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FINAL REPORT: CHARACTERISATION OF ACOUSTIC FIELDS GENERATED BY UXO REMOVAL - PHASE 2

(BEIS OFFSHORE ENERGY SEA SUB-CONTRACT OESEA-19-107)

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Characterisation of Acoustic Fields Generated by UXO Removal
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1 INTRODUCTION

1.1 SCOPE OF REPORT

This report describes the work for Offshore Energy SEA Sub-Contract OESEA-19-107. The report is a deliverable of the project, which has the aims to review the current practice of disposal of Unexploded Ordnance (UXO) on the seabed, a process termed Explosive Ordnance Disposal (EOD), and to study the acoustic characteristics of the resulting underwater explosions, including low order detonation by deflagration.

The work encompassed the following activities:

- Review of current practice (completed in Phase 1);
- Provision of a guidance protocol for those undertaking measurements of EOD for UXO in the ocean (initially drafted in Phase 1);
- Conducting a controlled field trial to study the mitigation benefits of low order detonation by deflagration and examine the sound generation mechanisms;
- Study of the sound generation mechanisms for different types of UXO detonations (high and low order) and long-range propagation;
- Collection and analysis of offshore in-situ measurements made by developers and researchers.

The review of current practice was completed in Phase 1 and reported earlier in the project. However, a summary is also provided in Section 2 of this report.

The guidance protocol was also drafted in Phase 1 of the project and circulated to the project Steering Group (SG) consisting of stakeholders from developers, regulators and Statutory Nature Conservation Bodies (SNCBs). During Phase 2, the comments on the protocol were discussed at a meeting of the SG and the protocol was revised in response to the comments which were summarised in a compilation document (along with responses). The protocol is a separate document, but a brief summary of it is included as Section 3.

Section 4 describes the work to conduct a controlled experimental trial to determine the reduction in acoustic output from a low-order disposal technique (deflagration). The experimental trial was conducted in Limehillock Quarry, Scotland. The aim of the trial was to enable direct comparison of the acoustic output from high order detonations with that from low-order deflagration. This work has also been described in a scientific paper to be submitted to a peer-reviewed journal.

Predictions of noise levels for Environment Impact Assessment for EOD requires a valid source model for the explosion and a suitable propagation model to predict the relevant acoustic metrics, such as peak sound pressure and sound exposure level (SEL) in the region of interest. The theoretical study of the sound generation mechanisms for UXO detonations and a study of the long-range propagation is described in Section 5.

The aims of the project included the collection and analysis of offshore in-situ measurements made by developers and researchers. This objective has been difficult to achieve fully because of the lack of available data from developers and researchers. This in turn has made it very difficult to experimentally validate the propagation modelling studies in Section 5. In Section

6, a description of progress within this task is given along with plans for further work. Finally, conclusions are drawn in Section 7.

The Deliverables of the project are as follows:

- review of current practice (completed in Phase 1);
- a scientific paper to be submitted to a peer-reviewed journal;
- revised guidance protocol for those undertaking measurements of EOD for UXO in the ocean;
- technical report summarising all technical outputs (this document);
- presentation of results of the controlled experiment during the Noise Abatement Workshop (or marine pile driving and UXO disposal) held at The Royal Society on November 12th 2019 (organised by NPL and CEFAS and funded by the UK Acoustics Network). The Workshop was attended by developers, regulators and SNCBs and the presentation and discussions were summarised in the Workshop Report [Merchant & Robinson 2020];
- presentation of the provisional project outline at MSCC Underwater Sound Forum held at the University of Exeter May 21st 2019.
- presentation of a project update (including results of the controlled experiment) at the MSCC Underwater Sound Forum held at The Scottish Government offices in Edinburgh on November 20th 2019.

1.2 BACKGROUND

Unexploded ordnance (UXO) litters the seabeds of European seas such as the North Sea, the Irish Sea and the Baltic, mainly as the result of military conflicts of the past [Davies 1996, Eitner & Tröster 2018, Albright 2012]. Military activities, dumping, accidents, ordnance development, and military training have left significant quantities of unexploded ordnance in European coastal waters. UXO that is unsafe to move and is generally disposed of with a high order detonation. There is concern that it can cause acute environmental damage through noise impact even at a considerable distance from the detonation. Damage to marine biota has to be balanced against the need for public safety, and the desire to expand green renewable forms of energy, such as offshore wind.

The location and spatial size of many offshore wind farm developments and cable connector projects means there is 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 & 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 in order to reduce health and safety risks to a tolerable level. When UXO cannot be avoided or safely removed, explosive ordnance disposal is necessary. This typically involves detonation on site, and the favoured disposal method is to use high-order detonation conducted by exploding an additional donor charge placed adjacent to the UXO munition [Albright 2012, Aker 2012, Sayle *et al.* 2009, Cooper *et al*. 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 Brenda-Beckman *et al.* 2015;Yelverton *et al.* 1973; Simonis *et al.* 2020; Dahl *et al.* 1996; 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].

The existence of 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 & Jenkins 2012, Popper *et al.* 2014]. Common mitigation strategies involve the use of spatial and temporal restrictions on the activity, passive acoustic monitoring for marine species, and the introduction of additional noise of lower amplitude to create an aversive reaction by use of Acoustic Deterrence Devices or small "scare" charges [JNCC 2010; Merchant & Robinson 2020]. Noise abatement technologies have also been employed including the use of bubble curtains to attenuate the radiated sound [Merchant & Robinson 2020; Loye & Arndt 1948; Demonico 1982; Croci *et al.* 2014; Schmidtke *et al.* 2009]. In recent years, there has been a focus on alternative methods of disposing of UXO [Koschinski 2011; Koschinski *et al.* 2009] 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 & Robinson 2020; ESTCP 2002]. Deflagration consists of a process where the UXO casing is penetrated by a shaped charge that generates insufficient shock to detonate. The explosive material inside the UXO reacts 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 project includes experimental work to compare the characteristics of the sound produced by deflagration with that of a traditional high-order detonation method. 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; Weston 1960], including characterisation of explosive sources in shallow water environments [Gaspin *et al.* 1979; Chapman 1985; Chapman 1988; Hannay & Chapman 1999; Soloway & Dahl 2014; Wiggins *et al.* 2019]. 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 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 from measurements made on UXO in-situ.

The JNCC guidelines [JNCC 2010] focus on minimising the risk of physical trauma and permanent auditory injury such as Permanent Threshold Shift in hearing (PTS). The distance at which detonations could cause physical injury must be established as part of a noise risk assessment to inform the licensing process and estimate the effectiveness of mitigation measures. The NMFS thresholds [NMFS 2016 & 2018; Southall 2019] incorporate the latest research results and provide an update of the 2007 thresholds [Southall *et al.* 2007] referred to in the guidelines which have been widely adopted by SNCBs and regulators. Estimates of PTS injury zones using NMFS thresholds have resulted in much larger impact ranges than were previously estimated, extending in the most extreme cases well beyond any effective mitigation zone (e.g. up to 15 km from detonation for a UXO charge of >700 kg). Such results raise grave concerns for the protection of the marine environment and for industry, as the consequence of a risk assessment concluding that an UXO detonation is likely to result in a large PTS injury zone is onerous. However, it is acknowledged that estimates are highly uncertain, due to gaps in the knowledge base.

1.3 CONSULTATION WITH STAKEHOLDERS

A Stakeholder Group (SG) was convened consisting of experts from four offshore windfarm developers, as well as from BEIS, The Crown Estate, The Marine Management Organisation (MMO), and Natural England. The SG was convened for three online meetings and provided comments on the guidance protocol.

The project was presented at two meetings of the MSCC Underwater Sound Forum, including the meeting held at The Scottish Government offices in Edinburgh on November 20th 2019, where the results of controlled experiment were presented.

Several teleconference meetings were held with TNO from the Netherlands where the Dutch experiences with EOD and the possibility of future collaboration were discussed.

The results of the controlled experiment were presented in the Noise Abatement Workshop (or marine pile driving and UXO disposal) held at The Royal Society on November 12th 2019 (organised by NPL and CEFAS and funded by the UK Acoustics Network). The Workshop was attended by nearly 100 delegates from developers, regulators and SNCBs. The Workshop provided an opportunity for discussion of issues related to noise abatement in syndicate groups, one of which was dedicated to UXO disposal. This enabled frank discussions between delegates and the potential providers of low-order EOD, and publicised the project and its results. The presentation and discussions were summarised in the Workshop Report [Merchant & Robinson 2020] which has had wide circulation amongst the delegates and is available from the UKAN web-site at: https://acoustics.ac.uk/resources/report-from-the-noise-abatement-workshop-at-the-royal-society-19-november-2019/

In addition to the above, extensive discussions have been undertaken with suppliers on low-order EOD using deflagration, specifically staff of EODEX and Alford Technologies. These discussions focused on the non-acoustic obstacles preventing the rapid adoption of deflagration as a technology for UXO clearance.

2 REVIEW OF AND CURRENT PRACTICE IN UXO REMOVAL

2.1 CURRENT PRACTICE

Offshore developers are required to perform surveys in search of unexploded ordnance prior to commencement of construction work as part of the licensing requirement, commonly employing both acoustic and electromagnetic techniques. The survey utilises a towed magnetometer to identify any ferrous objects on the seabed, and these objects are then classified by the surveyors as potential UXO in the survey area. Other historic or seabed data collected (e.g. high-resolution geophysical survey aimed at charactering seabed geology and materials) can also be used to identify presence of UXO.

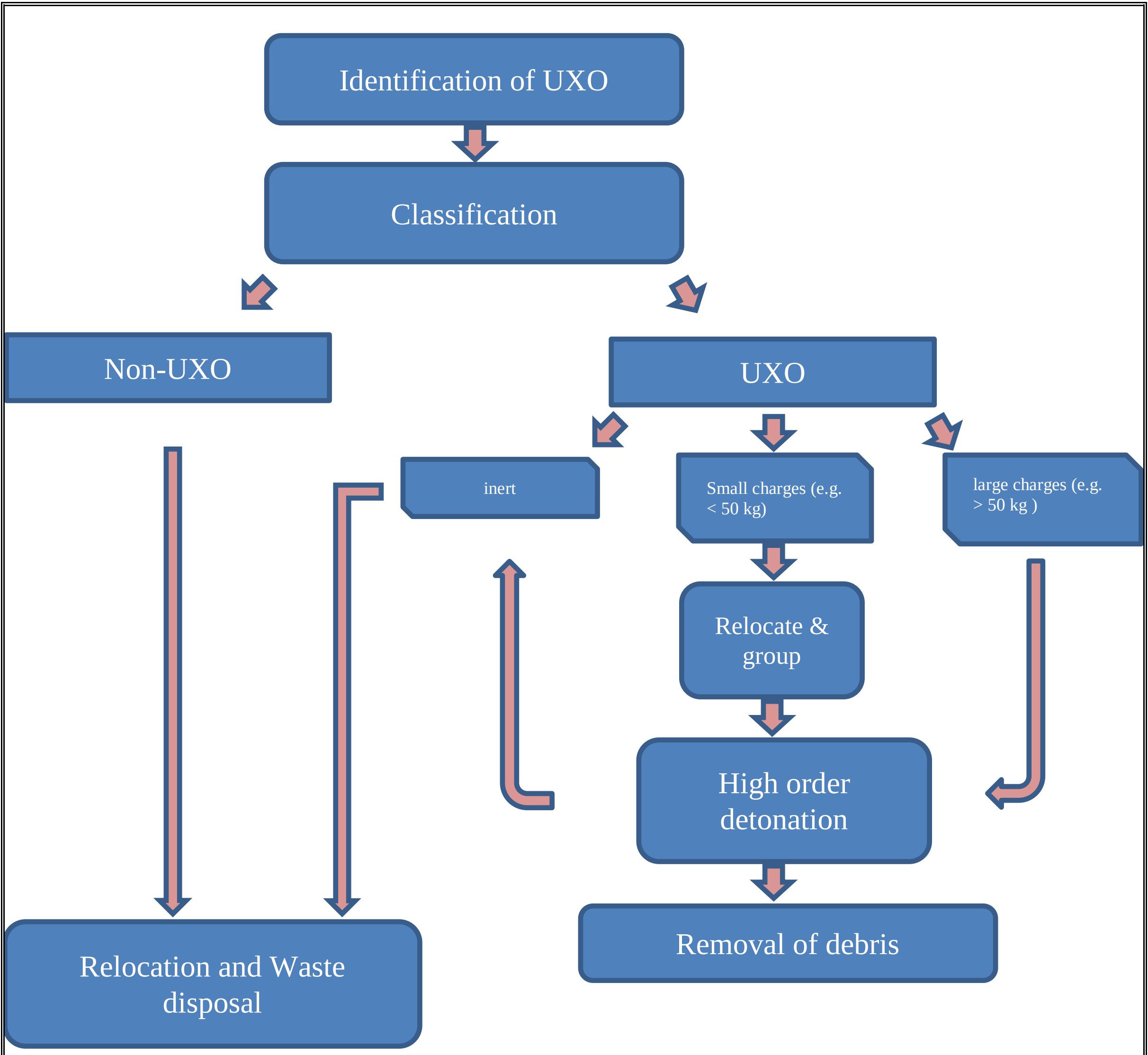

Figure 2-1 Flowchart of a typical EOD process

Figure 2-1 shows a process flow schematic for a typical EOD operation. Any potential UXO identified will be targeted for more detailed, often visual, survey by a remote operated vehicle (ROV) to confirm the UXO hazard and to determine the UXO type, size and other characteristics. An explosive ordnance disposal expert will assess the threat of the object to the development activities. If a UXO hazard is classified as high risk, the preferred action would be to avoid the UXO if possible. Strategic avoidance of UXO presence in a windfarm construction area can often be costly and in many cases is considered impractical. The most practical measure is often to physically dispose of the UXO, by either relocation when considered safe to do so, or using disposal by detonation.

A common method used for the disposal of UXO is the deliberate detonation initiated by a small donor charge placed on the munition to initiate an explosion of the main charge. This can be physically carried out in a number of ways: human divers can be used, but preferably an ROV is deployed from the support vessel to place the explosive charge on the target UXO. A common way of initiating the detonation will be through the use of shock tube connected to a detonator placed in the donor charge. The advantage of such method is that that the explosive material is only considered in danger of detonation if the donor charge, detonator, detonation line (shock tube or electrical line) and a firing mechanism (trigger) are all in place. The initiation of the detonator in the donor charge then takes places either non-electrically using shock tube or via an electrical line triggered from EOD vessel. Once the donor charge including detonator and detonation line has been set up correctly, and all personnel and equipment have been safely recovered and transited outside the detonation safety radius (typically 500 m – 1 km), the detonation procedure can commence. Note: both non-electrical and electrically based detonation lines (physically connecting the donor charge and the firing mechanism) can be used, however shock tube (a thin plastic tube containing explosive material) is often preferred as it has lower risk of accidental firing due to electrical interference.

After a successful detonation, it is common to remove any debris (typically metal fragments of the UXO casing) to ensure no explosive materials remain. Typically, a grid of 10 m x 10 m centred around the detonation site will be surveyed to search for fragmentation and scraps of the UXO. Any fragments with reasonable dimensions will be recovered to check for explosive material. Once checked, it will be certified “Free-From Explosive” and any explosive remnants considered inert and safe will be transported onshore for disposal.

2.2 MITIGATION

2.2.1 General

There are a number of different categories of noise mitigation which in general could be applied to UXO clearance.

