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Environmental concerns when utilizing detonation as the clearance method for dumped munitions

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Abstract

Common methods for clearing dumped munitions include low-order and high-order detonations. Low-order detonations produce subsonic explosions, typically leaving behind large explosive fragments, while high-order detonations involve supersonic explosions, usually destroying the entire munition. However, both methods may result in incomplete combustion and the release of explosive materials into the aquatic environment. Additional environmental impacts include noise pollution, shock waves, metal toxicity, and the spread of bomb fragments. To therefore estimate the detonation hazards further experiments were conducted under controlled conditions using six 1000L Intermediate bulk container tanks. Explosive charges were detonated at both low-order and high-order detonations. On average, the low-order detonations (Tanks A & B) left 8.76 ppm of explosive residues, while high-order detonations (Tanks C & D) left significantly less residue, averaging 1.18 ppm. These values were based on a starting explosive concentration of 115 ppm before detonation. The findings confirmed that low-order detonations leave more explosive residue, leading to a higher risk of toxicity. High-order detonations, though resulting in less explosive residue, release fragments at high velocity, posing a serious environmental threat and increasing the risk of accidental explosions.

1.0 INTRODUCTION

During the World Wars, common practice was to dump unwanted munitions in the aquatic environment around the world. Most of these munitions i.e. more than 500,000 tonns have been dumped in marine waters but the USA and Switzerland freshwater was highly affected with explosive contamination (Koschinski & Kock, 2015). Considering that there is only 3% of freshwater on earth, it is a priority to protect these resources (Francis, 2011); (Capper, 2012). World War Junk is a ticking bomb as these munitions are losing their stability and are becoming more sensitive with age. Although, there is a low risk of spontaneous explosion under normal sea conditions. However, as per the records of British Geological Society there were 47 spontaneous detonations of dumped munitions in 1992 and 2004 at Beauforts Dyke dumping grounds.

(Kirchgeorg et al., 2018). It was observed that the munitions dumped in the Baltic Sea post-World War II are 70-100% corroded thus leaching out toxic, carcinogenic and mutagenic explosives into the environment (Koschinski, 2009). Along with the risk of unplanned explosion there is also a high risk of toxicity in the marine species. The explosive concentration was found in the range of 0.01 – 10 ng/L at one of the dumping sites at the Bay of Kiel. The detection of explosives in even trace quantities is alarming and shows their potential to enter the food chain (Bełdowski et al., 2024). Conventional explosives like 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 majorly exploited during the two world wars and there is evidence of the presence of these reported potential carcinogenic compounds (explosives) in global water courses (USEPA 8330 B); (Vaněk et al., 2003); (Bełdowski et al., 2020); (Koschinski, 2009); (Koske et al., 2020); (Strehse & Maser, 2020); (Beck et al., 2018); (Raupers et al., 2023). There are various concerns in the clearance of these dumped munitions i.e. threat to marine life, spreading of explosives in the marine environment, unplanned detonation, economic challenges and high risk (Beck et al., 2018; Raupers et al., 2023). In order to destroy these munitions, they are exploded using either deflagration or detonation. An explosion is a rapid increase in the amount and release of energy, usually due to high temperature and the release of gases with high pressure (Gaskell, 2011). Explosives are those energetic materials that triggers explosion in the presence of a stimulus such as friction, electric spark, chemical reaction, etc.

Explosions involve heating of the reactive material or explosive which results in an exothermic reaction; further heat can increase the reaction rate and lead to deflagration i.e. the self-reactive reaction. The initial source of heat to the material can also be provided by a fast-traveling shock wave. Under certain conditions of initiation and confinement, the deflagration reaction can transit to supersonic but at a constant reaction rate, known as detonation. In the deflagration mode, the reactive material dissociates from the unreacted ones whereas in the detonation mode, the detonated products flow with great velocity toward the undetonated explosive. A shock front/zone propagates at an extremely high pressure and an explosive velocity at high temperatures. Behind the shock front i.e. the original material in the chemical reaction zone rapidly converts into reaction products. Temperatures and pressures in the detonation zone can exceed several million atmospheres and 3000ºC (Gaskell, 2011). Detonation velocity decides the type of detonation, if the velocity ranges between 1000 – 5000 m/s it is termed as low order detonation (LO detonation) and when the velocity of detonation is higher i.e. 5000-10,000 m/s it is known as high order detonation (HO detonation) (von Benda-Beckmann et al., 2015); (Kiciński & Szturomski, 2020); (Bełdowski et al., 2024).

