**Annex 4**

# Mitigation inventory for explosive use in the marine environment

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## 1 Introduction

Explosives can produce the loudest source of human made underwater noise, producing sound with impulsive characteristics e.g. a rapid rise time and high peak pressure. They are used in the marine environment by multiple sectors, oil and gas (perforating wells, decommissioning), harbour construction and shipping channels and for wreck removal as well as military activities. In addition, any new development must ensure their site is clear of unexploded ordnance (UXO) before works can commence, and this may involve the detonation of munitions.

This inventory aims to provide background information on explosive use in the marine environment and details of mitigation methods currently used or under development that can be employed to reduce the risk of impacts on marine species.

## 2 Explosive use in the marine environment

For decades, explosives have routinely been used in the marine environment. Many military ordnances have been detonated during both war and peace time (i.e. testing). Smaller charges are widely used, for example during salvage operations, harbour clearance, harbour bottom alterations, rock and concrete blasting, steel cutting, propeller removal etc. (Department of Navy 1956). They have been used as fishing aids (Cassano et al. 1990), seismic energy sources (Swisdak & Michael, 1978, Richardson et al. 1995), sonar sources (explosive echo ranging against submarine targets; Urick et al. 1967), and acoustic deterrents (Shaughnessy et al. 1981; Mate and Harvey, 1987, Simonis et al. 2020, Krumpel et al. 2021). More recently, explosive charges are now utilised in a tool that can be used when responding to major oil blowouts.

An explosive is a substance or mixture of substances which, when suitably initiated, is capable of a rapid and violent chemical reaction. This reaction is always accompanied by a sudden rise in pressure resulting from the formation of gasses and their expansion by the heat liberated in the reaction (Department of Navy, 1956). The pressure signature of an underwater detonation is composed of the initial broad-band shock pulse (or wave) followed by an exponential decay and a succession of oscillating bubbles resulting from oscillations of the gas globe when rising to the surface (Richardson et al. 1995). A low-frequency seismic precursor can also be seen in the signal at larger distances which is the result of a faster sound speed in the ground where a seismic pressure wave radiates and also couples to the water thus extending over a longer time (perceived as a rumble) (Haak & Abshagen 2024). Whereas the underwater shock pulse is relevant for injuries, the latter is also of interest for estimating the efficacy of noise abatement (section 6.3).

The leading edge of the underwater blast front rises fast and contains much of the high frequency energy (Parvin et al. 2007, Haak & Abshagen 2024). The rise time is much faster than, for example, airguns, and can result in a greater extent of biological injury (Richardson et al. 1995). Both the steep wave front and the high peak pressure determine the severity of injuries (Landsberg 2000). The positive acoustic impulse, i.e. the average level of the blast wave pressure multiplied by its duration, is an often-used measure of energy and is also closely correlated with organ damage, especially to air containing structures such as swim bladder or lung in animals (Parvin et al. 2007). Cavitation by the negative pressure occurring shortly after the shock wave may cause nitrogen bubble formation in the blood and tissues of diving animals (Lewis 1996). At large distances from the explosion, the propagation of the shock wave is like other sound waves, but as high frequency components are absorbed and scattered, the waveform becomes extended over time and is dominated by low frequency energy. This is consequently perceived as a “rumble” at distance (Parvin et al. 2007).

The impact on the environment of explosives is mainly a function of the charge number, and charge weight used. Further, charge depth, water depth or in general propagation conditions and bottom topography are important factors.

Examples of explosive use in the marine environment include:

**i. Unexploded ordnance (UXO) and its removal**

UXO is usually detonated out of health and safety or economic considerations e.g., before construction of offshore installations. After World Wars (WW) I and II, many UXO were left undetonated in the marine environment while others were dumped (often also referred to as sea-dumped munitions) (Böttcher et al. 2011, Ordtek Ltd. 2015). UXO includes sea mines, torpedoes, depth charges, air-dropped charges, artillery projectiles, rockets, land mines and land service ammunition (e.g. mortars, grenades, small arms ammunition), which may be found in isolation or in munition dump areas. It is estimated that during WWII, 10% of military ordnances deployed during combat in the seas around the UK failed to detonate (Alpha Associates, 2011a). During WWI, over 128,000 sea mines were deployed around the UK with an additional 100,000 deployed in the North Sea during WWII. For UK waters, there is no record of mine-sweeping activities after WWI, and it is estimated only 15-30% were recovered after WWII (Alpha Associates, 2011a). Worldwide, it is estimated that more than 550,000 mines were deployed during WWII, and it is unknown how many were detonated or recovered in total. In most cases, the locations of deployed munitions have been recorded in war diaries (e.g. mine laying). It will require some effort to make this information available from the archives. However, post-war archiving of diaries from mine sweeping activities may be incomplete. Also, post-war dumping activities were often carried out by civilian vessels where record keeping was poor. En-route dumping also occurred which is a challenge for locating items which were dumped in such manner. Further, positioning during WWI and WWII was much less accurate compared to modern GPS systems or munitions may have been relocated e.g., by bottom trawl fishery and thus, even recorded positions can considerably deviate from the real positions.

In addition, munition-laden ships lay wrecked on the seabed. For example, the HMS Royal Oak was sunk in Scapa Flow, Scotland complete with all its ordnances (Westman, 2006); the SS Richard Montgomery in the Thames Estuary was sunk with 6,127-ton net explosive quantity (NEQ) on board and the SS Kielce with 1,750-ton NEQ in the English Channel. Attempts to clear the Kielce in 1967 resulted in an unplanned explosion which resulted in significant damage to properties onshore and the seismic effect was recorded out to nearly 5,000 miles (MCA, 2000).

Following the world wars, ordnance has continued to enter the marine environment, predominantly through military training exercises and surplus ordnances have been routinely dumped at sea. The Beaufort's Dyke munition dump site is purported to contain in the order of 1.2 million tonnes of explosive items including chemical munitions (Callaway et al. 2011) and there are a further 19 reported mixed Abandoned Explosive Ordnance dumpsites around the UK. During dumping operations in Skagerrak (Norway) and off Måseskär (Sweden), complete ships and semi-finished hulls were filled with chemical munitions objects which also contain explosives and were scuttled after WWII (HELCOM 2024).

Currently, UXOs can be expected anywhere in the sea. Any new development at sea must demonstrate its site is clear of UXO before works can commence. Therefore, UXO removal activities have increased locally due to recent offshore renewable energy development (Böttcher et al. 2016, 2017).

The impact of UXO removal on the environment depends on the amplitude of the shock wave which is driven by various factors such as charge weight, charge depth, type of explosion (see section 6.5.1) and bottom topography. Further, unburnt residue can contaminate the environment (Maser et al. 2023).

### ii. Ship-shock trials

Explosives can be used to test the robustness of a ship, submarine or other seagoing vessel within military context.

To demonstrate a battleship's ability to withstand the effects of nearby underwater explosions and retain its required combat capabilities, some Navies perform “ship shock” tests, also called “Live Fire Test and Evaluation (LFT&E)”. In these trials, explosive charges with ascending sizes are detonated close to the ship’s hull, or charges of fixed sizes are progressively moved closer to the hull. The largest charges used during ship shock trials are often in the order of 1,000 kg, but much larger charges have been reported. During a four-month testing operation, the aircraft carrier USS Gerald R. Ford withstood the impact of three 18.1 metric ton underwater blasts, released at distances progressively closer to the ship (US Navy 2021). Ship shock trials are usually performed with the first-in-class ship of a new series to enable correcting possible design deficiencies in later produced ships. They are performed with a crew on board and are not intended to damage equipment. Thus, additional simulations can extrapolate measured effects to realistic combat conditions (Mair et al. 1998).