Noise abatement/reduction
This consists of a reduction of sound energy emitted into the marine environment at source. Methods include:

- low-order detonations where the ordnance is disposed of or rendered safe without a high order detonation, such that the source level is significantly reduced;
- barrier methods which attenuate the emitted sound, for example bubble curtains.

Spatial-temporal restrictions
This consists of restricting the EOD noise-generating activities, through either:

- real time restriction during the activity based on short-range detection of marine mammals using visual or passive acoustic detection (temporarily halting the EOD if marine mammals are detected within a specified exclusion radius);

- planning stage restrictions (restricting activity in specific areas at specific times during the presence of sensitive species).

Acoustic deterrents

This involves the introduction of additional acoustic noise of lesser intensity with the intention of dispersing animals before the more harmful noise levels generated by the EOD are emitted. Examples include:
- use of acoustic deterrent devices (ADDs) prior to EOD activity;
- use of small scare charges at increasing charge size deployed before the main charge is initiated.

2.2.2 General mitigation procedures in UK waters

In the UK, the explosive ordnance disposal operation is subjected to a pre-detonation mitigation procedure to help mitigate marine mammal impact. It commonly involves three types of mitigation measures:
- active acoustic deterrents (such as the use of ADDs and scare charges),
- passive acoustic monitoring, and visual monitoring;
- the use of bubble curtains (in recent licences).

This is conducted under the guidance provided by JNCC for explosive events and requires continuous monitoring up to 60 minutes before detonation; operations have to be delayed if marine mammals are seen in the vicinity. It should be noted that although there have been several studies on the effectiveness of ADDs, the use of scare charges has yet to be properly evaluated.

2.2.3 Bubble curtains

Where high order underwater detonations cannot be avoided, bubble curtains offer a barrier method which enables sound attenuation of the explosive shock wave. Bubble curtains have been reported to be effective for pile driving noise, with between 10 dB and 20 dB reductions in SEL reported. There is also evidence that the method can be effective to reduce the noise levels of explosions [Nützel 2008; Schmidtke 2009], where test detonations demonstrated that it was possible to reduce the impact area significantly when using a double bubble curtain. However, there has not been extensive controlled testing to determine the required characteristics of the bubble curtain for these types of sound sources, and bubble curtains are potentially expensive to employ, and may be ineffective in areas with deep water and/or strong water currents.

2.2.4 Low order techniques

In order to minimise the impact of high order detonation of UXO, other methods can also be employed [Koschinski 2015]. These have been applied successfully on land-based munitions, and sometimes for munitions at sea. Examples include:

- freezing the munition to render it inactive;
- water abrasive suspension cutting in order to physically disrupt the munition;
- disposal in a Static Detonation Chamber;
- photolytic destruction of the munition;

- low-order deflagration.

The latter technique, deflagration, has been the subject of recent research and has been successfully used for on-land and at-sea EOD by the military, showing promise for noise abatement at source. For this reason, it has been chosen for further study in this project.

2.3 DEFLAGRATION

Deflagration is a low order technique to neutralise explosives. A shaped charge is attached externally to a target UXO. Upon detonation, the shaped charge generates plasma which penetrates the casing of the UXO and generates and consumes the explosive. Such low-order disposal is characterized by a *partial* energetic reaction of high explosive filler in the ordnance, such that a high order detonation does not take place.

Such low-order detonation techniques have matured as a means of rendering land-based surface UXO safe [ESTCP 2002]. However, there is very little measured acoustic data on generating low-order detonations with UXO underwater. In a US study, tests on explosive-filled 155 mm projectiles and bombs with a low-order deflagration tool in water were conducted in 2001[ESTCP 2002]. The results showed that low-order detonation procedures were very effective in reducing the blast effects while in all cases causing a complete disruption of the ordnance. Pressure histories were measured and compared to equivalent yields in pounds of TNT. Using peak sound pressure as the metric, the yield reductions exceeded 97 percent over what would have been expected for high order detonations, with significant reductions in impulse and bubble period calculations. All estimates exceeded the 25 percent reduction in yield that was used to arbitrarily define “low-order” [ESTCP 2002].

More recently the deflagration method has been used for EOD at sea for European navies, for example in Poland. Evidence from size of surface plumes would indicate that the deflagration method is substantially less energetic than high order disposal [ESTCP 2002].

The deflagration method shows considerable promise for noise abatement at source in UXO disposal. However, prior to this project, no attempts have been made to measure a “like-for-like” difference in the radiated acoustic pressure pulse. The US study compared to theoretical values for high-order detonations, and any attempts to measure deflagration on “real” UXO at sea would not enable a like-for-like comparison (each UXO being different in size construction, location, degree of burial, degree of degradation, etc). Therefore, it was proposed that a controlled experiment be conducted to determine the reduction in radiated sound pressure for deflagration for the same size of test munition. This could be attempted in an open water at sea trial, but such a trial would itself add noise to the marine environment and be subject to licensing restrictions. An alternative was a controlled experiment in a quarry-based facility (such as that operated at Limehillock Quarry by Thornton Tomasetti Defence Ltd).

3 SUMMARY OF PROTOCOL FOR OFFSHORE MEASUREMENTS

Given offshore measurement of UXO is often part of a more complex measurement campaign, acoustic measurement can be constrained by safety and other environmental factors thus introducing uncertainty in the measurement. A protocol was drafted in order to aid and inform offshore developers of the best practice for performing such measurement with considerations of these external variables. The motivation for undertaking measurement of the sound radiated by the explosion is often the requirement for assessment of impact on aquatic fauna by regulatory framework for offshore development. Collection of data in a common manner allows direct comparison and can fill current data and knowledge gaps on direct measurement of UXO. The guidance protocol is available as a separate document [NPL 2020].

The protocol document is suitable for measurement of underwater sound generated during an Explosive Ordnance Disposal operation, commonly undertaken in construction of offshore windfarms, oil and gas platforms as well as construction of other marine renewable energy devices (MREDs). In general, this applies to any party involved in making in-situ acoustic measurements of underwater explosions. The EOD may be undertaken by either high order detonation (where a substantial donor charge is used to detonate and destroy the UXO), or low order detonation where a smaller charge is used to disrupt and/or consume the UXO. This protocol covers only the measurement of the radiated sound field in shallow water (<100m).

The guidance in the protocol document covers:

- choice of hydrophone and acquisition systems, including calibration requirements;
- deployment techniques;
- minimum requirement for measuring radiated noise from UXO;
- data handling and analysis;
- reporting requirement.

The following sections provide a summary of the recommended instrumentation and methodologies for the acoustic measurement of an UXO explosion.

3.1 INSTRUMENTATION

Table 1 outlines the key characteristics for the measuring instrumentation and recommended setting with regards to measurement of underwater explosion.

3.2 DEPLOYMENT METHODOLOGY

For measurement of underwater explosions, one of the following generic deployment methods should be adopted depending on available resource and conditions.

3.2.1 Static Deployment

A static deployment typically consists of hydrophone(s) connected to an autonomous recorder that can be moored at the bottom of the seabed to allow remote acoustic measurement in the water column (Figure 3-1). This system enables multiple units to be deployed at the same time in order to monitor the sound propagation at several fixed ranges simultaneously. This is considered a more cost-effective method for measuring underwater explosions if multiple ranges are required. Field deployment of a static system is typically more complex than vessel-based deployment, as it requires a mooring to be built and prepared prior to the field trial. Recovery requires either a surface buoy connected to a seabed anchor or an acoustic release system, which enables the recorder to be hauled to the surface.

Table 1 Summary of recommended instrumentation specification for UXO measurement.

Performance Characteristic	Recommended Specifications	
	Explosion	Background noise
Frequency range:	20 Hz – 20 kHz	
Sensitivity:	Less than -200 re 1V/ µPa (for use at a minimum range of 1 km)	Between -185 to -165 dB re 1 V/µPa
Frequency response	Invariant with frequency (flat response) in the range 20 Hz to 20 kHz (to a tolerance of ±1 dB)	
Dynamic range:	System dynamic ranges of in excess of 60 dB are preferred. Analogue to digital converter (ADC) Minimum 16 bit resolution (nominal dynamic range 96 dB), Preferable 24 bit resolution (nominal dynamic range 144 dB)	
Signal to noise ratio	Minimum 6 dB level difference	
Directionality:	Omnidirectional to within +/- 2 dB up to 20 kHz	
Sampling frequency:	44.8kHz (for one-third octave levels required up to 20 kHz)	Twice the maximum frequency of interest (defined by the maximum hearing response of relevant receptors)
Filtering:	Any filter characteristics should be known and corrections applied (low pass and high pass filtering caused by instrumentation). Any low frequency roll-off in recorder performance due to high pass electronic filtering must be measured so that suitable corrections can be applied.	
System self-noise:	Ideally 6 dB below the lowest sound level.	
Calibration	Calibrated to traceable standard within the last 2 years	
Data storage	Raw data ideally stored in lossless format. Any compression used must be reported, and uncompressed data must be recoverable before analysis. Metadata to be stored: instrument calibration and ADC scaling factor, amplifier gains, sampling frequency and resolution	

3.2.2 Vessel-based deployment

This involves deployment of a hydrophone (either individually or in arrays) from a vessel (Figure 3-1), with the analysis and recording equipment remaining on the vessel, which can be either anchored or drifting. The method has the advantage that deployment can be quick and mobile, allowing flexibility to suit different operational changes. The risk of losing instrumentation is low, the data can typically be monitored as they are acquired and instrument settings can be adjusted in real time to provide the optimal setting for the required dynamic range to avoid signal saturation.

3.3 MINIMUM REQUIREMENT

In general, the measurement shall be chosen to satisfy at least one of the following requirements:

- Measurement at fixed location(s) to monitor the source output for comparison with other underwater explosion events.
- Measurement to assess the accuracy of predictions made from numerical models.
- Measurement for validation of models of source radiation mechanisms.
- Measurement to derive a source output metric (e.g. a source level).
- Measurement that allow comparison with a normative threshold level (i.e. NMFS guideline 2018).

3.3.1 Recommended Range Measurement

The minimum range for measurement is governed by two factors:

- safety considerations requiring all deployments and vessels to be outside the exclusion zone defined during the EOD operation;
- the dynamic range of the instrumentation used (governing the maximum acoustic signal that can be faithfully recorded).

It is recommended that a measurement is made at 1 km range for all EOD clearances wherever possible. In some situations, it may be possible to deploy a high dynamic range static measuring system closer than 1 km before the EOD operation begins. Except under exceptional circumstances, attempts must be made to take measurement at 1 km.

If the recommended range cannot be used due to excessive peak pressure or limitation of measuring instrumentation, it is acceptable to use an alternative range to ensure the full waveform is captured without saturating or distorting the signal, provided requirements described in 3.1 can be satisfied. However, the maximum range for a measurement station is recommended to be ideally within 20 km.

3.3.2 Spatial configuration of measurements

The minimum number of sampling locations recommended in the protocol is one single location. Where operation is restricted by safety considerations and limited resources, this may be the only option. However, while even one good quality measurement is better than none, it is recommended that where possible, measurements are made at three or more locations. There are two options for the spatial configuration of measurement locations.

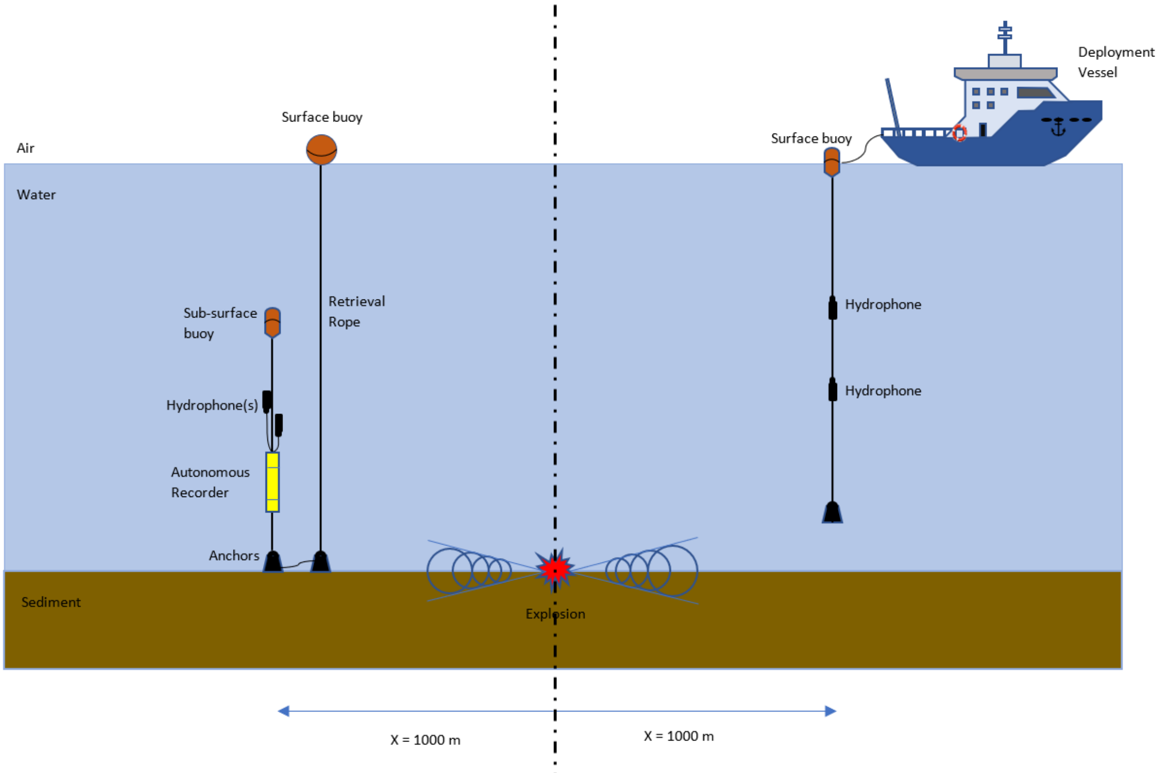

Figure 3-1 Example of field deployment strategies.

Measurements along a transect

A number of measurement stations are positioned in a straight line along a single azimuthal bearing from the UXO position, with the closest position no closer than that defined in 3.3.1 Such a strategy enables the propagation of the acoustic wave along a specified transect to be empirically estimated by determining the properties of the acoustic pulse as a function of range. It is recommended that (if possible) ranges are selected by at least an approximate tripling of distance relative to the 1 km minimum range (for example, say 1 km, 3 km, 10 km, etc.) in order to observe significant changes in sound pressure over long distances.

Measurements at fixed grid locations (along a variety of bearings)

A number of fixed measurement stations are located along a variety of different bearings and at different ranges from the UXO. This measurement strategy is more suited to an EOD campaign where numerous UXO are to be cleared from an area, and where re-positioning of the measurement stations after each EOD clearance is not practical. Here the stations would be positioned on a grid in the vicinity around the UXO grouping, with the bearings and ranges to the stations varying for each UXO.

3.4 DATA HANDLING AND ANALYSIS

3.4.1 Data Processing

The data processing to convert the digitized waveform data to sound pressure should be conducted according to following:

i) Identify event from waveform data.

ii) Confirm data not saturated.
iii) Digital filtering to isolate frequency of interest.
iv) Obtain frequency spectrum through Fourier analysis.
v) Convert electrical signal to absolute pressure using system sensitivity information.
vi) Determine acoustic metrics.
vii) Perform further analysis.

3.4.2 Acoustic Metrics

Two acoustic metrics, peak sound pressure and single pulse sound exposure level ($\mathrm{SEL_{sp}}$) are considered here [ISO 18405:2017, ISO 80000-8:2020].

