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Methods for Safe Destruction and Utilization of 120 mm HE-FRAG Mortar Ammunition

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Abstract:

This review surveys contemporary methods for the disposal and utilization of 120 mm high-explosive fragmentation mortar rounds, including munitions that have exceeded their service life. Conventional and alternative demilitarization technologies are examined, including detonation and burning methods, mechanical disassembly, abrasive water-jet cutting, thermal and chemical treatments, advanced physico-chemical solutions, cryogenic techniques, and material recycling pathways. The methods are comparatively evaluated in terms of destruction efficiency, occupational and environmental risks, regulatory constraints, operational feasibility, and cost. Based on an analysis of international literature, standards, and case studies, the review identifies best practices and proposes criteria for selecting appropriate demilitarization routes under varying operational and regulatory conditions. The findings support safe, efficient, and environmentally responsible ammunition stockpile management.

Keywords:

120 mm mortar ammunition, demilitarization, disposal method, TNT/RDX, HE mortar

1 Introduction

The safe management and disposal of military munitions are of paramount importance for both defense organizations and civilian authorities. In this context, 120 mm high-explosive (HE) fragmentation mortar rounds (Fig. 1) warrant particular attention owing to their widespread employment, substantial explosive charge and the hazards posed by ageing stockpiles that have exceeded recommended storage lifetimes or require periodic technical inspection [1]. Improper storage, handling or transport of these rounds can precipitate unintended initiation, dispersal of toxic residues and significant risks to personnel and the environment.

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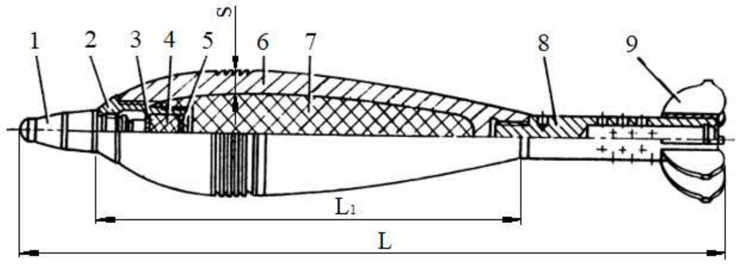

Fig. 1 120 mm *high-explosive fragmentation mortar ammunition* [2]. *1. Fuse, 2. Fuse adapter, 3. O-ring, 4. Detonator, 5. Carboard spacer, 6. Cast iron body, 7. Explosive filler, 8. Steel tail boom, 9. Stabilizing fins*

A typical 120 mm HE fragmentation round is constructed to deliver reliable fragmentation and stable flight. The projectile body is commonly manufactured from high-strength spheroidal graphite cast iron (EN-GJS-450-10), with an overall length of approximately 700 mm and a warhead length of roughly 400 mm; total mass is generally between 15.5 and 16 kg, while the main explosive charge normally ranges from 2.5 to 3.0 kg (commonly TNT, RDX or composite formulations such as A-IX-1, TG-40 or Composition B). Casing thickness may reach up to ~22 mm, and stabilization is achieved by fixed tail fins; the fuse assembly permits both instantaneous and delayed functioning.

Storage and logistical handling of these munitions are governed by national and international standards that prescribe appropriate temperature ranges, ventilation, packaging and transport measures to mitigate risk [3]. The physicochemical properties of common energetic fillers – for example, TNT's melting point (~80.85 °C), density (~1.65 $g \cdot cm^{-3}$) and detonation characteristics – exert a decisive influence on the choice of dismantling and disposal techniques, since such properties determine susceptibility to thermal, mechanical and chemical treatments.

A broad spectrum of demilitarization and reutilization technologies is available. Conventional approaches include controlled detonation, open burning/open detonation (OB/OD) and mechanical disassembly (including abrasive water-jet cutting). Advanced and emerging methods encompass thermal extraction (melt-out, steam extraction), supercritical water oxidation (SCWO), chemical neutralization (solvolysis, hydrolysis, oxidative treatment), enzymatic degradation, plasma-arc and laser-based processes, cavitation-assisted destruction and cryogenic cryofracture. Each technology entails specific trade-offs with respect to destruction efficiency, occupational safety, environmental emissions, monitoring requirements, logistical feasibility and cost.

This review consolidates contemporary knowledge on disposal and recycling pathways for 120 mm HE fragmentation mortar rounds. It critically assesses technological readiness, environmental and occupational health implications, and provides practical decision criteria to assist military and industrial stakeholders in selecting safe, efficient and environmentally responsible demilitarization strategies.

2 Technological Characteristics of Ammunition Disposal Processes

Ammunition disposal represents a complex technical and technological process aimed at the safe and irreversible withdrawal from use. The goal is the complete elimination of the possibility of explosive reaction through disassembly, neutralization of energetic materials, and transformation of their components into chemically and functionally inert substances, which do not pose a threat to the environment or human health. Two main approaches have been distinguished for this purpose – destruction and utilization:

- **Destruction** is a disposal process aimed at the permanent and safe elimination of ammunition by converting it into unusable and non-hazardous materials.
- **Utilization** is a process aimed at recovering the economic value of materials or individual components obtained from ammunition, through technological methods of processing, recycling, or reuse in industrial or civilian applications.

2.1 Ammunition Destruction

Ammunition Destruction via Controlled and Uncontrolled Detonation

Destruction of ammunition by detonation, as part of the disposal of hazardous and obsolete munitions, is a well-established and widely used method. This process comprises two main types of detonation: controlled detonation and uncontrolled detonation (Open Detonation – OD).

