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Abbreviations and Terms

AEODP	Allied Explosive Ordnance Disposal Publications, contain a series of publications addressing the disposal of munitions.
AXO	Abandoned Explosive Ordnance, means explosive ordnance that has not been used during an armed conflict, that has been left behind or dumped by a party to an armed conflict, and which is no longer under control of the party that left it behind or dumped it.
BiP	Blow in Place, refers to the controlled detonation of unexploded ordnance (UXO) or other explosive devices at the exact location where they are discovered.
Bubble curtain	Is a wall of rising air bubbles created by pumping compressed air through a perforated pipe submerged in water, forming a pneumatic barrier to control sound, debris, and contaminants.
Critical diameter	The smallest diameter of a cylindrical charge that can sustain a stable, high-order detonation. If the diameter is less than this value, the detonation will fail and die out.
CRREL	US Army Corps of Engineers, Cold Regions Research and Engineering Laboratory is developing innovative solutions for science and engineering challenges in extreme environments. CRREL is based in Hanover, New Hampshire, USA.
dB	Decibel is a logarithmic unit for sound intensity, loudness, and sound pressure level. The decibel scale is not linear; each 10 dB increase represents a tenfold increase in intensity.
DDT	Deflagration-to-detonation transition is a phenomenon where a subsonic flame, or deflagration, accelerates and transforms into a supersonic detonation wave.
Disposal	The process of rendering explosive ordnance safe, either through demilitarization (neutralizing its military potential by destroying its energetic material) or destruction.
EO	Explosive ordnance, refers to any munitions or devices designed to explode, detonate, or produce an explosive effect, such as bombs, mines, artillery shells, and rockets, along with their components. The term broadly encompasses conventional explosives, as well as devices that may contain nuclear fission/fusion materials or biological and chemical agents.
EOD	Explosive Ordnance Disposal, refers to the specialized profession and procedures for detecting, identifying, evaluating, render safe, recovering, and disposing of explosive ordnance, including conventional munitions, improvised explosive devices (IEDs), and weapons of mass destruction.
ERW	Explosive Remnants of War refers to munitions that failed to detonate as intended (UXO) or were left behind by warring parties (AXO) after an armed conflict has ended.
FFI	Forsvarets forskningsinstiutt, The Norwegian Defence Research Establishment, is the prime institution responsible for defence-related research in Norway.
Gas bubble	Is the complex process following an underwater explosion, where the high-pressure, high-temperature gases from the detonated explosive rapidly expand to form a bubble.
HMX	Is a military explosive with the chemical name Octahydro-1,3,5,7-tetranitro-1,3,5,7-tetrazocine. It is a powerful, high-melting-point, colourless, crystalline with extreme power and ability to detonate violently at high temperatures.
HOD	High-Order Detonation refers to the rapid, supersonic propagation of a chemical reaction in an explosive material, creating a high-amplitude shock wave and a loud, instantaneous release of high-pressure gases, as opposed to a lower-velocity deflagration or partial detonation. This full-detonation event is characterized by extreme pressure and temperature, which causes significant brisance (shattering) and heave (lifting/throwing) of the surrounding environment.
IED	Improvised Explosive Device is a device placed or fabricated in an improvised manner incorporating explosive material, destructive, lethal, noxious, incendiary, pyrotechnic

	materials or chemicals designed to destroy, disfigure, distract or harass. They may incorporate military stores but are normally devised from non-military components.
LOD	Low-Order Detonation or Deflagration is an incomplete and relatively slow detonation where the shockwave travels slower than the speed of sound (subsonic), being closer to a combustion than an explosion.
MSIAC	Munitions Safety Information Analysis Centre is a NATO project office funded and directed by its member nations to eliminate safety risks from unintended reactions of munitions and energetic materials throughout their lifecycle.
MUNIMAP	Baltic Sea Munitions Remediation Roadmap is a project funded by EU's Interreg Baltic Sea Region programme and co-funded by the European Union. It will develop a legal and administrative framework for public authorities to initiate joint remediation of dumped munitions from the Baltic Sea and Skagerrak, which pose threats to the marine ecosystem and hinder the maritime economy.
NATO STANAGs	The North Atlantic Treaty Organization Standardization Agreements is a normative document published by the NATO Standardization Office that establishes a common standard among NATO member states for military procedures, technical specifications, or equipment to ensure operational and logistical interoperability.
NAVSEA	The US Naval Sea Systems Command is the largest of the Navy's five systems commands which build and support America's Fleet of ships and combat systems.
NEQ	Net Explosive Quantity refers to the actual mass of explosive material within a product, excluding the weight of packaging, casings, or other non-explosive components.
OSPAR	The Oslo and Paris Convention is an international convention and commission established to protect the marine environment of the North-East Atlantic Ocean, including areas beyond national jurisdiction. The Oslo Convention from 1972 against dumping was broadened to cover land-based sources of marine pollution and the offshore industry by the Paris Convention of 1974. These two conventions were unified, updated and extended in 1992 to the OSPAR Convention.
Peak pressure	Is the maximum instantaneous change in water pressure created by a very short, high-energy event, such as an explosion or the impact from a pile drive.
Pipe bomb	A small homemade bomb typically consisting of a metal pipe filled with an explosive material.
RDX	Royal Demolition Explosive with the chemical name hexahydro-1,3,5-trinitro-1,3,5-triazine, is a powerful, white crystalline military-grade high explosive. Also known as cyclonite or hexogen.
Tallboy	A 12,000-pound (5400 kg) "earthquake" bomb developed by the British during World War II, designed to penetrate deep into the ground before detonating.
ROV	Remotely Operated Vehicle, an underwater robot controlled from a surface vessel via a cable to explore the ocean.
TNT	Is a military grade explosive with the chemical name 2,4,6-trinitrotoluene. It is a yellow, solid organic compound and was the standard high-explosive during WWII.
UNCLOS	United Nations Convention on the Law of the Sea is an international treaty that establishes a comprehensive legal framework for all marine and maritime activities.
US AARDC	United States Army Armament Research and Development Command
UXO	Unexploded Ordnance is munitions which has been primed, fused, armed or otherwise prepared for action, and which has been dropped, fired, launched, projected, or placed in such a manner as to constitute a hazard to operations, installations, personnel or material and remains unexploded either by malfunction or design or for any other cause.
Waterjet	Is an industrial tool that cuts various materials by directing a very high-pressure stream of water, often mixed with an abrasive, at high velocity. Typical pressure is 4000 to 6200 bar which will cut up to 15 cm of steel.

WWI	World War I, a global conflict from July 28, 1914, to November 11, 1918.
WWII	World War II or the Second World War was a global conflict from 1939 to 1945. The largest and deadliest war in history, involving most of the world's nations and resulting in the deaths of tens of millions of people.

Executive summary

This report, D9.1, is part of Work Package 9 of the Horizon Europe-funded MMinE-SwEEPER project provides a comprehensive summary of current methods for disposing of marine explosive remnants of war (ERW), with a focus on high-order (HOD) and low-order disposal (LOD) techniques. Still millions of tonnes of munitions, including chemical and conventional types, remain on European seabeds, posing risks to marine ecosystems, human safety, and infrastructure development.

The report compares HOD and LOD in terms of environmental impact, safety, and cost. HOD, the traditional method, ensures complete destruction but generates intense shock waves and noise, potentially harming marine life. LOD, including deflagration and partial detonation, reduces peak pressure and seabed damage but leaves significant explosive residues, raising contamination concerns. Technologies such as lasers and waterjets are explored as alternative disposal methods.