Peak Sound pressure level
The peak sound pressure should be calculated for the acoustic pulse from the sound pressure waveform, this can arise from the compressional or rarefactional sound pressure and is sometimes referred to the zero to peak sound pressure, $L_{p,pk}$, defined by:-

$$L_{p,pk} = 20\log_{10}\left(\frac{p_{pk}}{p_0}\right)\ dB$$

where p_0 = 1 µPa.

Single pulse sound exposure level ($\mathrm{SEL_{sp}}$)
The single pulse sound exposure level, $\mathrm{SEL_{sp}}$, should be calculated for the specific acoustic pulse as a broadband value with frequency covering at least bandwidth between 20 Hz and 20 kHz. To calculate the SEL corresponding to a specific acoustic event requires the SEL to be calculated over the pulse duration.

The single pulse sound energy is calculated for the entire duration of the pulse from the time series, where f_s is the sampling frequency, and t_0 and t_{100} are the 0% and 100% sound exposure points. The values t_0 and t_{100} are the start and end time of the acoustic pulse [ISO 18406:2017; NPL 2014]:

$$E_{100} = \frac{1}{f_s}\sum_{i=t_0 f_s}^{t_{100} f_s}\{p^2(t_i)\}$$

The total broadband signal pulse sound exposure level, $\mathrm{SEL_{sp}}$, in dB re 1 µPa^{2}s is given in

$$SEL_{\mathrm{sp}} = 10\log_{10}\frac{E_{100}}{E_{ref}}\ dB$$

where $E_{100} = E(t_{100})$ is the 100% sound exposure and E_{ref} is 1 µPa^{2}s.

3.5 REPORTING REQUIREMENT

Whenever a measurement is undertaken, auxiliary data must accompany the acoustic measurement in order to aid the interpretation of the results. It is beneficial to record any auxiliary data that are relevant, as these can be correlated with the measured level during the analysis [ISO 18406:2017].

Table 2 Summary of protocol reporting requirement.

Measurements	**Mandatory**	**Optional**
Operational	- Date/time of recordings - Hydrophone depths in the water column - Coordinates of UXO sources and hydrophone measuring stations - Water depth at measurement locations	- Sound speed profile of the water column - Wind speed - Significant wave height - Tidal state during measurement - Precipitation - Presence of other vessels (within 5 km radius, where data available)
Explosive Characteristic	- Identifier and coordinate of UXO - UXO physical size or charge size - Water depth at UXO location - Description of UXO (e.g. munition type, state of submergence, approximate age) - Method of detonation - Number of UXO	- Seabed type at the measurement locations (Folk sediment classification or similar is sufficient; the classification used should be stated)
Deployment Configurations	- Measurement system description (including acquisition system type, bandwidth, system self-noise dynamic range, sampling frequency, etc.) - Data compression routine, if used - Description/diagram of deployment method and configurations - Hydrophone specification (type, model, directionality, nominal sensitivity) - Calibration details (Calibration standard, dates and certificate)	- Field calibration methods and results
Analysis	- Broadband peak sound pressure and peak sound pressure level. - Sound exposure level, including broadband and one-third octave band levels	- Pulse duration for the associated broadband pulse - Peak compressional and peak rarefactional sound pressure level - The signal to noise ratio calculated from background noise level - The waveform of the underwater explosion, including the bubble oscillations, in graphical form

4 EXPERIMENTAL COMPARISON OF DEFLAGRATION AND HIGH-ORDER DETONATIONS

This chapter describes the experimental trial conducted in Limehillock Quarry, Scotland. The aim of the experiment was to compare the acoustic output from high-order detonations with low-order deflagration, and to expedite this it was decided to conduct an experiment in a controlled environment where a “like-for-like” comparison could be made. To this end, a controlled 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. 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 seabed was not an issue). Clearly, this experimental configuration is not similar to that which exists during actual offshore EOD operations, but the simplifications allowed a true comparison to be made without all of the extra uncertainties that exist in EOD operations offshore.

4.1 EXPERIMENTAL METHOD

4.1.1 Measurement configuration

Figure 4-1 Limehillock Quarry – hillside viewpoint

The measurement trial was undertaken in Limehillock Quarry, near Keith in the northeast of Scotland. The facility is used extensively for in-water shock testing of structures for offshore marine applications and was operated by Thornton Tomasetti who provided all the logistical support for the trial. The quarry has dimensions of approximately 250 m long by 125 m wide, is a little over 20 m deep on average and is filled with fresh water (Figure 4-1). The bathymetry between the position of the explosive source and that of the furthest hydrophone was 20.1 m ±1 m. During the trial, the water temperature was stable at 10.5 °C for the shallowest 9 m of the water column, but beneath this depth the temperature declined to 6.1 °C at the bottom.

Measurements of the acoustic pulse from each explosive source were 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 and deployment may be seen in Figure 4-2.

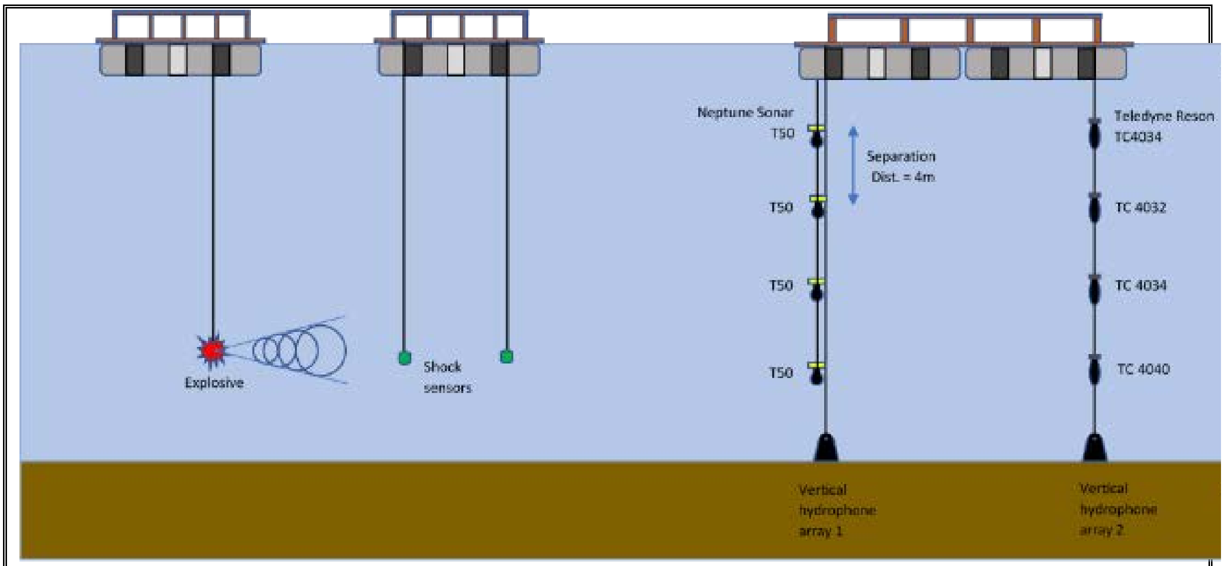

Figure 4-2 Schematic diagram of the measurement configuration in the trial (distances shown are not to scale).

Measured sound speed profile and experimental setup are shown in Figure 4-3. The sound speed is constant for the top part down to 9 m, followed by a large negative gradient initially and then a small negative gradient. The blue dotted line is the depth of the thermocline. The bottom of the quarry is relatively flat around 20 m deep.

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 µV/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 µs. 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 (Figure 4-4) 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.

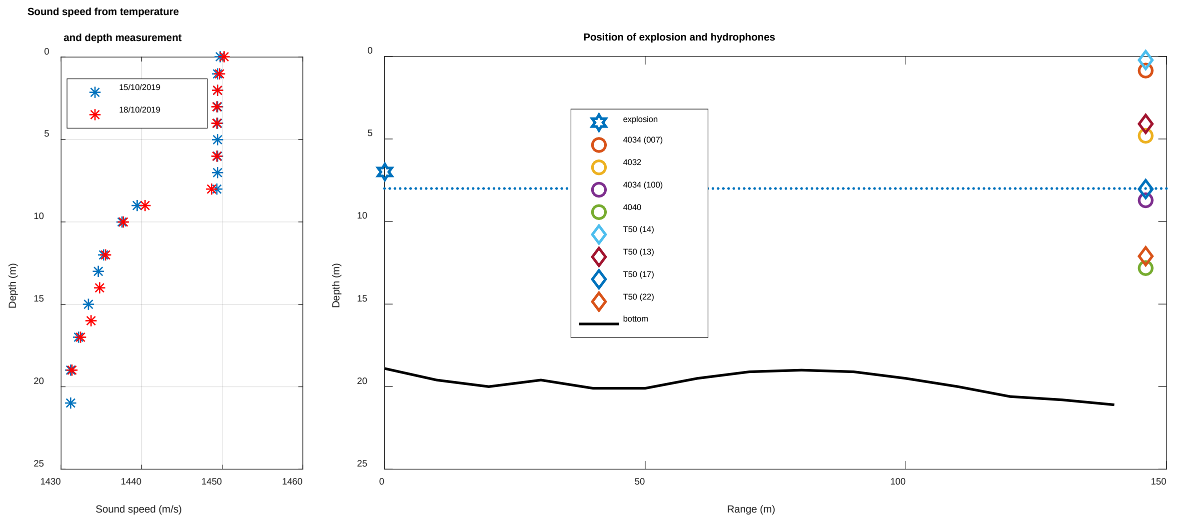

Figure 4-3 Sound speed profile (left), measurement set up (right)

Figure 4-4 Left: Near field pressure gauge deployment pontoons; the buoy is used to mark the position of the explosive. Right: Far field acoustic array deployment on a floating barge.

For the measurements made at 147 m from the source, two four-element hydrophone arrays were deployed from a tethered floating pontoon (Figure 4-4). The first array consisted of four T50 hydrophones (manufactured by Neptune Sonar, with nominal sensitivity 28 µV/Pa), and the second array was made up by four hydrophones manufactured by Teledyne Reson, consisting of 2 x TC4034 (9 µV/Pa), a TC4040 (38 µV/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 preamplifier) 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 µs), and two National Instrument USB 6363 DAQ cards sampling at 250 kilo-samples per second (time resolution of 4 µs). 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 & 2020]. This was done by comparison in a closed coupler in the range 5 Hz to 315 Hz. Free-field reciprocity was used to calibrate all hydrophones over the frequency range 750 Hz to 20 kHz, with two hydrophones being calibrated up to 200 kHz. Before and after deployment, the hydrophone sensitivities were checked at 250 Hz by use of 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).

4.1.2 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 was 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 prevent any residue from the deflagration 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).

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 finally 250 g, this latter being the largest size of charge used in deflagration. The test results are summarised in Table 3.

Figure 4-5 shows a photograph of a 10 kg high order detonation and Figure 4-6 shows an example of the waveforms acquired during a high order explosion using the vertical arrays at 147 m away from the surrogate shells.

Figure 4-5 A 10 kg high-order detonation at the quarry site (courtesy of Thornton Tomasetti Defence Ltd)

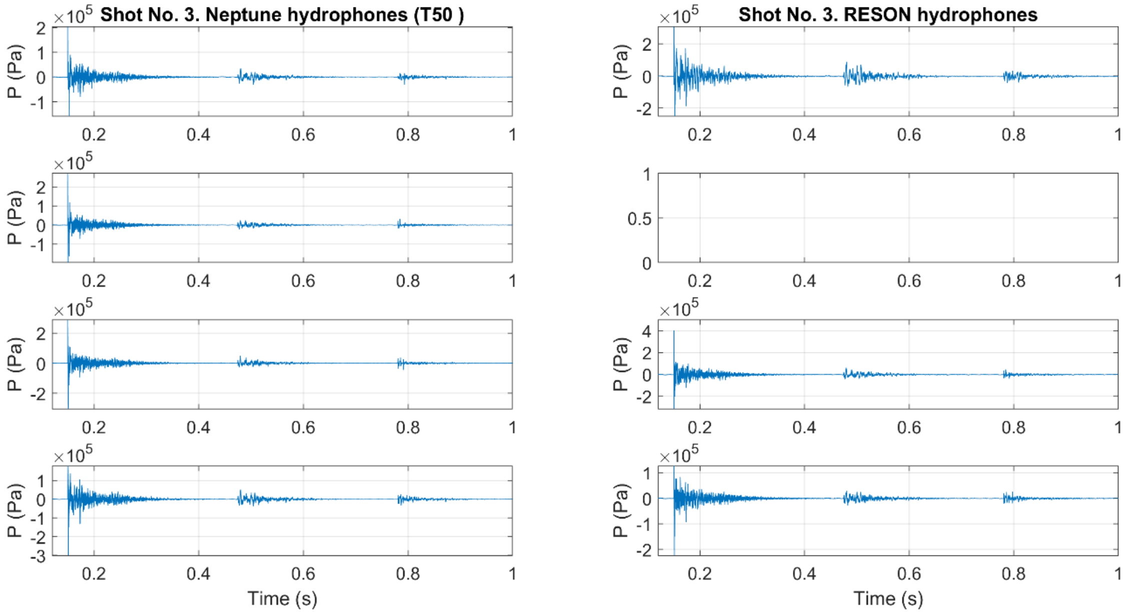

Figure 4-6 Example of acoustic waveforms acquired from far field vertical arrays during field measurement. Note that second element of the second array was inactive for high order measurement.

Table 3 Summary of test results.

ID	Charge Type	Low/ High order	Detonation Method	Distance (charge float - STV01 Aft Face)	Distance (charge float - PG1/PG2)*	Distance (charge float - PG3/PG4)*	Water Depth	Charge depth	Sound levels (air)	Low Order Burn Weight
1	10kg	HO	Shock Tube	146m	11.1m	21.0m	18m	7m	123dB	N/A
2	10kg	HO	Shock Tube	147m	11.1m	21.0m	18m	7m	123dB	N/A
3	5kg	HO	Shock Tube	146m	11.1m	21.0m	18m	7m	123dB	N/A
4	5kg	HO	Shock Tube	146m	11.1m	21.0m	18m	7m	124dB	N/A
5	10kg	LO	Shock Tube	146m	11.1m	21.0m	18m	7m	100dB	4.7kg
6	10kg	LO	Shock Tube	146m	11.1m	21.0m	18m	7m	100dB	5.9kg
7	5kg	LO	Shock Tube	146m	11.1m	21.0m	18m	7m	101dB	2.9kg
8	5kg	LO	Shock Tube	146m	11.1m	21.0m	18m	7m	101dB	2.6kg
9	25g Vulcan/End Plate	HO	Shock Tube	146m	12.7m	21.6m	18m	7m	103dB	N/A
10	48g Vulcan	HO	Shock Tube	146m	12.7m	21.6m	18m	7m	105dB	N/A
11	25g Vulcan	HO	Electrical	146m	12.7m	21.6m	18m	7m	104dB	N/A
12	15g Vulcan	HO	Electrical	146m	12.7m	21.6m	18m	7m	101dB	N/A
13	10 kg (2 x 5kg tubes)	HO	Electrical	146m	12.7m	21.6m	18m	7m	125dB	N/A
14	18.4kg (Estimated Wastage)	HO	Electrical	146m	12.7m	21.6m	18m	7m	126dB	N/A
15	48g Vulcan against End Plate	HO	Electrical	146m	12.9m	21.8m	18m	7m	105dB	N/A
16	48g Vulcan	HO	Electrical	146m	12.9m	21.8m	18m	7m	106dB	N/A
17	250g Pluto Bottler	HO	Electrical	146m	12.9m	21.8m	18m	7m	113dB	N/A

* PG1/PG2, PG3/PG4 denote the pontoon used for the shock sensors deployment.

