches out to a range of about 10^5 times the charge radius (Cole, 1948; Weston, 1960). Beyond this range, the propagation may be considered linear and use can be made of conventional linear propagation models and metrics such as source level (ISO 18405, 2017).

In general, the sources in the previous studies have been suspended in the water column. The characterisation of UXO detonations presents additional difficulties because the condition of the ordnance itself can lead to a wide variation in the acoustic source level. The UXO will most likely be resting on the seabed and may be partially buried, and after perhaps 75 years in place may be substantially physically degraded (Cristaudo and Puleo, 2020). It is not possible to be certain of the effective charge size (and therefore the source level) for high-order detonations of UXO in real offshore environments because each individual UXO may be buried to a different degree on a different seabed type and with a different degree of physical degradation. This uncertainty makes

it difficult to draw definitive conclusions about measurements made on UXO disposals *in-situ*.

Since the aim to the work reported here is to compare the acoustic output from high-order detonations with low-order deflagration, it was decided to conduct an experiment in a controlled environment to facilitate a “like-for-like” comparison. To this end, a field experiment was carried out in a flooded quarry where the environmental conditions, the quality of the munition, and the positioning of the source and acoustic instrumentation could be controlled (Cheong et al., 2020).

The ordnance used for the experiment were specially-designed surrogate munitions such that each type used was identical (so variation through degradation was not an issue and the effective charge size would be known precisely), and the munitions were suspended at the same depth in the water column (so that proximity to the quarry floor was not an issue). Clearly, this experimental configuration is not similar to the situation in actual offshore EOD operations, but the simplifications allowed a true comparison to be made without extra uncertainties that exist in EOD operations offshore.

2. Experimental method

2.1. Measurement configuration

The measurement trial was undertaken in Limehillock Quarry, near Keith in the north of Scotland. The facility is used extensively for in-water shock testing of structures for offshore marine applications, and was operated by Thornton Tomasetti Defence Ltd. (www.thorntontomasetti.com), who provided the logistical support for the trial.

The quarry is approximately 250 m long by 125 m wide, is a little over 20 m deep on average, and is filled with fresh water. The bathymetry between the position of the explosive source and that of the furthest hydrophone was $20.1 \text{ m} \pm 1 \text{ m}$. During the trial, the water temperature was stable at 10.5°C for the shallowest 9 m of the water column, but the temperature declined to 6.1°C at the bottom.

The acoustic pulse from each explosive source was recorded at two measurement stations with sensors suspended from the water surface. These were: (i) close to the source (nominally 10 m and 20 m); and (ii) at a distance of 147 m (at the far end of the quarry). The configuration is illustrated in Fig. 1.

For the stations closer to the source, two types of underwater shock

transducers were employed: T11 transducers (manufactured by Neptune Sonar, nominal charge sensitivity: 0.07 pC/kPa; maximum pressure: 275 MPa) and 138A26 transducers (manufactured by PCB, nominal voltage sensitivity: 0.29 μ V/Pa; maximum pressure: 172 MPa). The shock transducers were powered by a PCB 482C05 four-channel unity-gain signal conditioner with additional PCB 422E06 charge amplifiers being used for the T11 transducers. A 16-channel Yokogawa DL750 data recorder was used for capturing the data. All data were sampled at 500 kilosamples per second giving a time base resolution of 2 μ s. The DL750 data acquisition system was triggered by a 'Charge Probe' which is fixed directly to the explosive and provided a voltage step at the time of detonation. The shock pressure sensors were suspended from floating pontoons and due to a slight re-positioning of the source between detonations, their separation distances varied between measurement sets. The distances were measured on the surface with a laser rangefinder (confirmed by the acoustic propagation delay) and ranged between 11.1 m and 12.9 m for the closer pair, and between 21.0 m 21.8 m for the other pair. All four sensors were deployed at 7 m water depth, the same depth chosen for all of the source charges.

For the measurements made at 147 m from the source, two four-element hydrophone arrays were deployed from a tethered floating pontoon. The first array consisted of four T50 hydrophones (manufactured by Neptune Sonar, with nominal sensitivity 28 μ V/Pa), and the second array was made up by four hydrophones manufactured by Teledyne Reson, consisting of 2 x TC4034 (9 μ V/Pa), a TC4040 (38 μ V/Pa), and a TC4032 (6 mV/Pa). Note that a number of insensitive hydrophones were used to measure the expected high amplitude pulses generated during the high-order detonations, but in addition hydrophones with a variety of sensitivities were used (including a highly sensitive TC4032) to cover the anticipated lower acoustic output from the deflagration. Except for the TC4032 (which has a built in pre-amplifier) the hydrophones were connected to high input impedance Teledyne Reson VP2000 amplifiers, and the acquisition was made using a PicoScope 4824 sampling at 1.25 mega-samples per second (time resolution of 0.8 μ s), and two National Instrument USB 6363 DAQ cards sampling at 250 kilo-samples per second (time resolution of 4 μ s). All the hydrophone data were recorded by two different digitisers simultaneously providing some redundancy in order to avoid data loss by unexpected system failure. The trigger output from the DL750 used for the shock sensors was routed via a 200 m co-axial cable to the data acquisition system on the pontoon at 147 m in order to provide a common trigger and time-base between all data sets.

All hydrophones were calibrated traceable to national standards in the laboratory before the trial using the methods described in IEC 60565 (IEC 60565, 2019; IEC 60565, 2020), by comparison in a closed coupler in the range 5 Hz to 315 Hz, and the free-field reciprocity method in the range 750 Hz to 20 kHz for all hydrophones, with two hydrophones calibrated at frequencies up to 200 kHz. Before and after deployment, the hydrophone sensitivities were checked at 250 Hz using a portable calibrated pistonphone (this enabled a full system sensitivity check as recordings were made on the acquisition systems of signals of known sound pressure level).

2.2. Preparation of explosive sources

The aim in the choice of munitions was to use identical examples for both high-order and for deflagration, and to use an explosive constrained within steel containers to simulate a real UXO.