Several international and national regulations for underwater explosive ordnance disposal exist. Conventions like UNCLOS, OSPAR, and the London Protocol, and national guidelines from Germany and the UK are examples. There is a need for internationally recognized norms and standards to ensure that the approaches used are effective, safe, and environmentally responsible.

Key findings show that while LOD offers reduced acoustic and physical impact, it carries higher risks of incomplete combustion and site contamination. HOD remains more reliable but environmentally disruptive. The report recommends further studies of the environmental impact of high-order and low-order disposal methods for safe and sustainable ERW clearance.

1 Introduction

The aim of the Working Package (WP) 9 is to investigate and compile approaches and methods to finally deal with single munitions objects or entire munition dumping areas. Physical and chemical impacts of the environment and related mitigation and monitoring practices will be considered. One of the dedicated objectives will be to compile and assess high-order (HOD) and low-order disposal (LOD) approaches as well as mitigation measures for HOD. Task 9.1 focus on facts connected to blow-in-place approaches for clearing munitions in marine environments by HOD and LOD methods. Standards and regulations concerning clearing munitions in the participating countries are also summarized. Task 9.1 is also linked to WP2, which will analyse the existing European regulatory and responsibility frameworks relevant to the remediation of marine munitions, focusing on key concerns and requirements identified by stakeholders. The current report, Deliverable (D) 9.1, summaries the current knowledge of HOD and LOD and the standards and regulations in participating countries. HOD and LOD are compared related to facts, impacts and cost issues. It gives also information of other approaches than classical HOD and LOD disposal methods.

Millions of tonnes of conventional and chemical munitions were dumped globally, often at designated sites but also randomly due to poor navigation or record-keeping after WWI and WWII. These include all kinds of munitions like sea mines, bombs, grenades, and torpedoes, many of which remain live and potentially explosive today. Activities like bottom trawling, offshore construction, and wind farm development risk triggering explosions, endangering marine life and human workers [1].

Up until the 1960s, dumping into the sea was considered a safe and inexpensive way to dispose of munitions. For this reason, many countries continued to discard their own outdated war materials in the sea during the post-war years. The British chose Beaufort's Dyke for this purpose, a 250-metre-deep trench between Scotland and Northern Ireland, which experts estimate now contains over a million tonnes of munitions. The Americans, on the other hand, dumped their remaining munitions in the waters off Hawaii, Nova Scotia, Newfoundland, and probably at other sites as well [1]. The Norwegians used a dozen of dumping grounds to dispose of outdated munitions up to the late 1960s [2]. Other European countries might face similar situations since sea disposal was considered a routine part of inventory management [3]. According to present knowledge, there are around 385 000 metric tons of munitions resting on the seabed in the dumping areas of the Baltic Sea [3] including around 40 000 metric tons of chemical munitions. It is expected to be around 1.3 million metric tons of munitions resting on the North Sea seabed in German waters, mostly conventional munitions [4]. I It is estimated to be dumped over 400 000 metric tons of munitions in Norwegian waters [5] including approximately 160 000 metric tons of chemical munitions in scuttled ships in Skagerrak [6]. Summarized a total of more than 3 million metric tons of munitions is dumped in these waters. In addition, there will be hundreds of war wrecks containing munitions and probably hundreds of thousands sea mines still on the seabed [7].

Due to the increasing exploitation of the seabed in the form of wind farms, pipes and cables, the risk for encounters of dumped munitions has increased. According to the OSPAR[1] Commission, it is reported approximately 900 encounters each year, but there is no obvious trend in the number of encounters reported over time [8]. As the explosive charge in dumped munitions still is functional, it poses both a safety and security risk [9]. As most of the explosive charge and some other compounds in munitions are toxic, it also poses a risk for the environment [10, 11, 12, 13, 14]. The different risk aspects of dumped munitions are illustrated in Figure 1.

Clearing of dumped munitions and unexploded ordnance in marine waters is often performed by rapid response to encounters of munitions by Explosive Ordnance Disposal units. According to OSPAR, most of these encounters

[1] Oslo-Paris Convention

are destructed by blasting [7]. Due to safety, the most common disposal method for underwater conventional munitions has historically been to use a high-order controlled detonation conducted by exploding a demolition charge placed adjacent to the munitions for disposal [9]. This method is referred to as blast or blow-in-place (BiP). A variation of this method is to relocate the munitions to safer locations for the environment or nearby infrastructure and blow-in place at the new site.

Munitions on the seabed can be divided into two main categories. Unexploded ordnance (UXO) means explosive ordnance that has been primed, fused, armed, or otherwise prepared for use and used in an armed conflict. It may have been fired, dropped, launched or projected and should have exploded but failed to do so [15]. Abandoned explosive ordnance (AXO) means explosive ordnance that has not been used during an armed conflict, that has been left behind or dumped by a party to an armed conflict, and which is no longer under control of the party that left it behind or dumped it [15]. Abandoned explosive ordnance may or may not have been primed, fused, armed or otherwise prepared for use. As it can be difficult to distinguish between UXO and AXO munitions on the seabed, all munitions in the seabed are referred to Explosive Remnants of War (ERW) in this report.

ERW is mainly handled by Explosive Ordnance Disposal (EOD) units. This is specialized military and police units, as well as their associated procedures, that detect, identify, evaluate, render safe, and dispose of explosive hazards, including ERW and improvised explosive devices (IEDs) [15].