4.1.3 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” has been called “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]. 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^{TM} is fitted with a low-density incendiary projectile made of magnesium 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.

Figure 4-7 Top Left: a photograph of a 10 kg shell showing the 48 g shaped charge used to initiate deflagration placed on the end cap. Top Right: Shell after deflagration, showing that the central portion of the explosive has been consumed by the deflagration process, with residual explosive left around the outer rim. Bottom Left: Penetrated steel endcap by Vulcan^{TM} after deflagration. Bottom right: Buckling of steel end cap due to pressure built-up during deflagration.

Figure 4-7 shows a photograph of a 10 kg shell showing the 48 g shaped charge used to initiate deflagration in position on the end cap. Also shown is a photograph of the shell after deflagration, illustrating that the central portion of the explosive has been consumed by the deflagration process, with residual explosive left around to outer rim.

For the high-order detonations of the shells, a detonator was placed into the shell to initiate a high-order detonation directly.

4.2 RESULTS AND DISCUSSION

4.2.1 Measurement results

The recorded data for the acoustic pulses were analysed and two particular acoustic metrics were calculated: peak sound pressure in MPa (and its level in dB re 1 μPa); and the sound exposure level or SEL in dB re 1 μPa^{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].

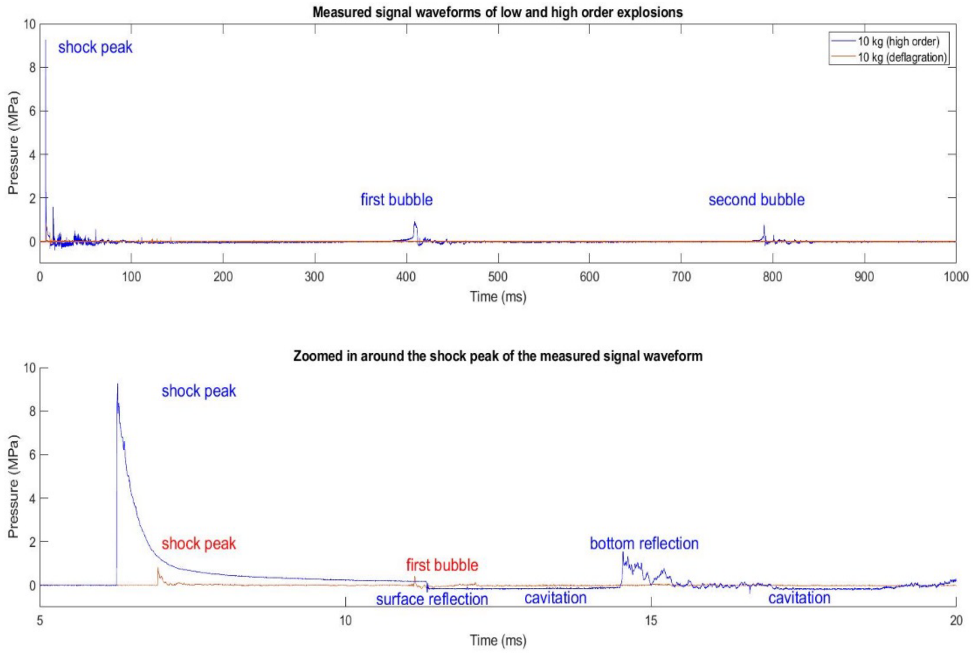

Figure 4-8 Recorded waveforms at 11 m from a 10 kg high-order detonation and a 10 kg deflagration showing the various phases of the signals including the initial shock wave, the bubble pulses, and reflections from surface and bottom.

An example of the recorded time waveforms from the shock pressure sensors is shown in Figure 4-8 for a high-order detonation of a 10 kg charge. 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 μPa) 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. The bottom reflection is also observed arriving at around 14 ms.

Figure 4-9 presents the sound pressure power spectral density for a high order detonation of a 5 kg charge at measured at distances of 11.1 m and 21.0 m, calculated from a waveform record length of 1 second for a high order detonation of a 5 kg charge measured at distances of 11 m and 21 m. Each plot shows the spectra at each of the shock pressure transducers (two at each distance). Also shown are 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 is due to cavitation close to water surface caused by the shock wave.

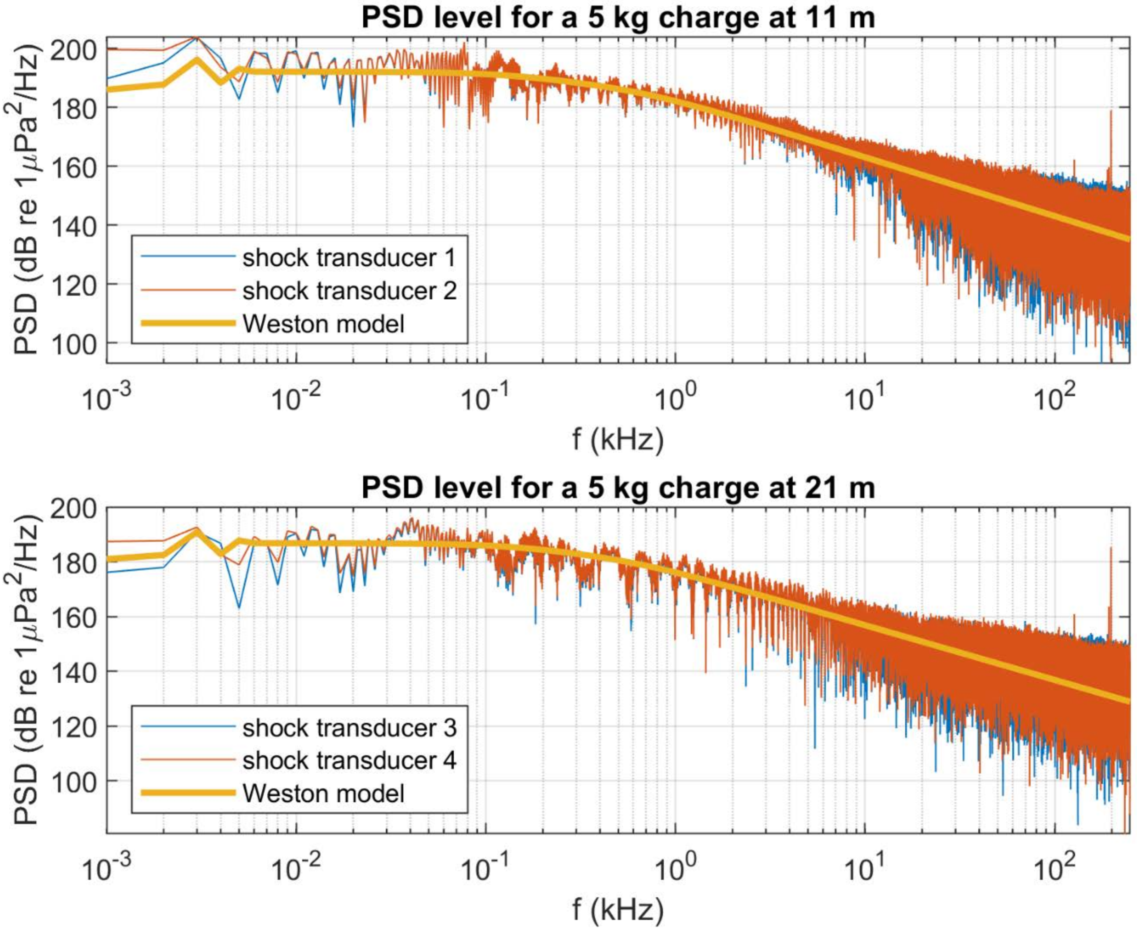

Figure 4-9 The sound pressure power spectral density (PSD) for a high order detonation of a 5 kg charge at measured at 11.1 m and 21.0 m. The plots show the spectra at the shock pressure transducers at each distance and the spectra predicted by the model of Weston for the equivalent charge size.

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]:

$$p_{\mathrm{pk}} = K_p \left(\frac{R}{W^{1/3}}\right)^{\alpha} \qquad (4.1)$$

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 and α are the shock and pressure coefficients, which are determined empirically. This equation was developed for TNT due to the historical use of TNT as a benchmark for energy from high explosives (a spherical TNT charge of density 1520 kg/m^3 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 Figure 4-10 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 equation (4.1) 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 of -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 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 and a metal plate (an end cap from the shells).

Figure 4-10 shows the peak sound pressure level for all the measured charges from 11 m to 147 m plotted against scaled range, 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 straight line with a negative gradient. The plots show 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 are close to the modelled data but consistently slightly lower in 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).

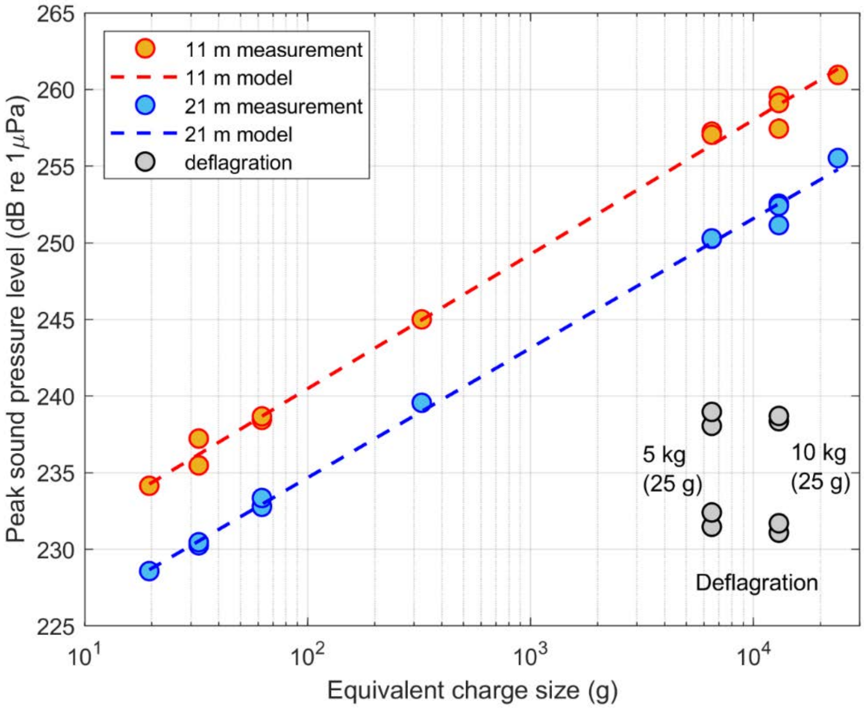

Figure 4-10 The peak sound pressure level at a nominal distance of 11 and 21 m plotted against charge size for all detonations. Note the charge size is expressed in TNT equivalent charge size. The solid line shows the prediction from the model of Weston. The results of the deflagration are shown on the bottom right of the plot.

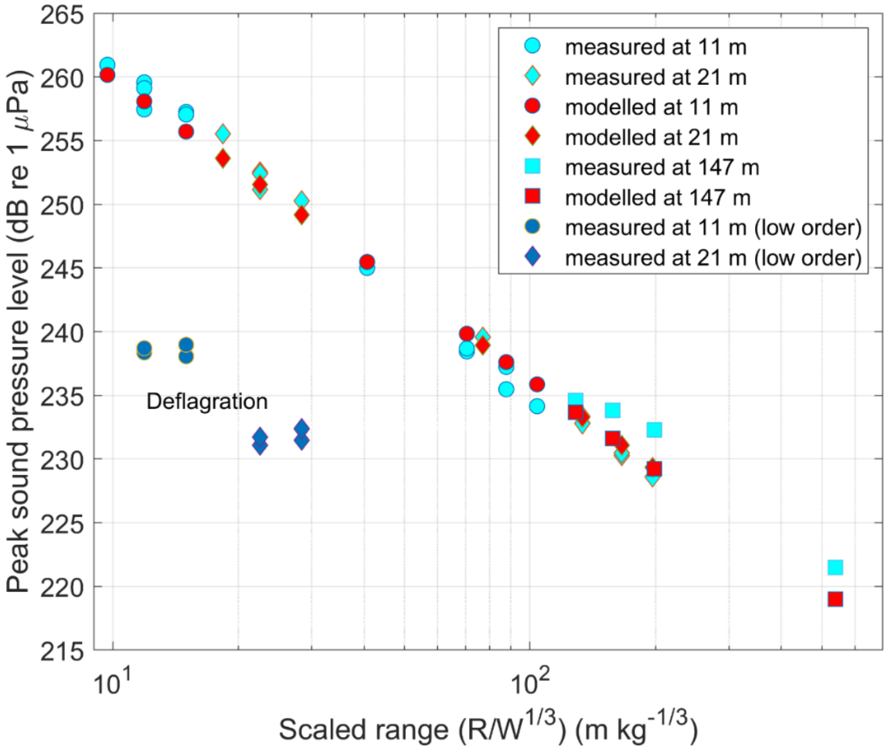

Figure 4-**11** Peak sound pressure level for all the measured charges plotted against scaled range from 10 m to 147 m, showing the measured data (blue) and predicted values (red). The data for the deflagration is shown in the solid black symbols (bottom left).

The SEL, a metric commonly used in exposure calculations for marine fauna, is also substantially reduced when using deflagration. Figure 4-12 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. 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).

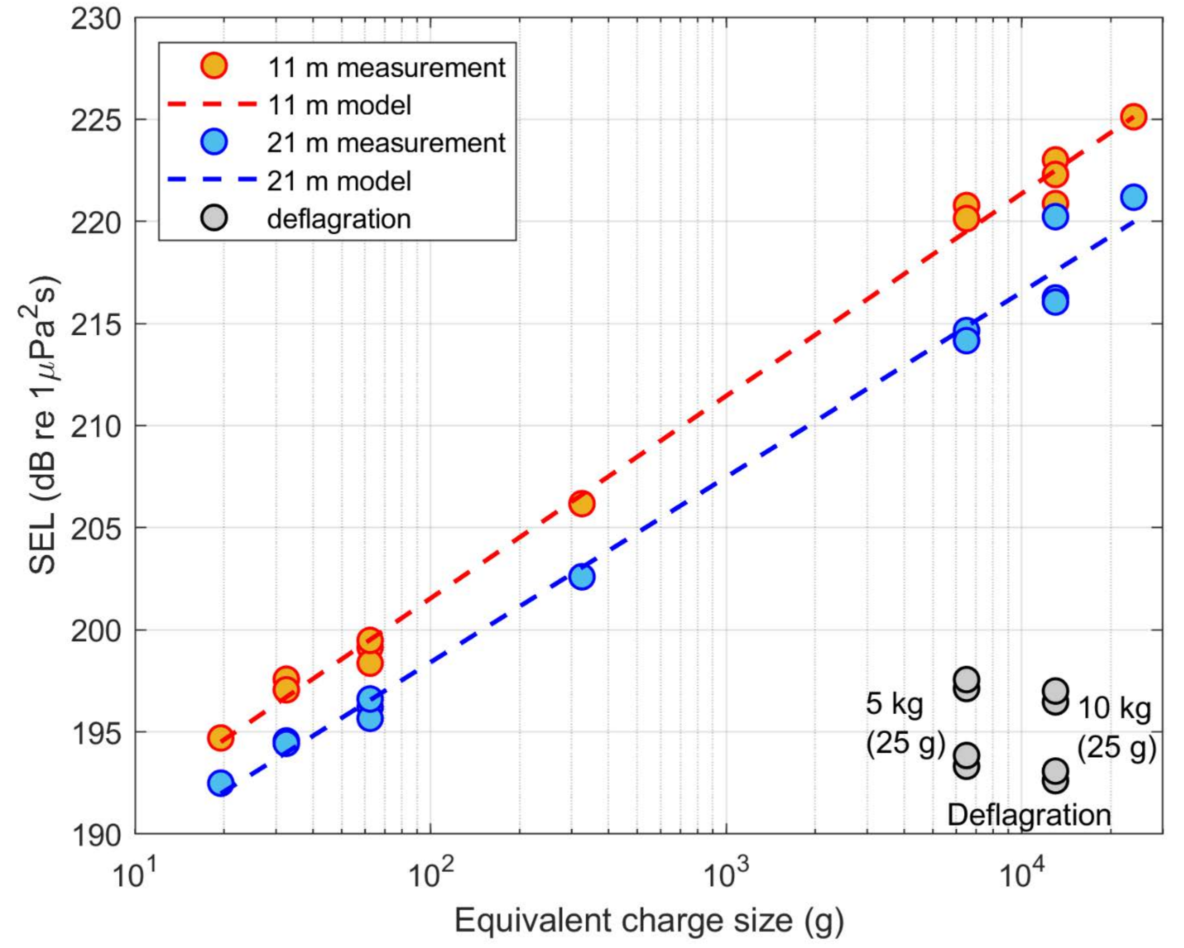

Figure 4-12 The SEL at a nominal distances of 11 m and 21 m plotted against charge size for all the detonations. The low-order deflagration data appear in the bottom left of the plot, with size of main charge and shaped charge indicated.