For this purpose, a number of "surrogate shells" were fabricated which consisted of steel cylinders containing either 10 kg or 5 kg of plastic explosive. The cylinders were of approximate diameter 200 mm and length 600 mm and had end caps secured with external bolts. The explosive filler was a plastic explosive (PE4) which consisted of 88% RDX plastic explosive (Grade 1 A), 11% plasticiser and 1% penta-erythritol dioleate. PE4 is a common and relatively insensitive hand-mouldable general-purpose plastic explosive which may be used

underwater, and ignites at 218 °C. The design, manufacture and operation of all the explosives were undertaken by staff of Alford Technologies Ltd. (www.explosives.net).

For the high order tests, the surrogate shell was suspended from a float via 3 mm steel wires. The wires were measured to ensure that the charge was always at 7 m depth by taking into account how much of the float would be submerged under the weight of the charge and charge casing. For the deflagration tests, a large steel "catch-plate" was suspended in the water several metres beneath the charge to catch any unconsumed residue from the deflagration and prevent it from dropping to the quarry floor (and requiring retrieval after the test). The steel catch plate was suspended from a floating pontoon, with the charge float positioned in the centre of a moon-pool (an aperture in the pontoon which exposed the water surface). The catch plate was unnecessary for the high-order detonations where the explosive is consumed by the explosion with the products distributed throughout the water column.

A total of 17 charges were detonated during the trial. These consisted of four 10 kg shells and four 5 kg shells, with two of each size undergoing high-order detonation and two undergoing deflagration. Also, two other large charges were detonated by high-order: a 10 kg charge consisting of two 5 kg shells, and an 18.4 kg charge to dispose of explosive unused in the trial. In addition, detonations were carried out on a number of the shaped charges that were used in the deflagration process to determine the acoustic output of the shaped charges alone, and with the charge placed against a metal plate (the typical configuration when in use). The shaped charges were of size 15 g, 25 g, 48 g and 250 g, this latter being the largest size of charge used in deflagration. Fig. 2 shows a photograph of a 10 kg high order detonation.

2.3. The deflagration method

In general, ordnance is designed to be insensitive to mechanical and thermal impact, such as would occur from bullet or fragmentation impact. Thus, it is possible to penetrate UXO with a high velocity projectile and not cause any initial reaction. "Low-order" detonation tools or "disruptors" are designed to transmit enough reaction energy to the explosive charge so that the case ruptures, but not so much energy as to cause a full detonative chain reaction due to over-pressure. The definition of "low order" is "any explosive yield less than a full high-order" (Cooper, 1996; ESTCP, 2002). With insufficient shock to detonate, the explosive material may instead react with a rapid burn, and this process is termed deflagration (essentially, vigorous burning with the reaction occurring at sub-sonic speeds). In the EOD community, it is taken to mean any process whereby a cased munition is caused to burn internally before bursting open, but without complete detonation of the contents.

The tool used for the work described here was a VULCAN™ shaped charge designed by Sydney Alford and manufactured by Alford Technologies (Patent WO03/058155, 2003). The shaped charge detonates and punches a small hole through the case of UXO, igniting and consuming the explosive fill which generates gas from the decomposition of the explosive. The accumulation of this gas causes the pressure to rise rapidly causing the UXO case to burst at the weakest point before a full detonation can occur, without instigating a high-order detonation. In contrast to the more commonly-used copper armour piercing shaped charge, when used for low order techniques the VULCAN™ is fitted with a low-density incendiary projectile which forms a plasma jet which ignites as it forms. This provides a simple and reliable means of bringing about relatively gentle deflagration of small and large steel cased munitions with only a low probability of causing detonation.

Fig. 3 shows a photograph of a 10 kg surrogate shell showing the 25 g shaped charge used to initiate deflagration in position on the end cap. Also shown is a photograph of the shell after deflagration, showing that the central portion of the explosive had been consumed by the deflagration process, with residual explosive left around to outer rim



Fig. 2. A 10 kg high-order detonation at the quarry site (courtesy of Thornton Tomasetti Defence Ltd).

(or escaping through the punctured casing).

For the high-order detonations of the shells, an explosive detonator was placed into the shell to initiate a high-order detonation directly. This ensured a full high-order detonation of shell contents so that a like-for-like comparison could be made, one of the objectives of this controlled study. If the experiment described here were attempted with as part of EOD operations at sea, the effective charge size would not always be known exactly because the donor charge may not detonate all of the munition.

3. Results and discussion

3.1. Measurement results

The recorded data for the acoustic pulses were analysed and two acoustic metrics were calculated: peak sound pressure in MPa (and its level in dB re 1 μ Pa); and the sound exposure level or SEL in dB re 1 μ Pa 2 s. The focus was on these metrics because they are key to the calculation of exposure for marine fauna (Southall et al., 2019; NMFS, 2018; Popper et al., 2014). The definitions of these terms were adopted

from ISO 18405 (ISO 18405, 2017), with the calculations on the acoustic pulse following the procedure described in NPL GPG133 (Robinson et al., 2014) and ISO 18406 (18406, 2017).

An example of the recorded time waveforms from the shock pressure sensors at 11 m is shown in Fig. 4 for a high-order detonation of a 10 kg charge and a 10 kg deflagration. The upper plot shows a one second time window, which is sufficient to see the first and second bubble pulses caused by the explosion (generated as the bubble repeatedly expands and then collapses). The lower plot shows an expanded view of 15 ms around the shock peaks. The shock wave for the high-order detonation exhibits a very short rise time with a peak pressure of around 9 MPa (a peak sound pressure level of 259 dB re 1 μ Pa) whereas for the deflagration, the peak pressure is around 0.7 MPa. The exponential decay of the waveforms is interrupted by the surface reflection, after which some cavitation is evident (bubble formation caused when the shock wave reaches the water surface). The bottom reflection is also observed arriving at around 14 ms.

Fig. 5 shows the sound pressure power spectral density calculated from a waveform record length of 1 s for a high order detonation of a 5 kg charge measured at distances of 11 m and 21 m. Each plot shows



Fig. 3. Left: a photograph of a 10 kg shell showing the 25 g shaped charge used to initiate deflagration. Right: a photograph of the shell and contents after deflagration (white and grey matter around inner edge of shell).