### iii. Military training

Various military exercises take place on, in and above the water, for which specified training areas have been demarcated. These exercise areas are often publicly accessible areas unless they are designated as restricted areas.

Among others, the following activities may include surface or underwater explosions:

- Firing and impact of guns or cannons of various calibres from land, ship and aircraft
- Firing and in air detonations of missiles against sea targets
- Firing and detonations of torpedoes
- Mine hunting, deactivating exercises or intentional blasting
- Mine diving training and following training explosions
- Testing of new weapons systems
- Depth-charge exercises for training purposes.

### iv. Rock removal in harbours and shipping lanes

Underwater blasts can also occur as part of construction activities. Underwater blasting is used to fragment the rock so that it can subsequently be dredged and removed. For this purpose, typically a series of vertical holes are drilled into the rock and explosive charges based on nitro-glycerine or ammonium nitrate are inserted. On top of the explosives, a filler can be added to direct explosion forces into the surrounding rock. To synchronise multiple charges to detonate simultaneously, a detonating cord can be used. Often, short delay electric detonators are used instead to distribute the energy across a longer time signal (IADC 2016). Several factors determine the impact on the environment, e.g., overall charge number and weight, charge weight per delay, time delay between detonations of serial charges, detonation velocity of the explosive used, charge depth within the hole, type of rock, and spacing between blast holes.

### v. Cutting

Explosives are regularly used for cutting purposes, for example during ship repair/upgrades, harbour alterations, salvage operations, removing platforms and other offshore infrastructure etc.

Explosive cutting has been used successfully by the UK oil and gas industry during decommissioning for a range of activities (DESNZ, 2023). For example, they can be used to cut mooring cables, lines and chains, to sever piles, well conductors, caissons, risers and tubing. Before plugging and abandoning wells, the tubulars can be cut off at a predetermined depth using explosives although cutting tools are also extensively used.

Similarly, 70% of platforms removed from the Gulf of Mexico in the 1980-90s were done so using explosives (National Research Council 1996). The use of linear shaped charges and explosive cutting charges/tape is common, both of which use a high-velocity explosive energy to push a V-shaped band of cutting material (usually copper) through the target substrate (e.g. steel).

### vi. Perforating well casings

After oil and gas wells have been drilled, a connection between the wellbore and the reservoir is needed before the fluids can be pumped to the surface. Well perforating is the process of punching holes in the casing to create that connection. This is achieved using high-energy shape charge explosives, often located over a kilometre or more below the seabed. The charges are held in perforating guns and when fired, have enough power to punch through the casing into the surrounding bedrock.

For charges deep below the seabed, energy emitted from blasts will be largely absorbed in the surrounding rock to the extent that any associated sound pressure reaching the water column would likely have negligible environmental effects. This is due to the fact sound attenuates far more strongly in deep compressed sediments than in the water column (Jensen, 2011). However, the associated noise in the water column due to confined explosives is currently not well understood, and there is limited data available on the potential for environmental impact from these sound sources. For example, Nedwell and Edwards 2004 observed that the noise generated during a wellhead severance in the North Sea was like that expected from an open water detonation. It was conjectured that this behaviour occurred because of the pipework and sediment (Nedwell and Edwards 2004, referenced in DESNZ, 2023).

## 3 Effects on marine life

Several reviews regarding potential impacts of underwater explosives on marine life have been published, for example Parvin et al. 2007, Koschinski 2011 and Weilgart, 2018. Often the focus is on protected species such as marine mammals and reptiles but also diving birds and protected or commercially exploited fish species of various life stages (and even invertebrates for which the knowledge is scarce) can be affected by explosions (Koschinski 2011). Some of the effects described below can be generalised to some extent. Effect distances however may vary between species groups, size and life stage.

Injuries to marine wildlife result mainly from the shock wave associated with the blast (Lance & Bass 2015). The explosive shock wave can result in compression of tissues or organs resulting in injury (Landsberg, 2000), the extent of which relates to the short signal rise time and high peak pressure signature of detonations (Koschinski, 2011). As vertebrate bodies are of similar consistency as water, the pressure of the blast wave passes easily through (Landsberg, 2000).

Massive damage in marine vertebrates can occur e.g. in the lungs, intestines, sinuses and ear cavities due to differential tissue displacement disrupting cells or tissues of different densities such as muscle and fat. This is particularly true at interfaces with gas-filled cavities capable of compression, which can be shredded or torn by instantaneous compression of the gas (Landsberg, 2000). Rapid increases in blood pressure can result in rupture and haemorrhage in the brain and ears (Ketten, 1995); air embolism in the cerebro-vascular system can result from rupture of lung alveoli (Landsberg, 2000), and gas embolism can occur during the phase of negative pressure just after the initial shock pulse due to nitrogen bubble formation in supersaturated tissues or fluids in diving animals (Lewis, 1996). Parvin et al. (2007) reviewed levels of peak pressure that may cause lethal and physical injury from animal studies and suggested lethal/injury ranges, although much of the data these were based on were old. Many injury standards have been developed for humans, however experimental data behind them is often lacking and often animal models were used (Lance & Bass 2015). Analysis of human blast injury data found a 50% risk of fatality due to pulmonary damage from underwater blast at 302kPa*ms impulse, and a 20% risk of pulmonary injury at 1km from a 20kg charge (Lance et al. 2015).

In a study of 24 harbour porpoise carcasses examined following UXO clearance in the Baltic Sea, ten were found to have evidence of blast trauma (Siebert et al. 2022). Seven animals were found to have damage to the middle ear, and it was noted bycaught animals from the Baltic Sea have also shown indications of acoustic trauma, suggesting civil and military explosions have been a threat in the past (based on Wohlsein et al. 2019).

Sub-lethal effects include irreversible hearing damage (trauma or a permanent hearing shift (PTS)) or reversible hearing damage like a temporary threshold shift (TTS), both of which may affect an individual's fitness, particularly those species that rely on this sense for prey acquisition (Richardson et al. 1995). This can result in increased mortality risk from malnutrition, predation (Richardson et al. 1995) or increased bycatch or collision risk (Wohlsein et al. 2019; Siebert et al. 2019, 2020, 2022). Depending on the charge weight and location of the detonation, harbour porpoises may suffer acoustic trauma or reversible hearing damage at distances much larger than 10km from the blast in the worst case (von Benda-Beckmann et al. 2015). Cumulative impact of the anticipated explosions for offshore windfarm construction raises high conservation concerns about the number of potentially affected animals (von Benda-Beckmann et al. 2015).

At close ranges, underwater explosions are lethal to most fish species regardless of size, shape, or internal anatomy. At increasing range, bony fish species with swim bladders are more vulnerable compared to those without, such as flatfish (Yelverton et al., 1975; Young, 1991; Lewis, 1996). Fish eggs have been shown to be killed by shock waves from explosions (Keevin & Hempen, 1997) or larval development was inhibited (Stein 2010). There is no comprehensive study on the effects of shock waves on fish larvae, but there is evidence that smaller animals are more seriously affected by strong impulses than larger ones (Yelverton et al., 1975; Young, 1991). Further, fish close to the surface seem to be more vulnerable than fish deeper in the water column (Young, 1991; Lewis, 1996), which might be attributed to the surface-reflected pulse. Fish are killed by internal bleeding and massive organ and tissue damage—most frequently in the swim bladder, kidney and liver, but also in the body cavity, pericardial sac and gut (Yelverton et al., 1975; Continental Shelf Associates, 2004).