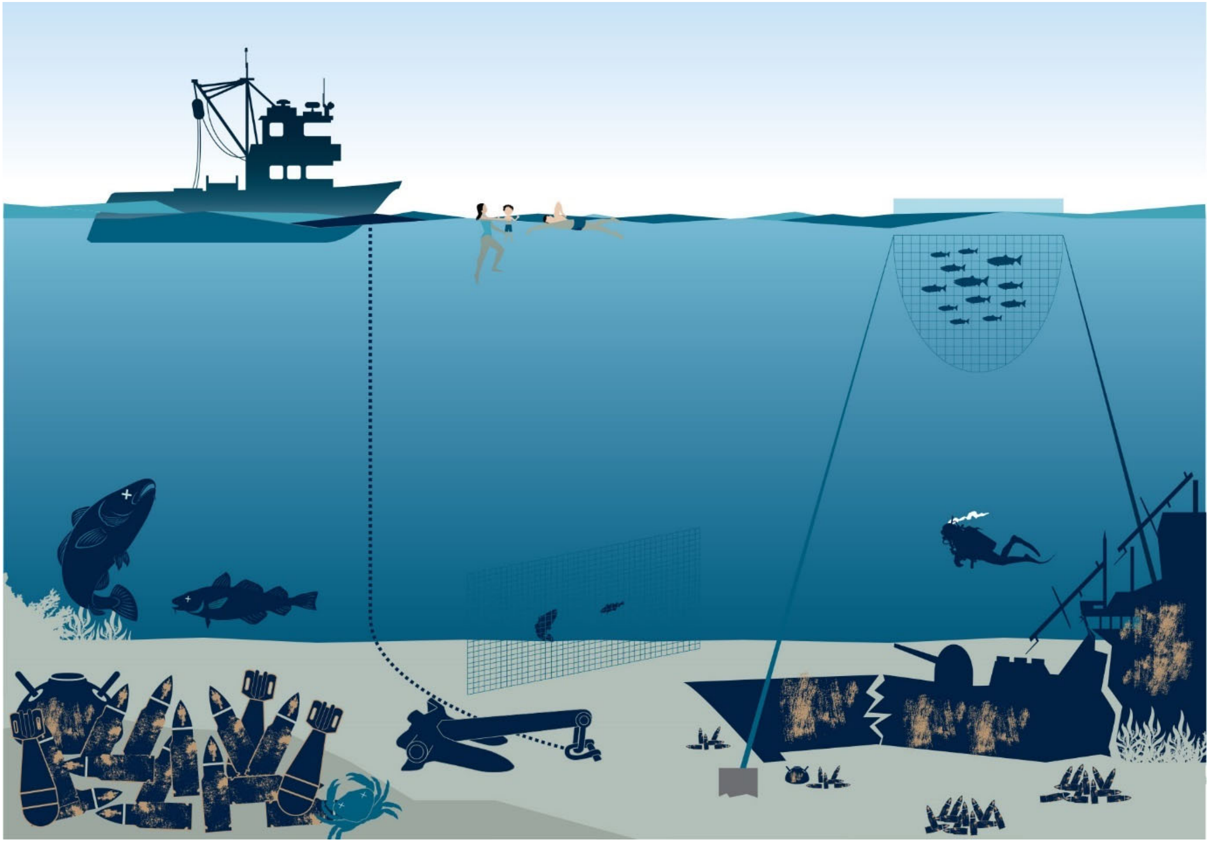

Figure 1: Risk aspects of ERW. Illustration: FFI.

1.1 Reactions of explosives

There are only two reaction modes of an explosive: detonation, a shock-driven reaction that is a material constant of high explosives, and combustion, a surface-driven process. An explosive can only be optimized for one of these modes:

- Detonation, through formulation and oxygen balance
- Combustion, through the use of control additives

Combustion speed is highly influenced by the surroundings – primarily pressure increases due to enclosure. The mass combustion rate results from combustion pressure and the recent active burning surface.

In low-order detonation (LOD) methods that intentionally rely on accelerated combustion of the main charge, the explosive is being used in a mode it was not designed for. This leads to an “aggressive” pressure dependency which is considered uncontrollable as propellant even within well-defined surrounding conditions of a gun or a rocket motor with its thrust nozzle. In aged munitions submerged into the sea, the surrounding "enclosure" conditions are influenced not only by seawater but also by the main charge casing. These casings are well defined for uncorroded grenades while lower manufacturing tolerances of aerial bombs increase the variability. However, the variability is very large for marine munitions like bottom and anchor mines, torpedoes or depth charges. A large variety of corrosion states and strongly varying main charge composition further increase the variability of the casing. As a result, accelerated combustion cannot proceed in a stable manner under these unfavourable and unpredictable conditions.

For shaped charge LOD methods, the critical diameter is an important property of high explosive materials. The critical diameter is defined as the minimum diameter of an unconfined cylindrical high explosive charge that can sustain a self-propagating detonation. For WWII explosives, this diameter typically falls within the centimetre range. If the diameter is smaller than the critical diameter, the detonation will not continue and will instead cease.

A shaped charge generates a very thin, high-velocity fluent metal jet that travels faster than the detonation velocity. This jet penetrates the munition shell, passes through the high explosive, and exits through the rear side of the shell. The two penetration pinholes in the shell act as nozzles for combustion. Combustion is initiated along the jet's path through the explosive material. The intense shock caused by the jet tip interacting with the explosive should not result in detonation, as the interaction cross-section is significantly below the critical diameter. However, the combustion ignited along the jet path propagates radially outward. As the cylindrical burning surface expands progressively, the nozzle size remains constant. This, combined with the aggressive burning behaviour, leads to a rapidly increasing pressure, which can potentially result in a deflagration-to-detonation transition (DDT). Higher initial temperatures of the explosive further accelerate combustion. A DDT becomes possible when the combustion velocity approaches the speed of sound. To prevent this transition, the shell must rupture – causing a pressure drop – or the burning surface must decrease, halting the progressive combustion. This highly dynamic, self-accelerating process inherently carries a risk of DDT and, consequently, partial high-order detonation (HOD) of the munitions. Alternatively, if the burning explosive is mechanically disrupted, the sudden pressure drop from the shell rupture may significantly slow the combustion, which can be completely extinguished upon contact with water.

Low-order detonation means to couple a shock wave into the explosive. One method to achieve this involves the use of ballistic discs – plates accelerated by explosives that impact the munitions surface. The resulting impact generates a shock wave that propagates into the explosive. This shock must be strong enough to cause spontaneous ignition, followed by rapidly accelerated combustion due to self-confinement by the explosive material. However, based on the earlier explanations, this method also lacks stability. The process may either accelerate into a DDT or decay into slower combustion.

2 High-order detonation (HOD)

A high-order detonation (HOD) is a rapid, supersonic event where an explosive material rapidly converts to hot gases with high pressure, generating a powerful shock wave. High-order detonations are characterized by high detonation velocities (5,000 to 10,000 m/s) resulting in an extremely short rise time of the pulse and subsequent shock waves that can proliferate for many kilometres [16]. As the shock wave spreads out, the amplitude will decrease due to geometric damping. Since the propagation velocity depends on the amplitude, the velocity will change behind the shock wave, causing the shock wave not to retain its shape but to stretch out. Energy will be lost as it propagates, and eventually the shock wave will transform into a pressure wave [17].

To achieve an HOD, an external explosive charge is placed adjacent to the ERW object which by detonation initiates a full detonation of the explosive charges in the ERW, resulting in the rapid release of energy and complete destruction of the ordnance. Due to safety, this has been the favoured EOD method for ERW [14].

The detonation produces large amounts of gas that expands into a gas bubble. This bubble expands until the pressure is equal to the water surrounding the gas bubble. Due to the inertia of the gas, the bubble will continue to expand for a while after this. The expansion of the gas bubble is then reversed, and it collapses as illustrated in Figure 2. As the gas bubble collapse, the pressure in the bubble increases and this results in a new pressure wave that propagates radially outward. This process repeats itself several times and oscillations of 10 or more have been observed [17]. If the first gas bubble penetrates the water surface, the oscillations will be interrupted. A huge water column will rise into the air due to the penetration of the water surface by the gas bubble and the collapse of the first bubble as illustrated to the left in Figure 2.

Underwater detonations differ from detonations in air due to the differences in sound velocity and the density to the surrounding medias. In contrast to air, the oscillation collapse of the gas bubble will create a series of pressure pulses in water as illustrated to the left in Figure 2. Due to the oscillation of the gas bubble (bubble pulses) it will propagate in the water for a much longer time than the pressure pulse in air [18].