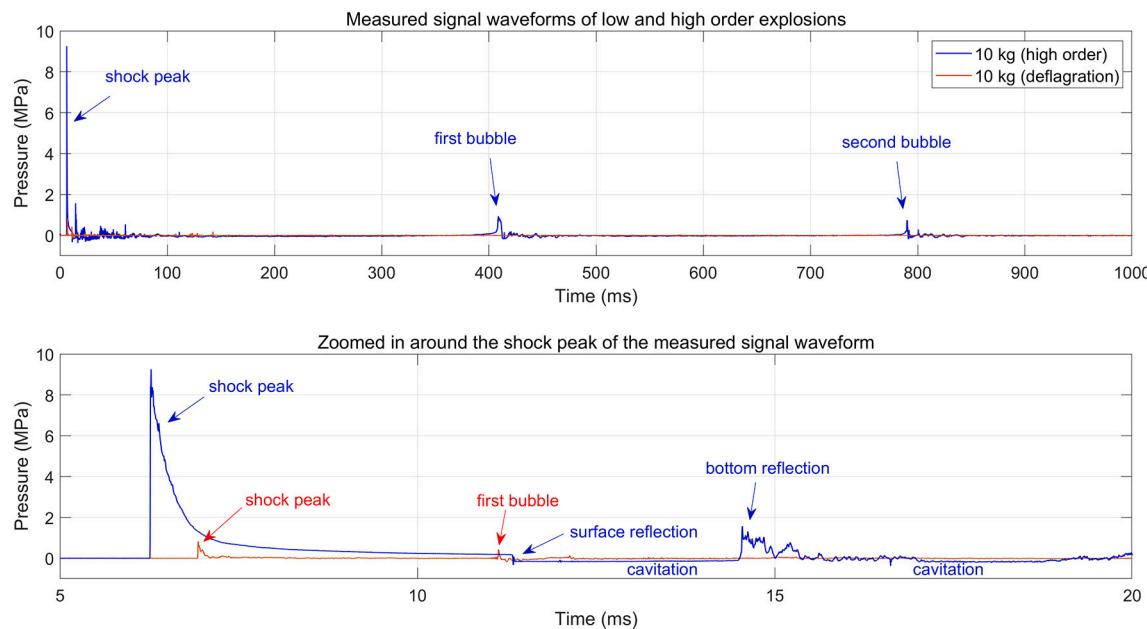


Fig. 4. Recorded waveforms at 11 m from a 10 kg high-order detonation and a 10 kg deflagration showing the various phases of the signals including the initial shock wave, the bubble pulses, and reflections from surface and bottom.

the spectra at each of the shock pressure transducers (two at each distance). Also shown are the spectra predicted by the model of Weston (Weston, 1960) for the equivalent charge size. Ignoring the frequency domain interference due to reflected signals, the overall measured levels are close to those predicted by the model. The higher levels observed at frequencies above 10 kHz are due to cavitation close to the water surface caused by the shock wave.

The empirical models of Arons, Cole and Weston predict the peak pressure in the initial positive-going shock wave as a function of scaled range as follows (Cole, 1948; Arons, 1954; Weston, 1960):

$$p_{\text{pk}} = K_p \left(\frac{R}{W^{1/3}} \right)^\alpha \quad (1)$$

where p_{pk} is the peak pressure in Pa, R is the measurement range in metres, W is the charge weight in kilograms of equivalent TNT, and K_p

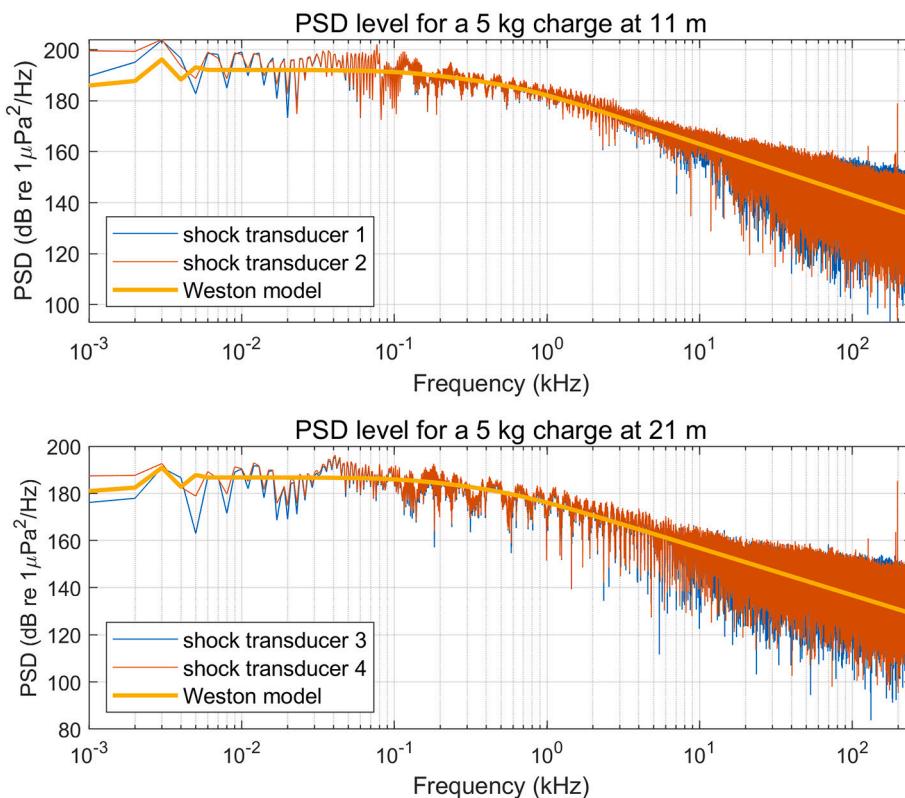


Fig. 5. The sound pressure power spectral density for a high order detonation of a 5 kg charge at measured at 11 m and 21 m, showing the measurements made by each of the four shock transducers and the predictions of the model by Weston.

