



Environmental impacts of low and high order detonations in water

Bhumika Sharma^a, Joshua Wardrop^a, Federica Persico^{a,*}, Sally Webb^a,
Frederic Coulon^b, Tracey Temple^a

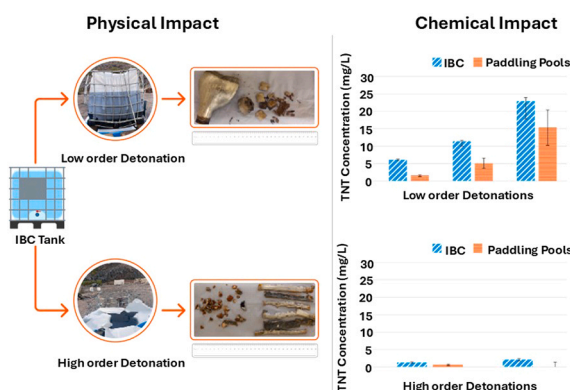
^a Cranfield University, Cranfield Defence & Security, Defence Academy of the United Kingdom, Shrivenham SN6 8LA, UK

^b Cranfield University, School of Water, Energy and Environment, Cranfield MK43 0AL, UK

HIGHLIGHTS

- A semi-controlled method to evaluate the environmental impact of LO/HO detonations.
- HO generates more fragments with lower mass and smaller size compared to LO.
- LO releases more explosive residues compared to HO resulting in more contamination.
- Partial detonation phenomenon was observed while replicating LO.

GRAPHICAL ABSTRACT



ARTICLE INFO

Keywords:
Underwater detonation
Explosive residues
Fragmentation
Stopping distance

ABSTRACT

The clearance of dumped munitions often relies on low order (LO) and high order (HO) detonation techniques, both of which pose significant risks to aquatic ecosystems. LO detonation leaves behind substantial explosive residues, whereas HO detonation generates intense shock waves and extensive fragmentation. This study examines the environmental impact of these detonation methods, including partial detonation, under semi-controlled conditions using six 1000-litre Intermediate Bulk Container (IBC) tanks. Partial detonation represents an incomplete LO detonation, resulting in the high transfer of TNT to the aquatic environment. Explosive residues were almost 8 times higher after LO detonations (8.7 ± 2.8 mg/L) compared to HO (1.2 ± 0.4 mg/L). Fragmentation analysis revealed that HO produced more than twice the number of fragments compared to LO, increasing the potential for physical damage. By integrating these findings with modelling, the fragment stopping distances were estimated. The maximum distance covered by the fragments ranged between 94.9 and 107.1 m. The acute toxicity spatial extent of explosive contamination from a single World War (WW) munition detonation was found to be 25–40 m (LO); 36–58 m (Partial); 14–23 m (HO). Considering, there are stockpiles of munitions in the water bodies, this distance can be much larger. These insights aid to minimise both chemical and physical environmental impacts, particularly in the context of World War-era munitions clearance.

* Corresponding author.

E-mail address: federica.persico@cranfield.ac.uk (F. Persico).

<https://doi.org/10.1016/j.jhazmat.2025.139140>

Received 20 February 2025; Received in revised form 17 June 2025; Accepted 2 July 2025

Available online 3 July 2025

0304-3894/© 2025 The Authors. Published by Elsevier B.V. This is an open access article under the CC BY license (<http://creativecommons.org/licenses/by/4.0/>).

1. Introduction

Munitions filled with conventional explosives such as 2,4,6-trinitrotoluene (TNT), 1,3,5-Trinitroperhydro-1,3,5-triazine (RDX) and 1,3,5,7-Tetranitro-1,3,5,7-tetrazocane (HMX) were extensively used during the two World Wars [33]. As a result, vast quantities of Unexploded Ordnance (UXO) have been dumped in marine environments around the world [3]. The clearance of these munitions presents significant challenges, including high costs, substantial risk to the operators and environmental hazards. These abandoned munitions interfere with infrastructure development, restrict tourism, and create economic burdens in countries such as the UK and Germany [4]. Further to this, it is becoming crucial to clear these munitions for both environmental, economic and safety purposes.

Currently, the primary methods for UXO clearance involve in-situ detonation. Detonation is a rapid release of energy due to high temperatures and the expansion of gases at high pressure [10]. Two common detonation techniques used for UXO disposal are Low-Order (LO) and High-Order (HO) detonations. LO detonation uses a small, shaped charge, which penetrates the munition casing with the formation of a plasma-like jet. LO ruptures the UXO, which does not usually result in complete detonation exposing the munition's contents directly into the surrounding aquatic environment. A LO has a velocity that ranges between 1000 – 5000 m/s. HO detonation, uses a donor charge that is placed next to the munition which acts as a stimulus to initiate the munition [16]. The velocity of a HO detonation ranges from 5000 to 10,000 m/s [4,14,35]. While both methods effectively eliminate UXO, studies indicate that LO detonations leave up to 10 % of the explosive charge in the environment, whereas HO detonations result in significantly lower residual explosives [16]. Maser et al., [19] further investigated post-detonation explosive concentrations, showing that LO detonations can lead to explosive residues of up to 1 mg/L in water and 10 g/kg in sediments, while HO detonations produce lower concentrations of 353 ng/L and 175 µg/kg in water and sediments, respectively.

The environmental and toxicological risks associated with residual explosives are well-documented. Explosives such as RDX, HMX and TNT are toxic, carcinogenic and mutagenic, for example, Maser & Strehse, [20] found that mussels near corroding munitions and exposed explosive chunks exhibited bioaccumulation of TNT and its derivatives, posing significant health risks when consumed. Concentrations of TNT, RDX, and 1,3-dinitro-benzene (DNB) at a UXO dumpsite in the Bay of Kiel in the Baltic Sea ranged from 0.01 to 10 ng/L, with concentrations near exposed explosives being orders of magnitude higher [3]. Similarly, mussels near corroded mines in the western Baltic Sea accumulated 4-ADNT at concentrations up to 10 ng/g, while mussels near exposed Hexanite had significantly higher concentrations of TNT and its derivatives [26]. These findings suggest a potential risk of bioaccumulation within the food chain. Human exposure to TNT and its degradation products has been linked to liver impairment, red blood cell disorders, aplastic anaemia, skin and hair damage, hemotoxicity, and carcinogenic effects [17,2,9]. HO detonations have traditionally been the preferred method for UXO clearance, however, their environmental impact, particularly in terms of noise pollution, has raised concerns [31].

Despite advancements in UXO clearance, no method achieves 100 % removal of explosive residues. Unburnt and partially burnt explosive particles persist due to shock wave reflections during detonation [1]. The presence of these residues poses ongoing risks to aquatic organisms. Monitoring explosive toxicity and evaluating clearance efficacy are critical factors in determining the most appropriate method for UXO disposal at dumpsites, training grounds, and storage facilities [1].

The high-amplitude sound waves generated by HO detonations can travel up to 25 km underwater, disrupting marine life (OSW0038 Technical Report). Studies on harbour porpoises indicate that 88 explosions per year can cause permanent hearing loss in 1280 to 5450 individuals [35]. Reports highlight a lack of adequate mitigation

measures for HO detonations, for instance, in 2011, 19 pilot whales were stranded and died in Kyle of Durness (UK) following HO detonations conducted by the Royal Navy [6]. Comparative studies by Lepper et al. [16] indicate that LO detonations produce significantly lower acoustic impacts (224–226 dB re 1µPa².s) with a reduction of approximately 20 dB compared to HO detonations (243–246 dB re 1µPa².s). Consequently, regulatory bodies such as the US Department of Defence and the UK Parliament have advocated for the use of LO detonations over HO methods to minimize environmental damage ([31,8]). Various noise mitigation strategies, including acoustic deterrent devices and bubble curtains, have been explored to reduce the impact of HO detonations. Bubble curtains have been shown to lower sound pressure by 16–19 dB [24].

