Agenda Item 4.4	Priorities in the Implementation of the Triennium Work Plan (2010-2012) Review of New Information on the Extent of Negative Effects of Sound
Document 4-10	**Underwater Noise Pollution From Munitions Clearance and Disposal, Possible Effects on Marine Vertebrates, and Its Mitigation**
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PAPER

Underwater Noise Pollution From Munitions Clearance and Disposal, Possible Effects on Marine Vertebrates, and Its Mitigation

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ABSTRACT

Underwater detonations have the potential for serious injury in marine vertebrates such as fishes, reptiles, birds and mammals. The high detonation velocity creates a shock wave. The main reason for injury is the extremely short signal rise time combined with a high overpressure. A negative pressure phase generating cavitation shortly after the peak overpressure can increase organ and tissue damage. Due to surface reflection generating a reversed phase replica of the detonation, this phenomenon is very pronounced in shallow waters. Organs most seriously affected by detonations are those with gas/tissue interfaces (e.g., ears, lungs, swim bladders, air sacs, intestines). Observed injuries include disruption of cells and tissues by differential displacement, internal bleeding, embolism, and auditory damage. Furthermore, compression of the thorax by the shock wave initiates a rapid increase in blood pressure, which can cause damage in the brain and ears. In order to protect marine life, all possible attempts should be made to avoid underwater detonations. For detonations that cannot be avoided due to safety considerations, a number of mitigation measures are presented including bubble curtains, scaring devices, visual and acoustic monitoring, and seasonal and spatial planning. However, mitigation measures have varying degrees of efficiency. Low-order detonations are not a real alternative due to the release of toxic munitions constituents to the environment. For each detonation, a proper site- and munitions-specific risk assessment and mitigation strategy must be developed.
Keywords: detonation shock wave, mitigation, blast trauma, acoustic trauma, marine vertebrates

Introduction

Underwater detonations occur in various parts of the sea under numerous circumstances, including illegal blast fishing, rock demolition blasts and other underwater construction, oil-and-gas industry development, during mine demolition training and other military purposes, as well as demolition of unexploded marine munitions. Furthermore, spontaneous detonation has been described in marine ammunition dumps (e.g., Ford et al., 2005). This can occur due to instability of munitions fill (e.g., triggered by earthquakes, mudslides, offshore construction activity, and possibly seismic operations, etc.). The reasons for spontaneous detonation are not fully understood. A very common method used for the disruption of underwater munitions is the intentional detonation initiated by placing a small donor charge on the munitions in order to initiate an explosion of the main charge. This procedure is referred to as "Blow-in-Place."

Underwater detonations represent the loudest anthropogenic point sources of noise in the oceans and have the potential for serious injury in marine vertebrates and invertebrates (e.g., Richardson et al., 1995; Lewis, 1996). This paper aims to concisely summarize current knowledge on the possible effects of detonations on marine vertebrates (i.e., marine mammals, birds, reptiles, and fish). Many species of these classes have a legal conservation status, which prohibits taking, killing or even disturbance of protected taxa. Since the effects of detonations can be deleterious to individual animals and even in some circumstances at the population level (dependent on the species' distribution, abundance, and migration patterns), mitigation measures for typical munitions related detonations are suggested.

Basic Principles of Underwater Detonation Physics

Urick (1967) describes some basic phenomena of underwater detonations. By conversion of a solid explosive material into a much larger volume of gaseous reaction products, a pressure wave initiated inside the explosive material propagates into the surrounding water. The extremely high detonation velocity (on the order of several thousand meters per second) of explosives such as TNT or RDX creates a shock wave characterized by a pressure signature with a tremendously steep front and a very high maximum pressure or "overpressure" followed by a rapid decay (Figure 1). A shock wave is created because the detonation velocity and the expansion of the resulting gas bubble are faster than the speed of sound. Depending on the water depth, this primary pulse can be followed by a pronounced negative phase and a number of oscillating bubble pulses resulting from multiple collapses of the gas bubble (Figure 1).