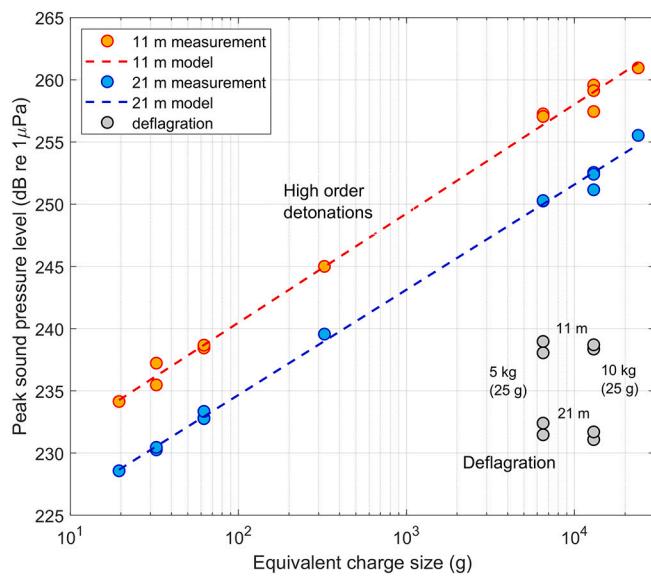


Fig. 6. The peak sound pressure level at distances of 11 m and 21 m plotted against charge size for all the detonations. The dotted lines show the prediction from the model of Eq. (1). The results of the deflagration are shown on the bottom right of the plot.

and α are the shock and pressure coefficients, which are determined empirically (different authors report slightly different values for these constants). This equation was developed for TNT due to its historical use as a benchmark for energy from high explosives (a spherical TNT charge of density 1520 kg/m³ is assumed). For other forms of explosive, the peak pressure can be predicted through use of explosive-dependent coefficients that are used to scale W to give a TNT-equivalent weight. A value of 1.3 has been used as the coefficient for the PE4 explosive used in this study (value obtained from Alford Technologies). Although originally formulated for spherical charges, the equation has been successfully employed for non-spherical charge geometries (Gaspin et al., 1979; Chapman, 1985).

A key finding from the study is illustrated by Fig. 6 which shows the peak sound pressure levels at distances of 11 m and 21 m plotted against charge size for all the detonations. The high-order detonations are clustered to the upper right of the plot, with the results of the shaped charges toward the bottom left (with lower charge sizes). The dotted lines represent fits to the data using the model of Eq. (1) which demonstrates that an empirical model of this type can be used to predict the peak sound pressure levels for all the charge sizes used. The model fit was undertaken using a two-parameter least-squares fit solving for values of the coefficients, with values of α equal to -1.31 and -1.27 for the 11 m and 21 m data respectively (obtained with RMS decibel errors of 0.73 dB and 0.55 dB, and goodness of fit (r^2) estimates of 0.996 and 0.998).

The results of the measurements of charges where deflagration was used are shown on the bottom right of the plot in grey symbols. This clearly shows a much lower level than for the high-order detonations for the same charge size, with a > 20 dB reduction in level (a factor of 10 reduction in peak sound pressure). For the 5 kg charge, a reduction in peak sound pressure levels of 20 dB and 21 dB are observed at 11 m and 21 m respectively.

The results obtained for the shaped charges of varying sizes show that the levels obtained for the deflagrations are very close to those for the equivalent size of shaped charges when detonated alone (either free or against a metal plate (an end cap from a surrogate munition).

Fig. 7 shows the peak sound pressure level for all the measured charges from 11 m to 147 m plotted against scaled range ($R/W^{1/3}$), which is the range divided by the cube root of the effective charge size. When plotted in this form, the data should follow an approximate

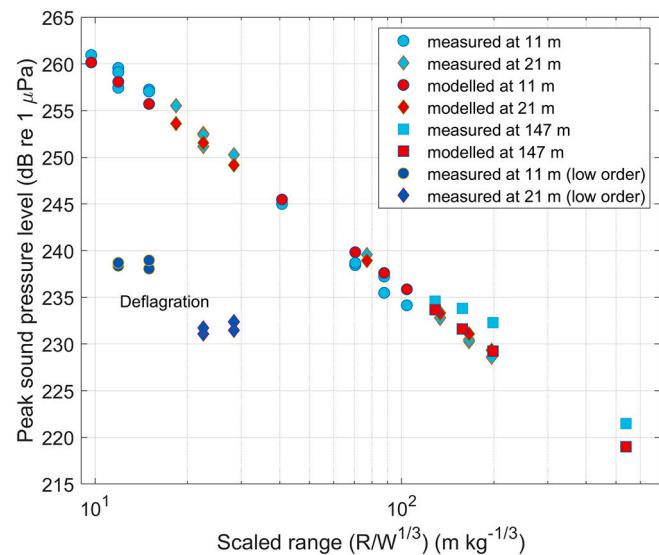


Fig. 7. Peak sound pressure level for all the measured charges plotted against scaled range from 11 m to 147 m, showing the measured data (blue) and predicted values (red). Again, the data for the deflagration (bottom left of the plot) is shown to be more than 20 dB lower. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

straight line with a negative gradient. The plots shows the measured and predicted values from the model of Cole and Arons (Cole, 1948; Arons, 1954), and that the measured data for all high-order detonations is close to the modelled values but is consistently slightly lower level. However, the peak sound pressure levels measured for low-order deflagrations (bottom left of the figure) are much reduced (by more than 20 dB).

The SEL, a metric commonly used in exposure calculations for marine fauna, is also substantially reduced when using deflagration. Fig. 8 shows the SEL at nominal distances of both 11 m and 21 m calculated for a one second integration time plotted against charge size for all the detonations. The results of the measurements of charges where deflagration was used are shown on the bottom right of the plot.