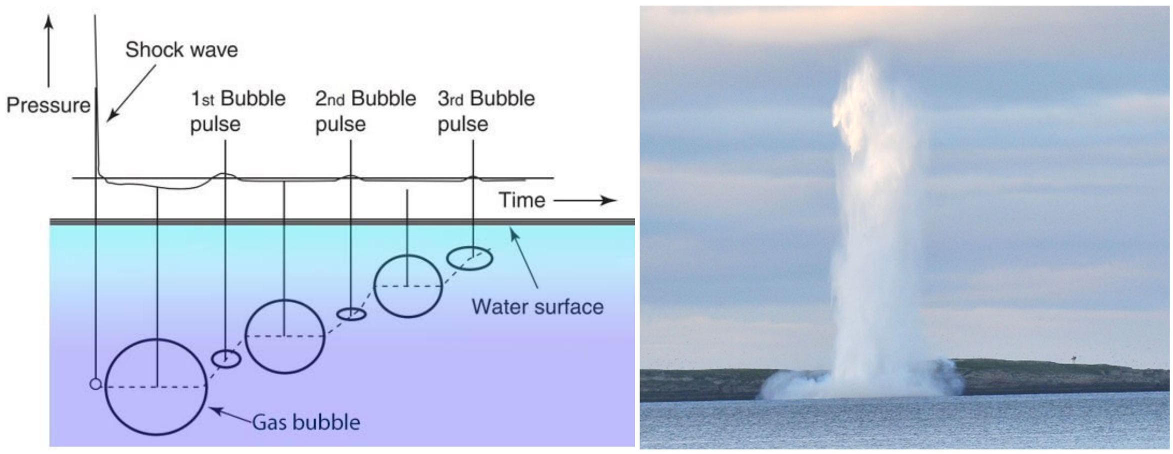

Figure 2: Left: Schematic illustration of underwater explosion phenomenon based on Snay H.G [19]. Right: High-order detonation of ERW at shallow depth will generate a huge water column into the air as a result of the gas bubble penetration of the water surface. Photo: FFI.

3 Low-order disposal (LOD)

Due to the speed of the reaction, a distinction is made between combustion, deflagration and detonation. Normal combustion is a process with a propagation velocity of the order of mm/s, for deflagration m/s, and for detonation—km/s [20]. Low-order disposal of ERW can be classified into low-order deflagration and low-order detonation. Low-order deflagration is an incomplete or partial energetic reaction of an explosive, resulting in a slower, less intense explosion with a subsonic shock wave and significantly reduced blast effects compared to a high-order detonation. A deflagration is a rapid combustion process where a flame front moves through an explosive at speeds slower than the speed of sound (< 1000 m/s). If a deflagration occurs within a confined space, a deflagration can accelerate and transform into a detonation [21]. Peak pressures produced by deflagrations are orders of magnitude lower than those from HOD [14].

Low-order detonation is characterized by a much lower detonation velocity than HOD (> 1000 and < 5000 m/s) [19]. It occurs when the detonation reaction does not reach steady state and hence the maximum detonation velocity is not reached. It is still a detonation with a supersonic reaction rate, which produces a shock wave. Low-order detonation may occur when non-planned stimuli occur which may take place during disposal operations as mentions in chapter 1.1. Low-order detonation is also a risk with high performance propellants.

Low-order disposal of dumped munitions in marine environments can be achieved by using different shaped charges as mentions in chapter 1.1. There are several companies producing low-order tools for achieving low-order disposal of ERW. The Vulcan™ is a highly versatile, user-filled, modular shaped charge system in service worldwide to induce low-order disposal on land and underwater [22]. Used as a tool for producing low-order disruption of target munitions, it results in a low-order above 90 % of the time, providing operators with high confidence. Vulcan™ can counter many types of ERW, both on the surface and subsurface to a depth of 80 m using the supplied accessories. The French company Suprameca offers a range of technical solutions for low-order disposal of ERW [23]. The German HL-21 shaped charge has also been used as a low-order tool [24].

There will always be a possibility that a planned low-order disposal of ERW will turn into a high-order detonation. As mentioned by Alford Technologies, only around 90 % of the low-order attempts turn into a low-order disposal [22]. Seven types of munitions objects and a total of 82 ERW with a net explosive quantity (NEQ) varying from 6 kg to 700 kg, were successfully neutralised using low-order deflagration in the Moray West Offshore Wind Farm, Scotland [25]. A British WWII Tallboy bomb was neutralised on the fairway connecting the Polish Baltic ports of Świnoujście and Szczecin by low-order disposal [26]. After an initial deflagration of the bomb, the deflagration turned into a detonation.

Low-order disposal of ERW will result in the formation of large fragments as illustrated in Figure 3. Studies of the fragmentation of high and low-order disposal of a pipe bomb shows larger fragments using low-order methods and a higher number of fragments using high-order methods [27]. The use of low-order methods will not cause a crater on the seabed as shown in Figure 3 and this was also the experience from the disposal of 82 ERWs in the Moray West Offshore Wind Farm, Scotland [25].

Figure 3: A sea mine disposal by low-order deflagration. Left: Pluton™ deflagration charges placed on the mine shell. Right: After disposal, where large chunks of explosives are visible and no crater. Photo: Norwegian Naval EOD Command.

4 Comparing HOD and LOD

The main environmental difference between HOD and LOD are the shock wave strength and the remnants of the explosive charge. These differences are discussed in the two following chapters.

4.1 Pressure wave

HOD will create a supersonic shock wave with high intensity whereas LOD will generate a shock wave with intensity an order of magnitude lower [14]. There are many factors influencing the intensity of an underwater shock wave. It will be the amount and type of explosive that determine the initial energy released. More energy = higher peak pressure and faster shock wave. The temperature, salinity and pressure (depth) will affect the speed and attenuation of the shock wave as these factors affect the density of the water. The shock wave will decay exponentially with the distance from the detonation as shown in Figure 4 according to the Arons formula (1) [28]. This means that the peak pressure at 110 meters from the detonation is only around 6,7 % of the peak pressure 10 meters from the detonation. At 210 meters the peak pressure has dropped to 3,2 % of the peak pressure at 10 meters. Still, a substantial peak pressure can be observed 10 km from the detonation in open water (Figure 4).

$$p = k\,(W^{1/3}/r)^{1.13} \qquad (1)$$

where p = peak pressure (Pa)
$k = 5.25 \cdot 10^7$ (charge constant for TNT)
W = charge weight (kg)
r = distance (meters)

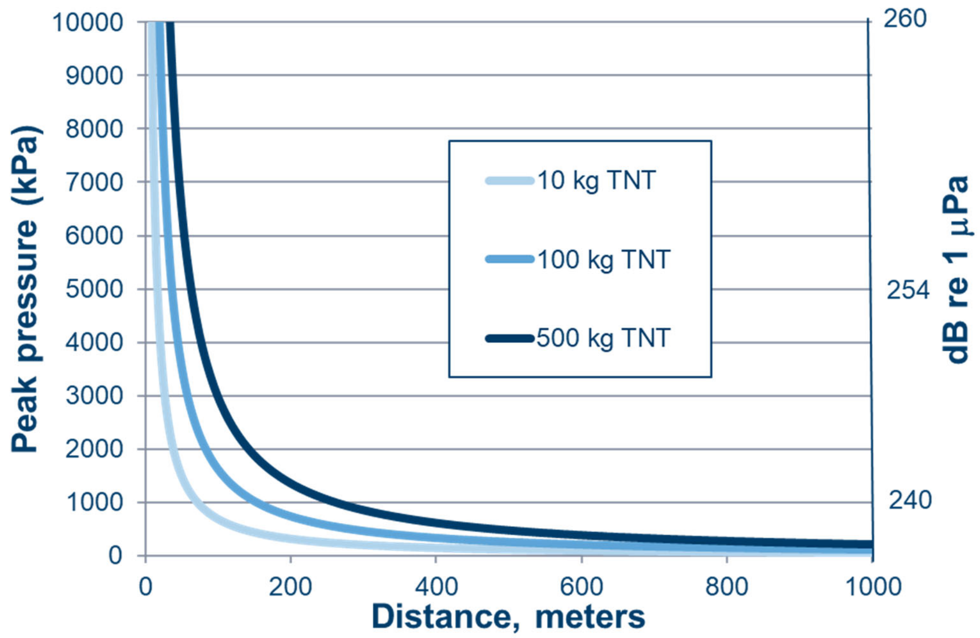

Figure 4: Peak pressure after detonation of 10, 100 and 500 kg TNT in open water as a function of distance. Diagram based on Arons formula (1) [28].