The shock wave and very high sound pressure propagate in all directions and have the potential to seriously harm marine vertebrates such as cartilaginous and bony fishes, reptiles, birds, and mammals (Richardson et al., 1995). The potential injury depends on the topography and overall water depth, charge weight and type, sediment type, position of the munitions on the bottom and the animal's size and position in the water column as well as its proximity to the source (Ketten, 1995). Furthermore, there are differences between tissues, organs and organisms. Also the orientation of the animal with respect to the incoming shock wave may be important (Yelverton et al., 1973; Landsberg, 2000).

In shallow water, surface-reflected pulses arrive milliseconds after the direct pulse resulting in rapid pressure changes from a positive to a negative peak (Hannay and Chapman, 1999) (Figure 2). Combined with the positive peak overpressure from direct radiation this can increase injuries (Landsberg, 2000). Cavitation (i.e., formation of gas bubbles in a partial vacuum causing water to vaporize; Urick, 1967) can be created due to high-amplitude negative pressures and can also result in injury.

Potential Effects—Injury to Marine Vertebrates

Injuries directly caused by the shock wave (often referred to as "primary blast injury") originate from the compression of tissues or organs by the incoming wave front (Landsberg, 2000). Both the extremely short signal rise time and the high peak pressure in the pressure signature of a detonation are related to the extent of injury to marine vertebrates. The pressure of the blast wave is transmitted directly through the body as it is of similar consistency to water (Landsberg, 2000). High-amplitude pressure pulses may cause differential tissue displacement disrupting cells and tissues of different density such as muscle and fat. Especially at the interface with gas-filled cavities capable of compression, molecules are displaced resulting in damage to these tissues. Tissues at these interfaces are torn or shredded by instantaneous compression of the gas. Hence, massive damage can occur in the lungs, intestines, sinuses, and ear cavities (Landsberg, 2000). Furthermore, the compression of the thorax by the

FIGURE 2

Typical pressure signature of an underwater explosion in shallow water where the surface-reflected pulse arrives rapidly (modified from Hannay & Chapman, 1999).

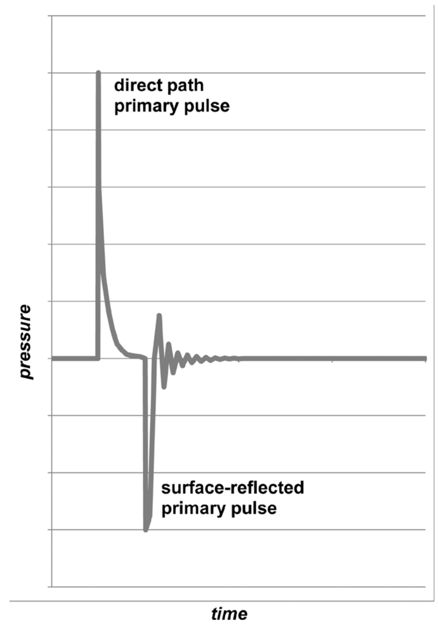
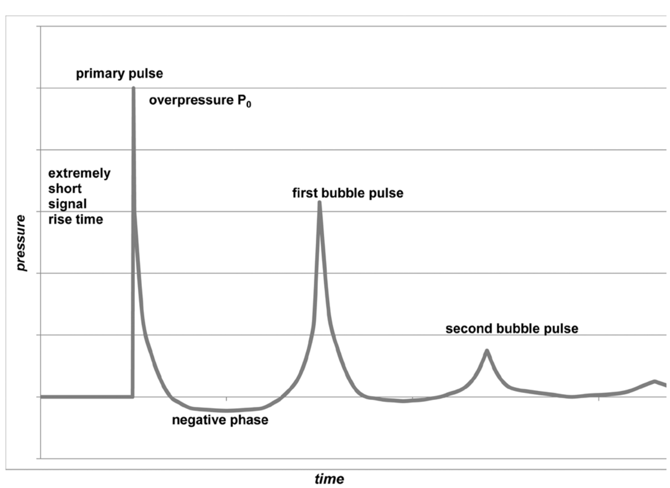