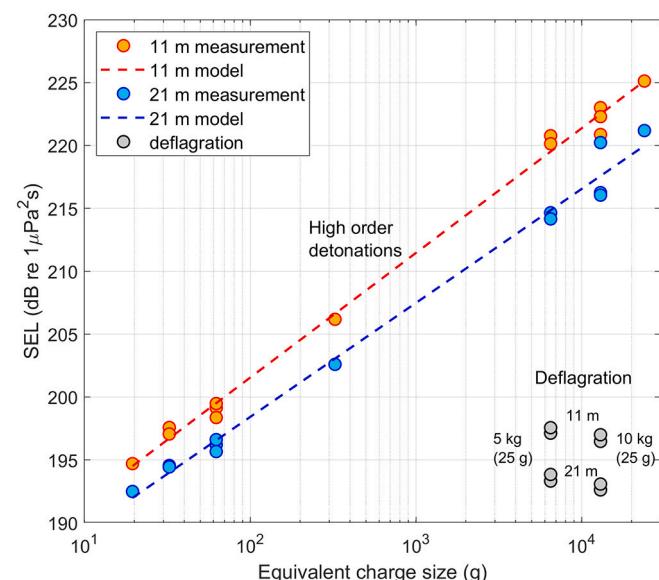


Fig. 8. The SEL at a nominal distances of 11 m and 21 m plotted against charge size for all the detonations. The low-order deflagration data appear in the bottom right of the plot.

The data clearly show a much lower level than for the high-order detonations for the same charge size, with more than 20 dB reduction in SEL observed, equivalent to a factor of more than 100 in acoustic energy (for the 5 kg charge, a reduction in SEL of 23 dB and 21 dB are observed at 11 m and 21 m respectively, whereas for the 10 kg charge size, a reduction in SEL of 24 dB and 23 dB are observed at 11 m and 21 m respectively).

The empirical models established by Arons, Cole, and Weston (Cole, 1948; Arons, 1954; Weston, 1960) may also be used to predict the sound exposure as a function of scaled range as follows:

$$E = K_E W^{\frac{1}{3}} \left(\frac{W^{\frac{1}{3}}}{R} \right)^{\beta} \quad (2)$$

where E is the sound exposure in Pa^2s , and W and R have the same meanings as for Eq. (1), and K_E and β are again determined empirically.

The dotted lines show the fit of the model which shows a different value of shock coefficient, β , for 11 m (a value of 1.49) than for 21 m (where the value is 1.36).

3.2. Discussion

The results of this study show that low-order deflagration offers a much lower amplitude of peak sound pressure than high-order detonations (by a factor of just over 10 in our trials). The peak sound pressure during deflagration appears to be due only to the size of the shaped charge used to initiate deflagration. This was in accord with the visual impression during the trial where the high-order detonations of a 10 kg shell caused a large airborne plume of water (see Fig. 2), whereas the deflagration of the same size shell barely disturbed the surface of the water. One difference between the high-order detonations and the deflagration was the presence of the catch-plate for the deflagration. Since the levels measured for the deflagration were very similar to those of the shaped charges alone (with or without placement against a metal plate), it may be concluded that the catch plate did not significantly influence the radiated sound levels (though a small effect cannot be discounted).

Since the peak sound pressure levels scale with charge size (in agreement with existing model formulations), this enables the acoustic output to be predicted for deflagration as long as the size of the shaped charge is known. In addition, since the maximum size of shaped charge used for UXO deflagration is of the order of 250 g, much greater reduction factors are feasible for very large UXO sizes (which can range up to several hundred kilograms). A reduction in peak sound pressure level from EOD operations is highly desirable for mitigation to reduce the source level from the UXO detonation, and to reduce the radius of impact zones over which the Permanent Threshold Shift and Temporary Threshold Shift thresholds are exceeded for exposure in the framework currently adopted by many regulators (Southall et al., 2019; NMFS, 2018).

The calculation of SEL is more challenging than the peak sound pressure level in the enclosed quarry because there are reflections from boundaries which arrive during the longer integration time used (one second). Estimating the peak sound pressure close to the source is not influenced by this because the shock front arrives first and any time window used to isolate it is very short. The time for the SEL calculation was kept long to include two pulses due to the gas bubbles produced by each explosion, and this inevitably includes reflections, for example from the water surface, and quarry bottom and side walls. This problem is likely to be worse for the measurements at greater distance from the source, and this is likely to contribute to the slightly poorer agreement with the model at 21 m compared to 11 m, and the different value of shock coefficient obtained. The slightly higher SEL for smaller charges (15 g, 25 g and 48 g) between the 11 m and 21 m giving rise to the differing fitted gradients is likely to be due to two factors. Firstly, the bottom reflection loss is reduced for 21 m, and secondly, the relative

contribution of surface reflection and cavitation effect will differ for the two ranges. The SEL at 11 m is dominated by the initial shock wave pulse, with much smaller contribution from the cavitation, but the shock wave is much lower at 21 m, while the contribution from cavitation remains similar to that of at 11 m, hence giving a higher relative cavitation contribution to the SEL at 21 m.

The values of the shock coefficient calculated for the fitted models here differ slightly from the empirical fits reported in previous work where, for example, values of between -1.1 and -1.2 are typical for the value of α in Eq. (1) (Cole, 1948; Arons, 1954; Weston, 1960). This could be caused by a number of factors such as the experiment was conducted in fresh water rather than sea water (where properties such as absorption, sound speed and density are different), and because much of the previous work used direct detonation of spherical charges (whereas we are using a cylindrical shell to simulate a UXO). For the SEL calculation, the lack of an acoustic free-field due to the presence of reflected signals also influenced the SEL results (tending to cause an overestimate).

Using the Weston model (as plotted in Fig. 7) it is possible to calculate either the peak sound pressure level or the SEL at any range within the "nonlinear" region where the shock wave propagates. Values for the two metrics for charge sizes where more than one example of high-order detonation was measured are shown in Table 1 for a nominal distance of 1 m. Note that these do not represent source levels (for example, as defined in ISO 18405) which are defined in the far field for a linear monopole source.

Calculation of energy source levels is more problematic in the presence of reflected signals making these estimates somewhat less reliable. The values for the deflagration will be lower by the same 20 dB factor noted for the received peak sound pressure levels.