This study aims to compare the environmental impact of LO and HO detonations by assessing their physical and chemical effects, quantifying explosive residues, and determining hemi-spherical distribution of TNT for minimising environmental and ecological harm.

2. Materials and methods

2.1. Materials

The explosives used in this study included 2,4,6-Trinitrotoluene (TNT) and a Pentaerythritol tetranitrate (PETN)-based plastic explosive, composed of 86 % PETN, 13 % plasticizer, and 1 % 2,3-Dimethyl-2,3-dinitrobutane (DMNB), supplied by Alford's Pvt Ltd. The modular shaped charge systems (Vulcans) [36] used to achieve LO detonation were also sourced from the same supplier. Boss Super Green Polytetrafluoroethylene (PTFE) Compound was used as a sealing agent, while paddling pools were purchased from Amazon. The syringe plunger for sampling and the metallic pipe for the pipe bomb were custom manufactured in-house at Cranfield University. For this study, TNT was used as it is representative of legacy unexploded ordnance (UXO) formulations commonly encountered from the WW era. In-addition, the TNT proportions used enabled simulation of typical energetic behaviour and residue generation and avoidance of full tank rupturing.

2.2. Experimental set up

Standard IBC's encased by a galvanized steel cage were filled with 1000 L of tap water (pH 7.2) (Fig. 1). Given the high pressures generated by the detonations, particularly high-order (HO) detonations, there was

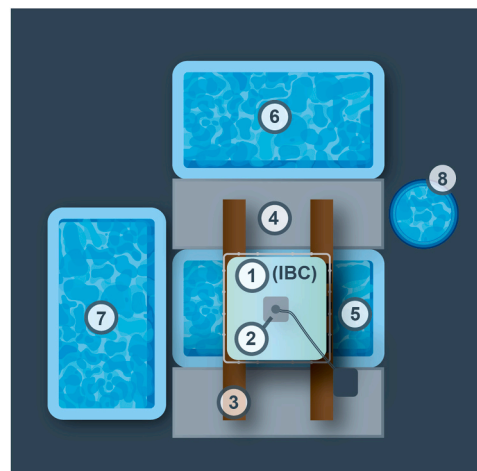


Fig. 1. Aerial view of the experimental setup showing (1) IBC tank with dimensions 1000 × 1160 × 1200 mm (2). Pipe bomb suspended at the centre of the IBC tank i.e. 500 mm height (3) Wooden blocks with dimensions 2600 × 250 × 150 mm (4) Concrete blocks (1600 × 800 × 800 mm) (5–8) Paddling pools A-D.

a significant risk of plastic container rupture, posing both safety hazards and methodological challenges. To mitigate this, the tops of the IBC tanks were removed, allowing detonation pressure to dissipate upward and improving the structural integrity of the vessel. This modification effectively transformed the IBC tanks into cost-effective standardised 1 m open-top aquariums.

The pipe bombs were prepared by melting 115 g of TNT flakes in a water bath at 100°C for 30 min. Meanwhile, galvanized steel pipes (150 mm in height, 34 mm in diameter) were preheated at the same temperature for 30 min. Once fully melted, 100 g of TNT was poured into the preheated pipes and allowed to cool. To ensure complete filling and eliminate voids or cracks formed during cooling, an additional 15 g of melted TNT was added. The pipes were left to cool to room temperature before sealing the end caps with 4 g of PTFE to prevent leakage. The final weight of the prepared pipe bombs was 622 ± 2 g.

The pipe bombs were suspended centrally in the middle of the IBC using 14-gauge electric wire to distribute the detonation pressure evenly on the IBC tank to avoid reflected shock waves or refraction waves [11]. The setup was designed to create a representative explosive train e.g. initiation of detonator (electric), booster (PENO), main charge (TNT) the explosives were aligned to ensure initiation [25]. Each tank was supported by wooden blocks and a stable platform surrounded by paddling pools (polyvinylchloride) to collect the water flowing out of the IBC's post-detonation. Each tank was labelled in alphabetical order (A-F), a total of six detonations were undertaken (3 X HO, 1 X Partial and 2 X LO).

To ensure that LO detonation was achieved, a Vulcan was used (Fig. 2a). A Vulcan is a modular shaped charge system which consists of a jet forming cone disc connected to a Davey Bickford electric detonator which penetrates the metal casing of a munition. Both magnesium and copper cone versions are available to achieve LO with copper having a greater penetration power but a higher risk of generating HO. Alfords provided both types to trial LO as they are both currently used in real-life scenarios. For tank A, a copper cone was used and for both B and C tanks a magnesium cone was used (Vulcan, Alfords). For the Vulcan to initiate the charge, 20 g of PENO, a 2,2-bis[(nitro oxy)methyl]propane-1,3-diyl dinitrate (PETN based plastic explosive) was added to trigger the main TNT charge. HO detonations were also achieved using a Davey Bickford

electric detonator, however, instead of using a Vulcan, 20 g of PENO was placed in intimate contact with the main TNT charge by removing the sealed caps from the pipe bombs (Fig. 2b).

Although the study was conducted in an outdoor environment, the experiments were performed under semi-controlled conditions as certain parameters e.g. amount of explosive, amount of water, type of detonation using Vulcan for LO, size of IBC etc. were controlled and in-house prepared pipe bombs were used. All detonations and sampling occurred on Thursday 04th April 2024 between 10:42–15:08 (10:43, 12:33, 13:15, 13:51, 14:30, 15:00). The average air temperature ranged 14.2 ± 0.6 °C. There were no adverse weather conditions despite a brief 10-minute light shower around 14:00 which did not impact the experiment.

2.3. Sampling

Two 50 mL pre-detonation water samples were collected to assess potential pre-contamination. The detonations were performed sequentially in the following order: LO (A, B & C), and HO (D, E and F). Subsequently the charge in tank C only partially detonated with only the end caps rupturing and exposing the explosive charge. Once it was considered safe to sample the water in terms of vapour dissipation and fragment dispersal i.e. 5 min after each detonation, 12 individual grab water samples were collected from each tank using 50 mL disposable syringes. To enable collection of the samples from the 1 m tank, the disposable syringes were attached to a 1 m long steel plunger. Moreover, the water that was expelled from the IBCs was collected in the paddling pools. Therefore, a total of 138 water samples were collected from all six detonations, each set included 2 pre-detonation samples, 12 grab samples from the IBC, 8 grab samples from the paddling pools and 1 positive control. All the samples were stored at 4°C in 50 mL amber vials before analysis to avoid photodegradation of TNT.

The pipe bomb debris including metal fragments, detonation wire, metal cap etc. were also sampled from each tank, post-detonation for explosive residue and then analysis using High Performance Liquid Chromatography (HPLC).

Following the partial detonation of the charge in Tank C, there was an opportunity to undertake a degradation study. Therefore, 12 grab water samples were taken on the day of detonation and then the tank was covered with an opaque and waterproof polyethylene tarpaulin and left undisturbed under natural conditions for four weeks. At the four-week point, a further 12 grab water samples and all visible metal fragments were collected, stored in the laboratory at 4°C until HPLC analysis.

2.4. Explosive extraction

Each grab water sample was manually shaken for 30 s to ensure thorough mixing and homogeneity of the TNT precipitate, as TNT solubility in water is low (130 mg/L at 20°C) [18]. 10 mL sub-samples were taken from each vial of the main sample and filtered using 0.22 µm nylon filters prior to HPLC analysis.