Controlled detonation is a method for ammunition destruction in a strictly regulated and controlled environment, using auxiliary explosive charges to initiate the primary detonation. After the initial explosion, residual explosive substances are subjected to additional neutralization to eliminate any potential risk. The main objective of this method is to achieve safe, irreversible, and environmentally responsible destruction of non-standard, obsolete, or hazardous ammunition [4].

In most cases, controlled detonations are carried out in blast pits, engineered excavations, or natural karst caves, which limit the risk of fragment, shockwave, and toxic emission dispersal (Fig. 2). Blast pits are lined with sand, clay, or other energy-absorbing materials to reduce shockwave propagation and fragmentation. For large quantities of ammunition, underground galleries or isolated quarry sections are used as additional protective barriers [5, 6].

The choice of location depends on geological characteristics, distance from populated areas, availability of suitable infrastructure, and the ability to control detonation parameters [7].

Ammunition is prepared for detonation using auxiliary explosive devices and timers or remote control, ensuring precise timing of the explosion. A protocol of double-checking security and technical integrity of systems is applied to prevent accidental ignition. After detonation, specialized teams inspect and analyze the area for residual toxic substances (e.g., heavy metals, nitro compounds, unexploded fragments). If necessary, decontamination or collection of residual materials is performed for subsequent reutilization or safe storage.

Main drawbacks of this method include:

- potential release of hazardous chemical substances that may contaminate the environment,
- increased costs and the need for additional safety infrastructure.

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Fig. 2 Controlled ammunition detonation in an engineered blast pit with energy-absorbing materials [8]

Uncontrolled detonation is applied when ammunition cannot be safely moved or processed otherwise. The method is based on the “blow-in-place” approach, where ammunition is detonated directly on site without prior disassembly or transport, making it suitable for emergency situations or open battlefields [9]. The procedure involves localization of ammunition, direct detonation, and assessment of potential consequences. Unlike the controlled method, it does not guarantee limited contamination or safe management of residual materials [10]. Advantages include speed and lack of infrastructure requirements, but safety risks and environmental damage are significantly higher. Studies indicate that explosive compounds like TNT and RDX, commonly used in conventional munitions, may persist in the environment for long periods, causing serious soil and water contamination [11, 12]. Uncontrolled detonation should only be used as a last resort when no safe alternatives exist.

Incineration

Incineration is a method for ammunition destruction through thermal treatment in specialized facilities, whereby explosive substances and associated components are decomposed at high temperatures (Fig. 3). This method is used when detonation or chemical neutralization is not applicable or does not provide the required safety level. Incineration is particularly effective for munitions containing explosives, heavy metals, and toxic chemicals, which can be decomposed at temperatures ranging from 800 °C to 1 200 °C [13]. Emission control systems such as acid gas scrubbers and activated carbon filters for organic pollutants are employed [14]. Advantages include high efficiency, reduced risk of accidental detonation, and potential reuse of residual materials.

Main disadvantages include the release of dioxins, furans, and other harmful emissions, requiring precise control and advanced filtration technology. In addition, construction and maintenance of incineration facilities require significant financial resources and high-tech infrastructure, suitable primarily for long-term applications.

Fig. 3 Rotating incinerator for explosive waste (EWI – APE 1236) [15]

Open Burning

Open burning is a method for destroying ammunition and other hazardous materials through thermal decomposition in an uncontrolled environment – on open areas or in non-equipped facilities lacking emission capture and purification systems. This approach is mainly used when ammunition cannot be safely transported to specialized facilities, or when rapid disposal of large quantities of unstable or obsolete explosives is required.

Burning involves placing ammunition or components in a secured open area, followed by ignition using an external source – usually flammable liquids or controlled ignition. Nevertheless, the process poses serious environmental risks as uncontrolled burning releases harmful pollutants such as dioxins, furans, acid gases, and heavy metals, contaminating air, soil, and water.

Plasma and Laser Technologies for Ammunition Destruction

Plasma and laser technologies are modern approaches to ammunition destruction, providing high precision and control, while significantly reducing environmental and health risks compared to traditional methods such as open burning or uncontrolled detonation (Fig. 4). Plasma technology uses ionized gas at very high temperatures (over 10 000 °C) generated by electric discharge, breaking down chemical bonds in explosives into safe gases and inert residues [16]. The process is energy-efficient, minimally prone to accidental explosions, and environmentally friendly [17].

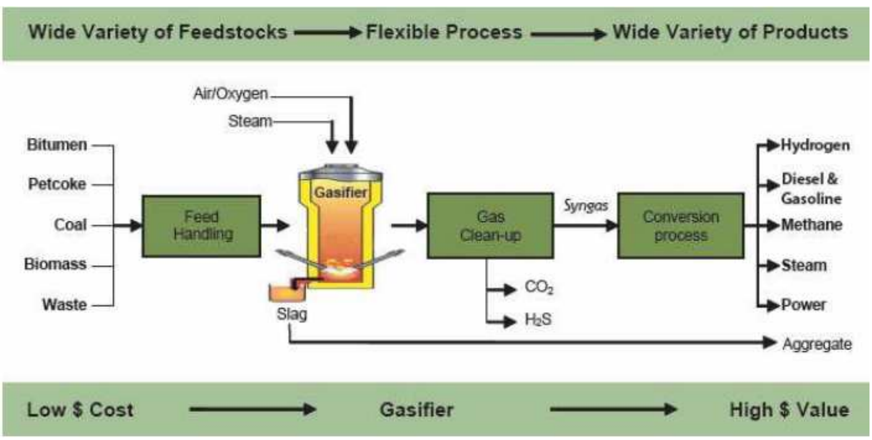

Fig. 4 Plasma technology for ammunition destruction [18]

Laser technology uses directed high-intensity laser beams for localized heating, melting, or destruction of specific ammunition parts, preventing spontaneous detonation and ensuring safe operation in a controlled environment [19]. Both methods are highly accurate, safe, and do not require physical disassembly of ammunition but demand substantial investment, specialized maintenance, and trained personnel. Their application is generally limited to small volumes or specific materials due to high cost and complexity, yet they offer significant ecological benefits, avoiding toxic emissions and reducing risks to workers and the environment.