From a consideration of the acoustic output alone, this study has shown low-order deflagration to be an effective mitigation measure. However, other aspects need also consideration. For example, a feature of the deflagration method is that not all the explosive is consumed during the process. In this trial, for the two 10 kg charges that underwent deflagration, the weight of explosive consumed was 4.7 kg and 5.9 kg respectively, and for the two 5 kg charges it was 2.9 kg and 2.6 kg. A UXO will typically burst or break open under the action of deflagration. It is undesirable to leave the explosive residue on the seabed because, while the risk of explosion has been removed, toxic chemicals may leak into the environment, an established risk with UXO degradation where toxins have been shown to accumulate in shell fish (Strehse et al., 2017; Appel et al., 2018; Maser and Strehse, 2020). The remnants need to be collected, e.g. by ROV, as part of the complete EOD operation, including any small particulate matter. In the case of deflagration, the remnants are expected to be within close proximity to the UXO (within a few metres), which is why the use of the catch plate in the quarry was sufficient to capture the residue. However, the potential for chemical contamination from residues remains to be assessed.

Compared to high-order detonations, deflagration also offers the potential for reduced seabed destruction. The logistics, procedures, and costs are likely to be similar to those routinely used for high-order

Table 1

Estimates of peak sound pressure level and SEL for five charges for a nominal one metre range. Note that these do not represent linear monopole source levels.

Charge size (g)	Equivalent charge size (g, TNT)	Peak sound pressure level (dB re 1 μPa)	SEL (dB re 1 $\mu\text{Pa}^2\text{s}$)
25	32.5	262	218
48	62.4	265	221
250	325	270	228
5000	6500	280	242
10,000	13,000	283	245

operations (with ROVs used for charge placement and/or residue collection). However, the techniques are not yet familiar within the civil offshore EOD community, regulators or developers and there is a need for a transfer of expertise, and technology to the wider community, and to transfer knowledge about the balance of risks to regulators and developers. There is a greater need to identify type of munition to ensure the success of deflagration, and not all UXO may be suitable candidates for the technique (for example, where degradation is too severe for identification). However, the technique is ready for trial in offshore EOD operations. The results of this study demonstrate a reduction in acoustic output when using the technique, enable predictions to be made of the likely acoustic output in the field, and will inform the choice of UXO disposal method (in balance with other considerations).

4. Conclusions

In this work, a controlled field experiment has been carried out to quantify the difference in acoustic output levels from two EOD methods. Results demonstrate that the deflagration method offers a substantial reduction in acoustic output over traditional high-order methods, with the peak sound pressure level and sound exposure level observed being typically more than 20 dB lower for the deflagration of the same sized munition (a reduction factor of just over 10 in peak sound pressure, and 100 in acoustic energy), and with the acoustic output depending on the size of the shaped charge (rather than the size of the UXO itself). Fits to semi-empirical equations for peak pressure and SEL, developed by earlier researchers, are shown to be consistent with these new results, enabling the prediction of the acoustic output levels from a variety of sizes of shaped charges. Compared to high-order methods, deflagration offers the potential for greatly reduced acoustic noise exposure of marine fauna and reduced destruction of the seabed. Offshore trials of the method will enable assessment to be made of the operational efficacy and the potential for any residual chemical contamination.

CRediT authorship contribution statement

Stephen P. Robinson: Conceptualization, Methodology, Investigation, Writing - original draft. **Lian Wang:** Formal analysis, Investigation, Methodology. **Sei-Him Cheong:** Software, Investigation, Methodology. **Paul A. Lepper:** Conceptualization, Methodology, Investigation, Writing - review & editing. **Francesca Marubini:** Conceptualization, Writing - review & editing. **John P. Hartley:** Conceptualization, Writing - review & editing, Project administration.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

This project was funded by the UK's Department for Business, Energy and Industrial Strategy, UK Government's Offshore Strategic Environmental Assessment programme (contract OESEA-19-107). The authors would like to acknowledge the contributions of the staff of Thornton Tomasetti during the controlled experiment (particularly Nick Misselbrook and Shaun Butcher), and of Alford Technologies for the design of the surrogate munitions and conducting the explosives operations, particularly Andy Carss.

References

Aker, J., Howard, B., Reid, M., 2012. Risk management for unexploded ordnance (UXO) in the marine environment. *Dalhousie Journal of Interdisciplinary Management* 8 <https://doi.org/10.5931/djim.v8i2.366>. Available from: djim.management.dal.ca.

Albright, R.D., 2012. Cleanup of chemical and explosive munitions. In: Chapter 6 -Location, Identification and Environmental Remediation, Second edition. Elsevier, pp. 71–98. <https://doi.org/10.1016/B978-1-4377-3477-5.00006-4>. ISBN: 9781437734775.

Appel, D., Strehse, J.S., Martin, H.-J., Maser, E., 2018. Bioaccumulation of 2,4,6-trinitrotoluene (TNT) and its metabolites leaking from corroded munition in transplanted blue mussels (*M. edulis*). *Mar. Pollut. Bull.* 135, 1072–1078.

Arons, A.B., 1954. Underwater explosion shock wave parameters at large distances from the charge. *J. Acoust. Soc. Am.* 26, 343–346.

Arons, A.B., 1970. Evolution of explosion pressure-wave characteristics in the region relatively close to origin. *J. Acoust. Soc. Am.* 47, 91.

Beddington, J., Kinloch, A.J., 2005. *Munitions Dumped at Sea: A Literature Review*. Imperial College Consultants, London.

Brownlow, A., Baily, J., Dagleish, M., Deaville, R., Foster, G., Jensen, S.-K., Krupp, E., Law, R., Penrose, R., Perkins, M., Read, F., Jepson, P., 2015. Investigation into the long-finned pilot whale mass stranding event, Kyle of Durness, 2011. In: *Report AC22/Inf.4.6.f, 22nd ASCOBANS Advisory Committee Meeting*, The Hague, Netherlands, 29 September - 1 October 2015, Available from. https://www.ascobans.org/sites/default/files/document/AC22_Inf_4.6.f.KyleOfDurness_MSE.pdf.

Chapman, N.R., 1985. Measurement of the waveform parameters of shallow explosive charges. *J. Acoust. Soc. Am.* 78, 672–681.

Chapman, N.R., 1988. Source levels of shallow explosive charges. *J. Acoust. Soc. Am.* 84, 697–702.

Cheong, S.-H., Wang, L., Lepper, P.A., Robinson, S.P., 2020. Characterisation of acoustic fields generated by UXO removal, phase 2. In: Offshore Energy SEA Sub-Contract OESEA-19-107, NPL Report AC 19, June. Available from. https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/893773/NPL_2020_-Characterisation_of_Acoustic_Fields_Generated_by_UXO_Removal.pdf.