At the time of the experiment, standard operating procedures (SOP) state that when explosive residues were visually present as observed on Tank A & B (LO) the fragments should be cleaned with soap and water in order to ensure that they were safe to transport back to the laboratory. For Tanks D, E and F (HO) there were no visible residues on the fragments therefore they were safe to collect without washing. For Tank C, the water samples and fragments sat for four weeks to provide time for any volatile compounds to stabilise before handling (this was in line with Alford's SOP). This enabled the fragments and water sampled to be transported to the laboratory for the analysis.

The fragments were air dried, weighed and measured in the laboratory before extraction of any TNT for residual explosive analysis. Twenty-five mL of 1:1 acetonitrile and water ratio was added to the fragments in a polyethylene bag to dissolve the explosive residues. The

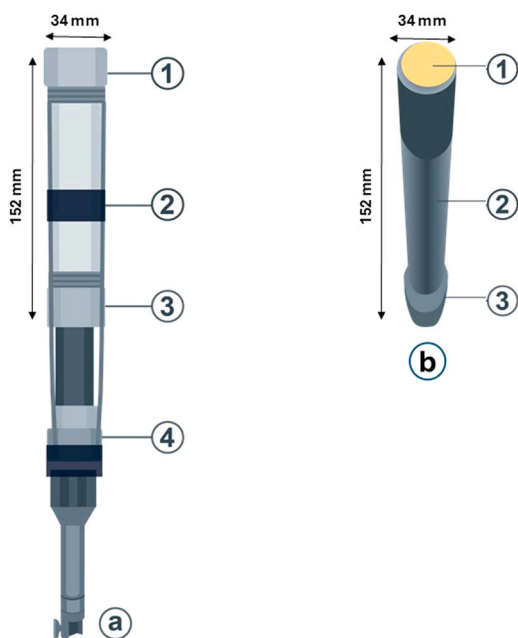


Fig. 2. Pipe bomb detonation mechanisms (a) LO detonation (1) Cap (2) Pipe filled with TNT (3) Cap (4) Vulcan containing PENO (b) HO detonation (1) PENO (2) TNT (3) Cap.

solution was then filtered and stored in a 50 mL amber vial prior to analysis. The extraction procedure was undertaken in triplicate to ensure accurate results.

As the fragments from tank A and B were thoroughly cleaned before leaving the detonation site, it was assumed that no explosive residue would be remaining, therefore, no further analysis was undertaken. The fragments from Tank C (partial detonation) were collected 4 weeks post-detonation and analysed for any degradation products. After four weeks of detonation, tank C fragments contained large TNT residues visible to the naked eye (Fig. 3c). Hence, tank C fragments were extracted in triplicate using 100 mL of acetonitrile and water in the ratio 1:1. 10 mL sub-sample was collected and syringe filtered using 0.22 μm nylon filter prior HPLC analysis.

2.4.1. HPLC analysis

Analysis was performed using HPLC-1260 Infinity (Agilent) equipped with Eclipse plus C18 column of dimension $150 \times 4.6 \text{ mm}$, 3.5 μm . Mobile phase of HPLC set-up consisted of acetonitrile and water in the ratio 60:40. Isocratic flow was maintained with flow rate of 1.5 mL/min. The sample injection volume was 10 μL , the column temperature was set at 30°C and the run time was three minutes. Peak detection was at 254 nm using photo diode array detector (DAD). Each sample was analysed in triplicate. A five-level external calibration curve was done using TNT standards at concentrations of 5, 10, 15, 20, and 25 mg/L. The limit of detection (LOD) and limit of quantification (LOQ) of the method ranges from 1.3 – 1.6 mg/L and 3.9 – 4.8 mg/L, respectively.

2.5. Stopping distance of HO fragments

Assessing the lethality of a fragment in a water environment is extremely complex and the injury thresholds from penetration of low-velocity (<120 m/s) fragments have not been well characterised within the literature [39]. A conservative assumption is that fragment at a nominal very low velocity (e.g. 1 ms) could present a detrimental to risk to aquatic species. There are also other issues [34,38] to consider regarding fragmentation, such as the initiation of underwater stockpiles [13,40] where one detonation can lead to the initiation of subsequent munitions (known as sympathetic detonation). This phenomenon can increase the distance that a fragment can reach increasing the environmental and safety impact associated with the fragmentation from

munitions. The fragments will travel various distances depending on the velocity of fragments and this is usually only applicable for HO. The velocity of the fragments was calculated using the Gurney's Eq. (1) [28]:

$$V_0 = \sqrt{2E} \left(\frac{M}{C} + \frac{1}{2} \right)^{-1/2} \quad (1)$$

Where V_0 is the velocity of fragments, $\sqrt{2E}$ is Gurney's constant for HO detonation of TNT i.e. 2700 m/s, M the mass of the fragment and C the original mass of the explosive in the pipe bomb.

Based on the velocity, it is possible to estimate the stopping distance of these fragments through water although, due to the complexity of the phenomenon (e.g. material of the pipe bomb, shape of the fragments, water flow) the following calculations represent a conservative estimate.

To understand the extent to which the fragment experiences resistance and deceleration in water the Hydrodynamic Drag Force (Rayleigh's Drag equation) (2) was calculated:

$$F_D = \frac{1}{2} \rho_w v^2 C_D A \quad (2)$$

Where F_D is the drag force (N), ρ_w is the density of water (kg m^{-3}), v is the velocity of the object (ms^{-1}), C_D is the drag coefficient and A the cross-sectional area of the fragment. Because of the cylindrical shape of the pipe bomb, two different C_D values were used to account for the different dragging conditions that the fragment can experience. A cylinder has two distinct geometric profiles (the curved "side" and circular "end"), the explosion generates a radially outward force causing the cylinder to fragment. Whilst it is more likely that a larger fragment is generated perpendicular to the detonation (the shape of larger fragments observed here support this assumption, likely generated from the curved "side"), smaller fragments may not. Additionally, the fragments may tumble due to a range of factors such as unbalanced densities, asymmetrical forces, or water resistance resulting in some oscillation or spin. An approach considering both scenarios therefore captures the variability in drag behaviours. To estimate the best-case scenario where the drag is maximised, and the fragment is positioned perpendicularly to the flow, a C_D of 2.1 was used [29,7]. Whilst a more conservative estimate, using a C_D of 0.1, where drag is minimised was used to estimate the worst-case scenario [29,7]. These two coefficients were utilised as, in reality, each fragment will be positioned between these two extremes.



Fig. 3. Pipe bomb fragments produced from low order detonations (A-B), partial detonation (C) the red circle shows the undetonated TNT and high order detonations (D-F).

Using Newton second law (3) it is possible to substitute the drag force in Eq. (2).

$$F_D = ma \quad (3)$$

Where m is mass (kg) and a is acceleration (ms^{-2}). This substitution makes it possible to explicitly express the acceleration (Eq. (4)).

$$a = \left(\frac{1}{2} \frac{\rho_w C_D A}{m} \right) v^2 \quad (4)$$

The acceleration can also be expressed as the temporal derivative of velocity $\left(\frac{dv}{dt} \right)$ and the velocity is the temporal derivative of distance $\left(\frac{dx}{dt} \right)$ meaning that this can be expressed as Eq. (5).

$$a = v \frac{dv}{dx} \quad (5)$$

Hence, Eqs. (4) and (5) can be combined and the stopping distance x can be isolated from the formula obtaining Eq. (6).

$$x = \frac{1}{k} \ln \left(\frac{v_0}{v_{\text{final}}} \right) \quad (6)$$

Where V_{final} is the velocity of the fragment at a nominal small value (i.e. 1 ms) and k is $\left(\frac{1}{2} \frac{\rho_w C_D A}{m} \right)$.