FIGURE 1

Typical pressure signature of an underwater explosion in deep water (modified from Urick, 1967).



shock wave causes rapid increase in blood pressure (Landsberg, 2000). Possible consequences include the rupture of blood vessels (e.g., in the brain) and hemorrhages in the brain and ears (Ketten, 1995). Rupture of lung alveoli can lead to air embolism in the cerebro-vascular system inhibiting oxygen supply to the brain (Landsberg, 2000). Injury resulting from cavitation occurring shortly after the shock wave includes gas embolism caused by nitrogen bubble formation in supersaturated tissues and fluids in diving animals (Lewis, 1996).

A number of sublethal blast effects have been documented, which may contribute to increased mortality by predation. Sublethal auditory effects can affect the fitness of affected marine animals because hearing is vital for their behaviour and ecology. This is especially important for marine mammals that rely on this sense for their orientation and prey acquisition (Richardson et al., 1995). Any sublethal impact that would lead to reduced survival, growth, or reproduction can impact populations (National Research Council, 2005). Such effects attributed to underwater noise and marine mammals require further studies.

Injury to Fishes

At very close ranges, underwater explosions are lethal to most fish species regardless of size, shape, or internal anatomy. At greater distances, species with gas-filled swim bladders suffer higher mortality than those without swim bladders (e.g., flatfish) (Yelverton et al., 1975; Young, 1991; Lewis, 1996). In a documented case, only 3% of killed fish floated to the surface (Gitschlag et al., 2000). Effects to larval stages are mostly unknown. There is no comprehensive study determining the effects on fish larvae. However, fish eggs have been shown to be killed by explosions (Keevin & Hempen, 1997). Also there is clear evidence that smaller animals are more seriously affected by strong impulses than larger ones (Yelverton et al., 1975; Young, 1991). Fish close to the surface seem to be more vulnerable than fish deeper in the water column (Young, 1991; Lewis, 1996). This can be attributed to the surface-reflected pulse (Figure 2). Fish are killed by internal bleeding and massive organ and tissue damage—most frequently in the swim bladder, kidney and liver, but also in the body cavity, pericardial sac and gut (Yelverton et al., 1975; Continental Shelf Associates, 2004).

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

Injury to Reptiles

In sea turtles, tissues affected by detonations are mainly those at air-fluid interfaces (e.g., ear cavities, lungs, and the gastrointestinal tract). At close ranges, skeletal or shell fractures and brain damage can be assumed (Klima et al., 1988; Continental Shelf Associates, 2004). Quantitative data concerning direct effects of underwater explosions on turtles are not available. In an experiment, five turtles of different species and sizes (0.8-6.8 kg) were exposed to simultaneous detonations of four 23 kg charges at distances between 229 and 915 m (Klima et al., 1988). Unconsciousness and dilation of blood vessels were reported at a distance of up to 915 m. The animals did not appear to return to normal until three weeks after the detonation. Three turtles (91-182 kg) exposed to a 545-kg detonation showed different degrees of injury at distances between 200 and 900 m. The closest animal was killed; at 366 m a turtle suffered "minor injury" whereas at 908 m the animal appeared uninjured (Lewis, 1996). There are a few other reported incidents where turtles were killed during explosions; Klima et al. (1988) report an incident of 51 turtles found dead on Texas beaches in 1986. These mortalities were attributed to the explosive removal of offshore oil and gas structures using 22 detonations of unknown charge weight.