Bioremediation of Ammunition and Toxic Substances

Bioremediation is an effective biotechnological method for destroying residual toxic warfare substances, including TNT, RDX, HMX, and other nitro compounds in obsolete or unused ammunition. It offers an environmentally sustainable and economically viable approach to degrading and detoxifying hazardous components.

Various microorganisms, such as strains from *Pseudomonas*, *Clostridium*, and *Rhodococcus*, can degrade and transform explosives into non-toxic or mildly toxic products via enzymatic systems that reduce nitro groups and decompose nitroaromatic compounds. For example, *Clostridium* spp. can reduce RDX to amine derivatives, which are safer and more easily degradable. TNT biotransformation occurs under aerobic and anaerobic conditions. An example is *Indiicoccus explosivorum* (strain S5-TSA-19) (Fig. 5).

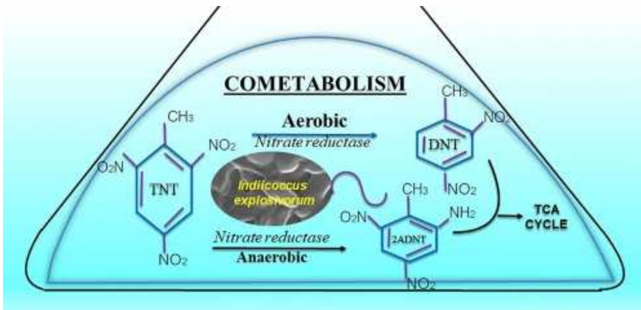

Fig. 5 Degradation of 2,4,6-trinitrotoluene (TNT) by Indiicoccus explosivorum (strain S5-TSA-19) [20]

Fig. 6 presents a schematic of the stepwise bacterial reduction of 2,4,6-trinitrotoluene (TNT), in which each of the three nitro groups (–NO_2) is reduced in turn. The principal intermediate and terminal products depicted in the scheme are as follows:

TNT (2,4,6-trinitrotoluene)
→ 4-ADNT (4-amino-2,6-dinitrotoluene)
→ 2,4-DANT (2,4-diamino-6-nitrotoluene)
→ TAT (2,4,6-triaminotoluene) or DHANT / DANTON (2,4-dihydroxylamino-6-nitrotoluene).

This pathway is followed by complete mineralization: bioremediation of 2,4,6-TNT culminates in the total degradation of the organic molecule to simple, non-toxic inorganic end-products – carbon dioxide (CO_2), ammonium ion (NH_4^+) and water (H_2O).

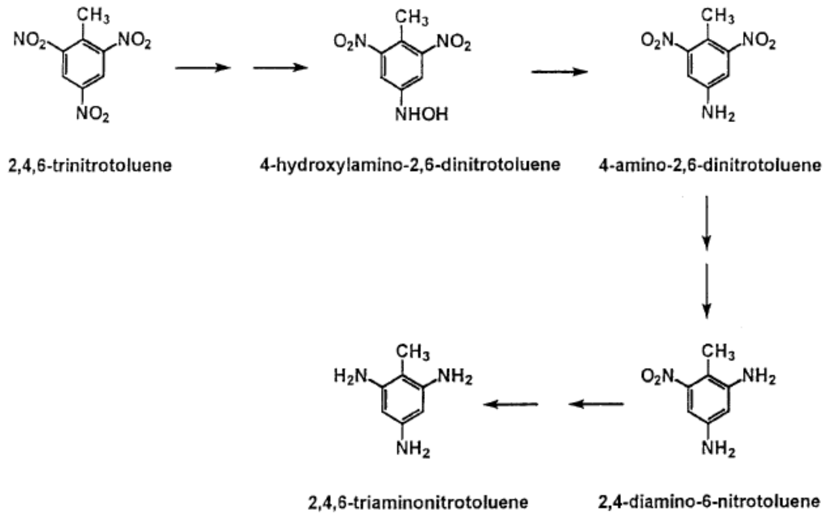

Fig. 6 Transformation of 2,4,6-TNT by sequential reductions [21]

Cavitation-Based Destruction

Cavitation is the process of formation, growth and sudden collapse of microscopic gas bubbles within a liquid medium, induced by local pressure fluctuations – for example, from ultrasonic waves or mechanical motion. Upon bubble collapse, local temperatures can exceed 5 000 K and pressures can surpass 1 000 atmospheres, producing intense mechanical and chemical effects in the surrounding medium. These extreme conditions enable the molecular-level degradation of explosive compounds while reducing the risk of uncontrolled detonation and the release of harmful emissions [22].