There is virtually no information on blast effects on sharks. Since internal organs most commonly ruptured in bony fishes are the swim bladder, kidney and liver (Yelverton et al., 1975), kidney and liver damage are also a likely blast injury in sharks. With 25% of its body weight, the liver is a major fat storage and a shark's primary hydrostatic organ (Baldridge, 1970). Rupture of blood vessels in or near the liver caused by high-amplitude pressure changes from detonations (cf. Landsberg, 2000) may further result in fat embolism.

An assessment of potential impacts on the marine environment from explosive use is usually mandatory in marine licence applications and key when determining mitigation requirements. Typically, these involve predicting areas and times/ranges within which lethal/physical injury, auditory injury and disturbance will occur for the species of concern. This is usually done by modelling the propagation of sound and shock waves and relating this to published relevant noise exposure thresholds.

## 4 Published mitigation guidelines

Unlike for seismic surveys, few countries have dedicated mitigation and risk assessment guidelines for when using explosives in the marine environment, with an internet search identifying the examples below.

All these have several factors in common. All require detailed descriptions of the proposed operations, justification as to why explosives are needed and an assessment of potential risks to sensitive or protected species. A number also highlight the importance of early consultation with the relevant regulatory body and/or advisory agencies. Those that relate to turtles and marine mammals require identification of an injury/mitigation zone which is to be clear of animals before detonations commence, using visual observers to check the area. Those specifically for fish rely more on seasonal restrictions for explosive use and the identification of areas where they can't be used. Several prohibit the use of scare charges (section 6.2) and two discuss the use of acoustic deterrents as a complementary mitigation tool. All guidelines/guidance are more relevant in preventing injury rather than disturbance.

- **Canada**

*Guidelines for the use of explosives in or near Canadian fisheries waters (1998)*[1]

These guidelines consider the type of explosives to be used, where they can be used and the likely impact to fish species and habitat. Explosives are not to be used in or near fish habitat if they produce an instantaneous pressure change within the fish swim bladder of greater than 100kPaor produce a peak particle velocity > 13mm/s in a spawning bed during e.g. incubation. They also state that no explosive is to be knowingly detonated with 500m of any marine mammal, or no visual contact from an observer using 7x35 power binoculars.

They stipulate information to be included in a licence application, which includes estimation of lethal ranges and assessment of potential impacts. Applicants are also required to submit a mitigation plan, in which the timing of operations is to be considered, and methods to reduce impacts e.g. time-delay detonations if multiple charges are needed and reducing large detonations into a series of smaller ones. Also, any other measures that may be appropriate such as use of bubble curtains, noise generating devices to scare fish away or removal/exclusion of fish from the work area.

- **United States**

There are no national US regulations regarding explosive use and marine mammal protection. Instead, mitigation requirements are included in authorisations issued under regulations that implement the Marine Mammal Protection Act (1972) and/or the Endangered Species Act (1973). For example, blasting operations during a channel expansion project[2] in Florida included requirements for a detailed blasting plan, visual observers, aerial surveys, delays in operations if animals observed within identified areas and acoustic monitoring of blast events. At least six observers were required, and watches were to be conducted an hour before and after each blasting event.

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[1] Wright, D.G. and Hopky, G.E. 1998. Canadian Technical Report of fisheries and Aquatic Sciences 2107. https://publications.gc.ca/collections/Collection/Fs97-6-2107E.pdf

[2] https://www.federalregister.gov/documents/2018/05/04/2018-09499/takes-of-marine-mammals-incidental-to-specified-activities-taking-marine-mammals-incidental-to

*Platform Removal Observer Program*[3]

US Federal regulations have required the use of National Oceanic and Atmospheric Administration (NOAA) Fisheries Service approved observers to perform biological monitoring during the explosive removal of oil and gas structures in the Gulf of Mexico since 1987. The purpose of the Platform Removal Observer Program is to protect sea turtles and marine mammals from impacts of underwater explosives used in the platform removal process. In addition, the program assesses the impacts of underwater explosives on these protected species. It includes documenting sightings of sea turtles and marine mammals both before and after detonations and recommending delays in detonating explosives when these are present. In addition, observers record the condition of observed animals and coordinate retrieval of impacted animals for medical examination, rehabilitation, and necropsy.

Monitoring is performed from vessels, barges, or platforms provided by the oil or gas company responsible for structure removal. No night-time blasting is permitted. If sea turtles or marine mammals are observed within the impact zone during a specified time of a pre-detonation surface survey, the survey will continue for an additional period as specified in the monitoring protocols. This process continues until no animals are observed within the impact zone. Upon completion of the pre-detonation surface survey, a pre-detonation aerial survey may be initiated. If protected species are observed during the aerial survey, the survey is aborted and opportunistic surface monitoring is conducted during a prescribed waiting period, generally 30 or 45 minutes. The entire pre-detonation aerial survey is then repeated. This process continues until no protected species are observed within the impact zone during the arial survey. At this stage, an 'all clear' signal is communicated, and the explosives are detonated immediately. The aerial survey continues until after the detonation is completed but if this is delayed for an extensive period, the aerial survey is terminated and replaced with surface monitoring and then a repeat of the aerial survey process till the explosives are ready to detonate. Divers should recover any injured or dead sea turtles or marine mammals observed.

- **United Kingdom**

*JNCC guidelines for minimising the risk of injury to marine mammals from using explosives (2025)*[4] *and when clearing UXOs (2025)*[5]

Originally published in 2010, these guidelines were updated in 2025 (JNCC 2025a) and new guidelines were published for UXO clearance (JNCC 2025b). Both sets of guidelines follow a similar format to the JNCC guidelines for geophysical and piling works. However larger mitigation zones and longer pre-detonation searches are required. For UXO clearance, the guidelines consider high and low order clearance methods in line with a Joint Position Statement[6] published by the UK Department for Environment, Food and Rural Affairs (Defra), which prioritises the use of low noise clearance methods to reduce environmental impacts including those relating to noise.

Although detailed EIA guidance is not provided in the JNCC guidelines, it is highlighted that an impact assessment will be required for the application process and a need to estimate distances at which marine mammals may be injured. Guidance is provided on things to consider at the planning stage, e.g. what species may be present, seasonal considerations etc. Visual, and where appropriate, acoustic monitoring is to be undertaken before, during and after operations, with operations delayed if animals are observed within a defined mitigation zone. Acoustic deterrents devices may also be used as complementary measure, and for UXO clearance, bubble curtains should be considered for high-order clearances.

[3] https://www.fisheries.noaa.gov/southeast/fisheries-observers/platform-removal-observer-program
[4] http://data.jncc.gov.uk/data/24cc180d-4030-49dd-8977-a04ebe0d7aca/JNCC-Guidelines-Explosives-Guidelines-201008-Web.pdf
[5] https://hub.jncc.gov.uk/assets/cbd480f1-47ea-4d78-b94c-04e0f9389daa
[6] https://www.gov.uk/government/publications/marine-environment-unexploded-ordnance-clearance-joint-position-statement

*Unexploded ordnance clearance joint position statement*[7]

In November 2021 (updated January 2022), a joint statement was published which sets out the position of UK and devolved governments, regulators and statutory advisors on the use of lower noise alternatives to high-order detonation of UXOs when clearing UXOs from the marine environment. This statement was updated in January 2025 and now requires the use low noise methods of clearance to be the default method and high order clearances only to be used in exceptional circumstances.