Based on studies by FFI on the effects of peak pressure from underwater detonations on cod [29], peak pressure > 240 dB re 1 µPa most probably will be lethal. Peak pressure between 220 and 240 dB re 1 µPa makes healable damage but can be lethal if several detonations occur. Peak pressure between 180 and 220 dB re 1 µPa will give small or no physical effects, but stress reactions can be observed. Stress and escape reaction can be observed with peak pressure of 100 to 180 dB re 1 µPa. No response is expected below 100 dB re 1 µPa. Higher organisms with specialized hearing organs and air-filled structures such as lungs and swim bladders are more susceptible to barotrauma than invertebrates [30]. The potential for damage increases with decreasing individual size [31].

Table 1. Effects of peak pressure on fish with swim bladder [29].

Peak pressure (kPa)	Effects on fish	dB re 1 µPa
> 1000	High risk of lethal effect	> 240
100 – 1000	Healable damage to organs but lethal if several detonations	220 - 240
1 - 100	Small or no physical effects, but stress reactions	180 - 220
0,1 - 1	Stress and escape response	160 - 180
0,001 – 0,1	Moderate escape response	100 - 160
< 0,001	No response	< 100

If the detonation is done at shallow depth, the gas bubble will penetrate the surface and much of the energy will be ventilated into the air as shown in Figure 2. This will decrease the peak pressure substantial and reduce the environmental damage of an underwater detonation. The peak pressure will typical be reduced by 10 dB re 1 µPa by this method [32]. In addition, islets and reefs in the detonation area will contribute to reduce the peak pressure. According to a study by FFI, shallow islets and reefs can reduce the peak pressure by 50 dB re 1 mPa [32].

The peak pressure can be decreased by 15-20 dB re 1 μPa using low order methods [14] and for large ERWs up to 40 dB re 1 μPa reduction can be achieved. The clearing of 82 ERWs (mostly 15-inch projectiles) at Moray West Offshore Wind Farm by deflagration methods showed a decrease in the peak pressure by around 16 dB re 1 μPa compared to modelled peak pressures in open water [25]. As the ERWs were located on the sea bottom, some energy will be transferred to the ground and give rise to a decreased peak pressure to some degree [25]. As a comparison, it can be noted that the use of bubble curtains often reduces the peak pressure by 12-20 dB re 1 μPa [33,34]. The highest peak pressure observed at 1 km distance was 208.4 dB re 1 μPa for a 15-inch projectile. The estimated maximum peak pressure at 100 meters distance is above 220 dB re 1 μPa. As Table 1 shows, stress reactions and small physical effects can occur on fish and marine mammals from 180 to 220 dB re 1 mPa and damage to organs above 220 dB re 1 μPa. According to studies by FFI, escape reactions of fish in fish farms can occur from 170 dB re 1 μPa [33]. Low-order disposal of ERW will reduce the peak pressure but can still be harmful for marine organisms close to the disposal position, and care should be taken not to harm fish farms or marine mammals.

The pressure wave can also be destructive to vessels close to underwater detonation. According to Bogdan Szturomski a peak pressure < 232 dB re 1 μPa is safe for all vessels [35]. Peak pressures up to 246 dB re 1 μPa will damage sensitive electronics and crack brittle materials, while warship will be safe.

4.2 Contamination

Cold Regions Research laboratory (CRREL) has done comprehensive studies on the residues of explosives after live fire and blow in place on land [36-40]. Their results indicate that very little explosive residues are left after life fire high-order detonations. Only 0.0011 % or lower amounts of the explosive charge are deposited on the ground [38]. This means that more than 99.99 % of the explosive charge is converted to combustion gases. Blow in place high-order detonations gives some more remnants of the explosive charge on the ground compared to live fire. A maximum of 0.027 % and a mean of 0.0012 % are deposited on the ground for mortars and artillery shells [40]. Lower calibre munitions seem to give more explosive remnants on the ground. It is therefore expected that munitions with large explosive charges will have a more complete combustion than munitions with small explosive charges. The results from low-order detonation shows that the size of the explosive remnants are more than 100 times higher compared to high-order detonations. As much as 22 % of the explosive charge could be recovered from the ground [40]. Low-order detonations or partial detonations can leave large chunks of explosives on the ground as shown in Figure 5. It is expected that underwater detonation of munitions will give much of the same remnants of explosives as shown above for detonations on land.

Figure 5: Chunks of explosives in a Norwegian firing range. Photo: FFI.

To investigate the pollution of the marine environment after low-order versus high-order operations, two comparable mines dropped by the British Royal Air Force (RAF) during World War II in Denmark's Sejerø Bay were blown up by either low-order or high-order detonations by the Danish Royal Navy [13]. Concentration of explosives in the water and sediment were measured after the disposal. The results showed that the explosive concentration after low-order disposal caused a several 1000-fold increases in the marine environment compared to high-order disposal.

Recently, Cranfield University has measured the remnants of explosives after disposal of pipe bombs using high and low-order disposal methods in a water tank [27]. The results showed that low-order disposal generated the highest concentration of explosives, around an order of magnitude higher than high-order detonation. Partial detonation of the pipe bomb generated the highest concentration in this study.

NAVSEA[2] studied low-order detonations of 155 mm artillery projectiles and Mk 82 bombs and identified high amounts of explosive residues after the disposal [24]. The recovered amount from the artillery projectiles varied from around 10 % of the explosive charge to 49 %, with an average of 25 %. The recovered amount of explosive after the bomb disposal varied from 41 % to 89 %, with a mean of 72 %.

In connection with a NATO Naval EOD training exercise in Norwegian waters in 2014, a sea mine was disposed of using low-order methods (Pluton™ charge). A geotextile was placed close to the mine in two directions to collect fragments of unexploded explosive particles (Figure 6). A total of 27.4 kg explosive remnants were collected on the geotextile, in the mine shell and close to the mine, which is around 20 % of the total explosive charge in the mine. Chunks > 1 kg was observed, but most particles was just some centimetres in diameter (Figure 6). The explosive chunks were not distributed far away from the mine, just a few meters. Small particles < 2 mm were not included in the collected amount and there were also small explosive particles outside the geotextile which were not collected. Therefore, the remnants of the explosive charge from this low-order disposal were > 20 % (FFI, not published results).

It is no doubt that the use of low-order disposal methods of ERW will cause contamination of the site by explosives. This contamination will mostly be as chunks, fragments or particles of the explosive charge. Some of the contamination can therefore be collected after the low-order disposal by divers or by use of ROV in deeper water. Small particles will be difficult or impossible to collect from the seabed, so the seabed will for a long time be contaminated by explosives.