The use of cavitation-based methods for munitions destruction offers several key advantages. First, the process takes place within a liquid barrier, providing an additional physical safeguard and reducing the likelihood of an explosive reaction. Second, cavitation-driven fragmentation is energy-efficient and can enable complete decomposition of energetic materials without the high temperatures or aggressive chemicals required by alternative techniques. Third, the method is environmentally favorable – it does not produce toxic gases nor contaminate soil and watercourses.

Practical applications of cavitation include both fixed and mobile installations capable of processing a variety of munition types – from artillery projectiles to mines and rocket motors. Cavitation systems employ ultrasonic generators or hydrodynamic devices to generate controlled cavitation within specially designed liquid chambers. This arrangement affords precise process control and the ability to adapt to different substrate materials and explosive compositions [23].

Cavitation may be induced by several methods:

- Ultrasonic cavitation: high-frequency sound waves generate bubbles in the liquid that, upon collapse, produce localized peaks of temperature and pressure.
- Hydrodynamic cavitation: rapid fluid motion through constrictions or nozzles produces local pressure drops and consequent bubble formation.
- Acoustic cavitation: directed acoustic beams create cavitation bubbles at targeted loci that collapse and destroy the intended material.

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The cavitation destruction process typically involves immersing the munition in a liquid bath in which cavitation is initiated. Bubble collapse generates localized heating and intense mechanical impulses that compromise the munition's structure and prevent detonation.

The mechanism of explosive degradation by a submerged cavitation water jet is illustrated in Fig. 7.

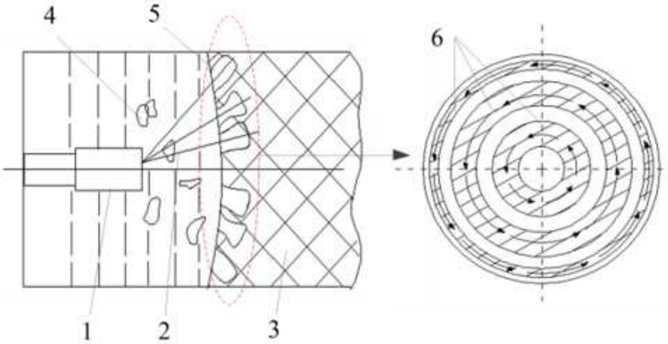

Fig. 7 Diagram of cavitation water jet impact marks on the explosive surface [24].
1. Disperser; 2. Cavitation jet; 3. Explosive; 4. Fragmented explosive; 5. Pits; 6. Annular grooves

The cavitation jet initiates localized surface damage, forming pits and grooves – clear evidence of concentrated mechanical impact caused by bubble collapse (Fig. 8). These marks indicate the onset of material cracking, serving as nuclei for subsequent fragmentation.

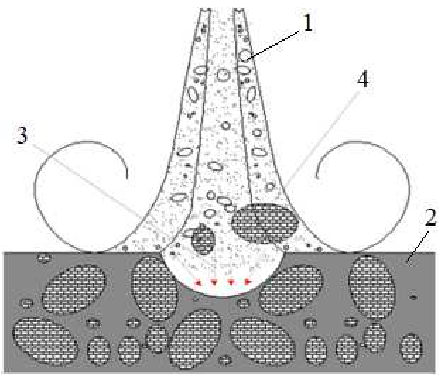

Fig. 8 Destruction of an explosive by a submerged cavitation water jet [24].
1. Cavitation jet; 2. Explosive; 3. Impact; 4. Detached particles.

Here, the jet impact generates high local stresses that exceed the explosive's structural strength, resulting in particle detachment and progressive disintegration (Fig. 9).

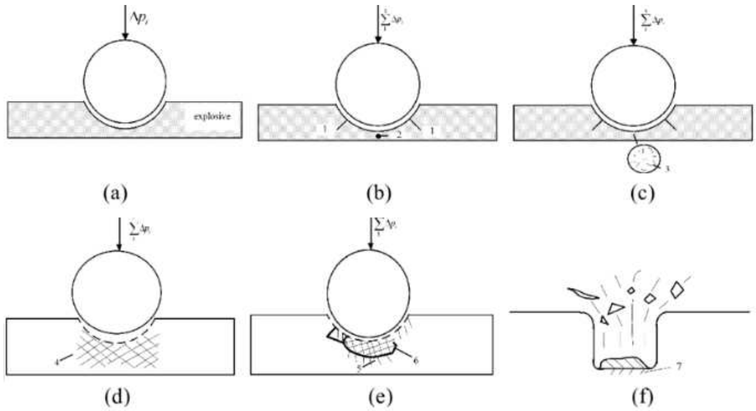

Fig. 9 Micro-mechanism of cavitation-induced destruction [24, 25]

At the micro-level, the process evolves through successive stages:

- (a) high-pressure contact and surface deformation
- (b–c) formation and growth of internal cracks
- (d–e) compression and propagation of radial cracks
- (f–g) formation of pits and fine fragmentation.

Cavitation-based destruction thus provides a controlled, non-detonative disintegration of explosives. The resulting surface marks and fragmentation patterns confirm its efficiency, safety, and ecological viability [26, 27].

2.2 Munitions Disposal

Munitions reutilization (disposal) constitutes a complex process aimed at the safe neutralization, recycling or destruction of munitions that are obsolete, damaged or no longer compliant with contemporary standards [28]. The primary objective of this process is to recover and valorize valuable materials and components while simultaneously minimizing environmental risks and preventing incidents associated with uncontrolled detonations or releases of toxic substances.

The process typically comprises the following principal stages:

- identification and classification of munitions,
- neutralization and dismantling of hazardous components,
- recycling or environmentally sound destruction of recovered materials.