Injury to Seabirds

Because pressure is transmitted directly through the thoracic wall, both fully submerged birds and those floating on the surface can be injured by detonations. Only one specific study investigating blast effects on water birds is known to the author. Yelverton et al. (1973) found extensive pulmonary hemorrhages, ruptured air sacs and ear drums, ruptured livers and coronary air embolism in mallard ducks on the surface close to detonations. Submerged ducks had the same injuries and also kidney damage. They suffered more serious injuries than swimming ducks at the same distance. This may be because the lungs of swimming ducks were above the water and surges of circulatory fluid pressure were lower when only a part of the body was in contact with water. In birds, the tissue/air interface is very large compared to other marine vertebrates due to the large lung/air sac system. Also, birds possess air-filled ear cavities that are highly susceptible to blast injuries.

Some bird species such as ducks carry air within their plumage for insulation and buoyancy. It is possible that this compressible air cushion shields swimming birds from detonation effects to a limited extent. Diving birds, however, can suffer damage of the auditory system not shielded by the plumage. Also, birds not carrying air between their feathers (such as cormorants) may be affected by ruptured tissue in the respiratory tract (air sac system and lungs) at much closer ranges than ducks. However, this is mainly speculative and needs to be further investigated.

Injury and Auditory Effects to Marine Mammals

There are some anecdotal reports of cetacean deaths which could be linked to underwater detonations. Three humpback whales died within 3 days as a consequence of severe blast injuries (mechanical trauma in the ears) from detonations of 1,700 to 5,000 kg of explosives (Ketten, 1995). A mass mortality event occurred in the Azov Sea in August 1982 as a result of an explosion at a gas extraction platform. More than 2,000 dead harbor porpoises washed ashore following this event (http://www.iucnredlist.org/apps/redlist/details/17030/0). Based on experimental data from terrestrial mammals held under water it is assumed that small marine mammals are more vulnerable than larger ones (Yelverton et al., 1973; Young, 1991). However, compared to terrestrial mammals, marine mammals possess some adaptations to high-pressure changes, especially in the ears (Ketten, 1995).

As in other marine vertebrates, gas-filled cavities in marine mammals are the organs most vulnerable to blast effects (Ketten, 1995). These are mainly the ear cavities (e.g., in pinnipeds), lungs, nasal sacs, and the gastrointestinal tract (e.g., Yelverton et al., 1973).

Depending on the severity of the blast, auditory effects (acoustic trauma) can either be temporary or permanent. A temporary threshold shift (a well-known effect from loud rock music concerts) is caused by physiologic exhaustion of sensory cells (fatigue of stereocilia). A permanent threshold shift can be the result of a loss of hair cell bodies and subsequent neuronal degeneration or severe injuries including damage in middle and inner ear caused by blast overpressure: rupture of ear drum, fracture of ossicular chain, or damage to the basilar membrane (Ketten, 1995; Landsberg, 2000). With respect to hearing impairment, pinnipeds are assumed to be more sensitive than cetaceans (Southall et al., 2007). Furthermore, harbor porpoises may be more sensitive than bottlenose dolphins (Lucke et al., 2009).

Mitigation Measures

In order to mitigate the impact of detonations on marine life, delineation of possible impact zones and predetonation surveys are necessary to assess what animals can be affected. This must be based on a site-specific shock wave propagation model and best available estimation of safe ranges (Yelverton et al., 1973, 1975; Goertner, 1982; Thiele & Stepputat, 1998). However, predictions of safe ranges are often based on mortality or serious injury and therefore an adequate safety margin must be added. In a case study in Portugal, it has been shown that simply doubling the calculated distance in order to reduce the risk of auditory trauma (O'Keeffe & Young, 1984) is not sufficient (Dos Santos et al., 2010).

Avoid detonations

The best practice for mitigating blast effects described above is avoiding detonations whenever possible. Some ecosystems are very sensitive to detonations. This is especially true for tropical and cold water coral reefs. In these habitats, any detonation is destructive not only to marine vertebrates but also to the entire ecosystem. Also if individuals or populations of rare species (such as the critically endangered harbor porpoise population in the Baltic Proper) are directly threatened by the effects of a detonation, attempts to avoid detonations must be given the highest priority of all possible mitigation measures.