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:

$$E = K_E \, W^{\frac{1}{3}} \left(\frac{W^{\frac{1}{3}}}{R} \right)^{\beta} \qquad (4.2)$$

where E is the sound exposure in Pa^{2}s, and W and R have the same meanings as for equation (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).

4.2.2 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 approximately 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 Figure 4-5), 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 models), 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 of the UXO, 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 and others [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 is not influenced by this because the shock front arrives first and the 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 quarry side walls. This problem is likely to be worse for measurements at greater distances from the source which 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 equation (4.1) [Cole 1948; Arons 1954; Weston 1960]. This could be caused by a number of factors such as the fact that 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 here 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 is likely to have had some effect.

Using the Weston model (as plotted in Figure 4-10) it is possible to use the measured data to calculate a source level using either the peak sound pressure level or the SEL (to give the Energy Source Level). Doing this for the charge sizes where more than one example of high-order detonation was measured gives the values shown in Table 4 below.

Table 4. Estimates of Source Level for five charges.

Charge size (g)	Equivalent. charge size (g, TNT)	Peak sound pressure SL (dB re 1 µPa.m)	Energy SL (dB re 1 $\mu\text{Pa}^2\text{sm}^2$)
25	32.5	262	218
48	62.4	265	221
250	325	270	228
5000	6500	280	242
10000	13000	283	245

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 are lower by the same 20 dB factor noted for the received levels of peak sound pressure level.

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 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, chemicals may leak into the environment; the remnants are to be collected e.g. by ROV as part of the complete EOD operation.

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 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. 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 will enable predictions to be made of the likely acoustic output in the field.

4.2.3 Peak pressure signal processing considerations

The impulse generated by explosion contains very large signal bandwidth. Examples of waveforms are shown in Figure 4-13. The peak of the impulse is from the contributions of all the signal over the entire frequency range. However, the peak perceived by a receptor depends on its hearing range. It is important to examine the effects of signal processing bandwidth on the shock wave peak since it is one of the metrics for impact assessment. The data in Figure 4-13 from the pressure gauges were sampled at 500 kHz with a useful signal bandwidth of 250 kHz which is high for sound used by any marine fauna. It can be seen the amplitude of the measured signal is quite high even at the highest frequency of the data acquisition system. It is very useful to examine the effect of signal bandwidth on the peak for practical purposes. One is for measurement of the signal, and the other is for the modelling of the signal propagation.

Figure 4-13 shows a synthesised shock waveform based on the measured data of 10 kg charge explosion with a normalised peak in Limehillock trial. The shock waveform consists of a sharp rise to the peak with a decay time period of 6 µs, followed by an exponential decay using the time constant by Weston (1960). To account for slower decay of the waveform after the time constant, another two larger time constants were applied at $T = 2.2t_0$, and $T = 4.0t_0$. The blue line is for the synthesised signal. A number of low pass filters were applied to the signal so that the peak value of the signal can be compared. The bandwidths are 3 kHz, 6 kHz, 12 kHz, 24 kHz, 48 kHz, 96 kHz and 192 kHz respectively. The difference between the original shock wave signal and low-pass filtered signals is shown in Table 5. It can be seen that the difference is less than 0.5 dB if the processing signal bandwidth is greater or equal to 12 kHz.

This information is useful in selecting frequency range both in setting the sampling frequency of a measurement device and for calculating the response of a given underwater channel. The time required to run propagation models can be substantial for large distance such as 10's km over frequency range above 10's kHz. Use of lower signal bandwidths with an acceptable error can reduce running time significantly.

Table 5 Difference between original shock wave signal and low-pass filtered signals

Bandwidth (kHz)	3	6	12	24	48	96	192
Difference (dB)	-2.5	-1.0	-0.2	0.3	0.5	0.3	0.1

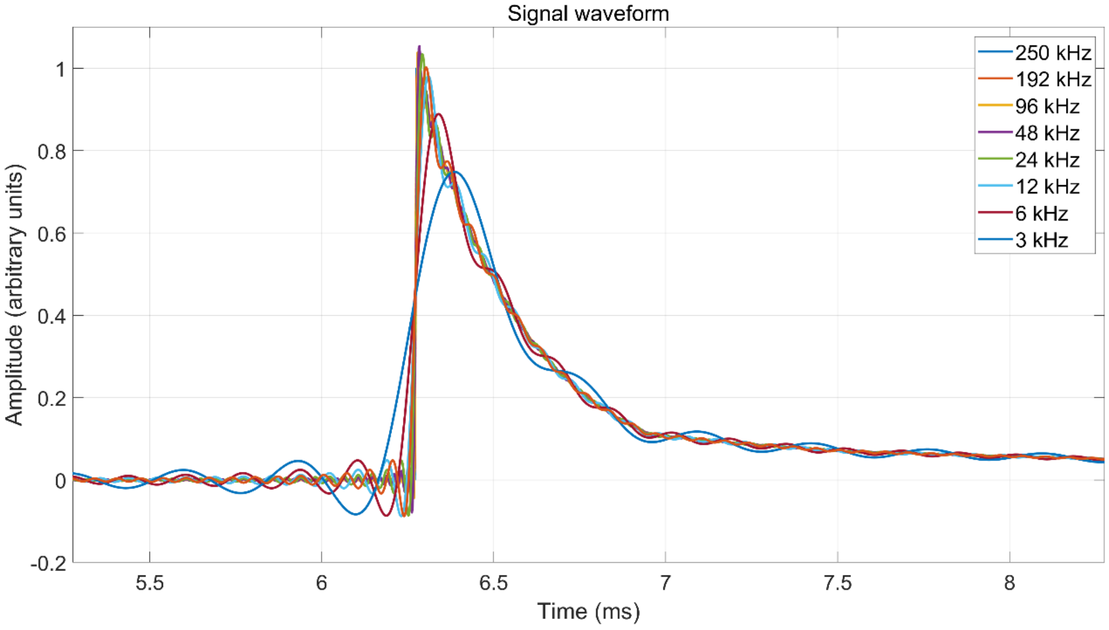

Figure 4-13 Shock wave peak with different processing bandwidth

4.3 CONCLUSIONS

In this work, a controlled field experiment has been carried out to quantify the difference in acoustic output levels from two EOD methods. Measurements 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 size munition 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 in the years after World War II, 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.

5 REVIEW OF THEORITICAL APPROACHES TO ESTIMATION OF SOUND SOURCE CHARACTERISTICS AND SIGNAL PROPAGATION

5.1 INTRODUCTION

One of the key aims of this project is to provide scientific background to project developers and regulators to support best practice on the estimation of the likely acoustic levels in related metrics for signals at various ranges from common UXO clearance activities in UK waters. This review requires two key considerations:

1. consideration and review of the suitability of available source characteristics models / empirical data;
2. review of propagation models / empirical data for likely UXO detonation type signals and environments.

These two modelling approaches in combination are necessary to allow reliable estimation of potential levels versus range from UXO clearance operations in UK waters. The remainder of this chapter will report on progress towards a review of both of these requirements. Section 5.2 provides a review of available models for explosive source characterisation based on available literature. These data are reviewed in context of previous studies (Section 5.2) and data from the current project (Section 5.4). Section 5.3 provides a review of currently available propagation modelling approaches for UXO type signals and Section 5.4 reviews available models with particular relevance to impact metrics of current relevance in shallow water. Section 5.5 discusses of current progress and plans for model validation in collaboration with industry partners under phase 3 of this project.

5.2 REVIEW OF MODELLING TECHNIQUES FOR EXPLOSIVE SOURCE CHARACTERISATION

5.2.1 Background to explosive source characterisation

Study of underwater explosion originated during World War II. Most of the work concerned the effects of large explosives on the integrity of a physical structure (such as the hull of a vessel). Small charges were sometimes used as signal source for communications, propagation loss studies, seabed characterisation, and geophysical surveys for oil and gas exploration [Weston 1960]. A comprehensive description of underwater explosions was first given by Cole [Cole 1948].

The behaviour of an underwater explosion in un-bounded (free-field) medium is depicted in Figure 5-1 with the top trace for the pressure history versus time and the bottom describing the size of a gas bubble generated by the explosion. The blue spot indicates an explosion. A spherical explosive in an infinite water medium will generate a spherical shock wave front with gas bubbles following the shock wave. The shock wave is generated by the explosion with an expanding gas bubble of very high temperature and pressure to reach a pressure peak $P_{\max}$ almost instantaneously, then followed by an exponential decay initially, and slower rate of decay thereafter. It is this shock wave that governs the peak sound pressure in the acoustic pulse that is radiated by the explosive source. In a free-field environment close to the source the speed of propagation of the initial shock waveform is supersonic (travelling faster than the sound speed within the medium) and changes in its amplitude are effectively non-linear not obeying simple scaling laws [Costanzo 2010]. However, at ranges (R) greater than 2 or 3 times of the radius of an equivalent sphere of the solid explosive, the speed of propagation has reduced to the speed of sound in the medium. Nevertheless, non-linear amplitude behaviours can exist for between 10^4 to 10^5 times the radius of the explosive [Arons 1970].

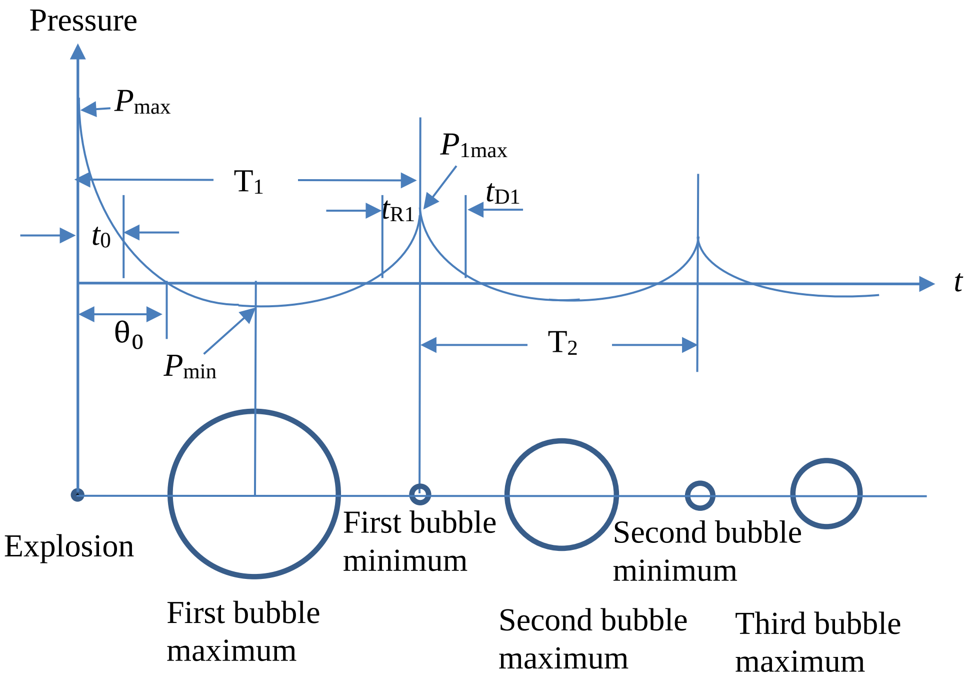

Figure 5-1 Schematic of an underwater explosion in unbounded medium.

The time t_0 in Figure 5-1 is the time constant of the exponential decay at which the pressure reaches an amplitude of P_{max}/e. The gas bubble grows continuously and eventually reaches a maximum size (with a corresponding minimum pressure P_{min}) due to the combination of the inertia of the water mass movement and the internal gas pressure inside the bubble. The bubble now undergoes compression after reaching maximum size and generates a positive pulse where a peak P_{1max} is formed when the bubble again reaches a minimum size. The process repeats as an oscillation until the dynamic energy of the bubble is exhausted. The total Sound Exposure Level of the acoustic pulse radiated during the explosion is governed by the combination of the above processes.

In practice, the gas bubble generated behaves very differently in shallow water. It starts to drift up towards water surface after the first size maximum due to buoyancy. Depending on the depth of the explosion and the size of the charge, the bubble may reach the water surface therefore affecting the radiated acoustic signature.

5.2.2 Empirical equations for sound radiated by underwater explosions

The source characteristics of explosions as monopole acoustic sources has been investigated extensively in a number of key studies to determine the characteristics of underwater explosions [Arons 1954, Weston 1960, Gaspin & Shuler 1972, Gaspin *et al.* 1979]. A number of semi-empirical equations were derived to describe the main parameters of underwater explosions based on a large number of measurements of various explosives different charge size, distance and depth, described in a key publication by Weston [Weston 1960]. TNT was assumed to be the explosive for the equation derived. Different scale factors of equivalent charge weight were then applied to the equations to account for the use of different explosives [Swisdak 1978].

It is helpful to provide some summary of the mathematical description of the waves generated by explosion provided by this literature.

5.2.3 For the shock wave in the non-linear propagation region

For the peak sound pressure, P_{max}:

$$P_{max} = 5.24 \times 10^7 \left(\frac{w^{\frac{1}{3}}}{R}\right)^{\alpha} \qquad (5.1)$$

where the sound pressure is (in Pa), *w* is the charge weight in kg, *R* is the slant range in meters, α=1.13 [Arons 1954], or α=1.18 [Weston 1960] for TNT. The term $\frac{w^{\frac{1}{3}}}{R}$ is referred to as *scaled range*. Note that the original equations were all in Imperial Units, but SI units are used for all equations within this report. The prediction of the peak sound pressure using Equation (5.1) produces good agreement with experimental results over very large scaled ranges (more than three orders of magnitude). The power factor of the scaled range derived from experimental results [Arons 1954; Cole 1948] and confirmed by finite amplitude wave theory [Kirkwood-Bethe 1942] indicates the reduction of the peak sound pressure with range is not equivalent to spherical spreading (inverse relationship of sound pressure with range) because of the non-linear nature of the wave.

Pressure positive impulse, I_0 (in Pa·s)

$$I_0 = \int_0^{\theta_0} P(t)dt = 6697.9w^{1/3}\left(\frac{w^{1/3}}{R}\right)^{0.94} \qquad (5.2)$$

where $P(t)$ is the pressure waveform, and θ_0 is the time duration of positive shock wave as shown in Figure 5-1.