Demilitarization (Disarming)

Mechanical demilitarization is a principal component of the disposal chain and comprises the deliberate disassembly of munitions using cutting tools on metal-working machinery or by abrasive water-jet cutting (Fig. 10). Operations typically include separation of the casing, removal of energetic fillers and dismantling of fuses. This approach is mainly applicable to munitions in sound physical condition and enables selective recovery of components suitable for reuse or recycling. Demilitarization not only prepares munitions for safe disposal but also constitutes a key enabler for transitioning obsolete armaments to sustainable, responsible management in accordance with international safety and environmental requirements.

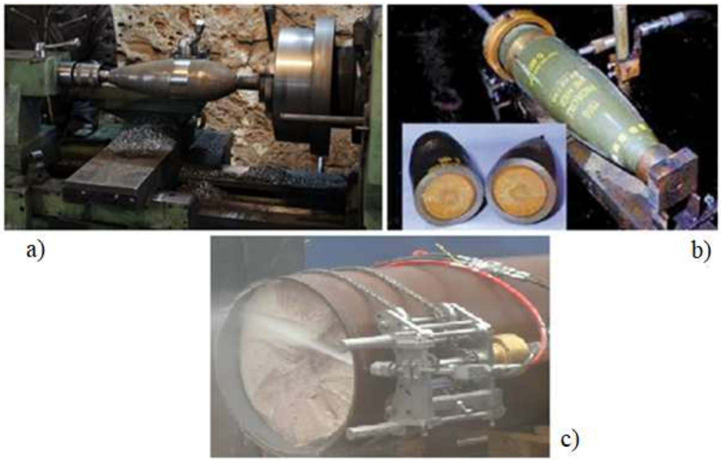

Fig. 10 Mechanical disassembly: (a) lathe operation for case removal; (b, c) water-abrasive cutting [29, 30]

Demilitarization not only prepares munitions for safe disposal but also constitutes a key enabler for transitioning obsolete armaments into sustainable, responsible management in accordance with international safety and environmental standards. Alongside mechanical methods, thermal and chemical techniques are used in practice.

Thermal Methods

Thermal methods are a primary technological approach for demilitarization and disposal of munitions, using heat to extract, neutralize, or destroy energetic materials. These methods are suited for organic explosives such as TNT and RDX, which can plastify or decompose under controlled heating. The process typically involves heating with steam, hot air, or infrared energy until explosives melt or soften (melt-out), allowing safe removal by pouring or mechanical extraction (Fig. 11). Automated systems control temperature and heating duration, preventing accidental ignition. Organic solvents may assist in dissolving compact or hard-to-access charges, and all operations occur in enclosed chambers with filtration and cooling to protect personnel and the environment.

Fig. 11 Extraction of explosive filler from a munition [31]

Innovative thermal methods include Supercritical Water Oxidation (SCWO), which uses water above 374 °C and 22.1 MPa. Supercritical water dissolves organics and oxygen efficiently, rapidly oxidizing explosives to CO_2, H_2O, and benign salts (Fig. 12).

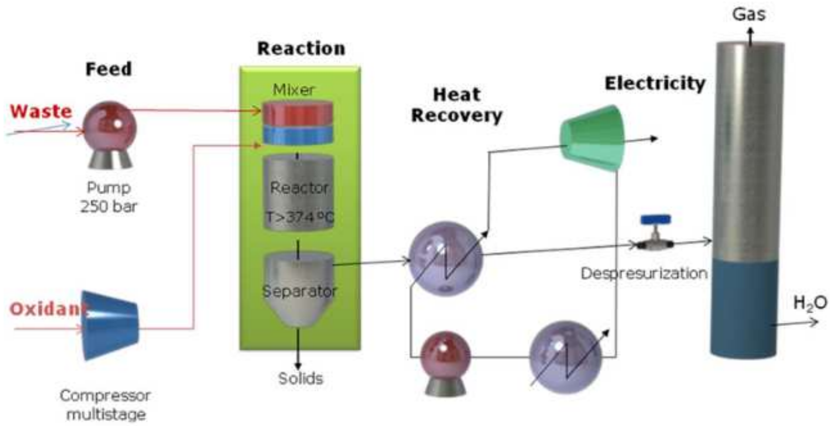

Fig. 12 Block diagram of a SCWO process [32, 33]

SCWO achieves > 99.99 % destruction efficiency, is environmentally friendly, and can be partially self-sufficient energy due to exothermic reactions. It is used in both mobile and large-scale facilities worldwide, including the US, Japan, and Switzerland.

Overall, thermal methods are effective, safe, and automatable, making them essential for processing obsolete or non-compliant munitions in accordance with modern safety and environmental standards [34].

Chemical Demilitarization

Chemical demilitarization encompasses a suite of precisely controlled reactions and processes designed to render energetic materials inert while minimizing environmental harm. These methods are particularly valuable for unstable, contaminated or otherwise inaccessible charges, where mechanical or thermal approaches are impractical or unsafe. The principal approaches comprise:

- solvolysis (dissolution): controlled dissolution of charges in organic solvents to enable subsequent neutralization and separation of energetic constituents,
- hydrolysis: chemical cleavage in aqueous acidic or alkaline media to convert explosives into less reactive, water-soluble species,
- oxidative destruction: application of strong oxidants (optionally catalyzed) to oxidize organic energetic molecules to inorganic residues,
- enzymatic/biocatalytic routes: utilization of specific enzymes to selectively degrade nitroaromatic and nitramine compounds under mild, environmentally benign conditions (largely experimental) [34].