Cole, R.H., 1948. Underwater Explosions. Princeton University Press, Princeton, NJ.

Cooper, P.W., 1996. Explosives Engineering. Wiley-VCH (ISBN 0-471-18636-8).

Cooper, N., Cooke, S., 2018. Considerations for dealing with unexploded ordnance on maritime engineering projects. *Proceedings of the Institution of Civil Engineers - Maritime Engineering* 171 (3), 121–131 (ISSN 1741-7597 | E-ISSN 1751-7737).

Cristaudo, D., Puleo, J.A., 2020. Observation of munitions migration and burial in the swash and breaker zones. *Ocean Eng.* 205. <https://doi.org/10.1016/j.oceaneng.2020.107322>.

Croci, K., Arrigoni, M., Boyce, P., Gabillet, C., Grandjean, H., 2014. Mitigation of underwater explosion effects by bubble curtains: experiments and modelling. In: *23rd MABS (Military Aspects of Blast and Shock)*, Oxford, UK, Sep 2014, United Kingdom, 14p. <https://hal.archives-ouvertes.fr/hal-01071652>.

Dahl, P.H., Jenkins, A.K., Casper, B., Kotecki, S.E., Bowman, V., Boerger, C., Dall'Osto, D.R., Babina, M.A., Popper, A.N., 2020. Physical effects of sound exposure from underwater explosions on Pacific sardines (*Sardinops sagax*). *J. Acoust. Soc. Am.* 147 (4), 2383–2395.

Danil, K., St. Leger, J.A., 2011. Seabird and dolphin mortality associated with underwater detonation exercises. *Mar. Technol. Soc. J.* 45, 89–95. <https://doi.org/10.4031/mtsj.45.6.5>.

Davies, G., 1996. Munitions dump explodes into headlines again. *Mar. Pollut. Bull.* 32 (3), 250–251.

Detloff, K., Ludwichowski, I., Deimer, P., Schütte, H.-J., Karlowski, U., Koschinski, S., 2012. Environmental nongovernmental organizations' perspective on underwater munitions. *Mar. Technol. Soc. J.* 46 (1), 11–16.

Domenico, S.N., 1982. Acoustic wave propagation in air-bubble curtains in water—part I: history and theory. *GEOPHYSICS* 47, 345–353. <https://doi.org/10.1190/1.1441340>.

Ettrier, J., Tröster, S., 2018. Hazardous contaminated sites in the North and the Baltic Sea. In: Research News RN08. Fraunhofer Institute for Chemical Technology, Munich Available from. www.Fraunhofer.de.

ESTCP, 2002. Report UX-0104, Low-Order Underwater Detonation. Environmental Security Technology Certification Program, U.S. Department of Defense Available from. www.serdp-estcp.org/download/file/MM-0104.

Finneran, J.J., Jenkins, A.K., 2012. Criteria and Thresholds for U.S. Navy Acoustic and Explosive Effects Analysis. SSC Pacific, San Diego, CA. <https://doi.org/10.21236/ADA561707>.

Finneran, J.J., Schlundt, C.E., Carder, D.A., Clark, J.A., Young, J.A., Gaspin, J.B., 2000. Auditory and behavioral responses of bottlenose dolphins (*Tursiops truncatus*) and white whales (*Delphinapterus leucas*) to impulsive sounds resembling distant signatures of underwater explosions. *J. Acoust. Soc. Am.* 108, 417–431.

Gaspin, J.B., Shuler, V.K., 1972. Source levels of shallow underwater explosions. *J. Acoust. Soc. Am.* 51, 1202. <https://doi.org/10.1121/1.1912961>.

Gaspin, J.B., Goertner, J.A., Blatstein, I.M., 1979. The determination of acoustic source levels for shallow underwater explosions. *J. Acoust. Soc. Am.* 66, 1453–1462.

Hannay, B., Chapman, N.R., 1999. Source levels for shallow underwater sound charges. *J. Acoust. Soc. Am.* 105 (1), 260–263.

IEC 60565-1, 2020. Underwater Acoustics – Hydrophones – Calibration of Hydrophones – Part 1: Procedures for Free-field Calibration of Hydrophones. International Electrotechnical Commission, Geneva, Switzerland.

IEC 60565-2, 2019. Underwater Acoustics – Hydrophones – Calibration of Hydrophones – Part 2: Procedures for Low Frequency Pressure Calibration. International Electrotechnical Commission, Geneva, Switzerland.

ISO 18405, 2017. Underwater Acoustics – Terminology. ISO (the International Organization for Standardization), Switzerland (2017).

ISO 18406, 2017. Underwater Acoustics – Measurement of Radiated Underwater Sound from Percussive Pile Driving. ISO (the International Organization for Standardization), Switzerland (2017).

JNCC, 2010. JNCC Guidelines for Minimising the Risk of Injury to Marine Mammals From

Using Explosives (August 2010). Available. www.jncc.gov.uk.

Ketten, D.R., Lien, J., Todd, S., 1993. Blast injury in humpback whale ears: evidence and implications. *J. Acoust. Soc. Am.* 94, 1849–1850. <https://doi.org/10.1121/1.407688>.

Koschinski, S., 2011. Underwater noise pollution from munitions clearance and disposal, possible effects on marine vertebrates, and its mitigation. *Mar. Technol. Soc. J.* 45 (6), 80–88.

Koschinski, S., Kock, K.H., 2009. "Underwater Unexploded Ordnance - Methods for a Cetacean-friendly Removal of Explosives as Alternatives to Blasting", *Reports Int. Whal. Comm. SC/61 E*. https://literatur.thuenen.de/digibib_extern/dk041983.pdf.

Koschinski, S., Kock, K.H., 2015. "Underwater Unexploded Ordnance - Methods for a Cetacean-friendly Removal of Explosives as Alternatives to Blasting", 22nd ASCOBANS Advisory Committee Meeting.