The shock wave time constant that defines the exponential decay of the peak, t_0 (in µs)

$$t_0 = \frac{I_0}{P_{max}} = 127.9w^{1/3}\left(\frac{w^{1/3}}{R}\right)^{-0.19} \qquad \text{[Cole \textit{et al.} 1946]} \qquad (5.3)$$

A number of alternatives have also been given:

$$t_0 = 92.5w^{1/3}\left(\frac{w^{1/3}}{R}\right)^{-0.22}$$ [Arons 1954] (5.4)

$$t_0 = 81.2w^{1/3}\left(\frac{w^{1/3}}{R}\right)^{-0.14}$$ [Chapman 1985] (5.5)

The spectral density of the sound energy flux density due to the shock wave, E_0:

$$E_0 = \frac{2}{\rho c}\frac{P_{max}^2}{\frac{1}{t_0^2}+\omega^2}$$ [Weston 1960] (5.6)

where ρ is the density of water, and c is the sound speed in water, $\omega=2\pi f$, f is frequency.

5.2.4 The first bubble

The peak sound pressure, P_1:

$$P_1 = 9.44 \times 10^6\left(\frac{w^{\frac{1}{3}}}{R}\right)$$ [Arons, 1948] (5.7)

The pressure impulse, I_1 (in Pa·s):

$$I_1 = 4.16 \times 10^4\left(\frac{w^{2/3}}{R}\right)(z_0 + 10.06)^{-1/6}$$ [Arons 1948] (5.8)

The time constant, t_1 (in µs):

$$t_1 = 1.0196w^{1/3}(z_0 + 10.06)^{-1/6}$$ (5.9)

The spectral density of the sound energy flux density, E_1:

$$E_1 = \frac{2}{\rho c}A_1^2$$ [Weston 1960] (5.10)

where:

$$A_1 = P_1\left(\frac{2/t_1}{\frac{1}{t_1^2}+\omega^2}\right)$$ (5.11)

The time delay between the shock wave and the first bubble, T_1 (s):

$$T_1 = 2.11w^{1/3}(z_0 + 10.06)^{5/6}$$ [Chapman 1985] (5.12)

5.2.5 The second bubble

In this case, the key parameters are given by:

$$\frac{P_1}{P_2} = 4.72$$ [Weston 1960] (5.13)

$$\frac{I_1}{I_2} = 2.47$$ [Weston 1960] (5.14)

$$t_2 = \frac{I_2}{2P_2}$$ [Weston 1960] (5.15)

The spectral density of the sound energy flux density, E_2:

$$E_2 = \frac{2}{\rho c} A_2^2$$ [Weston 1960](5.16)

where:

$$A_2 = P_2 \left(\frac{2/t_2}{\frac{1}{t_2^2} + \omega^2} \right) \qquad (5.17)$$

The time delay between the first bubble and the second bubble, T_2 (s):

$$T_2 = 1.48 w^{1/3} (z_0 + 10.06)^{5/6}$$ [Chapman 1985] (5.18)

5.2.6 The spectral density of the total energy flux density

Combining the shock wave and the first two bubbles, the spectral density of the energy flux density of the explosion received at a distance R can be approximately expressed as:

$$E = \frac{2}{\rho c} \left({E_0}^{1/2} + A_1 e^{-i\omega T_1} + A_2 e^{-i\omega (T_1 + T_2)} \right)^2 \qquad (5.19)$$

Equation (5.16) has been used to produce the Energy Source Level of a given explosion determined from SEL alone (not peak sound pressure) [Von Benda-Beckmann *et al*. 2014].

In order to account for the contribution from negative pressure between the pulses, the spectrum at low frequencies are given by

$$E = \frac{2}{\rho c} \{ [I_0 + I_1 \cos(\omega T_1) + I_2 \cos(\omega T_3) - N \sin(\omega T_3)]^2 + [I_0 + I_1 \sin(\omega T_1) + I_2 \sin(\omega T_3) - N(1 - \cos(\omega T_3))]^2 \}$$ [Weston, 1960] (5.20)

Where $N = (I_0 + I_1 + I_2)/(\omega T_3)$. This equation is valid for frequency well below $1/(\omega T_1)$.

5.2.7 The sound exposure level

Using the energy flux in [Arons, 1954], the sound exposure level generated by an explosion in unbounded medium is given as

$$SEL = 10\log\left[1.46 \times 10^{11} w^{\frac{1}{3}} \left(\frac{w^{\frac{1}{3}}}{R} \right)^{2.08} \right] + 120 \text{ re } \mu Pa^2 s \qquad (5.21)$$

5.2.8 Summary on source characteristics

Equation (5.1) and Equation (5.21) provide the peak sound pressure and SEL of an underwater explosion under free-field conditions. Equation (5.20) can be used to examine the spectrum of the explosion. Although these models outlined above are range-dependent they are not necessarily equivalent to a linearly scaling monopole-type source level that would typically be used with longer range propagation models such as those outlined in Section 5.3. These types of models are more typically used for prediction of levels at greater distances (greater than several km's) for impact assessments within shallow water environments. In this case multipath propagation introduces a complicated signal waveform because of interferences among the signals arriving at different times from the direct path, resulting in greater variation of shock wave.

Although the source models cannot be applied directly with propagation models for long range predictions, it is possible to use the source models such as Equation (5.10) and (5.21) at close range where the contributions from reflected waves by the water surface and the bottom are relatively small compared to the direct path due to cavitation occurring near the surface, and greater reflection losses from the bottom with large grazing angles before total internal reflection [Frisk, 1994]. This has be demonstrated by the comparisons between measured and predicted results in Section 5.5.

5.3 LONG RANGE FAR-FIELD PROPAGATION MODELS

To assess the impact of an explosion over a wider area of interest in typical operational environments, the acoustic metrics have to be determined by either measurements (which is not always practical), or by modelling. The modelling involves representing the explosion as an acoustic source generated by the explosion of known linear Source Level, and propagation model(s) to predict the acoustic field at distance from the source. For UXO sources both the source level and propagation characteristics are likely to be frequency dependant and therefore treatment of broadband (multi-frequency) signals may require careful consideration. There are a number of propagation methodologies (outlined below) that can be used for such analysis, some are available for download free of charge, however these complex models often require some expertise to run successfully. These models also vary in accuracy and suitability dependant on modelling requirements. [Wang *et al.* 2014].

Commonly available propagation models are categorised, based on their underlying methodologies [Jensen *et al.* 2011; Etter 2013; Wang *et al.* 2014] including:

- Ray tracing
- Normal mode
- Parabolic equation
- Wavenumber integration
- Energy flux
- Finite Difference, Finite Element models

The ray tracing method is most applicable at high frequencies where the water depth is much greater than the acoustic wavelength. Energy flux methodology codes are often the most computationally quickest, but it can only be used with a constant sound speed and do not resolve the field in terms of depth in the water column. Wave number integration codes are commonly used for uniform depth profiles (range independent) channels. In cases where depth and seabed vary with range (range dependant) wave number codes such as [OASES] can also be used. Adiabatic normal mode approximation and parabolic equations are all very efficient at lower frequencies. Finite difference and finite element models tend to be most used in the vicinity of the source. Some of the earliest modelling for long range propagation of explosive sound was first developed by Pekeris using Normal mode theory [Pekeris 1948].

5.4 PREDICTION OF ACOUSTIC METRICS OF UNDERWATER EXPLOSION IN SHALLOW WATER

5.4.1 Predictions using modelling

In order to determine the acoustic metrics, such as the peak sound pressure and SEL by an explosion in shallow underwater channel at longer ranges from the source, the equivalent (linear) Source Level of the explosive source has to be derived from the shock wave and bubble pulse values in the far-field. At shorter ranges acoustic waveforms from explosive sources are highly non-linear as a function of range (outlined in Section 5.2). To obtain useful far-field linear Source Level estimations requires the use of measured data from the explosion recorded at ranges where the acoustic waves are assumed to propagate linearly [von Benda-Beckmann *et al.* 2015; Ainslie 2010; Jones & Clarke 2005; Jones *et al.* 2006]. The predicted Source Level is then calculated by accounting for the propagation loss (equivalent to propagating back to 1 m from the source) to generate a monopole Source Level for use in propagation modelling of the type outlined in Section 5.3. It is, however, currently uncertain at what distance the waves generated by the explosion may be considered to propagate linearly, since the non-linear interaction has been reported to be still in progress at distances of up to between 10^4 to 10^5 times the radius of the explosive [Arons 1970]. This distance is between 141 m to 1.41 km for 15 g of PE4 explosive, and 1.23 km to 12.3 km for a charge of 10 kg of PE4 explosive.

Prediction of the acoustic metrics in shallow water channel is challenging due to a number of factors. In addition to the fact that the explosive source is non-linear, there are large uncertainties on underwater acoustic channel properties, such as sound speeds and densities, seabed properties, layered structures within the seabed, and bathymetry. The sea surface conditions will also affect the propagation although mostly over the higher frequencies.

Two common approaches can be applied to estimate the key acoustic metrics of peak sound pressure and SEL.

Coherent approach

The use of a source spectrum derived from the shock wave and bubbles coherently combined with a propagation model to produce the received signal spectrum over a range of interest [Jones & Clarke 2005; Jones *et al.* 2006]. Peak sound pressure can then be obtained with an inverse Fourier transform (FFT) of the spectrum, and the SEL calculated simply from a summation of the squared spectrum values.

In order to predict the peak sound level accurately, the non-linear effect should be taken into account. One possible way is to add extra spreading loss up to the range where the signal propagation becomes linear. However, this range has not been quantified definitively [Arons 1970].

Incoherent approach

Another approach is to use the energy spectrum of the source and incoherent propagation models [Weston 1960; von Benda-Beckmann *et al.* 2015] to calculate SEL. It is not possible to find peak sound pressure directly through this approach. However, it is possible to derive a scale factor to relate the peak pressure with SEL [von Benda-Beckmann *et al*. 2015].

5.4.2 Comparison of prediction with experiment

Most reported examples in the scientific literature of predictions of acoustic levels from explosions in shallow water differ from the observed measured values, with the predicted values in general being an overestimate.

For example, measurements of peak sound pressure from small explosive detonations along several tracks of moderate distances (between 2 km and 5 km) in shallow water of less than 100 m deep within the Australian Region [Jones *et al* 2004, 2005, 2006] were about 15 dB less than those predicted from weak shock theory [Gaspin *et al.* 1971]. Simulations with multipath propagation from source to receiver including a spread of time delays indicate that much of the over-estimate can be reduced, indicating that the dispersive nature of the propagation may be affecting the results.

There is also a large discrepancy between the measured SEL and its prediction [von Benda-Beckmann *et al.* 2015]. At the moment, it is not clear what the true reasons are for the differences. To start to address some of these issues a discussion of the planned collection and analysis of empirical data from actual UXO clearance operations in UK waters to better understand longer range propagation in Phase 3 of this project is included in Section 6.

5.5 SOURCE MODEL COMPARSION WITH MEASURED DATA FROM LIMEHILLOCK QUARRY

The data collected from Limehillock trial provide useful free-field information on explosion at very close range where there was a separation of the shock wave from other paths such as surface and bottom reflections. A number of important parameters to describe the source characteristics of an explosion as mentioned in Section 5.1 can be found from the measured signal wave forms at close range.

Figure 5-2 shows measured and modelled sound peak pressure as a function of scaled range $w^{1/3}/R$ for all the charge sizes at two ranges, 11.1 m and 21 m respectively. In this case Weston’s empirical model [Weston 1960] shows good agreement with the measured data at these shorter ranges.

The time constant of the shock wave for all 68 signal waveforms is plotted in Figure 5-3. The horizontal axis is for measurement and the vertical axis is for model. The red line in the plot indicates a total agreement between the modelled data and the measured data. Three estimates by [Arons 1954; Coles 1946; Chapman 1985] are used. It can be seen that results fit best to that of [Arons 1954], less to [Coles 1946], and least to [Chapman 1985] for the data set collected. It is not possible to explain the reasons for the differences without further investigations.

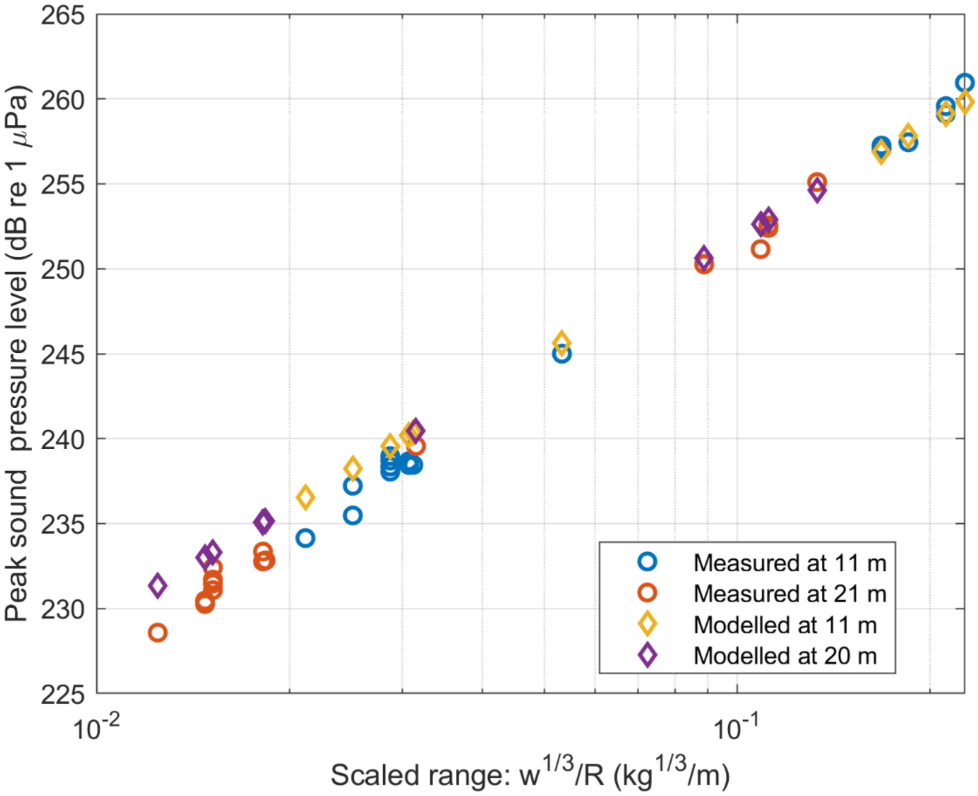

Figure 5-2 Measured and modelled peak sound pressure level for Limehillock trial.