Chemical methods offer clear benefits: they can achieve complete destruction without open combustion, handle complex or contaminated waste streams, and reduce the risk of accidental detonation during processing [35]. Their chief limitations lie in the potential formation of toxic intermediates and the requirement for tight control of reaction parameters (temperature, pressure, reagent dosage and kinetics). For this reason, all operations must be performed in sealed, instrumented systems with continuous monitoring and with adequate downstream treatment of effluents and residues. When correctly implemented, chemical routes achieve effective mineralization, yielding stable, non-toxic inorganic end-products. In practice, these techniques are most effective when integrated into hybrid process chains – for example after mechanical disassembly or alongside thermal treatments – thereby combining the strengths of each method to maximize safety and throughput. Accordingly, chemical demilitarization should be confined to certified facilities and executed by trained specialists only, following a comprehensive assessment of munition type, material condition and environmental implications.

2.3 Cryogenic Treatment

Cryogenic treatment involves cooling munitions to extremely low temperatures (typically below −150 °C) by immersion in or contact with liquid nitrogen (Fig. 13). Severe cooling induces physicochemical changes in the constituent materials: they become markedly more brittle and the molecular mobility of the energetic compounds is sharply reduced, thereby diminishing their sensitivity to shock, friction and heat [36].

Cryogenic conditioning of munition bodies facilitates their mechanical disassembly because metals embrittle and are prone to fracture under impact or compressive load. This enables the safe separation of charges and components without resorting to cutting, drilling or heating operations that might otherwise trigger unintended detonation. Consequently, the risk of accidental explosions is substantially reduced. Furthermore, cooled energetic fillers (e.g. TNT, RDX) show diminished tendency to auto-ignition or decomposition, rendering them safer for subsequent chemical or thermal processing.

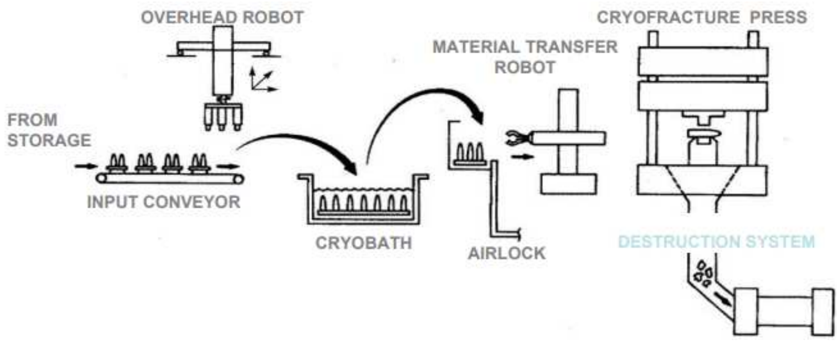

Fig. 13 Schematic of principal stages of cryogenic disposal for fragment-fused mortar rounds [37]

The typical process sequence is shown in Fig. 14:

- preparation: munitions are sorted and prepared for processing [37],
- liquid-nitrogen cooling: robotic handling systems (Fig. 14.1) place munitions into a cryogenic chamber or bath (Figs 14.2–14.3) and cool them to the target temperature (commonly below −150 °C). Liquid nitrogen supplies the required cooling and induces embrittlement of both the metal casing and the contained energetic material,

- mechanical fracturing: after cooling, munitions are subjected to controlled mechanical loads (e.g. compression – Fig. 14.4 or impact – Fig. 14.5) to effect fracture (Fig. 14.6). At cryogenic temperatures the materials fracture readily and without detonation,
- disassembly and segregation: fractured fragments are separated – metal casings (Fig. 14.7), explosive residues (Fig. 14.8) and other materials are segregated for further treatment or disposal.

Recovered energetic materials are subjected to further treatments for safe destruction or recovery, while metallic components may be recycled. This approach enables the safe and controlled disassembly of munitions, markedly reducing the risk of inadvertent detonation and facilitating their subsequent environmentally responsible disposal. It is predominantly employed in arsenals, logistics hubs and specialized military disposal facilities in countries with advanced munition safety technologies.

Fig. 14 Stages of cryogenic demilitarization [37]

3 Quantitative and Comparative Overview of Ammunition Demilitarization Methods on a Global Scale

The accumulation of obsolete, surplus, or unserviceable ammunition poses a significant security, environmental, and economic challenge on a global scale. According to UN and NATO data, over 100 million tons of conventional ammunition are stored or awaiting disposal worldwide, with a significant portion produced during the Cold War period and exceeding safe operational lifetimes [38–41]. This situation necessitates the implementation of reliable, economically feasible, and environmentally responsible demilitarization technologies.

International practice indicates that the choice of disposal method is determined by four key criteria: safety, environmental impact, economic efficiency, and technological complexity. Quantitative assessments of these indicators have been published in official reports by government and international organizations, as well as in scientific studies.

Official assessments by the U.S. Department of Defense indicate that the average approximate cost of ammunition demilitarization is around 1 000 USD/ton, based on real operational experience and used as a planning reference for surplus stock destruction [42]. Comparable figures are reported for EU countries and Southeast Europe, where costs vary between 900 and 1 200 USD/ton depending on the applied technology and environmental control measures.

A detailed analysis by Small Arms Survey and UNODA shows that disposal costs strongly depend on the type of ammunition and processing method – ranging from 130–700 USD/ton for small-caliber or casing components, up to over 2 000 USD/ton for high-energy explosives [43, 44]. The use of high-temperature incineration with gas cleaning systems further increases costs to approximately 1 600 USD/ton due to high energy consumption and the need for complex environmental installations [45].