- **Australia**

*Policy and guidelines for fish habitat conservation and management (2013)*[8]

Published by the New South Wales Department of Primary Industries, this document is aimed at protecting fish species and habitat. It covers a range of topics including a section on the use of explosives, electrical devices and other dangerous substances in waterways. It states that a proponent must be able to demonstrate that the use of such devices is the only method suitable and that alternative methods to undertake the works have been investigated. The use of explosives and other dangerous substances in highly sensitive key fish habitat or in commercial fishing grounds will generally not be approved. Blast programs must be designed to minimise the impacts on surrounding fish and fish habitat, and any impacts adequately compensated. In addition, explosives and other dangerous substances should generally not be used in shallow water (less than 2m). If there is potential for high fish mortality, measures should be in place to reduce impacts including the use of properly designed bubble curtains or physical barriers, limiting the timing of blasts to avoid major migration periods, spawning seasons or larval drift, and using non-explosive noise techniques to move fish from the immediate blast zone.

- **Miscellaneous**

*Thematic assessment on Hazardous Submerged Objects in the Baltic Sea* (HELCOM 2024)

In May 2024, HELCOM published its *Thematic assessment on Hazardous Submerged Objects in the Baltic Sea,* a report on environmental risks of submerged objects. The report provides a detailed chapter on mitigation, which states if detonations of unexploded ordnance are inevitable due to imminent danger to humans posed by certain munitions, a combination of suitable mitigation measures are to be applied to minimize adverse environmental effects. It provides a list of potential mitigation methods which covers the planning stage, plus measures before, during and after detonation.

## 5 Environmental impact assessment (EIA)

Environmental impact assessments (EIA) are required by regulators when planning to use explosives or for UXO clearance. Involvement of nature conservation and fishery agencies is recommended. EIAs should be undertaken in conjunction with planning, rather than being viewed as a separate or distinct stage. The assessment process requires identification of an environmental baseline and consideration of this information is important when planning explosive operations. For example:

- Identification of species and habitats of concern: what sensitive/protected species may be present, do they have preferred habitat, what legal protections are in place; identify vulnerability of protected habitats

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[7] https://www.gov.uk/government/publications/marine-environment-unexploded-ordnance-clearance-joint-position-statement

[8] New South Wales Department of Primary Industries, Department of Trade and Investment, Regional Infrastructure and Services. http://www.dpi.nsw.gov.au/__data/assets/pdf_file/0009/468927/Policy-and-guidelines-for-fish-habitat.pdf

- Will the detonation occur in a sensitive/important area: can the detonation be moved (e.g. UXOs), are you in or near a protected area where additional restrictions or mitigation requirements are in place;
- When will the detonation take place: can sensitive seasons e.g. breeding, spawning, migration, occurrence of protected species be avoided? If information is lacking, assume animals could be present any time of the year. There may be seasonal restrictions for certain operations e.g. during fish spawning, seal pupping, porpoise calving/mating.
- Can protected species be deterred: analyse suitable deterrents and assess deterrent range in relation to injury radius (see below).
- Can the impact on protected species be mitigated, e.g., by technical measures such as bubble curtains.

Risks to human health, both of those deploying the explosives and others nearby, will always be a primary consideration. Strict regulations are in place for when handling explosives (e.g., Frey 2020). These are not discussed in this document, but it is highlighted they must be abided by and will influence any blasting plan.

Impact assessments usually predict the distance from the blast within which animals may be injured and disturbed. These outputs should be used to inform mitigation requirements and consideration of mitigation at the planning stage means it can more easily be incorporated into the programme of works.

Assessments typically involve propagation modelling of sound and shock waves from the proposed blast and identification of ranges within which fatality, physical and auditory injury and disturbance may start to occur.

Other operations that will occur at same time as the proposed explosive use, and any that may be occurring prior to or after should also be considered, which may result in prolonged exposure (cumulative impacts) to loud sound. The predicted impact ranges can help determine which projects to include.

**Special case: Addressing UXOs in impact assessments**

The clearance of UXOs is considered a special case as it involves the use of explosives for safety reasons rather than to perform a specific purpose like cutting a substrate. Clearance of UXOs often involves the detonation of the UXO plus a donor charge which may be used to initiate a detonation in the UXO. The clearance of UXOs is particularly important for new developments, as sites need to be certified safe before installation of infrastructure can commence.

The level of uncertainty around potential risks from UXO clearance can be much higher, in part because of the volume of explosive material present (can be much larger compared to other uses of explosives), and the device may have been in the water for many years and the effects of this will be unknown. Associated safety procedures for explosive ordnance disposal are described in Frey et al. (2020).

Uncertainties regarding whether UXOs may be found on a development site can be reduced by conducting a basic historic desk-study beforehand. Knowledge on the occurrence of UXO in specific areas is available but the quantity and quality of this can vary. Where UXO clearance is undertaken by commercial developers rather than the relevant country's Navy, it is beneficial for a project if mitigation options for UXO clearance are reviewed and assessed before the start of the project in order to avoid long and costly delays during the project. Uncertainties with respect to number and size of UXOs when applying for licences, and whether or how many detonations are needed, make environmental impact assessments difficult, especially with respect to cumulative impacts. It can be advantageous to undertake investigative surveys of potential UXOs prior to applying for a licence to clear UXOs, providing certainty on what clearance is required although time constraints can make this difficult.

Not all UXOs need to be exploded; some items can be safe to handle and can be recovered for disposal onshore, and sometimes, planned infrastructure can be moved to avoid devices. Some devices can also be moved before detonation if it's near a sensitive structure or environmental feature, but this depends on the integrity of the device. However, this means that the dangerous objects will remain in the marine environment. These decisions need to be undertaken by UXO experts on a case-by-case basis. To avoid negative impacts on the marine environment, methods to avoid detonation are routinely considered first. When this is not possible, clearance options that do not involve blast-in-place are normally considered.

## 6 Overview of mitigation measures

Any mitigation employed should be proportional to the predicted risk therefore a 'one size fits all' approach should not be employed. Methods to reduce potential impacts from explosive use on the marine environment are best considered at the planning stage and mitigation methods can be divided into those that reduce noise at the receiver (pre-detonation mitigation) and those that reduce noise levels at the source (noise reduction/abatement methods). Some of the technical mitigation measures presented below are still experimental and may need further development and should be accompanied by research to be able to improve measures in the future and to reach BAT and BEP.

### 6.1 Planning

**Operational considerations**

The first step for any proposed operation is to determine a need for explosive use. Regulators will require justification as to why explosives need to be used, and many require consideration of alternatives in their applications. Early engagement with regulators and advisory bodies is recommended.