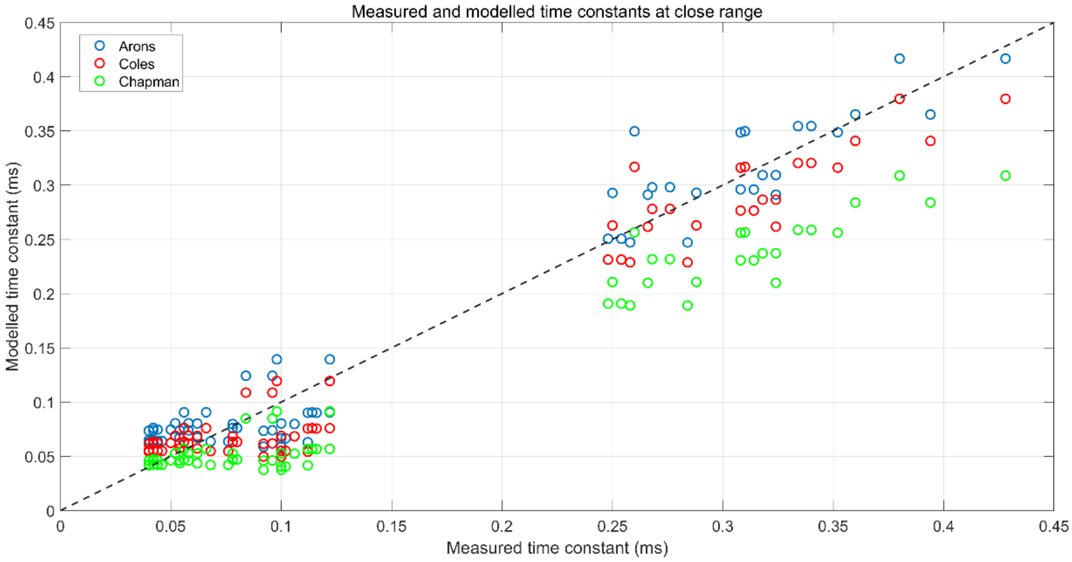

Figure 5-3 Measured and modelled time constants of the shock wave. (Note: data close to the theoretical perfect match shown as the solid red line indicate good correlation between measured and modelled data.)

Although the time constants follow similar trends, the data vary even for charges of the same size. The spread of the time constant is large as indicated by **[Arons 1954]**. This time constant is important as it is the primary influence on variability in the lower frequency part of the overall frequency spectrum. The time delays of the first and second bubbles are needed in calculating the spectrum of the explosion signal with Weston model [Weston 1960], which are necessary to be able to apply frequency weighted marine mammal SEL criteria.

Although there may be many oscillating bubbles that radiate acoustic energy after the shock wave, their contributions are often negligible after the first two [Weston 1960]. It is however useful to compare the peak amplitudes of the first two bubbles against the shock wave peak. The shot number and corresponding charge size are given in Table 6. Figure 5-4 shows measured relative peak of the first two bubbles to that of the shock wave at two nominal ranges, 11 m and 21 m. It is noticed that the second bubble is about 10 dB lower than the first bubble which is about 10 dB lower than the shock wave. The level of the peak pressure from the first two bubbles of the 18.4 kg charge explosion is much less than the shock wave due to the shallow depth of the detonation where a substantial amount energy was released through the surface plumes. All 10 kg high order explosions demonstrated similar level of bubble peaks for both the first and second bubbles. It is however difficult to explain this phenomenon without further tests.

Table 6 Shot number and charge size of Limehillock trial

Shot number	1	2	3	4	5	6	7	8	9
Charge size (kg)	10	10	5	5	0.025	0.025	0.025	0.025	0.025
Shot number	10	11	12	13	14	15	16	17	
Charge size (kg)	0.048	0.025	0.015	10	18.4	0.048	0.048	0.25	

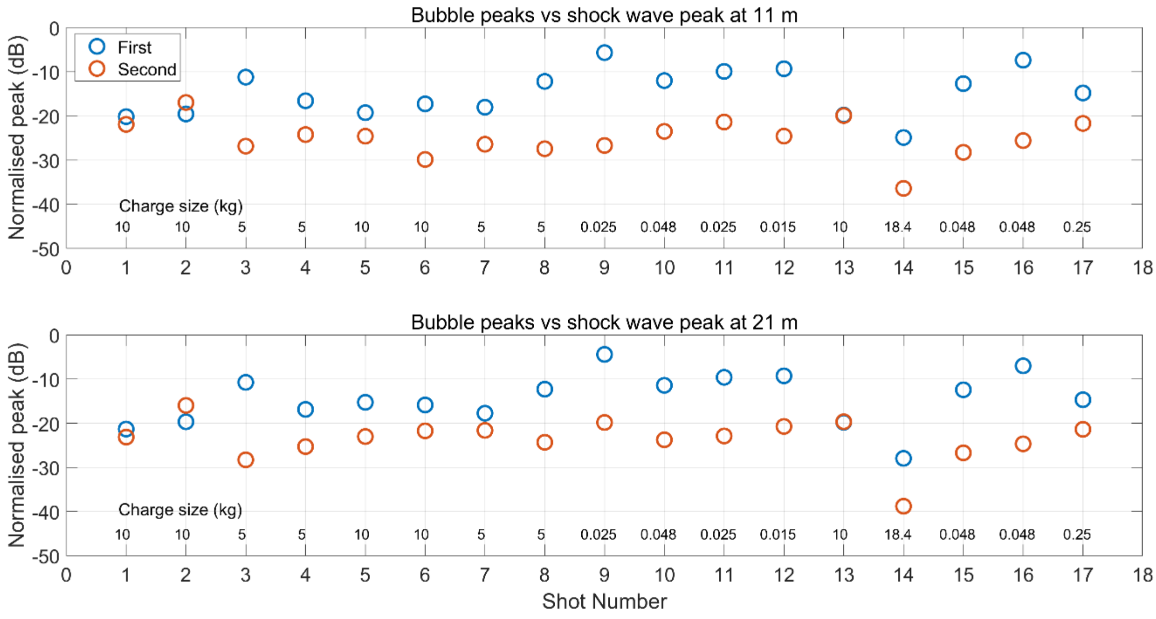

Figure 5-4 Relative peak level of bubbles vs the shock wave

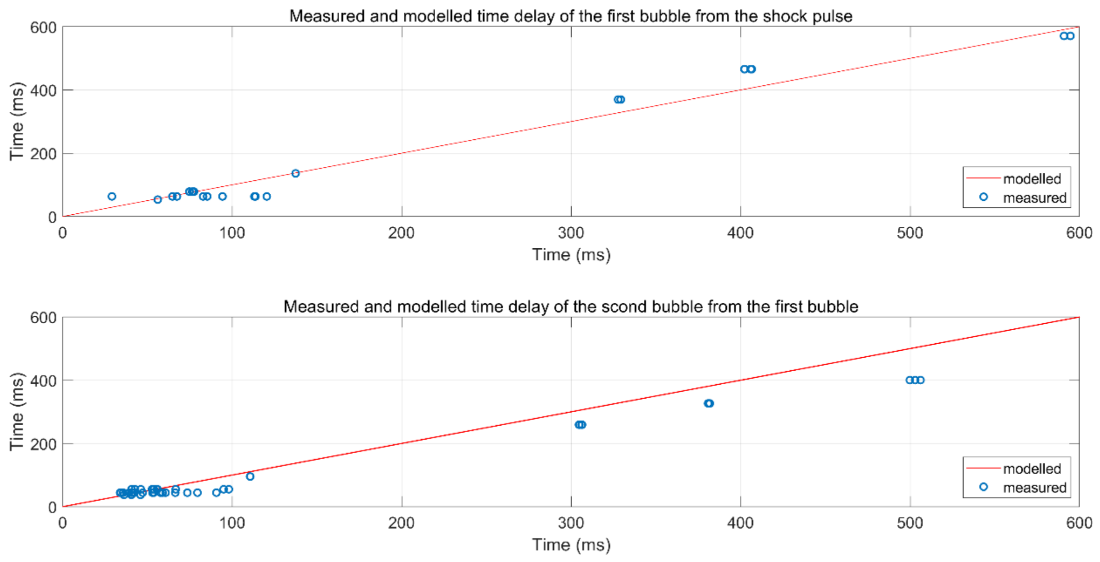

Figure 5-5 Measured and modelled [Chapman 1985] bubble time delays

Measured and modelled time delay of the first and the second bubbles are shown in Figure 5-5. It seems the model [Chapman 1985] is reasonable in comparison with the measured data.

The sound pressure level power spectral densities of six charge sizes: 15 g, 25 g, 48 g, 5 kg, 10 kg and 18.4 kg are plotted in Figure 5-6 with two measured data by pressure gauge 1 (PG1) and pressure gauge 2 (PG2), and predicted spectrum by Equation (5.20). The general agreement is good albeit that the model is applicable only to a source in free field condition whereas the measurement was in a shallow water channel there where signals reflected from surface and bottom are included. It is noticed that the model predicts a roll off to f^2 at high frequencies. The measured data decays much slower because of the cavitation effect by the reflected shock wave from water surface. The large variation of the PSD around 1 kHz for the low order explosions might be from the contributions by bubbles. However, the roll-off of the spectrum of the low order is the same as the high order from 4 kHz and above.

5.5.1 Concluding remarks on source model validation

The data collected from the Limehillock Quarry were used to verify the source models Equation (5.1) for peak sound pressure, Equation (5.20), for PSD, Equation (5.21) for SEL, and some other important parameters for underwater explosive sources. In general, good agreement was found between the measured and modelled results. The condition for measurements by the shock pressure sensors was free-field for the peak of the signals where the direct path from the shock wave can be separated in time clearly. Multipath reflections from the water surface, bottom and walls of the quarry were observed as arriving later in time. As expected, the measured peak sound pressure is in very good agreement with the model predictions. There is also good agreement between the measured data and model predictions for the PSD and SEL, except there is higher spectrum level in PSD caused by cavitation in the measurements.

It is sensible to use these models to predict the required acoustic metrics at a close range, *R*, in shallow water with a source placed well away from boundaries, where the contributions from surface and bottom reflections are small in comparison with the direct path as mentioned in Section 5.2.8.

It is necessary to modify the models where UXO is on seabed. The peak sound pressure will be higher because it is the sum of direct path and the first bottom reflection, and both should arrive at essentially the same time to a receiver in water column. The peak sound pressure will therefore depends on seabed properties as $P_{\mathrm{pk}} = (1+R_{\mathrm{b}})P_{\max}$ where $P_{\max}$ is given by Equation (5.10), and R_{b} is reflection coefficient of seabed. There is likely to be an increase of impact range in comparison with the result using only the model Equation (5.1) for the source in mid-water column.

For impact assessment over a long distance, a source signal can be derived from the models in Section 5.2 for propagation models. Although the signal propagates non-linearly, it is reasonable to ignore the effect over a short distance, for example for $R<10D$ where prediction of the waveform with propagation models should generate sensible results. However, the signal amplitude over a longer distance will be over-estimated because the non-linear effect of the signal cannot be taken into account by the propagation models. To account for the effect, measured data at larger distances, ideally greater than 10^5 of explosive charge radius, should be used to re-scale the Source Level. The re-scaled prediction is then valid only for the linear propagation. To cover the whole range for the signal propagation, it is non-trivial to find solutions to connect the results between the close (nonlinear) range and the longer (linear) range.

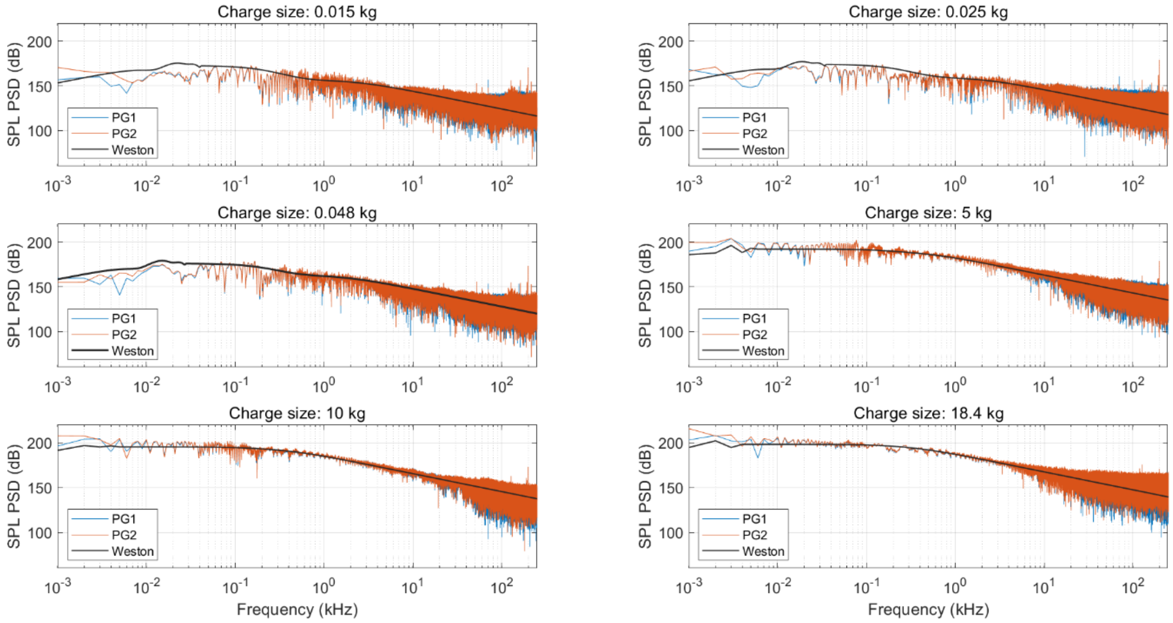

Figure 5-6 Measured and modelled sound pressure spectral density level (in dB re 1 μPa^2/Hz) for different charge sizes.

5.6 SUMMARY

The equations outlined in Section 5.2, namely Equation (5.1) for peak sound pressure [Weston 1960] and Equation (5.20) for PSD and Equation (5.21) for SEL [Arons, 1954], are generally well supported by empirical data from well-defined explosive charges in the original studies of known charge size, for example equivalent grams of TNT. They are applicable to explosions in un-bounded medium over a long distance due to non-linear propagation of the signal waveform up to ranges between 10^4 to 10^5 times the radius of the explosive [Arons 1970].

Note that the scaled range parameter (size / range ratio) commonly referred to in this literature is related to both effective charge size and range based on empirical measurement in a free-field environment within the non-linear propagation region. These equations can be used to usefully predict characteristics in amplitude and time (both peak sound pressure level and SEL) of likely source characteristics in free-field (where no interaction of the waveform with for example the surface has occurred) for the non-linear part of the propagation.

However, the review undertaken here does substantiate the proposition that the peak sound pressure, signal power spectrum density and sound exposure level can be usefully predicted using Equations (1), (20) and (21) up to a range where the nearest multipath starts to affect the direct path signal. The outcomes of these earlier studies were supported by the results of the quarry trials in this study, showing a good correlation between models of Equation (5.1) [Weston, 1960] and peak sound pressure, Equation (5.20) and PSD, and Equation (5.21) [Arons, 1954] and SEL in a similar controlled environment as outlined as in Section 5.5.

5.6.1 Consideration of UXO clearance versus known explosive charges

It should also be noted that in the case of actual UXO clearance operations, the sound source usually involves the near instantaneous combination two charge types: a) the original explosive material from the legacy munition under clearance; and b) a high order detonation of an added ‘donor’ charge of modern explosive material used to initiate either high order detonation or low order deflagration of the original explosive charge described in a). Prediction of the contribution from the secondary ‘modern’ donor charge is much more likely to fall in line with the predictive models outlined in Section 5.2. Prediction of the contribution from the original explosive charge to the overall levels may however be much more complicated due to a number of factors including:

- Type, physical dimensions and shape of munitions;
- degradation of munition due to long exposure to environment;
- degree to which the munition is buried in sediment ;
- seabed type;
- potential for aggregation (multiple devices co-located).

The received sound levels from both the UXO and the donor charge will be affected by additional factors:

- type of explosive used;
- water depth at UXO location;
- variations in environmental conditions (seabed, bathymetry, sea-state, etc) along the path from the source to receiver.