2.6. TNT mass balance

The potential TNT residues left post LO and HO detonations were calculated to understand the spread of TNT and its impact to the aquatic system. For this purpose, TNT was quantified from both the water samples collected from the IBC's and the paddling pools as well as from the fragment samples. WW era UXO are generally cleared using detonations, scaling up was done to understand the impact of these detonations on the aquatic system and connect it to the real-life issues. The basis of this calculation was experimental data collected from the IBC detonations which includes:

- (i) Estimating the percentage of TNT consumed for mass balance, the initial concentration of TNT was 115 mg/L, x is the TNT concentration after detonation.

$$\frac{(115 - x)}{115} 100 \quad (7)$$

- (ii) Calculating the radius (r) of the hemisphere (as the TNT is mixed within a hemi-spherical volume underwater) using the formula;

$$r = \sqrt[3]{\left(\frac{3V}{2\pi} \right)} \quad (8)$$

3. Results and discussion

The environmental impacts of LO and HO detonations were assessed through a comparative analysis of fragmentation characteristics, dispersion patterns, and residual chemical contamination. Physical effects were evaluated based on fragment size, mass, and velocity, while chemical impacts were determined by analysing post-detonation TNT residues in water and on metal fragments. Additionally, the dissolution rate of TNT was monitored in a semi-controlled setup over four weeks.

3.1. Detonation fragments and dispersion

The fragmentation analysis showed distinct differences in the

detonation energy from LO and HO detonations. This was seen in the partial damage to the IBC tanks from the LO detonations this was due to the insufficient pressure creating more of a pushing effect. This was expected as evidence of LO shows pushing effect whereas HO leads to higher powered scattering effect [23].

The pipe bomb fragmentation pattern of LO vs HO detonations was also compared on the basis of the size and weight of the fragments. Tank A (LO) exhibited a partial rupture of the main pipe body, producing one fragment measuring 133×104 mm. Tank B (LO) showed more extensive fragmentation, with the pipe splitting into two bulky pieces (142×47 mm and 75×40 mm), attributed to the different shaped charges used (copper in Tank A and magnesium in Tank B). Magnesium is less penetrating than a copper cone leading to larger fragments [12]. As mentioned Tank C resulted in partial detonation while LO is generally achievable using a Vulcan it is not always a reliable process or used for large scale detonations. In reality, munitions can undergo partial detonation due to malfunction of the detonator or inhomogeneity in the explosive charge [1]. This is the case for many UXO and dumped munitions from the WW leading to higher risk of these munitions undergoing partial detonation and exposing the energetic materials contributing to contamination.

In contrast, HO detonations, characterised by high pressure and velocity, caused complete rupture of the IBC tanks D, E and F, with similar fragment sizes (116–141 mm in length, 10–18 mm in width). These results highlight the more aggressive nature of HO detonations, leading to more uniform fragmentation due to the higher detonation pressures and velocities.

Fragments from both LO and HO detonations were categorised by weight (small, medium, large) as shown in Table 1. The number of fragments produced during LO detonations ranged from 26 in Tank A to 36 in Tank B. In comparison, the number of fragments produced during HO detonations was higher, with Tanks D, E, and F producing 63, 47, and 59 fragments, respectively. The average mass of HO fragments was less than 100 g and resulted in a greater number of small fragments. These high velocity smaller fragments are propelled outwards causing secondary damage, in addition to cause mechanical trauma, they may also introduce explosive residues into the body of the nearby organisms [39]. The mass of small HO fragments ranged from 0.03 g to 9.7 g, while medium fragments had an average mass of 25.9 ± 7.4 g.

3.1.1. Stopping distance of the fragments

The distance that fragments travel in water is influenced by their size, velocity, and shape [37]. Based on Gurney's equation, the stopping distance of HO fragments was calculated, considering two scenarios: when fragments travel perpendicular to water flow (Fig. 4a) and when they travel streamlined with the flow (Fig. 4b). In both cases, smaller fragments travelled shorter distances than larger fragments due to greater water resistance. The average stopping distance for medium-sized fragments ranged from 0.09 to 0.1 m, whereas small fragments covered distances of 0.05–0.07 m in the perpendicular flow scenario. In the streamlined scenario, small fragments travelled 5.3–9.5 m, while medium fragments travelled 94.9–107.1 m.

LO fragments, due to the low detonation velocity, travel shorter distances, posing a localised physical and chemical risk [39]. In contrast, HO fragments, with higher velocity, have the potential to travel further posing risks to aquatic organisms at greater distances from the detonation site. The velocity of fragments and their stopping distance should be taken into account during munitions clearance in aquatic environments.

3.2. Chemical residues and dissolution

3.2.1. TNT concentration in water post-detonation and dissolution

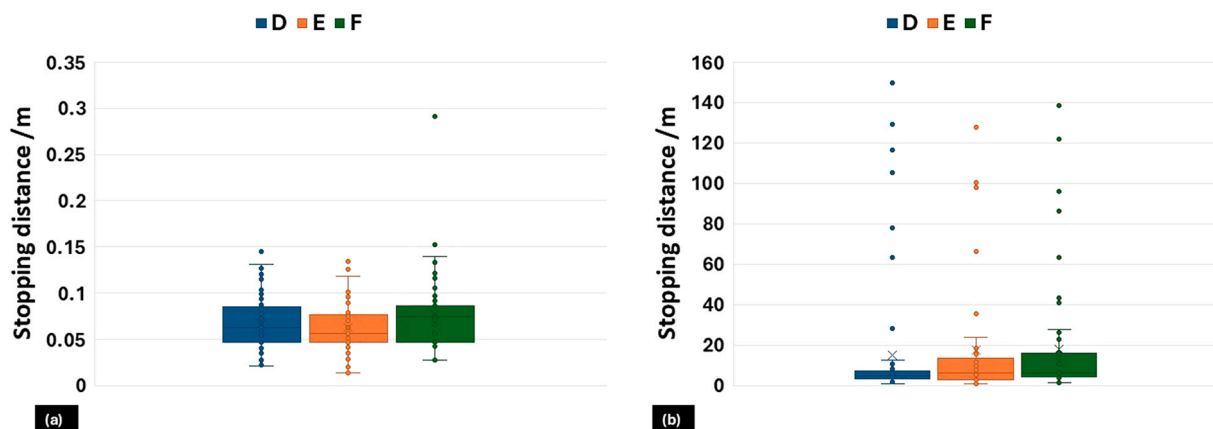
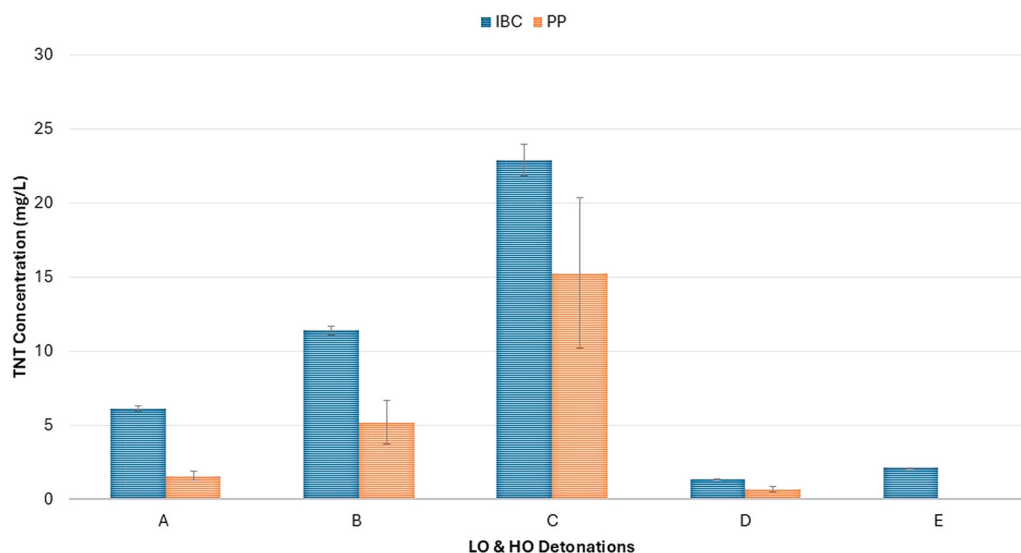
Explosive residues were quantified using HPLC analysis of water samples from IBC tanks and surrounding paddling pools (Fig. 5). While PENO was used as the detonator, its concentration was below the detection limit, leaving TNT as the primary contaminant. LO