Lewis, J.A., 1996. Effects of Underwater Explosions on Life in the Sea. Defence Science and Technology Organization, Canberra, Australia. <https://apps.dtic.mil/dtic/tr/fulltext/u2/a315490.pdf>.

Loye, D.P., Arndt, W.F., 1948. A sheet of air bubble as an acoustic screen for underwater noise. *J. Acoust. Soc. Am.* 20 (2), 143–145.

Maser, E., Strehse, J.S., 2020. Don't blast: blast-in-place (BiP) operations of dumped World War munitions in the oceans significantly increase hazards to the environment and the human seafood consumer. *Arch. Toxicol.* 13.

Merchant, N.D., Robinson, S.P., 2020. Abatement of underwater noise pollution from pile-driving and explosions in UK waters. In: *Report of the UKAN Noise Abatement Workshop*, 12 November 2019 at The Royal Society, London, <https://doi.org/10.6084/m9.figshare.11815449>.

Merchant, N.D., Andersson, M.H., Box, T., Le Courtois, F., Cronin, D., Holdsworth, N., Kinneberg, N., Mendes, S., Merck, T., Mouat, J., Norro, A.M.J., Ollivier, B., Pinto, C., Stamp, P., Tougaard, J., 2020. Impulsive noise pollution in the Northeast Atlantic: reported activity during 2015–2017. *Mar. Pollut. Bull.* 152. <https://doi.org/10.1016/j.marpolbul.2020.110951>.

NMFS, 2018. Revisions to technical guidance for assessing the effects of anthropogenic sound on marine mammal hearing. In: NOAA Technical Memorandum NMFS-OPR-59. US Dept. of Commer., NOAA 167p.

Parsons, E.C.M., Birks, I., Evans, P.G.H., Gordon, J.C.D., Shrimpton, J.H., Pooley, S., 2000. The possible impacts of military activity on cetaceans in west Scotland. *European Research on Cetaceans* 14, 185–190.

Patent WO 03/058155 A1, 2003. International Patent "Device for Disruption of Explosive Ordnance", 17 July 2003.

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., Løkkeborg, S., Rogers, P.H., Southall, B.L., Zedde, D.G., Tavolga, W.N., 2014. "Sound Exposure Guidelines for Fishes and Sea Turtles: A Technical Report" ASA S3/SC1.4 TR-2014. ANSI Accredited Standards Committee S3/SC1, American National Standards Institute <https://doi.org/10.1007/978-3-319-06659-2>. 2014.

Robinson, S.P., Lepper, P.A., Hazelwood, R.A., 2014. "Good Practice for Underwater Noise Measurement", NPL Good Practice Guide No. 133. National Measurement Office, Marine Scotland, The Crown Estate ISSN: 1368-6550. Available from. www.npl.co.uk/acoustics.

Sayle, S., Windeyer, T.C.M., Conrod, S., Stephenson, M., 2009. Site assessment and risk management framework for underwater munitions. *Mar. Technol. Soc. J.* 43 (4), 41–51. <https://doi.org/10.4031/MTSJ.43.4.10>.

Schmidtke, E.B., 2010. "Schockwellendämpfung mit einem Luftblasenschleier zum Schutz der Meeressäuger", (Shock wave damping with an air bubble curtain to protect marine mammals). In: Proceedings of DAGA 2010, pp. 689–690. Berlin, March. http://pub.degaakustik.de/DAGA_2010/data/articles/000140.pdf.

Schmidtke, E.B., 2012. "Schockwellendämpfung mit einem Luftblasenschleier im Flachwasser", (Shock wave damping with an air bubble curtain in shallow water). In: Proceedings of DAGA 2012, pp. 949–950. Darmstadt, March. http://pub.degaakustik.de/DAGA_2012/data/articles/000332.pdf.

Sertlek, H.O., Slabbeekorn, H., ten Cate, C., Ainslie, M.A., 2019. Source specific sound mapping: spatial, temporal and spectral distribution of sound in the Dutch North Sea. *Environ. Pollut.* 247, 1143–1157.

Soloway, A.G., Dahl, P.H., 2014. Peak sound pressure and sound exposure level from underwater explosions in shallow water. *J. Acoust. Soc. Am.* 136 (3), El218–223.

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., 2019. Marine mammal noise exposure criteria: updated scientific recommendations for residual hearing effects. *Aquat. Mamm.* 45 (2), 125–232. <https://doi.org/10.1578/AM.45.2.2019.125>.

Strehse, J.S., Appel, D., Geist, C., Martin, H.-J., Maser, E., 2017. Biomonitoring of 2,4,6-trinitrotoluene and degradation products in the marine environment with transplanted blue mussels (*M. edulis*). *Toxicology* 390, 117–123.

Sundermeyer, J.K., Lucke, K., Dähne, M., Gallus, A., Krügel, K., Siebert, U., 2012. Effects of underwater explosions on presence and habitat use of harbor porpoises in the German Baltic Sea. In: Popper, A.N., Hawkins, A. (Eds.), *The Effects of Noise on Aquatic Life. Advances in Experimental Medicine and Biology*. vol. 730 Springer, New York, NY. https://doi.org/10.1007/978-1-4419-7311-5_64.

Todd, S., Stevick, P., Lien, J., Marques, F., Ketten, D., 1996. Behavioral effects of exposure to underwater explosions in humpback whales (*Megaptera novaeangliae*). *Can. J. Zool.* 74, 1661–1672.

von Benda-Beckmann, A.M., Aarts, G., Sertlek, H.O., Lucke, K., Verboom, W.C., Kastelein, R.A., Ketten, D.R., van Bemmelen, R., Lam, F.A., Kirkwood, R.J., Ainslie, M.A., 2015. Assessing the impact of underwater clearance of unexploded ordnance on harbour porpoises (*Phocoena phocoena*) in the southern North Sea. *Aquat. Mamm.* 41 (4), 503–523.

Weston, D., 1960. Underwater explosions as acoustic sources. *Proc. Phys. Soc.* 76, 233–249.

Yelverton, J.T., Richmond, D.R., Fletcher, E.R., Jones, R.K., 1973. Safe Distances From Underwater Explosions for Mammals and Birds. Lovelace Foundation for Medical Education and Research, Albuquerque NM 87108 (AD-766 952).