The variance caused by many of these factors are realities of real UXO clearance operations currently underway or planned in UK waters. Many of these factors for example the degradation of explosive material over time or partial or complete burial of munition may result in sound levels significantly lower than predicted by the models outlined above based just on charge size. The potential individual and cumulative effects of many of these factors provides a potential high level of uncertainty in overall level prediction in terms of absolute level from the original UXO explosive charge. Conversely, the effects of aggregation of multiple munitions into one place may provide net acoustic levels higher than that from a single munition. In this case comparison of theoretical combined maxima and measured in-situ levels during actual clearance operations will be invaluable.

The capability to deconvolve the direct effects of any one of these factors based on available historical data is not feasible within the current study. However, to help address this, Section 6 of this report outlines the review of available data sets of real UXO clearances in collaboration with industry partners to be conducted in Phase 3 of the project. This will provide some insight on the potential influence of these effects on prediction of the overall acoustic level.

However, it is reasonable to conclude that the overall combined acoustic output of both the original and donor charges potentially observed from ‘real’ UXO clearances will likely lie somewhere between the theoretical prediction of two limits: (i) at minimum, that of just the donor charge assuming no additional contribution from the original explosives; and (ii) a potential worst case maximum of the combined explosive charge of both the donor and original charge detonating at levels predicted for the non-degraded free-field levels. The initial comparison of the models outlined in Section 5.2 therefore can provide useful guides to predicting both of these limits.

In the case of a successful deflagration, the measured levels from the controlled quarry experiment show that the contribution from the original explosive material would be significantly lower than for high order, with the primary contribution to the overall level coming from the more predictable (and modest-sized) donor charge. The data outlined in Section 4 from the quarry trials and Section 5.4 suggest that reasonable prediction of levels from deflagrations trails can be made based on the models outlined in Section 4 and 5.2 from the donor charge alone at shorter ranges.

6 FUTURE ANALYSIS OF OFFSHORE EOD ACOUSTIC DATA

6.1 CURRENT STATUS

Up to now, it has been difficult to obtain data for acoustic measurements conducted offshore. This is often because such measurements are not mandated by marine licences and so are not always conducted. In England and Wales, bubble curtains are sometimes mandated with measurements taken outside the bubble curtain (if they are made at all). In Scottish waters, the increased water depth militates against bubble curtains and EOD operations do not typically use noise abatement. When they are conducted, there has been no standardised way of undertaking the measurements (though the protocol produced as an output of this project will help to standardise the methods used). Often, measurements have been made with equipment that is either unsuitable or using deployments of opportunity (which were intended for other purposes but happened to record UXO disposal exercises). Where measurements are made, they are owned by the developer, and issues of confidentiality sometimes militates against their use in the current project (without confidentiality agreements).

The above factors have made it difficult to obtain offshore data for analysis within the project so far. The ideal scenario would be that a developer is willing to make measurements using the protocol produced by the project, and with the active participation of the project partners in designing the measurement campaign, and full provision of all data to the project. Ideally, the EOD operation would include at least some UXO which are treated with deflagration rather than only high-order methods.

6.2 OBJECTIVES

The objectives of the analysis of in-situ data measured during actual EOD operations is as follows:

- build up a data-set of acoustic measurements of EOD operations on UXO in real offshore conditions for a variety of scenarios (unmitigated high-order, high-order mitigated with bubble curtain deployments, high-order mitigated with scare charge deployments, low-order deflagration);
- analyse recordings from scare charges of known size to validate propagation loss modelling;
- use of scare charge data to ‘calibrate’ propagation models for recordings of EOD and estimate effective charge size;
- for each EOD explosion (with or without mitigation), estimate range to PTS threshold with both metrics.

The outputs and recommendations from the analysis can be used to provide:

- guidance for making predictions for future impact assessments (guidance on propagation loss for use in predictive models);
- guidance for regulators and advisers when revising mitigation measures (for example, when assessing whether scare charges effective are effective);
- guidance for producing realistic cumulative assessments (actual impact zone).

6.3 MORAY EAST

The only data set currently made available is from Moray East offshore windfarm (OWF). The data was provided by the University of Aberdeen with permission from the windfarm developer.

A total of 17 UXO targets had been identified within the windfarm site and cable route. The acoustic monitoring programme was integrated into the early construction stages as part of the Marine Mammal Monitoring Programme run by University of Aberdeen. The waveform data extracted and classified by the University of Aberdeen and CEFAS, and acoustic analysis is being undertaken by NPL & Loughborough University. The data has the following features:

- UXO of size between less than 1 kg and up to 175 kg high explosive;
- All EOD undertaken with high-order detonations
- Donor charges used of between 1 kg and 25 kg
- No noise abatement used (no bubble curtains)
- Mitigation: ADDs, followed by scare charges (50g to 200g)
- Measurements made with 7 bottom mounted noise recorders
- More than 500 recordings made at ranges of between 1.8 km and 54 km
- Around 60% of waveforms suitable for waveform analysis
- High-order charges measured at ranges of between 9 km and 54 km
- Scare charges measured at ranges of 5 km to 54 km

The Moray East data is currently being analysed. An online briefing meeting was held with the developer, University of Aberdeen, CEFAS, Marine Scotland and Scottish Natural Heritage.

6.4 OTHER SOURCES OF DATA

6.4.1 Existing data

Existing data has been offered from three sources:

Hornsea OWF
Data has been measured by contractors using a fixed grid of acoustic recorders, with protocol draft provide to contractor. Bubble curtains were used as noise abatement for all UXO (about 70 in total). Reports have been completed by the contractor, and we await approval from developer before data can be provided.

East Anglia OWF
Offer of data made by developer after report received from contractor. NDA agreed with developer. We await the data.

TNO
Modest volume of data will be made available by developer for a Danish windfarm, with data already analysed by TNO

6.4.2 Future data sets

Neart na Gaoithe OWF

The EOD process will be underway in early summer 2020 for Neart na Gaoithe OWF. This Scottish OWF is not expecting to employ bubble curtains as UXOs are at depth >40m (i.e. bubble curtain deployment unlikely to be effective) but will use ADDs and scare charges as part of mitigation measures. The contractors are expected to adopt the guidance protocol, and the project partners have been involved in discussions with the developer and with SNH and SMRU regarding the design of the measurement campaign. Clearance will take place by high order detonation.

Seagreen OWF and Hornsea 2 OWF

Discussions are ongoing with developers about obtaining data from these two OWFs.

7 CONCLUSION

7.1 SUMMARY

This report describes the work for Offshore Energy SEA Sub-Contract OESEA-19-107. The project addresses Phase 2 of the work to characterise the acoustic fields generated during the disposal of Unexploded Ordnance (UXO) on the seabed, a process termed Explosive Ordnance Disposal (EOD).

The work encompassed a review of current practice (completed in Phase 1), provision of a guidance protocol for those undertaking measurements of EOD for UXO in the ocean (initially drafted in Phase 1), conducting a controlled field trial to study the mitigation benefits of low order detonation by deflagration and examine the sound generation mechanisms, study of the sound generation mechanisms for different types of UXO detonations (high and low order) and long-range propagation and collection and analysis of offshore in-situ measurements made by developers and researchers.

The guidance protocol drafted in Phase 1 of the project and circulated to the project Steering Group was revised in response to comments (which were summarised in a compilation document with responses). This protocol is a separate document (but a brief summary of it has been included as Section 3).

The controlled field experiment was carried out to quantify the difference in acoustic output levels from two EOD methods. Measurements 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, and with the acoustic output depending on the size of the shaped charge (rather than the size of the UXO itself). A semi-empirical equation for peak pressure, developed in the years after World War II is shown to be consistent with these new results. This has been summarised in a scientific paper to be submitted to a peer-reviewed journal.

A theoretical study of the sound generation mechanisms for UXO detonations and a study of the long-range propagation has been carried out. Predictions of noise levels for EOD requires a proper source model for the explosion and a suitable propagation model to predict the relevant acoustic metrics, such as peak sound pressure and sound exposure level (SEL) in the region of interest. It has not been possible to experimentally validate the modelling because it has been difficult to obtain data from developers and researchers. This in turn has made it very difficult to experimentally validate the propagation modelling studies.

The deliverables and outputs of the project are as follows:

- a scientific paper to be submitted to a peer-reviewed journal;
- revised guidance protocol for or those undertaking offshore measurements of EOD;
- technical report summarising all technical outputs (this document);
- presentation of results of the controlled experiment the Noise Abatement Workshop at The Royal Society on November 12th 2019 and inclusion of summary in the Workshop Report;
- presentation of the project at the MSCC Underwater Sound Forum on November 20th 2019.

7.2 NON-ACOUSTIC OBSTACLES TO ADOPTION OF DEFLAGRATION

Extensive discussions have been undertaken with developers which have brought into focus a number of non-acoustic obstacles preventing the rapid adoption of deflagration as a technology for UXO clearance. The Noise Abatement Workshop provided the first opportunity for in-depth discussion on these matters. Subsequent to that meeting, further discussions were undertaken with the Steering Group members and with suppliers on low-order EOD using deflagration, specifically staff of EODEX and Alford Technologies.

The issues discussed are strictly beyond the scope of this project, but they are worth listing here.

Chemical toxins
The spread of toxins may potentially be much reduced with deflagration (the explosion is less violent and more localised and so should not spread the toxins over a large area). However, concern has been expressed over the possibility of residual explosive left on the seabed leaking toxins into the water column at a greater extent than before the UXO was fragmented by the deflagration. This problem is largely removed if the residues are physically collected post deflagration.

Logistics and operational procedures
Concern has been expressed about the operational procedures used for deflagration, in terms of safety, logistics, risks and cost. It has been proposed that these are likely to be similar to those for a high-order EOD, but there is a need for education of developers and operators, by suppliers of deflagration, perhaps with example method statements made available for inspection, and with ROVs used for collection and handling of shaped charges and explosives rather than divers.

Residual explosives
The seabed destruction under deflagration is likely to be much reduced compared to high-order EOD, but concern has been expressed about the residual explosive left on the seabed (the deflagration process does not consume all the explosive). Methods for collection of the residues are required, preferably using ROVs. These are currently available, but developers and operators need educating about the methodology and the risks.

Reliability
The high reliability claimed for deflagration has been challenged in some quarters, and it is difficult to see how this can be addressed until the method is actually attempted in offshore EOD operations so that some data becomes available. If data on success rates can be made available from EOD for military applications, of from applications in air, this may provide more confidence.

Applicability of deflagration to all UXO
There is a question raised over the suitability of deflagration for highly degraded UXO, where the munition cannot be identified. There is more potential for the shaped charge to be positioned incorrectly on the UXO, and this requires the UXO to be correctly identified. In cases where the UXO cannot be identified, a high-order detonation may be the only option.

Access to technology and scalability

There is only one supplier of a service for deflagration currently. Wide adoption of the technique might require a roll-out of procedures and technology, possibly through licensed use and training.

7.3 FUTURE WORK

There are a still a number of key knowledge gaps with regard to measurement and prediction of acoustic fields from underwater explosions during UXO disposal.

There is uncertainty in the characteristics of the acoustic output of UXO disposal due to the effect of age, state of corrosion, design, composition, position, sediment type, and degree of burial, orientation and multiple device aggregation. Establishment of a complete record of UXO detonations in UK waters with data provided by developers and researchers would allow this knowledge gap to be filled.

Regarding propagation, it is very difficult to predict the acoustic metrics such as peak sound pressure level, and sound exposure level (SEL) due to a number of uncertainties in the modelling process. The source level from an explosion has to be derived either through measurements, or from prediction by the empirical equations. In addition to the uncertainties from the source level, there are large uncertainties on underwater acoustic channel properties. These uncertainties are likely to affect the prediction of peak sound pressure more than the SEL. The study into propagation in the project so far has been unable to undertake sufficient experimental validation of propagation over long ranges because of lack of offshore measured data. With all the in-situ field data obtained from UXO clearance operations, a major issue is uncertainty over the size of the UXO detonation (how much of the UXO detonates along with the donor charge). However, the use of scare charges provides an opportunity to “calibrate” the propagation because these sources are much lower amplitude and, being of known size, are therefore “easier” to measure even at close ranges. The propagation validated against the scare charge source, can then be applied to the main high-order UXO detonation.

A controlled experiment to evaluate the effectiveness of bubble curtains for sound attenuation in EOD would be valuable. Again, such experiments are difficult and expensive at sea, and are very unlikely to be controlled (with like-for-like comparisons). It is possible that such an experiment could be undertaken using the quarry-based approach used for the deflagration tests (Limehillock quarry has the capability to produce bubble curtains).

Seabed vibration and particle motion remain unknown effects for UXO sources. The detonations generate acoustic waves which propagate on and through the seabed, and a full understanding of this aspect of the propagation is currently lacking, though it is known that sound propagating through the seabed can influence the sound in the water column at some range from the source, for example through an upwardly refracted or reflected wave which re-enters the water column. Waves propagating along the surface of the seabed will not re-radiate into the water column but have the potential to harm benthic creatures, another aspect which is poorly understood. In addition, measurement and/or modelling is required of acoustic particle velocity to assess potential exposure of fish and invertebrates to the sound fields generated by explosions. Whether this can be accommodated within the scope of a future the project remains to be decided.

Further discussions with TNO regarding future collaboration are worthwhile, especially since they have experience with measuring UXO and access to EOD operations in Dutch waters. It may also be worth making further contact with JPIO European consortium on UXO, though much of their focus seems to have been on finding UXO and on chemical pollution.

A major cornerstone of any future work has to be the acquisition of acoustic data measured offshore, both for high-order detonations, *and* deflagration. The only feasible way this is likely to occur is with cooperation with an existing windfarm developer, such that the data is generated by UXO clearance programme that is already in the planning stage. The ideal scenario would be that a developer is willing to make measurements using the protocol produced by the project, and with the active participation of the project partners in designing the measurement campaign, and full provision of all data to the project. If needed, NPL and Loughborough University could provide additional equipment for the campaigns. Ideally, the EOD operation would include at least some UXO which are treated with deflagration rather than only high-order methods. Currently, there are offers of data which include unabated high-order EOD with scare charges and ADDs, abated high-order EOD with bubble curtains, but none utilising deflagration. Further discussions with EODEX and Alford Technologies regarding provision of example method statements and procedures for deflagration will help with adoption by developers.

Analysis of in-situ data measured during actual EOD operations will enable the following to be achieved:

- a valuable data-set of acoustic measurements of EOD operations on UXO in real offshore conditions for a variety of scenarios may be built up (mitigated and unmitigated, high-order and low-order);
- the recordings from scare charges of known size in mid-water column can be used to validate propagation loss modelling, potentially including both the nonlinear region and the linear region at greater range from the source;
- the models obtained for the scare charges may be used to ‘calibrate’ propagation models for measured data of high-order EOD and estimates of effective charge size may be made;
- measured data from deflagration attempted offshore will enable validation of the predictions from the controlled quarry experiment, confirming that the source level depends only on the shaped charge;
- for the variety of EOD operations (with or without mitigation, high and low-order), the range for PTS threshold exceedance may be estimated.

A paper has already been prepared describing the controlled experiment comparing deflagration with high-order EOD. Another paper pulling together the analysis of the offshore data from a variety of OWF scenarios, which included both high-order and deflagration, with and without bubbles curtains, and including scare charges, would be the most comprehensive paper of its kind and a valuable contribution to the field.

The outputs and recommendations from the future analysis can be used to provide:

- guidance for making predictions for future impact assessments (guidance on propagation loss for use in predictive models);
- guidance for regulators and advisers when revising mitigation measures (for example, when assessing whether scare charges effective are effective);
- guidance for producing realistic cumulative assessments (actual impact zone).

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