Table 1

Fragment characteristics from low, partial and high order detonations including the quantity of fragments, size (mm) and mass (g).

	LO						Partial			HO					
	Tank A (S, M, L)*			Tank B (S, M, L)*			Tank C (S, M, L)*			Tank D (S, M)*		Tank E (S, M)*		Tank F (S, M)*	
Quantity of fragments	19	6	1	30	5	1	5	5	1	57	6	43	4	54	5
Mean Mass (g)	4.7	41.4	288	5.3	49.7	270	3.1	32.1	392.6	2.8	25.8	5.9	27.8	6.1	23.7
Length (mm)	12.4	29.6	133	16	52.4	142	16.6	34.8	150	15	133.8	17.8	129	14.1	127.8
Width (mm)	6.1	23.8	104	8.6	22.4	47	9.2	24.2	34	12	13.6	11.9	14.2	10	14

* Fragments were categorised by size: S:small (<10 g), M: medium (10–100 g) and L: large (>100 g).

**Fig. 4.** Estimated stopping distance in water for each fragment generated: A. is a best-case scenario with the fragments traveling perpendicular to the flow ($C_D = 2.1$). B is a worst-case scenario with the fragments traveling streamline with the flow ($C_D = 0.1$).**Fig. 5.** TNT residues remaining post detonations in water collected from both IBC tanks and paddling pools (PP).

detonations resulted in high residual TNT concentrations in IBC water (6.1 – 11.4 mg/L) and paddling pools (1.6 – 5.2 mg/L). The samples collected immediately after partial detonation (Tank C) left the highest concentration of TNT (22.9 mg/L in IBC; 15.3 mg/L in paddling pools), highlighting the risks of incomplete clearance operations. HO detonations produced lower and more consistent TNT residues (<1–2.2 mg/L), as the more complete combustion process minimised residual explosives.

Despite HO yielding lower TNT contamination, the risk remains due to its high fragmentation and dispersal potential. LO detonations, while more contained, retain more TNT near the detonation site, increasing

localized toxicity risks.

The combined water samples (IBC's and PP) from both LO and HO detonations confirmed considerable variation in TNT residues. For LO detonations, TNT concentrations ranged from 5.5 to 13.1 mg/L, with an average of 8.8 mg/L. In contrast, HO detonations resulted in more consistent residual TNT concentrations, ranging from <1–2.2 mg/L, with an average of 1.2 mg/L. The partial detonation in Tank C left the highest concentration of TNT, with an average of 22.9 mg/L, indicating the spread of undetonated explosives in the aquatic environment. These results suggest the potential of acute toxicity of TNT in the aquatic biota even after the clearance of munitions using either LO or HO detonation.

Thus, it is necessary to restrict the spread of undetonated TNT left after LO, partial and HO detonation. The concentration of un-exploded TNT in all the three types of detonations i.e. LO, Partial and HO were concerning as they were above the lethal dose for 50 % population of fish or LD50 value of TNT for fish and the limit of TNT in drinking water as per the USEPA ([27]; USEPA 2015).

To evaluate the long-term persistence of residual TNT, Tank C (partial detonation) was left undisturbed for four weeks. Post-detonation TNT concentration increased from 22.9 ± 4.2 mg/L to 29 ± 5.5 mg/L, indicating a dissolution rate of approximately 1.5 mg/L per week, although, the increase in TNT concentration was not statistically significant ($p > 0.05$). In the presence of sunlight TNT tends to show pink coloration and the intensity of colour gradually darkens with time (4–6 h) and ultimately results in the formation of pink water [30]. This discolouration is observed in the case of Tank C, suggesting photolysis, producing transformation products of TNT that are often more toxic than the parent compound [5]. During the HPLC analysis, two transformation products were identified e.g. 2,4-aminodinitrotoluene (ADNT) and 2,6-dinitrotoluene (DNT), although they have not been reported upon in any detail as these compounds consistently fell below the Limit of Quantification (LOQ) suggesting negligible concern. However, in real scenarios regarding cumulative contamination, the presence of more than 500,000 tons of dumped munitions in UK waters [15], even after clearance could lead to persistent contamination necessitating for long-term environmental monitoring.

3.2.2. TNT residues on metal fragments

Due to the SOP of the site, it was possible only to analyse the fragments from Tank C, D, E and F. The chemical analysis of fragments was performed to detect the amount of un-detonated TNT residues remaining on the fragments as previous research showed there is a significant amount of un-detonated explosive carried by the fragments [1]. The explosive residue is not distributed equally i.e. some of the fragments were more contaminated than others [1]. The pipe cap fragments had the least or no explosive residue as they were not in intimate contact due to the layer of PTFE compared to the fragments from the main body. The amount of TNT left on the fragments was higher in case of the partial detonation (Tank C) with 326.7 mg detected, whereas in HO detonations the residues ranged from 0.3 to 1 mg.

3.2.3. TNT mass balance

The TNT used in the experiments was 115 g per 1000 L of water. The mass balance of TNT consumption was calculated for both water and fragment samples. HO detonations (Tanks D and E) consumed over 98.5 % of TNT, suggesting minimal residual toxicity risk (Table 2). In contrast, partial detonation in Tank C resulted in 82.4 % TNT consumption, consistent with previous studies indicating that partial detonations leave substantial amounts of un-detonated explosives [21].

3.2.4. Scaling up of TNT contamination

Given the extensive dumping of munitions in the sea, the potential risk of TNT contamination is significant. Munitions like the Mark (VI)

and S1 Type 1 contain substantial TNT quantities, ranging from 54 kg to 227 kg [22]. Based on the experimental data, the spread of TNT contamination can be categorised into different risk zones, with concentrations as low as 0.1 mg/L posing a hazard to aquatic organisms [32]. Understanding the scale of TNT contamination and its environmental impact is crucial for managing the risks posed by underwater munitions. To estimate the extent and impact of TNT contamination, the volume of water affected by these munitions was categorised into four different zones: red, orange, yellow, and green. This division was based on the reported toxicity risk from TNT as follows:

Red and Orange Zones: zones where TNT concentration > 0.8 mg/L, indicating a high risk of acute TNT toxicity as LD50 value of TNT for fish is 0.8–3.7 mg/L, [27]. Orange zone ranges between 0.1 and 0.8 mg/L and red zone is above 0.8 mg/L.

Yellow zone: corresponds to the US EPA drinking water limit for cancer risk (0.1 mg/L) [32], representing a potential for chronic toxicity.

Green zone: Below 0.1 mg/L, TNT is considered non-toxic based on existing literature. A concentration of 0.001 mg/L defines a detectable but safe zone.