HO detonations were favoured disposal method for the clearance of dumped munitions for a long time. In 2011, Kyle of Durness, 19 pilot whales beached and died as a result of high-order bombings at the sea by Royal Navy. There are reports mentioning lack of proper mitigation measures as the primary cause of this event (Kelley, 2016). The production of high altitude sound waves in high order detonation results in the complete loss of hearing and death of various aquatic

species (Beckmann 2015). Thus, nowadays LO detonations are preferred over HO detonations, In 2020, the UK Parliament issued a memorandum prioritizing LO detonations by commercial and military sectors for the disposal of items in UK waters due to the reduction in detonation sound up to 20dB in LO detonations (Parliament, 2020).

LO detonation does not resolve the issue completely, there are serious toxicity concerns and risk of bioaccumulation of explosives (Maser et al., 2024); (Kirchgeorg et al., 2018); (Voie & Mariussen, 2017). A study to investigate the effect on explosive concentrations in the sea post detonation resulted in high order detonations lead to the increment of explosive concentrations up to 353 ng/L & 175 µg/Kg in water and sediments respectively. Low order detonations produced massive non-combusted explosive residues and resulted in the increment of explosive concentration up to 1 mg/L for water and 10 g/Kg for sediments respectively which is way beyond the safety limits i.e. the LD50 value of TNT for fish is 0.8-3.7 mg/L whereas the TNT limit in the drinking water for cancer risk in human is 0.1 mg/L as per USEPA (Talmage et al 1999; EPA 2014). Thus, after detonation the explosive concentration rise in the water and sediments as explosive chunks spread across the marine environment. Many researchers compared the two different types of detonations but not on the same parameters. In the aforementioned study, four mines were detonated with different corrosion rate, explosive amount, intact/open state. Whereas in the other study, 10Kg Composite B was used to initiate HO detonation while LO detonations were done using 250 g Pluton^{TM}. In-addition the amount of Amatol explosive in the selected World War munitions varied from 170–430Kg. (Maser et al.,2024); (Lepper et al., 2024). Thus, it is becoming crucial to understand the overall effect of these detonations on aquatic ecosystem under controlled conditions. In this study the comparison of both the detonations was done using the same main charge i.e. 115 g TNT with different detonation mechanisms. Research data suggest that no detonation results in 100% removal of explosives from the environment, there is always a presence of partially burnt and unburnt explosive particles (Novik et al., 2023); (Lotufo et al., 2019); (Brannon et al., 2005). Therefore, this study focuses on estimating the extent of explosives remaining post detonation in low order vs high order detonations. The detonations were compared based on the chemical analysis of explosive residues in water.

2.0 MATERIALS AND METHODOLOGY

2.1 Experimental set-up

The experimental setup shown in Fig 1 comprises of IBC tanks with dimensions (1000mm x 1160mm x 1200mm) that were used for both LO and HO detonation experiments. IBC tanks are square high density polyethene or HDPE plastic tanks surrounded by a galvanized steel cage with the top removed to reduce the detonation pressure. The tanks were filled with 1000 L of tap water. Tanks were supported by big wooden blocks and a stable platform surrounded by paddling pools to collect the flowing water post-detonation. The experiments focussed on detonating steel Pipe bombs using 20 g PENO; 2,2-Bis[(nitrooxy)methyl]propane-1,3-diyl dinitrate (PETN) based plastic explosive that was used to trigger 115 g of 2-methyl-1,3,5-trinitrobenzene (TNT). The

entire pipe bombs weighed approximately 623 g each. The pipe bombs were suspended centrally in the IBC tank using 14 gauge wire to spread the pressure evenly and to avoid the rupture of the IBC tanks. There were six detonations in total, three for LO and three for HO respectively. Experiments were conducted at Alford's explosive test facility, Broadmead, UK. To ensure LO detonations Vulcans were used as shown in Fig 2 (a). The Vulcans consisted of a Magnesium Jet forming cone disc and a Davey Bickford electric detonator. Fig 2 (b) depicts HO detonations in which PENO was directly added to the main charge and attached to the electric detonator.