A comparative evaluation of the main demilitarization methods – open detonation, incineration, combined mechanical and thermal treatment, cryogenic processing, and cavitation-based destruction – is presented in Tab. 1. The data indicate that open detonation remains the most economically affordable method but involves high environmental risks and operational restrictions in the EU. Conversely, combined mechanical-thermal technology demonstrates the highest safety level and lowest environmental impact, with moderate technological complexity and controllable costs.

Tab. 1 Comparative quantitative assessment of main ammunition demilitarization methods

Method	Safety	Environmental impact	Approx. cost [USD/ton]	Technological complexity	References
Open detonation	Medium	High	300–600	Low	[3, 5]
Incineration	Medium	Medium	1 200–1 600	Medium	[5, 7]
Mechanical + Thermal	High	Low	900–1 200	Medium	[4–7]
Cryogenic treatment	High	Low	1 800–2 500	High	[6, 8]
Cavitation-based	Medium	Medium	1 000–1 400	Medium	[8, 9]

An aggregated visual interpretation of the comparative indicators is provided in the radar diagram (Fig. 15), which clearly highlights the advantages of the mechanical-thermal approach regarding safety and environmental sustainability compared to other methods.

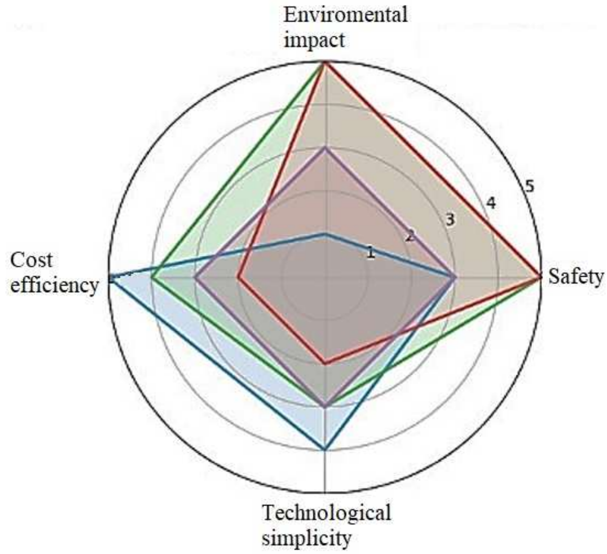

Fig. 15 Radar chart for comparative assessment of demilitarization methods by indicators: safety, environmental impact, cost, and technological complexity (based on data from [46]*)*

Quantitative data from international practice demonstrate that combined technological solutions, including mechanical casing separation and controlled thermal extraction of explosives, most closely meet contemporary industrial safety, environmental protection, and EU regulatory compliance requirements. These findings justify selecting this approach as a priority for the experimental and analytical investigations presented in the subsequent section.

Alongside economic and technological metrics, environmental aspects of ammunition demilitarization occupy a central role in international practice, particularly in the context of policies aimed at reducing carbon emissions and environmental contamination. Different disposal methods exhibit significantly varying levels of gas emissions, residual toxic products, and carbon footprints, which directly affect their applicability in EU and other industrialized countries.

In open detonation, still employed in several non-EU states, uncontrolled emissions of CO_2, CO, NO_x, NH_3, and particulate matter are reported, alongside the release of toxic nitrogen- and sulfur-containing compounds. According to OSCE and UNODA estimates, the destruction of 1 ton of TNT by open detonation generates approximately 2.5–3.0 tons of CO_2 equivalent, with no capture or filtration possibilities. Consequently, this method is strictly limited or banned in Germany, France, the Netherlands, and Scandinavian countries, permitted only under emergency conditions at controlled ranges.

Incineration, widely used in the USA, France, and the UK, provides a higher level of emission control but entails significant energy consumption and a substantial carbon footprint. U.S. Department of Defense data indicate that standard ammunition incineration lines generate 1.2–1.8 tons of CO_2 equivalent per ton of material, alongside NO_x and dioxins, requiring advanced gas-cleaning systems [4, 7]. This results in

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high capital and operational costs, as well as increased public and regulatory scrutiny in countries like Germany and Austria.

Combined mechanical-thermal technologies, applied in Germany, Switzerland, the Czech Republic, and partially in the USA, demonstrate the lowest environmental impact among industrially applicable methods. Here, the ammunition casing is mechanically separated, and the explosive content is extracted through controlled thermal treatment (steam, hot water, or low-temperature heating), enabling near-complete gas capture. NATO MSIAC and Small Arms Survey report emissions for this approach not exceeding 0.3–0.5 tons CO_2 equivalent per ton of ammunition, 4–6 times lower than conventional incineration [46]. This method is therefore preferred in countries with high environmental standards and strict regulations.

Cryogenic technologies, experimentally developed and applied in the USA and Canada, effectively eliminate thermal initiation risks and significantly limit toxic gas formation. Nevertheless, their carbon footprint remains relatively high (1.5–2.0 tons CO_2 equivalent per ton) due to the energy-intensive production of cryogenic agents, restricting their industrial scalability.

Cavitation-based hydrodynamic methods, tested in Japan and South Korea, show moderate environmental performance but are not yet sufficiently standardized for large-scale disposal of heavy-caliber ammunition, such as 120 mm mortar rounds.