Operational considerations when planning include:

- The amount of explosives: As a general rule, explosives should be limited to what is necessary in terms of the number of blasts and the charge weight. Reducing the charge weight will reduce the amount of energy released into the marine environment (Keevin & Hempen 1997). All the guidelines reviewed for this document required a detailed description of the planned activities and that consideration is given to minimising the volume of explosive material required. Improvements in computer software applying multi-physics techniques and simulation technology can be used to optimise the type, amount, size and location of explosive charge for specific applications (DESNZ 2023).
- The number of explosions: If multiple detonations are required, the interval between explosions has an influence on the likelihood that hearing damage occurs (Southall et al. 2019). Besides the danger from the peak pressure and energy from single impulses, the cumulative sound exposure level ($SEL_{cum}$) needs to be considered. Typically, the $SEL_{cum}$ is calculated over 24 hours, for precautionary reasons not including the likely recovery of the ear between impulses which is still a matter of further research.
- The type of charge to be used: for example, the use of shaped charges[9], where applicable, can significantly reduce the required amount of explosive (Spence et al. 2007). As a positive side-effect,

[9] An explosive charge shaped to focus the effect of the explosive energy. Used to cut and form metal, penetrate metal and perforate wells in the oil and gas industry.

their use may speed up decommissioning activities as they are more effective at cutting than bulk charges (Spence et al. 2007), reducing the duration of operations.

- Initiation of the blast: How the blast is initiated will vary with operation. A blasting cap[10] adds little to the magnitude of an explosion while a detonating cord[11] has an associated kill radius that extends along the cord from the firing mechanism to the explosive being detonated (Keevin & Hempen 1997). Acoustic or remote detonators are also available which also reduce risks to personnel. These, however, may be impeded by some methods of mitigation e.g. bubble curtains.
- Staged[12] or delayed detonations: In some applications such as rock blasting, detonations can be split up in a series of time-delayed smaller explosions (see section 6.5.4). The use of time delays can reduce the pressure amplitude from a detonation by using a series of smaller explosions.
- Stemming/Buried explosive detonations: A stemming (filling at the top of drilling holes with explosives) prevents loss of blast energy into the water column (see section 6.5.4).
- Use of explosives with lower detonation velocity: depending on the purpose of explosions it may be possible to use explosives in which the chemical reaction is slower than in high explosives. For example, certain packaged emulsion explosives have a detonation velocity closer to that in black powder than that of TNT. High detonation velocities are responsible for the creation of a shock wave. If clearing UXOs, shaped donor charges which open the casings and thus initiate deflagration rather than a high-order detonation in the UXO are available. In a deflagration, the detonation velocity is very low, and no shock wave is produced. However, contamination of the environment by unburnt residue needs to be considered (see section 6.5.1).
- Use of craters as a tool to mitigate the noise emissions has been suggested in Germany (Nützel 2008). Further research is necessary to substantiate these findings.
- When a UXO is removed due to project requirements and not due to the immediate safety of humans, sensitive times and areas for affected species must be taken into account to find spatiotemporal suggestions for nature friendly removal options, also in cases when no environmental impact assessment is currently required. Successful mitigation strategies include the use of bubble curtains to attenuate the peak levels and $SEL_{cum}$ emitted as well as to reduce the exposed area.
- Deterrence of animals away from the detonation is another effective tool as a mitigation strategy in cases when no noise mitigation is feasible.
- Conducting the detonations only during daylight hours and in suitable weather conditions enables visual as well as acoustic pre and post searches to be undertaken ahead of detonations to ensure species of concern are not within the injury range.

### 6.2 Mitigation at receiver: prior to detonation

The following methods should be thoroughly planned for each specific case (see section 6.1) and can be implemented prior to a detonation taking place. They aim to reduce the levels of noise received by individual animals (the receiver) by monitoring a defined area (e.g. safety/exclusion zone or mitigation area) around the detonation and ensuring it is clear of protected species before operations begin. It should be noted that often a combination of the following approaches is required, and full consideration should always been given to minimising environmental impacts at source (section 6.3):

[10] A form of detonator that works by creating a small explosion of its own that in turn triggers the explosion of a more powerful device.
[11] A thin flexible tube filled with explosive, often used in quarrying, mining and civil engineering.
[12] Use of a primary and secondary detonation

- **Pre-detonation searches**

The purpose of this search is to determine whether any protected species are within a defined area or zone prior to detonation; if they are, operations are delayed until the animals have moved far enough away to reduce potential impacts. These zones are usually monitored visually by experienced protected species observers (also known as marine mammal observers), often in combination with passive acoustic monitoring (PAM). However, in large detonations the impact zone can be much larger than what can be monitored by visual or acoustic methods. Deep diving cetaceans such as beaked or sperm whales might be difficult to monitor due to the duration of their dives which can last for more than an hour and the sound speed profile can hamper detection when using PAM equipment at the surface. In the UK and US guidelines discussed in section 4, observations are required for at least one hour prior to the detonation and both also require a post-detonation search (section 6.4). If other noise mitigation measures like deterrence or bubble curtains are considered, all ships involved should partake in the pre and post detonation searches.

For visual observations to be effective, the search is reliant on having suitable weather conditions and only conducting detonations during daylight hours. Some marine mammal species can also be monitored acoustically. When monitoring acoustically, it is vital the equipment being used can detect the required frequencies for the species being monitored, and the distances at which these can be detected as well as the sound speed profile should be accounted for. In some countries, such as the UK and US, mitigation personnel are required to have undergone approved training before undertaking such work.

Searches are often undertaken from vessels. However, a clear view of the entire mitigation zone is required for visual surveys and deployment of hydrophones should be considered carefully to ensure they will be effective (i.e. no background noise that may mask marine mammal signals and no refraction of sound). Depending on the size of the danger zone, a number of vessels may be required. Aerial platforms and unmanned devices e.g. drones with live video feeds, can also be of use.

- **Exclusion/mitigation zone**

The area visually observed prior to a detonation must be agreed before operations commence. A 1km visual search zone is typically used in the UK (JNCC, 2024a and b), as this is considered the maximum distance cetaceans in UK waters may be reliably observed although the full extent of the mitigation zone is determined at the impact assessment stage. Other countries/guidelines use modelling to determine the size of this zone.

Depending on the operations to be performed and outputs from the impact assessment, additional technical mitigation measures for deterring animals at greater distances from the detonation may be required e.g. when the predicted injury zone is larger than can be visually and/or acoustically monitored. Noise modelling provided in licence applications can help to inform additional requirements.

- **Acoustic deterrents**

Acoustic deterrent devices (ADDs) have been used to deter marine mammals from specified areas across various marine industries and are commonly used prior to piling. Market-available ADDs are very variable with respect to the sound levels produced, frequency range, temporal pattern/duty cycle and harmonics and a good knowledge of the biology of the species of concern is required for choosing an appropriate ADD. In addition, there are also differences in the method of deployment and operating functions (McGarry et al. 2020).

Literature concerning ADDs suggests 100% exclusion for harbour porpoises can be achieved up to approximately 1km from a Lofitech Seal Scarer (McGarry et al. 2022). Beyond this, nearly complete exclusion cannot be guaranteed (e.g. Brandt et al. 2012; Brandt et al. 2013; Dähne et al. 2017) although certain devices will have some deterrence effect on harbour porpoises up to approximately 7.5km (Brandt et al. 2012; 2013) or even 12 km (Dähne et al. 2017). Brandt et al. define a radius of 1.9 km as a range where deterrence by harbour porpoise can be efficiently achieved and suggest that not all animals can be displaced due to difference in the avoidance reaction.

The evidence for other species is limited. Minke whales appear to also react strongly to specified ADDs increasing speed and moving away when the ADD is activated. The signal also caused minke whales to increase dive duration (McGarry et al. 2017, Boisseau et al. 2021). Some devices have also been shown to deter seals to approximately 1km (Götz and Janik, 2010, Gordon et al. 2015). A review of the evidence base for application of ADDs as marine mammal mitigation was first published in 2020 and in its latest version also includes an ADD selection database (McGarry et al. 2022).