Fig 1 : Experimental Setup

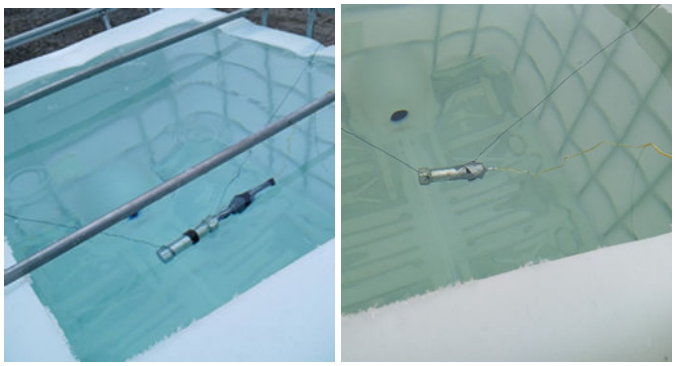

Fig 2: IBC aerial view (a) LO detonations (b) HO detonations

2.2 Sampling:

12 grab water samples of volume 50 mL each were collected using a 50 mL syringe connected to a 1 m long syringe plunger for residue analysis. Two 50 mL quality control samples were also collected pre-detonation from each tank to ensure that the source of explosive is only from the explosion and there is no cross-contamination between the samples. Field duplicates were also sampled from each tank to verify the accuracy of the analysis. Control or field blanks and field duplicates were collected along with the samples to maintain the QA/QC standards. All the samples were collected and stored in amber vials at 4^0C until analysis by High Performance Liquid Chromatography (HPLC) to avoid photo-degradation of TNT. 6 mL grab water samples were then taken from every vial and directly syringe filtered using 0.22 microns nylon filter for HPLC analysis in triplicates.

2.3 Analysis

Samples were analysed using HPLC-1260 Infinity (Agilent) equipped with Eclipse plus C18 column of dimension 150 X 4.6 mm, 3.5 µm. Mobile phase 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 and column temperature were 10 µL and 30°C respectively. This method had a very short run time of 3 minutes. Peak detection was done at 254 nm using Photo Diode Array Detectors (DAD). The detection limit of the method was found to be 0.78 ppm.

3.0 RESULTS & DISCUSSION

The low order and high order detonations were compared under controlled conditions using the same amount of explosive charge used for filling the pipe bomb i.e. 115 g TNT (main charge) and 20g PENO (detonator). The pipe bomb was suspended in the centre using 14 gauge wire to avoid reflected shock waves or rarefaction waves (Han et al., 2018). Explosive train are the steps in which the explosives are aligned to initiate a munition or explosive device, such as a primer, detonator, booster, and main charge(Siegel, 2013). In this study 20 g PENO is used to trigger 115 g TNT.