Following LO, partial, and high-order HO detonations of a pipe bomb, residual TNT was 5.8 %, 17.6 %, and 1.1 %, respectively. These calculations assume a hemispherical dispersion of TNT in the aquatic environment with contamination radii detailed in Table 3 and Fig. 6.

Assuming that the TNT fraction lost in the test detonations is the same for old munitions, Fig. 6 compares the hemispherical radius of TNT contamination following a LO, partial or HO detonation, for the four identified zones (red, yellow, orange and green) of Mark 1 (M) munition containing the highest amount of TNT i.e. 227 Kg to estimate the worst-case scenario for TNT distribution. The hemispherical radius as shown in Fig. 6(a) was used to calculate the hemispherical spread of TNT underwater. Fig. 6(b) represents the LO, partial detonation and HO detonation of the WW Naval mine Mark I (M) [22]. It has been observed that the radius of the red, orange, yellow and green zones for LO detonations is approximately twice the radius of all the zones for HO detonations whereas partial detonation leads to the maximum spread of TNT contamination. The toxicity risk is maximum for failed or partial detonation, then LO detonation and HO has the least impact to the biota in terms of toxicity.

It is worth noting that these values are calculated assuming negligible effect of pressure, water currents, salinity, temperature, transformation or degradation of explosive etc. Moreover, the data in this study was generated following the detonation of a single munition, hence it is expected that the values may vary depending on the parameters listed above, the number of munitions to be detonated and the amount of explosive charge. As per the Joint Nature Conservation Committee (JNCC) the default mitigation zone, which represents the area to be cleared of aquatic organisms' before commencing any type of detonation, has a radius of 1 km. However, based on this study, it is suggested that the radius of the mitigation zone should depend on both the amount of explosive charge and the type of detonation.

4. Conclusion

This study provides the first comparative assessment of LO and HO underwater detonations in semi-controlled conditions, highlighting the implications of detonation type on environmental safety and munitions clearance efficiency. It revealed significant differences in fragmentation size, mass, and dispersion between LO and HO detonations, with HO producing a greater number of small, high-velocity fragments capable of extensive dispersion. In contrast, LO results in the generation of larger, bulkier fragments creating a localised impact. Chemical analysis demonstrates that LO and partial detonations leave significantly higher TNT concentrations in water and on metal fragments, potentially leading to persistent environmental impact. HO detonations, while more effective in reducing residual TNT may introduce risks of smaller TNT-laden

Table 2

Mass Balance of TNT for LO, partial detonation and HO.

Detonation	IBC Tank	TNT Recovered		Total mass of TNT recovered (g)	Percentage of TNT depleted (%)
		Water (g/1000 L)	Fragments (g)		
LO	A	4.3	-	4.3 ± 0.6	96.2 %
	B	8.9	-	8.9 ± 1.0	92.2 %
Partial	C	19.8	3.3×10^{-1}	20.2 ± 3.6	82.4 %
	D	1.1	3.1×10^{-4}	1.1 ± 0.1	99 %
HO	E	1.3	1×10^{-3}	1.3 ± 0.2	98.8 %
	F	Below the LOD			

Table 3

The radius of hemispheres for the red, orange, yellow and green zone calculated for HO, LO and partial detonation for the UXOs.

WW Munitions	Radius of hemisphere (m)											
	Red Zone (4 ppm)			Orange Zone (0.8 ppm)			Yellow Zone (0.1 ppm)			Green Zone (0.001 ppm)		
	LO	PO*	HO	LO	PO*	HO	LO	PO*	HO	LO	PO*	HO
Mark VI	7.2	10.4	4.2	12.3	17.8	7.1	24.6	35.7	14.2	114.4	165.6	65.7
S1 Type I	7.3	10.6	4.2	12.5	18.2	7.2	25.1	36.3	14.4	116.4	168.6	66.9
ELIA	8.8	12.8	5.1	15.1	21.9	8.7	30.3	43.8	17.4	140.4	203.3	80.7
Mark I (M)	11.6	16.8	6.7	19.9	28.8	11.4	39.8	57.6	22.8	184.6	267.2	106

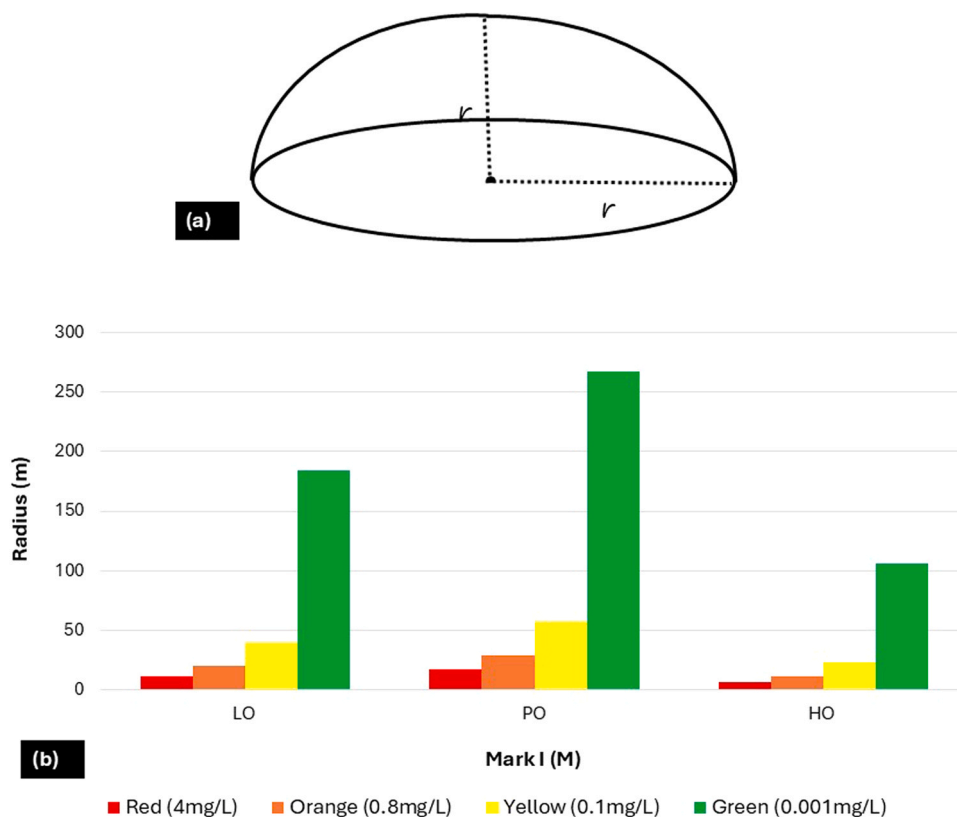


Fig. 6. (a): The hemispherical radius contaminated with TNT post-detonation categorised into each zone. Red (4 ppm), Orange (0.8 ppm), Yellow (0.1 ppm) and Green (0.001 ppm); (b) WW munition: Mark I (M) detonated using LO, partial and HO detonations.