For clearance of underwater munitions, this means that recovery methods that allow safe disposal on land should be preferred (Koschinski & Kock, 2009). Some new methods and technologies have been presented at the three International Dialogues on Underwater Munitions and the MIREMAR conference (Minimizing Risks for the Environment in Marine Ammunition Removal in the Baltic and North Sea, Neumünster/Germany, 16-18 November 2010) including remotely operated salvage robots, underwater jet cutting, in situ destruction in mobile detonation chambers or treatment of energetic compounds using ultraviolet radiation as well as transport or treatment in salvage pressure containers or reactors.

Spatial planning for construction work in munitions-contaminated waters (such as the Nord Stream pipeline in the Baltic Sea) and rerouting or relocation can help avoid large concentrations of explosives in the construction area or corridor and minimize the potential need for underwater detonation.

In mine demolition training, it is debatable if large explosive charges (of up to a few 100 kg) are always required. Even though case specific, the attachment of a donor charge to a concrete "dummy" mine or a mine with a much smaller charge should be sufficient for training in many cases.

Depending on the local circumstances and type of ammunition, it may not always be possible to use the safe recovery methods mentioned above. This may be the case when the safety of personnel dealing with the ammunition cannot be adequately assured. The expense of utilizing safe recovery methods rather than detonation should not be the determining factor because true costs (e.g., for environmental damage) may far outweigh the immediate expenses. If a detonation cannot be totally avoided, the surrounding sea life must be carefully considered and other mitigation measures conducted.

Physical Measures to Reduce Shock Waves

Bubble curtains have been shown to effectively reduce the sound pressure and the shock wave from a detonation (Nützel, 2008; Schmidtke, 2010). Bubble curtains are recommended by some natural conservation agencies in the United States for protection of rare or commercially valuable fish species from underwater detonations (Keevin et al., 1997; Keevin & Hempen, 1997; Keevin, 1998). Bubble curtains are walls of bubbles released from a nozzle pipe resting on the seafloor and connected to a compressor. Damping effects of bubble curtains can be explained by adiabatic compression of the bubbles resulting in temperature rise, oscillation of bubbles and loss of energy due to viscosity and thermal transfer between bubbles and water, emission of rarefaction waves by each bubble, and decrease of shock velocity due to compressibility (Grandjean, 2011). The efficiency of bubble curtains depends on their width and shape, air volume, and bubble size.

Bubble curtains can thus substantially reduce the danger zones for marine organisms provided that their radius is large enough. For example, a bubble curtain with a 22-m radius used in the detonation of a 300-kg mine containing "Schießwolle 39" (45% TNT + Al) proved ineffective (Schmidtke et al., 2009), whereas a bubble curtain with a radius of 70 m was able to reduce the peak pressure of the shock wave by 16-19 dB. Depending on the propagation properties of the water, this would reduce the critical range approximately by a factor of 10. However, even the damped shock wave can harm marine life with the remaining pressure. Furthermore, any detonation, especially those from old ammunition releases toxic munitions constituents into the water due to incomplete combustion. This cannot be prevented using a bubble curtain (Pfeiffer, 2009).

In shallow water, other dampening strategies could be used. A part of the energy could be redirected to the surface by either positioning the ammunition in a crater (http://schleswig-holstein.nabu.de/imperia/md/content/schleswigholstein/gutachtenstellungnahmen/Miremar/schmidtke_reducingshockwaves-workshop.pdf) or by the placement of a rigid ring around the ammunition (rigid shockwave shaper) or an air cushion on the top (collapsible shockwave shaper) (fundamentals, see Wallace, 1982). However, these theoretic approaches require further studies.