ADDs have been used for marine mammals prior to UXO clearance in offshore windfarm construction areas in waters of the North Sea[13] however substantial consideration is needed regarding the effectiveness of the devices for the species of concern and the distances at which they are fully effective. In addition, the duration the device is activated for needs to be considered carefully. It should be long enough to enable animals to swim the required distance but not too long so introducing unnecessary disturbance or result in habituation (Thompson et al. 2020). If an ADD is required to be active for a long period of time (e.g. during construction blasting), consider whether quieter options for the required task are available.

Since some ADDs have been reported to cause TTS in harbour porpoises (Schaffeld et al. 2019) and are considered as harmful when used continuously (Findlay et al. 2024) their use must be carefully considered with an EIA and discussion with the appropriate regulator and advisors is recommended.

- **Scare charges**

Often referred to as scare charges, this involves detonation of a sequence of small but increasing in size charges[14], implemented at the end of a pre-detonation search (and ADD operation, if used) but prior to detonation of the main device. However, some of these charges are large enough to injure marine vertebrates themselves (e.g., Nix and Chapman 1985; McAnnuff et al. 1994, Simonis et al. 2020) and thus are not a preferred option. They have been used to reduce fish kills and as part of marine mammal mitigation protocols for clearance of larger UXOs, with the aim of deterring marine mammals an even greater distance from the blast than ADDs, but their scaring effect is not proven (Lewis 1996, Keevin and Hempen 1997, Robinson et al. 2022). Their very short duration might provide limited information on source direction and therefore limited deterrent effect on marine mammals. And assuming no animals are within the mitigation zone before they are applied, it would be impossible for observers to confirm their effectiveness. Therefore, studies confirming or disproving the efficacy of scare charges have never been published. Odontocetes may also be attracted to fishes killed by explosions, and thus attracted rather than repelled by scare charges (Continental Shelf Associates 2004). As with ADDs, it cannot be guaranteed that all animals will respond the same, as the motivation to exploit a resource such as food, can influence responses (Götz and Janik 2010).

### 6.3 Mitigation at source: noise reduction/abatement methods

The following methods aim to reduce the radiation of noise emissions from the source. There are commercially available noise abatement systems which have been used effectively for piling operations however evidence of effectiveness during explosive use is more limited.

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[13] https://marine.gov.scot/sites/default/files/uxo_clearance_cetacean_risk_assessment_03122018_redacted.pdf; https://infrastructure.planninginspectorate.gov.uk/wp-content/ipc/uploads/projects/EN010109/EN010109-000423-6.3.10.4%20Marine%20Mammal%20Unexploded%20Ordnance%20(UXO)%20Assessment.pdf

[14] For example, charges can ranges from 50-200g with between 5-15 minutes between each detonation

- **Bubble curtains**

Bubble curtains are formed by compressed air that is pumped through one or more nozzle hoses laid around the position of the noise source at the seafloor. The air ascends through the nozzles into the water column up to the water surface and thereby builds a curtain of bubbles arising vertically along the tube. Impulsive sound will be absorbed, reflected and scattered from the ascending air bubbles, and thereby reduced.

Bubble curtains have been proven effective when used during piling (e.g. OSPAR Commission, 2021, Verfuss et al., 2019) however less evidence is available for explosive use. When using explosives, it is considered bubble curtains are most likely to be used during UXO clearance and harbour/coastal works but recently have also been deployed successfully in ship-shock trials[15]. The success of bubble curtains depends on the effectiveness of their design (Bellmann et al. 2020). Site-specific environmental parameters including water depth and currents can limit their effectiveness (Bellmann et al. 2020, Novik, 2023) and evidence of effectiveness in deeper waters (e.g. deeper than 40m) is limited (Verfuss et al., 2019, Bellmann et al. 2020). Limiting factors are compressor size and number, bubble curtain length and size of the nozzles. In Germany experience from two unpublished trials in 2022/23 during military testing shows that a double bubble curtain with sufficient air and bubble curtain length provides a good solution to attenuate explosions noise if the bubble curtain is checked via drone footage for full coverage of the testing site. Controlled tests to understand their efficacy during mine explosions have been undertaken in the German Baltic Sea (Schmidtke 2009, 2010, 2012, Haak & Abshagen 2024). A single bubble curtain around a 300kg mine in 12m water depth (70m radius, air volume stream 1 $m^3*min^{-1}*m^{-1}$) provided a 16-19dB reduction in peak pressure (Schmidtke 2010). Reference measurements using 100g charges without and with a double bubble curtain (radii between 60 and 100m) showed that the bubble curtain significantly reduces the high-frequency component of the underwater shock wave but its effectiveness is limited by the low frequency component of its seismic precursor (see Section 1). The energetic average attenuation was approximately 14 dB reduction for the peak level and at least 7 dB for the sound exposure level (SEL) (Haak & Abshagen 2024). Even if the attenuation of the SEL of the high-frequency signal component is significantly higher at over 25 dB re 1µ$Pa^2$s, the overall attenuation of the SEL is limited by the low-frequency signal component transmitted via the ground which cannot be reduced by the bubble curtain.

A 1000m long bubble curtain employed at 30m depth in a confined area between Bergen and Stavanger (North Sea) to protect an aquaculture facility from the detonation of four 500kg detonations (Grimsbo and Kvadsheim 2018) reported a reduction of 6.2-12.4dB peak pressure, compared to an unmitigated detonation. However, when a bubble curtain was deployed during the clearance of two UXOs in the English southern North Sea (24m water depth), noise monitoring reported a reduction of 10-15dB for a 2.5kg donor charge but only 5 dB reduction in peak level and none in SEL for a 220kg charge (SOFIA Offshore Wind Farm 2022) . This may have been due to the size of the bubble curtain (r=45 m) which may have been too small for the large charge (cf. Schmidtke et al. 2009, Schmidtke 2010). Bubble curtains were also used for UXO clearance during installation of the Nord Stream 2 gas pipeline in the Finnish EEZ (Sitowise 2018) however no evaluation of the effectiveness of the bubble curtain is presented.

The air volume in the water (density of bubbles) is critical for the damping effect from bubble curtains (Nützel, 2008, tested on single, double and triple bubble curtains for small charges). However, the relationship between air volume and damping effect is not linear, as the research results by Schmidtke (2010) show damping of the same order of magnitude at an air volume flow (air generated by the compressor) of $1m^3$/min/m and 0.5 $m^2$/min/m. The air volume at the exit point in the nozzle pipe is a function of the

[15] https://www.ndr.de/nachrichten/schleswig-holstein/Fregatte-Karlsruhe-mit-175-Kilogramm-Sprengstoff-angegriffen,marine1496.html

hydrostatic pressure which must be considered when used in deeper waters than 12m which was the depth in the experiment.

Further, there are scaling effects with respect to the length of a nozzle hose (and thus the overall amount of air needed) in relation to the charge weight and type of explosive. Larger explosive charges in naval mines contain ingredients that generate much more gas during the reaction than can be expected from the reaction of pure TNT, so that the flow of displaced water generates a considerable part of the pressure level, which cannot be damped by the air bubbles (Schmidtke et al. 2009). The mixture of hexanite contains, among other substances, aluminium powder, which serves as a reaction catalyst and triggers the aforementioned effect. This has consequences for the minimum distance of the bubble curtain from the blasting position. In a blast of a German moored mine with 300kg of hexanite at 12m water depth, this effect occurred, making a bubble curtain placed at 22m distance ineffective (Schmidtke et al. 2009). At a bubble curtain radius of 70m, the bubble curtain showed the desired reduction in peak pressure without the described effect (Schmidtke 2010).