fragments into the environment. Given the significant quantities of TNT present in munitions such as the Mark (VI) and S1 Type 1 (ranging from 54 kg to 227 kg), these research findings highlight the potential for widespread contamination following detonation or leakage. Therefore, this work provided the basis for a framework for assessing acute and chronic exposure risks by categorising contamination into 4 zones (red, orange, yellow, and green) based on TNT toxicity levels. The red and orange zones indicate immediate toxicity to marine life (LD50: 0.8–3.7 mg/L), while the yellow zone represents long-term human health risks at concentrations exceeding 0.1 mg/L. The green zone, with TNT levels below 0.1 mg/L, is considered a non-toxic but detectable threshold. These classifications provide a structured approach to understanding contamination dispersion and its implications for ecosystem and human health. The analysis of detonation efficiency further reveals that TNT residues vary significantly depending on the type of explosion. LO detonations result in the highest residual TNT (6–18 %), while HO detonations leave minimal contamination (1.1 %). The results confirm that high-order detonation, results in minimal residual explosive contamination compared to low-order events. Thus, from a chemical residue and long-term environmental exposure perspective, high-order detonation is the preferable technique for UXO clearance, provided

physical risks are managed. Sample size, 115 g of TNT for each detonation condition was limited to two replicates due to safety constraints and the survivability of the tanks to ensure the collection of water. While sufficient for these type of insightful experiments, future studies should incorporate larger charge sizes and different detonation mechanisms to enable statistical analysis. These findings emphasise the need for controlled detonation strategies to minimise persistent TNT pollution. By quantifying TNT dispersion in water and assessing its toxicological implications, this study advances current methodologies for evaluating underwater munition risks. The findings have direct implications for environmental risk assessments of underwater munitions clearance, supporting the need for regulatory measures that account for both physical fragmentation and chemical pollution risks. It also supports exposure assessment models and informs future ecotoxicological testing strategies. This study was conducted under semi-controlled laboratory conditions using static water to isolate detonation-related effects in IBC. However, in natural marine environments, salinity gradients, current dynamics, and biotic interactions may influence both dissolution and transformation rates of TNT and the physical damage caused by the detonations which needs to be further explored. Extrapolation to real ecosystems should thus be made with caution. Following ISO 16308

guidance, risk characterisation ratios (RCR = PEC/PNEC) should also be considered in future field-based assessments to determine habitat-specific thresholds.

Environmental implications

This study evaluates the environmental impact of clearance of dumped munitions on the aquatic biota following low order (LO) and high order (HO) detonations under semi-controlled environmental conditions. The findings indicated that HO has a greater physical impact on the environment whereas LO result in higher chemical contamination. In addition, HO was found to have more widespread environmental impact, compared to LO which has more localised impacts. This research provides an insight in the potential environmental implications of detonating real world war munition on site.

CRediT authorship contribution statement

Joshua Wardrop: Writing – review & editing, Methodology, Data curation. **Bhumika Sharma:** Writing – original draft, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Sally Webb:** Writing – review & editing, Methodology, Investigation. **Federica Persico:** Writing – review & editing, Visualization. **Tracey Temple:** Writing – review & editing, Supervision, Funding acquisition, Conceptualization. **Frederic Coulon:** Writing – review & editing, Supervision, Funding acquisition.

Declaration of Competing Interest

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

Acknowledgements

Authors would like to thank Alford's Technology Ltd for the conduction of detonations especially Mr. Thierry Pope. Captain Harry Holland, Cranfield Workshops and Technicians for their help with the experimental setup and analysis. Special thanks to Lt Col (Ret) Liz Nelson for proof-reading the manuscript. The authors are also grateful to Mr. David Piper for the design of the graphical abstract. Special thanks to UK Ministry of Defence and DNV for sponsoring the research work. For the purposes of open access, the author has applied a Creative Commons Attribution (CC BY) licence to any Accepted Author Manuscript version arising from this submission.

Data availability

The DOI of the data is included in the manuscript under the data availability statement