In summary, international experience clearly indicates that combined mechanical-thermal technologies achieve an optimal balance among safety, environmental sustainability, and economic efficiency, making them the preferred choice for ammunition demilitarization in the EU and industrialized countries. These conclusions directly support the research approach adopted in this study and justify its applicability under real industrial conditions.

4 Results and Discussion

Based on a systematic review of technologies for the safe disposal and demilitarization of munitions, the following consolidated conclusions and practical recommendations can be drawn:

- **Complexity of the issue**: The disposal and demilitarization of munitions require a multidisciplinary approach – integrating mechanical, thermal, chemical, physic-chemical (including cavitation), and cryogenic methods according to the condition and type of ammunition.
- **Preferred primary workflow for post-production periodic inspection**: For post-production periodic inspection of manufactured munitions (including 120 mm high-explosive mortar shells), the most suitable approach is a combined workflow of mechanical processing followed by thermal extraction/processing. This sequence enables safe opening, controlled removal of energetic charges, and reduced environmental impact during subsequent disposal.
- **Role of mechanical disassembly**: Mechanical operations constitute the critical primary stage – they enable localized reduction of mass/volume of hazardous components, facilitate subsequent thermal or chemical procedures, and reduce the risk of accidental detonation when executed correctly.
- **Effectiveness and limitations of thermal methods**: Thermal technologies such as melt-out and supercritical water oxidation (SCWO) demonstrate high efficiency in the extraction and complete degradation of organic explosives.

SCWO achieves near-total mineralization but is energy- and capital-intensive, requiring stringent safety and emission controls.

- **Chemical methods – applicability and risks**: Chemical processes (solvolysis, hydrolysis, oxidative destruction, enzymatic methods) are valuable for unstable or contaminated charges but require enclosed reactor systems and rigorous process control, as partial reactions may produce toxic intermediates.
- **Cavitation and cryogenic technologies as supplementary options**: Cavitation methods provide a non-contact, precise mechanical/chemical effect within a liquid barrier, while cryogenic treatment (cooling below ~–150 °C) renders casings and charges brittle and safer for mechanical disassembly. Both approaches are suitable as adjunct solutions in hybrid disposal workflows.
- **Environmental and regulatory framework**: Compliance with national and European regulations (including periodic inspection requirements and safety standards) is mandatory. Method selection must consider environmental risks, monitoring of soil/water/air, and licensing requirements for operators.
- **Operational safety and personnel qualification**: All methods should be implemented only by certified operators in appropriately equipped and approved facilities, with integrated monitoring systems, emergency protocols, and procedures for effluent and emission management.
- **Limitations of the present review**: This publication is a literature review; conclusions are drawn from published data and standards and do not include original experimental results. Pilot-scale and field testing are recommended to validate and optimize processes.
- **Directions for future research and implementation**:
  - conduct experimental and pilot-scale studies to evaluate combined workflows (mechanical + thermal; mechanical + cavitation; cryogenic prior to mechanical) on real munitions,
  - develop methodologies for monitoring and assessing residual contaminants after different treatments,
  - perform economic and life-cycle (LCA) analyses to select optimal technological solutions in a national context,
  - standardize procedures and provide training/certification for personnel to ensure safe application.

5 Conclusions

The review and conducted analyses indicate that, for post-production periodic technical inspection of munitions, the most appropriate and technically justified approach is a combined method that integrates mechanical and thermal treatment. Periodic inspection aims to determine the composition, structure and properties of the explosive materials (EM), as well as the condition of the critical contact interfaces between the EM and the casings – with particular emphasis on signs of ageing and metal corrosion. These parameters are pivotal to safe operation and storage and therefore demand reliable, operationally applicable and environmentally responsible technological solutions.

The technique proposed and examined in this study comprises two consecutive stages: (1) mechanical processing – a primary lathe cutting operation using a parting tool, whereby the casing is split into two halves and (2) thermal treatment – application of a heat carrier (steam) to effect controlled melting and homogeneous removal of the contact layer of the explosive. This combination affords the following substantive advantages for periodic inspection:

- enhanced safety: controlled mechanical opening followed by thermal extraction reduces the risk of inadvertent mechanical or thermal initiation of the explosive material,
- robust diagnostic information: the recovered charge enables comprehensive chemical, structural and analytical assessment (composition, degradation state, presence of ageing products),
- operational efficiency: the procedure is suitable for random production sampling and can be automated/robotized for high-throughput inspection,
- environmental and technological flexibility: the extracted explosive material can be subsequently neutralized by an appropriate method – controlled detonation, incineration, cavitation-based destruction or cryogenic treatment – chosen according to its condition and quantity.

From a regulatory compliance perspective, the combined approach satisfies periodic inspection requirements applicable within the EU (including safety and life-cycle traceability obligations), while providing a practical solution for assessment of critical contact zones in 120 mm high-explosive mortar rounds – the subject matter of this study.

Practical recommendations: implementation of the method should be supported by certified processing cells, robotic manipulators for handling, systems for precise control of cutting speed and temperature, adequate means for capture and treatment of emissions and residues, and comprehensive operator training. Extracted samples must undergo full analytical characterization (chemical analysis, microstructure, corrosion status), and selection of the subsequent neutralization route should be based on those results and a thorough environmental impact assessment.

In conclusion, for safe, effective and regulatory-compliant post-production periodic inspection of munitions, the combined mechanical–thermal method represents the preferred technical solution – delivering a balance of diagnostic accuracy, operational safety and opportunities for environmentally responsible downstream treatment of recovered materials.

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