Avoid Sensitive Times and Areas

In order to safeguard protected marine species when detonating underwater munitions, it is necessary to avoid times and areas in which these species can occur (Dolman et al., 2009). A good knowledge on the occurrence, life cycle parameters and behavior of migrating species is essential to this approach. Known feeding, migration, nursery, spawning, summering or overwintering areas of sensitive species can be fed into data bases used for planning and execution of clearance activities. The Baltic Ordnance Safety Board (BOSB) recently agreed to incorporate a "biology factor" in the prioritization system for mine clearance activities in the Baltic Sea. This means that areas of concern for sensitive biology are taken into consideration during the planning and execution of clearance activities (G. Möller, COM Mine Warfare Data Center, Berga/Sweden, personal communication).

Protected-Species Observers

The implementation of a monitoring scheme in order to maintain a safe "exclusion zone" around the blast is another mitigation measure.

Certain regulations require observations starting as early as 48 h before a planned detonation using shipboard surveys for protected species as well as pre- and post-detonation aerial surveys (Gitschlag & Herczeg, 1994; Clarke & Norman, 2005; Viada et al., 2008). This mitigation measure relies on the thorough determination of possible impact zones, a skilled observer team, and good sightings conditions (calm sea, good light). Often, more than one platform is needed to cover the whole exclusion zone, which may have a radius of several kilometers (Clarke & Norman, 2005; Dos Santos et al., 2010). For marine mammals, often visual and passive acoustic methods are used in combination. However, acoustic methods are of no use if animals do not vocalize or are orientated away from the acoustic monitoring device. Visual and acoustic monitoring of marine mammals was conducted in the Finnish Exclusive Economic Zone during construction of the Nord Stream pipeline in the Baltic Sea, and only one seal was visually detected during clearance of 49 munitions (Nord Stream, 2011). The low detection rate may have been due to the limitations mentioned above. Seals only vocalize under water during a short period of the year (Van Parijs et al., 1999). Protected-species observers can only be regarded as one component of a strategy for minimizing the risk to marine life. The method is very dependent on conditions and affected species.

Acoustic Deterrents

The use of acoustic deterrents such as pingers, seal scarers, or scaring charges in order to maintain an exclusion zone around the explosion site needs careful consideration. The range of a typical gillnet pinger is only a few hundred meters, and it only works for certain cetaceans (e.g., Culik et al., 2001). The effectiveness of seal scarers with respect to pinnipeds is unclear. Results of different studies are contradictory (Jacobs & Terhune, 2002; Fjälling et al., 2006; Graham et al., 2009). The motivation to exploit a food resource and habituation seems to influence the scale of avoidance of seal scarers. Whereas seal scarers seem to have a repellent effect on some small cetaceans (Olesiuk et al., 2002), acoustic scaring devices are not suitable for birds, reptiles, and fishes (e.g., Melvin et al., 1999).

The possible risks and benefits of small scare charges must be carefully balanced. For single detonations (such as in accidental mine finds), it may be beneficial to scare marine mammals away prior to a harmful explosion using small scare charges. However, it must be considered that, similar to the effect on human divers, even a charge of 10 or 20 g can be harmful to marine life at ranges of up to a few hundred meters (Young, 1991).

Fish scaring charges of 20 g were used during munitions clearance for the Nord Stream pipeline in the Baltic Sea (Nord Stream, 2011). However, the scaring effect of such charges is questionable as no flight response has been reported in experiments conducted so far (Lewis, 1996; Keevin & Hempen, 1997). Depending on the charge weight, fish size and distance, scaring charges may contribute to fish mortality. Moreover, in areas where detonations occur on a regular basis (such as the Gulf of Mexico, where explosives are used for the common but debatable practice of decommissioning oil and gas platforms) scaring charges could attract marine mammals or turtles to the detonation site to feed on dead fish and be subsequently exposed to further explosions (Continental Shelf Associates, 2004). In that case, a scare charge could pose a significant threat to protected species.