References

- [1] Abdul-Karim, N., Blackman, C.S., Gill, P.P., Wingstedt, E.M.M., Reif, B. A. P., 2014. Post-blast explosive residue – a review of formation and dispersion theories and experimental research. *RSC Adv* 4 (97), 54354–54371. <https://doi.org/10.1039/C4RA04195J>.
- [2] Ahlborg, G., Einistö, P., Sorsa, M., 1988. Mutagenic activity and metabolites in the urine of workers exposed to trinitrotoluene (TNT). *Occup Environ Med* 45 (5), 353–358. <https://doi.org/10.1136/oem.45.5.353>.
- [3] Beck, A., van der Lee, E., Eggert, A., Stamer, B., Gledhill, M., Schlosser, C., Achterberg, E., 2019. In situ measurements of explosive compound dissolution fluxes from exposed munition material in the Baltic Sea. *Environ Sci Technol* 53. <https://doi.org/10.1021/acs.est.8b06974>.
- [4] Beldowski, J., Achterberg, E., Andresen, C., Beck, A., Brenner, M., Böttcher, C., Cumming, A., Czub, M., Frey, T., Kammann, U., Kampmeier, M., Koschinski, S., Koske, D., Köser, K., Lang, T., Lastumäki, A., Lehtonen, K., Lundgreen, K., Lindgren, F., & Mesk, L. (2024). Thematic assessment on Hazardous Submerged Objects in the Baltic Sea Warfare Materials in the Baltic Sea 2..
- [5] Bhanot, P., Celin, S.M., Sreekrishnan, T.R., Kalsi, A., Sahai, S.K., Sharma, P., 2020. Application of integrated treatment strategies for explosive industry wastewater—a critical review. *J Water Process Eng* 35, 101232. <https://doi.org/10.1016/j.jwpe.2020.101232>.
- [6] Brownlow, A., Baily, J., Dagleish, M., Deaville, R., Foster, G., Jensen, S.K., & Jepson, P. (2015). Investigation into the long-finned pilot whale mass stranding event, Kyle of Durness, 22nd July 2011. Department for Environment Food and Rural Affairs (DEFRA) Scottish Marine Animal Stranding Scheme. 60p. (https://strandings.org/wp-content/uploads/2021/05/Kyle_of_Durness_Mass_Stranding_Report.pdf).
- [7] Clancy, L.J., 1975. *Aerodynamics (Section 11.17)*. Pitman Publishing, London. ISBN 978-0-470-15837-1.
- [8] Danil, K., St. Leger, J.A., 2011. Seabird and dolphin mortality associated with underwater detonation exercises. *Mar Technol Soc J* 45 (6), 89–95. <https://doi.org/10.4031/MTSJ.45.6.5>.
- [9] Esteve-Núñez, A., Caballero, A., Ramos, J.L., 2001. Biological degradation of 2,4,6-trinitrotoluene. *Microbiol Mol Biol Rev* 65 (3), 335–352. <https://doi.org/10.1128/mmb.65.3.335-352.2001>.
- [10] Gaskell, D.R., 2011. *Forensic Investigation of Explosions*, 2nd ed.). CRC Press. <https://doi.org/10.1201/b11938>.
- [11] Han, Y., Xie, X., Jiang, Z., Duan, Y., Wen, Y., 2018. Equation of state of detonation products for TNT by aquarium experiment. *AIP Conf Proc* 1979 (1), 100016. <https://doi.org/10.1063/1.5044888>.
- [12] Haynes, W.M. (Ed.), 2014. *CRC Handbook of Chemistry and Physics*. CRC Press. <https://doi.org/10.1201/b17118>.
- [13] Hu, H.-w., Wang, J., Bian, Y.-l., Lu, Z.-b., Yang, Q., 2022. Experiments of sympathetic detonation performance of explosives with shell in water. *J Unmanned Undersea Syst* 30 (3), 308–313. <https://doi.org/10.11993/j.issn.2096-3920.2022.03.005>.
- [14] Kiciński, R., Szuromski, B., 2020. Pressure Wave Caused by Trinitrotoluene (TNT) underwater explosion—short review. *Article 10. Appl Sci* 10 (10). <https://doi.org/10.3390/app10103433>.
- [15] Koschinski, S. & Kock, K.H., 2015. Underwater unexploded ordnance—Methods for a cetacean-friendly removal of explosives as alternatives to blasting..
- [16] Lepper, P.A., Cheong, S.-H., Robinson, S.P., Wang, L., Tougaard, J., Griffiths, E.T., Hartley, J.P., 2024. *In-situ* comparison of high-order detonations and low-order deflagration methodologies for underwater unexploded ordnance (UXO) disposal. *Mar Pollut Bull* 199, 115965. <https://doi.org/10.1016/j.marpolbul.2023.115965>.
- [17] Lima, D.R.S., Bezerra, M.L.S., Neves, E.B., Moreira, F.R., 2011. Impact of ammunition and military explosives on human health and the environment. *Rev Environ Health* 26 (2), 101–110. <https://doi.org/10.1515/rev.2011.014>.
- [18] Maser, E., Andresen, K.J., Bünnig, T.H., Clausen, O.R., Wichert, U., Strehse, J.S., 2023. Environmental and human toxicology studies on explosive chemicals leaking from submerged munitions. *Propellants Explos Pyrotech* 48. <https://doi.org/10.1002/prep.202300181>.
- [19] Maser, E., Andresen, K.J., Bünnig, T.H., Clausen, O.R., Wichert, U., Strehse, J.S., 2023. Ecotoxicological risk of world war relic munitions in the sea after low- and high-order blast-in-place operations. *Environ Sci Technol* 57 (48), 20169–20181. <https://doi.org/10.1021/acs.est.3c04873>.
- [20] Maser, E., Strehse, J.S., 2020. Don't Blast": Blast-in-place (BiP) operations of dumped World War munitions in the oceans significantly increase hazards to the environment and the human seafood consumer. *Arch Toxicol* 94 (6), 1941–1953. <https://doi.org/10.1007/s00204-020-02743-0>.
- [21] Miętkiewicz, R., 2022. High explosive unexploded ordnance neutralization—Tallboy air bomb case study. *Def Technol* 18 (3), 524–535. <https://doi.org/10.1016/j.dt.2021.03.011>.
- [22] NavWeaps (nd), UK/Britain Mines (http://www.navweaps.com/Weapons/WAMBR_Mines.php).
- [23] Newhouse, 1976. Department of the treasury Modular Explosives Training Program Introduction to Explosives from <https://www.ojp.gov/ncjrs/virtual-library/abstracts/modular-explosives-training-program-introduction-explosives>.
- [24] Schmidtke, E., Nützel, B., Ludwig, S., 2009. Risk mitigation for sea mammals - The use of air bubbles against shock waves. *NAG/DAGA 2009*. Rotterdam 269–270. (https://pub.dega-akustik.de/NAG_DAGA_2009/data/articles/000311.pdf).
- [25] Siegel, J., 2013. *Encyclopedia of forensic sciences*. ScienceDirect. (<http://www.sciencedirect.com/5070/referencework/9780123821669/encyclopedia-of-forensic-sciences>).
- [26] Strehse, J.S., Maser, E., 2020. Marine bivalves as bioindicators for environmental pollutants with focus on dumped munitions in the sea: a review. *Mar Environ Res* 158, 105006. <https://doi.org/10.1016/j.marenvres.2020.105006>.
- [27] Talmage, S.S., Opreko, D.M., Maxwell, C.J., Welsh, C.J.E., Cretella, F.M., Reno, P. H., Daniel, F.B., 1999. Nitroaromatic munition compounds: environmental effects and screening values. In: Ware, G.W. (Ed.), *Reviews of Environmental Contamination and Toxicology: Continuation of Residue Reviews*. Springer, pp. 1–156. https://doi.org/10.1007/978-1-4757-6427-7_1.
- [28] Thawani, B., Hazael, R., Critchley, R., 2021. Numerical modelling study of a modified sandbag system for ballistic protection. *J Comput Sci* 53, 101403. <https://doi.org/10.1016/j.jocs.2021.101403>.
- [29] The Engineering Toolbox (2004). Drag Coefficient. [online] Available at: (https://www.engineeringtoolbox.com/drag-coefficient-d_627.html).
- [30] Thorn, K.A., 2019. ¹³C and ¹⁵N NMR identification of product compound classes from aqueous and solid phase photodegradation of 2,4,6- trinitrotoluene. *PLoS ONE* 14 (10). <https://doi.org/10.1371/journal.pone.0224112>.
- [31] UK Parliament (2022). Marine environment: unexploded ordnance clearance joint interim position statement, Updated 13 January 2022. (<https://www.gov.uk/government/publications/marine-environment-unexploded-ordnance-clearance-joint>

- interim-position-statement/marine-environment-unexploded-ordnance-clearance-joint-interim-position-statement).
- [32] US EPA, O. (2019, June 12). EPA Method 8330B (SW-846): Nitroaromatics, Nitramines, and Nitrate Esters by High Performance Liquid Chromatography (HPLC) [Data and Tools]. US EPA. (<https://www.epa.gov/esam/epa-method-8330-b-sw-846-nitroaromatics-nitramines-and-nitrate-esters-high-performance-liquid>).
- [33] Vaněk, T., Nepovím, A., Podlipná, R., Zeman, S., Vágner, M., 2003. Phytoremediation of selected explosives. *Water Air Soil Pollut Focus* 3 (3), 259–267. <https://doi.org/10.1023/A:1023981818382>.
- [34] Victor, A.C., 1996. A simple method for calculating sympathetic detonation of cylindrical, cased explosive charges. *Propellants Explos Pyrotech* 21 (2), 90–99. <https://doi.org/10.1002/prop.19960210208>.
- [35] von Benda-Beckmann, S., Aarts, G., Sertlek, H.O., Lucke, K., Verboom, W., Kastelein, R., Ketten, D., Van Bemmelen, R., Lam, F.-P., Kirkwood, R., Ainslie, M., 2015. Assessing the impact of underwater clearance of unexploded ordnance on harbour porpoises (*Phocoena phocoena*) in the Southern North Sea. *Aquat Mamm* 41, 503–523. <https://doi.org/10.1578/AM.41.4.2015.503>.
- [36] Vulcan (nd), Alford. (<https://www.explosives.net/products/vulcan/>).
- [37] Weil, Y.A., Mosheiff, R., Liebergall, M., 2006. Blast and penetrating fragment injuries to the extremities. *JAAOS J Am Acad Orthop Surg* 14 (10), S136.
- [38] Yang, T.H., Wang, C., Li, T., 2022. Numerical simulation study of sympathetic detonation in stages. *Def Technol* 18, 1382–1393. <https://doi.org/10.1016/j.dt.2021.08.009>.
- [39] Young, L., Gregory, T.R., Robert, T.B., Timothy, J.W., Jennie, M.B., Geoffrey, L., 2015. When physics meets biology: low and high-velocity penetration, blunt impact, and blast injuries to the brain. *Front Neurol* 6 (89). <https://doi.org/10.3389/fneur.2015.00089>.
- [40] Zhang, Y., Wang, C., Li, T., 2020. Investigation of underwater sympathetic detonation. *Propellants Explos Pyrotech* 45 (6), 857–864. <https://doi.org/10.1002/prop.202000099>.



DSPACE

<https://dspace.org/>

Environmental impacts of low and high order detonations in water

Sharma, Bhumika; Wardrop, Joshua; Persico, Federica; Webb, Sally; Coulon, Frederic ...

2025-09-05

Elsevier

<https://doi.org/10.1016/j.jhazmat.2025.139140>

Sharma B, Wardrop J, Persico F, et al., (2025) Environmental impacts of low and high order detonations in water. Journal of Hazardous Materials, Volume 495, September 2025, Article number 139140