However, without a precise knowledge of the effect described by Schmidtke et al. (2009), only some rough assumptions can be made regarding the necessary bubble curtain distance. The exact boundary conditions are unknown. Based on the results of the investigation, a necessary bubble curtain radius of approx. 70m, corresponding to a nozzle hose length of 440m, can be assumed for blasts of mines containing up to 300kg explosives - until further research results are available. For larger charges, the distance should be increased even further. For pure TNT, the distance can be reduced somewhat if necessary.

The German Federal Government consider bubble curtains to be the best available technique and environmental practice for UXO clearance because they show the highest potential to reduce impacts of shock wave on marine wildlife by significantly reducing the affected danger area (Bundestag, 2018). This will soon be further specified in a guidance on “Nature conservation and technical requirements for the clearance and removal of munitions in the North Sea and Baltic Sea” currently under development.

- **Isolation casings and cofferdams**

For explosive use in shallow waters, the use of cofferdams or similar may be a consideration. This involves enclosing the area where explosives will be detonated in a structure and pumping the water out. The dam design will vary with water depth and may be single or double walled and isolate the noise source from the marine environment. These systems are reviewed in Annex I of OSPAR Commission, 2021 in relation to piling. Nevertheless, as it is also a near-source noise abatement system, it seems not to be suitable for UXO clearance in deeper waters.

- **Detonation in air**

A method to avoid the coupling of a shock wave to the water column is detonation in air where a UXO can be relocated to a sandbank exposed at low tide (Bleicher 2021). This method is only feasible when UXO can safely be relocated and does not compromise safety and conservation objectives of the area.

- **Experimental methods: Resonators**

Developed for use during piling, resonators are now being considered for use during explosions (Verfuss et al. 2019). Resonators consist of an array of (solely or mainly) resonating units that are deployed around the noise source to absorb the emitted sound. Unlike bubble curtains, which are built of ascending air bubbles from a nozzle hose laid at the seafloor, there are a variety of different ways to build resonators. Currently, two suppliers have commercially available systems, each supplier with its own resonating material and design (see Verfuss et al. 2019 for a review). To date, one system has been used in tank trials with simulated UXO noise, demonstrating the potential for this method during explosive use (Wochner et al. 2017 a & b). However, it might be suited for small charges only as overpressure and the hot gas globe from a detonation can demolish the noise abatement system which is currently designed to be positioned near (a few metres) the sound source.

### 6.4 Monitoring of effectiveness

When noise abatement systems such as bubble curtains are used, or in the case of UXOs, alternative clearance methods are employed, it is important to verify their effectiveness. Noise or pressure measurements help in validating assumptions or model output with respect to source level, propagation and reduction of shock waves and underwater sound. Guidance on in-situ underwater sound measurements of UXOs was published in 2020[16] for the UK and an example of where this has been applied on a commercial clearance campaign was published in 2024 (Ref to be added when available).

When scaring devices are used to mitigate blast effects on e.g., odontocetes, it can be helpful to use passive acoustic monitors (i.e., electronic click detectors, CPODs or broadband recorders) to verify in hindsight whether this has been successful and whether animals return to the site. In a suitable design, a larger area can be covered compared to protected species observers and online PAM systems which are part of the safety procedures.

Further, a dedicated post-detonation search can help in validating whether mitigation measures were sufficient. If injured animals are found, rehabilitation may still be possible.

Harbour porpoise data from click detectors and broadband data from acoustic monitoring stations deployed for MSFD[17] assessment purposes showed that in the case of detonating 42 WWII ground mines in the Baltic Sea porpoises were not sufficiently deterred and could be severely injured by the high received sound pressures (Gallus 2020, DW-ShipConsult 2020). Post-detonation examination of stranded porpoises after the same event revealed blast trauma (Siebert et al. 2022). Due to the retrospective study design, a clear connection with the detonations could not be established. Nevertheless, mitigation measures should be improved in the future and supported by noise and marine mammal monitoring.

### 6.5 Specific mitigation methods for different purposes

#### 6.5.1 UXO removal

In addition to the mitigation measures briefly described above, there are a few options specifically available for when clearing UXOs.

The traditional way of disposing of underwater UXOs is to detonate a donor charge on the device or drive a drone with a charge next to it to initiate a blast. Known as high-order, the explosives burn faster than the speed of sound and in respect to UXOs, the detonation generally results in an explosive ordnance producing the designed/intended explosive yield with the aim of completely detonating the main charge. Disadvantages to this include:

- High blast, noise and pressure in water and sediment from the combined explosion of the donor charge and the UXO itself;
- Physical disturbance of benthic habitats and formation of post-blast craters and resuspension of sediments including contaminants from sediments, and sedimentation altering benthic habitats;

[16] Protocol for in-situ measurement of underwater explosions, version 2 11 (publishing.service.gov.uk)
[17] EU Marine Strategy Framework Directive

- Residue from the explosion and hydrophobic liquids in the water column which can contain contaminants, can be seen as a visible slick on the surface until dissipated by wave/tidal action; and
- Increased risk to personnel and assets in close proximity.

Subsequently, detonation is always considered a last resort when clearing areas of UXOs and when detonation is required, mitigation measures are needed. In addition to the mitigation methods described in sections 6.1, 6.2 and 6.3, consisting of a set of measures including relocation to less sensitive places or selection of less sensitive periods, protected species monitoring, use of deterrents, deployment of a bubble curtain, etc. the following additional options may also be utilised.

- **Micro-siting**

For some projects it may be possible to alter the location of new infrastructure thus removing a need to detonate UXOs discovered. The ability to do this will be project and location specific, and is typically easier for cable laying projects than, for example, turbine foundations within a wind farm.

There is the potential for object migration, both by the UXO or the infrastructure concerned, which may lead to future problems. The Nord Stream 2 gas pipeline project designed and installed UXO-berms to prevent the pipeline from moving towards UXOs in the vicinity that had not been cleared (Sitowise 2019). Concerns have also been raised regarding chemical leaching from corroded UXOs left on the seabed (Appel et al. 2018, Strehse et al. 2024), so once found, it may be preferable to remove UXOs regardless of their location relative to new/planned infrastructure.

- **Low order detonation/deflagration**

Alternative approaches to high-order detonation are now coming to the commercial market, for example, tools which utilise a process referred to as deflagration (ESTCH 2002, Robinson et al. 2020).

Chemical conversion of explosives is categorized as high-order or low-order depending on their detonation velocity. In high-order it releases energy at supersonic speed which causes a strong pressure wave, known as the blast wave or shock wave. Low-order conversion release energy at a lower velocity. From the underwater noise perspective, it is desired that the explosive burns slower than the speed of sound (subsonic). As a result, they lack the explosive blast wave associated with high-order (Chesterfield 2018, Jorolemon et al. 2022, Hampton 2023). When considered in the context of UXO clearance, a method can be used to penetrate the shell with insufficient shock to detonate the device, instead causing a rapid burn of the explosive material within (ESTCH 2002), called deflagration. Weakening the shell with an explosive cutting charge (shaped charge) induces the deflagration and the sudden pressure loss usually prevents the transition from deflagration to detonation (Hubbard & Tomlinson 1989).