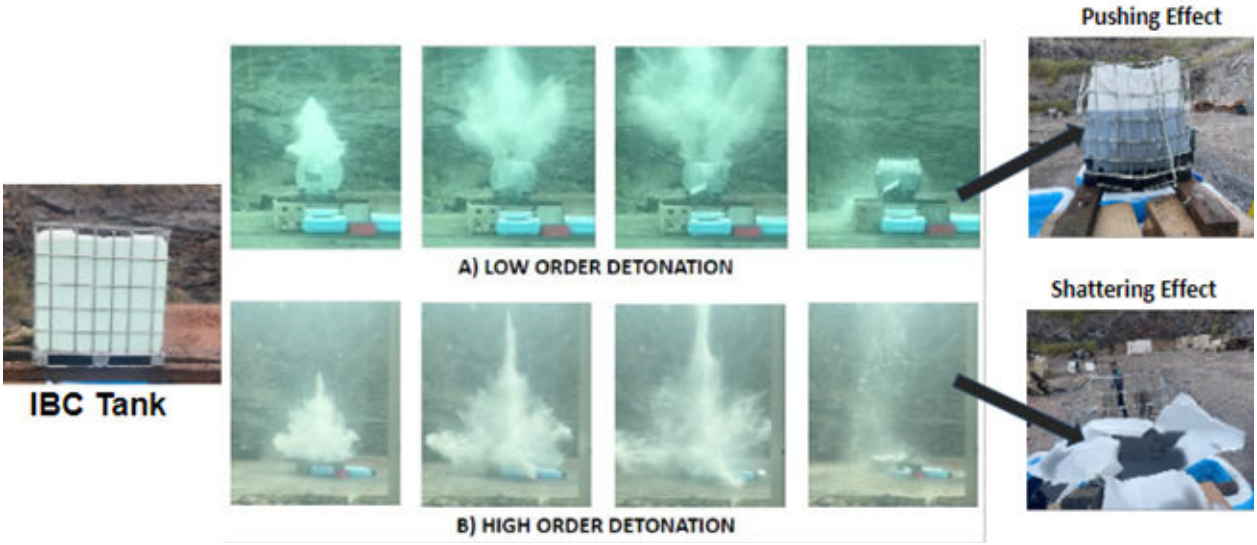

Fig 3: (Left) Pre-detonation: IBC tank with top cut off to reduce the explosion pressure (Center A & B) Detonation: Stages of LO and HO detonations (Right) Post-detonation: Showing the pushing and shattering effect of LO and HO detonations respectively

Fig 3 depicts the pushing effect of low order detonation and shattering effect of high order detonation. As shown in the figure low order detonation leads to the pushing effect as it doesn't generate enough pressure to completely rupture the IBC Tank whereas HO detonation leads to more severe damage with the high pressure and velocity of detonation (Newhouser).

The chemical analysis of the water samples collected post LO and HO detonations shows a huge variation in the amount of explosive residues left. For both high and low order, 115 g TNT was the starting mass in 1000 L of water which corresponds to 115 ppm. The box plot in Fig 4 shows the concentration of explosive residues left in water. The average concentration of explosives in A, B, C ppm and D tank are 6.12 ppm, 11.41 ppm, 1.38 ppm and 2.16 ppm respectively. As the concentration of PENO fall below the detection limit of the instrument only TNT was analysed in the samples.