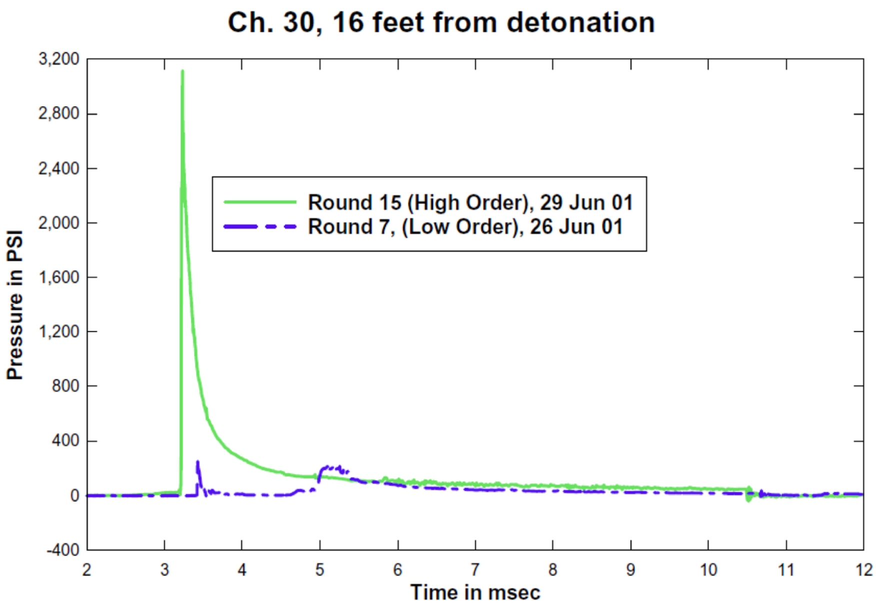
Possible Alternative: Low-Order Detonation?

Low-order detonations lack the rapid rise and exponential decay of pressure that is characteristic of high-order detonations (Figure 3). Thus, intentional low-order detonations are viewed as an alternative means to the traditional high-order detonation procedure referred to as Blow-in-Place. Both procedures are used for the disruption of submerged unexploded ordnance that is considered unsafe to move. Low-order detonations reduce the shock wave and other effects compared to the Blow-in-Place procedure (ESTCP, 2002).

The main disadvantage of low-order detonations is that, on average, in new ammunition more than 25% of the original explosive fill remains unreacted after a low-order detonation (ESTCP, 2002). As many underwater munitions are saturated with water over due to decades of immersion, these often detonate low-order unintentionally releasing a significant amount of unreacted particles to the environment. These unreacted materials can be ingested by filter-feeding organisms. Furthermore, TNT and its metabolites can be absorbed through the skin. In the body, TNT is mutagenic, hepatotoxic and damages erythrocytes (Bolt et al., 2006). These mechanisms are well documented for human workers but still remain unclear for the marine biocenosis. Biodegration products such as Amino-DNTs have an even higher toxicity than the source substance and can be

FIGURE 3

Pressure time histories of 155-mm projectile high- and low-order detonations (ESTCP, 2002).



accumulated (an effect shown in oligochaete worms) (Lachance et al., 2004).

Conclusion

Before blasting, a proper risk assessment and mitigation strategy should be developed in order to protect the marine environment. This must include a thorough determination of possible impact zones and predetonation surveys to analyze what animals can be affected. A site-specific shock wave propagation model is needed for the estimation of safe ranges, and an adequate safety margin has to be established in a precautionary manner. Possible alternatives to blasting should be considered, and best available techniques should be identified. For this, it is necessary to balance environmental costs and expenses. If for safety reasons a detonation cannot be avoided, a combination of mitigation measures appropriate to protect the environment should be implemented.

In the light of large amounts of unexploded ordnance and dumped marine munitions in certain areas such as the Baltic and North Seas and the urgent need to remove them from shipping lanes, ports and ecosystems, it is necessary to find a cost-efficient and environmentally friendly method for their treatment. In order to develop best environmental practices, more research is needed on safe recovery methods and mitigation of impacts for marine animals. Mitigation techniques should be improved in the future.

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