[2] Naval Sea Systems Command

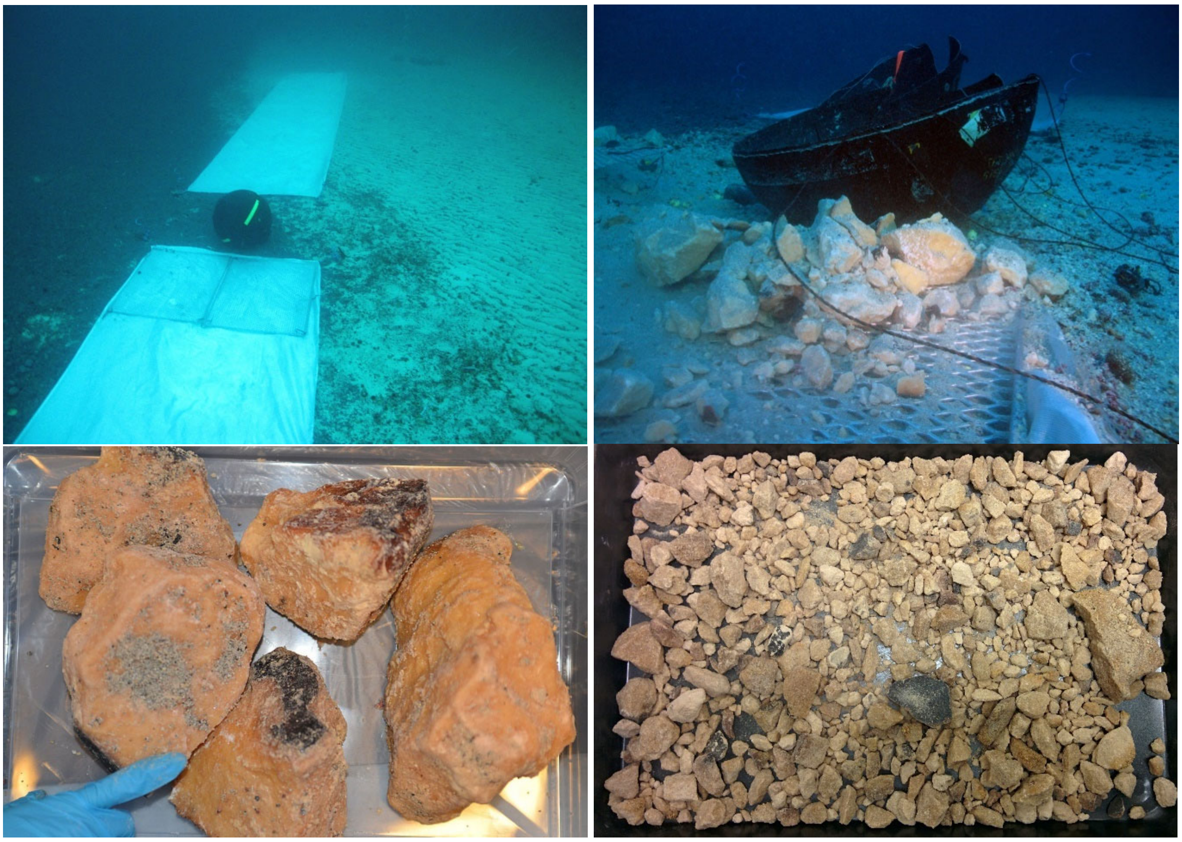

Figure 6: Set up of the low-order experiment and chunks of explosives after disposal of a US MK6 mod 4 sea mine. Photo: FFI and the Norwegian Naval EOD Command.

4.3 Cost

There are many factors influencing the cost of underwater clearance of ERW. If the ERW is located at shallow water, it can be handled by divers. If it is located in deeper water, a Remotely Operated Vehicle (ROV) is needed and thereby also a vessel that can operated the ROV. The cost will also be dependent of the type of ERW and number of objects. Tidal current, weather conditions and visibility can result in limitations to ERW clearance operations. If the ERW is located close to resident areas, cost for the evacuation of the residents can add to the total cost of the clearance operation. The cost for high-order and low-order hardware will be negligible in the total cost for an ERW clearance operation [24]. The cost for ERW clearance using high or low-order methods will therefore be much the same.

Underwater clearance of ERW at shallow depth will need at least four divers to meet diving safety requirements. In addition to labour cost of divers, rental of boat, travel time and rental of decompression chamber will be additional costs. In a study by the NAVSEA in 2002, the major cost elements of underwater explosive operations were identified as diver operations, explosive operations, and environmental and safety surveillance [24]. NAVSEA have estimated that the time for low-order disposal is the same as for high-order disposal. For low-order disposal, additional cost for collecting and disposal of explosive remnants on the seabed after the ERW disposal must be planned for. As a planned low-order disposal can turn into a high-order disposal, environmental surveillance will still be required out to the ranges expected for high-order detonation.

In the Tallboy case on the fairway connecting the Polish Baltic ports of Świnoujście and Szczecin, a lot of time were used to prepare a suitable low-order disposal method and to identify the physical condition of the bomb [26]. A series of tests were performed on available Tallboy fragments to check the low-order donor charge to ensure penetration of the bomb shell. Such a challenging object of ERW will cause a significantly higher cost than a simpler object with a substantial lower amount of explosives.

A similar situation as the Tallboy case in Poland occurred in Norwegian waters in 2013. A WWII naval mine was discovered close to a gas pipe in Norwegian waters at 240 m depth. A lot of time was spent to prepare and evaluate the different disposal methods in addition to simulate the damage of the gas pipe by a high-order detonation. In this situation, the solution became to move the mine and use a high-order disposal method.

For underwater ERW disposal in deep waters it will be necessary with a vessel that can operate a ROV. Vessel with such capabilities is costly to operate and > 17.000€/day must be expected. It will therefore be much more expensive to do ERW clearance at deep water locations than shallow locations where divers can operate.

The cost for underwater clearance of ERW will span over a large range independently of disposal method used. As little as 850€ for a single simple ERW to > 85.000€ for a large and complex ERW must be expected. Key factors determining the cost will be:

- Water depth
- Number of ERW
- Type of ERW
- Position relative to residents or infrastructure
- Weather conditions

5 Other disposal methods

5.1 Laser

A study by the US AARDC[3] concluded in 1981 that the use of a CO_2 laser of about 10 kilowatts output has advantages for some demilitarization operations, but it is not practical for many [41]. MSIAC[4] concluded in 2006 that laser methods for removing explosives still is immature for this application [42].

In the DEFLAG project — Safe Deflagration of Duds by Laser Technology funded by the German Federal Ministry of Education and Research, a procedure that uses a 2-kW fiber laser to defuse the bombs by targeted deflagration were developed [43]. This method uses a mobile, automated laser system to create a grooved notch along the length of the unexploded bomb, weakening its case. Thereafter the explosive is deflagrated in a controlled way. The primary goal was to dislodge the detonator and break the ignition chain, safely neutralizing the explosive without causing a high-order explosion or spreading unreacted materials. At the end of the project in 2019, field tests of the laser-based method for disposing of unexploded ordnance (UXO) were successful, showing that a bomb could be made to deflagrate, or burn along a pre-cut notch, rather than detonate, with only a small portion of the explosive igniting.

A successor to DEFLAG is the UNLOWDET project funded by the German Federal Ministry for Economic Affairs and Climate Action. It aims to develop a laser-based underwater method for the low-order detonation of unexploded ordnance [44]. In order to provide a safe defusing method for ERW, the shell material needs to be partially weakened to about 1/3 of the material thickness [45]. Studies have been done in UNLOWDET to achieve this by the use of a Yb:YAG laser at a laser power of 2 kW. The latest validation of the laser approach in the field showed that the weakening and subsequent initiation of a low-order event worked on munitions samples. To produce consistent results, further investigations using the laser induced initiation must be carried out [46]. As the laser methods still are under development, it will take some time before these methods are available for commercial use.