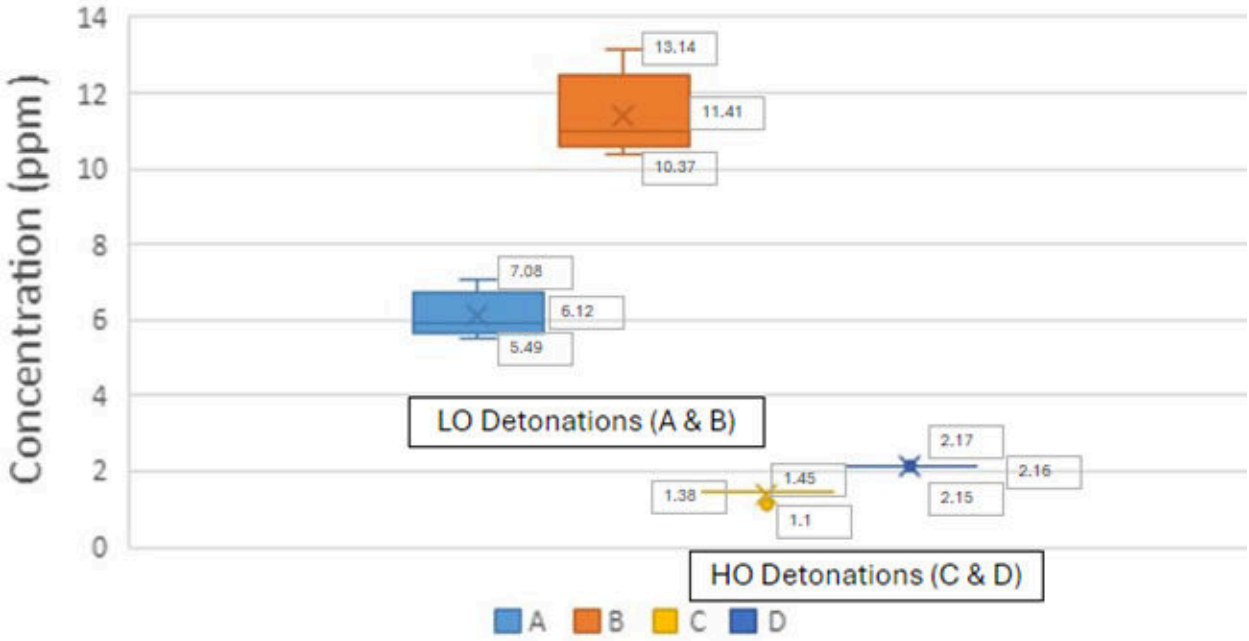

Fig 4: Box plot comparing the residual explosive concentration in water following LO and HO detonations

Table 1 summarises the TNT concentration in individual grab samples along with the standard deviation and average concentration values, the limit of detection of HPLC for this analysis was found to be 1 ppm.

Table 1: TNT concentration in grab samples

Sample ID	Explosive Concentration (ppm)			
	LOW ORDER		HIGH ORDER	
	Tank A	Tank B	Tank C	Tank D
1	6.93	12.95	1.1	2.16
2	6.12	13.14	1.11	2.16
3	7.08	11.33	1.43	2.15
4	6.19	12.51	1.44	2.16
5	6.81	12.34	1.44	2.17
6	5.72	11.32	1.44	2.16
7	6.53	10.45	1.45	2.16
8	5.6	10.68	1.44	2.16
9	5.77	10.65	1.44	2.15
10	5.69	10.62	1.44	2.17
11	5.52	10.58	1.44	2.16
12	5.49	10.37	1.43	2.16

Average	6.120833333	11.41166667	1.383333333	2.16
S.D.	0.581650603	1.039255269	0.130128142	0.006030227

LO detonation is highly preferred over HO detonations for dumped munition clearance. The supersonic blast wave pressure released post- HO detonations is life threatening for aquatic lives, it can cause serious injuries resulting in hearing damage, lung damage or casualties (Beckmann 2015); (Kelley, 2016). The pressure generated by subsonic blast waves of LO detonation results in less environmental damage than HO. However, LO also contributes to high toxicity with the release of explosives in the aquatic environment. TNT is reported as potential carcinogen as per USEPA 8330 B. The post-detonation concentrations of this study are way beyond the USEPA limits considering there are hundred thousand tonnes of corroded munitions dumped in the sea, it is becoming a major environmental threat. Research is needed to investigate suitable mitigation measures to minimalize the hazardous aftereffects such as toxicology and noise pollution of detonation for the clearance of dumped munitions.

4.0 CONCLUSION

The clearance of world war munitions is a major challenge as well as necessity, the corroded munitions are leaching toxic explosives in the aquatic environment. However, the most preferred clearance method i.e. detonation also possess serious environmental concerns. As per the results of this study, high order detonation leads to >98% combustion of the parent explosive and low order results in >90% of detonation. Although high order detonation tends to give more satisfactory results in terms of explosive residue percentage but it creates life threatening noise issue for the aquatic animals. On the other hand, the explosive residues left post-low order detonation become a major toxicity hazard to the aquatic population near the point of detonation and will lead to the widespread of explosives across the aquatic system. Due to the high dilution of undetonated explosive in the surrounding water, toxicity issue is ignored. The concentration of explosives in the water is hazardous to the aquatic species and have the potential to enter the food chain.

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