**Table 1 characterisation of detonations based on their detonation velocity (after Kiciński & Szturomski 2020)**

| | Detonation velocity [$m*s^{-1}$] | Shock wave |
|---|---|---|
| High-order | 5,000 to 10,000 | yes |
| Low-order | >1,000 and <5,000 | above sound speed (1,500 $m*s^{-1}$) |
| Deflagration | <1,000 | no |

Several commercial companies offer this method of clearance. Experimental measurements comparing sound levels from several of these tools with high-order detonations indicate that peak sound levels and the overall acoustic energy of detonation can be greatly reduced (Robinson et al. 2020, Cheong et al., 2023, Wang et al. in prep). They compared low and high-order detonations of surrogate shells containing between 2.5kg and 18.7kg of explosive material.

One of these tools was used in a UXO clearance operation in Danish Kattegat waters with charge sizes between 34 and 430 kg. Noise measurements were undertaken with four low-order clearances and four high-order operations in comparison (Lepper et al. 2024). At two of each of these mines of comparable size and corrosion state, contaminants were also analysed pre and post operation (Maser et al. 2024). The results demonstrate a reduction in peak sound pressure level and sound exposure level around 20 dB for deflagration compared to high-order detonation. The damage to the seabed was also considerably reduced for deflagration. However, in all four deflagrations residue was scattered in and around the remaining mine carcasses (Lepper et al. 2024). Chemical analyses revealed a significant increase of contamination with toxic energetic compounds in water and sediment by both types of operations. Due to the ongoing corrosion of the metal shells, all four mines were shown to leak explosive chemicals into the environment already before operations. Whereas after the high-order detonation water concentrations were increased 350-fold and sediment concentrations 250-fold, the increase after deflagration was 315,000-fold and 1,000,000-fold, respectively. Hence, the ecotoxicological risk increased significantly (Maser et al. 2024).

This same tool has also been used on a commercial scale in Scottish waters and successfully cleared 82 UXOs (Oliva et al. 2024). Seven types of UXO with net explosive quantities varying between 6kg and 700kg were deflagrated. None resulted in a high order detonation. If after the first deflagration there was any explosive material left, a second one was carried out, ensuring all residual explosive material was deflagrated with remaining metal casings safely recovered with a grab. Post-detonation surveys reported no seabed damage or craters. Noise measurements were taken for 31 of the devices representing all types cleared including the largest. The highest measured L0-pk sound level, measured at 1km, was 208.4 dB re 1 µPa. Injury ranges estimated using the measured sound levels predicted injury within 1.5km, with the greatest ranges estimated for very high frequency cetaceans (harbour porpoise) (Oliva et al. 2024). The report corroborated conclusions in Robinson et al. 2020, that noise produced during these clearances was representative of the disposal clearance tool rather than the UXO net explosive quantity.

Concerns have been raised that a low-order process cannot be fully controlled and could result in a high-order detonation of residual explosive. While secondary explosives such as TNT in the main charge usually deflagrate without detonation, including primary (initiatory) explosives, intermediate explosives used as boosters or certain age-deteriorated charges in the burning process can result in a deflagration-to-detonation transition. Also, in certain mixtures of fillings exhibiting high levels of explosiveness, the likelihood of transition into a detonation is increased (Hubbard & Tomlinson 1989). However, provided appropriate safety and environmental measures are in place, it will reduce the explosive yield and associated impacts (ESTCH 2002).

- **Deactivating ammunition**

As an alternative to blasting or deflagration, there are deactivation methods in which the ignition chain is interrupted. The detonator is separated from the ammunition by using lasers (still experimental) or small explosive charges, which enables subsequent handling of the UXO. This defusing technique is also a low-order method where the fuse is blast off the main charge by a limited detonation. In certain British ground mines, the gear box can be separated from the main charge using detonating cord (Kinast 2021) which would reduce the energetic conversion of explosive mass from 300 kg to 240 grams only.

Water jet cutting systems are becoming increasingly common place in underwater operations and it has been suggested to use this technology to cut a hole into a UXO and flush out the explosive filling also using an appropriate capture technology for the fluid in order to avoid environmental contamination (Schmit 2020). A demonstration has shown a low environmental contamination during the operation in a pool (Lotufo et al. 2023). This technology is still in an experimental stage and requires further development.

### 6.5.2 Ship shock trials

In ship shock trials, usually explosive charges with ascending sizes are detonated close to the ship's hull, or of the same size of charge is moved progressively closer to the ship. The vessel is equipped with sensor technology to detect changes in the vessel's stability, impact on electronic systems, crew and soldiers. There are several mitigation measures for ship shock trials which relate to the number and size of the charges used, shock wave propagation as well as the use of non-explosive alternative sources.

In order to reduce the impact on the marine environment, the number and size of charges used in a ship shock trial should be kept to the absolute minimum required for the test. Detonating increasing charges close to the ship has a similar impact on the ship but a smaller impact on the environment compared to moving a large charge successively closer to the ship. However, there may be limitations when an even wave front is required for the testing of a very large vessel. Modelling in connection with modern sensor technology can help to further reduce the number of charges and also the charge size required.

The shock wave propagation can be reduced by use of a bubble curtain (see section 6.3). Recently, this has been applied in a ship shock trial of the German former frigate ship Karlsruhe (Bundeswehr 2024). This abatement method is limited to charges detonated close to the ship because both, the charge and the vessel need to be within a closed bubble curtain.

In addition, all mitigation at receiver measures discussed in section 6.2 are applicable.

### 6.5.3 Military training exercises

Certain exercise areas are subject to restrictions on use of underwater blasting during specific periods. In "train as we fight" operations it is difficult to apply practical mitigation methods. The emphasis in mitigation here is on the planning stage (section 6.1) in order to avoid sensitive times, areas and protected species when using explosives. In addition, mitigation at receiver measures discussed in section 6.2, such as pre-detonation search and use of acoustic deterrent devices are applicable.

Further, there are possibilities to reduce the number of charges and the charge size. E.g., to demonstrate the ability of a mine diver or mine hunting group there is no need for detonating charges of hundreds of kilogrammes. In some cases, it may be sufficient to detonate an inert mine with a small donor charge or underwater drone.

### 6.5.4 Rock removal

Small charges are commonly used during harbour clearance, harbour bottom alterations, and rock blasting (Department of Navy, 1956). During harbour extension works in Scotland, rock blasting was used next to an area frequently used by bottlenose dolphins, harbour porpoises and grey seals. To avoid harm to marine mammals, a combination of bubble curtains, marine mammal observers and fish scarers (scare charges) were applied (DRAGADOS 2019). Mitigation measures during the planning stage (section 6.1), mitigation at receiver (section 6.2) and mitigation at source (section 6.3) are all relevant in these types of operation. The timing of operations also needs to be considered. Specific mitigation methods for construction works are available, such as time-delay detonations if multiple charges are needed and reducing large detonations into a series of smaller ones. This reduces the peak pressure and thus decreases the impact zone. Stemming (buried explosive detonations) prevents unrestricted venting of boreholes and loss of blast energy into the water column. In shallow water, also cofferdams can be applicable.

### 6.5.5 Cutting

Simulations or computational analysis of the performance of charges can be used to identify the optimal charge size required for a given objective (DESNZ, 2023), reducing the need to use unnecessarily large charges. The use of shaped charges (as opposed to bulk charges) greatly reduces the amount of explosive material and therefore costs required as they focus the explosive energy along the line to be cut. Use of alternatives such as abrasive water jet cutting can also be considered in order to avoid shock waves.

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