5.2 Waterjet

The use of water jets for demilitarization dates at least as far back as 1924 when patents were issued to Knight in the US for a washout system for high explosive projectiles [47]. Increased pressure led to the use of the application on tactical missiles in at the US Army Redstone Arsenal in 1954 and further increases in pressure were made by the US Navy in the 1970s [47]. The use of water jets for cutting purposes originated with Franz in Canada in 1968 and the idea was commercialized by Ingersoll-Rand [48]. The use of abrasives to improve cutting performance was introduced in 1982 by Flow International, however it was not until the 1990s that research was published on their use for disassembly of munitions [47]. A summary of the use of waterjets on munitions by Paul Miller in 2018, states that it is extremely unlikely that a commercial waterjet can initiate secondary high explosives or propellants [49]. Physics makes it functionally impossible to achieve the velocities or the large enough jet diameters required to detonate secondary high explosives with current commercial units. Sensitive primary explosives should however be assumed to initiate using commercial waterjet units, although sufficient research has not yet been performed. At least 700,000 high-explosive munitions have been safely cut or washed out with waterjet and abrasive waterjet at pressures above 380 MPa, with an additional unconfirmed number more than two million rounds. Waterjets

[3] Army Armament Research and Development Command

[4] MSIAC: Munitions Safety Information Analysis Center in NATO.

have shown an excellent safety record in use around hazardous materials and may be one of the safest methods of cutting metals and composites when energetics is present [49]. It will therefore be a tool that can be used for rendering safe ERW in order to move it to a safe disposal site.

There are some disadvantages when waterjet is used to cut munitions [48]. Waterjet techniques produce a large quantity of contaminated water. This wastewater needs to be trapped and treated, which introduces a considerable cost. As the energetic compounds are toxic, it is difficult to dispose of. Although water, in sufficient quantity, desensitizes TNT, wastewater containing RDX and HMX can still detonate and propagate while in piping. Reactive or pyrophoric metals can react vigorously with water, with an explosion as a result. For instance, aluminum and water will result in an exothermic reaction (produces heat) and hydrogen will be produced as a decomposition product. Aluminum is a compound added to explosives, especially the explosive charge used in sea mines and torpedoes. Torpex, Minol, Trialen and Schießwolle (Hexanite) are examples of energetics containing aluminum.

6 Regulations and standards

Historically, national militaries have been the entities primarily responsible for survey, disposal or removal of underwater EO. In recent years, however, there has been a notable shift, with an increasing number of NGOs, private companies, and specialized commercial entities becoming involved in underwater survey and clearance efforts [50]. This shift accompanied the wider use of the water resources, particularly the sea, for critical infrastructure and trade. This growing diversification of actors has highlighted a need for internationally recognized norms and standards to ensure that the approaches used are effective, safe, and environmentally responsible.

In addition to national legislating preventing pollution of the marine environment, there are several international laws and conventions for protecting the marine environment. The main ones are listed below.

The United Nations Convention on the Law of the Sea, adopted in 1982, is a broad legal framework that governs maritime activities, setting out State responsibilities regarding navigation, resource use, and environmental protection [51].

OSPAR[5] Convention is the current legislative instrument regulating international cooperation on environmental protection in the North-East Atlantic. OSPAR has collected the best available information on the munitions dumping sites including their estimated location and contents, where known. Reports of munitions encounters are collected centrally, in line with OSPAR Recommendation 2010/20, and presented in the OSPAR Data Portal [8]. There is an annual reporting from each country on encounters of munitions where information about position, type of ERW, conditions of the ERW and disposal method and disposal position.

The London Convention, formally the "Convention on the Prevention of Marine Pollution by Dumping of Wastes and Other Matter 1972," is an international treaty to protect the marine environment from human-caused pollution through dumping [52]. It was one of the first global treaties to address ocean pollution, prohibiting the dumping of certain hazardous wastes and requiring permits for others. The Convention also established the London Protocol, a more modern and precautionary agreement from 1996 designed to eventually replace the Convention itself by adding new measures to prevent marine pollution.

The Barcelona Convention is a regional environmental treaty for protecting the Mediterranean Sea and its coastal areas from pollution and promoting sustainable development [53]. The Contracting Parties to the Barcelona Convention agree to individually or jointly take all appropriate measures in accordance with the provisions of the Convention and the Protocols in force to which they are party to prevent, abate, combat and to the fullest possible extent eliminate pollution of the Mediterranean Sea Area and to protect and enhance the marine environment in that Area so as to contribute towards its sustainable development.

Convention on the Protection of the Marine Environment of the Baltic Sea Area (also known as the Helsinki Convention) integrates measures to manage hazardous substances particularly chemical munitions in dump sites since 1994 [54]. In 2023, the Council of the Baltic Sea States adopted declarations reinforcing their commitments [55], and the Baltic Sea Action Plan [56] of the Helsinki Commission which includes provision to coordinate underwater conventional EO and chemical munitions remediation.

There are few national guidelines for the offshore disposal of ERW. Germany have developed a comprehensive guideline to address the challenges associated with the disposal of ERW in marine environments [57]. The quality guideline applies to the entire process of EOD in marine waters, from the desk-based preliminary survey to clearance of target points and ERW safety sign-off for areas or points. The guideline is valid for German territorial waters and Germany's exclusive economic zone (EEZ) and is only to a limited extent valid to EOD performed by

[5] Oslo-Paris Convention.

military authorities. The guideline lists several competent national authorities which will review the proposed disposal and mitigation methods. The authorities will define a detonation site and a maximum NEQ[6], which may be initiated at the detonation site during each individual detonation in agreement with the EOD service provider. There are no competent authorities outside the German territorial waters. This means that the EOD service provider will make the decision together with the client (e.g. a wind farm operator) or their consultant.

The UK Department for Environment, Food & Rural Affairs have recently established a guideline for minimizing the environmental impacts from unexploded ordnance clearance in English, Welsh and Northern Irish waters [58]. This guidance supports marine users to minimise environmental impacts when clearing unexploded ordnance within the UK marine environment, in relation to commercial marine developments. The guidance sets out how the signatories expect applicants to approach marine licensing for activities relating to UXO clearance. It also offers guidance to prospective applicants on how to effectively prepare and submit licence applications, aligned with the overarching principles of this general approach. This guideline states that low noise methods of underwater UXO clearance should be the default method used to clear any type of UXO in the marine environment. High-order clearance methods should always be the last resort. Regardless of the clearance tool or method used, all applicants should avoid, reduce and mitigate environmental impacts as far as possible. UK have also published a protocol for in-situ underwater measurement of explosive ordnance disposal for UXO [59].

United Nations Mine Action Service have published a guideline for the survey and clearance of explosive ordnance (EO) in underwater environments, including territorial waters, lakes, rivers, ports, and canals up to 50 meters deep [60]. It aims to ensure safe, effective, and environmentally responsible operations. This guideline is similar to the German guideline, but shorter and less detailed.

There are several NATO STANAGs (AEODP) that cover procedures, doctrine, and guidance for Explosive Ordnance Disposal (EOD). One of these is the AEODP-14 –Identification and Disposal of Surface, Air, and Underwater Munitions, which comprises vital EOD related information on identification, associated hazard, safety precautions, and EOD render safe procedures and disposal procedures for explosive ordnance.

A survey by the EU-Interreg project MUNIMAP (Baltic Sea Munitions Remediation Roadmap) has compared national approaches to the issue of munitions in the sea [61]. The national response procedures for various scenarios related to encounters of munitions in the sea are described and responsible authorities are listed. In most countries, initial reports of munitions encounters are made to the police. In some cases, however, the first point of contact may be the Navy Headquarters, Coast Guard, Fire Service, or Maritime Office. Encounters of ERW in marine environments are primarily handled by the national Navy EOD diving teams. This team will consider and evaluate the risks associated with the ERW and determine the appropriate method for disposal. In some countries and for civilian munitions items, the police bomb squad will handle the encounter. Private companies can also handle encounters of munitions. In Germany, an authorisation and review by national authorities is necessary for private companies in German territorial waters [57]. In UK, private companies need a marine license authorized by the Marine Directorate – Licensing Operations Team [25].

In Work Package 2 (WP2), MMinE-SwEEPER aims to analyse the existing European regulatory and responsibility frameworks relevant to the remediation of marine munitions, focusing on key concerns and requirements identified by stakeholders during the activities conducted in Work Package 1 (WP1). More details about the national regulations and standards will therefore be published under WP2.

[6] Net Explosive Quantity

7 Conclusions and recommendations

The comparative assessment of high-order (HOD) and low-order disposal (LOD) demonstrates that underwater explosive ordnance disposal remains a technically, environmentally, and operationally complex challenge. HOD continues to offer the most predictable and complete neutralisation of energetic materials, as its supersonic detonation front and full reaction of the explosive charge greatly reduce the amount of unreacted energetics released into the marine environment. This reliability, combined with the method's long operational history has shown high operational safety. HOD has therefore been the dominant approach in many national ERW disposal procedures. However, the significant acoustic footprint associated with HOD—characterised by very high peak pressures and long-range propagation of shock waves—represents a major environmental drawback, especially for sensitive marine fauna such as marine mammals and fish with swim bladders. Numerous studies show that peak pressures associated with HOD can cause stress, injury, or mortality at considerable distances, even when mitigation measures are applied.

In contrast, LOD techniques—whether based on deflagration, shaped charges, ballistic discs, or other subsonic initiation processes—offer substantial reductions in peak pressure and thus lower acoustic and barotrauma risks for marine mammals and fish. Field experience, such as the Moray West Offshore Wind Farm disposal operations, demonstrates reductions of around 15–20 dB re 1 µPa, contributing meaningfully to environmental protection efforts. However, LOD have some critical limitations. Most importantly, LOD reactions are inherently less stable because they rely on combustion behaviour for which the original explosives were not designed. Ageing, corrosion, unpredictable casing integrity, and compositional variability in ERW further compromise the controllability of a low-order outcome. This means that even well-planned LOD disposals can escalate into unintended high-order events, complicating risk assessment and planning. In addition, LOD typically leaves behind substantial explosive residues—often tens of percent of the original charge—introducing persistent contamination risks in sediments and may require post-operation clean-up.

The environmental trade-offs between acoustic impact and chemical contamination therefore remain the main risk difference between HOD and LOD. While HOD generates stronger shock waves, its completeness of combustion minimises long-term chemical hazards. Conversely, LOD reduces acoustic footprint but produces far greater contamination of the seabed due to unreacted explosive fragments and particulates. Both types of impact have ecological consequences: while blast injuries are acute and immediate, contamination can lead to chronic, bioaccumulative, and ecosystem-level effects, particularly for compounds such as TNT, RDX, and HMX. This underscores the necessity of choosing the disposal method based not only on immediate operational requirements but on long-term environmental management.

Although the safety aspect of the disposal method is most important, cost considerations will also be a factor influencing the method selection. The hardware costs for HOD and LOD are relatively small compared to vessel operations, diver deployment, ROV systems, and environmental monitoring necessary for both methods. The water depth, number of ERW, type of ERW, position of the ERW and weather conditions will affect the cost greatly. The cost for underwater clearance of ERW will span over a large range independently of disposal method used. As little as 850€ for a single simple ERW to > 850.000€ for a large and complex ERW must be expected. HOD may require the use of mitigation measures like bubble curtains, which will increase the costs for this method whereas LOD disposals require additional time for site clean-up and post-disposal surveys, and it may require HOD safety zones as a deflagration-to-detonation transition is possible. Complex cases—such as large WWII bombs, torpedoes, or munitions located near critical infrastructure—can substantially increase costs regardless of method. For deep-water operations, vessel costs dominate to such an extent that method-specific expenses become marginal in comparison.

Emerging disposal methods, such as laser-based shell weakening and waterjet cutting, show promise in providing safer pathways for render-safe procedures prior to final disposal. Laser methods have recently demonstrated successful controlled weakening of munition casings to promote safe deflagration, though further validation is needed before widespread adoption. Waterjet systems, already widely used for demilitarisation on land, may offer improved safety margins for removing explosives from intact shells underwater. However, challenges remain, including the management of contaminated wastewater and technical limitations on cutting efficiency at depth. These technologies will likely complement rather than replace HOD or LOD in the near term but represent important contributions to the future disposal toolbox.

Regulatory frameworks governing underwater EOD continue to evolve, driven by growing awareness of environmental impacts and the expanding human activity at sea. National guidelines—such as Germany's Quality Guideline for Offshore Explosive Ordnance Disposal and the UK's recent focus on minimising environmental impacts through prioritisation of low-noise clearance methods—illustrate a trend toward harmonisation and environmental precaution. Still major gaps persist in international standardisation. While conventions such as UNCLS, OSPAR, the London Protocol, and the Helsinki Convention provide overarching environmental protection mandates, they do not offer detailed technical requirements for ERW disposal. NATO STANAGs, United Nations IMAS standards, and EU-level initiatives such as MUNIMAP help address procedural consistency, but a genuinely unified regulatory framework remains lacking. There is a need for international recognized norms and standards to ensure that the approaches used are effective, safe, and environmentally responsible. MMinE-SwEEPER will also address aspects of the regulatory, policy, security and decision-making process for disposal of ERW in future deliveries in WP 1 and 2.

Taken together, the evidence indicates that no single disposal method can be universally recommended across all ERW scenarios. Instead, method selection must follow a rigorous, site-specific risk assessment that balances safety, environmental impact, cost, logistical constraints, and regulatory requirements. HOD remains the most reliable method for ensuring complete neutralisation, especially where contamination risk is a priority. LOD provides meaningful acoustic advantages but demands careful planning, cleanup, and acceptance of the potential for greater explosives contamination. Emerging technologies offer valuable future alternatives but are not yet mature enough to replace existing practices fully.

The result in this report shows that there is need for continued innovation and collaborative policy development to address the complex challenges of underwater munitions disposal. The scale of the contamination of explosives and heavy metals after the use of HOD and LOD for underwater disposal of ERW need to be more extensively studied, in order to give a more precise risk assessment. LOD methods decrease the pressure wave, but not necessary to a level not harmful to marine mammals and fish. Therefore, mitigation measures can also be necessary to implement using LOD methods. The mitigation effects of bubble curtains and other mitigation measures for the generated pressure wave need to be studied in more detail, to optimise the effect of these measures.

Overall, the continued development of advanced mitigation measures, improved modelling tools for predicting environmental impact, and clearer international standards will be essential for achieving safer and more sustainable underwater munitions remediation. The future deliverables 9.3-9.5 of MMinE-SwEEPER will further elaborate on mitigation measures, their effectiveness, effort and costs. They will also discuss other ERW disposal methods like cover-up and recovery, as an alternative to HOD and LOD. A more detailed discussion of the contamination risk during ERW remediation activities will be given in deliverable 9.6 and 9.7.

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